UNIVERSITY OF SOUTHAMPTON

VIBRATION-INDUCED WHITE FINGER IN DOCKYARD EMPLOYEES

Christopher Mark Nelson

Thesis submitted for the degree of Doctor of Philosophy

INSTITUTE OF SOUND AND VIBRATION RESEARCH

FACULTY OF ENGINEERING AND APPLIED SCIENCE

May 1992

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING AND APPLIED SCIENCE

INSTITUTE OF SOUND AND VIBRATION RESEARCH

Doctor of Philosophy

VIBRATION-INDUCED WHITE FINGER IN DOCKYARD EMPLOYEES

by Christopher Mark Nelson

Vibration-induced white finger (VWF) is a vascular condition associated with occupational exposure to hand-transmitted vibration. The fingers are prone to intermittent blanching attacks which may be triggered by cold conditions and are usually accompanied by numbness and tingling or pain. VWF has been associated with the use of various tools and processes, among which are the percussive and rotary metal-working tools used in ship repair work. This thesis describes a study of dose-effect relationships for VWF in dockyard employees.

A review of the literature revealed more than 40 epidemiological studies of VWF in workers using hand-held metal-working tools. Measurements of tool vibration have also been reported, but few researchers have combined epidemiological studies of VWF with measurements of the vibration exposures involved. Some dose-effect relationships have been suggested and current standards contain tentative dose-effect guidance. Some recent authors have suggested that the frequency weighting and time-dependencies assumed in current standards are inadequate.

Methods for the measurement of hand-transmitted vibration were assessed. The vibration characteristics of sixteen pneumatic tools commonly used in dockyard work were measured in the laboratory. Repeated measurements were made in three axes at each hand position and analysis included the computation of narrow-band spectra, acceleration magnitudes in octave bands and overall frequency-weighted and unweighted acceleration magnitudes.

A survey of vibration-exposed employees in a dockyard was conducted by questionnaire. Information related to symptoms of VWF, and the history of use of vibrating tools was obtained from each individual. The severity of blanching in each affected individual was recorded using a scoring system.

The severity and prevalence of symptoms were related to various measures of vibration 'dose' (i.e. combinations of measured vibration magnitudes and reported exposure times) by logistic regression and survival analysis. A highly significant relationship between VWF severity and exposure time was demonstrated. However, the use of frequency-weighted acceleration in dose calculations reduced the goodness of fit, while unweighted acceleration gave a small improvement in some cases. This suggests that higher frequencies in the range 6.3 Hz to 1250 Hz are of greater importance than current standards imply. The effect of vibration magnitude was found to be small compared with that of exposure time and no clear effect of vibration direction or vibration frequency was demonstrated.

No evidence was found for a time-dependency of the form assumed in current standards. It is possible that the risk of VWF may not be directly related to the vibration magnitude, but that a 'threshold' magnitude exists, below which the hazard is small and above which it is proportional to a function of the exposure time. Further investigation of this hypothesis is recommended.

CONTENTS

Page No.

Page No.

Page No.

ACKNOWLEDGEMENTS

I wish to thank the following people:

My supervisor, Professor M.J. Griffin. His clarity of thought and constructive comments have been a regular source of inspiration and encouragement.

Dr C. Osmond of the M.R.C. Environmental Epidemiology Unit, Southampton, for many helpful discussions and advice regarding statistical procedures.

Surgeon Captain P.J. Truesdale (Principal Medical Officer) and Mr E. Walker at Devonport for their helpful suggestions and comments during the project. Also Mr P. Ley, Mr D. Graham, Mr D. Lee, and Mr L. Lewis for their day-to-day help with practical arrangements at Devonport and Mr R. Cann for arranging the loan of the pneumatic tools.

The 1242 gentlemen in Devonport dockyard who took part in the questionnaire survey with such good humour.

My friends and colleagues, past and present, in the Human Factors Research Unit. Their support and companionship has been greatly appreciated.

Finally, my wife, Siobhan, who has been so tolerant of the demands of this work on my time and has provided me with support and encouragement during the writing of this thesis.

CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

Many different effects on health of occupational exposures to vibration have been reported in the literature. *Vibration disease* and *vibration syndrome* are collective terms which have been used to describe a number of conditions which can affect the vascular, neurological and musculoskeletal systems. For example, Futatsuka *et al.* (1985) listed 38 different complaints associated with habitual exposure to hand-transmitted vibration.

To approach an understanding of the effects of vibration on health, it is logical to study the components of the 'vibration syndrome' separately. This thesis is concerned primarily with *vibration-induced white finger* (VWF). This vascular condition is one of the most well-known effects of occupational exposure to hand-transmitted vibration and is a prescribed industrial injury in the United Kingdom (Department of Health and Social Security, 1985).

The thesis describes a study of vibration-induced white finger in users of pneumatic tools in ship repair work in Devonport Royal Dockyard. Details of symptoms of VWF and histories of tool use were documented in a questionnaire survey of several hundred vibration-exposed personnel. Measurements of the vibration characteristics of pneumatic tools were made. The relationships between the development of VWF and various measures of vibration exposure were investigated.

This chapter contains an introduction to vibration-induced white finger (Section 1.2) and describes the objectives of the study (Section 1.3). In the final section of the chapter (Section 1.4) the structure of the thesis is explained.

1.2 VIBRATION-INDUCED WHITE FINGER

1.2.1 Primary Raynaud's Phenomenon

Episodic blanching of the fingers, often accompanied by numbness and tingling, is known as *Raynaud's phenomenon* after Dr Maurice Raynaud who first described the condition in his M.D. thesis (Raynaud, 1888).

Finger blanching in Raynaud's phenomenon is usually precipitated by cold conditions and accompanied by a loss of sensation. On recovery, the fingers regain their normal colour. In a small proportion of patients the attacks become progressively more frequent and severe and the fingers become cyanotic in appearance, indicating permanent impairment of circulation. Tissue necrosis and gangrene have been reported in rare cases (Taylor and Pelmear, 1975).

When no external cause for such symptoms is identified, the condition is known as *primary Raynaud's disease* or *constitutional white (or cold) finger*. Primary Raynaud's disease appears to be hereditary, and symptoms are usually symmetrical (i.e. both hands are similarly affected). This condition is more commonly diagnosed in women than in men, and its prevalence in the general population has been estimated, in various published studies (see Griffin, 1990), from 1% to 22%. A study by Heslop *et al.* (1983), of patients in a general practice in the south of England, revealed prevalences of 17.6% (women) and 8.3% (men).

A number of causes of *secondary Raynaud's phenomenon* have been identified and several of these were listed by Taylor and Pelmear (1975). This list, which is reproduced in

Table 1.1, included vascular, neurological and connective tissue diseases, trauma (including vibration) and intoxication.

Table 1.1 Causes of Raynaud's phenomenon (after Taylor & Pelmear, 1975)

PRIMARY

Raynaud's Disease
Constitutional White Finger

SECONDARY

1. Connective Tissue Disease
    - (a) Scleroderma
    - (b) Systemic Lupus Erythematosus
    - (c) Rheumatoid Arthritis
    - (d) Dermatomyositis
    - (e) Polyarteritis Nodosa
    - (f) Mixed Connective Tissue Disease

2. Trauma
    - (i) Direct to Extremities
        - (a) Following injury, fracture or operation
        - (b) Of occupational origin (vibration)
        - (c) Frostbite and Immersion Syndrome
    - (ii) To Proximal Vessels by Compression
        - (a) Thoracic outlet syndrome (cervical rib, scalenus anterior muscle)
        - (b) Costoclavicular and hyperabduction syndromes

3. Occlusive Vascular Disease
    - (a) Thromboangiitis obliterans
    - (b) Arteriosclerosis
    - (c) Embolism
    - (d) Thrombosis

4. Dysglobulinaemia
    - (a) Cold haemagglutination syndrome
        - Cryoglobulinaemia
        - Macroglobulinaemia

5. Intoxication
    - (a) Acro-osteoylis
    - (b) Ergot
    - (c) Nicotine

6. Neurogenic
    - (a) Poliomyelitis
    - (b) Syringomyelia
    - (c) Hemiplegia

1.2.2 Vibration-induced Raynaud's Phenomenon

One of the first studies to suggest a link between Raynaud's phenomenon with exposure to hand-transmitted vibration was that by Loriga (1911) who observed symptoms in miners using pneumatic drilling machines. From the 1930s to the present day, many more researchers have observed the condition in workers exposed to vibration from a wide range of sources. A list of tools and processes associated with VWF was produced by Griffin (1980) from several hundreds of reports of the phenomenon in the literature. This list is reproduced in Table 1.2. A review of publications which have reported vascular symptoms among users of percussive and rotary metal-working tools, or which have described measurements of the vibration characteristics of such tools is included in Chapter 2.

Table 1.2 *Tools and processes associated with vibration-induced white finger (from Griffin, 1980)*

PERCUSSIVE METAL-WORKING TOOLS	PNEUMATIC HAMMERS AND DRILLS USED IN MINING ETC.
Pneumatic riveting	Pneumatic hammers
Pneumatic caulking	Pneumatic rock (etc.) drills
Chipping hammers	
Pneumatic fettling	CHAIN SAWS
Pneumatic drilling	Chain saws
Pneumatic clinching and flanging	A/V chain saws
Holding-up	
Swaging	OTHER PROCESSES AND TOOLS
	Shoe pounding-up machines
GRINDERS AND OTHER ROTARY TOOLS	Concrete vibro-thickeners
Pedestal grinders	Concrete levelling vibrotables
Hand-held portable grinders	
Flex driven grinders	
Flex driven polishers	
Rotary burring tools	

Several terms have been used to describe secondary Raynaud's phenomenon occurring as a result of vibration exposure. These include *Raynaud's phenomenon of occupational origin*, *Traumatic vasospastic disease* (TVD) and *vibration-induced white finger* (VWF). The Industrial Injuries Advisory Council have advised that 'vibration-induced white finger' is the preferred term in the United Kingdom (Department of Health and Social Security, 1970) and this term will be used in this thesis.

Taylor and Pelmear (1975) gave a clinical description of VWF. They stated that the early signs and symptoms are trivial (slight numbness or tingling), with no interference with work or other activities. With continued exposure to vibration, blanching attacks begin to occur, first affecting only a finger tip, but later extending to other areas. Attacks were said to be triggered by cold, and to be dependent on central body temperature, metabolic rate, vascular tone and emotional state. The duration of blanching attacks were said to be typically in the range 15-60 minutes, with a reactive hyperaemia (red flush) on recovery. As the condition advances, the frequency and duration of attacks tends to increase, sensitivity to touch and temperature are reduced and dexterity impaired. In advanced cases the fingers become cyanotic, occasionally leading to nutritional changes and skin necrosis (tissue death) at the finger tips. The 'Taylor-Pelmear staging system' was proposed for the classification of severities of VWF (see Section 2.4.1).

1.2.3 Mechanisms in Vibration-induced White Finger

The aetiology of VWF is not entirely understood. Several theories have been proposed and the condition is currently the subject of much medical research. Pyykkö and Starck (1986) reviewed the current knowledge. They concluded that the primary cause was increased resistance to circulation in the fingers after cooling, but that the cause of this was not known; however, they listed a number of possible physiological explanations. While acknowledging the absence of consensus regarding the mechanisms for VWF, Griffin (1990) described a hypothetical model for the condition, drawing on the information available in the literature. Study of the mechanisms for VWF is beyond the scope of this thesis. However, a brief summary of Griffin's tentative model is included below.

In cold conditions, the supply of blood to the extremities of the body is reduced by vasoconstriction (i.e. narrowing of the blood vessels). This is a normal function of the central nervous system and serves to conserve body core heat. The resulting drop in temperature can increase blood viscosity which may result in further decreased blood flow.

It is possible that vibration may cause damage to neurons (nerve-cells) in the hands and fingers, impairing local control of vasoconstriction. The circulation to the fingers may then be excessively reduced in cold conditions, resulting in blanching of parts distal to the locations of the nerve damage (e.g. finger tips or complete fingers). Vibration may also damage the blood vessels, causing permanent ischaemia of the fingers; in such cases, normal vasoconstriction in cold conditions might result in blanching. Injuries to these vessels might account for the cyanotic appearance of the hands of some VWF sufferers. Griffin's model allowed for possible separate effects of neuron damage (blanching, numbness, tingling) and blood vessel damage (acrocyanosis, eventual possible tissue death), and it was suggested that the two classes of injury might not be necessarily caused by the same types of vibration.

Numbness and tingling often accompany finger blanching. This may be attributed to the low skin temperatures during attacks. Repeated episodes of blanching may eventually result in nerve-cell degeneration from low temperatures and from reduced nutrition during interruptions to the blood supply. This, in turn, may further decrease the local control of vasoconstriction. Vibration damage to neurons may also be a direct cause of spontaneous numbness and tingling, which may be a different phenomenon to the neurological symptoms experienced *during* blanching attacks. This condition may develop independently of VWF; in this case, neurological symptoms would not necessarily be expected as a precursor to VWF as implied by the Taylor-Pelmear staging system.

1.2.4 Diagnostic Tests

No satisfactory diagnostic test for vibration-induced white finger has, as yet, been established. The aetiology of VWF is unclear, the symptoms are common to many other medical conditions (see Table 1.1) and it is difficult to demonstrate finger blanching at will (Griffin, 1990). An objective physiological test is desirable, particularly for diagnosis in individuals claiming to suffer from a vibration-induced condition.

Objective tests which have been considered for diagnostic purposes include measurements of vibrotactile thresholds, finger systolic blood pressure, finger temperature, nerve conduction velocity and aesthesiometry. Many tests have been shown to differentiate between persons with VWF and controls. However, tests of vascular function may not distinguish between VWF and other forms of Raynaud's phenomenon (e.g. Welsh, 1986) and tests of neurological function may be better indicators of past vibration exposure than of vascular injury (e.g. Hayward and Griffin, 1986).

In practice, many medical opinions in individual claims for compensation have been formed from subjective information given by the claimant and knowledge of his work history (Griffin, 1990). The majority of epidemiological studies of VWF appear to have relied on subjective reports of symptoms, usually obtained from the subjects by questionnaire.

1.3 OBJECTIVES OF STUDY

1.3.1 Devonport Dockyard Study

The presence of vibration-induced white finger in users of pneumatic tools (chipping hammers, riveting hammers, grinders, scalers, etc.) in ship repair work in British Naval Dockyards has been shown in several previous studies (Taylor *et al.*, 1975a; Oliver *et al.*, 1979; Payne, 1982). Although these studies, which are reviewed in Section 2.5, produced prevalence values for VWF, the vibration exposure was not investigated in detail.

At the start of the present study, the workforce at Devonport comprised approximately 12000 individuals, of whom up to 2000 were believed to be users of vibrating tools. This provided a larger population of vibration-exposed individuals than has been available in most previous studies.

An important objective of the study was to survey this population to establish the prevalence of VWF in different occupational groups in the dockyard and to determine the severity and history of the condition in affected individuals. This might allow the incidence rates for VWF to be estimated.

It was intended that a history of vibration exposure should be obtained from each individual, detailing the tools used and the approximate dates and durations for the use of each type of tool. This would aid the identification of the dockyard tools most closely associated with VWF.

The vibration characteristics of these tools were to be determined by measurements made in conditions intended to represent typical operations. The data obtained could be assessed in terms of the guidance for the assessment of hand-transmitted vibration exposures given in current standards ISO 5349 (International Organization for Standardization, 1986) and BS 6842 (British Standards Institution, 1987a).

1.3.2 Dose-effect Relationships

The standards ISO 5349 (1986) and BS 6842 (1987) describe methods for the evaluation of vibration exposures and, in appendices, dose-effect relationships for VWF are proposed. There is little epidemiological evidence to support the frequency weighting defined in the standards and the time-dependencies used are likely to have resulted from arbitrary agreement rather than scientific observation (see Section 2.3). It is desirable, therefore, that the relationships between VWF and different variables of vibration exposure (e.g. magnitude, frequency, direction, duration) should be studied further.

The review of literature in Chapter 2 identifies more than 40 epidemiological studies of VWF in users of metal-working tools and studies of the vibration characteristics of many of these tools. Few studies, however, have produced adequate epidemiological *and* vibration exposure data for an investigation of dose-effect relationships.

By combining vibration data obtained from tools used at Devonport and exposure time data obtained from the users of the tools, it was envisaged that a model of vibration 'dose' could be developed and compared with the severities and prevalences of VWF observed in different occupational groups in the dockyard.

The principal objective of the study was to compare different models of vibration dose (combinations of magnitude and exposure duration) when fitted to the epidemiological data from a large number of vibration-exposed workers. The effects of vibration direction and frequency content would be considered and different time-dependencies would be tested, with the aim of evolving a practical measure of 'dose' which would improve the prediction of VWF in exposed populations.

1.4 STRUCTURE OF THE THESIS

This thesis is divided into six chapters. The first chapter contains an introduction to vibration-induced white finger and explains the objectives of the research.

Chapter 2 contains a review of the literature. This includes reports of vibration measurements made on metal-working tools in industry and epidemiological studies of VWF, particularly in the ship repair industry. These studies are summarised in tabular form. Other sections describe standards, proposed methods for assessment of VWF severity and studies of the dose-effect relationship for VWF.

Chapter 3 is concerned with the measurement of vibration on pneumatic tools in use in the dockyard. The chapter describes assessments of transducers and mounting methods and the tool operating conditions in which the measurements were made. Repeated measurements were made in three axes at each hand position and the mean frequency-weighted and unweighted acceleration magnitudes are summarised in tabular form. Graphical and tabular data from these measurements are included as an appendix to the thesis.

Chapter 4 describes the questionnaire survey of vibration-exposed employees in Devonport dockyard. The design of the questionnaire is discussed, the surveyed population is described and the findings are summarised. This chapter also describes a selection procedure which was used to exclude persons with possible non-vibration-related symptoms from the investigation of dose-effect relationships.

Chapter 5 contains an account of the investigation of relationships between VWF and various alternative dose-effect models. The relationships between severity of VWF and the use of different tools are compared. The rates of development of VWF in different occupational groups are compared using survival analysis and the effects of frequency-weighting and different time-dependency relationships in the construction of vibration 'dose' models are shown using logistic regression.

Finally, Chapter 6 contains a summary of the findings of the study and the conclusions from the research. Suggestions for future work are also included.

CHAPTER 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

This chapter reviews publications which have described studies of exposure to hand-transmitted vibration, vibration-induced white finger in exposed populations and the relationship between vibration exposure and the resulting health effects.

Although vibration-related conditions have been associated with a variety of different tools and industrial processes, the emphasis here is on studies involving hand-held percussive and rotary metal working tools such as those associated with VWF in the present study at Devonport Dockyard.

The first section (2.2) is concerned with evaluation of the vibration characteristics of vibrating tools. Data from the literature are presented in tabular form, where possible, to allow comparison. Some of the practical difficulties with measurements of this kind and sources of inaccuracy are identified and discussed.

Section 2.3 describes standards for the evaluation of exposures to hand-transmitted vibration and for the assessment of the vibration severity of specific types of vibrating tool. These standards include documents produced by the British Standards Institution (BSI), the International Organization for Standardization (ISO) and the European Committee of Manufacturers of Compressors, Vacuum Pumps and Pneumatic Tools (PNEUROP).

Several schemes for the description and classification of severity of VWF have been proposed. These, which include the staging system (Taylor and Pelmear, 1975) and the scoring system (Griffin, 1982b), are discussed in Section 2.4.

Epidemiological studies of VWF in users of metal working hand tools are described in Section 2.5. Studies are listed in tabular form, showing the number of individuals exposed to vibration and the prevalence of finger blanching, neurological symptoms, latent period etc.

Section 2.6 is concerned with publications in which attempts have been made to develop quantitative relationships between VWF and vibration exposure. The magnitude, frequency content and duration of vibration and the prevalence, latent period and severity of VWF are among the variables considered.

2.2 STUDIES OF HAND TOOL VIBRATION CHARACTERISTICS

2.2.1 Background

Some of the earliest attempts at measuring the vibration characteristics of powered hand tools took place in the mid-1940s. Agate and Druett (1946, 1947) performed measurements on a variety of tools used in dockyard work, including chipping, riveting and scaling hammers and grinders. They used a 'Rochelle salt crystal', strapped to the tool under the hand, and produced displacement data in one-third octave bands between 40 Hz and 16 kHz. Although the fundamental frequency of operation of the tool was often assumed to be the dominant vibration frequency in early research, they recognised the presence, and possible importance, of vibrational energy over a wide range of frequencies. In contrast, Miura *et al.* (1957; 1959) used a 'portable vibrograph' and reported only the operating frequency and vibration displacement at that frequency (e.g. chipping hammer: 0.4-1.18 mm at 25 Hz, hand grinder: 0.024 mm at 52 Hz). Hunter *et al.* (1945)

measured the fundamental frequency of percussive tools used for riveting, caulking, fettling and scaling but did not investigate the magnitude of vibration.

The 1970s saw a rapid increase in the number of attempts to quantify the vibration characteristics of vibrating hand tools, with the publication of draft standards on the measurement and interpretation of hand-transmitted vibration, by both the British Standards Institution (1975) and the International Organisation for Standardization (1979). At this time, chain saw vibration was being studied extensively, particularly in Japan and Scandinavia, following a considerable increase in the use of these tools in forestry and a corresponding increase in the prevalence of VWF. This work resulted in the successful development of 'anti-vibration' saws with resiliently mounted handles. This achievement has not been repeated for many other kinds of vibrating tools.

Some reports of hand tool vibration measurement in the literature, particularly those concerned with percussive tools such as chipping and riveting hammers, have described instrumentation problems that may arise, such as d.c. shifts in transducers (see Section 2.2.2). Some published data may be erroneous due to this type of measurement artifact.

2.2.2 Chipping Hammer Studies

Those workers who have made measurements on chipping hammers, and have reported data for different frequencies of vibration, have obtained a wide range of acceleration values. The peak acceleration magnitudes occurring on these tools have been claimed to be as great as 100 000 g (Barber, 1982). Tables 2.1 and 2.2 summarise the available data in terms of r.m.s. acceleration in octave bands.

Table 2.1 Octave band acceleration magnitudes derived from published data from chipping hammer vibration measurements (handle/body of tool)

Octave band centre freq.	Octave band r.m.s. acceleration (ms^{-2}) 4	8	16	31,5	63	125	250	500	1000	2000	Notes
Agate & Druett (1947)	-	-	-	-	869	651	515	260	161	320	
Cherchi *et al*, (1968)	See text										
Miwa *et al*, (1974)	-	52	49	86	182	176	194	186	-	-	z-axis
Crosetti *et al*, (1974)	See text										
Kovshilo & Kodyskina (1975)	-	-	0,6	3,5	2,5	5,6	8,8	39,5	12,5	25,1	
Starck (1975)	-	-	-	44	-	-	-	125	-	-	Axial
								157			"
	-	-	-	-	-	-	-	63	-	314	Radial
								157			"
Fawer (1976)	-	16	10	10	20	20	20	30	20	20	Tool 1
	-	8	50	60	50	50	50	50	50	40	Tool 2
Redwood *et al*, (1977)	0,6	0,8	1,6	3	15	25	40	150	30	150	
Hempstock & O'Connor (1978)	2	2	3	15	20	17	20	55	70	-	Barrel
Brusl (1978)	-	-	29	29	42	67	92	104	-	-	
Harada & Matsumoto (1979)	-	-	50	130	244	158	187	202	-	-	Handle
	-	-	86	180	122	104	90	85	-	-	Barrel
Oliver *et al*, (1979)	47	65	80	120	110	95	66	85	60	-	Axial (Tool 1)
	38	48	70	450	450	250	150	140	120	-	Radial (Tool 1)
	100	90	100	55	53	48	50	49	42	-	Axial (Tool 2)
	85	90	110	65	65	65	57	65	65	-	Radial (Tool 2)
Bovenzi (1980)	-	-	6	32	46	49	43	80	-	-	Axial
	-	-	23	26	20	31	42	52	-	-	Radial
PNEUROP (1980)	-	-	-	14,7	23,0	30,2	39,5	63,1	109,1	-	Axial, mean
Auerbach (1982)	See text										
Reynolds *et al*, (1982)	-	39	35	110	99	106	127	136	173	-	Axial, handle
Tominaga (1982)	-	-	11	43	24	27	35	55	-	-	'Worst' tool
Rasmussen (1982)	-	8	3	11	19	30	40	60	67	-	
Lundström & Burstrom (1984)	-	-	1,4	2,7	12	11	14	47	107	-	
Clarke & Dalby (1986)	-	2,6	2,6	2,6	5,0	8	11	23	-	-	
Bovenzi (1988)	-	-	2	3	87	18	23	9	-	-	Axial
	-	-	1,4	1,5	4,4	3,4	6	9	-	-	Radial
Zhou & Chen (1990)	See text										

Table 2.2 *Octave band acceleration magnitudes derived from published data from chipping hammer chisel vibration measurements*

Octave band centre freq.	Octave band r.m.s. acceleration (ms^{-2})										
	4	8	16	31.5	63	125	250	500	1000	2000	Notes
Agate & Druett (1947)	-	-	-	-	170	164	142	157	250	469	
Kovshilo & Kodyskina (1975)	-	-	57	51	40	25	22	-	-	-	
Hempstock & O'Connor (1978)	12	15	30	20	30	100	350	800	600	-	
Reynolds *et al.* (1982)	-	1286	1964	17000	9225	8848	7826	6103	4676	-	Axial
Clarke *et al.* (1986)	-	-	14	19	21	27	168	693	-	-	Axial

Some of the values in Tables 2.1 and 2.2 are approximate, having been obtained from data presented graphically, often in one-third octave form, sometimes using a decibel scale and in one case in velocity units.

The study of Agate and Druett (1947) considered three chipping hammers. The 'medium sized' tool had a weight of 12¾ lb (5.8 kg) and was similar in size to the general purpose machines used in dockyard work in the 1980s. Data for the left and right hands were presented, the 'left hand' data presumably being obtained on the chisel of the tool. The measurements were made while the tool was engaged in an authentic task (cutting steel plate). These data, as shown in Tables 2.1 and 2.2, have been converted to octave band r.m.s. acceleration form from third-octave band peak displacement and are therefore approximate. However, comparison with the other more recent data suggests that these early measurements did not give accurate results, particularly at low frequencies.

Cherchi *et al.* (1968) made vibration measurements on three chipping hammers. Again, data were presented in displacement terms. The smallest of the three hammers (Atlas type KV638) had a weight of 9 kg. This suggests that the others were larger tools than are usually used in metal working. The operating frequency of the smallest tool was 23 Hz and the displacement measured at this frequency was 180 μm. Assuming the reported displacement to be a peak-to-peak measurement, and the motion at this frequency to be approximately sinusoidal, this is approximately equal to an r.m.s. acceleration of 1.32 ms^{-2}. The overall displacement was 476 μm. However, this cannot be converted to acceleration as the frequency content was not reported.

Crosetti *et al.* (1974) measured the vibration of a chipping hammer in three orthogonal axes using piezoelectric accelerometers (Kistler type 808). The tool was operated with controlled push force while cleaning a billet of steel. No frequency analysis was undertaken; the accelerometer output signal was fed to a chart recorder and the results recorded simply as positive and negative peak acceleration values at the fundamental frequency. It was assumed that only low frequencies were of any importance, since these were 'felt by the human limb'. (This assumption, that the relative contributions of different vibration frequencies are the same for subjective comfort responses and for injury, was also made by the standards committees who adopted a modified version of Miwa's constant discomfort curve as a frequency dependent base curve for imposing limits for regular hand-arm vibration exposures - see Section 2.3.1).

The vibration magnitudes reported by Crosetti were:

Longitudinal	-	80 g (800 ms^{-2})
Vertical	-	63 g (630 ms^{-2})
Transverse	-	68 g (680 ms^{-2})

at a frequency of 45 Hz. These measurements were made on the body of the chipping hammer. The measurement of longitudinal acceleration corresponds to a peak-to-peak displacement at 45 Hz of 10 mm. This amplitude might be considered excessively high for a tool of this size. It is possible that non-linear behaviour of the measuring apparatus, perhaps due to d.c. shifts in the accelerometer output, is responsible for this phenomenon.

Two demonstrations of the d.c. shift problem in piezoelectric accelerometers can be seen in the work of Kitchener (1977) and Frood (1977). They observed visible shifts in the zero line of an acceleration time history. By comparing acceleration data from a pneumatic tool in octave bands, it was shown that the use of a resilient mount under the accelerometer resulted in lower measured magnitudes at frequencies below approximately 100 Hz than were obtained from a rigidly mounted transducer. At higher frequencies the two mounting methods produced similar results.

The work of PNEUROP (European Committee of Manufacturers of Compressors, Vacuum Pumps and Pneumatic Tools, 1980) included a comparison of different piezoelectric accelerometers for use on percussive tools such as chipping hammers. They showed that the 'shock' accelerometers available at the time were not immune to d.c. shifts in such conditions, and that a general purpose accelerometer, mounted via a mechanical filter, gave satisfactory results in the frequency range 8 - 1000 Hz. This work was also reported by O'Connor and Lindqvist (1982). They stated that shocks contain frequencies which can excite the natural resonance of an accelerometer, and that d.c. shifts can result, making low frequency components difficult to measure. A potential solution to this problem was mechanical filtering. They made measurements in third-octave bands with two delta-shear piezoelectric accelerometers on mechanical filters mounted back-to-back on a chipping hammer handle and obtained practically identical results. When the performance of one of these transducers and that of a shock-rated accelerometer were compared, differences were apparent, especially in frequency bands below 100 Hz. When two shock accelerometers were compared back-to-back, there were also considerable differences in their output signals, although when the pressure of the air supply to the hammer was reduced they gave similar results.

These findings were important in the development of an understanding of the problems inherent in vibration measurements on percussive tools. Zero shifts can affect the low frequency end of the vibration spectrum and may remain undetected if no frequency analysis is performed. Some published data are presented simply as r.m.s. magnitudes (sometimes frequency weighted). These values may have been significantly elevated if measurement artifacts such as zero shifts were present. In the absence of frequency analysis, data may not be meaningful; elevated values at low frequencies are a useful indicator of d.c. shifts.

The causes of d.c. shifts with piezoelectric accelerometers were investigated by Chu (1987). He identified several causes of the phenomenon including overstress of piezoelectric sensing elements, physical movement of sensor parts, triboelectric cable noise and overload of signal conditioning circuits. This phenomenon is discussed further in Section 3.2.1.

PNEUROP (1980) also anticipated the requirement for standardised type tests for vibrating tools and developed a method for the testing of chipping hammers, which included a well-defined operating task for the tool (see Section 3.4.5). The method was evaluated in a 'Round Robin' trial in nine different laboratories using a Consolidated Pneumatic Tool Company No. 1 BSC chipping hammer. The octave band magnitudes from this study in Table 2.1 are the mean values, measured on the tool handle in the direction of chisel operation. The standard deviations were between 17% and 28% of the mean values and the variations were attributed to differences in the tool operators who had various levels of skill. Magnitudes at frequencies below 31.5 Hz were not reported, as the data in the 16 Hz band were thought to be dominated by instrumentation noise; the PNEUROP workers apparently recognised possible low-frequency artifacts, although they were confident that d.c. shifts were not a problem.

Kovshilo and Kodyskina (1975) made measurements on a large number of different pneumatic tools used in a Finnish dockyard. In accordance with the Soviet standard, their data were presented in octave bands as velocity in dB re. 10^{-6} cms^{-1}. After translation into acceleration units, the chipping hammer data are seen to have low values at the lower frequencies (0.6 ms^{-2} at 16 Hz), rising with increasing frequency as would be expected for a percussive vibration spectrum. The data reproduced here were from an Atlas Copco tool, type RRC-31. Spectra from another Atlas Copco tool (type R-2B) and from a Holman machine were also shown in this paper. The data were similar, although the lowest frequency (16 Hz) octave band magnitudes were of approximately 3 ms^{-2} r.m.s. The measurements were stated to be from the handle of the tool, along its axis in the vertical direction. This is a rather ambiguous description of the direction of the vibration measured. No details of transducer type, measurement techniques or apparatus were reported. Kovshilo and Kodyskina also published one set of data from a chipping hammer chisel, in octave bands from 16 to 250 Hz. The acceleration magnitudes fall with increasing frequency. This is unusual, the opposite trend being expected for such a high-shock vibration condition. The magnitude in the lowest octave band (16 Hz) corresponds to a peak-to peak displacement of about 50 mm. This seems an unlikely value, so these data may be in error.

Starck (1975) also made measurements on tools in a Finnish shipyard, and reported results in octave band r.m.s.

velocity form. A sound level meter was used, with a Brüel & Kjær accelerometer type 4340. Only the most severe components, according to the Soviet Standard, were published.

Fawer (1976) made measurements with a Brüel & Kjær type 4332 accelerometer in three axes near to the end of the cylinder of three different chipping hammers. Spectra were only presented for one axis (probably the longitudinal one). As two of the tools had very similar spectra, only one of them has been included in the table. The 8 Hz acceleration value of 16 ms^{-2} corresponds to a displacement of about 16 mm peak-to-peak. Overall r.m.s. acceleration values were given for each axis and tool and ranged from 700 to 1500 ms^{-2}.

The purpose of the study by Redwood *et al.* (1977) was to compare the vibration characteristics of two chipping hammers: a conventional tool and a modified hammer with a captive chisel. The data shown in the table are from the handle of the unmodified machine. Although the tool handle vibration was measured while chipping an iron casting, a soft wood work piece was employed while measuring on the modified chisel. The chisel data do not, therefore, represent authentic operating conditions and are not reproduced here. The paper contained examples of acceleration time histories illustrating d.c. shifts and described the use of a mechanical filter. The low magnitudes in the low frequency bands suggest that its use had the desired effect.

Hempstock and O'Connor (1978) published acceleration data for both the barrel and the chisel of the same chipping hammer. They used a piezoelectric accelerometer rigidly mounted on the tool by a hose clip. They were aware of the danger of d.c. shifts and the barrel data appear to be compatible with those of other workers. The 4 Hz band value measured on the chisel, however, represents a peak-to-peak displacement of approximately 50 mm and these data may therefore be suspect. (Even if the energy in the 4 Hz band was concentrated at the upper end of the band, e.g. at 5 Hz, the peak-to-peak displacement would be approximately 30 mm.)

Brusl (1978) also compared modified and unmodified chipping hammers. The data for the latter are shown here. The tool was employed in removing beads, welded onto a steel sheet, during vibration measurement. Since the variation in vibration characteristics of these tools is greatly dependent on the use to which the tool is put, an 'artificial' controlled tool task is a useful method for making direct comparisons between tools. Vibration in only one axis was measured (many workers have measured in three directions but reported only the most severe) and the orientation of the axis is not clear. A piezoelectric accelerometer (Brüel & Kjær type 4371) with mechanical filter was employed in this investigation.

The data from Harada and Matsumoto (1979) were obtained on the handle and the barrel of a chipping hammer (Kogyo type CH-11). No details of measurement techniques, instrumentation, axes or tool operating conditions were reported. The magnitudes reported are similar to those from Miwa and Yonekawa (1974). The presentation of vibration data as a set of one-third octave magnitudes suggests an awareness of the importance of the frequency content of the vibration spectra. In an earlier investigation, Matsumoto *et al.* (1969) had reported only the ranges of operating frequency and vibration displacement and acceleration. For a 'pneumer' (presumably a chipping hammer) these were 1560 - 3600 cycles per minute, 0.02 - 0.30 mm, 20.5 - 104.0 g). Harada and Matsumoto also presented measurements made on the handles of a chipping hammer fitted with a 'servo-arm', showing a reduction in acceleration magnitudes of approximately 25 dB.

Oliver *et al.* (1979) investigated the vibration characteristics of pneumatic hammers used in British Naval Dockyards. These included two chipping hammers: the Atlas Copco R30 and a Holman tool (designated (1) and (2) respectively in Table 2.1). A riveting hammer (Holman 60) was shown to have a very similar spectrum to the caulking hammer of the same make. The data show excessively high magnitudes at low frequencies, corresponding to displacements at 4 Hz of more than 100 mm! Again, no information on measurement techniques was included in this paper, other than the type of the accelerometer used.

Bovenzi *et al.* (1980) measured the vibration of several shipyard tools including a chipping hammer (Bohler M40). For these tests, the accelerometers (Bruel & Kjaer type 4367) were screwed directly into the tool itself; mechanical filters were not mentioned. It is perhaps surprising that the transverse axis showed greater low-frequency magnitudes than the longitudinal axis, although the absolute displacement value (2.3 mm r.m.s. at 16 Hz) is not unrealistic.

In 1982, Auerbach published an account of an investigation of the effect of a vibration-isolating handle on a chipping hammer. The data are not included in Table 2.1 because narrow band analysis was used and data were only published for selected frequencies; it is therefore difficult to compare these measurements with those made by other investigators. Auerbach made measurements on the handle of the tool using a rigidly mounted piezoelectric accelerometer (Endevco type 2225) and on the barrel with the accelerometer on a sheet metal mounting device. The vibration was measured in a direction perpendicular to the strike direction, with the tool running without load and chipping on cast iron.

The data presented by Reynolds *et al.* (1982a, 1984) were the result of a study of hand-transmitted vibration in industry by NIOSH (National Institute for Occupational Safety and Health) in the U.S.A. and were also documented by Wasserman *et al.* (1981) and Behrens *et al.* (1984). The data shown in Tables 2.1 and 2.2 are from one of four chipping hammers studied. The tool was being used for a slot chipping operation on cast iron. Vibration measurements were made in the longitudinal axis of the tool on the handle and on the chisel.

Although they were aware of the practical problems involved in measurements of this sort (d.c. shifts, instrumentation overloads etc.) the NIOSH workers rejected the use of mechanical filters on the basis that they could not be sure of the frequency response of an accelerometer so mounted. They elected to use instead, a high impact rated accelerometer (Bruel & Kjaer type 8309) rigidly fixed to the tool. The vibration conditions on the chisel were such that special arrangements had to be made to prevent the accelerometer becoming loose on its mounting during the operation. It was reported that accelerometers mounted on the chisels of chipping hammers failed after several minutes' exposure to these conditions.

The low frequency acceleration magnitudes measured on the chipping hammer handles by the NIOSH team are large in comparison with data from most other workers and their validity is therefore questionable. Few previous investigations had included chisel vibration, making comparisons difficult. However, the magnitudes reported (more than 1000 ms^{-2} in all octave bands) are at least one order of magnitude higher than those of Hempstock and O'Connor (1978).

The authors attempted to explain the very large apparent low-frequency displacements derived from these acceleration data by claiming that 'gross plastic deformations' occurred in the chisel during chipping operations and that therefore the principle of superposition did not apply and displacement values could not be calculated from acceleration data. No other evidence for these 'deformations', was reported. It seems more likely that their acceleration data were incorrect at low frequencies, possibly due to non-linear behaviour of the accelerometers. While defending the validity of their chisel data, the NIOSH researchers did, however, point out that levels measured on the handle were possibly of more relevance to an assessment of the operator's vibration exposure, since the handle had to be tightly held, whereas the chisel was allowed to slide through the fingers, resulting in poor mechanical coupling. However, the low-frequency magnitudes reported for the tool handles were high enough for their validity to be in doubt.

Tominaga (1982) published three spectra relating to rock drills, chipping hammers and riveting hammers. A triaxial accelerometer (PZT) was used, mounted on a small metal plate and attached to the tool with a hose clip. It is unclear which spectra relate to metal working tools. The data reproduced here are from the spectrum of greatest overall magnitude, although the others were similar.

Clarke *et al.* (1986) reported handle and chisel vibration in the longitudinal axis, measured using a general purpose accelerometer mounted via a mechanical filter on a block which was welded to the tool. The mechanical filter used was of their own design and manufacture. This device used two rubber discs, arranged in such a way that one was compressed while the other was extended at any instant. This was found to be an improvement on the proprietary mechanical filter which was destroyed when mounted on a chisel. The tool was used to chip the edge of a carbon steel bar which was clamped in a heavy steel block. The stroke length of the hammer was 56 mm. The purpose of this work was to investigate the degree of vibration isolation afforded by a sleeve of 'Sorbothane' placed over the chisel. A second set of data, obtained with the sleeve in place, showed reductions of up to 22 dB in some of the higher frequency bands, although a resonance in the thick resilient sleeve resulted in small increase in low frequency magnitudes.

Zhou and Chen (1990) quoted a frequency-weighted magnitude of 13.83 ms^{-2} for a 'casting cleaner' which was probably a chipping hammer. No details of measurement techniques were given, except that the equipment was manufactured by Bruel & Kjaer.

2.2.3 Riveting Hammer Studies

Pneumatic riveting tools were widely used in ship building and repair work before the advent of modern welding techniques. The large riveting hammers used in this type of (hot riveting) work are now rare, but smaller tools are commonly used in the aircraft industry.

Investigations of vibration exposures from riveting equipment are relatively few, compared with studies of chipping hammer vibration; examples of vibration data from riveting hammers are shown in Table 2.3.

The 1947 study by Agate and Druett included measurements of vibration on two riveting hammers. The data shown here are from the larger of the two, operating at 1050 beats per minute (17.5 Hz) and weighing 20½ lb (9.5 kg). The measurements were made while the machine was driving hot rivets of 1⅛ inches diameter into a steel plate against the force of a pneumatic 'holder up'. As with their chipping hammer data, the measurements were made in a single direction in third-octave band displacement terms and have been converted to octave band acceleration magnitudes for comparison with other data.

Table 2.3 Octave band acceleration magnitudes derived from published data from riveting hammer vibration measurements

	Octave band r.m.s. acceleration (ms^{-2})										
Octave band centre freq.	4	8	16	31.5	63	125	250	500	1000	2000	Notes
Agate &	-	-	-	-	36	44	51	43	45	67	Left hand
Druett (1947)	-	-	-	-	230	234	124	-	190	424	Right hand
Starck (1975)	-	-	-	20 24	-	-	-	-	-	-	
Voss *et al.* (1978)	1.0	1.5	2.3	14.6	6.7	10.4	14.2	15.4	17.0	-	
Miwa *et al.* (1979)	-	-	0.6	11.4	32.5	34.0	58.1	95.7	-	-	z-axis
Oliver *et al.*	56	76	95	75	62	59	54	67	52	-	Axial
(1979)	46	60	86	86	67	59	46	50	56	-	Radial
Tominaga (1982)	See text										
Dandanell & Engström (1986)	-	-	-	7	13	10	135	124	129	145	Axial
Zhou & Chen (1990)	See text										

Starck (1975) investigated a machine of similar weight (6.3 kg) but with a faster operating rate (29 Hz). Two measured velocity magnitudes were reported for the most severe component (the octave band at 31.5 Hz).

The data from the study by Voss *et al.* (1978) are from an Atlas Copco type RRN21 hammer which was one of three machines studied. These data were published as decibel values in third-octave bands. The lower magnitudes may indicate that this machine had a different size and purpose to those mentioned above; it is also possible that measurement techniques were better than those used in some earlier studies.

Measurements in three axes were made in 1979 by Miwa *et al.* on a small riveting hammer. A triaxial accelerometer (Rion Co.) of 70 g mass was used with a vibration meter. The three axes produced similar magnitudes of acceleration; the z-axis data are reproduced here in octave bands from the published third-octave band data. The low frequency magnitudes are of the same order as those of Voss *et al.*, although more high frequency energy was measured by Miwa.

Oliver *et al.* (1979) included a Holman type 60 riveting hammer in their study of vibrating tools in British Naval dockyards. Extremely high magnitudes at low frequencies indicate that here, as with their chipping hammer data, measurement problems were not identified.

A riveting hammer was included in the study by Tominaga (1982). However, as mentioned in Section 2.2.2, the published spectra were not clearly identified. The data in Table 2.1 may relate to this tool.

Dandanell and Engström (1986) published the results of an investigation of the vibration exposure of riveters working in the aircraft industry. A wide range of frequencies was measured: a displacement transducer (Bofors RLL-2) was used for frequencies up to 1 kHz, a piezoelectric shock accelerometer Brüel & Kjær 8309) for the range 1-40 kHz and an ultrasonic probe measured 'vibration intensity' in Wm^{-1} for frequencies up to 10 MHz. Measurements were made in the direction of strike on the hammer and on the 'bucking bar' at the other end of the rivet. The data in the table were reproduced from a ⅓-octave acceleration spectrum with a frequency range of approximately 50 Hz - 40 kHz. Similar magnitudes (especially at frequencies below 2 kHz) were published for the bucking bar vibration. Frequency-weighted acceleration values were produced according to ISO 5349;

these were 10 ms^{-2} r.m.s. and 11 ms^{-2} r.m.s. for the hammer and bucking bar respectively.

A frequency-weighted acceleration of 11.24 ms^{-2} r.m.s. for riveting was reported by Zhou and Chen (1990).

2.2.4 Scaling Tool Studies.

Scaling tools are widely used in ship repair work for the removal of rust, scale, old paint etc. from steel. Pneumatic scaling tools fall into three general categories:

a. Scaling hammers or 'nobblers'. A piston with a knurled head moves rapidly in and out of a cylinder in the hammer head which is held against the work surface.

b. Scaling chisels or pneumatic paint scrapers. Usually a cylindrical tool, with a wide, captive chisel mounted at one end, which vibrates against the work surface.

c. Needle scalers. These tools are often similar in appearance to type b., with a cluster of steel 'needles' in place of the chisel. Some needle scalers have a pistol grip handle at the rear end.

Few studies have been made of the vibration characteristics of scaling tools, compared to the attention received by chipping hammers, grinders, etc. However, several previous researchers have made investigations of tools similar to those encountered during the present study at Devonport. Examples of data from these studies are shown in Table 2.4.

Table 2.4 Octave band acceleration magnitudes derived from published data from scaling tool vibration measurements

	Octave band r.m.s. acceleration (ms^{-2})										
Octave band centre freq.	4	8	16	31,5	63	125	250	500	1000	2000	Notes
Scaling hammers (or nobblers):											
Agate & Druett (1947)	-	-	-	-	66	57	61	30	45	50	
Hempstock & O'Connor (1974)	-	70	60	40	50	40	60	50	40	-	Tool head
Kovshilo & Kodyskina (1975)	-	-	1,4	2,2	6,3	12,4	15,7	33,3	25,0	28,1	
Starck (1975)	-	-	2,3	10,9	-	-	94,3	-	-	-	Left hand
	-	-	-	-	27,7	70,7 78,5	-	-	-	-	Right hand
Starck *et al.* (1990)	See text.										
Needle scalers											
Hempstock & O'Connor (1974)	-	10	30	50	50	70	70	70	100	-	
Kovshilo & Kodyskina (1975)	-	-	0,7	4,0	3,5	5,0	5,6	12,5	12,5	99,8	
Starck (1975)	-	-	-	-	-	-	-	94,2 31,4	75,4	-	
Lundstrom &	-	3,4	3,8	3,5	10,6	6,4	15,4	5,4	164,0	-	x-axis
Burstrom (1984)	-	2,3	3,1	12,7	51,6	21,3	16,6	37,2	61,4	-	z-axis

In 1947, Agate and Druett included a scaling hammer (nobbler) in their study of many types of vibrating tool. This tool had an operating frequency of 4500 beats per minute (75 Hz) and weighed 4½ lb (2 kg). The vibration measurements made in this study were reported in displacement units in third-octave bands (up to 16 kHz for some tools). As before, the data reproduced here have been converted to octave band r.m.s. acceleration form for comparison with other studies. It has been assumed that 'third-octave amplitude' refers to the peak displacement value.

These data are from the left hand (piston end of the tool) in the direction of strike. Agate and Druett stated that there was 'less disturbance' from this tool than from any of the other piston operated (percussive) tools in the study. This was the case with the vibration magnitudes reported in displacement units, however, the acceleration values are high, and are of the same order of magnitude as those obtained from a similar tool during the present study of tools in Devonport Dockyard.

Another early study of scaling hammer vibration was that of Miura in 1957. The tool had a weight of 2 kg and an operating rate of 4200 beats per minute (70 Hz). Only the fundamental displacement amplitude was measured, at 0.172 mm, which corresponds to an acceleration of 23.5 ms^{-2} r.m.s., assuming the vibration at this frequency to be approximately sinusoidal.

Hempstock and O'Connor (1975a, 1975b) reported vibration data from a nobbler (scaling hammer). They rigidly attached a piezoelectric accelerometer to the head of the tool using a hose clip. The data shown in Table 2.4 were obtained with the operator's hand pushing down on the tool head. The acceleration was doubled at some frequencies when both hands were on the handle. Acceleration measured on the handle itself was much lower than on the head at low frequencies, but showed a very sharp peak in the response at the strike frequency (about 50 Hz). Only one axis of vibration was reported.

The vibration characteristics of a Jason needle scaler were also reported by Hempstock and O'Connor (1974). Again octave band r.m.s. acceleration values were given for one axis only, presumably in the direction of strike.

Kovshilo and Kodyskina (1975) reported measurements of vibration on several scaling tools. Data for one scaling hammer (Atlas Copco type RRC-12) and one needle scaler (Von Arx type 2B) are reproduced here. The data were originally reported as r.m.s. velocity values in octave bands in accordance with Soviet Standards.

Scaling hammers and needle scalers were also investigated by Starck (1975), again reporting the 'most harmful' octave band vibration magnitudes in velocity form. The hammers were 1.4 and 1.7 kg in weight and operated at a strike frequency of 69 Hz. The needle guns had an operating frequency of 78 Hz. In a later study, Starck *et al.* (1990) a value of 13 ms^{-2} r.m.s. was reported for a scaling hammer.

In 1984, Lundstrom and Burstrom published vibration data from a Von Arx needle gun type 45-B. These measurements included three axes at each hand position and data were presented as r.m.s. acceleration in one-third octave bands. These values are presented here, in octave band form, for two vibration axes (axial and radial) measured on the barrel of the tool. The other radial axis gave very similar results, and slightly lower magnitudes were measured on the handle.

2.2.5 Grinder Studies

Two distinct categories of grinder exist: pedestal grinders and hand-held grinders. In pedestal grinding, the machine is fixed and the operator holds the work piece against the rotating abrasive wheel. The vibration transmitted to the fingers is therefore dependent on the mass of the work piece. Because of this source of variability in pedestal grinder vibration, a meaningful comparison of data from different investigations would be difficult. Since pedestal grinding at Devonport Dockyard was not found to be widespread, measurements on this type of tool were not undertaken in the present study. Pedestal grinder vibration studies are not, therefore, included in this review. VWF has, however, been observed in some populations exposed to vibration from pedestal grinders, and vibration exposures have been measured by several workers (e.g. Agate *et al.* (1946), Hempstock and O'Connor (1974, 1975), Kitchener (1975), Starck *et al.* (1983), Hodges (1985), Xu and Ding (1990)).

Hand-held pneumatic and electric grinders are used in many industries such as steel fabrication and ship-building. Several different basic types of hand-held grinder exist: these may be simply categorised as the vertical, straight, angle and collet types. Descriptions of these grinder types are included below.

The variations found in the design and size of hand held grinders are such that it is difficult to make meaningful comparisons between vibration data in the literature, particularly in cases where the type of tool is not reported. However, the data presented in Table 2.5 show the range of acceleration magnitudes that have been reported. Again, for ease of comparison, octave band magnitudes are given in the table, although in many cases the data were presented in a different form in the original publications.

The vibration characteristics of rotary tools are usually found to have relatively low peak acceleration magnitudes compared with those of the percussive tools discussed previously (e.g. Bovenzi *et al.*, 1980; Reynolds *et al.*, 1984). Measurement problems involving non-linear behaviour of piezoelectric accelerometers, d.c. shifts, instrument overload, etc. are rarely reported, so many of the data presented here may be accepted with more confidence than, for example, those for chipping hammers. However, large variations in acceleration values can be seen in the published data, indicating that grinder vibration is highly variable; many factors appear to affect the vibration, including the positioning and alignment of transducers (e.g. O'Connor and Frood, 1983), the mass of the grinder itself, the speed of rotation, the composition and balance of the grinding wheel or disc (e.g. O'Connor and Frood, 1983, Eklund *et al.*, 1986; 1987) the mass and surface characteristics of the workpiece and the operator's grip and push forces. It is desirable, although not common practice in the examples included here, to describe in detail the tool operating conditions during vibration measurements. A document produced by PNEUROP (European Committee of Manufacturers of Compressors, Vacuum Pumps and Pneumatic Tools) in 1983 proposed standard procedures for the measurement of grinder vibration and the reporting of results, allowing comparisons to be made between the vibration characteristics of different tools, measured under identical conditions.

The work of PNEUROP in developing methods for making repeatable vibration measurements for hand-held grinders was reported in 1978 (European Committee of Manufacturers of Compressors, Vacuum Pumps and Pneumatic Tools, 1978). For grinders running at 6000 r.p.m they observed close agreement between vibration magnitudes for free-running and grinding operations in the octave band centred on 125 Hz (i.e. the band containing the fundamental frequency). Vibration at this frequency was attributed primarily to out-of-balance forces in the wheel. Magnitudes in the 250 Hz and 500 Hz bands were greater when grinding than when free-running, by a factor of between 2 and 10. Vibration at these frequencies was attributed to interactions between the abrasive wheel and the workpiece.

Table 2.5a Octave band acceleration magnitudes derived from published data from hand-held grinder vibration measurements

Octave band centre freq.	Octave band r,m,s, acceleration (ms^{-2}) 4	8	16	31,5	63	125	250	500	1000	2000	Notes
Vertical grinders;											
Kovshilo & Kodyskina (1975)	-	-	-	0,0	0,2	9,9	2,2	14,0	12,5	19,9	
Voss *et al*, (1978)	10,0	6,4	2,8	6,0	61,6	22,1	37,2	79,8	42,3	-	
Miwa *et al*, (1979)	-	-	0,3	0,4	4,7	15,4	19,6	25,5	-	-	
Wenstrom (1981)	-	-	-	-	4,0	16,5	17,7	37,7	-	-	
Reynolds *et al*, (1982)	-	0,2	0,3	0,8	1,2	2,0	3,3	2,4	2,6	-	Right hand, z-axis
Lundstrom & Burstrom (1984)	-	-	-	1,5	4,1	8,8	17,0	18,6	43,4	-	Left hand, y-axis
Scory *et al*, (1990)	-	-	-	0,3	17,8	31,7	8,8	9,8	6,0	-	x-axis (lab,)
	-	0,3	1,3	6,8	13,9	25,7	42,5	87,4	17,9	-	x-axis (field)
Straight grinders;											
Agate & Druett (1947)	-	-	-	-	64,7	72,3	88,1	65,3	73,3	229,0	Sml, LH
	-	-	-	-	-	-	30,6	20,0	34,1	27,3	Lge, RH
Starck (1975)	-	-	-	-	13,9	9,42 11,8	-	-	-		
Glass (1979)	-	-	0,9	1,0	50	84	84	44	-	-	RH, x-axis
Reynolds *et al*, (1982)	-	0,1	0,1	0,2	4,2	0,9	2,0	0,9	2,2	-	RH, z-axis
Eklund *et al*, (1986)	See text										
Clarke & Dalby (1987)	See text										
Hansson *et al*, (1987)	See text										
Xu & Ding	-	-	-	1,9	8,4	20,9	22,0	60,3	42,0	-	'Hanging' grinder

Table 2.5b *Octave band acceleration magnitudes derived from published data from hand-held grinder vibration measurements*

	Octave band r.m.s. acceleration (ms^{-2})										
Octave band centre freq.	4	8	16	31,5	63	125	250	500	1000	2000	Notes
Angle grinders;											
Starck (1975)	-	-	-	-	-	11,8	-	-	-	-	Main handle
						15,7					
						31,5					
	-	-	-	-	7,9	22,5	-	62,8	-	-	Side handle
Bovenzi *et al.*	-	-	0,2	0,5	0,9	2,0	7,8	19,6	-	-	Sml, z-axis
(1980)	-	-	0,6	0,6	8,7	3,5	5,4	56,6	-	-	Med, z-axis
	-	-	1,6	2,0	3,1	4,1	7,0	11,7	-	-	Lge, z-axis
Suggs *et al.* (1982)	0,1	0,2	0,2	0,4	13,9	3,7	5,8	16,7	28,9	-	z-axis
Hodges (1985)	-	0,8	0,6	1,7	22,9	29,2	64,8	73,1	13,3	-	Lge, front, z
	-	0,5	0,6	0,6	1,0	5,1	7,8	2,7	5,0	-	Sml, z-axis
Eklund *et al.* (1986)	See text										
Hansson *et al.* (1987)	See text										
Collet or die grinders;											
Hodges (1985)	-	0,5	0,5	0,5	0,8	7,1	30,3	7,4	9,3	-	stone, y-axis
		0,4	0,3	0,3	0,9	6,3	19,2	5,8	5,5	-	wheel, y-axis
Hansson *et al.* (1987)	See text										
Burström *et al.* (1987)	See text										
Unknown type;											
Miwa & Yonekawa (1974)	-	-	7,3	7,3	13,2	24,0	37,3	71,9	-	-	z-axis
Hempstock & O'Connor (1975)	1,3	1,2	1,7	2,5	4,0	6,0	6,8	8,5	10,0	9,5	Body, radial
Kitchener (1975)	-	-	0,2	0,9	2,5	10	5	16	31	40	Radial
Tominaga (1982)	-	3,6	4,9	5,7	12,7	20,4	31,2	47,6	-	-	Worst
Zhou & Chen (1990)	See text										

It was stated in the PNEUROP report that unbalance in the grinding wheel is useful in improving the efficiency of grinding because the dynamic forces of the wheel on the workpiece allow the operator to use a smaller push force than would be the case with a well-balanced wheel. It was observed that an experienced operator would sometimes deliberately introduce a state of unbalance into his grinding wheel.

Further work by PNEUROP was reported by O'Connor and Frood (1983). They found that the dominant axis of grinder vibration was usually in the direction perpendicular to the surface being ground and that vibration magnitudes varied with the position of the transducer on the handle, particularly in the high frequency bands. They recommended that the location of transducers should be specified exactly. It was also reported that out-of-balance forces from the grinding wheel were found to make a significant and variable contribution to the vibration. The 'free-running' vibration magnitude was said to be a good indicator of the balance of the wheel and the frequency weighted magnitude when grinding was found to be highly correlated with the out-of-balance of the wheel. O'Connor (1989) cited this finding, and those of Eklund *et al.* (1986; 1987) in an explanation of a draft ISO standard for grinder type testing (see Section 2.3.2).

Eklund *et al.* studied the effect of grinding wheel balance in three types of grinder: two angle grinders (Atlas Copco type LSV 36, fitted with grinding wheels of 125 mm diameter and Bosch type 1321 fitted with wheels of 180 mm diameter) and a straight grinder (Bahco type SF8-BT fitted with wheels of 76 mm diameter). Vibration measurements were made while free running (i.e. not grinding) with different wheels which were removed and remounted between measurements. It was found that a wide range of weighted acceleration values could be obtained for a single wheel (e.g. a range of 7 dB for a typical 125 mm wheel) and that the mean magnitudes for seven different wheels also had a large range (138 - 143 dB re. 10^{-6} ms^{-2} or 7.9 - 22.4 ms^{-2} r.m.s.). These findings were attributed to eccentricity of the centre hole position and in variations in mass unbalance respectively. By removing and remounting the larger wheels, the vibration could often be reduced. This effect was reported to be less pronounced in the 76 mm grinding wheels. and in larger wheels with large mass unbalance.

Grinding for up to 7 minutes had little overall effect on vibration; with some wheels the vibration magnitude increased and with some it decreased. Only the 180 mm wheels had significantly higher vibration at the start than after 7 minutes of grinding. It was suggested that, once mounted on the machine, the vibration produced by most wheels when grinding was 'fixed' and did not change with time. The vibration magnitude when free-running after 1 minute of grinding and the vibration while grinding was reported to be similar for the majority of wheels. This may have been the case in this study because the unbalance in the wheels dominated the vibration, even when grinding: the weighted acceleration magnitudes reported are large compared with other grinder studies (e.g. Clarke and Dalby (1987), see below).

Vertical grinders
In the present (Devonport Dockyard) study, vertical grinders were found to be the most used type of grinder in modern dockyard work. Most vertical grinders have a disc diameter of 7 or 9 inches (180 or 230 mm) and a maximum speed of approximately 6000 r.p.m. (100 Hz). Two cylindrical handles, one of which incorporates the trigger control, are usually attached to the body of the tool and are mounted at right angles to one another and to the axis of rotation of the disc. In some cases, both the edge and the face of the disc may be used for grinding.

Kovshilo and Kodyskina (1975) made measurements on five different vertical grinders, in their study of shipyard tools. The Atlas Copco LSS-4 data shown here are typical results; no data were obtained for frequencies below 63 Hz.

Several vertical grinders, all of Atlas Copco manufacture, were studied by Voss *et al.* (1978). Data from a typical spectrum are presented here. The value of 10 ms^{-2} r.m.s. in the 4 Hz band is surprisingly large; the corresponding peak displacement is in excess of 20 mm. It is possible that this is due to a rapid 'to-and-fro' motion of the grinder on the workpiece due to the operator's technique. Such a component at this frequency would be likely to make a dominant contribution to the frequency-weighted magnitude and illustrates the importance of comprehensive reporting of variables relating to the operating conditions of the tool if comparisons are to be made with standards or other measurements.

The measurements by Miwa *et al.* (1979) were made in three axes on a grinder fitted with a disc of 7 inches diameter. Magnitudes were similar for all axes; the data from the y-axis on the right handle are included here.

Data from a series of 'Round Robin' tests performed by several PNEUROP laboratories were reported by Wenstrom in 1981. The magnitudes shown were measured on machine as supplied by PNEUROP. When a different disc was fitted, the magnitude was doubled at 63 Hz but reduced by over 20% at 500 Hz. The axes in which these measurements were made was not reported.

The data from Reynolds *et al.* (1982) were obtained from a vertical grinder fitted with a sanding disc. These data are not therefore directly comparable with other magnitudes presented here.

Lundstrom and Burstrom (1984) produced 23 sets of spectra from vertical grinders. The data presented here represent a fairly severe example; the spectra exhibited similar shapes in all axes.

Scory *et al.* (1990) described a method for measuring the vibration of grinders in controlled conditions. The data in the table are the average values from 24 repeat measurements in the laboratory. Field measurements produced spectra with greater magnitudes (up to 20 dB greater) at all frequencies except the dominant frequency (approximately 100 Hz, presumably the frequency of rotation). The authors pointed out that variations in the method of tool use in the field resulted in significant differences in spectral content, but that the 100 Hz component, which dominated the weighted magnitude, was little affected.

Straight grinders

Straight grinders (also known as 'horizontal' or 'end' grinders) consist of a long, approximately cylindrical, body with a grinding wheel mounted at one end. The design of grinders, in contrast with that of many percussive tools, has changed considerably over several decades; straight pneumatic grinders have become less popular in recent years, since the advent of the faster disc and collet grinders, although straight high frequency electric types are common.

The two machines investigated by Agate and Druett in 1947 are unusual by modern standards: the first, smaller grinder was a high speed light weight device, held in one hand and powered by a flexible drive from a remote motor. The larger machine had an electric motor in the handle and its weight made it necessary to suspend the grinder over the workpiece with a counterweight.

Glass (1979) investigated the vibration transmitted to both hands in three axes from a large electric high-frequency straight grinder with an operating speed of 5400 r.p.m. while grinding the surfaces of large steel plates. The data presented here are for the most severe axis of vibration (right hand, x-axis).

The measurements reported by Reynolds *et al.* in 1982 were part of the NIOSH study; these example data are for a straight grinder with a 'course radial' wheel. The machine was also tested with 'fine radial' and 'flared cup' wheels. The 'total' acceleration magnitudes reported (root-sum-of-squares of acceleration magnitudes in three axes) ranged from 6.36 ms^{-2} r.m.s. (right hand, fine radial wheel) to 20.5 ms^{-2} r.m.s. (left hand, flared cup wheel). The frequency range of the measurements was 6.3 - 1000 Hz.

Clarke and Dalby (1987) investigated the vibration on an electric high frequency grinder (Fein type MYSHO 8521a running at 10200 r.p.m. with a '16 grit' grinding wheel of 125 mm diameter. A piezoelectric accelerometer was mounted on a stud attached to a curved metal 'former' which was held against the cylindrical handle of the grinder. The stud was long enough for the fingers to pass between the former and the transducer. The frequency response of this mounting device was not reported. Weighted acceleration magnitudes were found to be in the range 2.4 ms^{-2} to 5.5 ms^{-2} when the machine was operated in 'production conditions' for 60 second periods. Laboratory tests, involving a dummy wheel were carried out to demonstrate the effect of wheel balance on the vibration magnitude. The authors claimed that unbalance problems were caused not only by mass unbalance in the wheel, but also in eccentric mounting of the wheel on the shaft. They suggested closer tolerances in wheel manufacture as a possible palliative measure. This paper also reported the development of a prototype vibration-isolating handle for this machine, which was claimed to reduce the weighted magnitude by up to 66%, and of an isolating glove (up to 16% reduction). The handle and glove incorporated the 'Sorbothane' material investigated by Clarke *et al.* (1986) for use with chipping hammers.

Hansson *et al.* (1987) studied the vibration characteristics and exposure patterns for various vibrating hand tools used in car repair work. This included a straight grinder, Bahco type SF 8 TO. The tool was used for cutting and grinding car body parts. Of 14 frequency-weighted magnitudes reported, 8 were of approximately 3 ms^{-2} r.m.s. the maximum was about 4.5 ms^{-2} r.m.s. and the minimum about 1.25 ms^{-2} r.m.s.

Angle grinders

Angle grinders are disc grinding machines in which the axis of rotation of the disc is perpendicular to the body of the machine. Disc diameters vary typically from 3 to 9 inches (approximately 75 to 230 mm). A handle is usually provided at the rear end of the body; on large machines, a second, cylindrical, handle may be positioned near the forward end, on the left or right side of the body.

The three machines investigated by Bovenzi *et al.* (1980) varied in weight from 2.0 to 6.6 kg although the disc diameters were not reported. Three axes of vibration were measured: only the z-axis data are reproduced here. The small and medium sized grinders exhibited greater vibration magnitudes than the large machine. Additional measurements made with the tool free running (i.e. not grinding) revealed pronounced peaks in the vibration spectra from the smallest tool at the rotational frequency and its harmonics, indicating that out-of-balance forces were a major contributor to the hand-transmitted vibration.

The grinder studied by Suggs *et al.* (1982) was a large angle machine with a carborundum disc of 230 mm diameter. These vibration data were obtained using a Brüel & Kjær accelerometer type 4344 attached to a hand-held mount. The tool was operated by experienced workers in 'normal operations'. Measurements made in the z-axis on the rear handle are shown in the table; the side handle was found to have a similar vibration spectrum. The magnitudes are compatible with those measured by Bovenzi although a high acceleration value was found in the 63 Hz band. This may also be due to poor balancing of the wheel.

The vibration measurements made by Hodges (1985) included two angle grinders performing well-documented operations. The larger tool was an electric machine with two handles, fitted with a disc of 7.25 inches diameter, working on a gear casing. Piezoelectric accelerometers on mechanical filters were mounted on a triaxial block using a hose clip to secure the assembly to the tool. The measurement period was in excess of one minute. The frequency-weighted magnitudes obtained were 3.7, 3.6 and 7.0 ms^{-2} r.m.s. on the side handle and 4.3, 2.1 and 3.9 ms^{-2} r.m.s. on the rear handle in the x-, y- and z-axes respectively. The smaller tool was a pneumatic single-handed machine with a disc of 100 mm diameter, grinding a turbocharger impeller. measurement techniques were similar to those for the other tool. The frequency-weighted magnitudes were 1.0, 0.5 and 1.1 ms^{-2} r.m.s in the x-, y- and z-axes respectively. Octave band data for three axes of vibration at each hand position were presented for these tools; the z-axis values reproduced in the table had the greatest frequency-weighted magnitudes. The noise level of the instrumentation, expressed as an equivalent acceleration magnitude was reported for each octave band. This was generally more than 20 dB below the magnitude obtained for the grinding task in all bands.

Hansson *et al.* (1987) measured vibration on several types of angle grinder used in car body repair work. Weighted acceleration magnitudes ranging from 1.5 to 10 ms^{-2} r.m.s were reported.

This paper also reported measurements made on the front handles of five angle grinders while grinding weld beads on a test rig. The grinder types and mean weighted r.m.s. acceleration magnitudes obtained) were: Flex (3.2 ms^{-2}), AEG (3.2 ms^{-2}), Bosch (2.5 ms^{-2}), Manson (2.5 ms^{-2}) and Black & Decker (5.6 ms^{-2}). The machines were fitted with a 'Sungrip' anti-vibration handle and the measurements repeated. The weighted magnitudes were found to be reduced by 59 - 80%. The Flex grinder was also fitted with a vibration damping material between the rear handle and the tool body. This was reported to reduce the weighted magnitude on this handle (5 ms^{-2} r.m.s.) by 66%.

Collet grinders

Collet grinders (or die grinders) are usually similar in appearance to straight grinders but are often smaller machines. Instead of a fixed grinding wheel, a collet or chuck is provided in which small mounted stones, wheels, steel burrs, rotary files, etc. may be fitted.

Hodges (1985) made measurements on a small pneumatic collet grinder, fitted with various grinding devices including a mounted 'bulb' stone, 30 mm × 16 mm diameter, and a wheel of 1.5 inches diameter. The speed of rotation of the machine was 20000 r.p.m. The measurements were made while the machine was used to clean up a large gearbox casting after machining. Measurement techniques were as used for the angle grinders described above. With the mounted bulb stone, the magnitudes in the x-, y- and z-axes were 1.1, 2.2 and 1.0 ms^{-2} r.m.s. respectively. The weighted acceleration magnitudes obtained with the wheel were 0.8, 1.4 and 0.8 ms^{-2} r.m.s. The y-axis vibration was dominant in both cases and octave band values for this axis are included in the table. The maximum magnitude occurred in the 250 Hz band in this axis; however, high magnitudes (i.e. > 10 ms^{-2} r.m.s.) occurred in the z-axis in the two highest frequency bands. It is apparent that the vibration spectra of this high frequency rotary tool differed from those of the slower types of grinder, which often contain a dominant peak at the frequency of rotation of the grinding wheel or disc.

Two collet grinders, fitted with burrs, were investigated in the study by Hansson *et al.* (1987) of tools used in car body repair work. These were Atlas Copco type LSF 16 and Ingersoll Rand type DG120. Weighted magnitudes were found to be less than 2 ms^{-2} in all cases and typically approximately 1 ms^{-2} r.m.s. A similar magnitude (1.5 ms^{-2} r.m.s.) was obtained for a collet grinder tested by Burström *et al.* (1987).

2.3 STANDARDS

2.3.1 Vibration Exposure Standards

Several standardised procedures for the evaluation of hand-transmitted vibration exposures and the assessment of the likely health effects on exposed populations have been produced since the early 1970s. Most standards have contained guidance relating to vibration measurement techniques and instrumentation, the definition of axes, frequency weighting and time-dependency, etc. and tentative information relating to dose-effect relationships. In some cases, vibration 'limits' have been imposed.

Two standards of current primary interest are International Standard ISO 5349 'Mechanical vibration - Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration' (International Organization for Standardization, 1986) and British Standard BS 6842 'British Standard Guide to Measurement and evaluation of human exposure to vibration transmitted to the hand' (British Standards Institution, 1987a). Earlier standards were produced in the Soviet Union, Czechoslovakia and Japan and have been reviewed by Griffin (1980, 1990). The contents and evolution of ISO 5349 and BS 6842 are discussed below. Most current national standards are compatible with, but not always identical to, ISO 5349.

International Standard ISO 5349

In 1979 a Draft International Standard, ISO/DIS 5349 was published. This document was intended to set limits for 'safe' vibration exposure. These limits were defined by thresholds of constant acceleration at frequencies between 8 Hz and 16 Hz and constant velocity between 16 Hz and 1000 Hz. This frequency-dependency was derived, with some modification (see Griffin, 1980), from studies of equal comfort contours (Miwa, 1967). Multiplying factors were provided for five bands of daily exposure time, ranging from 'up to 30 minutes' to 'more than 4 hours/up to 8 hours' and for five categories for regular interruptions to vibration exposure during the working day, ranging from 'Uninterrupted/up to 10 minutes' to 'more than 40 minutes' (per working hour). Vibration was to be analysed as root-mean-square magnitudes in octave or one-third octave bands and the limits were not to be exceeded in any frequency band in any of the three directions of vibration.

The form of this document presented some problems. Firstly, with complex spectra it was possible to obtain different results when using octave and one-third octave band analysis. Secondly, the table of multiplying factors was not easy to interpret for some exposure patterns. Finally, the exposure boundaries and multiplying factors were described as 'provisional' and 'tentative' and the expected result of exceeding the limits (e.g. prevalence of VWF etc.) was not made clear. Thus, while it was usually possible to determine whether a particular vibration exposure exceeded the limit, which could be of use for governments or employers wishing to set 'safety' limits, the criteria by which the limits were chosen were not described.

A revision of this draft standard, ISO/DIS 5349.2 was published in 1984, followed in 1986 after further minor revisions, by the actual standard, ISO 5349. These versions followed a change in philosophy: the definition of 'vibration limits' was dropped in favour of a standard procedure for making vibration measurements and tentative dose-effect relationship information to aid the interpretation of vibration and exposure time data.

The same frequency-dependency was retained, but presented in the form of frequency-weighting factors for octave or one-third octave band measurements. This enabled magnitudes in separate frequency bands to be weighted and combined into an overall weighted r.m.s. magnitude. Alternatively, a filter network could be constructed for direct frequency weighting.

This use of a weighted value, obtained from magnitudes measured over a wide range of frequencies, instead of the greatest octave or third-octave band magnitude had been suggested several years earlier by Hempstock and O'Connor (1974). Griffin (1990) suggested that the earlier method was illogical; it required different limits for different analysis bandwidths yet, by considering only the band with greatest magnitude, it implied that there was no additive effect of vibration in different frequency bands.

The quantity used to define the severity of vibration exposure during a working day was defined as the 'energy-equivalent' frequency-weighted acceleration magnitude for a period of 4 hours, i.e. the r.m.s. weighted acceleration magnitude which if maintained for 4 hours would have the equivalent effect to the day's exposure:

$$(a_{h,w})_{eq(4)} = \left[\tfrac{1}{4} \int_0^{\tau} a_{h,w}^2(t)\, dt \right]^{1/2}$$

where $a_{h,w}(t)$ is the instantaneous value of the weighted acceleration and τ is the duration of the working day in hours.

The time-dependency adopted was that which is implicit in the root-mean-square averaging procedure: i.e. a change in the exposure duration is equivalent to the same change in the square of the acceleration.

The guidelines for interpretation of vibration data were contained in an appendix to the standard and related weighted acceleration, years of exposure and the percentile of population expected to develop vascular symptoms. This relationship was given in the form of a table which gave expected latent periods, in years, for 10, 20, 30, 40 and 50% of a population exposed to daily four-hour energy equivalent weighted acceleration magnitudes of 2, 5, 10, 20 and 50 ms^{-2} r.m.s. This relationship was also given in the form of an equation:

$$C = \left[((a_{h,w})_{eq(4)} \times T_F)/95 \right]^{2} \times 100$$

where C is the percentile of exposed persons expected to show vascular disorders and T_F is the latent period in years. It was stated that the relationship should not be used for values of C outside the range 10 - 50% or values of T_F outside the range 1 - 25 years. It can be seen that the percentage of persons affected was assumed to increase linearly with the square of the acceleration magnitude and with the square of the exposure duration.

The above equation can be attractive in that it enables a prediction of the latency and prevalence of VWF to be made for an exposed population with any value of $(a_{h,w})_{eq(4)}$ smaller than 50 ms^{-2} r.m.s. However, the existence of the equation implies a degree of precision for which there is little evidence in the data on which it was based. That the frequency weighting is correct for vascular disorders, that vibration magnitudes in all three axes are equally injurious and that there is no recovery effect due to intermittent exposure are merely assumptions for convenience. Also, Griffin (1990) observed that the dose-effect relationship in the appendix to ISO 5349 was derived by Brammer from his studies of latency (Brammer, 1977, 1982a, 1982b, 1983, 1986) which concerned groups of persons who used a single type of tool for the entire working day and had prevalences in excess of 50%. In the standard the data were extrapolated to shorter daily exposures and lower prevalences.

British Draft for Development DD43: 1975

This document (British Standards Institution, 1975) was similar in scope to the first draft of ISO 5349. Acceleration limits were defined at octave band centre frequencies from 4 Hz to 2000 Hz for cumulative daily exposure durations of 150 minutes or less and 400 minutes. The frequency-dependency assumed was the same as that of ISO/DIS 5349.1, but the frequency range was extended at either end. The limits defined in DD43 are illustrated in Figure 2.1 with those from ISO/DIS 5349.1.

Magnitudes above the 150 minute limit were described as 'unacceptable'; magnitudes below the 400 minute limit were 'acceptable'. The document did not include any guidance for the interpretation of magnitudes falling between the two boundaries.

Although octave band analysis was advocated in DD43, reference was made to an alternative approach, using a weighting filter to allow the weighted vibration magnitude to be represented by a single figure. (The later standards ISO 5349 and BS 6842 both used this approach in place of the definition of limits as a function of frequency.)

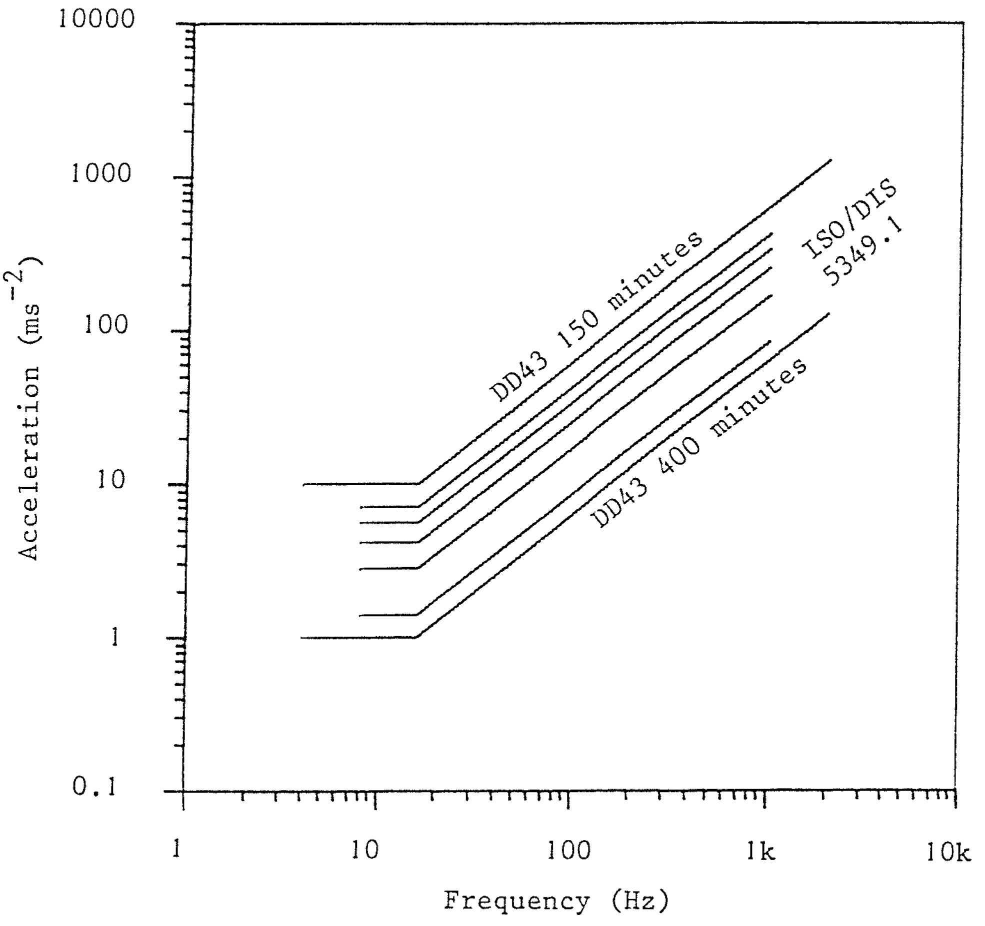


Figure 2.1 Octave band limits as defined in ISO/DIS 5349.1 (International Organization for Standardization, 1979) and DD43 (British Standards Institution, 1975)

British Standard BS 6842

This standard, which was published in 1987 to replace the Draft for Development DD43, was compatible with ISO 5349 but differed from it in content and in presentation of the dose-response relationship data.

The standards and draft standards discussed above had all contained some guidance on vibration transducers, mounting methods, instrumentation etc. BS 6842 contained a more comprehensive section concerning practical aspects of vibration measurement than previous documents; for example, the problem of d.c. shifts in piezoelectric accelerometers (see Section 3.2.1) was discussed and illustrated.

The frequency weighting was defined by a filter equation, in addition to the octave and one-third octave band weighting factors, and was designated W_h to complement the weightings W_b - W_g given in BS 6841 (British Standards Institution, 1987b) for whole-body vibration. The weighting definition included band-limiting filters at 6.3 Hz and 1250 Hz, thus avoiding any ambiguity regarding the treatment of frequencies outside the range 8 - 1000 Hz when producing a weighted acceleration magnitude.

BS 6842 differed from ISO 5349 in that the energy-equivalent frequency-weighted r.m.s. acceleration was normalised to a duration of 8 hours instead of 4 hours for the assessment of daily exposures. (However, both standards provided guidance for converting data from one form to the other.)

As with the International Standard, the information relating to dose-effect relationships was contained in an appendix and did not form an integral part of the standard. The appendix was cautious in its wording and stressed the paucity of data on which the guidance was based. To explain the choice of frequency- and time-dependencies, the origins of the frequency weighting were described and it was stated that the energy-equivalent time-dependency for daily exposures 'appears reasonable and is convenient for instrumentation' and that 'there is some evidence that ... if the vibration magnitude is halved, the time before the onset of symptoms will tend to be doubled'.

It was suggested that blanching in 10% of persons might occur after 8 years' exposure to a magnitude of 4 ms^{-2} r.m.s. for 4 hours per day. Frequency-weighted acceleration magnitudes corresponding to 10% incidence for daily exposure times from 15 minutes to 8 hours and lifetime exposure from 6 months to 16 years were listed in a table, using the daily and lifetime time-dependencies referred to above. While compatible with the information in the appendix to ISO 5349, this standard did not define a procedure for calculating exposure criteria for other prevalences and, in restricting the scope of the tentative relationship, reflected more appropriately the small quantity of data on which it was based.

2.3.2 Vibration Measurement Standards

The standards discussed in the previous section were concerned with the evaluation of hand-transmitted vibration *exposures*; i.e. measurement of the vibration and prediction of its likely effects. Other standards have been produced to define methods for the measurement of vibration on specific types of power tools; some measurement requirements are not intended for assessment of human exposure to vibration, but to compare the vibration of different tools.

PNEUROP Publications

Test procedures for the measurement of the vibration of grinding machines and chipping hammers were published by the European Committee of Manufacturers of Compressors, Vacuum Pumps and Pneumatic Tools (1983, 1985). The procedures were intended to be type tests for the comparison of different machines in well defined operating conditions.

Barber (1982) had stated that these test conditions were required to reduce variability in vibration measurements on a tool, while ensuring authenticity in the mode of operation. (He commented that this might be considered to be a contradiction in terms since real operations were known to involve large variations in vibration magnitudes!)

Recommended methods for mounting the accelerometers (and mechanical filters in the case of chipping hammers) were described in more detail than in the exposure standards. Measurement in one direction only was required, as the dominant axis was assumed to be known for each type of tool. The mass of the accelerometer was required to be less than 50 grams.

The operating conditions were also closely defined. For grinders the dimensions of the steel workpiece were defined, rotating speed was to monitored and controlled by push force and at least 8 repeat measurements of 2 minutes minimum duration were to be made. The vibration when running free (i.e. not grinding) was to be measured between runs to check for changes in the balance of the wheel.

For chipping hammers, a test rig was described (see Section 3.5.3). A piece of mild steel was clamped vertically between two plates of hardened steel. The operator was required to shave off a strip of the mild steel, 300 mm in length in 2 minutes. Five repeat measurements were required. Attempts to measure vibration on the chisel were not recommended.

International Standard ISO 8662

International Standard ISO 8662 Part 1 (International Organization for Standardization, 1988) Hand-held portable power tools - Measurement of vibrations at the handle - Part 1: General. This was the first part to be published of a standard intended to provide detailed guidance for type tests on specific categories of tools. It contains general specifications relating to transducers, mounting methods, instrumentation, etc., and refers the user to the relevant part of the standard for specific details.

Other parts of the standard were under development at the time of writing. Part 2 dealt with chipping hammers and riveting hammers, Part 3 with rock drills and rotary hammers, Part 4 with grinding machines and Part 5 with breakers for concrete, road, etc. and pick hammers. Parts 2 and 4 are of particular relevance for this review.

Part 2, which defined a type test procedure for chipping and riveting hammers, stated that measurements in typical work situations had not been found to be repeatable. The tool was therefore required to operate into a vertical steel tube filled with ball bearings (this suggests that repeatable measurements using the PNEUROP test rig were also thought be give poor repeatability). The accelerometer and mechanical filter were to be mounted half way along the handle and orientated in the z-axis (parallel to the direction of strike). The push force was to be monitored and controlled. five measurements of not less than 8 seconds duration were to be made and, for the measurements to be considered valid, the coefficient of variation (ratio of the standard deviation to the mean) of the five weighted acceleration values was to be less than 0.15.

Part 4 also defined an artificial operating condition for grinder type testing on the premise that repeatability of vibration measurements in real grinding tasks is poor. A dummy wheel, of known and typical unbalance, was to be mounted and the measurements made with the machine running free. (It was claimed that unbalance in abrasive wheels and discs was highly variable and a major contributor to vibration. It was also stated that free-running vibration could be reliably used to predict the vibration magnitudes generated when grinding (Eklund *et al.*, 1986; 1987). A down force, equivalent to the push force exerted when grinding, was to be applied using a weight and pulleys. The direction of vibration measured was parallel to the rotating shaft for angle grinders and vertical grinders and perpendicular to the shaft for straight grinders and die grinders. On handles, the accelerometer was to be mounted at a point 60 mm from the outer end. As in Part 2, five measurements of at least 8 seconds duration were to be made. A valid series of measurements should give a difference between the maximum and minimum weighted values of less than 3 dB (40%).

2.4 METHODS FOR THE DESCRIPTION OF VWF SEVERITY

2.4.1 Staging Systems

A system for the categorisation of the severity of vibration-induced white finger in an individual (Taylor and Pelmear, 1975) has been widely used in epidemiological research (e.g. Oliver *et al.*, 1979; Bovenzi *et al.*, 1980; Wasserman *et al.*, 1982) and in the assessment of individual conditions in claims for compensation (Hancock, 1989). This staging system is shown in Table 2.6.

Table 2.6 *Stages of vibration-induced white finger (after Taylor and Pelmear, 1975)*

Stage	Condition of Digits	Work and Social Interference
0	No blanching of digits.	No complaints.
0_T	Intermittent tingling.	No interference with activities.
0_N	Intermittent numbness.	No interference with activities.
1	Blanching of one or more fingertips with or without tingling and numbness.	No interference with activities.
2	Blanching of one or more fingers with numbness. Usually confined to winter.	Slight interference with home and social activities. No interference at work.
3	Extensive blanching. Frequent episodes summer as well as winter.	Definite interference at work, at home and with social activities. Restriction of hobbies.
4	Extensive blanching. Most fingers; frequent episodes summer and winter.	Occupation changed to avoid further vibration exposure because of severity of signs and symptoms.

Although it was widely adopted, the Taylor-Pelmear scale had certain practical limitations: the existence of stages 0_T and 0_N (in some versions combined into a single stage 0_{TN}) implied that tingling and numbness are early indicators of VWF. While this may often be the case, there is evidence that the vascular and neurological components of the 'vibration syndrome' develop independently (Brammer *et al.*, 1986; 1987) so these stages may not occur before the onset of blanching in all individuals.

Payne (1982) observed that stages 1, 2 and 3 were not mutually exclusive. Classification by the criteria in the column headed 'Work and Social Interference' is dependent not only on the physical severity of the condition but also on the individual's temperament and circumstances (e.g. interference with social activities will depend on what those activities are; an individual with very severe VWF may not be classed as Stage 4 simply because there is no prospect of acceptable alternative employment).

The symptoms experienced by an individual do not always fit neatly into any one category. James *et al.* (1989) observed that a patient with frequent blanching but with only one or two phalanges affected appears to fall between Stages 2 and 3.

Brammer *et al.* (1986) proposed that the scale should be revised to allow for separate classification of neurological and vascular symptoms, acknowledging that these can develop independently. A more elaborate staging system developed for use in Japan (Ishida *et al.*, 1986) also provided separate scales for vascular and neurological components of the 'vibration syndrome' and distinguished between subjective signs and symptoms and the findings of physiological tests.

Some of these problems were acknowledged by Taylor and Pelmear in 1987 when a revised version of the scale was proposed (Gemne *et al.*, 1987). This was known as the Stockholm Workshop Scale and is shown in Table 2.7.

The new scale improved on the original Taylor-Pelmear scale by the removal of the 0_T and 0_N stages, seasonal differences and the dependence on individual social and employment factors and by the addition of trophic skin changes (i.e. actual tissue damage resulting from blanching attacks) for Stage 4. It was proposed that each hand should be assessed separately, and that the number of digits affected on each hand should be recorded; an example might be:

2L(2)/1R(1)

meaning that the left hand is at stage 2 with two fingers affected and the right hand is at stage 1 with one finger affected.

Table 2.7 Stages of vibration-induced white finger - the 'Stockholm Workshop Scale' (after Gemne et al., 1987)

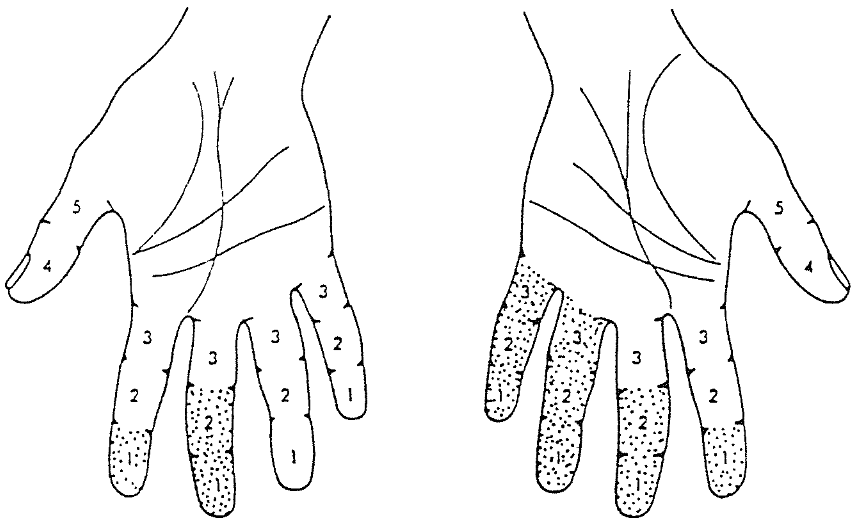
Stage	Grade	Description
0	-	No attacks.
1	Mild.	Occasional attacks affecting only the tips of one or more fingers.
2	Moderate.	Occasional attacks affecting distal and middle (rarely also proximal) phalanges of one or more fingers.
3	Severe.	Frequent attacks affecting all phalanges of most fingers.
4	Very severe.	As in Stage 3, with trophic skin changes in the fingertips.

One unsatisfactory aspect of the new scale was that the difficulty in staging some cases, particularly where the frequency of attacks is high but the extent of blanching is small, remained. (Jones *et al.*, 1989; Hancock, 1989).

Hancock suggested that a 'two step' procedure could resolve this problem. The first step involved staging based on extent of blanching alone according to the Stockholm workshop scale. A second step took frequency of attacks into account but also included subjective aspects such as restriction of hobbies and changes to life style; the resulting system would have been more complex than the Stockholm Workshop Scale and would have reintroduced some of the problems associated with the original Taylor-Pelmear scale.

2.4.2 Scoring Systems

A simple system for quantifying the severity of VWF was suggested by Stewart (1968). This system allocated a score of 1 for each affected finger on the worst affected hand, giving a range of possible values from 0 to 5. An improved scoring system was proposed by Griffin (1982b) who developed a method of assessing severity by counting the affected fingers and phalanges (Agate, 1946). Griffin's system is shown in Figure 2.2. A score was allocated to each phalanx: 1, 2 and 3 for the distal, medial and proximal phalanges of each finger respectively; 4 and 5 to the distal and proximal phalanges respectively of the thumbs. As blanching usually starts with one or more distal phalanges and rarely affects the thumbs (e.g. Wasserman *et al.*, 1982), these scores were considered to reflect the severity of the condition.



Right Hand

Digit	Th	1	2	3	4
Possible Score	4+5	1+2+3	1+2+3	1+2+3	1+2+3
*Actual Score	0	1	3	0	0
Total Score	4/33				

Left Hand

Digit	Th.	1	2	3	4
Possible Score	4+5	1+2+3	1+2+3	1+2+3	1+2+3
*Actual Score	0	1	3	6	6
Total Score	16/33				

Figure 2.2 *Scoring system for vibration-induced white finger (after Griffin, 1982b)*

This scoring system can produce a single number, between zero and 66, to represent the severity of the condition. If more detail of the extent of blanching is required, separate scores for each hand, or for each digit may be used. The system does not take account of neurological or other symptoms and does not take account of interference with leisure or work activities. It is, however, an objective method of assessment and the numerical result can be more appropriate than the staging systems for use in statistical analysis. Supplementary information relating to frequency of attacks and to other symptoms (e.g. numbness, tingling) may be considered necessary for a complete description of the condition in individual cases.

When proposing the Stockholm Workshop scale, Gemne *et al.* (1987) rejected the scoring system (which they attributed to Rigby and Cornish (1984)) on the grounds that it gave only a total score, with no indication of the effects on individual fingers. In fact, scoring of fingers separately would yield more information than the Stockholm Workshop scale which shows only the *number* of affected digits on each hand.

2.5 EPIDEMIOLOGICAL STUDIES

2.5.1 Terminology

Since the 1930s, many researchers have studied vibration-exposed populations and reported their findings in different ways (e.g. number of cases, prevalence of VWF, average latent period). The *prevalence* of a disease or condition is defined as 'the number of instances ... in a given population at a specified time' (Last, 1988). The term may also be used for the *prevalence rate* which is the ratio of this number to the total number of persons at risk in the population at that time and is often expressed as a percentage. The *latency* (also called *latent period* or *induction period*) is 'the period between exposure to a disease-causing agent and the appearance of manifestations of the disease' (Last, 1988).

Many studies of VWF have reported the prevalence and latency of the condition, with a wide range of results (see Table 2.8). Comparison of such data from different studies can be difficult because prevalence and latency data obtained in a cross-sectional study can be biased.

A simple prevalence figure must be influenced by the exposure history of the members of the population and the rate at which individuals have left or joined the group prior to the study (some may even have left *because* of vibration-related problems). Wilcox (1983) warned that the 'healthy worker effect' may influence data obtained from a cross-sectional study because individuals who are susceptible to vibration-induced conditions may change their employment before the survey. It would be of greater interest to measure the *incidence* (i.e. the rate at which new cases appear in the population) but for practical reasons it is often the prevalence which is observed.

Latent periods reported for VWF in some groups of workers have been obtained by taking the mean latency for those subjects affected at the time of survey (e.g. Taylor *et al.*, 1975a, 1975b; Payne, 1982). Griffin (1990) observed that as the prevalence of the condition in a fixed group will increase with continued vibration exposure, the mean latent period for those affected will also increase. The mean latency is therefore dependent on mean exposure time (as is the prevalence) and is shorter than the mean exposure time.

Brammer (1977) adopted 'rules of thumb' in order to accept or reject epidemiological data: he set minimum values for the size of the population and for the observed prevalence and required that the average duration of exposure of the members of the group should exceed the average latent period reported by those affected (this was to ensure stability in the prevalence rate). While this recognised the possible bias in a prevalence value, the actual reason for adopting the data selection criteria is questionable (achieving an improvement in the correlation between stage of VWF on the Taylor-Pelmear scale and the exposure time in years in Brammer's proposed dose-effect relationship).

2.5.2 Reported Incidences of VWF

One of the earliest publications documenting cases of vibration-induced white finger was that of Loriga (1911). He reported that workers using pneumatic hammers in marble and stone processing had various work-related symptoms including musculoskeletal and vascular problems in the hands and arms. However, workers using similar tools in metal work (fettling, chipping and riveting), together with hand grinders and sand rammers, reported fatigue, aching arms, headaches and insomnia but no finger blanching. Loriga believed that the blanching attacks experienced by the stone workers did not indicate a permanent condition. He stated that they were not to be regarded as the manifestation of a new pathogenic agent (i.e. vibration) but were a temporary phenomenon, attributed to fatigue and overwork.

VWF has been associated with the use of a diverse collection of tools and processes including chain saws, rock drills, percussive and rotary metal-working tools (chipping and riveting hammers, drills, grinders), pedestal grinders, scaling tools, polishers and leather 'pounding up' machines. Many of these studies were identified by Griffin (1980).

Griffin (1990) produced an updated list of studies which reported VWF resulting from the use of percussive metal-working tools (71 studies), grinders and other rotary tools (40 studies), hammers and drills used in mining work (67 studies) and chain saws (79 studies). In the first and second of these categories, the reported prevalences of VWF ranged from zero to 100% and latent periods from less than one year to 27 years. This suggests that the risk of VWF in different occupations and its occurrence in individuals is highly variable. This variability in reported prevalence and average latency values also indicates that these variables may not, in some cases, be a valid indicator of the severity of vibration to which a population is exposed. Griffin (1990) observed that the prevalence and average latent period will depend on the average duration of exposure, which is influenced by the rate at which the work force changes.

This section of the literature review covers some of the epidemiological studies concerning workers exposed to percussive and rotary metal-working tools which may be compared to the present study in Devonport Dockyard. Studies which identified prevalence, latency etc. of VWF are summarised in Table 2.8.

Many of the studies listed here were concerned primarily with physiological measurements (e.g. of vascular or neurological functions) to investigate the aetiology and mechanisms of VWF. An objective diagnostic test for VWF has yet to be developed; the data relating to individual symptoms of VWF were therefore obtained, in most studies, by questionnaire or interview.

Table 2.8a Reported examples of vibration-induced white finger associated with the use of percussive and rotary metal-working tools

Authors (date)	Occupation/tool	Exposed N	Prevalence (%) Blanching	Numbness	Tingling	Latency (years)
Loriga (1911)	chipping/grinding/ fettling	-	0	-	-	-
Seyring (1930)	chipping hammer	-	90 cases (mostly L Hand)	-	-	3 (50%)
Hunt (1936)	riveters	-	7 cases	-	-	-
McLaren (1937)	riveter	20	100	-	-	-
	caulkers	19	58	-	-	-
Reider (1938)	pneumatic hammer	250	34	-	70	-
Kimura (1943)	riveters	11	55	-	-	-
Brocklehurst (1945)	fettling (electric tool)	25	100	-	-	0,2 - 3,5
Gurdjian & Walker (1945)	small rivet hammer (women)	6	100	-	-	< 1
		(1 case probably primary Raynaud's)				
Hunter *et al*, (1945)	riveters	-	62	-	-	1 - 20+
	fettlers	-	71	-	-	1 - 20+
	caulkers	-	75	-	-	1 - 20+
	drillers	-	31	-	-	1 - 20+
	scalers	-	0	-	-	-
Lindqvist & Flemberg (1945)	riveters	-	10 cases	-	-	0 - 15
Dart (1946)	high speed grinders	112	9	41	-	-
McKinnon & Kemp (1946)	riveters	-	40	-	-	< 5
	holders on	-	25	-	-	< 5
	caulkers	-	22	-	-	< 5
	reamers (drillers)	-	9	-	-	< 5
	impact wrenches	-	4	-	-	< 5
Walker & Gurdjian (1946)	pneumatic hammers	6	100	-	-	< 1
		(Females - males said to have longer latent periods)				
Marshall *et al*, (1954)	pneumatic hammer (flanging/clinching)	31	94	55	13	0,1 - 10 (0,25 - 2)
Miura *et al*, (1956)	shipyard riveting	51	14	51	-	-
	shipyard chiselling	53	32	41	-	-
	shipyard drilling	58	5	21	-	-
	shipyard chipping	24	25	4	-	-
	automobile riveting	19	0	11	-	-

Table 2.8b Reported examples of vibration-induced white finger associated with the use of percussive and rotary metal-working tools

Authors (date)	Occupation/tool	Exposed N	Prevalence (%) Blanching	Numbness	Tingling	Latency (years)
Lloyd Davies *et al.* (1957)	riveters/caulkers/scalers	31	0	0	-	-
Harada & Fukuhara (1958)	riveting/holding up	38	29	79	-	-
Stýblová (1959)	riveters	104	76	-	85	-
	sheet metal hammer	50	98	-	96	-
	grinders/polishers	56	4	-	48	-
Brückner *et al.* (1963)	pneumatic hammer	88	52	-	-	-
Magos & Okos (1963)	iron chipping	15	27	-	-	3 - 11
	iron grinding	10	10	-	-	< 5
	iron grind/fettling	7	14			< 5
	steel chipping	194	61	-	-	< 11
	boiler-makers chip/caulk	42	33	-	-	< 11
	boiler-makers riveting	24	17	-	-	< 11
	boiler-makers drilling	27	7	-	-	< 11
	boiler-makers combined	26	3	-	-	< 11
	wagon assembly, combined	25	20	-	-	< 11
Malinskaya *et al.* (1964)	grinders (pneumatic and electric)	200	80	-	-	-
Takagi (1968)	chipping	30	87	0	-	-
Matsumoto *et al.* (1969)	pneumatic grinder	67	8	18	-	-
	swing grinder	67	12	28	-	-
	pneumer (ch, hammer?)	49	29	43	-	-
Trickovic *et al.* (1969)	rotary tools (metal work)	534	22	-	-	-
Yamada (1969)	pneu, grinder (steel)	-	7	-	-	-
Stewart & Goda (1970)	clinching/flanging	109	73	-	-	2,5 ± 3,7
	chipping/chiselling	93	72	-	-	4,3 ± 5,4
	riveting/holding on	40	28	-	-	7,2 ± 5,3
Mikulinsky *et al.* (1971)	rotary tools (high frequency)	296	20	-	-	5 - 7
Eskenasy (1972)	metal working tools	222	50	-	-	-
Asanova (1975)	hand grinders (shipyard)	37	49	-	73	-

Table 2.8c Reported examples of vibration-induced white finger associated with the use of percussive and rotary metal-working tools

Authors (date)	Occupation/tool	Exposed N	Prevalence (%) Blanching	Numbness	Tingling	Latency (years)
Lidström (1975)	drillers	40	13	-	-	-
	chisellers	49	2	-	-	-
	grinders	44	9	-	-	-
Taylor *et al*, (1975a)	chipping	98	57	-	19	5,3
	caulking	38	55	-	5	14,0
	swaging	2	50	-	50	0,6
	nobbling	31	35	-	10	16,5
	hand grinders	54	37	-	9	13,7
	hand grinders	22	14	-	9	1,6
	hand grinders	9	11	-	0	5,0
	hand grinders	81	7	-	1	18,0
	hand grinders	42	17	-	5	15,0
	hand grinders	13	23	-	15	27,0
	hand grinders	4	25	-	25	20,0
	hand grinders	7	43	-	14	-
	hand grinders	7	0	-	0	-
Leonida (1977)	foundry chip/grind	126	70	-	-	1 - 2
Suzuki (1978)	chipping hammers	21	23 - 31	21	-	some < 1
	pneumatic grinders	29	23 - 69	21	-	some < 1
	mixed tools	16	14 - 23	21	-	some < 1
Harada & Matsumoto (1979)	chipping hammers	33	54	51	-	-
	other tools (grinders)	13	8	31	-	-
Matsumoto *et al*, (1979, 1981)	chipping hammers	25	64	60	-	< 5 (36%)
Oliver *et al*, (1979)	caulkers	120	76	3	3	-
	caulkers	75	75	7	7	-
	paint chippers	127	23	8	8	-
	paint chippers	153	12	11	11	-
Bovenzi *et al*, (1980)	caulkers/grinders	169	31	43	79	< 10
Olsen *et al*, (1982) (also Voss *et al*,, 1978)	shipyard chisels	49	59	-	-	5 (median)
Payne (1982)	caulkers	54	59	4	15	15,2
Takamatsu *et al*, (1982) (Review of Japanese studies)	riveting (1943)	254	15	-	-	-
	riveting (1955)	51	8	-	-	-
	riveting (1962)	28	4	-	-	-
	riveting (1962)	33	9	-	-	-
	riveting (1977)	133	4	26	-	-
	chiselling (1943)	113	27	-	-	-
	chiselling (1955)	53	27	-	-	-
	chipping (1943)	64	9	-	-	-
	chipping (1965)	39	46	-	-	-

Table 2.8d Reported examples of vibration-induced white finger associated with the use of percussive and rotary metal-working tools

Authors (date)	Occupation/tool	Exposed N	Prevalence (%) Blanching	Numbness	Tingling	Latency (years)
Takamatsu *et al*, (1982) (continued)	air hammer (1970)	94	19	52	-	-
	chipping (1976)	24	17	75	-	-
	chip/grind (1977)	104	33	57	-	-
	chip/grind (1977)	71	20	35	-	-
	chip/grind (1977)	1124	3	11	-	-
	grinding (1953)	320	6	-	-	-
	grinding (1958)	24	0	-	-	-
	grinding (1960)	27	41	-	-	-
	grinding (1970)	91	10	43	-	-
	grinding (1973)	28	50	36	-	-
	grinding (1976)	41	20	15	-	-
	grinding (1977)	240	5	18	-	-
	angle sander (1970)	39	5	26	-	-
	grind/drill (1974)	65	31	25	-	-
	air drill (1955)	58	5	-	-	-
	impact wrench (1978)	36	14	42	-	-
	impact wrench (1978)	71	13	-	-	-
	mixed tools (1960)	83	12	-	-	-
Tominaga (1982) (after 500-2000 hours exposure)	chip, hammers/rock drills	80	18	-	-	-
	hand grinders	33	3	-	-	-
	impact wrenches	21	0	-	-	-
Wasserman *et al*, (1982)	foundry chip/grind	263	47	36	-	1,4 (med,)
	shipyard chip/grind	122	19	45	-	16,5 (med,)
Bovenzi *et al*, (1985)	chipping/grinding (foundry)	67	21	19	46	2 - 25 8,0 (median)
Engström & Dandanell (1986)	aircraft riveting	340	25	-	-	0 - 27
Jorulf (1986)	impact wrenches	262	12	21	-	< 10 (81%)
Yu *et al*, (1986)	riveters	705	15	-	-	-
	chippers	284	10	-	-	-
	grinders	39	18	-	-	-
Bovenzi (1988)	grinders/impact wrenches	76	26	45	-	-
Musson *et al*, (1989)	impact tools	169	17	29	29	-
Xu & Ding (1990)	hanging grinder	43	1	-	-	7,0
Zhou & Chen (1990)	casting cleaners	361	4	-	-	-
	riveters	113	5	-	-	-
	grinders	232	21	-	-	-
Starck *et al*, (1990)	scaling/grinding (shipyard)	171	5	-	-	16

The number of vibration-exposed individuals studied was reported for 112 of the 126 populations shown in Table 2.8. This varied from 2 to 1124, with 27 populations containing more than 100 individuals. Brammer (1982a) claimed that a group consisting of less than 30 persons was not likely to have a stable prevalence of VWF and should not be considered to offer valid epidemiological data. There are at least 36 such groups listed here.

Table 2.9 shows summary statistics calculated for the prevalences of VWF (blanching symptoms) reported in studies of riveters, chippers/chisellers/caulkers, grinders and groups using a combination of these tools. In Figure 2.3 the distributions of the prevalences reported in these studies is shown in graphical form.

In Table 2.9 the mean and median prevalence values from the studies of chippers (49% and 52% respectively) are greater than those for the other three groups. Figure 2.3 shows that more than half of the reported prevalences for the studies of riveters, grinders and multiple tool users were 20% or less; less than 20% of chipping populations had prevalences in this range. Prevalences of up to 100% were reported for chippers and riveters. No prevalences greater than 80% were reported for populations using grinders or assorted tools.

***Table 2.9** Summary statistics for reported percentage prevalences of vibration-induced white finger*

	Number of studies	Prevalence (%) Mean	Std dev.	Max.	Min.	Median
Riveters	20	32	30	100	0	21
Chippers	35	49	26	100	4	52
Grinders	30	21	21	80	0	16
Various	19	22	22	70	0	20

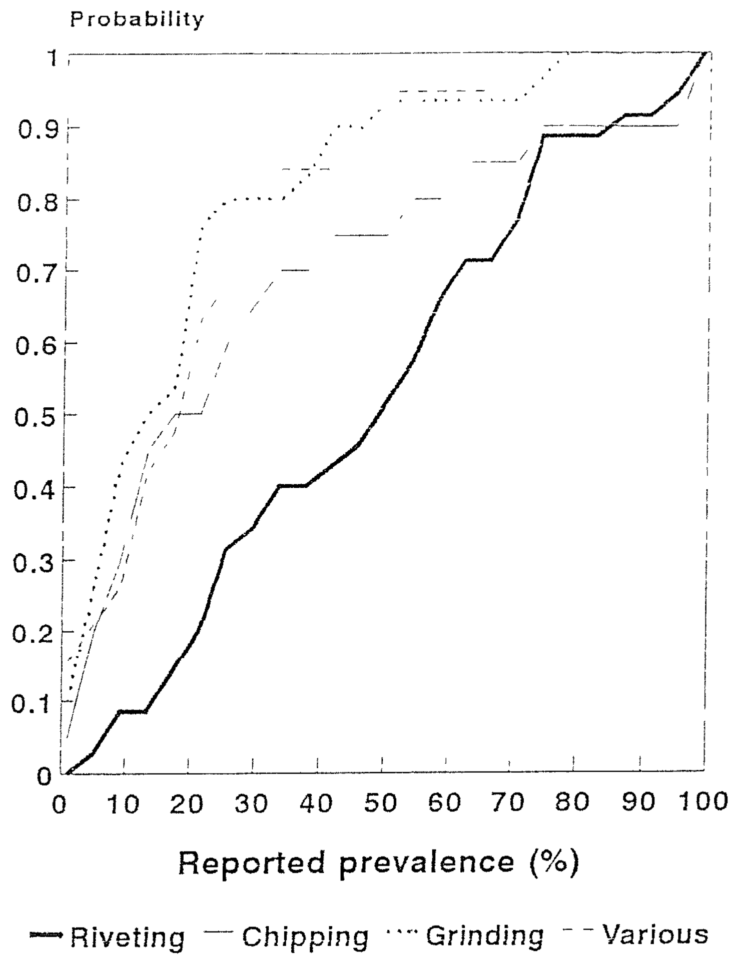


Figure 2.3 Cumulative probability functions from reports of VWF prevalence in populations using riveting hammers, chipping hammers, grinders and various tools

Although the population sizes, tools types, working practices and survey techniques are likely to be highly variable between the studies included in this review, the prevalence of finger blanching appears to be greater, on average, for groups of workers using percussive tools (chipping and riveting hammers) than for groups using grinders and combinations of different tools.

The latent periods shown in Table 2.8 relate to blanching symptoms and are mostly mean values for the affected persons. In one case standard deviations were also given. Three studies quoted a median value for affected persons (Wasserman *et al.*, 1982; Olsen *et al.*, 1982; Bovenzi *et* *al.*, 1985). Wasserman *et al.* concluded that because of the presence of outliers, the median value of latency was more meaningful than the mean. Where a range of latency values is indicated in the table (e.g. '1 - 20' or '< 5') this has, in some cases, been inferred from other information in the paper concerned. In view of the effect of prevalence on average latency values (see Section 2.5.1) the most meaningful measure of latency within a group may be a value for a particular percentile of the exposed population (e.g. Seyring, 1930; Matsumoto *et al.*, 1981).

2.5.3 Dockyard Studies

Many of the studies listed in Table 2.8 concerned workers in shipyards or dockyards. Of particular interest for comparison with data obtained in the present investigation at Devonport are the studies of Taylor *et al.* (1975a), Oliver *et al.*, (1979) and Payne (1982), which reported data obtained in British Naval dockyards: job descriptions and working practices similar to those at Devonport would be expected.

Taylor *et al.*, 1975a

The data included in this series of papers (see also Taylor *et al.* (1975b), Taylor and Pelmear (1976) and Pelmear *et al.* (1975)) were obtained in many different locations in Britain. The prevalence and latency data for 'chipping' (caulkers) and 'nobbling' (painters) were obtained in Rosyth dockyard. The prevalences of blanching symptoms among caulkers and painters were 55% and 35% respectively, with mean latent periods for those affected of 14.0 and 16.5 years respectively. Prevalences for those with tingling only (Taylor-Pelmear scale 0_T) were 5% and 10%.

The methods of presentation of data relating to prevalence, stage of VWF, latency, etc. were such that identification of individual study populations is difficult in some cases. The total number of caulkers and painters studied was 69 and the prevalences for Taylor-Pelmear Stages 1 and 2 were 25% and 22% respectively. However, these values were not reported separately for the two occupational groups.

Oliver *et al.*, 1979

This study was conducted in Portsmouth and Devonport dockyards. The work at Devonport was done approximately 6 years before the present study. The survey was conducted by questionnaire at an interview with the subject. At Devonport 120 caulkers and 127 paint chippers were interviewed; at Portsmouth the numbers were 75 and 153 respectively. The study included 97.6% of all caulkers and paint chippers. Severity of VWF was categorised using the Taylor-Pelmear scale.

It was shown that the severity (stage) of VWF symptoms increased with increased years of vibration exposure. The caulkers in both dockyards had, on average, longer histories of vibration exposure than the painters (90% of Devonport caulkers and 80% of Portsmouth caulkers had more than 20 years experience, while 60% of Devonport paint chippers (35% at Portsmouth) had been in the job less than 10 years).

The mean estimated daily vibration exposure times for caulkers at Devonport and Portsmouth were 6.0 hours and 5.1 hours respectively. For the paint chippers the times were 2.3 hours and 2.6 hours respectively.

The fingers affected by blanching were studied: the middle and ring fingers were most affected, with the dominant hand more affected among painters and the non-dominant hand more affected in caulkers. (This may reflect the greater severity of vibration on the chisel of a chipping hammer than on the handle, and is consistent with the results of Seyring (1930) and Takagi (1968) who found vascular symptoms mostly on the left hand.)

Vibration measurements were made on riveting and caulking hammers (see Section 2.2) and the magnitudes were shown to exceed the 150 minute exposure limit proposed by the British Standards Institution Draft for Development DD43 (British Standards Institution 1975). No attempt at relating vibration exposure to VWF was reported.

Payne, 1982

In this study of VWF and noise-induced hearing loss among caulkers at Rosyth dockyard 55 individuals (all but one of the caulkers then employed) took part. The author suggested that some self-selection may have influenced the results in the study by Oliver *et al.*.

The data relating to VWF symptoms were again obtained by a questionnaire survey. Prevalences observed were 59% for finger blanching (stages 1, 2 and 3) 4% for numbness only (Taylor-Pelmear stage 0_N) and 15% for tingling only (stage 0_T). The mean latent period for blanching was 15.2 years. The prevalence and stage of VWF was found to increase with increased years of exposure and the condition was generally more severe on the fingers on the hand usually in contact with the chisel, particularly the index finger. An average of 5.5 hours of each 8 hour day was said to be spent actually caulking.

This author addressed the possible sources of bias in the questionnaire data. He believed that under-reporting of symptoms (due to fear of compulsory retirement) or over-reporting (due to hope for compensation) was not likely to be a problem since no such actions had resulted from the earlier survey of the same workforce (Taylor *et al.*, 1975a). He also claimed that work records and workers' memories refuted the possibility of a significant bias due to a migration to other jobs of persons with VWF (the 'healthy worker effect').

Table 2.10 provides a summary of the epidemiological findings of the three previous surveys of VWF in British naval dockyards.

Table 2.10 *Vibration-induced white finger in British naval dockyard workers reported by Taylor et al.* (1975a), Oliver *et al.* (1979) and Payne (1982)

Dockyard	Occupation	Stage of VWF 0	$0_{T/N}$	1	2	3
Devonport (Oliver *et al.*)	caulkers (N=120)	21%	3%	40%	36%	-
	painters (N=127)	9%	8%	18%	5%	-
Portsmouth (Oliver *et al.*)	caulkers (N=75)	18%	7%	42%	33%	-
	painters (N=153)	77%	11%	10%	2%	-
Rosyth (Taylor *et al.*)	caulkers/painters (N=69)	46%	7%	25%	22%	-
	caulkers	40%	5%	—55%—		-
	painters	55%	10%	—35%—		-
Rosyth (Payne)	caulkers (N=55)	22%	19%	19%	20%	20%

Lloyd Davies *et al.*, 1957

This study was conducted in the British naval dockyard in Singapore and, unlike the studies in the home dockyards, found no evidence of VWF among riveters, caulkers and paint scalers. A sample of 31 Chinese, Indian and Malay dockyard workers in these occupations was chosen at random.

The riveters and caulkers were said to use the pneumatic tools for between 80 and 120 hours per month, while the scalers used them for approximately 120 hours in alternate months. Most subjects had been in the job for at least three years; ten of them for 15 years or more. The tools and operating methods were the same as those used in the British yards, except that a sling was used to support some riveting hammers in the Singapore yard, and that a typical riveter completed 100 rivets a day (300 rivets was said to be 'not uncommon' in British yards).

Some evidence of vibration injury to the skeletal system was found: 20% of subjects had cystic changes to the bones of the hands. (This was attributed to the 'jarring' which was said to occur because of poor riveting technique compared to that in the British dockyards.) However, no subject complained of numbness or pain in the fingers and no cyanosis or blanching was produced by a provocative cooling test in the vibration-exposed workers. Finger temperatures were, however, consistently found to be lower on the left hand than on the right. This was unexplained, but may indicate that some impairment of vascular function was present in the non-dominant hand. In some other studies of caulkers (Oliver *et al.*, 1979; Wasserman *et al.*, 1981; Payne, 1982) the non-dominant hand has been found to be more affected than the dominant hand.

Blanching was induced in two of three 'control' subjects who were known to have vascular dysfunction. One of these had been exposed to vibration from a motorcycle and to repeated cooling of the hands by working with volatile liquids. It was suggested that vibration causes Raynaud's phenomenon only in conditions of intermittent cooling and that the climate in Singapore prevented the development of VWF.

2.5.4 Other Studies

Other epidemiological studies of interest, in addition to those conducted in British naval dockyards, include those of Bovenzi *et al.* (1980) and Wasserman *et al.* (1982).

Bovenzi *et al.*, 1980
This study of 169 caulkers (100% of the population) and 60 control subjects in an Italian shipyard employed a self-administered questionnaire to establish the prevalence of VWF symptoms and other complaints such as arthralgia and Dupuytren's contracture. Work histories were also obtained. Physiological tests included x-rays of the upper limbs and measurements of finger temperature.

The prevalences observed among caulkers were 31% (blanching), 43% (numbness) and 79% (tingling). In the control groups the prevalences were 7%, 10% and 20% respectively. All cases of blanching corresponded to stages 1 or 2 on the Taylor-Pelmear scale. Latent periods were not quoted, but the average must have been less than 10 years (90% of caulkers had been in the job for 10 years or less).

A greater prevalence of arthralgia in the upper and lower limbs and the back was reported for the caulkers than for the controls, although it was recognised that this could be due, at least partly, to poor working postures. X-rays showed that 31.3% of caulkers had carpal cysts. This indicated an effect of vibration on bones and joints in addition to vascular or neurological complaints. Finger temperatures were shown to be generally lower in caulkers than in controls, but any difference between those with and without VWF were not reported.

The caulkers in this shipyard used chipping hammers and three different sized angle grinders. Vibration measurements were made (see Section 2.2) and the results were compared with the limits in the Draft International Standard ISO/DIS 5349 (1979). This showed the chipping hammer to produce the most severe vibration. In the group of caulkers with blanching, the use of chipping hammers was shown to take a greater proportion of the total work time than in the unaffected group. (However, the group with blanching had also been exposed to vibration for a greater number of years.)

Wasserman *et al.*, 1982

A study of 385 workers at two foundries and a shipyard in the U.S.A. was conducted by NIOSH (National Institute for Occupational Safety and Health). This work was also reported by Behrens *et al.* (1982; 1984).

A questionnaire, administered during interviews with the subjects, provided data relating to medical history (including VWF symptoms), occupational history and smoking/drinking habits. The subjects were then examined in turn by two doctors who tested for Raynaud's phenomenon and performed neurological tests. The diagnoses by questionnaire and by medical examination were found to be consistent, with disagreement in only 7 cases. The prevalence of primary Raynaud's phenomenon was found to be 2.6%. Subjects with 'confounding medical conditions' (14% of vibration-exposed and 12% of controls) were excluded from the analysis. After exclusions, 70% of the total study remained in the vibration-exposed group and 16% in the control group.

The prevalence of VWF among vibration-exposed workers was 47% in the foundries and 19% in the shipyard. The median latent periods were 1.4 years and 16.5 years respectively. (The median value quoted here is the median latent period for those affected, not the latent period for the 50th percentile of the exposed population. The median was believed to be a more useful measure of average latency because of the effect of outliers on the mean.)

In addition to the data for blanching, median latent periods were obtained for tingling (0.6 years in the foundries and 4.2 years in the shipyard) and numbness (0.8 years and 9.5 years respectively). This supports the opinion expressed by Taylor and Pelmear (1975) that these neurological symptoms can be precursory to VWF.

It was shown that the average severity of VWF (using the Taylor-Pelmear scale) was related to the number of years for which chipping hammers had been used. Although the prevalence was greater in the foundries than in the shipyard, no attempt was made to correlate this with the regular vibration exposure times in the two occupations. However, piece workers in the foundries were found to have more severe stages of VWF than hourly paid workers; this may suggest that they were exposed to vibration for a longer daily period.

The NIOSH study made measurements of vibration on chipping hammers and grinders (Wasserman *et al.*, 1981; Reynolds *et al.*, 1982; 1984). However, no attempt to derive a relationship between vibration magnitude and risk of VWF was reported.

2.6 DOSE-EFFECT RELATIONSHIPS

Although epidemiological studies of vibration-induced white finger have been made in different industries and attempts have been made to develop engineering methods for the evaluation of hand-transmitted vibration, the number of studies which have related measures of vibration exposure (magnitude, frequency, exposure time etc.) to measures of the resulting VWF (prevalence, severity etc.) are few. This section reviews studies in which attempts have been made to evolve quantitative relationships between these variables.

The task of quantifying vibration exposure is a complex one. Griffin (1981, 1982a) commented that if all exposures were of constant vibration magnitude, of single frequency and in one direction, it might be a trivial exercise to establish the relative effects of different vibration amplitudes, directions, frequencies and exposure durations. However, since all these parameters are, in practice, variable, it is necessary to establish averaging methods for each of them. Writing at a time when the International and British Standards had yet to be revised (to concentrate on standardised methods of vibration measurement and to include tentative dose-effect relationships) Griffin advocated the adoption of standardised averaging procedures and cumulative dose measures so that data subsequently obtained by different researchers might be used for improving understanding of dose-effect relationships.

2.6.1 The Effect of Vibration Magnitude

Using published data from various sources, Griffin (1980, 1981, 1982a, 1982b) showed that prevalence of VWF appeared to increase with frequency-weighted acceleration magnitude. An ogival relationship between prevalence and magnitude was produced:

$$P = 0.5\{1 + \sin[21.93\ \ln(a_{h,w}) - 55.14]\}$$

where P is the probability of VWF (range 0 - 1) and $a_{h,w}$ is the frequency-weighted acceleration (ms^{-2} r.m.s.). With 21 data points, the correlation coefficient for the relationship was 0.56. While this relationship was of little practical use because of the absence of any variable representing exposure time, the ogival (i.e. cumulative normal distribution) form of the prevalence function is logical for a dose-effect relationship, although the final prevalence value may not be 100% since some individuals appear not to be susceptible to VWF (e.g. Oliver *et al.*, 1979).

2.6.2 The Effect of Vibration Exposure Duration

Lifetime Exposure and Latency

Griffin observed, from the available data, that halving the weighted vibration magnitude appeared to reduce prevalence by approximately 10% for the same exposure period (in years) or to double the exposure period for the same prevalence. He produced a graph to illustrate this concept, showing prevalence as a function of acceleration up to 1000 ms^{-2}, as a series of idealised ogival functions for exposure periods of 1, 2, 4, 8 and 16 years, equally spaced on the acceleration axis. (The adoption of a frequency-weighted acceleration range extending as far as 1000 ms^{-2} r.m.s. is, perhaps, unrealistic in practice. Only one of Griffin's data points had a magnitude greater than 100 ms^{-2} and the accuracy of this is questionable.)

Futatsuka *et al.* (1984) also plotted prevalence as a function of weighted acceleration for different exposure periods, using data from a review of previous Japanese studies (Takamatsu *et al.*, 1982). They selected data from studies where the population was large and the methods 'less biased' and where prevalence had been related to exposure duration and vibration magnitude measured according to ISO/DIS 5349 (1979). The relationships between prevalence, weighted acceleration and exposure periods had a similar form to Griffin's idealised curves over the acceleration range for which data were available (approximately 3 - 30 ms^{-2} r.m.s.).

Taylor *et al.* (1975b) (also Taylor and Pelmear, 1976) reported that they had 'abandoned' the use of prevalence as an indicator of VWF severity in a population because of the inaccuracies caused by changing membership of the studied populations with time. However, they adopted mean latency as a replacement measure, which can also be considered to be subject to such biases (see Section 2.5.1). They demonstrated a strong inverse correlation between the weighted vibration magnitude and the mean latent period for VWF for five populations of workers using a variety of different tools. This appeared to support the concept that a linear inverse relationship exists between weighted acceleration and mean latent period. No account was taken of variability in daily exposure times or of the uncertainties inherent in the use of 'mean latency' data (e.g. what percentage of *exposed* persons is affected after the *mean* latent period?). It is interesting to observe that Hempstock and O'Connor (1977) included these data in a similar relationship, but also included two populations which did not fit this linear relationship so conveniently. The explanation offered for the outliers referred to differences in daily exposure patterns.

Griffin (1981, 1982a, 1982b) produced the following regression line relating the logarithms of the weighted acceleration and the latent period from thirteen studies:

$$L = 16.65 \quad A^{-0.48}$$

However, he observed that the scatter of data was large; two alternative regression lines:

$$L = 10/\sqrt{A} \quad \text{and} \quad L = 100/A$$

were plotted over the data points, illustrating that the true relationship between the two variables had yet to be determined.

A study of latency data by Brammer (1982a, 1983, 1986) used the results from seven studies which met the requirements of his 'rules' for the selection of epidemiological data (see Section 2.5.1). His relationship between latent period and weighted acceleration, obtained by a least-squares fitting procedure (with a coefficient of determination, $r^2 = 0.82$) was:

$$L = 78.7 / a_{h,w}^{1.07}$$

The exponent of 1.07 in this relationship implies a greater accuracy than can be readily achieved with such a small number of data; Brammer's relationship indicates a linear inverse relationship between latent period and acceleration magnitude.

Brammer also investigated the time for VWF symptoms to reach Stage 3 (Taylor-Pelmear Scale) and concluded that the ratio of this to the latent period (i.e. the time to reach Stage 1) was 3.2 ± 0.2. He claimed that this allowed the rate of progression of the disease to be predicted from the latent period which, in turn, could be calculated from the weighted acceleration. He stated that the latent periods within an exposed population were normally distributed and that the standard deviation was related to the latent period by:

$$\sigma = 0.01 + 0.46L$$

By assuming that the latent period in a population is normally distributed with known standard deviation and that the mean latent periods in the epidemiological data correspond to the latency values for the 50th percentiles, Brammer was able to project latency as a function of weighted acceleration for various percentiles of those workers *ultimately affected*. This appears to be of little practical value, as the number of exposed persons 'ultimately' affected is, presumably, always unknown! These relationships were said to apply only to groups whose members operate a single type of tool and who are exposed to vibration from that tool throughout the working day. This also restricted the application of the relationships in many real work situations.

Although the mean latency and weighted acceleration data used for the development of his dose-effect relationships ranged from approximately 2 to 6 years and from approximately 11 to 29 ms^{-2} r.m.s. respectively, Brammer (1982b) produced a relationship in tabular form which covered latent periods from 2 to 32 years and magnitudes from 1 to 25 ms^{-2} r.m.s. These relationships were subsequently adopted for use in the Appendix to the second draft of ISO 5359 (1979) and, later, to the full Standard (International Organization for Standardization, 1986).

The paper by Futatsuka *et al.* (1984) compared VWF data reported during the 1970s in Japan with the dose-effect relationship proposed by the ISO. The relationship between prevalence, latency and frequency-weighted acceleration was similar in form to that of Brammer, although lower prevalences were found (4, 8 and 15% corresponding to 10, 20 and 40% using the Brammer/ISO 5349 relationship). They suggested that this may be due to inadequacy of the frequency weighting or to variations in daily exposure or work pattern.

Daily Vibration Exposure Duration

The relationships suggested by Griffin, Futatsuka *et al.* and Brammer suggest that acceleration magnitude and exposure time may be of approximately equal importance in their respective contributions to VWF during an individual's working life, i.e. the expression:

$$at = \text{constant}$$

might usefully represent a vibration 'dose'. This is in contrast with the time-dependency generally assumed to apply for exposures occurring within one day:

$$a^2 t = \text{constant}$$

which is implicit in the use of root-mean-square averaging during vibration measurement. Futatsuka *et al.* accepted this by their use of ISO/DIS 5349 (1979) for quantifying vibration magnitude, while Griffin described r.m.s. averaging as 'the principal convenient method'. (The inverse relationship between the second power of the acceleration and the duration also allows the definition of the 4 hour (or 8 hour) 'energy equivalent' acceleration magnitude in the current International and British Standards (see Section 2.3.1).)

The availability of digital computing equipment has made alternative integrating or averaging methods practicable. For example, the vibration dose value, used in the evaluation of whole-body vibration exposures (British Standards Institution, 1987b) and root-mean-quad averaging are based on a fourth-power relationship between acceleration and time ($\mathrm{VDV} = (\int a^4 \mathrm{d}t)^{1/4}$; $a_{rmq} = (1/T \int a^4 \mathrm{d}t)^{1/4}$). Both quantities can be computed by linear integration of the acceleration time history.

The convenience of the second-power relationship for daily exposures is such that suggestions of alternatives are almost absent in the literature. Griffin (1990) discussed the possibilities of alternative time-dependencies. He concluded that there was insufficient evidence to choose one relationship in preference to another. The linear relationship which appears to fit latency data well over a period of months or years would allow unreasonably high magnitudes for short durations (the 'action level' of 2.8 ms^{-2} r.m.s. for 8 hours would equate to 3763 ms^{-2} r.m.s. for one minute). The same argument may apply to the (arbitrarily) accepted second-power or energy relationship (61 ms^{-2} r.m.s for one minute) since the current standards have been found to underestimate the VWF symptoms produced by short daily exposures to some tools (e.g. Engström & Dandanell, 1986). Griffin suggested that the fourth-power relationship, as used for the whole-body vibration dose value, might be appropriate; this would place more weight on the magnitude and would result in a smaller range of equivalent magnitudes for the wide range of possible daily exposure times. This possibility has not, however, been tested with epidemiological data.

It has been suggested that there is an effect of intermittency in daily vibration exposures (i.e. that a degree of 'recovery' is afforded by breaks in vibration exposure during the day, such that the risk is less than that for a single period of vibration with the same total duration). This possibility seems intuitively reasonable and was assumed in the Draft International Standard ISO/DIS 5349 (1979). Griffin (1990) stated that the possible benefits of intermittent exposure were not mentioned in subsequent International and British Standards because there were no epidemiological data to support the concept and because of the complexity of the time-dependency that would have resulted. A set of correction factors for the ISO exposure limits in cases of 'interrupted vibration exposure' was proposed by Hempstock and O'Connor (1977).

In an epidemiological study of 266 chain saw users by Miyashita *et al.* (1983), total hand tool operating time was used as a measure of vibration dose. This assumed that the vibration magnitude could be considered to be constant, since all subjects used the same general type of tool. Total operating time (*TOT*) was computed from hours/day × days/year × number of years. The chain saw operators (plus 47 control subjects) were classified by *TOT*, subjective symptoms were noted and a battery of physiological tests for peripheral circulation, sensory function and motor function was carried out. Most tests showed a functional deterioration with increased *TOT* while prevalence of Raynaud's phenomenon was observed to increase at 2000 hours (7.7%) and to have a more pronounced increase for total exposures above 8000 hours

(47.0%). The use of *TOT* as a measure of dose acknowledges the need to recognise differences in the daily exposure durations of different jobs or individuals. However, it does not allow for a possible difference between the time-dependencies for daily and lifetime exposures (as assumed in the current standards), nor does it make allowance for possible effects of intermittent exposure.

Other examples of the use of total operating time as an indicator of dose include an epidemiological study of chain saw operators by Huzl (1971) in which a correlation was demonstrated between VWF prevalence and the amount of timber cut (and therefore, by implication, with operating time). Tominaga (1982) produced a scatterplot showing an 'index of symptoms' as a function of *TOT*. This index was said to be determined by multivariate analysis and presumably gave a severity rating for the 'vibration syndrome' which has been considered to encompass a range of complaints in addition to VWF. An index number of 10 was referred to as the threshold between injured and healthy workers. Tominaga stated that the prevalence of VWF was 20% at approximately 1000 hours exposure and 35% at about 4000 hours. These prevalences are greater than those of Miyashita *et al.* and may be due to differences in the vibration characteristics of the tools concerned (Tominaga's subjects were users of rock drills, riveting and chipping hammers, while Miyashita's were chain saw users).

2.6.3 The Effect of Vibration Frequency

In some early studies it was assumed that all significant vibration occurred at the operating frequency of the tool. Hunter *et al.* (1946) made no measurements of vibration *magnitude*, but placed tools in categories according to their operating rates and concluded that tools with a vibration rate of 2000 - 3000 beats per minute (30 -

50 Hz) were most likely to produce white fingers. This assumption was also apparently made by Lloyd Davies *et al.* (1957) who used only the fundamental frequencies to describe the vibration characteristics of the riveting, chipping and scaling tools used by the subjects in their study.

Miura *et al.* (1957, 1959) made measurements of vibration displacement at the fundamental operating frequencies of the tools concerned. They produced a graph of vibration amplitude against frequency, showing lines of constant prevalence of VWF ('no complaint' and '50% with slight complaint'). This appeared to show that the vibration displacement required to cause the injury dropped with rising frequency, approximating to a line of constant velocity over much of the frequency range. This approach must now be considered to be simplistic, as variations in exposure duration and multiple frequencies of vibration were not considered. However, the proposed relationship gave a good fit with the available data and the relationship does not contradict the frequency-dependency assumed in the current standards ISO 5349 (1986) and BS 6842 (1987).

Agate and Druett (1947) performed frequency analyses and concluded that vibrations of large amplitude in the range 40 - 125 Hz were most likely to produce Raynaud's phenomenon and that tools with no vibration below 600 Hz were not likely to produce it. This is also compatible with the frequency dependency given in the standards.

Griffin (1980) published a graph of vibration acceleration against frequency on which reported incidences of VWF from other studies were marked. This form of presentation did not allow consideration of other variables such as prevalence of symptoms, exposure duration, or the possibility of broad band vibration spectra (the data were not available from all studies). Griffin noted that no tool included had a dominant frequency below 25 Hz, and that the only one above 250 Hz had a large vibration magnitude.

Futatsuka *et al.* (1984) produced a similar graph from the available Japanese data. In contrast with Griffin's graph, the occurrences of VWF were marked on this graph as rectangular zones, for each tool type, covering the range of magnitudes and frequencies, and acknowledging the broad band nature of the vibration. The frequency range of these data was approximately 20 - 1000 Hz. Again, the higher frequencies were generally associated with greater vibration magnitudes. The spread of the data, both in this graph and in Griffin's, was large and cannot be said to support fully the frequency-dependency defined in the standards. However, these studies do not contradict the understanding that VWF occurs where the dominant frequencies of vibration are in the range 20 - 1000 Hz, and that the acceleration magnitude required to produce the effect rises with increasing frequency.

Brammer (1982a) published a graph of r.m.s acceleration as a function of frequency on which were plotted curves representing vibrotactile thresholds, an equal sensation contour, vibration exposure magnitudes representing 50% VWF prevalence (Miura *et al.*, 1957) and thresholds for producing vasospasm in VWF sufferers. He also plotted a 'compromise' curve which was designated the 'assumed equinoxious contour'; this was a line of constant velocity from 16 Hz to 1000 Hz. Brammer noted that below 16 Hz there were few data on which to model the shape of the equinoxious contour other than the equal sensation contours of Miwa (1967) which suggested a flat frequency-dependency below 16 Hz. He chose to adopt a frequency weighting for use in his own work which give equal weight to acceleration components below 16 Hz and to velocity components at higher frequencies, commenting that this was identical to the ISO proposal (International Organization for Standardization, 1979).

In the majority of the studies of the effects of vibration magnitude and exposure duration (see Sections 2.6.1 and 2.6.2) the standard frequency weighting was used when quantifying vibration magnitudes for inclusion in dose-effect relationship models. Although the risk of VWF has been shown to be correlated with frequency-weighted acceleration, this does not necessarily confirm the validity of the weighting; if the important frequencies of vibration (for VWF) are dominant in the spectra for tools associated with VWF, then many different weighting curves might be expected to give similar results.

It has been suggested that the standard frequency weighting underestimates the importance of high frequencies. Engström and Dandanell (1986) found a higher prevalence of VWF among riveters than would be expected using the tentative dose-effect relationship in ISO 5349. Having measured greater magnitudes of acceleration in the range 1000 - 10000 Hz than in the range covered by the standard (frequencies below approximately 1000 Hz) they concluded that the standard frequency weighting was not appropriate for percussive tools which produced shocks with high frequency components. (It is also possible that the time-dependency in the International Standard was inappropriate; see Section 2.6.2 above.)

Starck *et al.* (1983) observed that the incidence of VWF among pedestal grinders in a foundry increased after the introduction of a new type of grinding wheel. The changes in vibration, according to the draft ISO standard, were not sufficient to explain this effect. It was believed that the new process produced more 'impulsive' vibration than before, and it was suggested that one-third octave band r.m.s. analysis underestimated the effect of this vibration.

Starck and Pyykkö (1986) and Starck *et al.* (1990) measured the impulsiveness (i.e. the crest factor) of vibration from a chain saw, a pedestal grinder and a pneumatic hammer, all of which were associated with cases of VWF. They found that the ISO 5349 method underestimated the risk of VWF for the hammer and the grinder, but not for the chain saw. Again, this was attributed to the impulsiveness of the vibration and it was suggested that this should be taken into account when assessing risk.

A similar conclusion was reached by Xu and Ding (1990) who suggested that the difference in the prevalences of VWF in two groups using different types of grinder was due to the 'impulsiveness' of one of the grinders.

Dupuis and Schäffer (1986) simulated the vibration from tools with different vibration crest factors, adjusted to have the same frequency-weighted r.m.s. magnitude, and measured the vibration transmitted to the wrist and elbow and the fingertip temperature. They found no effect on subjective reaction, dynamic response or finger temperature due to changes in impulsiveness and concluded that the existing frequency weighting was adequate. It is questionable, however, whether vibration exposures which could cause VWF over a longer period (months or years) would necessarily produce temporary changes in peripheral circulation, and therefore in finger temperature, during a single, short vibration exposure.

Lundström (1990) reviewed the literature concerning the effects of high-frequency and impulsive vibration, and concluded that the guidance in ISO 5349 was not sufficient to predict the effects of frequencies greater than 1000 Hz. He suggested that the shape of the frequency weighting and the upper band-limiting frequency might be changed in a future revision of the standard.

Similar evidence prompted NIOSH (National Institute for Occupational Safety and Health, 1989) to recommend that in future assessments of hand-transmitted vibration in the USA, unweighted acceleration values should be reported. A frequency range of 5 - 5000 Hz was suggested.

Wasserman (1989) commented that sufficient evidence had been obtained since the publication of ISO 5349 to throw some doubt on the adequacy of the frequency weighting, and he advocated the reporting of unweighted acceleration magnitudes in future work, pointing out that these could be weighted later if required. (On this occasion he did not mention that it would be necessary to preserve acceleration time histories or spectra to allow weighting after the event; also, if meaningful unweighted magnitudes were to be reported, the measurement bandwidth and characteristics of the band-limiting filter would need to be specified.)

There is also evidence that the standard weighting places too much emphasis on the low frequencies of vibration. For example, Tominaga (1982) studied vibration injuries in users of several different types of tool and found that the weighted vibration of a sand rammer was the greatest, although the latent period (expressed in hours as a total operating time) was considerably longer for the users of this machine than for the users of air hammers and rock drills. While the sand rammer had lower vibration magnitudes than these other tools in the range 100 - 500 Hz, it had a peak-to-peak displacement in the range 8 - 16 Hz of up to 40 mm and therefore, because of the shape of the weighting function, a greater overall weighted magnitude. It is logical that low frequencies of vibration are unlikely to contribute significantly to vascular or neurological conditions of the fingers, since it would be expected that such a process would involve the absorption of energy in the tissues of the fingers. Among several studies of the dynamic properties of the hand and arm is that of Griffin *et al.* (1982) who found that the transmissibility of vibration to the knuckle was approximately unity at frequencies below 100 Hz. Absorption of vibrational energy in this frequency range is therefore minimal.

2.6.4 The Effect of Vibration Direction

Although in many early studies of hand-transmitted vibration it was assumed (particularly for percussive tools) that the vibration in one particular direction was dominant (e.g. Miura *et al.*, 1957; Cherchi *et al.*, 1968), it has been shown that many tools and processes produce significant magnitudes in different axes. For example, Bovenzi *et al.* (1980) reported similar magnitudes over a wide range of frequencies in three orthogonal axes on a portable grinder and magnitudes on a chipping hammer in the transverse axis which exceeded those in the direction of strike at some frequencies. Because the vibration from many sources of exposure is multi-directional, few epidemiological investigations into the relative effects of vibration in different axes have been possible.

In the absence of knowledge of the effect of vibration direction, the current International and British Standards advocate the measurement of vibration in three orthogonal axes at each hand position, and the use of the greatest magnitude of the three to represent the severity. While this may be reasonable where one axis is dominant, it has been argued (Price and Hewitt, 1989) that the vector sum of the three magnitudes would be a more representative value. This argument relies on the assumption that the effects of vibration in all directions are equal. The x-, y- and z-axes defined in the standards are a convenience for measurement purposes, but the relative effects of vibration in these three directions will depend on many factors such as the geometry of the handle and the method of gripping the tool. It is reasonable, however, that vibration which acts with a compressive force on the flesh of the fingers (often x- or z-axis) and vibration which exerts a shear force (often y-axis) should not have the same potential for injury.

2.7 SUMMARY

Reports in the literature of measurements of hand-transmitted vibration have shown magnitudes and frequency spectra to be highly variable, even for tools of similar type. Although the validity of some data may be in doubt, due, for example, to low-frequency measurement artifacts, it is apparent that hand tool vibration is dependent on many parameters (measurement techniques and tool operating conditions) and may, even for one tool or process, vary over a wide range of values. This may make the evaluation of some exposures over long periods difficult and subject to poor accuracy.

Reports of epidemiological studies of VWF resulting from the use of metal-working power tools in industry have quoted prevalences of VWF ranging from zero to 100%. This reinforces the argument that a prevalence or mean latency value may not adequately reflect the severity of the vibration exposure of a group of workers, without knowledge of the history of exposure of all members of the group.

In some previous attempts to produce dose-effect relationships, epidemiological and vibration exposure data from a variety of sources were used. Some of the information available was incomplete (e.g. the use of vibration magnitudes based on the assumption of a dominant vibration frequency or axis) or was susceptible to bias (e.g. the use only of prevalence or mean latent period to describe the effect on the exposed population). Some recent studies have shown that the dose-effect models which have been adopted by standards bodies may require revision, particularly with reference to the frequency- and time-dependencies.

CHAPTER 3

MEASUREMENT OF PNEUMATIC TOOL VIBRATION

3.1 INTRODUCTION

The principal objective of this part of the study was to establish methods for the measurement of the vibration characteristics of pneumatic tools and to obtain vibration data for use in the investigation of dose-effect relationships for vibration-induced white finger in dockyard employees.

Evaluation of the severity of hand-transmitted vibration is a complex task. Among the parameters that require consideration are the vibration magnitude (usually expressed as an acceleration value in metres per second per second (ms^{-2})), the frequency content and the direction of the vibration. It was shown in Chapter 2 that the vibration characteristics associated with any one tool or process can be highly variable. This may be due to many different parameters such as the condition of the tool (e.g. unbalance in grinders), the material being worked (e.g. mass, hardness, rigidity), the techniques employed by the operator (e.g. grip force, push force) and speed of rotation or strike frequency of the tool.

A useful indicator of the severity of a vibration exposure would be a 'dose' value, derived from appropriate measurements of vibration and exposure times. Knowledge of the effects on health of vibration magnitude, frequency and direction and the duration and frequency of exposures, might allow the construction of a model which would describe such a 'dose' value. Current standards (ISO 5349, 1986; BS 6842, 1987) contain guidance, but the evidence on which this is based may be inadequate (see Section 2.3.1). The measurement techniques described in this chapter are intended to produce repeatable and comprehensive data from which alternative vibration 'doses' may be computed.

The methods used for the acquisition and analysis of vibration data in this study are described. The selection of transducers and the evaluation of methods for mounting them on vibrating tools are discussed.

Descriptions of the pneumatic tools investigated and the methods of tool operation during vibration measurements are described. The results of the vibration measurements on sixteen types of tool are discussed. Vibration data from these measurements are included in Appendices B and C.

3.2 DATA ACQUISITION AND ANALYSIS

3.2.1 Transducers

The vibration transducers were required to be small in size to minimise inconvenience to the tool operator, and to be low in mass to minimise any effect of loading on the vibration characteristics. (It is common practice to specify a transducer mass of less than one tenth of that of the specimen (Brüel & Kjær, 1978).) The resonance frequency of the transducer was also important because the vibration spectra of some pneumatic tools have been shown to contain components up to several thousand hertz (e.g. Dandanell & Engström, 1986).

Piezoelectric accelerometers were chosen for this application as the resonance frequency of these devices is high (typically > 20 kHz) and the dynamic range is large (typically 140 dB) compared with other types, such as piezoresistive accelerometers.

These devices contain a sensing element made from piezoelectric materials such as ferroelectric ceramics (e.g. lead zirconate titanate, bismuth titanate) or single crystals (e.g. quartz, tourmaline). Such materials become electrically charged when stressed. The piezoelectric element is mounted with a reaction mass so that a compressive or shear force is exerted on it when the transducer is subjected to acceleration in the sensitive axis. A charge amplifier is normally used to convert the charge output signal from the accelerometer to a low impedance voltage source.

Some of the pneumatic tools under consideration operated with a percussive action, resulting in high magnitude peak accelerations. Such conditions have been shown to result in damage to transducers and, with piezoelectric accelerometers, 'd.c. shifts' or 'zero shifts' (Kitchener, 1977; Frood, 1977; O'Connor and Lindqvist, 1982). This phenomenon is thought to be due to overloading of the piezoelectric element and can appear as a sudden shift in the zero value of an acceleration time history as shown in Figure 3.1. The decay following the d.c. shift is determined by the time constant of the charge amplifier circuit.

Occasionally, this phenomenon is difficult to detect by visual inspection of the time history. However, it is revealed in artificially high magnitudes at low frequencies in spectral analysis. Figure 3.2 shows power spectral density functions from two measurements made on a needle scaler in similar conditions. Differences may be seen between the low-frequency values in the two spectra. Above approximately 70 Hz, the spectra are similar. The low frequency artifact in curve 2 caused an increase from 2.85 ms^{-2} r.m.s. to 6.71 ms^{-2} r.m.s. in the frequency-weighted magnitude according to ISO 5349 (1986) and BS 6842 (1987).

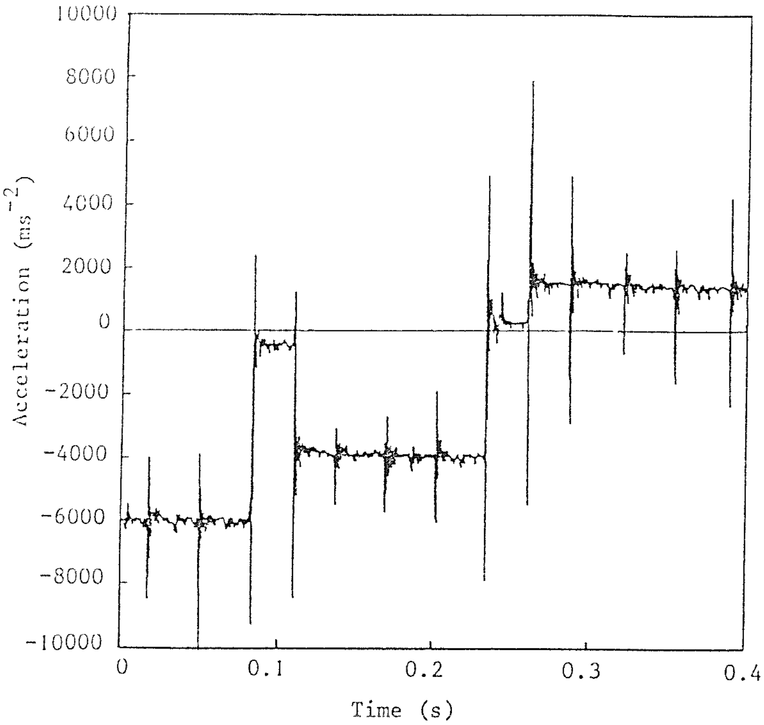


Figure 3.1 *Acceleration time history (chipping hammer handle, y-axis) showing d.c. shifts in the accelerometer output signal*

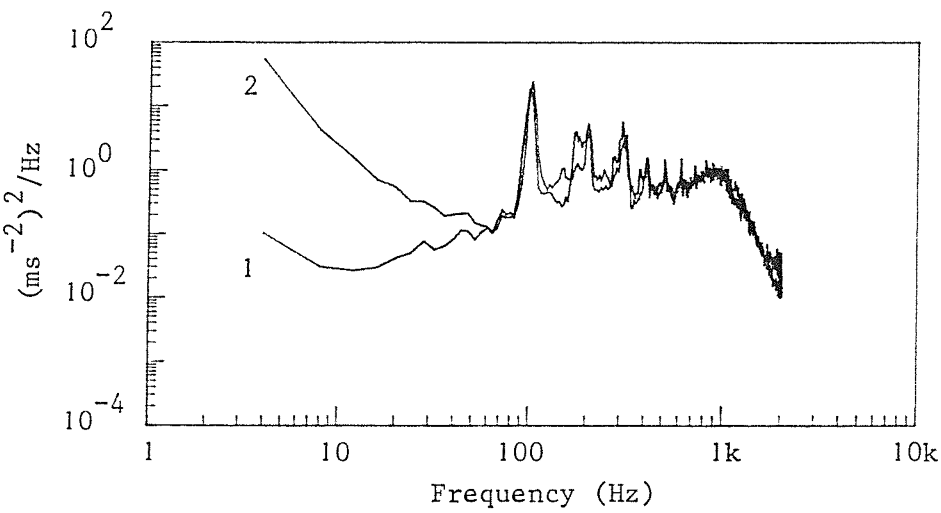


Figure 3.2 *Two acceleration power spectral density functions (needle scaler, x-axis) showing differences at low frequencies due to measurement artifact (Resolution = 3.98 Hz)*

Chu (1987) studied the causes of d.c. shifts. He attributed the phenomenon to 'domain switching' in ferroelectric ceramics. The problem may be reduced by the use of high coercivity materials, although the charge sensitivity is lower, requiring the use of built-in amplification. Single crystal piezoelectric materials, such as quartz, cannot exhibit domain switching. However, it is necessary to use a compression design in accelerometers using these materials and these are susceptible to d.c. shifts due to slippage between the mass and the pre-stressed element. Chu also identified other causes of d.c. shifts: base strain induced errors, cable noise, inadequate low-frequency response and overloading of the signal conditioning circuit.

The data presented above indicate the necessity either to use accelerometers which would not exhibit non-linear behaviour in high-shock conditions, or to provide the accelerometers with protection against high frequency shocks. Such protection can be afforded by a low-pass mechanical filter, consisting of a section of resilient material placed between the vibrating surface and the accelerometer. A commercially available mechanical filter (Brüel & Kjær type UA 0559) has the effect of introducing a highly damped resonance response (approximately +2.5 dB at 6 kHz, -3 dB at 12 kHz) when used with an accelerometer (type 4371) of mass 11 grams (manufacturer's information). The accelerometer's resonance frequency (approximately 42 kHz) is raised, and its resonance response reduced by approximately 30 dB. A disadvantage of this device is the increase in the mass of the accelerometer mount (16 grams per filter).

Two types of 'shock-rated' accelerometers (Brüel & Kjær type 8309 and Kistler type 8044 with quartz element) were tested on percussive tools. Both of these devices exhibited occasional d.c. shifts. Fewer errors were observed with general purpose accelerometers (Brüel & Kjær type 4371) mounted on mechanical filters. (PNEUROP (1980) and O'Connor and Lindqvist (1982) reported a similar finding.) The Brüel & Kjær type 4371 accelerometers (sensitivity 1 pC/ms^{-2}, mass 11 grams) were therefore chosen for use in this investigation. Spectral analysis (see Section 3.2.4) was performed on all acceleration time histories, allowing any low-frequency artifacts to be identified. The use of general purpose accelerometers also gave a greater sensitivity and dynamic range than would have been possible with most 'shock' accelerometers.

3.2.2 Signal Conditioning

Charge Amplifiers

Piezoelectric accelerometers are high impedance devices which produce a charge output, proportional to the acceleration to which they are subjected. If a voltage amplifier is used to condition such a signal, the sensitivity is affected by the additional capacitance associated with the cable. The use of charge amplifiers with these accelerometers is therefore normally recommended. The charge amplifier converts the charge on the accelerometer's capacitive element to a voltage, proportional to the acceleration, and has a low output impedance.

For all the vibration measurements in this study, each accelerometer output signal was conditioned with a Brüel and Kjær charge amplifier (type 2635). The frequency limits were set to give a frequency range of 2 - 3000 Hz. The output sensitivity (adjustable in increments of 10 dB) was set to give the greatest output signal possible without overload, in order to optimise the dynamic range of the instrumentation. The sensitivity setting used was dependent on the magnitudes of vibration involved and was determined by experiment before data recording was started. Typical settings gave sensitivities of 1, 3.15 or 10 mV/ms^{-2}. The charge amplifiers were equipped with overload detectors which were monitored during all vibration measurements.

Accelerometer Cables

The accelerometers were connected to their respective charge amplifiers using Brüel and Kjær low-noise co-axial cables with 'microdot' type connectors.

If high impedance accelerometer cables are allowed to move or bend, noise may be introduced, especially at low frequencies. This is due to the triboelectric effect: local capacitance changes in the cable which cause charges to be released. It is therefore good practice to keep the length of the cable between the accelerometer and the charge amplifier to a minimum and to secure the cable to minimise movement.

The cable lengths used were approximately 2 metres. This length was necessary to allow sufficient freedom of movement for the tool operator. Where the hose clip accelerometer assembly (see Section 3.3.1) was used, the three accelerometer cables were secured to the handle or body of the pneumatic tool, close to the accelerometers, with cable ties or adhesive tape, to minimise triboelectric noise. Where the miniature accelerometers were used on the ring on the operator's finger (see Section 3.3.2), the cables were taped to the back of his hand and to his forearm.

Anti-aliasing Filters

The charge amplifier output signals were low-pass filtered at 1250 Hz, before digital acquisition, to prevent aliasing. This cut-off frequency is that defined as the upper frequency limit in the weighting function W_h given in BS 6842:1987. The filters used were Kemo type VBF17 which gave a -48dB/octave Butterworth characteristic.

Calibration

The accelerometers and signal conditioning equipment were calibrated before use with a vibration calibration exciter (Brüel and Kjær type 4294). With each accelerometer mounted in turn on the calibrator, each channel was checked against the reference excitation of $10ms^{-2}$ r.m.s. at 159.2Hz (1000 radians/second).

Tape Recording

When vibration recording took place in the work-place, the charge amplifier output signals were recorded using a 7-channel F.M. cassette data recorder (Teac type R-71) which had a frequency range of 0 - 1250 Hz and a signal-to-noise ratio of 48 dB. A calibration signal was recorded on the tape before and after each measurement session. The recorded time histories were subsequently filtered and digitised in the same way as those produced in the laboratory.

3.2.3 Analogue-to-digital Conversion

Acceleration signals from three accelerometers (x-, y- and z-axes) were simultaneously digitised at a rate of 5000 samples per second using a 16-channel, 12-bit analogue-to-digital conversion device (MIP-34 Micro Input Processor) installed in a DEC PDP11/34 computer and operated under DATS11 software control. Each digitised time history was three seconds in duration (15000 samples).

3.2.4 Data Analysis

Power Spectral Density Functions

Analysis of vibration data was carried out using the DATS11 time-series analysis software package. A power spectral density function was calculated from each of the digital acceleration time histories. These spectra had a resolution of 4.88 Hz and 56 degrees of freedom. The Hanning spectral window was used in all cases. The power spectral density function is an indicator of the energy present in the acceleration signal per unit bandwidth; the units were therefore $(ms^{-2})^2/Hz$ as the original time histories were in ms^{-2}.

Frequency-weighted Acceleration Magnitudes

The frequency-weighted root-mean-square acceleration value, $a_{h,w}$, was calculated from each of the power spectral density functions using the formula:

$$a_{h,w} = \left[\int_{4.88}^{1249.28} H^2(f)\ G(f)\ df\right]^{1/2}$$

where $G(f)$ is the acceleration power spectral density function and $H(f)$ is the frequency weighting function specified in ISO 5349 (1986) and BS 6842 (1987) (weighting W_h. This weighting function was generated in digital form by interpolating between the weighting factors defined in BS 6842 for one-third octave band centre frequencies to give a weighting function with the same increment (4.88 Hz) as the acceleration power spectral density functions. The frequency weighting function is defined over the range 6.3 - 1250 Hz. The above integration procedure was performed over the 256 data values from 4.88 to 1249.28 Hz.

Unweighted Acceleration Magnitudes

The unweighted root-mean-square acceleration magnitude from each measurement, a_{lin}, was calculated over the same frequency range (4.88 - 1249.26 Hz) using a similar integration method without the weighting function $H(f)$:

$$a_{lin} = \left[\int_{4.88}^{1249.26} G(f)\ df\right]^{1/2}$$

Octave Band Acceleration Magnitudes

Octave band r.m.s. values were also calculated from the power spectral density functions. This procedure used trapezoidal integration on the power spectral density function, centred on the eight octave band centre frequencies from 8 to 1024 Hz.

The algorithm calculated the true octave band centre frequencies (i.e. a doubling in frequency for each band) rather than using the preferred frequencies conventionally used in analysis of this kind (International Electrotechnical Commission, 1966). Therefore, the last centre frequency was 1024 Hz, compared with the nominal 1000 Hz. A difference of 2.4% was therefore present in the frequency of the centre of the upper four bands.

Transfer Functions

In the investigations of the frequency responses of accelerometer mounts (see Section 3.3) the transmissibility of vibration was measured between an accelerometer rigidly mounted on a vibrating bar and an accelerometer mounted on the bar using the mounting device under test.

Data were acquired from the two accelerometers as described above. Transfer functions, $H(f)$, between the two accelerometers were calculated using the cross spectral density method:

$$H(f) = \frac{G_{io}(f)}{G_{ii}(f)}$$

where $G_{ii}(f)$ is the power spectral density of the vibration acceleration at the 'input' (i.e. on the vibrating bar) and $G_{io}(f)$ is the cross spectral density function between vibration acceleration at the 'input' and at the 'output' (i.e. on the mount).

3.3 ACCELEROMETER MOUNTING METHODS

In order to make measurements of vibration in three axes at the hand positions on vibrating tools, it was necessary to establish a method of mounting three orthogonally oriented transducers without damage or modification to the tool and with minimal effect on the vibration characteristics due to mass loading.

3.3.1 Hose Clip Accelerometer Mount

A device for attaching accelerometers to vibrating tools was produced and is shown in Figure 3.3.

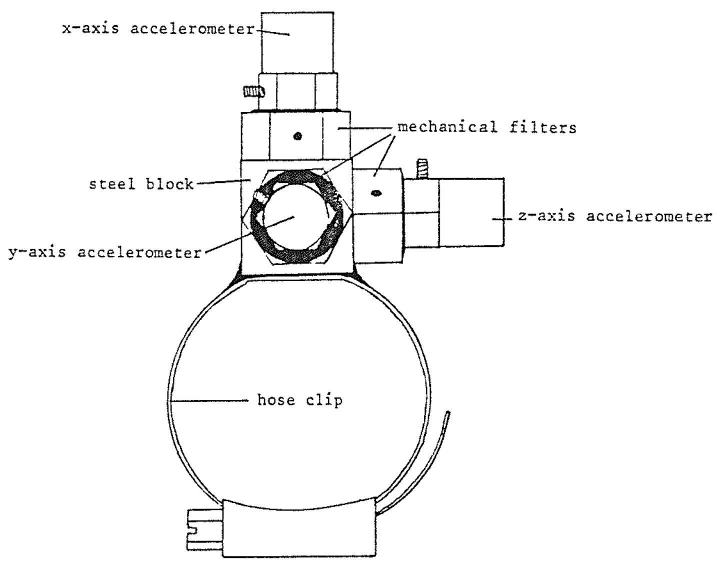


Figure 3.3 *Hose clip accelerometer assembly showing three triaxially mounted accelerometers with mechanical filters*

The assembly consisted of three piezoelectric accelerometers (Brüel & Kjær type 4371) each mounted on a mechanical filter (Brüel & Kjær type UA 0559) and attached to a face of a steel cube (20 x 20 x 20 mm) by means of a 10-32 UNF threaded stud. This cube was welded to a hose clip of suitable length for clamping tightly around the handle or body of the tool under investigation.

The mass of the cube and hose clip was 78 grams. The mass of each accelerometer was 11 grams and the mass of each mechanical filter was 16 grams. The total mass of the assembly was therefore 159 grams with mechanical filters and 111 grams without filters.

Evaluation of Frequency Response

The frequency response of the hose clip accelerometer mount, with three accelerometers, was tested in all three axes by mounting the assembly tightly on a handle made from solid steel bar, diameter 30 mm, length 100 mm, which was welded to a rigid steel support and mounted, with either vertical or horizontal orientation as required, on an electrodynamic vibrator (Derritron type VP85). An accelerometer (also Brüel & Kjær type 4371) was mounted on the handle support by means of a stud and tapped hole with the same orientation as the axis of the hose clip assembly under investigation.

The vibrator was driven by a digitally-generated random signal which had been equalised by digital filtering to give a flat acceleration power spectral density on the vibrator in the frequency range 10 Hz to 1000 Hz. The amplitude of the excitation was adjusted to give a frequency-weighted acceleration magnitude, $a_{h,w}$, of 8.0 ms^{-2} r.m.s. (See Section 3.2.4 for the method of calculating $a_{h,w}$.) The transfer function between the signals from the accelerometers mounted on the bar and on the hose clip were computed using the method also described in Section 3.2.4.

The transmissibility moduli are shown in Figure 3.4; the frequency response of the accelerometer mounting device is flat to within ± 2dB in the frequency range 10 Hz to 1 kHz.

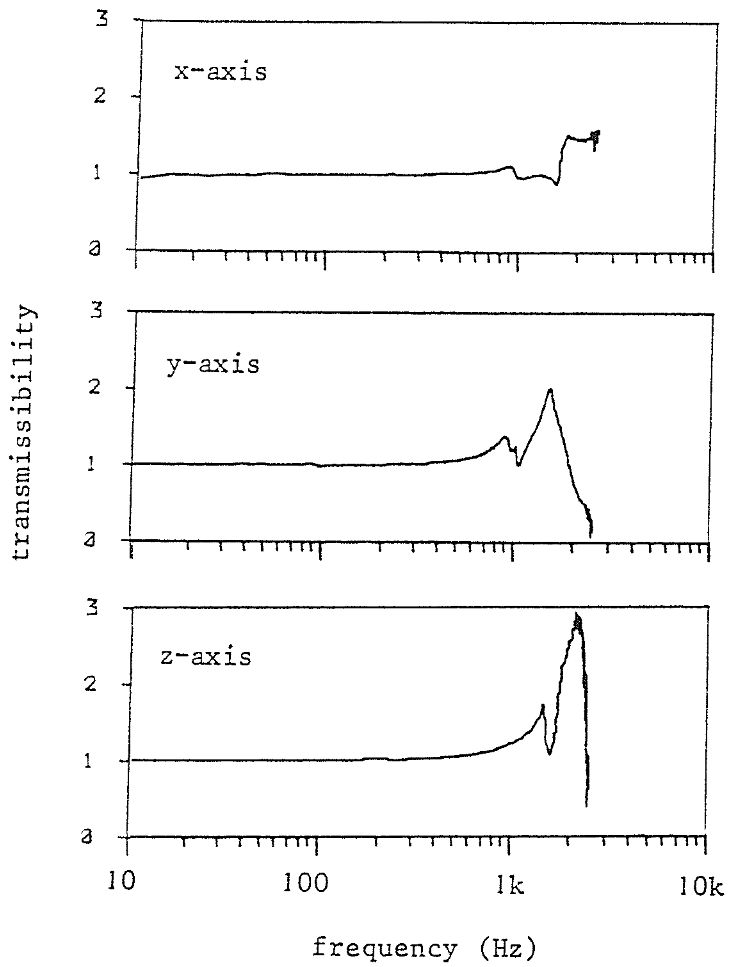


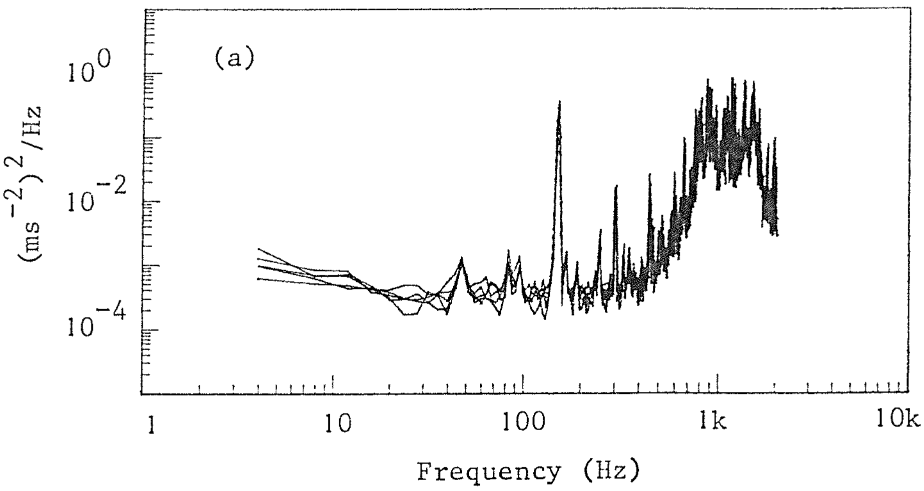
Figure 3.4 *Transmissibility between a vibrating handle and the hose clip accelerometer assembly in three axes*

The Effect of the Mass of the Transducer Assembly

The mass of the entire assembly, including accelerometers and mechanical filters, was approximately 0.15 kg. This is in excess of the 50 g maximum which has been suggested in some standards (e.g. ISO 8662/1, 1988). However, a mass of 0.15 kg is small (typically 5 - 10%) when compared with the masses of most of the pneumatic tools in this study. A series of test measurements was conducted using a tool with one of the lowest masses in the study (Thor angle grinder type 3S, mass 1.8 kg).

The tool was operated free running (i.e. not grinding) at full throttle for maximum repeatability. Five repeat measurements were made in the x-axis with the hose clip, mounting block and three accelerometers and mechanical filters attached to the tool. The spectra from these measurements are shown in Figure 3.5(a). The hose clip mount was then removed and the measurements were repeated with one accelerometer and filter, mounted by screwing a stud directly into a tapped hole in the tool body. The five spectra from these measurements are presented in Figure 3.5(b).

The r.m.s. acceleration magnitudes (unweighted) for the five measurements with the hose clip mount had a mean value of 11.26 ms^{-2} (standard deviation 0.32 ms^{-2}). For the measurements with the direct mounting method the mean value was 11.38 ms^{-2} (standard deviation 0.26 ms^{-2}). A test of significance (Student's t-test, $p < 0.01$) revealed that there was no significant difference between the magnitudes obtained with the two accelerometer mounting methods.



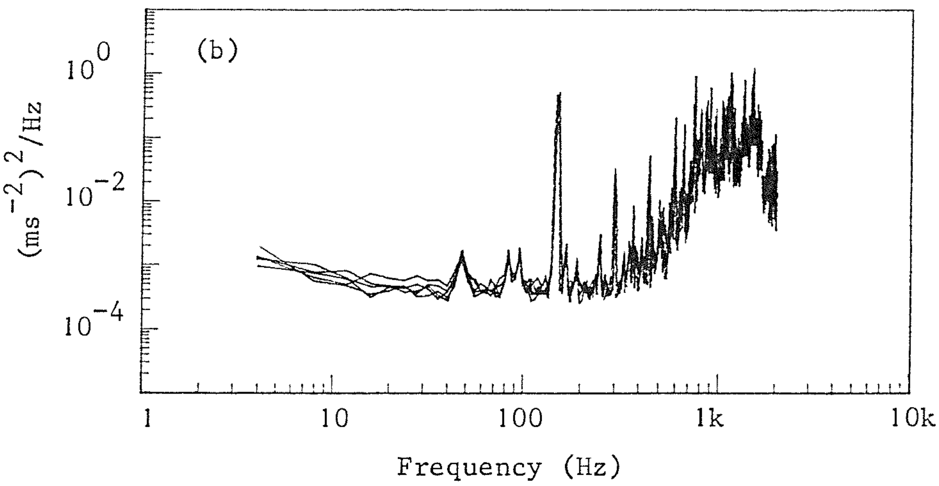


Figure 3.5 *Acceleration power spectral density functions for small angle grinder, measured with hose clip assembly (a) and rigidly mounted accelerometer (b) (Resolution = 4.88 Hz)*

Practical Limitations of Hose Clip Mount

The hose clip mount, accommodating three general purpose accelerometers and mechanical filters, was found to be convenient for measurement of vibration on pneumatic tools. The assembly could be easily mounted on the handles and bodies of most tools, its frequency response was shown to be flat in the range of interest and its mass was not found to have an appreciable effect on the vibration of a tool of low mass (1.8 kg). All vibration data in Appendix B were obtained using this device, unless otherwise indicated.

The hose clip arrangement was found to be impracticable for measurement of vibration on the chisel of a chipping hammer. The impulsive nature of the vibration caused the hose clip to slip along the chisel after a few seconds. A steel mounting block was welded to the side of the chisel, allowing rigid mounting of a mechanical filter. This resulted in the destruction of the mechanical filter and the accelerometer. Alternative methods were therefore required, to avoid the need for rigid coupling of the transducers to the vibrating surface of the chisel.

3.3.2 Hand-held Accelerometer Mount

Two situations were envisaged in which a device for triaxially mounting accelerometers on the hand of the tool operator might be desirable:

1. Use on tools with high peak acceleration values (e.g. on the chisel of a chipping hammer). Rigid mounting of accelerometers may result in damage (see above). However, if an accelerometer is held by hand against a vibrating surface, a resonance will occur in the mounting. This resonance is typically at a frequency in the range 1 to 5 kHz and has low damping (Harris and Crede, 1976; Brüel & Kjær, 1978). The resonance

frequency of the accelerometer itself (an order of magnitude greater) is therefore unlikely to be excited. A hand-held mounting device may therefore allow measurement of vibration at the hand-tool interface at low frequencies (below approximately 1 kHz), while protecting the transducer elements against the high frequency shock energy.

2. Recording the hand-transmitted vibration to which an individual is exposed during a working day. A vibration 'dose meter' would require accelerometers to be mounted on the worker's hands rather than on the tools. A ring-shaped mount, which could be worn on the finger might, with appropriate portable recording equipment, be suitable for this purpose.

A commercially available hand-held triaxial accelerometer mount (Brüel & Kjær 'hand adaptor' type UA 0891) has been previously described (Rasmussen, 1982). This was a 'T' shaped structure which was held against the vibrating surface between two fingers. This supported a block, in which were mounted the three accelerometers (type 4374).

The response of this device was measured using the same method as for the hose clip mount (Section 3.3.1). The mount was held, with the tightest possible grip force, against a solid steel handle, driven by an electrodynamic vibrator. The transmissibility of vibration between the handle and the accelerometer on the hand-held mount was measured in all three axes. The results are shown in Figure 3.6.

In all three axes, the resonance frequency was at approximately 800 Hz. The transmissibility at resonance was high (between 10 and 15) and caused some amplification at frequencies above approximately 500 Hz. Grip forces applied by tool operators were expected to be smaller than those applied during the tests described here. The effect of the resonance at lower frequencies was therefore expected to be unpredictable in practice.

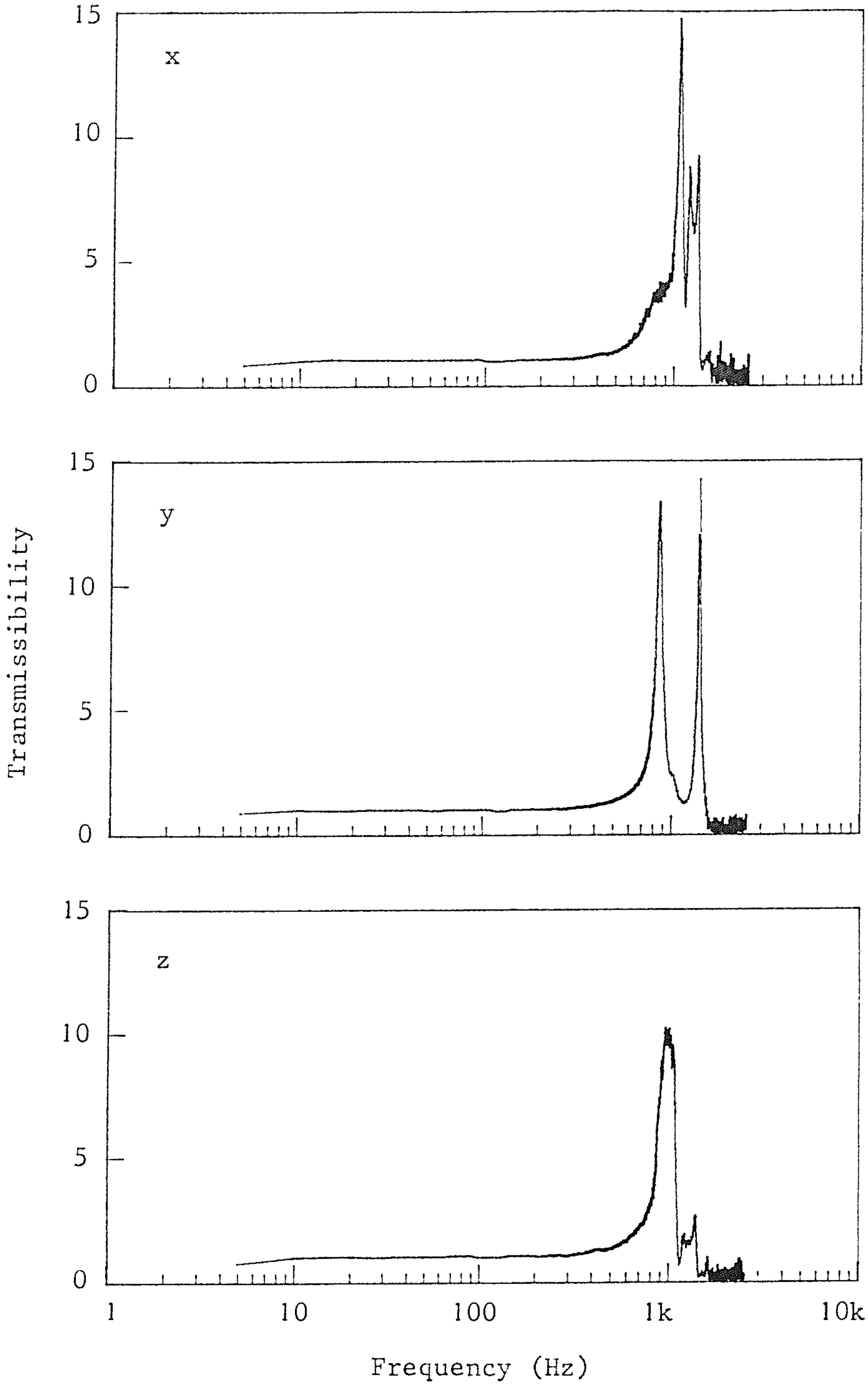


Figure 3.6 *Transmissibility between a vibrating handle and Brüel & Kjær 'hand adaptor' type UA 0891 in three axes*

Ring Design

An alternative hand-held accelerometer mount was fabricated from a single piece of aluminium alloy and is shown in Figure 3.7. The mass of the device was 18 grams.

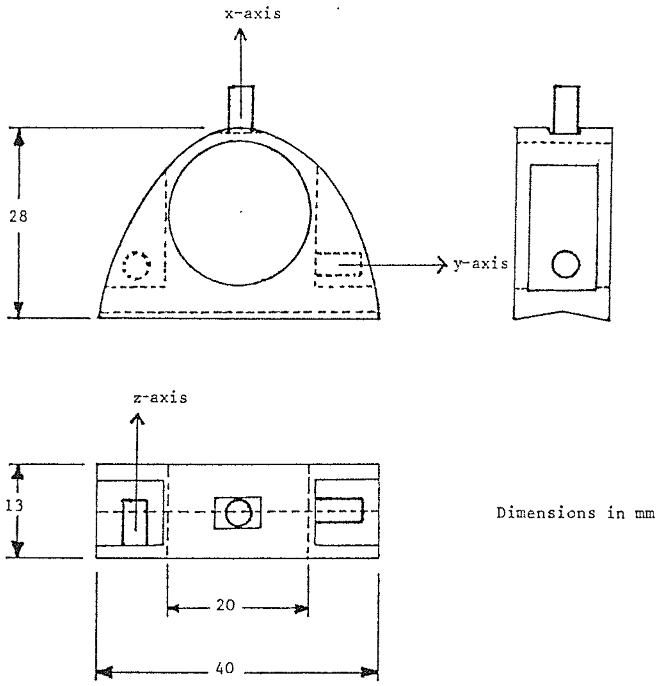


Figure 3.7 Aluminium ring for mounting accelerometers on the tool operator's finger

Experiments with a series of prototypes resulted in the incorporation of the following features in the ring:

1. A large surface area (40 x 13 mm) in contact with the surface of the tool to minimise any 'rocking' motion which might cause a resonance in the y- and z-axes.

2. A 'V'-shaped base to reduce rocking or slipping on cylindrical handles or tool surfaces.

3. Mounting positions for y- and z-axis accelerometers as close as possible to the tool surface, also to minimise any rocking effects.

4. A large finger-hole to accommodate a wide range of finger sizes. The 95th percentile male index finger breadth at the proximal interphalangeal joint is 23 mm (Pheasant, 1988). As the ring was not intended to pass beyond this joint but to sit on the medial phalanx of the index or middle finger, a diameter of 20 mm was chosen.

Two experiments were conducted to evaluate the performance characteristics of the mount.

Evaluation of Frequency Response

Two solid steel handles, one horizontally orientated for x- and z-axis vibration and one vertically orientated for y-axis vibration, were mounted in turn on a vertically orientated electrodynamic vibrator (Derritron type VP85). Each handle had a cylindrical section, 30 mm in diameter and 100 mm in length, for the hand to grip. A piezoelectric accelerometer (Brüel & Kjær type 4371) was mounted on the upper surface of the handle by a threaded stud and tapped hole. A miniature piezoelectric accelerometer (Kistler type 8614A1000) was mounted on the ring, in the appropriate position for the axis under investigation, with a thin layer of adhesive wax.

Six male subjects took part in the experiment. The ring was fitted to the middle phalanx of the index finger of the right hand. The internal diameter of the ring was adjusted for a snug fit on the finger with one or more layers of adhesive tape. For each of the three axes, the subjects were asked to hold the handle, adopting the postures shown in Figure 3.8.

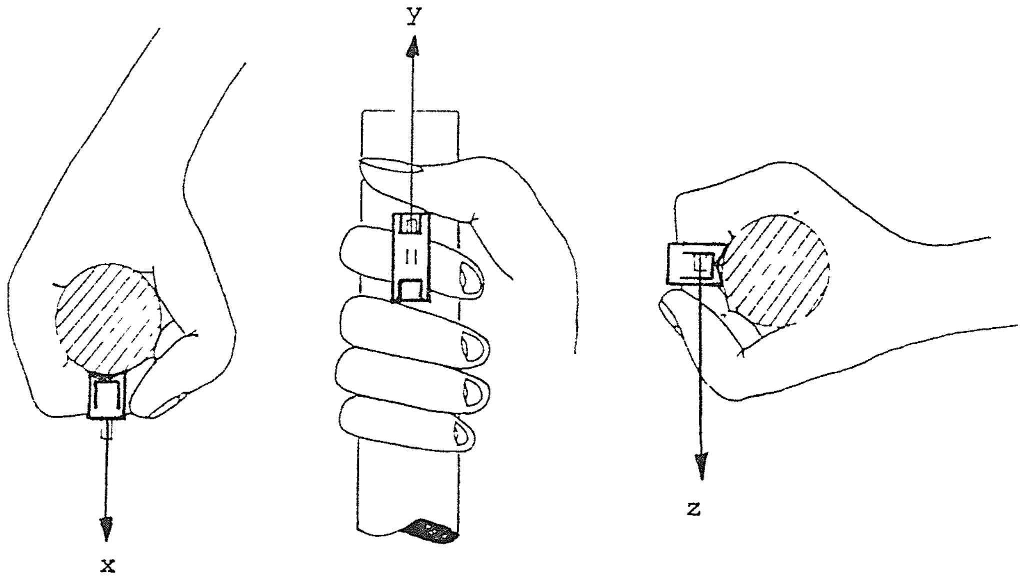


Figure 3.8 *Hand positions on vertically vibrating handles for evaluation of ring-type accelerometer mount in three axes*

To investigate the effect of grip force, subjects were asked to adopt three different grips:

1. The tightest possible grip
2. An 'average' comfortable grip
3. The least possible grip without slipping

Although not measured objectively, these three subjective grip forces were expected to cover the range likely to be used in the normal operation of pneumatic tools.

For each of the three axes, subjects were given four vibration exposures, each of five seconds duration. The first was a practice run, followed by an exposure with each of the three grip forces in turn. The order of grip forces and axes of vibration was balanced across subjects in order to eliminate any systematic errors due to a possible learning effect.

The vibrator was driven by a random Gaussian vibration signal with a band-width of 1250 Hz and a frequency-weighted acceleration magnitude, $a_{h,w}$ = 8.00 ms^{-2} r.m.s. The output signals from the two accelerometers were digitised during the last three seconds of each exposure and the transmissibility of vibration between the handle and the ring-mounted accelerometer was calculated for each subject/axis/grip force combination. The method used was that described in Section 3.2.4.

Figure 3.9 shows the transmissibility moduli for the six subjects for each of the nine axis/grip force combinations. In Figure 3.10 the three curves on each graph represent the mean and mean ± one standard deviation values for each condition. Little difference is apparent in Figure 3.10 between the mean curves for the three grip forces for each axis of vibration. It follows that subjects were able to maintain good contact with the surface of the handle during exposure to broad-band vibration with the three different grip forces.

In the x-axis, the mean transmissibility remained near unity (maximum value approximately 1.5) over the entire frequency range and was practically unaffected by grip force. The variability between subjects was very small at frequencies above approximately 100 Hz, although larger differences were observed at low frequencies. This may have been caused by momentary losses of contact between the ring and the handle, although this seems unlikely, especially with the tight grip force.

In the y-axis, the mean curve remained close to unity at all frequencies for the tight grip but dropped with increasing frequency to approximately 0.7 at 1000 Hz (medium grip) and to approximately 0.5 at 1000 Hz (loose grip). An increase in the variability of transmissibility between subjects with reduced grip force was apparent. The maximum value of the standard deviation of transmissibility in this axis was approximately 30% of the mean.

In the z-axis a small peak in the response was observed for some subjects at around 150 Hz, with transmissibility reduced to around 0.5 at frequencies above approximately 400 Hz. A possible explanation for this response is that the ring 'rocked' in the z-axis direction because of the geometry of the base area. An increase in the width of the ring might have reduced this phenomenon but would have made it suitable for use on fewer tool handles.

3.3.3 Comparison of Mounts on Pneumatic Tools

An experiment was conducted to compare the performance of the ring and the hose clip methods of accelerometer mounting by making measurements with the two devices simultaneously on vibrating tools.

Two pneumatic hand tools (a grinder and a scaling tool) were chosen for their different vibration characteristics:

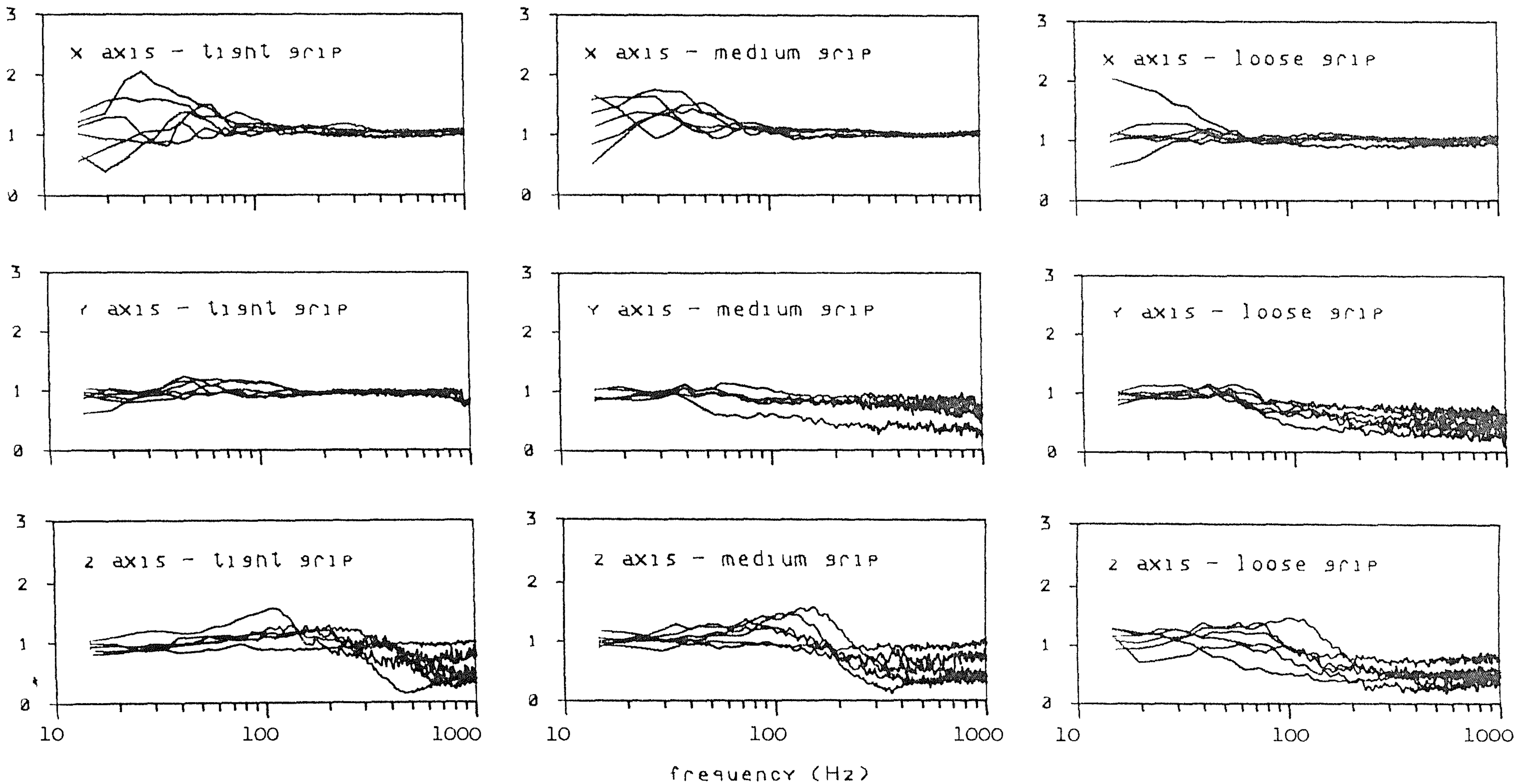


Figure 3.9 *Transfer function moduli between the handle and the ring, six subjects*

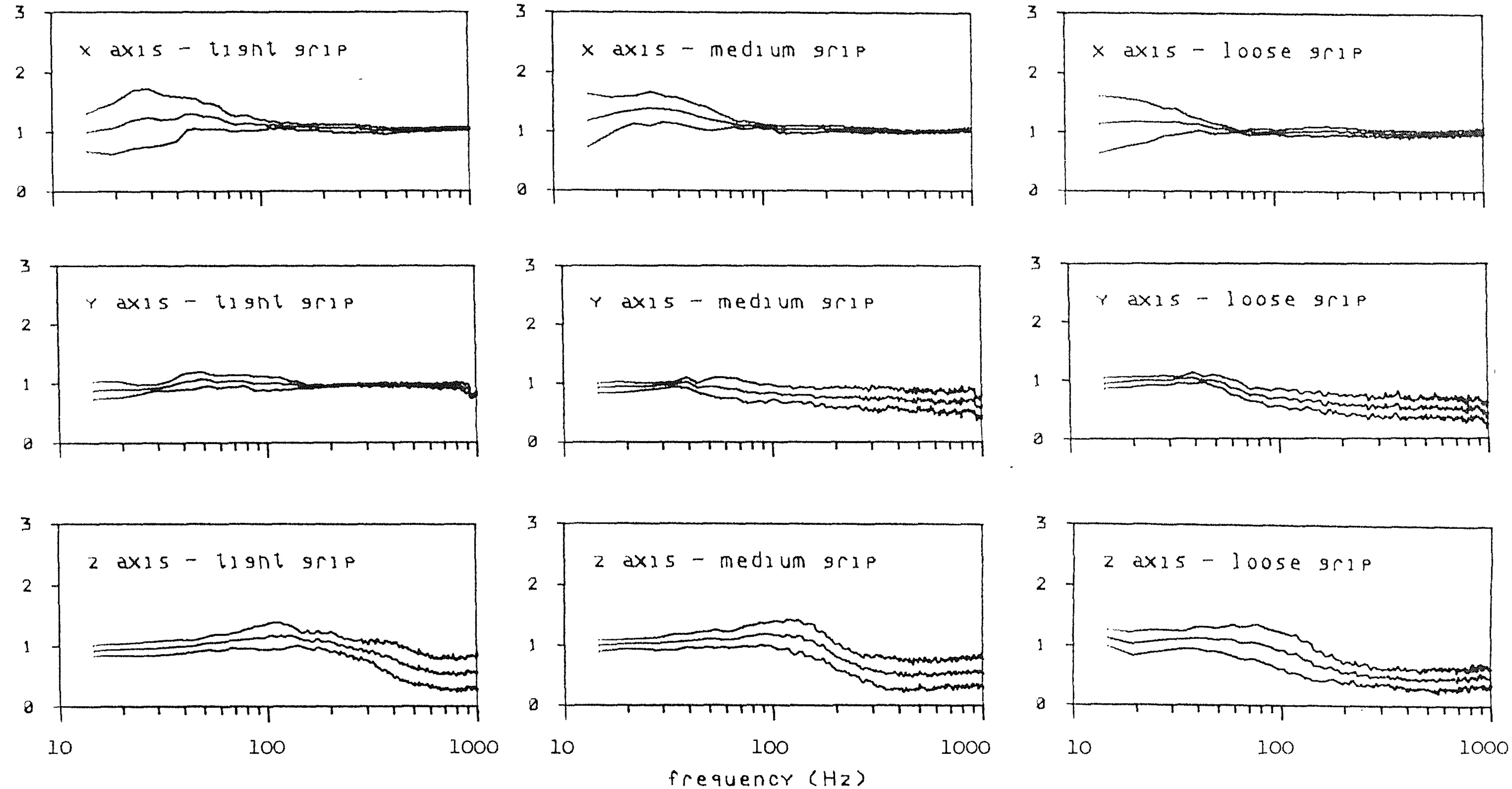


Figure 3.10 *Transfer function moduli for six subjects (mean ± 1 standard deviation)*

1. Vertical grinder. Thor type 5VL (7 inch disc). This rotary tool had a fairly 'smooth', broad band vibration spectrum.

2. Chisel scaler. CPT 'Superior Paint Scraper'. This tool had a percussive action which resulted in a 'peaky' spectrum.

An accelerometer (Brüel & Kjær type 4371) and mechanical filter were attached to the tool handle using the hose clip mount. The orientation of the x-, y- and z-axis transducers on the two tools was the same as that shown in Section 3.5 (Figures 3.25 and 3.33). A miniature accelerometer (Brüel and Kjær type 4374, mass 0.65 kg) was mounted on the ring with a thin layer of adhesive wax. The ring was positioned on the tool operator's index finger and held firmly against the tool surface, close to, and aligned with, the hose clip assembly. Acquisition of data from both accelerometers was then performed over a three-second period while the tool was operated at full throttle against a flat, mild steel surface. The sampling rate and filter settings were as described in the previous section. The procedure was repeated for all three axes (i.e. for three orientations of the accelerometers on the hose clip and on the ring).

In the case of the chisel scaler, the tests were repeated with a 1 mm layer of neoprene rubber attached with adhesive to the underside of the ring. This was done because the tool operator had felt that the ring was slipping on the tool surface.

A power spectral density function was computed from each acceleration time history. These spectra (resolution 4.88 Hz) are presented in Figure 3.11.

These data are presented as pairs of spectra for comparison, instead of transfer functions as before, because the coherency between the jubilee clip and ring data was found to be low at some frequencies: the 'peaky' nature of the spectra (particularly for the scaling tool) resulted in low magnitudes of vibration at some frequencies.

The frequency-weighted magnitude from each measurement was computed using the method given in Section 3.2.4. These values are given in Table 3.1.

Table 3.1 *Frequency-weighted r.m.s. acceleration magnitudes (ms^{-2}) from measurements on pneumatic tools with two transducer mounting methods*

	Hose clip mount	Ring mount
Vertical grinder:		
x	1.32	1.76
y	1.54	2.00
z	2.23	2.74
Chisel scaler:		
x	2.23	11.69
y	15.68	21.89
z	5.43	13.16
Chisel scaler (rubber layer on ring):		
x	1.23	2.64
y	19.76	18.75
z	3.47	5.75

The data from the grinder, obtained by the two mounting methods, are of the same order of magnitude in all axes. The greater values from the ring at low frequencies, especially in the y-axis, may indicate that the ring moved during the test. The greatest difference between the frequency-weighted acceleration magnitudes for the two transducers was a factor of 0.33.

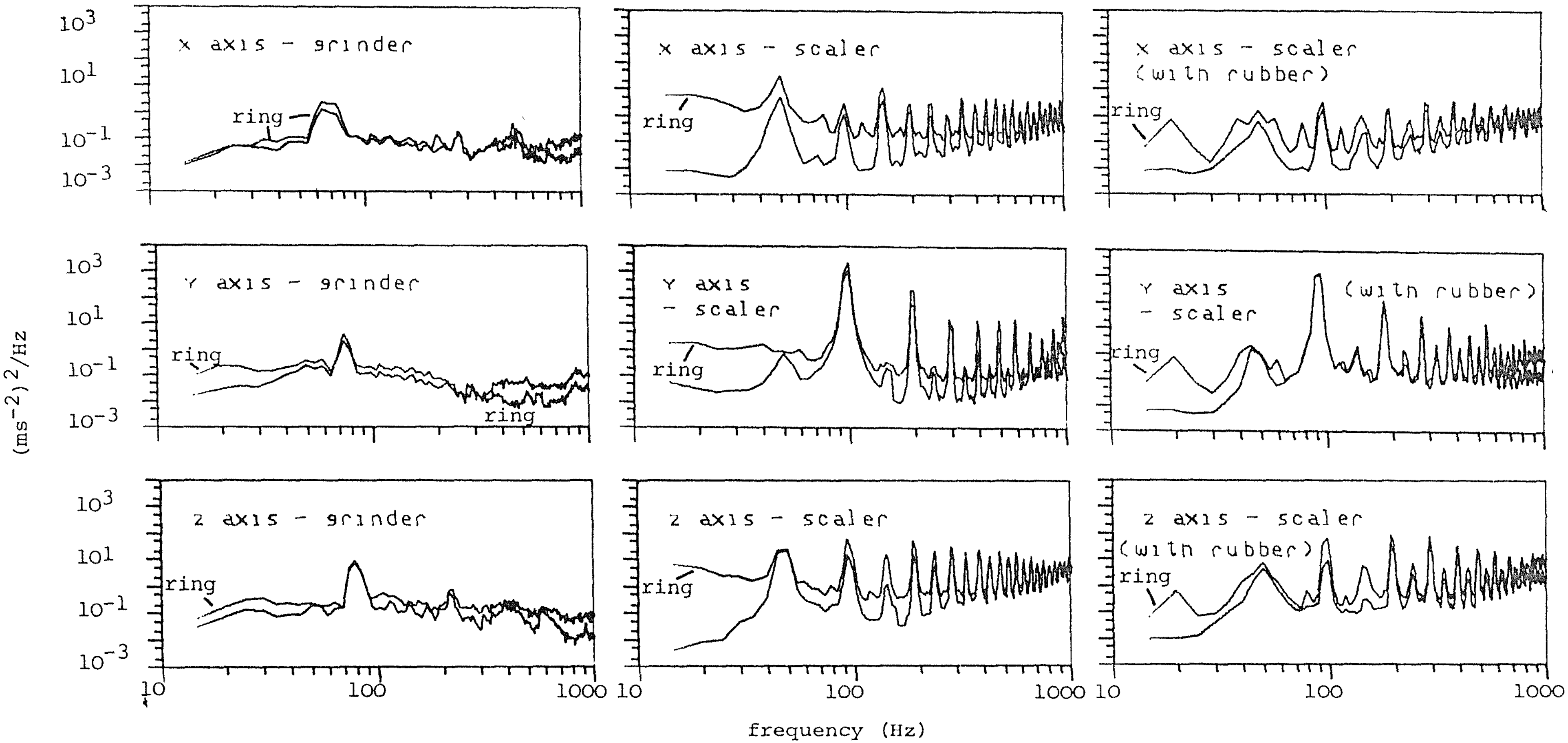


Figure 3.11 *Acceleration power spectral density functions on hose clip and ring mounts (Resolution = 4.88 Hz)*

The acceleration spectra measured on the scaling tool by the two methods were more different. Although the peak values in the spectra were similar, the data from the ring-mounted accelerometer exhibited elevated magnitudes at frequencies between the peaks. These elevations can be seen to rise with decreasing frequency and are typical of the low-frequency measurement artifacts (possibly attributable to d.c. shifts) described in Section 3.2.1. The effect was greatest in the x-axis where the frequency-weighted magnitude measured with the ring was a factor of 5.2 greater than that obtained with the hose clip.

With the addition of the thin layer of rubber to the underside of the ring, the discrepancy in the measurements made with the two mounting methods was reduced. The low frequency magnitudes from the ring-mounted accelerometer were closer to those for the hose clip mounted transducer, particularly in the x- and z-axes, and the weighted acceleration values obtained by the two methods were now of the same order of magnitude (factors of 2.1 and 1.7 difference in the x- and z-axes respectively). The spectra show that the remaining differences were mostly at frequencies below approximately 30 Hz. (Differences between the weighted values are emphasised because the weighting function given in current standards places most weight on the low end of the frequency range.)

It was concluded that the rubber layer on the underside of the ring should be retained. Three miniature accelerometers (Brüel & Kjær type 4374, mass 0.65 grams each) were attached to the ring with cyanoacrylate adhesive, and a protective covering of silicone rubber was fitted over the accelerometers.

The chipping hammer chisel data, recorded at Devonport on a tool operated by an experienced caulker (see Section 3.5.3) and presented in Appendix B, were obtained with the ring-mounted accelerometers.

As the ring device was found to give a performance similar to the hose clip method for some tools, it may be suitable for future use in a portable system for recording vibration 'dose', in which the individual's hands would be required to remain instrumented during the period of investigation.

3.4 LASER-DOPPLER VELOCIMETRY

Because of the practical problems inherent in the use of accelerometers to measure the vibration of pneumatic tools (d.c. shifts, slipping of transducer mounts, risk of transducer damage etc.) a non-contact method of measurement was investigated.

3.4.1 Laser Doppler Vibrometer

This instrument was a portable, hand-held, on-axis apparatus, developed within the I.S.V.R., which used the laser doppler velocimetry technique. In this device, the monochromatic light from a 2 mW He-Ne laser was projected normally onto the vibrating surface under investigation, and underwent a Doppler shift, on reflection at the surface, proportional to the velocity of the surface in the direction of the incident beam. The instrument detected the Doppler shift and produced an output voltage proportional to the velocity of the target surface. The sensitivity of the instrument was 6.32 V/ms^{-1} with a flat frequency response from d.c. to 20 kHz. The theory of operation of this instrument has been described in detail by Halliwell (1979).

Assessment of Dynamic Range

A piezoelectric accelerometer (Brüel & Kjær type 4371) was mounted on a calibration shaker (Brüel & Kjær type 4291) and vibrated sinusoidally at 10 ms^{-2} peak, 80 Hz. A piece of retro-reflective tape was attached to the upper surface of the accelerometer. This was used as a target for the laser beam from the vibrometer. (This special reflective surface was required to ensure that laser light was not scattered at the vibrating surface, but was reflected in the direction of incidence.) The accelerometer and laser vibrometer signals were amplified, low-pass filtered at 2 kHz cut-off frequency and digitised at 5000 samples per second. The velocity time history from the laser vibrometer was then digitally differentiated to give acceleration. Power spectral density functions were calculated from each of the two acceleration time histories.

The two power spectral density functions are shown in Figure 3.12. The peak at 80 Hz in each spectrum is of the same magnitude, indicating that the calibration of the two devices is correct. However, the noise levels at other frequencies were higher for the laser vibrometer spectrum: the dynamic range of the device, after digital differentiation of the velocity signal, was found to be between 30 and 40 dB. The accelerometer signal showed a much lower noise floor (dynamic range in excess of 60 dB) which was determined by the resolution of the analogue-to-digital converter.

After converting the velocity output to give an acceleration signal, the dynamic range of the laser vibrometer was found to be smaller than that obtained with an accelerometer and charge amplifier. The range of approximately 40 dB (100:1) was thought to be insufficient for the measurement of the vibration characteristics of many pneumatic tools; some of the spectra shown in Appendix B confirm this. However, the instrument may be suitable for the measurement of vibration of chipping hammer chisel vibration. Accelerometer data from this tool (see Figure B2 in Appendix B) suggested that a dynamic range of about 40 dB would be sufficient, since high acceleration magnitudes were present throughout the frequency range, with no large differences between the magnitudes of the peaks and troughs present in the spectra.

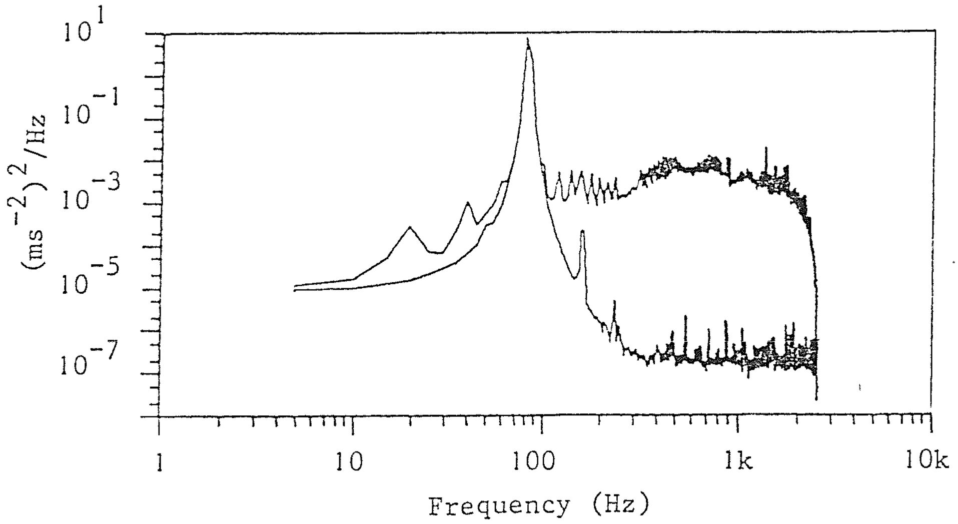


Figure 3.12 Acceleration power spectral density of 80 Hz sinusoidal vibration measured simultaneously with the laser vibrometer and a piezoelectric accelerometer (Resolution = 4.88 Hz)

3.4.2 Comparison of Laser Vibrometer with Accelerometers

Experiments were conducted to compare the performance of the laser doppler vibrometer with accelerometers (hose clip and ring-mounted) for the measurement of pneumatic tool vibration.

Two tools were used in this investigation:

1. Chisel scaler. CPT 'Superior Paint Scraper'. This tool was also used for evaluation of the hose clip and ring accelerometer mounts (see Section 3.3.3).

2. Chipping hammer. CPT 'Boyer Superior No. 1'. The vibration on the chisel of this tool had been found to be too severe to allow the use of a hose clip mount or a rigidly-mounted accelerometer.

Chisel Scaler

The scaling tool was used for a simultaneous comparison of three vibration measurement methods: hose clip-mounted and ring-mounted accelerometers and the laser vibrometer. Measurements were made in the longitudinal axis of the tool (y-axis) which was operated at full throttle on a flat horizontal steel surface. Figure 3.13 shows the transducer arrangement. The hose clip mount, with y-axis mechanical filter and accelerometer, was attached to the tool close to the position of the operator's rear hand. Retro-reflective tape was attached to the top surface of this accelerometer for use as a target for the beam from the laser vibrometer. The tool operator wore the ring on the middle finger of the hand operating the trigger of the tool; he held the tool in such a way that the accelerometers on the ring and hose clip were aligned.

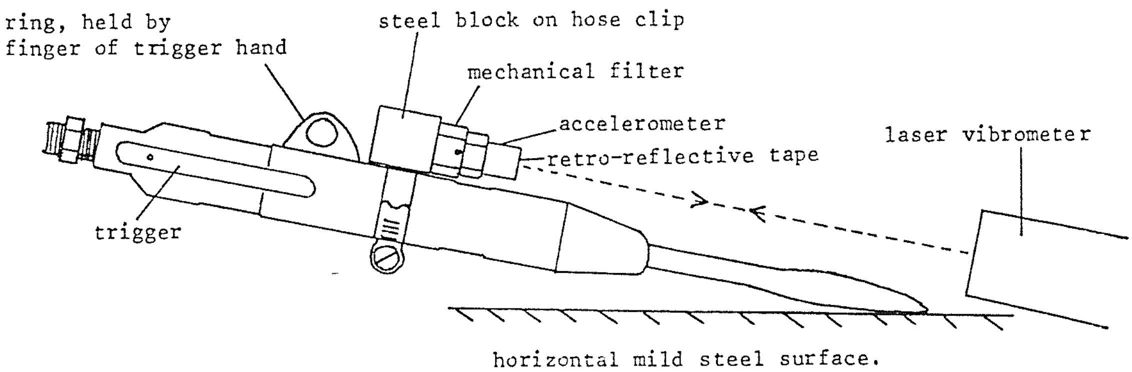


Figure 3.13 Simultaneous use of hose clip and ring-mounted accelerometers and laser vibrometer on scaling tool

Simultaneous three-second time histories from each transducer were acquired. The velocity data from the laser vibrometer were digitally differentiated to allow comparison with the data from the accelerometers.

Figure 3.14 contains a segment of acceleration time history, 0.1 seconds in duration, from the scaling tool as measured using the three techniques. The hose clip mounted accelerometer and laser doppler vibrometer produced waveforms which appear very similar. The ring mounted accelerometer produced a waveform of similar magnitude but with a lower high-frequency content. This is confirmed by a comparison of the three power spectral density functions (Figure 3.15). Close agreement exists between the three spectra, although the magnitudes from the ring are lower at frequencies above approximately 400 Hz. A summary of the data from this test is presented in Table 3.2 which contains r.m.s. acceleration values for eight octave bands and for the overall frequency-weighted and unweighted r.m.s. magnitudes ($a_{h,w}$ and a_{lin} respectively). The overall values are in close agreement; the differences were less than 15% of the magnitudes for both weighted and unweighted acceleration measurements.

Table 3.2 *Octave band and overall r.m.s. acceleration magnitudes (ms^{-2}) from three measurement methods on chisel scaler (y-axis)*

OCTAVE BAND FREQ.	HOSE CLIP	RING	LASER
8	0.59	0.67	0.30
16	1.20	0.92	0.99
32	3.11	2.52	2.29
64	82.64	82.04	76.26
128	66.46	68.70	67.18
256	35.80	50.62	35.51
512	35.72	20.26	42.41
1024	72.24	21.64	65.85
Overall unweighted r.m.s.	137.96	122.06	133.16
Frequency weighted r.m.s.	19.89	19.87	18.54

The octave band values had deviations of less than 30%, with the exception of the lowest (8 Hz) frequency band and the high frequency end of the range where the ring showed signs of poor coupling to the tool surface.

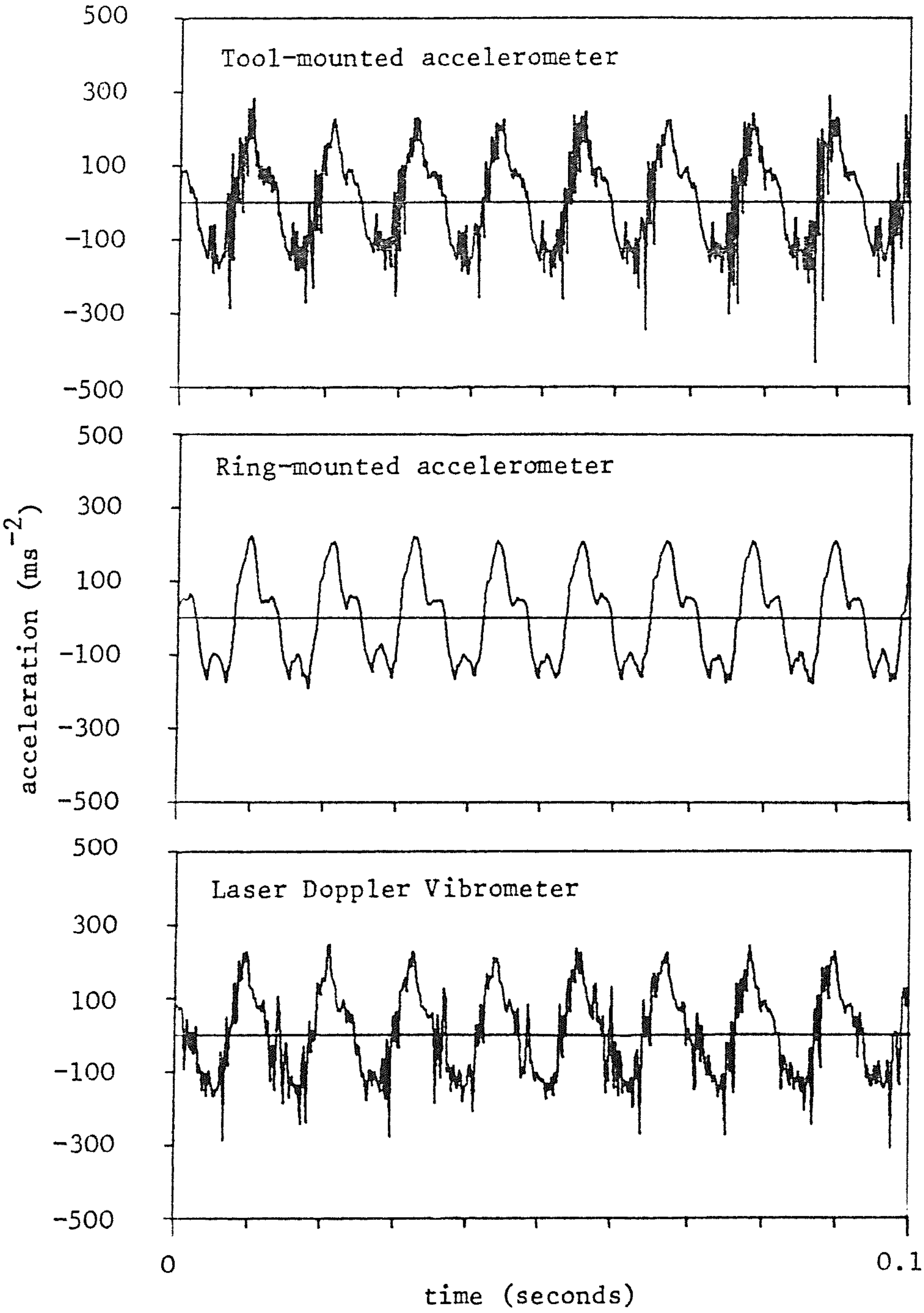


Figure 3.14 Examples of acceleration time histories for three measurement methods on chisel scaler (y-axis)

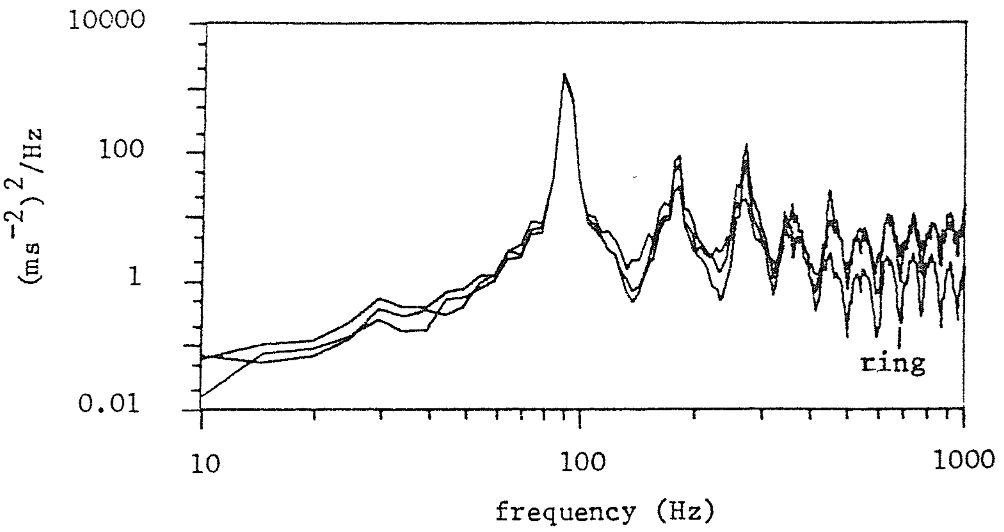


Figure 3.15 Acceleration power spectral density functions for three measurement methods on chisel scaler (y-axis) (Resolution = 4.88 Hz)

Chipping Hammer

Only the ring and the laser vibrometer were tested on the chisel of the chipping hammer, as the hose clip mount had previously failed on this tool (see Section 3.3.2). A steel cube (approximately 20 mm each side) was welded to the side of a 'gouge' type chisel as shown in Figure 3.16. The retro-reflective tape target for the laser vibrometer was attached to the forward face of this block. The ring was held by the operator against the chisel alongside the block during the test, such that its y-axis accelerometer was aligned with the main axis of the chisel. The chipping hammer was operated perpendicularly against a massive steel block. This is not an authentic mode of operation, but provided a 'steady-state' operating condition which could be maintained by an unskilled operator while the laser beam was kept on target. Several attempts were necessary, however, before this was achieved for a period of three seconds and the tool had to be run at slightly less than full throttle, since it proved difficult to hold the ring on the chisel and keep the beam on target when running at full speed.

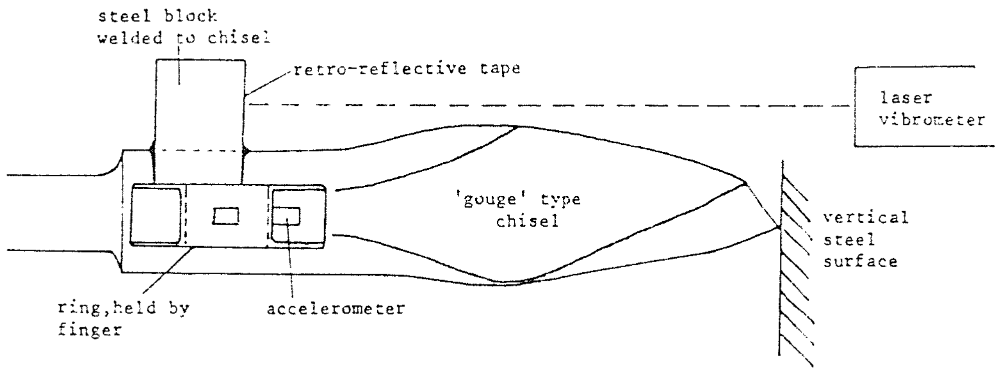


Figure 3.16 Simultaneous use of ring-mounted accelerometer and laser vibrometer on chipping hammer chisel

Figure 3.17 compares the waveforms of the y-axis vibration of the chipping hammer chisel measured with the ring-mounted accelerometer and with the laser vibrometer. The laser vibrometer data appears to contain more high frequency energy than the accelerometer data. The power spectral densities from the two signals are compared in Figure 3.18. The ring shows a greater vibration magnitude in the frequency range 100 - 700 Hz but falls below the magnitude from the laser vibrometer at higher frequencies. Both spectra show the wide-band nature of the vibration spectrum on this tool - the acceleration is of the same order of magnitude over the range 10 - 1000 Hz. The octave band and r.m.s. values are presented in Table 3.3.

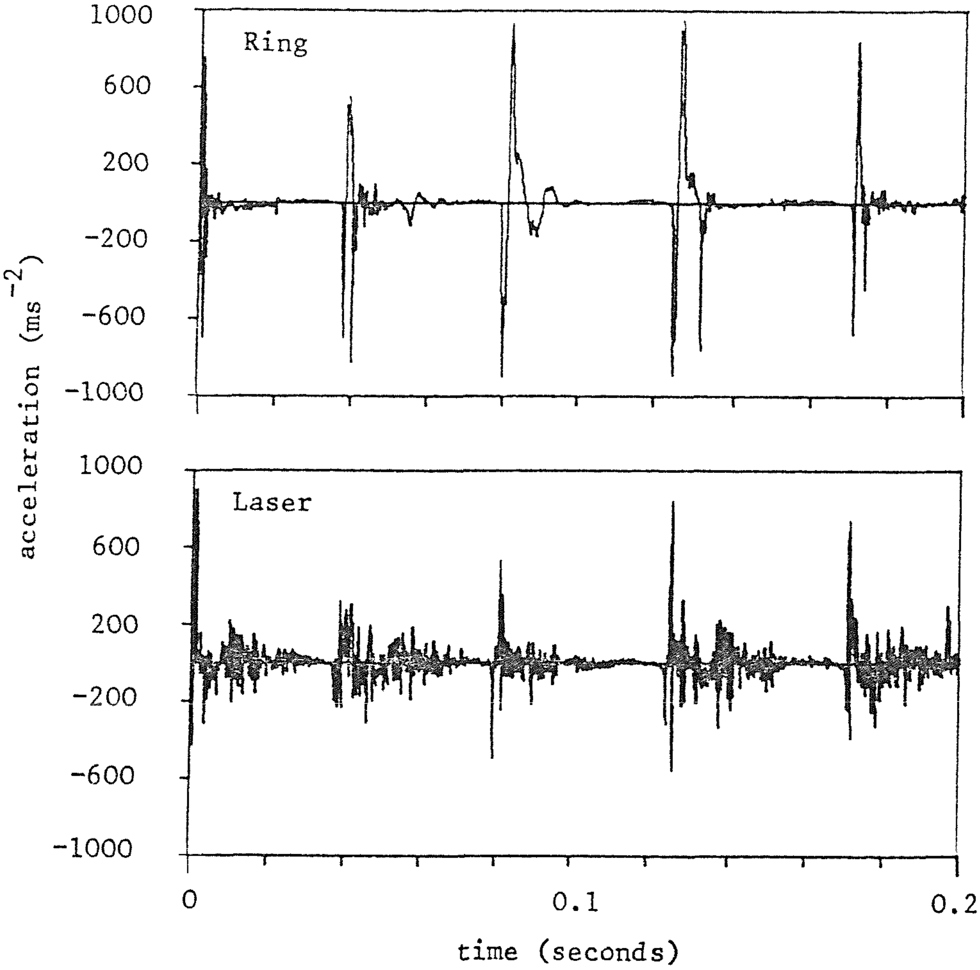


Figure 3.17 Examples of acceleration time histories from ring-mounted accelerometer and laser vibrometer on chipping hammer chisel, y-axis

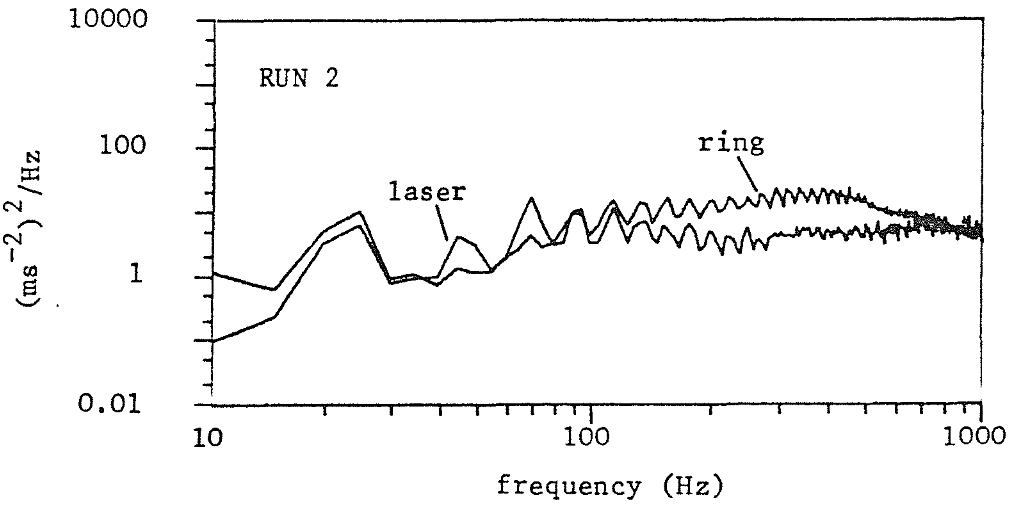


Figure 3.18 Acceleration power spectral density functions for ring-mounted accelerometer and laser vibrometer on chipping hammer chisel, y-axis (Resolution = 4.88 Hz)

Table 3.3 Octave band and overall r.m.s. acceleration magnitudes (ms^{-2}) from two measurement methods on chipping hammer chisel (y-axis)

OCTAVE BAND FREQ.	RING	LASER
8	2.85	0.74
16	6.89	5.30
32	7.82	7.42
64	12.70	16.36
128	31.25	22.87
256	53.55	27.11
512	66.96	43.51
1024	52.01	59.91
Overall unweighted r.m.s.	108.20	91.10
Frequency weighted r.m.s.	9.38	7.61

In Figure 3.19, the running r.m.s. acceleration magnitude (unweighted) is shown over the 3-second period of vibration recording. It may be observed that although the ring and laser vibrometer gave similar magnitudes for most of the duration of the measurement, the acceleration experienced by the ring-mounted accelerometer increased rapidly, for up to 0.2 seconds on four occasions during the three seconds. This accounts for the differences in the measured magnitudes and may be attributed to small occasional movements of the ring on the tool surface. The higher magnitudes for the ring at frequencies below about 20 Hz indicate that the ring moved with greater displacement than did the chisel (as measured with the laser vibrometer).

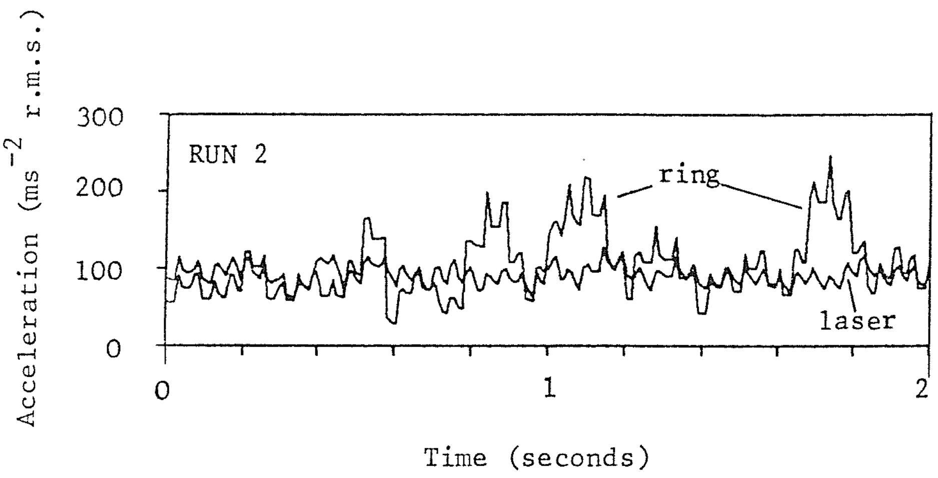


Figure 3.19 Running r.m.s. acceleration magnitudes from ring-mounted accelerometer and laser vibrometer on chipping hammer chisel, y-axis, integration time = 0.02 seconds

Conclusions

The laser doppler vibrometer was used successfully for the measurement of tool vibration under controlled laboratory conditions. However, the dynamic range of the instrument, in acceleration terms, was found to be inadequate for the vibration characteristics of some tools.

The vibrometer was difficult to use for measurements on hand-held tools because it was necessary for the laser beam to be maintained on target throughout the measurement period. Suitably plane target areas were not available in all three axes and had to be artificially produced, for example by attaching a block of steel to the chipping hammer chisel. Separate trials had to be conducted for each axis of vibration. This made the procedure time-consuming compared with the use of triaxially-mounted accelerometers. For this reason, vibration measurements on a chipping hammer at Devonport were made with the ring-mounted accelerometers.

Data were obtained for three axes of vibration on the chipping hammer chisel with an unskilled operator. These are presented in Appendix C and discussed in Section 3.6.2.

3.5 PNEUMATIC TOOLS AND TEST CONDITIONS

3.5.1 Selection of Tools

Many different types of pneumatic hand tool were in use at Devonport dockyard. The stores catalogue listed over 140 categories. However, the types of tools commonly in use in the occupations associated with VWF were relatively few.

The tool types found to have been most commonly used by these groups were chipping hammers, riveting hammers, grinders, drilling machines and scaling tools. Among the less frequently used tools were impact wrenches, power wire brushes, power hacksaws and sanders. The pneumatic tools used by all vibration-exposed persons taking part in this study were identified from the questionnaire data and are summarised in Table 4.7. It was necessary to select a set of tools for vibration testing which were representative of those used in typical work by the studied population. The tools chosen for study were found to be typical of types most commonly in use in the dockyard and are listed in Table 3.4.

Table 3.4 Pneumatic tools selected for vibration measurement

CATEGORY	MANUFACTURER	MODEL	SERIAL NUMBER
Chipping Hammer	CPT	Boyer Superior No. 1	F392333
Vertical Grinder	Thor	5VL 40962T	18007
Disc Cutter	Thor	5VL 8211	1772
Angle grinder	Thor	3S	8167
End Grinder	Thor	3L6	1968
Collet Grinder	ATA	STR18	720761
Pistol Drilling Machine	Atlas Copco	LBB 22 HO 22	A34574
Morse Drilling Machine	CPT	315, size 2	619216
Nobbler	CPT	No 5	F575021
Needle scaler	Trelawney	2BS	JT5985
Needle pistol	Von Arx	23-B	2385 10660
Chisel Scaler	CPT	Superior Paint Scraper	F910480
Power Wire Brush	CPT	3320A	442375
Disc Sander	Thor	5V 40016T	13885
Power Hacksaw	Cengar	Cengar Saw	8208039
Impact Wrench	Atlas Copco	LMS 36 HR 13	B388057

The tools in Table 3.4 are described below. All were obtained from the pneumatic tool store at Devonport and all had been in use previously. They were not, therefore, in new condition, but were typical of used, but recently serviced, machines in dockyard use. The grinders were fitted with new discs, wheels or burrs as appropriate.

Chipping Hammer

Pneumatic chipping hammers had been in dockyard use for over 40 years, during which period their design had remained substantially unchanged. These tools were used for caulking (removal of excess metal from welds, etc.), removing old boiler tubes, removing cement and tiles from decks, nut splitting and general steel cutting jobs.

The chisel, which was not captive in the machine, was held by the operator's hand, usually resting on the forefinger or held under the fingers of the foremost hand. The operator's dominant hand usually held the rear of the tool, operating the trigger; however, many caulkers claimed to be able to work with either hand if required.

Several types of chipping hammer were in use in Devonport Dockyard. The most commonly used machine, on which the vibration measurements were made, was the CPT (Consolidated Pneumatic Tool Company) Boyer Superior No. 1. This 'medium duty' machine had an outside trigger operated by the thumb and a mass of approximately 5 kg. It operated at a rate of about 1800 impacts per minute.

Two patterns of chisel in common use were the flat conventional cutting chisel and the pointed gouge. These types were 80 mm and 120 mm in length respectively.

Grinding Machines

The most commonly used type of hand-held grinding machine in use at Devonport was the vertical grinder. This type of machine was fitted with a grinding disc or a cutting wheel of either 7 inch or 9 inch diameter. The tools were held by two cylindrical handles, perpendicular to the rotating shaft and approximately at right angles to each other. The trigger or throttle control was mounted on the right hand handle. The most common model in this class was the Thor type 5VL which had a rotational speed of approximately 6000 r.p.m. and a weight of approximately 5.2 kg. Two such machines were used in vibration tests: one fitted with a grinding disc and one with a cutting wheel, both of 7 inches diameter.

Angle grinders were also in common use. These had a smaller grinding disc, 4 inches in diameter. These tools were normally held in one hand while the other hand was sometimes used to steady the tool. A Thor type 3S was tested. This tool had a single pistol-grip handle and had a mass of 1.8 kg.

Prior to the introduction of the vertical grinder, end grinders (or horizontal or straight grinders) were popular in the dockyard; many of the older men had had extensive use of these machines. End grinders were still in occasional dockyard use at the time of the study. The grinding wheel was mounted at the end of the cylindrical body of the machine which was held in both hands. A Thor type 3LG was used for vibration testing. This had a 3 inch wheel and a mass of about 1.8 kg.

In recent years, collet grinders (or die grinders) had become widespread in dockyard use, particularly in submarine work. These high speed tools were mostly cylindrical in shape, with a collet at one end in which was held a burr, mounted grinding point or cutter. Vibration measurements were made on an ATA type STR18 fitted with a tapered burr. The operating speed of this tool was 30000 r.p.m.

Drilling Machines

Most pneumatic drilling machines at Devonport were of two basic types: pistol grip drills and Morse drilling machines.

The pistol machines were small and held in one hand, the index finger of which operated the pistol-type trigger. Most were capable of accepting parallel shank drills up to 6 mm in diameter. Vibration measurements were conducted on an Atlas Copco type LBB 22 HO 22 machine fitted with a 7/32" drill. This tool had a nominal speed of 2200 r.p.m. and a mass of approximately 1 kg.

The larger (Morse) machines were available in several sizes and could be fitted with Morse taper drills for drilling holes up to 76 mm in diameter and for reaming work. Most machines had two long cylindrical handles, perpendicular to the axis of rotation, one of which incorporated a twist-grip throttle. The machine was often mounted in a supporting jig which provided an end-stop for the feed screw on the rear end. A No. 2 Morse drilling machine was chosen for vibration testing, being a widely used type at Devonport which would accept drill sizes up to 22 mm. This was a CPT type 315 of mass 7 kg. It was fitted with a 53/64 inch drill.

Scalers

Pneumatic tools used in the removal of scale, old paint and rust fell into three categories: nobblers (or scaling hammers), chisel scalers (or scrapers) and needle scalers.

The nobbler was the oldest type of scaler in dockyard use, consisting of a hard metal piston vibrating in a massive cylinder, to which was attached a long supporting handle with a trigger lever at the opposite end. The operator was required to hold the tool with one hand at either end of the handle, pushing the piston down onto the surface being worked. Vibration measurements were made on a typical nobbler, CPT type No. 5, mass 2.5 kg, operating rate 3600 blows/minute.

The chisel scaler was introduced more recently than the nobbler. This consisted of a cylindrical body, inside which an axially reciprocating piston delivered blows to a chisel which was captive at one end. Again, the trigger was mounted at the rear end of the tool, requiring the use of both hands under most conditions. The tool chosen for vibration testing was a CPT 'Superior Paint Scraper' model CP 75. This delivered 8400 blows/minute and had a mass of approximately 1.4 kg.

Some needle scalers were similar in construction and appearance to the chisel scaler described above. In place of the chisel, however, was a cluster of steel needles which were made to vibrate rapidly against the work surface. This type of scaler was particularly popular for use on submarine pressure hulls, where the use of other scaling machines was prohibited. Measurements were made on a Trelawney type 2BS with 12 needles, each of 3 mm diameter. The mass of this tool was 1.6 kg.

A larger type of needle scaler, with a pistol-type handle, was more recently introduced at Devonport. Measurements were also made on a Von Arx type 23-B.

Power Wire Brush

Used mostly by painters for buffing metal when a clean surface was required before painting, these tools were similar to vertical grinding machines, with a rotating wire brush in place of the grinding disc. Measurements were made on a Consolidated Pneumatic Tool Company type 3320A with a brush 5 inches in diameter and a rated speed of 4500 r.p.m. This tool had a mass of 5.5 kg.

Sander

The various kinds of power sander employed at Devonport included rotating disc, orbital, reciprocating and belt types. Vertical rotary machines were the most popular type. The tool tested was a Thor type 5VL, fitted with a 7 inch disc of Scotchbrite metal conditioning material. Speed 6000 r.p.m.

Power Hacksaw

This reciprocating tool used standard hacksaw blades for cutting a variety of metals, laminates, etc. The machine had a handle at the rear end, similar in shape to that of a chipping hammer, with an outside trigger. At the forward end, the blade protruded through a cylindrical sleeve which was held by the other hand. The Cengar saw had a maximum speed of 1200 strokes per minute and a mass of 2.5 kg.

Impact Wrench

Torque and impact wrenches used in the dockyard were of various sizes up to 1½ inch square drive. The half-inch square drive was a commonly used size and a tool of this size (Atlas Copco type LMS 36 HR 13) was used for measurement purposes. This had a mass of 3 kg and a pistol type handle. It was tested while fitted with a 13/16" socket.

3.5.2 Axes of Vibration

Vibration was measured on each tool in three orthogonal axes at a point on the handle or body of the tool close to the position of each of the operator's hands.

The biodynamic coordinate system defined in ISO 5349 (1986) and BS 6842 (1987) is shown in Figure 3.20. In this system, the origin lies at the head of the third metacarpal bone and the z-axis is defined as the longitudinal direction of this bone.

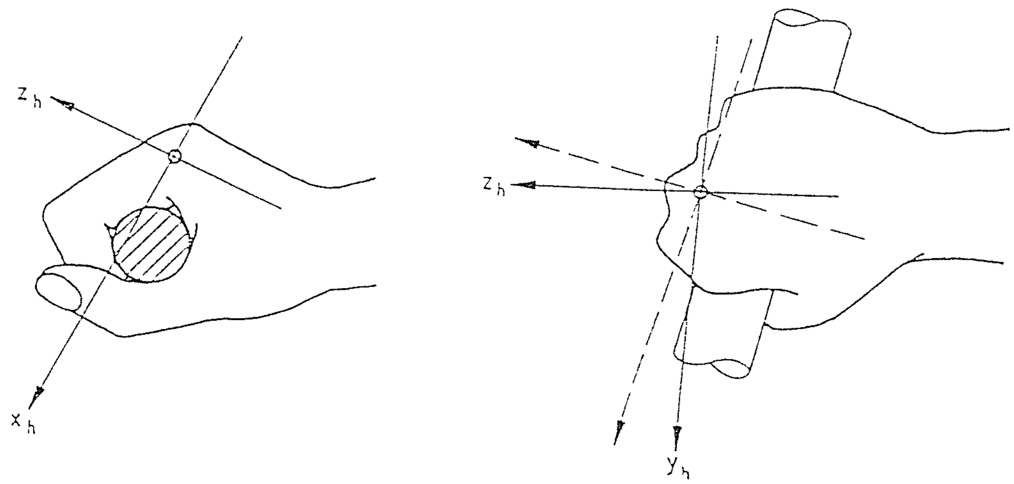


Figure 3.20 Coordinate system for the hand from BS 6842:1987. (—— = anatomical system; - - - = basicentric system.)

Although this is a suitably well-defined coordinate system for the study of vibration transmitted through the hand to the arm, it does not fully describe the orientation of the fingers, which is desirable in a study of vibration exposure relating to VWF.

The coordinate system used in this study is a finger-centred system and is illustrated in Figure 3.21. The z-axis is defined by the orientation of the middle phalanx of the finger.

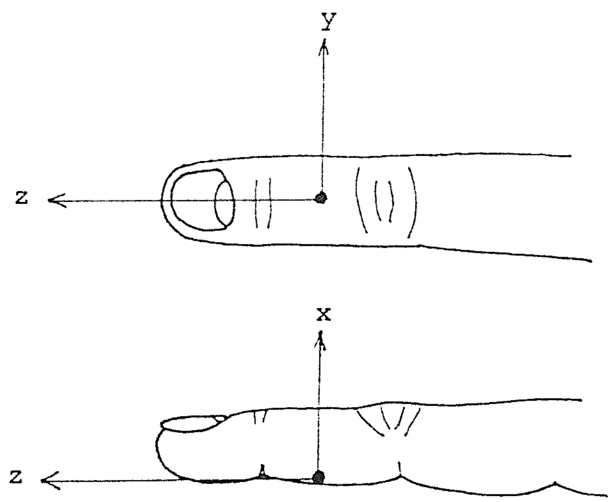


Figure 3.21 Finger-centred coordinate system.

The accelerometer mounting ring (see Section 3.3.2) was worn on the middle phalanx and was therefore correctly aligned with this coordinate system. The x-, y- and z-axes of the tool-centred coordinate system employed by the hose clip accelerometer mount (Section 3.3.1) were aligned as closely as possible with the above axes, as defined by the hand posture, when this device was used.

The axes of vibration measured on each of the tools tested are described in Section 3.5.3 below. In each case, the accelerometer mount was positioned as close as possible to the centre of the normal position of the hand.

3.5.3 Tool Operating Conditions

Vibration measurements on power tools have been shown to produce results with high variability. The data from published results in Tables 2.1 to 2.5 show wide variations in vibration magnitudes from tools of similar types. Investigations by PNEUROP (European Committee of Manufacturers of Compressors, Vacuum Pumps and Pneumatic Tools, 1978; 1980) into methods for the measurement of vibration on grinders and percussive tools showed that it was necessary to control the operation of the tool if measurements were to be repeatable. This work has resulted in the drafting of the various parts of ISO 8662 *Hand-held portable power tools - Measurement of vibration at the handles* (see Section 2.3.2). In this standard the coefficient of variation (ratio of standard deviation to mean) of weighted acceleration magnitudes obtained in repeated measurements is required to be smaller than 0.15.

To achieve repeatability, a 'steady state' operating condition was defined for each tool, which could be set up and replicated in the laboratory. In these operating conditions, which are described individually below, the tools were required to perform tasks 'representative' of dockyard work. For example, grinding machines were tested while grinding on a steel workpiece. Although better repeatability might have been achieved with 'free-running' machines (Eklund *et al.*, 1986) a grinding task was believed to be more appropriate for determining the vibration magnitudes to which the studied population may have been exposed.

It is likely that magnitudes of vibration in dockyard use were highly variable, compared with data obtained in the laboratory (see Scory *et al.* 1990). An assessment of this variability was beyond the scope of this study. The magnitudes obtained in the laboratory were assumed to be representative of typical work, for the purpose of relating vibration exposure to VWF (see Chapter 5)

All of the tools were powered in the laboratory by a conventional workshop compressed air supply with a nominal pressure of 90 pounds per square inch. With one exception (the chipping hammer) the tools were operated by the author. Practice time was allowed for familiarisation with the tools and operating tasks before data were recorded. In order to control the effects on tool vibration of any reaction from the workpiece, all tools tested in the laboratory were operated against a large steel cube of side length 30 mm and mass 212 kg.

Chipping Hammer

Satisfactory operation of this type of tool by an unskilled person proved to be unnecessary, attempts usually resulting in slipping and damage to the cutting edge of the chisel. Measurements were therefore made on the chipping hammer in the dockyard, with an experienced caulker operating the machine. Data were recorded on tape as described in Section 3.2.2.

A test rig was fabricated, similar to that specified in the chipping hammer test procedure published by PNEUROP (1985). A mild steel plate, 10 mm in thickness, was welded to a massive bench in a vertical position and clamped between two plates of hardened steel. This arrangement is illustrated in Figure 3.22. The caulker was asked to chip off a strip of steel, approximately 2 mm thick, in a period of 2 minutes. This was repeated several times, the hardened steel plates being lowered slightly between runs to expose more mild steel. The ten three-second time histories which were used for digital analysis were taken at random from sections of the recorded two-minute time histories.

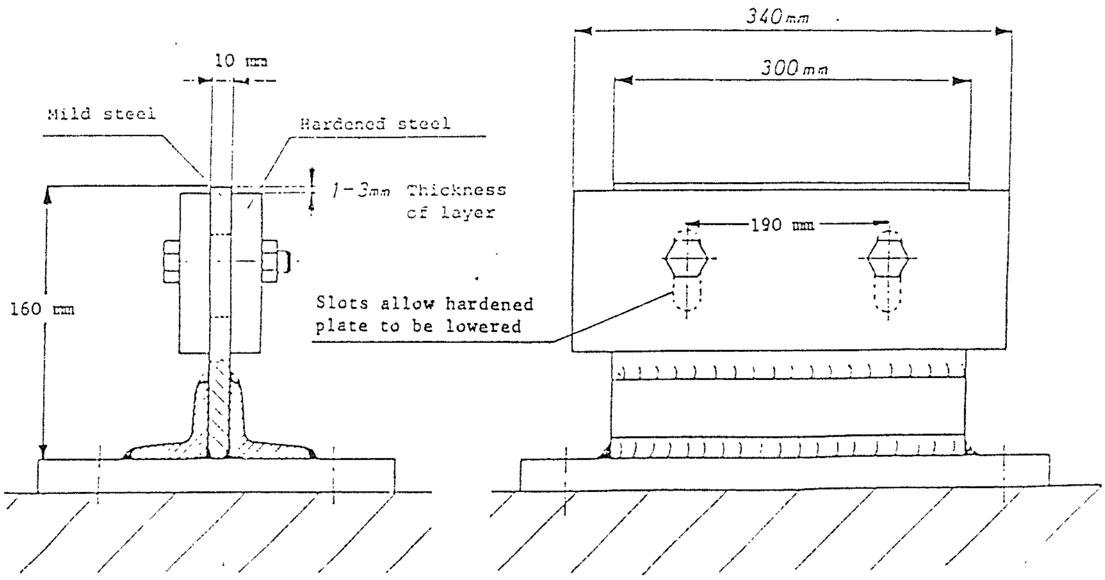


Figure 3.22 Vibration test rig for chipping hammers (Adapted from PNEUROP, 1985)

During some runs, vibration was measured in three axes on the handle of the machine, using the hose clip assembly. The three axes were defined as shown in Figure 3.23 with the x- and y-axes perpendicular to the strike direction and the z-axis in the direction of strike. On other runs, chisel vibration was measured, using the ring-shaped accelerometer mount. This was placed on the middle phalanx of the caulker's middle finger (inside his glove) and held against the side of the chisel. Figure 3.24 shows the orientation of the ring on the chisel as viewed from above.

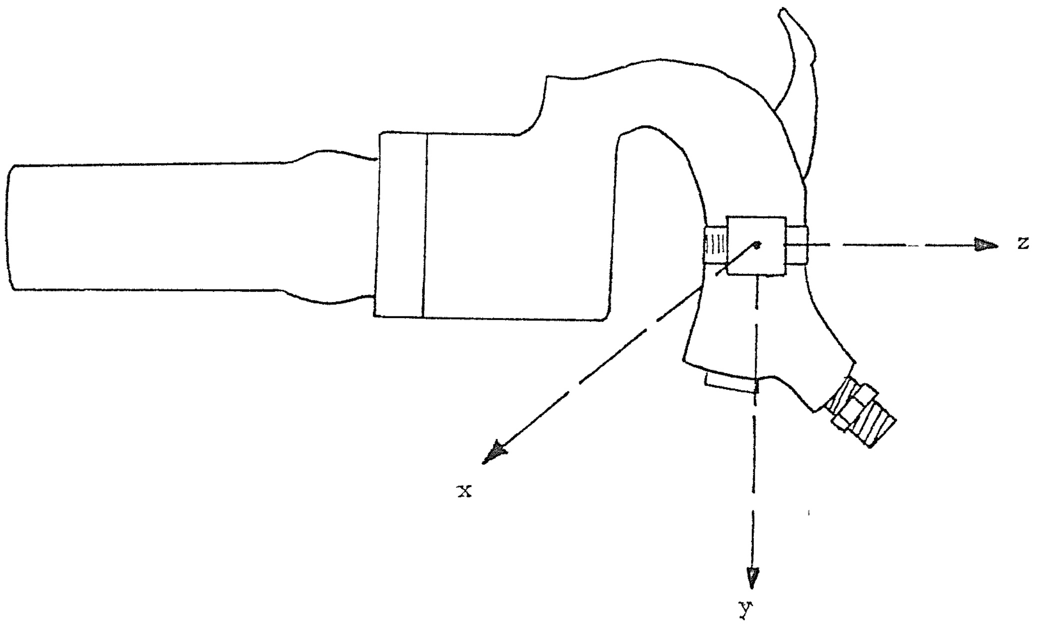


Figure 3.23 *Position of hose clip accelerometer mount on chipping hammer handle*

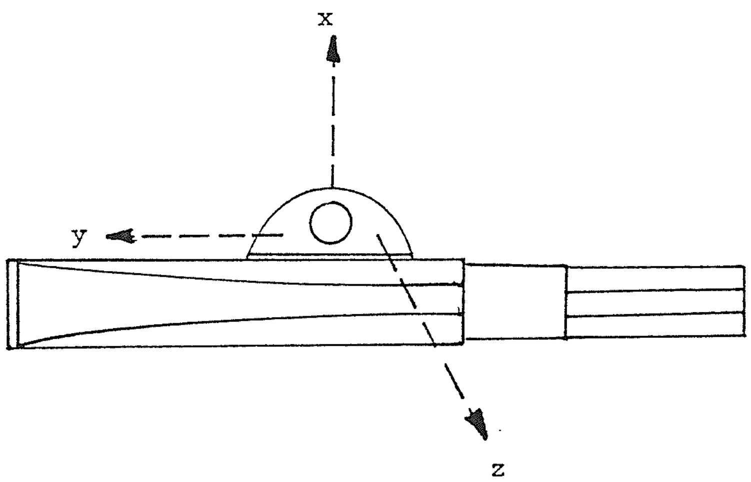


Figure 3.24 *Position of ring type accelerometer mount on chipping hammer chisel*

Grinders, Sander and Power Wire Brush

All grinders were operated on the surface of a horizontal mild steel plate, approximately 300 × 200 mm and 30 mm thick, which was securely bolted to the massive steel block. The rotational speed of each machine was monitored using a digital tachometer with an optical sensor directed at a reflective spot on the rotating shaft. Each machine was operated at full throttle and loaded by adjusting the push force against the work surface until the rotational speed was stabilised at approximately 80% of the maximum, unloaded speed. The vibration measurements were made when this 'steady state' condition had been reached. This conformed with the relevant section of the PNEUROP recommended test procedure for the measurement of grinder vibration (PNEUROP, 1983).

Thor 5VL Vertical Grinder

This tool was operated with the rotating shaft in the vertical orientation. The hose clip assembly was attached to each of the two handles in turn, at a distance of 30 mm from the tool body. The orientation of the hose clip on the handles is shown in Figure 3.25. The x- and z-axis accelerometers were placed at an angle of 45° with the rotating shaft of the tool.

In addition to the vibration measurements with the controlled operating task, this machine was also tested running freely (i.e. not grinding) and with excessive loading by pushing hard against the work surface. This was done to investigate the magnitude of the change in vibration due to push force.

Thor 5VL with Cutting Disc

The other 5VL machine, which was fitted with a cutting disc, was operated in a horizontal position, i.e. with the edge of the wheel cutting down through the steel surface.

The two hand positions were therefore reversed, requiring different orientation of the accelerometer assemblies with respect to the tool. This is shown in Figure 3.26.

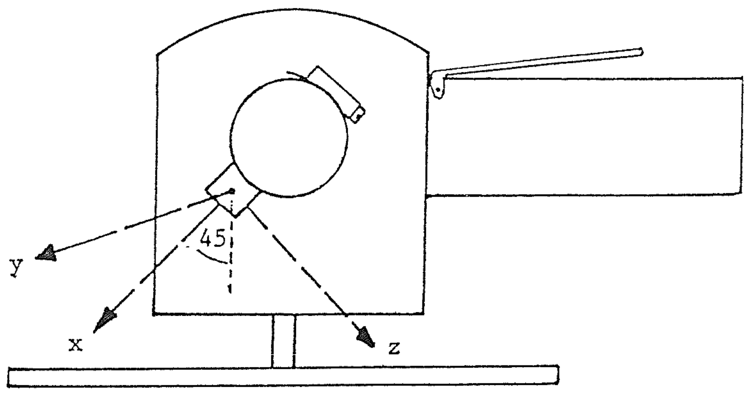


Figure 3.25 *Hose clip accelerometer mount on left handle of vertical grinder (The same arrangements were made with the rotary sander and the power wire brush)*

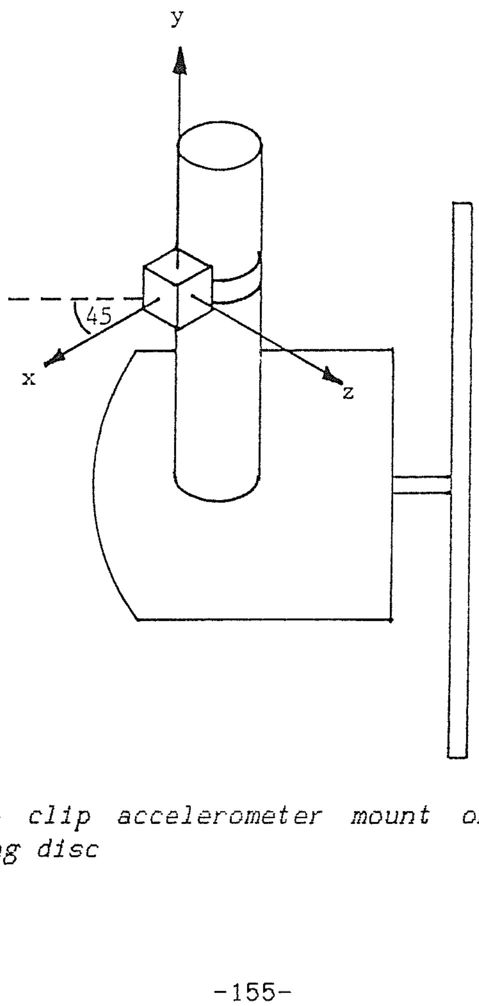


Figure 3.26 *Hose clip accelerometer mount on handle of vertical grinder with cutting disc*

Thor 5VL Sander and CPT 3320A Power Wire Brush

These two machines were similar in shape and method of operation to the vertical grinder. The methods for accelerometer mounting and testing were therefore identical to those described above for the Thor 5VL grinder (see Figure 3.25).

Thor 3S Angle Grinder.

This pistol-grip tool was operated in one hand, the other hand applying light pressure to hold the tool steady while measurements were made. One measuring position only was adopted with the hose clip assembly mounted around the handle. The position of the hose clip mount is shown in Figure 3.27.

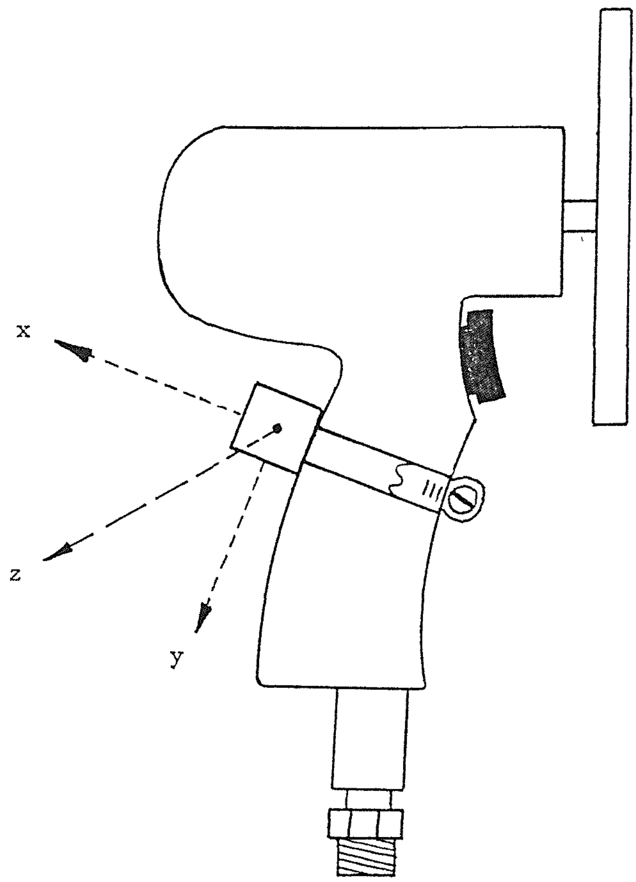


Figure 3.27 *Hose clip accelerometer mount on angle grinder*

Thor 301G End Grinder

The end grinder was held in a horizontal position during use, grinding the steel surface with the edge of the wheel. The hose clip was attached at the positions of the two hands: one near to the trigger, the other at the narrowest point of the tool body at the wheel end of the machine. See Figure 3.28.

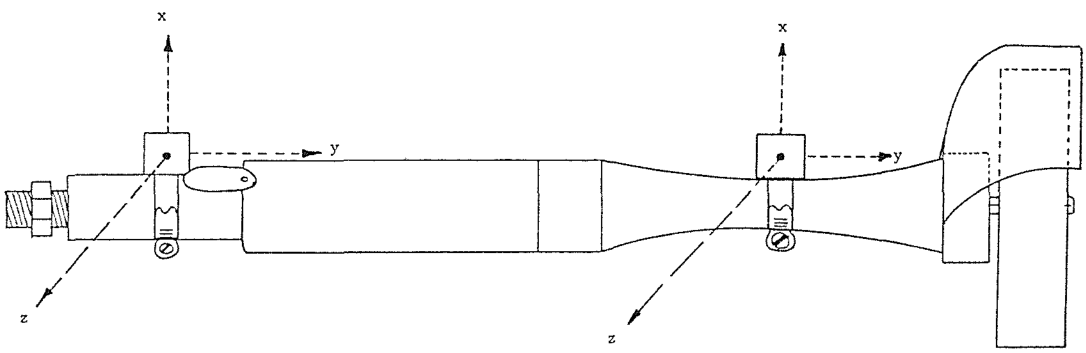


Figure 3.28 *Hose clip accelerometer mount on horizontal grinder for two hand positions*

ATA STR18 Collet Grinder

As this tool had a short body (approximately 150 mm), only one measuring position was used. The hose clip was mounted close to the trigger in the same orientation as that adopted for the horizontal grinder (see Figure 3.29). The tool was held horizontally, the side of a burr being used to grind on the steel surface.

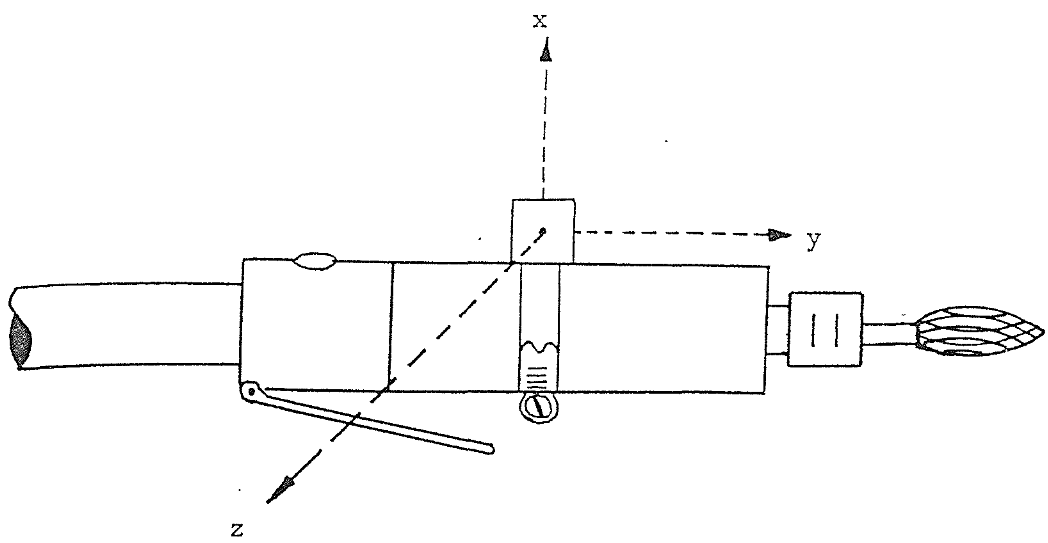


Figure 3.29 Hose clip accelerometer mount on collet grinder

Drilling Machines

On the pistol drilling machine, the accelerometer assembly was mounted in a single position on the handle (see Figure 3.30). The machine was operated vertically into a block of mild steel which was bolted to the massive mild steel block.

On the Morse drilling machine, hose clip transducer assemblies were mounted on both handles. The x- and z-axes were aligned at an angle of 45° to the axis of rotation (see Figure 3.31). The machine was positioned vertically and was operated into a mild steel block which was rigidly bolted to the massive steel block. A steel frame was positioned over the machine, providing a backstop against which the feed screw was turned during the drilling operations.

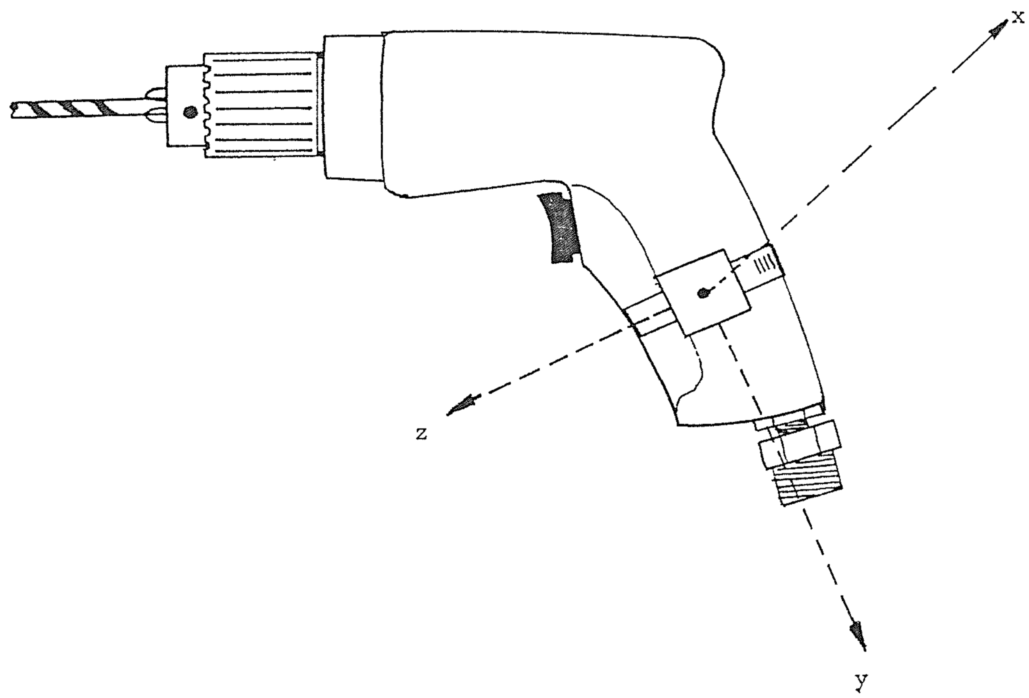


Figure 3.30 Hose clip accelerometer mount on pistol drilling machine

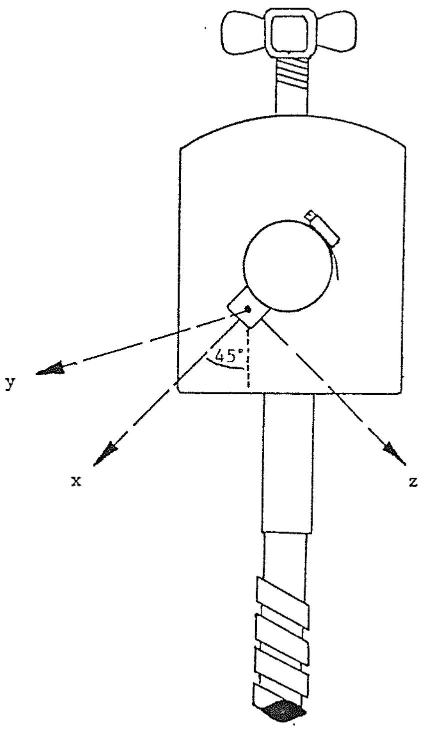


Figure 3.31 Hose clip accelerometer mounts on left handle of morse type drilling machine (similar arrangement on other handle)

Scaling Tools

The four scaling tools investigated all had cylindrical handles or a body on which the hose clip accelerometer mounts could be conveniently positioned. All of the scaling tools required two-handed operation in normal use. Two measurement positions were therefore adopted for each of these tools. These are illustrated in Figures 3.32 to 3.34.

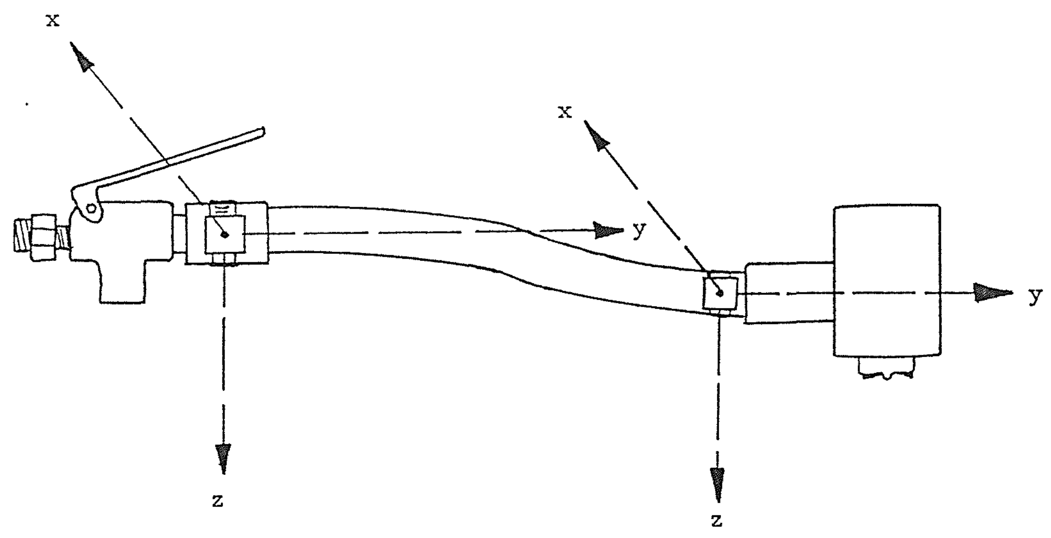


Figure 3.32 *Hose clip accelerometer mounts on nobbler*

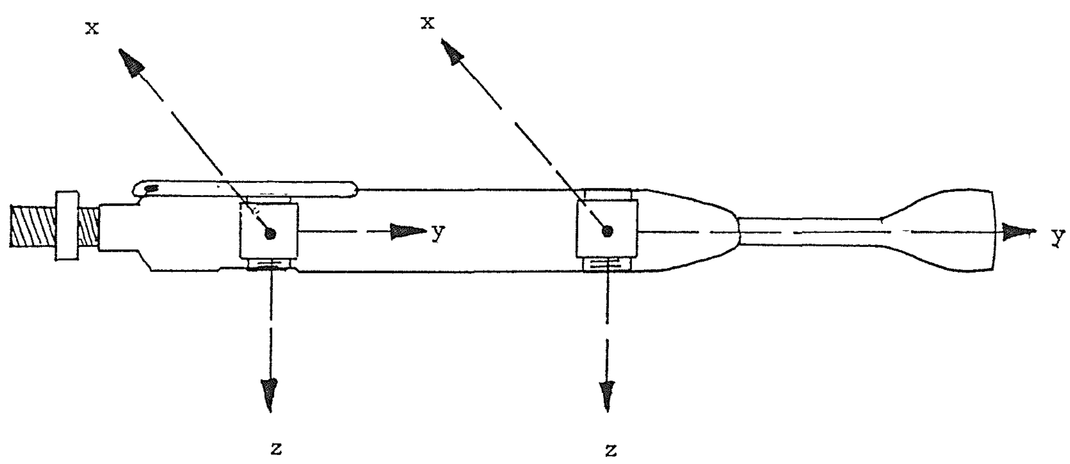


Figure 3.33 *Hose clip accelerometer mounts on chisel scaler (similar arrangements were used for the cylindrical needle scaler)*

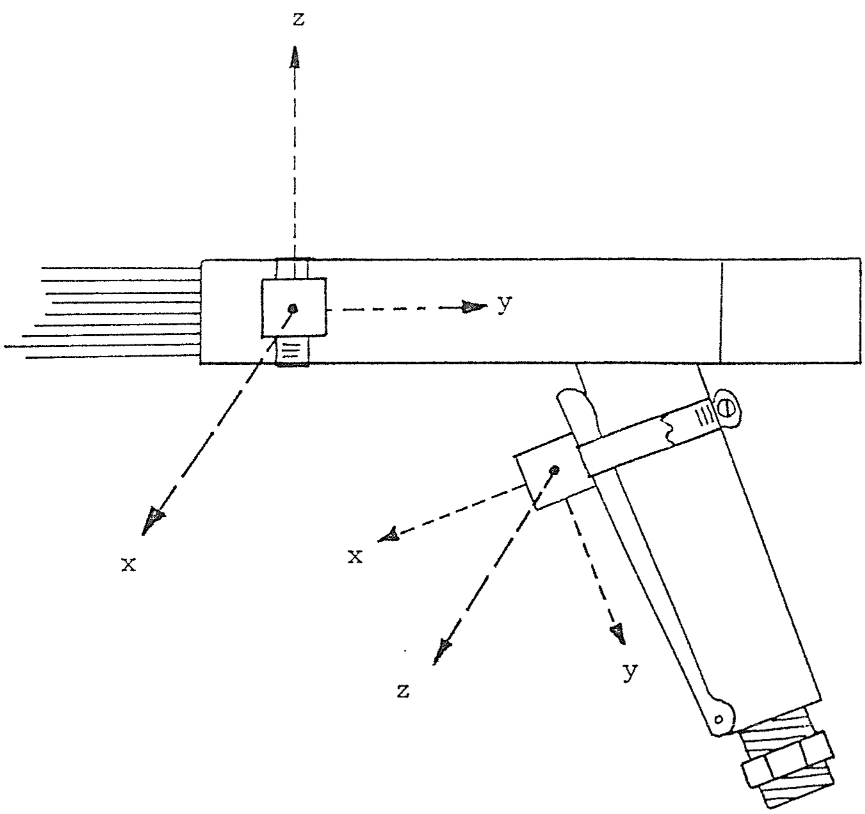


Figure 3.34 Hose clip accelerometer mounts on pistol-type needle scaler

The scaling tools were operated against the steel block: on a vertical surface (needle guns and chisel scaler) or on a horizontal surface (nobbler). The tools were held steady, operating at right angles to the work surface with the push force which appeared, by trial and error, to inflict maximum 'damage' to the surface. With the nobbler and Trelawney needle gun, this push force was also varied to establish the effect on the vibration characteristics.

Impact Wrench

One hand position only was measured on this pistol-grip tool. This is shown in Figure 3.35. A 13/16 inch nut was tightened onto a stud, holding a steel plate onto a horizontal concrete surface. Measurements were made from the time at which the tool started its 'hammering' action after spinning the nut.

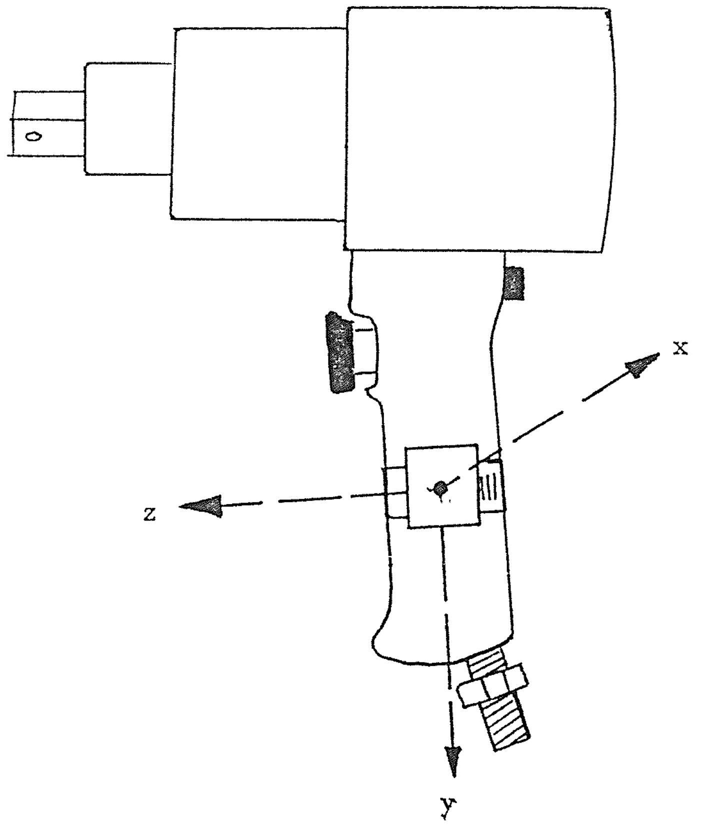


Figure 3.35 Hose clip accelerometer mount on impact wrench

Power Hacksaw

The vibration of this machine was assessed while cutting through an aluminium bar of 12 mm thickness which was firmly clamped in a horizontal position. Measurements were made on the handle at the rear of the tool and on the cylindrical barrel at the forward end (see Figure 3.36). The speed control was set to maximum throughout.

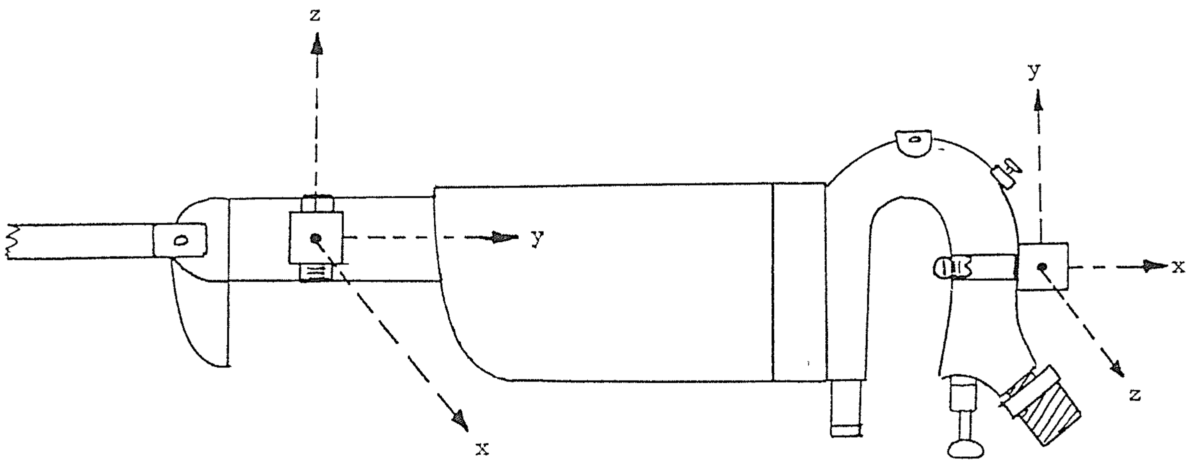


Figure 3.36 Hose clip accelerometer mount on power hacksaw

3.6 RESULTS AND DISCUSSION

3.6.1 Measurements in Controlled Conditions

The data from the vibration measurements made on the pneumatic tools in the laboratory under controlled operating conditions are presented in Appendix B. For each hand position on each of the sixteen tools, the root-mean-square acceleration magnitudes in eight octave bands and the overall frequency-weighted ($a_{h,w}$) and unweighted (a_{lin}) root-mean-square magnitudes are shown in tabular form. The values given are the means and standard deviations from repeated measurements. These mean values were used to represent tool vibration magnitudes in the investigation of dose-response relationships for VWF (see Chapter 5). Comparison of the mean octave band magnitudes from Appendix B with those shown in Chapter 2 (Tables 2.1 - 2.5) shows that the magnitudes obtained in the present study were, in many cases, of similar order to those in the literature which were free of suspected measurement artifact.

Appendix B also contains the acceleration power spectral densities from the repeated measurements, and example sections of acceleration time histories for each axis of vibration.

Inspection of the power spectral density graphs reveals that the vibration on some of the rotary tools (grinders, sander etc.) was dominated by a peak at the frequency of rotation; this is expected in some rotary machines (Eklund *et al.*, 1986; O'Connor, 1989), because of out-of-balance forces. Peaks in the spectra at the tool operating frequencies were also present for many of the percussive tools (needle scalers, chipping hammer etc.). However, the impulsive nature of the vibration on some of these tools also resulted in high-frequency magnitudes of the same order.

The most severe vibration characteristics were recorded on the chipping hammer (mean values: $a_{h,w}$ = 8 ms^{-2} r.m.s., a_{lin} = 115 ms^{-2} r.m.s. in the 'worst' axis) where high magnitudes were present throughout the measured frequency range, and on the nobbler ($a_{h,w}$ = 38 ms^{-2} r.m.s., a_{lin} = 138 ms^{-2} r.m.s.) where a dominant peak was present at the operating frequency. Most of the rotary tools had maximum frequency-weighted acceleration magnitudes below 5 ms^{-2} r.m.s. while the percussive tools generally exhibited at least one axis with a weighted magnitude of 8 ms^{-2} r.m.s. or greater. The unweighted acceleration magnitudes (measurement bandwidth 1250 Hz) were typically an order of magnitude greater than the weighted values. For tools with high frequency vibration components, unweighted magnitudes in excess of 80 ms^{-2} r.m.s. were observed.

The mean weighted and unweighted acceleration magnitudes for each tool/hand position/axis are summarised in Table 3.5.

Table 3.5 Mean frequency-weighted acceleration magnitudes ($a_{h,w}$) and unweighted acceleration magnitudes (a_{lin}) in ms^{-2} r.m.s. from repeated laboratory measurements of pneumatic tool vibration

Tool	Position	$a_{h,w}$ x	$a_{h,w}$ y	$a_{h,w}$ z	a_{lin} x	a_{lin} y	a_{lin} z
Chipping Hammer	Handle	2,08	3,83	8,38*	29,25	34,50	54,34*
	Chisel	5,65	5,35	8,01*	62,53	114,82*	32,06
Vertical Grinder	Left handle	1,34*	1,25	1,24	6,53	10,73*	6,40
	Right handle	0,94	3,57*	3,02	6,90	16,64*	14,28
Disc Cutter	Left handle	1,11	1,11	2,04*	19,04*	5,69	16,57
	Right handle	2,23	2,27*	1,54	20,39	35,45*	15,47
Angle Grinder	Pistol grip	0,51	1,40*	0,83	9,80	11,27	14,17*
End Grinder	Trigger end	1,24*	0,52	0,79	19,12*	14,43	12,59
	Wheel end	2,14*	0,52	1,44	25,21*	11,28	19,28
Collet Grinder	Body	2,24*	1,81	1,76	76,85*	39,26	59,88
Power Wire Brush	Left handle	1,25	1,35*	0,65	3,69	7,61*	3,83
	Right handle	1,12	0,64	1,14*	5,21	5,23	7,23*
Disc sander	Left handle	5,46*	3,81	1,61	23,20*	16,40	7,28
	Right handle	1,51	3,14	3,31*	7,87	15,39	16,30*
Pistol Drill	Pistol grip	1,78	1,74	3,64*	18,49	14,88	23,77*
Morse Drill	Left handle	0,69	0,88	0,99*	10,43*	9,05	9,41
	Right handle	1,49*	0,80	1,37	9,91	9,31*	8,44
Nobbler	Trigger end	1,86	5,32	6,36*	21,50	35,35	56,33*
	Piston end	3,24	2,75	38,32*	20,91	24,80	127,54*
Needle Scaler (straight)	Trigger end	2,18	10,88*	3,41	38,60	70,28*	48,40
	Needle end	2,95	10,39*	4,19	69,88	83,50*	60,27
Needle Scaler (pistol)	Handle	13,43*	6,69	2,86	134,13*	67,45	39,16
	Barrel	9,69	18,93*	5,06	100,30	121,70	129,74*
Chisel Scaler	Trigger end	1,63	19,14*	3,73	46,40	126,79*	38,60
	Chisel end	5,24	19,05*	6,95	86,88	120,28*	72,05
Impact Wrench	Pistol grip	1,68	3,36	4,03*	29,23	34,34	38,56*
Power Hacksaw	Trigger end	5,16*	4,06	2,74	24,13	30,20*	14,05
	Barrel	1,73	4,37*	2,22	10,46	15,73*	14,48

* denotes axis of greatest vibration magnitude

Where the spectra in Appendix B are superimposed, they represent repeated measurements made under similar conditions. Inspection of these spectra reveals that repeatability was, in general, better for the percussive tools (e.g. needle scalers, chipping hammer) than for some rotary tools (e.g. Morse drilling machine, collet grinder). The coefficient of variation (ratio of the standard deviation to the mean) may be obtained from the tabulated acceleration magnitudes in Appendix B. For both frequency-weighted and unweighted acceleration, this had a value of 0.25 or less on many percussive, and some rotary, tools. Variability was greater than this on some other tools. For example, the coefficient of variation for the magnitudes measured on the Morse drilling machine was greater than unity in some axes. The greatest variations were obtained on tools with low vibration magnitudes ($a_{h,w}$ = 1.49 ms^{-2} r.m.s., Morse drill, mean value, dominant axis). This was attributed to difficulties in controlling some aspects of tool operation (e.g. push force, operating speed). For some tools with low vibration magnitudes, the effects of variations in some operating parameters appear to be greater than for (percussive) tools with high magnitudes.

3.6.2 Additional Vibration Data

Laser Doppler Data from Chipping Hammer Chisel

Following the evaluation of the laser doppler vibrometer (see Section 3.4) it was decided that it would not prove to be practicable for use in the field. However, the vibrometer was used to measure the vibration of the chipping hammer chisel in the laboratory.

The machine was operated with the chisel point held against a massive steel block; this method of operation was found to be practical with an unskilled operator.

Three time histories of three seconds duration were acquired in each of the three axes on the chisel. A steel block of side length 20 mm, welded to the side of the chisel and covered with retro-reflective tape, was used as a target for the laser beam. The velocity signals were digitised and digitally differentiated to give acceleration, as described previously.

Acceleration power spectral densities are shown in Figure C1 in Appendix C. Frequency-weighted and unweighted r.m.s. acceleration magnitudes are presented in Table C1.

Although the tool operating conditions were different, these data may be compared with those in Appendix B (Figure B2, Table B2), which were obtained with a skilled operator and with accelerometers mounted on a ring. The frequency-weighted magnitudes are of the same order, while the spectral shapes in all three axes show similar features in both sets of data: small peaks at the strike frequency (approximately 30 Hz) and its harmonics, with a generally flat spectrum throughout the frequency range. The unweighted values are higher in the laser data. This difference may be due to the different operation of the chipping hammer or to the limited high-frequency response of the ring.

Additional Chipping Hammer Data

An additional set of vibration data from a dockyard chipping hammer was obtained at a later date than those in Appendix B. As with the original tool investigated at Devonport, an experienced caulker operated the machine which was used on the PNEUROP test rig (see Section 3.5.3). On this occasion, a tape recorder was not used; output signals from the charge amplifiers were digitised on site, using the portable *HVLab* data acquisition and analysis system. The cut-off frequency of the anti-aliasing filters and the sampling rate were the same as those used in the laboratory measurements (1250 Hz and 5000 samples/second respectively).

Five time histories, each of three seconds duration, were acquired in three axes on the handle of the tool, using the hose clip accelerometer assembly (see Section 3.3.1), and on the chisel, using the ring-mounted accelerometers (see Section 3.3.2). A further set of five runs was made on the handle, using hose clip-mounted piezoresistive accelerometers (Entran type EGCSY 240D-200).

The data from these trials are included in Appendix C. Figure C2 shows the acceleration power spectral densities. The mean and standard deviation r.m.s. acceleration magnitudes (weighted and unweighted) are presented in Table C2.

The magnitudes obtained on the chisel were greater than those in Appendix B and in Table C1 (laser vibrometer data). The shapes of the power spectral densities show a large variability in low-frequency magnitudes. This, and the large standard deviations for acceleration magnitude, indicate that some of the data may not be reliable. This may be due to movement of the ring or impacts between the ring and the chisel resulting in overloading of the accelerometer or amplifier (low-frequency measurement artifacts are discussed in Section 3.2.1). Those spectra which do not appear to have unduly large magnitudes at low frequencies have frequency-weighted r.m.s. acceleration magnitudes of approximately 7, 12 and 11 ms^{-2} in the x-, y- and z-axes respectively (compared with mean values for all five runs of 21, 19 and 22 ms^{-2}). The smaller values are compatible with those from the other tests.

Of the data obtained on the handle of the tool, the second set of five measurements had the lower magnitudes, which are closer to those in Appendix B than those in the first set. However, the shapes of the first set of spectra do not suggest the presence of measurement artifact.

The hardened steel plates of the PNEUROP test rig had been lowered several times between the two sets of measurements on the handle of the chipping hammer, and the tool operator reported that he felt the task to be 'more difficult' at certain times. It is possible that the hardness of the metal in the test rig or the rigidity of the rig (tightness of clamping of the hardened steel plates) varied between runs.

It was concluded that the magnitude of vibration on a chipping hammer of this type is highly variable, even in controlled test conditions such as those of the PNEUROP test. Differences in (unweighted) acceleration magnitudes of a factor of up to approximately 6 may be encountered between measurements in apparently similar conditions.

The Effects of Loading Force on Vibration

During the laboratory tests, the effect of push force on the vibration characteristics of three tools was investigated by making measurements in the dominant axis with the tools working unloaded (i.e. free-running at full speed with no workpiece) and with the tools heavily loaded (i.e. with an excessive push force against the workpiece).

Figure C3 in Appendix C shows the effect of loading on the vibration of the Thor 5VL vertical grinder. Without loading, the spectrum was dominated by a single peak at the rotational frequency (with smaller peaks at its harmonics) due to out-of-balance forces. When the machine was heavily loaded, the principal peak was reduced in magnitude and frequency. Table C3 shows that the fundamental frequency in the unloaded state dominated the vibration spectrum. The frequency-weighted and unweighted magnitudes were reduced by 88% and 92% respectively by increasing the push force of the tool against the workpiece.

In the case of the Trelawney needle gun (Figure C4. Table C4) the spectral peak, at approximately 70 Hz in the unloaded state, was reduced in magnitude by loading heavily. Higher harmonics of the operating frequency were, however, excited under a high loading force. The mean unweighted magnitude was raised by approximately 37% although the weighted value was reduced by about 7%.

The nobbler also had a dominant peak in its vibration spectrum at the operating frequency (100 Hz approximately) and its harmonics (Figure C5, Table C5). The shape of the spectrum was little affected by varying the push force. The magnitude of the principal peak was, however, reduced by increasing the push force, reducing the acceleration magnitudes under heavy loading to approximately 55% (weighted) and 70% (unweighted) of their values in the unloaded state.

3.7 CONCLUSIONS

The vibration magnitudes measured in the laboratory on 16 pneumatic dockyard tools (see Table 3.5 and Appendix B) were obtained under controlled operating conditions for repeatability. The performance of transducers and mounting methods were evaluated prior to making the measurements. Piezoelectric accelerometers, mounted on mechanical filters and attached to the tool by a hose clip, were found to be convenient for most applications. A set of ring-mounted accelerometers and a laser doppler vibrometer were also evaluated and used for measurement of high peak vibration on a chipping hammer.

The vibration characteristics of the sixteen tools, all of which were commonly in use at Devonport dockyard, were investigated. Vibration measurements were made in three orthogonal axes at the positions of both hands, where applicable, while the tools were performing controlled tasks in the laboratory. These tasks were chosen to allow repeatable measurements and were intended to represent 'typical' operating conditions. The variations in vibration characteristics caused by varying the push force were investigated for some tools and changes in magnitude were investigated for some tools and changes in magnitude of up to 50% were observed. Magnitudes obtained from various different measurements on chipping hammers revealed greater differences between magnitudes. It is therefore apparent that in normal use, magnitudes are highly variable, perhaps over an order of magnitude. However, it was assumed that the laboratory measurements were made in conditions which were sufficiently representative of 'normal' use to allow the vibration severities of different tools to be compared, and to demonstrate the frequency content and direction of vibration for each tool to be observed.

For each hand position/axis combination, vibration acceleration data are presented in tabular form in Appendix B as unweighted r.m.s. magnitudes, frequency-weighted r.m.s. magnitudes (using the weighting curve defined in current standards) and octave band r.m.s. magnitudes. The mean and standard deviation values are presented where repeated measurements were made. Acceleration power spectral density functions and example time history segments are presented graphically, also in Appendix B.

CHAPTER 4

SURVEY OF VIBRATION-EXPOSED DOCKYARD EMPLOYEES

4.1 INTRODUCTION

A total of 1242 employees in Devonport Royal Dockyard were included in a questionnaire survey to ascertain the extent and severity of vibration-induced injuries in the dockyard.

This chapter describes the form of the questionnaire and its administration. The surveyed dockyard population is described and the findings from the questionnaire are summarised.

4.1.1 Objectives

The purpose of the survey was to obtain information from dockyard employees on symptoms of vibration-induced white finger and on past and present exposure to hand-transmitted vibration. Employees who were currently or who had been previously engaged in occupations involving the use of hand-held pneumatic tools were included. The objective was to acquire this data in a suitable form for use in the investigation of quantitative dose-response relationships for VWF. The two main areas of interest were:

1. Symptoms characteristic of vibration-induced vascular or neurological conditions (e.g. blanching or blueness of fingers, numbness, tingling, etc.) and their severity and history.

2. Other medical conditions likely to result in similar signs and symptoms (e.g. injury to the fingers or

hands, disease of the nervous or vascular systems, Primary Raynaud's Disease).

3. The individual's history of vibration exposure over his entire working life to date (tools used, dates, times, etc.).

In view of the complex nature of the information being requested from each of several hundred individuals, the questionnaire was administered by interview.

4.2 DESCRIPTION OF QUESTIONNAIRE

4.2.1 Development of Questionnaire

The questionnaire used in the survey at Devonport is reproduced in Appendix A. The sections dealing with the medical aspects of the survey were developed in consultation with medical staff at Devonport from a draft based on an earlier questionnaire from a previous project (Hayward & Griffin, 1986).

It was intended that the interview with the subject would be completed in a maximum of thirty minutes. The questions in the document were therefore designed with simple 'yes/no' or numerical responses where possible. This simplified the numerical coding of responses for computer entry and subsequent statistical analysis.

There is not yet an accepted objective diagnostic test for vibration-induced white finger. The symptoms of VWF occur intermittently in most cases. Attempts to stimulate blanching attacks artificially have been shown to be unreliable (e.g. Taylor *et al.*, 1986) and would have been impractical in a survey of this scale. Thus, in order to establish the presence (if any) and the severity of the signs and symptoms of VWF, it was necessary to rely on the information given by the subject. The questionnaire was designed to record each individual's description of his symptoms in a quantitative manner.

4.2.2 Content of Questionnaire

The following notes give a page-by-page description of the questionnaire.

Page 1
Containing information for subject identification in the dockyard, this page also recorded basic personal details (date of birth, sex and ethnic group).

Page 2 ***Social History***
There have been suggestions that smoking and drinking habits may have an influence on the existence or severity of vascular symptoms. A record was therefore made of each individual's estimated weekly consumption of alcohol (in 'units': one unit = ½ pint beer, 1 glass of wine or 1 measure of spirits) and tobacco (number of cigarettes or equivalent).

Page 3 ***Medical History***
Questions about present and past medical/hospital treatment and currently prescribed drugs were included so as to identify any conditions or possible side-effects likely to be confused with VWF symptoms. A list of drugs acting on the vascular system (including beta-blockers) and on the central nervous system was consulted to identify relevant drug treatments. A final question required the interviewer to make a judgement regarding the relevance of any information given, providing a criterion for the exclusion of the subject in subsequent computer analysis.

Page 4 ***Injury to Fingers, Hand, Arm, Shoulders or Neck***

Details of such injuries were recorded on the questionnaire. In order to simplify data handling, only the existence, or otherwise, of an injury and the interviewer's judgement as to whether the subject should be excluded from the analysis were coded for computer entry. The criteria for exclusion were the existence of injuries involving the loss of all or part of a digit, or injury to the upper limb resulting in lasting neurological or vascular disturbance.

Page 5 ***Related Medical Conditions***

A list of diseases and medical conditions which may cause symptoms similar to those associated with VWF was compiled in collaboration with dockyard medical staff. The list was read out to the subjects. The categories of disease were: 'Heart or circulation trouble', 'Neurological disease', 'Connective tissue disease', 'Degenerative disease' and 'Endocrine disease'. The existence of any relevant condition was noted and coded for computer entry.

Page 6 ***Hand Symptoms***

This section dealt with general circulation problems (cold hands or feet, chilblains). Family history of white fingers or Raynaud's phenomenon was recorded and, where this occurred, the occupation of the individual(s) was ascertained to establish the likelihood of occupational vibration exposure. Finally, a visual inspection of the subject's hands was made. The presence of blanching or cyanosis of digits or other relevant signs were noted and coded for computer entry.

Page 7 ***Blanching***

In this section the subject was asked to provide details of any occurrence of finger blanching. This was achieved by indicating graphically those areas of the hands affected in the 'worst possible attack' and using a scoring system to assess the severity of the case

(Griffin, 1982). A weighted score is allocated to each affected phalanx, allowing a maximum score of 33 on each hand (see Figure 2.2). In addition to providing a numerical indication of blanching severity, the mapping of affected areas on a diagram of the hand was desirable for the study of the location of blanching.

Other questions dealt with duration of attacks, conditions under which they occurred and any resulting handicap. The questions 'When did you last notice this?' and 'How many attacks did you have last winter/summer?' were an addition to the questionnaire from serial number 0318 onwards and were inserted to identify those individuals who had suffered blanching in the past but were no longer affected.

Page 8 ***Blueness***

There is evidence that cyanosis of the fingers can occur in VWF sufferers, either in association with blanching attacks or at other times (Pelmear and Taylor, 1975). This page recorded episodes of blue fingers reported by the subject, using a scoring system similar to that used for blanching.

Page 9 ***Numbness***

Paraesthesia during finger blanching attacks is common but not universal. Numbness was therefore considered separately from blanching. It has been suggested that numbness and tingling can be indicators of the early stages of VWF before blanching attacks begin (Taylor and Pelmear, 1975). This made it necessary to establish whether numbness occurred *only* during blanching attacks or whether it had been experienced at other times and, if so, the approximate date on which it was first noticed. The fingers affected by numbness and the conditions under which it occurred were documented.

Page 10 *Tingling*

Unusual tingling sensations in the fingers are often experienced after exposure to hand-transmitted vibration or on recovery from an attack of finger blanching. Like numbness, it has also been said to indicate the early stages of VWF. This page was similar in structure to that dealing with numbness.

Page 11 *Other Signs*

Intended to ensure that no effects of vibration on the upper extremities had gone unnoticed, two final questions dealt with trouble with the grip and any other problems with the fingers or hands.

Pages 12-14 *Vibration Exposure*

This section was used to record all vibration exposures which had occurred during the subject's working life. The date of his first regular use of vibrating tools was coded for computer entry. Each type of tool was allocated a code number; these are listed in Appendix D. The tool codes were entered in the table together with starting and finishing dates, hours per day, days per week and weeks per year. Where the work pattern for a particular tool had changed, more than one entry was made for that tool. The final column in the table ('Total Exposure (Hours)') was calculated from the other numbers in the row by simple arithmetic.

A similar table was used to record vibration from sources other than the individual's regular employment (excessive periods using power tools, motor mower, motor cycle etc.).

4.3 ADMINISTRATION OF QUESTIONNAIRE

4.3.1 Identification of Subjects

Dockyard 'centres' in which vibrating tools had been issued were identified by means of information supplied by the pneumatic tool stores. The groups of employees who were users of these tools were identified by consultation with the foreman. Computer printed personnel lists were obtained, enabling individuals to be checked off as they were seen for interview.

Prior to commencing the survey, it was estimated that these people, together with those employees who had used vibrating tools earlier in their careers, would total more than 2000. Dockyard workers involved in the use of pneumatic hand tools included shipwrights, combined trades (caulker/riveter/burner/driller), painters, boilermakers, smiths, masons and joiners. Most dockyard centres contained several gangs, each of approximately 12 men. Interviews were arranged on a gang-by-gang basis.

In addition to the systematic interviewing of 'industrial' employees, supervisors and office staff in the centres investigated who had a history of vibration exposure were interviewed. A memorandum was circulated to other 'non-industrial' staff, inviting them to come forward to take part in the survey if they had been previously employed in work involving vibration exposure. A small number of individuals (approximately ten) responded to this invitation.

The population of 1242 individuals who took part in the study is described in Section 4.4.

4.3.2 Locations for Interviews

The geographical size of the dockyard precluded the use of a single location for interviewing, because many employees would have lost too much working time in travelling. Supervisors were therefore asked to provide suitable locations near to the places of work. In view of the confidential nature of some parts of the questionnaire, a room or office affording some privacy was requested, although this was not always possible. From time to time, interviewing had to take place in a corner of the supervisors' office.

4.3.3 Timetabling of Interviews

Interviews were conducted at intervals ranging from 15 to 30 minutes. (Longer periods were allowed for employees in certain jobs, such as shipwrights and combined tradesmen, where large numbers of different power tools were in regular use, as recording information on tool use was the most time-consuming part of the process). In areas where a two-week or three-week shift pattern was being worked, it was necessary to return in consecutive weeks in order to include all available employees.

4.3.4 Pilot Study

Prior to commencing the main survey, a pilot study was conducted to rehearse the administration of the questionnaire and to ensure that the required information could be obtained. Three groups of men, from different areas of dockyard work, were chosen for the pilot study.

Group 1 ***Shipwrights***
These twelve men were working on frigate refits. A wide range of power tools, generally light in nature, were used

for cutting laminates, aluminium etc. The daily time spent using tools was low, making accurate recording of tool use difficult and time consuming. Very little evidence of vibration injury was reported.

Group 2 ***Shipwrights (GRP Shop)***

This group consisted of eleven shipwrights working in the boathouse. They were engaged in work on small boats using sanders, small drills and power saws etc. on wood or glass-reinforced plastic. Five men reported blanching, although in two cases this was believed to be the direct result of specific past injuries.

Group 3 ***Combined trades***

The number of different pneumatic tools used by this group was relatively small (mostly chipping hammers, various grinders and drilling machines) and tools were generally used for long periods during the working day. This made the recording of vibration exposure data simpler than for the previous groups. However, a large proportion reported VWF-like symptoms, requiring more time for that part of the questionnaire to be completed. Ten of the twelve men in this group reported some effect, nine of them including blanching.

A simple dose-effect relationship model was constructed, to establish whether the questionnaire data were sufficiently accurate to allow such a relationship to be observed. Linear regression analysis on the data from the 12 combined tradesmen produced the following result:

$$S = 12.11 + 0.00053H + 0.0.00011G$$

where: *S* is the blanching score
H is the total number of hours worked with caulking and riveting hammers
G is the total number of hours worked with grinders.

This model is clearly incomplete, as shown by the large constant term suggesting the existence of other variables which affect the severity of blanching. However, a positive relationship between finger blanching and vibration exposure was shown to exist, even for this small sample. The coefficient of determination, r^2, was 0.39.

This study of thirty-five employees provided an early insight into the different degrees of vibration exposure and prevalence of VWF symptoms in different dockyard occupations. Some simple preliminary statistical analysis on this small sample produced encouraging results, allowing the main body of the survey to be commenced with confidence that the required information could be obtained.

4.3.5 The Main Survey

The main questionnaire survey was conducted over seven separate periods, each of two or three weeks duration. The total time from commencement to completion of the survey was 21 months. Periods between visits to the dockyard were used for entering questionnaire data into the computer for later analysis and for the vibration measurements in the laboratory. No interviewing took place during the midsummer months (July to September) in case subjects' recollections of VWF symptoms, which might occur only during the winter months, were poor at this time of the year.

The original intention had been to include all dockyard personnel who had, at some time, been employed in jobs involving the use of pneumatic tools. However, it became apparent as the survey progressed that some groups of workers received very small vibration exposures and showed few, if any, signs of vibration injury. It was decided that little benefit would result from interviewing all individuals in such groups (e.g. shipwrights, welders and joiners) so priority was given, in the time available, to other groups (e.g. combined trades, painters, boilermakers and smiths) in which the vibration exposures were significantly greater and in which greater prevalences of vibration-related conditions were in evidence. The largest possible numbers of persons from these groups were included. Where only part of an occupational group was surveyed (shipwrights, welders, etc.), it is unlikely that any bias was introduced, as the interviews took place in a random 'gang-by-gang' order.

Some individuals were missed, for various reasons which included sickness, pressure of work and misunderstandings about interview times. These made up less than 5% of the total number in most groups of workers and were not pursued, in view of the limited time available for completion of the survey. Any significant biasing of the results was considered to be unlikely: most were missed for reasons unconnected with their health and many of those men who were on long-term sick leave were likely to have been excluded from the analysis on medical grounds using the procedure described in Section 4.5.

Three combined tradesmen refused to take part in the exercise. Reluctance to cooperate was not a problem with any other group.

4.4 DESCRIPTION OF THE SAMPLE POPULATION

4.4.1 Combined Trades

The principal vibrating tools used by this group were chipping hammers, grinders and drilling machines. The history of tool use in this group was largely dependent on the age of the individual. Until the early 1980s, apprenticeships were served in the individual trades of caulker/riveter, burner or driller. (The caulkers and riveters had merged in about 1960 as the demand for riveting had been reduced.) When the three trades were amalgamated, many men took part in a short programme of cross-training to equip them for the other aspects of the new combined trade (caulker/riveter/burner/driller). In practice, however, most had continued to work predominantly at their original types of work. Some of the older men were not required to undertake cross-training and retained their original classification. Those employees who served their apprenticeship after the introduction of the combined trade received equal levels of training in all aspects of the job. Many of these had since put in approximately equal amounts of time using the caulkers', burners' and drillers' tools, although there were some who had worked almost exclusively at one single aspect of the combined trade.

As the combined tradesmen were interviewed, a record was made of their principal trade in the case of the older men. The younger individuals were coded as 'combined trades'. The numbers of men from each group who took part are shown below.

Caulker/Riveters:	75
Burners:	32
Drillers:	27
Combined trades:	70
Total:	204

Thus, a sample of 204 individuals was obtained, which could be split into smaller subgroups for more detailed analysis of the effects of tool types.

4.4.2 Painters

The three main pneumatic tools used for preparation of surfaces to be painted (the nobbler, the needle scaler and the chisel scaler) were used extensively by painters working in both ship repair work and dockyard maintenance. Chipping hammers were also used by many of these individuals for the removal of tiles and cement.

The total number of painters included in the survey was 532, this being the largest occupational group in the study. Those painters who were involved in regular use of the pneumatic tools were not tradesmen, but skilled labourers. They had not, therefore, served an apprenticeship and were a more mobile group, many individuals having been employed in a number of different jobs prior to entering the Dockyard. Lower total vibration exposure times were therefore recorded for many of the older men than might have been expected. Some persons had used other vibrating tools (e.g. jack hammers) in previous jobs.

4.4.3 Boilermakers

Boilermakers were the third group of dockyard employees of particular interest in the study and, again, the maximum practical number of men was included. The boilermakers' job involved the use of a similar range of pneumatic tools to that used by the combined tradesmen (chipping hammers, grinders, drilling machines etc.) although the average regular exposure times were lower.

A total of 224 boilermakers were interviewed. These included afloat workers, shop workers and those engaged in dockyard maintenance work.

4.4.4 Shipwrights

Several hundred of the original 2000 subjects expected to be involved in the survey were shipwrights. Their work involved the use of a large number of different power tools. These were mainly light tools such as jigsaws, pistol drills and sanders. Periods of tool use per day were typically of the order of seconds or minutes, rather than hours. Little evidence of vibration-induced effects on health was found in a sample survey of 68 shipwrights (see Section 4.6) so it was decided not to survey the remainder.

4.4.5 Welders

Welders were included in the survey because they were known to be users of pneumatic grinding machines. It was found, however, that use of grinders was rare for most welders and, as with shipwrights, little evidence of VWF was found. It was not considered necessary to continue the survey in this group. A total of 101 welders were interviewed (approximately 50% of those in the dockyard).

4.4.6 Other groups

In addition to the five groups described above, other occupations involved the use of vibrating tools and were included in the study. Some of these groups were very small, making intra-group statistical analysis impractical. Others, like the shipwrights and welders, were observed to have low prevalences of VWF symptoms. A summary of the remaining occupations studied is presented below.

Masons

The masons worked in close association with the paintshop, and were exposed to vibration from pneumatic picks and chipping hammers during the occasional removal of tiles and cement from decks etc. A total of 23 individuals were interviewed.

Bricklayers

These 6 individuals worked with the boilermakers and occasionally used chipping hammers for demolition work.

Smiths

The smiths had various power tools at their disposal, including scalers and chipping hammers. The most commonly used machines were grinders, both of the pedestal and hand-held types. A total of 36 smiths were interviewed.

Foundry Workers

The fettling shop attached to the foundry employed only a small number of persons. Grinding machines were in regular use by the six individuals interviewed.

Sawmillmen

A total of 18 men from the sawmill were interviewed as they were known to be occasional chainsaw users.

Joiners and Pattern-makers

This group used a variety of power tools such as sanders, small drilling machines, power saws etc. Few of the tools concerned, however, were of a type likely to exhibit severe vibration characteristics. After 14 individuals had been investigated, it became clear that vibration exposure was minimal and little evidence of VWF was found. No further woodworkers were therefore included.

Machinists

The survey included eight machinists who were users of pneumatic tools only on rare occasions. No further members of this occupational group were surveyed.

Others not included

Other dockyard occupations, in which it was understood that pneumatic power tools were used occasionally and for short periods (e.g. fitters and turners), were not included in the survey. The results for the shipwrights and welders suggested that data obtained from further groups with even lower usage of tools would have shown low prevalences of VWF.

4.4.7 Summary of the Surveyed Population

The numbers of individuals in each occupational group who took part in the survey are summarised below:

Caulker/riveters	75
Burners	32
Drillers	27
Combined trades	71
(Total combined trades	205)
Painters	532
Boilermakers	224
Shipwrights	68
Welders	101
Masons	23
Bricklayers	6
Smiths	36
Foundry workers	6
Sawmillmen	18
Joiners/pattern-makers	14
Machinists	8
Total	1242

4.5 SELECTION OF SUBJECTS FOR FURTHER ANALYSIS

The presence in an individual of symptoms of a vascular or neurological condition (e.g. finger blanching, numbness, tingling) may not be due to vibration injury. Other causes of these symptoms exist; these can include primary Raynaud's disease, past injuries to the upper extremities, vascular or neurological diseases and drug treatments. A list of such conditions (see Table 1.1) was produced by Taylor and Pelmear (1975).

In Section 4.2 the content of the questionnaire was discussed. The questions relating to medical history and details of injuries were intended to identify individuals whose symptoms may have had causes other than vibration.

The purpose of the study was not to diagnose individual cases of VWF, but to investigate dose-effect relationships for VWF. It was therefore desirable that statistical analysis of the questionnaire data should exclude persons with possible alternative causes of symptoms. The selection procedure described below left a group in which any relevant symptoms could be assumed to have resulted solely from exposure to vibration. Some persons with a vibration-induced condition may have been excluded in the process; the true number of VWF cases might be expected to lie between that observed in the population before the selection process and that observed in the selected group.

Subjects were excluded from the analysis if one or more of the following conditions were met:

1. Reply 'yes' to [Q304] : *Any aspect of medical history considered relevant?*

2. Reply 'yes' to [Q402] : *Any of the above (injuries) considered relevant?*

3. Reply 'yes' to [Q502] : *Any of the above (medical conditions) considered relevant?*

4. Reply 'yes' to [Q603] : *Have you had chilblains in the last ten years?*

5. Reply 'yes' to [Q604] : *Do any members of your family experience white fingers?* **and** reply 'no' to [Q605] : *Do they use vibrating tools?*

6. Evidence of blanching **before** start of vibration exposure from comparison of replies to [Q703] : *When did you first notice this?* (blanching) and [Q1202] : *When did you first start working with vibrating tools?*

The criteria for the responses to 1, 2 and 3 above were discussed in Section 4.2.2.

Of the original 1242 subjects in the survey, 921 remained following this selection procedure. Those who had experienced blanching totalled 19% of the selected group, compared with 24.3% of the original sample. The exclusion of more persons with blanching than persons without blanching is encouraging, as the selection procedure was intended to reject individuals with related, but non-vibration-induced, conditions. The effects of the selection procedure on the prevalence of relevant symptoms are summarised in Section 4.6.4.

The exclusion from the analysis of persons with relevant health problems was expected to reduce the average age of the study sample. However, Table 4.1 and Figure 4.1 show that a bias toward the younger age groups existed in the original distribution, and that this was only slightly modified by the selection procedure.

Table 4.1 Age distribution of subjects in selected and original groups

Age range	Original (%)	Selected (%)
16 - 20	1.6	2.1
21 - 25	17.3	19.5
26 - 30	12.7	14.5
31 - 35	10.7	11.4
36 - 40	9.3	10.1
41 - 45	10.1	10.0
56 - 50	13.9	12.9
51 - 55	10.2	8.4
56 - 60	9.1	7.2
61 - 65	5.0	3.9

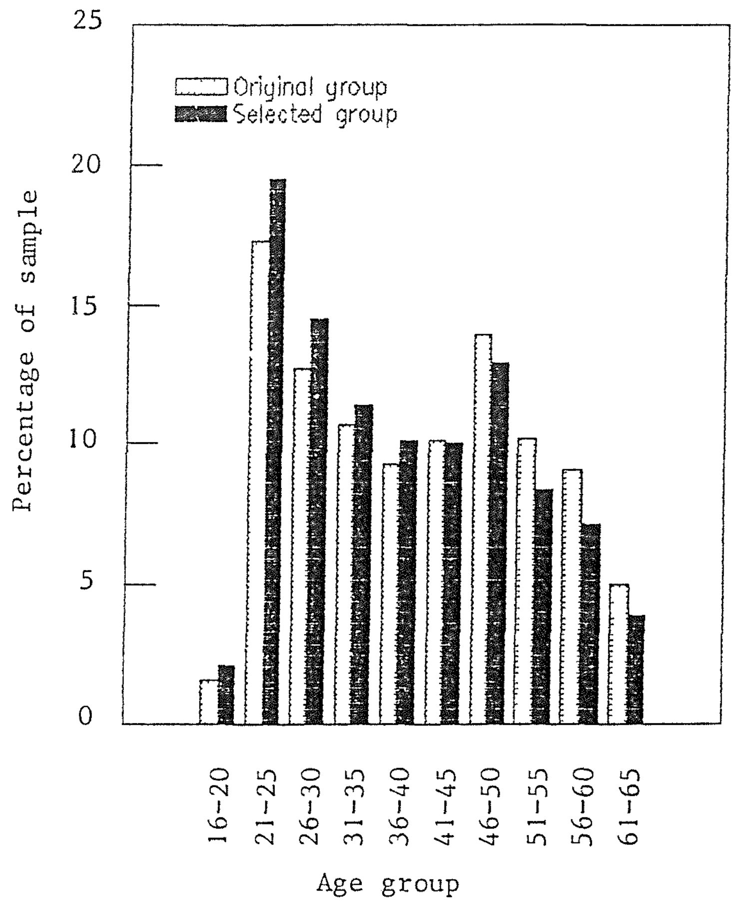


Figure 4.1 *The effect of subject selection on the age distribution*

4.6 SUMMARY OF QUESTIONNAIRE RESPONSES

The responses to the questionnaire by the 1242 individuals surveyed, and of the 921 individuals remaining after the selection procedure, are summarised below.

4.6.1 Personal Details

Age

The age distribution of the overall studied population was described in Section 4.5 where it was shown that the effect of the subject selection procedure was small. The median and inter-quartile range values for age in individual occupational groups, before and after selection, are shown in Table 4.2. These values were computed using the *SPSS* procedure PERCENTILE.

Table 4.2 *Medians and interquartile ranges for age in occupational groups before and after selection procedure*

	Before selection			After selection		
Group	N	Median (years)	Interquartile range (years)	N	Median (years)	Interquartile range (years)
Caulker/riveters	75	55	45-59	42	51	41-57
Burners	32	43	37-53	24	43	36-47
Drillers	26*	56	49-59	7*	58	48-62
Combined Trades	71	25	22-28	52	25	22-28
Painters	532	35	26-47	412	32	25-46
Boilermakers	224	43	32-49	179	42	31-49
Shipwrights	68	47	35-50	48	44	31-49
Welders	101	41	30-53	65	37	28-52
Masons	23	43	28-51	21	39	28-50
Bricklayers	6	53	30-58	4	53	35-56
Smiths	36	32	24-49	29	31	23-49
Foundry Workers	6	36	29-43	5	33	28-39
Sawmillmen	18	42	39-49	15	41	36-47
Joiners	14	44	34-55	10	38	32-58
Machinists	8	36	31-56	7	36	30-60
Unknown	1	43	-	0	-	-
Overall	1241	39	28-50	920	37	27-48

*Age not recorded for one subject

Gender

All subjects interviewed were male.

Ethnic Group

Caucasian	-	1238
Asian	-	3
Negroid	-	1
Mongoloid	-	0

The overwhelming predominance of caucasians meant that it was not possible to investigate any possible differences in VWF susceptibility between persons of different race.

4.6.2 Social History

Smoking

A total of 833 persons (67%) of the original sample and 589 (64%) of the selected subjects had, at some time, been regular smokers.

	Original sample	Selected subjects
Never regularly	409	332
Under 20 per day	333	239
20 or more per day	453	320
Pipe	18	11
Cigars	20	12
Unknown	9	7

A total of 495 individuals in the original sample and 355 from the selected group were still regular smokers at the time of interview.

Alcohol Consumption

The drinking habits reported are summarised below.

	Original sample	Selected subjects
Teetotal	116	69
Occasional drinker	438	327
Regular drinker	688	525

'Regular' drinkers were defined as those who drank alcohol once or more per week. The mean weekly consumption of the regular drinkers was 16.2 units for the original sample and 16.1 units for the selected subjects. (1 unit = ½ pint of beer, 1 glass of wine, 1 single measure of spirits.)

4.6.3 Medical History

Responses to questions about medical history and general hand symptoms are presented in Table 4.3.

Table 4.3 Responses to medical background questions from all 1242 subjects (i.e. before selection)

Subject of question	Positive replies (N)	(%)
Medical supervision at present	191	15.4
Taking tablets at present	166	13.4
Past hospital/outpatient treatment	467	37.6
Any of above considered relevant	101	8.1
Injuries to upper extremities	629	50.6
Injuries considered relevant	114	9.2
Related medical conditions	362	29.1
Condition considered relevant	110	8.9
Cold hands a problem	297	23.9
Cold feet a problem	197	15.9
Chilblains in last 10 years	80	6.4
White fingers in family	62	5.0
If so, any vibration exposure?	26	2.1
Visible signs at interview	41	3.3

The data in Table 4.3 refer to the original (pre-selection) group and were used in the subject selection process described in Section 4.5.

4.6.4 White Finger Symptoms

A total of 302 persons reported blanching of the fingers. Blueness was reported by 41, numbness by 414 and tingling by 487. Among selected subjects, 175 reported blanching, 22 had blueness, 261 had numbness, and tingling was reported by 324 persons.

Tables 4.4 and 4.5 show the distribution of symptoms among members of the different occupational groups, before and after the subject selection procedure respectively (see Section 4.5).

Table 4.4 *Prevalence of finger symptoms before subject selection*

Occupation	(N)	Blanching %	Blueness %	Numbness %	Tingling %
Caulker/riveters	(75)	82.7	20.0	82.7	85.3
Burners	(32)	6.3	-	18.8	37.5
Drillers	(27)	40.7	-	44.4	37.0
Combined Trades	(71)	35.2	10.0	43.7	57.7
Painters	(532)	19.4	3.3	32.7	43.1
Boilermakers	(224)	24.6	1.3	33.0	31.7
Shipwrights	(68)	13.2	1.5	19.1	17.6
Welders	(101)	15.8	3.0	18.8	18.8
Masons	(23)	8.7	4.3	8.7	13.0
Bricklayers	(6)	16.7	-	16.7	50.0
Smiths	(36)	13.9	-	22.2	25.0
Foundry Workers	(6)	66.7	-	66.7	83.3
Sawmillmen	(18)	16.7	-	11.1	16.7
Joiners	(14)	21.4	-	28.6	21.4
Machinists	(8)	12.5	-	12.5	37.5
Total	(1242)	24.3	3.3	33.3	39.2

Table 4.5 Prevalence of finger symptoms after subject selection

Occupation	(N)	Blanching %	Blueness %	Numbness %	Tingling %
Caulker/riveters	(42)	81.0	11.9	81.0	83.3
Burners	(24)	-	-	8.3	25.0
Drillers	(8)	62.5	-	62.5	50.0
Combined Trades	(52)	32.7	11.5	36.5	51.9
Painters	(412)	15.8	1.4	30.1	41.0
Boilermakers	(179)	20.7	1.1	29.6	28.5
Shipwrights	(48)	2.1	2.1	8.3	10.4
Welders	(65)	6.2	1.6	9.2	10.8
Masons	(21)	9.5	4.8	9.5	14.3
Bricklayers	(4)	25.0	-	25.0	50.0
Smiths	(29)	6.9	-	13.8	17.2
Foundry Workers	(5)	60.0	-	60.0	80.0
Sawmillmen	(15)	6.7	-	6.7	13.3
Joiners	(10)	20.0	-	20.0	10.0
Machinists	(7)	14.3	-	14.3	42.9
Total	(921)	19.0	2.4	28.3	35.2

In most groups, the prevalences were slightly reduced by the selection procedure. This is not unexpected: the purpose of subject selection was to exclude any individuals with possible causes of symptoms other than vibration. It is possible, however, that some of the 321 subjects who were excluded did have vibration-induced vascular injuries. The *true* prevalences would therefore be expected to lie between the values in Table 4.4 and Table 4.5.

The group with the greatest prevalence of blanching, after subject selection, was the caulker/riveters (81.0%). The combined trades had a lower prevalence (32.7%) but this was expected because of their lower average age. The painters and boilermakers had prevalences of 15.8% and 20.7% respectively. Some other groups (e.g. the drillers and foundry workers) had high prevalences but the small numbers of individuals in these groups limited the possibilities for further analysis.

The prevalence of Raynaud's phenomenon in a normal healthy population (without vibration exposure) is thought to be in the range 5 - 10% (Taylor and Brammer, 1982). A value of 8.3% was determined by Heslop *et al.* (1983) for male patients in a general practice. The blanching prevalences in some groups in Table 4.5 (shipwrights, welders, etc.) may therefore be within the normal range for unexposed populations.

The numbers of persons who had experienced any blueness of the fingers were small (2.4% overall). Those who reported blueness were predominantly caulker/riveters (11.9%) and combined trades (11.5%).

Numbness prevalences were slightly greater than those for blanching in most occupational groups, the exception being the painters where 30.1% (almost twice the blanching prevalence) reported it. In most groups, tingling of the fingers was reported by more individuals than were the other symptoms, particularly among the painters (41.0%) and the combined trades (51.9%).

Table 4.6 provides an indication of the severity of the blanching found within groups, expressed as the median blanching score for those affected by blanching. (Median values were computed using the *SPSS* procedure FREQUENCIES.) In the four largest groups after selection (caulker/riveters. combined trades, painters and boilermakers) the caulker/riveters had the highest median score (24); the other three groups each had a median score of 12.

Figure 4.2 illustrates the distributions of blanching scores for these four occupational groups. The ordinate values on the graphs show the percentage of individuals in the group with blanching scores *smaller* than that indicated on the abscissa. (This percentage is equal to 100 minus the prevalence of blanching, at *score* = 0, and rises to 100% with increasing score.) The group with the greatest prevalence (the caulker/riveters) had blanching scores evenly distributed over the range 0 to 66, while the majority of affected persons in the other three groups (more than 95%) had scores below 30. Inspection of the two curves for each group reveals that the score distributions were little affected by the subject selection procedure.

Table 4.6 Blanching score. Median scores for subjects with blanching

Occupational Group	Original sample N	Original sample Median	Selected subjects N	Selected subjects Median
Caulker/riveters	62	24.0	34	24.0
Burners	2	36.0	-	-
Drillers	11	12.0	5	12.0
Combined Trades	25	8.0	17	8.0
Painters	103	12.0	65	12.0
Boilermakers	55	9.0	37	12.0
Shipwrights	9	6.5	1	24.0
Welders	16	7.5	4	48.0
Masons	2	15.0	2	15.0
Bricklayers	1	8.0	1	8.0
Smiths	5	6.0	2	4.0
Foundry workers	4	4.0	3	4.0
Sawmillmen	3	5.0	-	-
Joiners	3	6.0	2	4.5
Machinists	1	12.0	1	12.0
Total	302	12.0	175	12.0

The following summary of questionnaire responses regarding VWF symptoms refers to the *selected* subjects.

Blanching

Of the 175 persons with blanching, 155 reported that attacks could be brought on by cold conditions, 131 said that handling cold objects induced attacks and 58 reported that they believed that vibration from power tools was responsible. Blanching occurred *only* in cold conditions for 124 persons (71%).

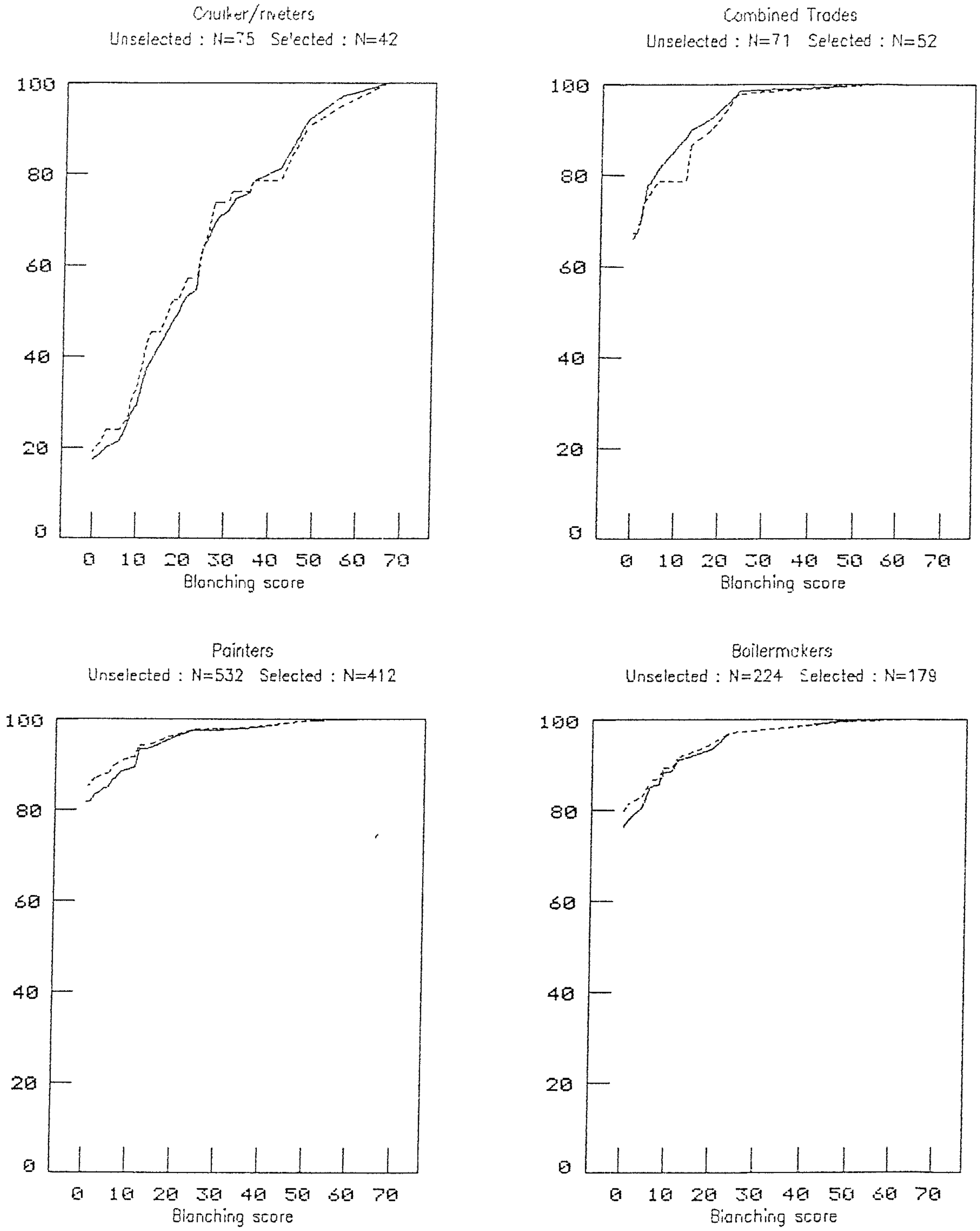


Figure 4.2 *Cumulative distribution of blanching scores among subjects in four occupational groups (—— = original subjects; - - - = selected subjects.)*

Occurrence and duration of attacks

A total of 79 men experienced blanching throughout the year while 87 were affected only during the winter months. Three men said they were only affected during the summer - mostly when swimming, which was discontinued in winter. The remaining six men were unable to reply to the question. (The identification of swimming as the principal activity causing attacks in some individuals is indicative of the effect life style may have on the apparent severity of the condition!)

Several individuals had suffered from blanching in the past but had not been affected for at least one year prior to the interview. Disregarding a few who had only ever had one attack, these totalled 29 and included 18 painters, seven boilermakers, one caulker/riveter, one smith, one bricklayer and one foundry worker. Most of them had stopped receiving regular vibration exposure and had ceased to be affected by blanching after this.

The responses to the question regarding the duration of the longest blanching attack varied over an extremely wide range. After exclusion of 12 persons who could not reply and seven who said that an attack could last all day, the median value was 27.5 minutes in a range between 1 minute and 4 hours. Many men reported that an attack of blanching would persist until the hands were warmed. The reported durations of attacks could therefore reflect the extent of subjects' willingness to endure the experience, rather than the severity of the condition. However, calculation of a nonparametric correlation coefficient (Kendall's tau) between blanching score and maximum attack duration, for all selected subjects with blanching, gave a value of $\tau = 0.22$, indicating a significant relationship ($p < 0.001$). This indicates that the average duration of blanching attacks may increase with the extent of blanching.

Handicap

Social handicap was claimed by 60 persons (34% of those with blanching) who said that the condition had interfered with leisure activities: swimming in particular was said to cause problems. Those who admitted that blanching attacks interfered with their work totalled 44 (25%).

An analysis of variance of blanching scores was carried out between those giving positive answers and those giving negative answers to the questions relating to handicap in leisure activities and at work respectively ([Q722] and [Q723]). A significant difference ($p < 0.05$) was found in both cases.

Blanching Distribution

Figure 4.3 shows the distribution of blanching over the ten digits, in terms of the mean blanching scores for affected individuals in the four high-prevalence groups. It is apparent that the thumbs were affected to a lesser extent than the four fingers (this was anticipated in the design of the scoring system, in which blanching of the thumbs is given more weight than blanching of fingers). For most groups the second and third fingers had the highest average scores. However, for the caulker/riveters, the fourth fingers were the worst affected, particularly on the left hand. This may be due to the close proximity of the fourth finger to the chisel when using a chipping hammer: the left hand was the preferred chisel hand for most right-handed caulkers. This was the only group in which the mean total scores for the left and right hands were significantly different (Student's t-test, $p < 0.05$).

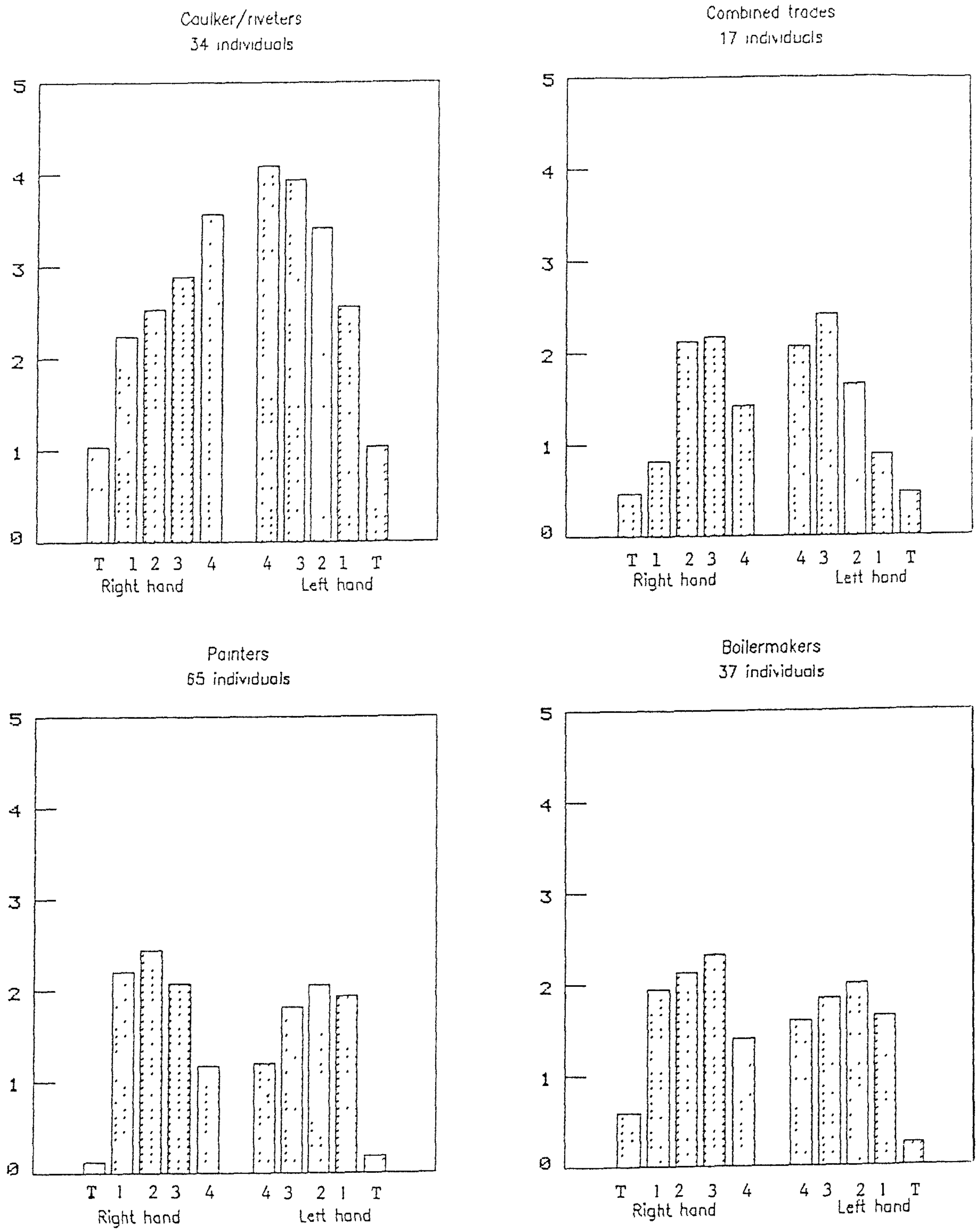


Figure 4.3 *Mean blanching scores for all digits in affected selected subjects in four occupational groups*

Blueness

Localised cyanosis of the fingers had been experienced by 22 individuals, 17 of whom had also suffered blanching attacks. Of these, 13 believed that blueness had first occurred at around the same time as blanching, one before blanching and one after blanching. The other two had no recollection. Attacks of blueness occurred only after blanching for 12 men and in no cases did blueness occur before blanching. Two men said that blueness sometimes occurred without a blanching attack and three were undecided. Although cyanosis was reported by a minority of those individuals with blanching of the fingers, it would seem that the blueness was associated with blanching attacks in most cases.

A total of 15 persons were able to estimate the longest continuous period of blueness; this varied between 2 and 100 minutes with a median value of 10 minutes.

Blueness was experienced only in winter by 11 individuals; eight reported attacks throughout the year and three were unsure of the time of year in which the attacks occurred.

Numbness

Although 261 persons experienced numbness in the fingers, in six people it had only occurred at night. This was assumed to be due to sleeping position and disregarded.

Numbness was experienced by 193 persons immediately after using vibrating tools. It was experienced only in cold conditions by 148 persons.

Those who had blanching *and* numbness totalled 161. All of these experienced numbness during blanching attacks. Numbness did occur at other times (i.e. without blanching and when not using vibrating tools) in 24 of these cases. Two of these believed that numbness had first happened before blanching started, 10 said it had started after the first blanching attack and 20 thought that blanching and numbness had first occurred at about the same time. This does not support the theory that episodic numbness is an early indication of the development of VWF, which was assumed in the development of the Taylor-Pelmear scale for assessment of VWF severity (Taylor And Pelmear, 1975). This finding supports more recent suggestions (e.g. Brammer *et al.*, 1986; Gemne *et al.*, 1987) that the vascular and neurological effects of vibration may develop separately.

Tingling

This was reported by 306 subjects, excluding those who experienced it only at night. Tingling immediately after vibration exposure was experienced by 253 persons.

A total of 153 individuals had tingling *and* blanching and 135 of these experienced tingling during or after blanching attacks. Of those in whom tingling could occur without blanching or vibration exposure, three thought that tingling had first happened before the onset of blanching, 12 thought it had started after blanching and seven said that blanching and tingling first occurred at about the same time. Tingling, like numbness, was not therefore found to be a reliable early indicator of a developing VWF condition, particularly as many individuals experienced tingling during and after the use of power tools from the start of their working lives.

Tingling occurred only in cold conditions in 117 individuals.

4.6.5 Other Signs

Problems with gripping were reported by 173 of the 1242 subjects. In most cases (109 men) this was attributed to numbness. Other problems were reported by 147 men. These included skin complaints and five cases of swelling of the hand or wrist during and after use of vibrating tools (particularly nobblers or needle guns).

Dupuytrens contracture had been diagnosed in six individuals (0.48%). Greater prevalences have been found in some previous studies: de Rosa *et al.* (1970) reported 15.7% in 70 users of vibrating tools. Landrgot *et al.* (1975) observed a prevalence of 11%, but found no significant difference between vibration-exposed workers and a group of controls.

Carpal tunnel syndrome had been diagnosed in seven individuals (0.56%). Chatterjee *et al.* (1982) reported a prevalence of 44% among vibration-exposed workers (rock drillers) and 7% in their control group.

The prevalences for both carpal tunnel syndrome and Dupuytren's contracture were small compared with previously reported values for persons without vibration exposure. No evidence for increased prevalence of these conditions with exposure to vibration was found.

4.6.6 Vibration Exposure

Approximately 100 different types of power tool were identified by the participants in the survey. These tools are listed in Appendix D. Although many of these had been used only occasionally and by very few of the men, others were observed to be in regular use by the majority of employees in some of the dockyard jobs investigated. Table 4.7 illustrates the reported usage of pneumatic hand tools within these occupational groups. For clarity, the table includes only those tools used regularly by 20 or more of the persons interviewed. Data are presented as the average number of hours worked per person per year with each tool type. These were calculated by dividing the total number of hours worked with a tool by the number of years for which the individual had been working, before calculating the mean value for the relevant individuals in the occupational group. (The numbers of individuals are shown in brackets.) These data are independent of the ages of the workers and provide a more meaningful method of comparing tool use in the different dockyard occupations than an average of the *total* (lifetime) exposure times. (However, annual exposure times, averaged over the employees' entire working lives, are not useful for those tools used on rare occasions (i.e. less than once a year) or for short periods only.)

The total number of hours of use of each tool type was computed for each individual. These values were used in the investigation of dose-effect relationships for VWF (see Chapter 5).

The accuracy of exposure time data obtained from a subject's recollection may be questioned. Fright (1991) carried out hierarchical task analyses on operations involving the use of vertical grinders, small angle grinders and needle scalers in Devonport dockyard. The total measured exposure times (ranging from 13 minutes to more than 5 hours) were compared with the operators' estimates. Although a tendency to overestimate the exposure time was found for jobs involving multiple changes of posture, a Pearson correlation coefficient of 0.95 ($p < 0.001$) was obtained between the estimated and measured durations. The ability of this (Devonport) population to recall daily vibration exposure time (which is not the same as the time spent on a job involving the use of a vibrating tool) was therefore demonstrated.

Table 4.7 Mean hours/year worked with vibrating tools (number of persons in brackets)

	Caulker/rivs (75)	Burners (32)	Drillers (27)	Combined (71)	Painters (532)	Boilermkrs (224)	Shipwrts (68)	Welders (101)	Masons (23)	Bricklayers (6)	Smiths (36)	Foundry (6)	Sawmill (18)	Joiners (14)	Machinists (8)
Chipping Hammer (metal)	900 (75)	27 (22)	4 (7)	261 (71)	78 (3)	98 (209)	13 (24)	17 (16)	- -	- -	53 (13)	13 (6)	- -	- -	1 (1)
Riveting Hammer	179 (64)	9 (13)	2 (7)	27 (63)	95 (11)	57 (124)	26 (16)	7 (2)	- -	- -	6 (1)	- -	- -	- -	- -
Pistol Drilling Machine	16 (18)	21 (16)	363 (26)	110 (58)	111 (12)	132 (187)	174 (67)	42 (17)	- -	- -	85 (30)	- -	31 (1)	76 (12)	22 (1)
Morse Drilling Machine	55 (32)	30 (19)	940 (27)	132 (70)	109 (5)	76 (196)	49 (28)	88 (9)	- -	- -	27 (3)	- -	- -	1 (1)	14 (2)
Vertical Grinder	239 (72)	40 (22)	7 (8)	265 (71)	144 (7)	88 (190)	45 (43)	66 (41)	- -	- -	123 (33)	617 (6)	31 (1)	- -	23 (4)
Angle Grinder	92 (42)	7 (6)	9 (3)	81 (40)	7 (6)	61 (89)	28 (30)	38 (65)	- -	- -	97 (17)	- -	- -	- -	- -
End Grinder	102 (29)	- -	2 (1)	15 (3)	- -	61 (27)	77 (2)	2 (1)	- -	- -	93 (1)	23 (6)	- -	- -	- -
Collet Grinder	51 (19)	1 (1)	- -	75 (26)	178 (1)	48 (48)	2 (1)	98 (5)	- -	- -	57 (14)	87 (6)	- -	- -	4 (1)
Power Wire Brush	2 (1)	- -	- -	25 (2)	23 (261)	42 (3)	- -	44 (55)	123 (4)	- -	55 (13)	- -	- -	- -	45 (1)
Nobbler	33 (6)	54 (4)	24 (2)	66 (5)	98 (421)	55 (4)	- -	67 (5)	120 (1)	- -	26 (14)	- -	167 (2)	- -	4 (2)
Needle Scaler	- -	1 (1)	- -	58 (2)	113 (392)	39 (6)	- -	4 (6)	24 (1)	- -	35 (7)	- -	1 (1)	- -	135 (2)
Needle Pistol	- -	- -	- -	- -	213 (30)	- -	- -	- -	66 (19)	- -	- -	- -	- -	- -	- -
Chisel Scaler	5 (2)	25 (2)	66 (1)	198 (3)	150 (490)	- -	- -	30 (5)	68 (2)	- -	- -	2 (1)	- -	- -	269 (1)
Chipp.ng Hammer (cement)	40 (7)	1 (1)	22 (6)	13 (1)	38 (263)	- -	5 (2)	63 (3)	104 (23)	212 (6)	- -	- -	- -	2 (1)	- -
Impact Wrench	30 (24)	1 (5)	4 (6)	13 (4)	37 (9)	38 (170)	54 (54)	5 (3)	- -	- -	- -	- -	- -	- -	- -
Chain Saw	15 (1)	9 (1)	4 (1)	- -	157 (4)	10 (2)	22 (47)	- -	- -	- -	- -	4 (2)	365 (18)	2 (2)	80 (1)
Jig Saw	- -	- -	- -	- -	122 (1)	52 (37)	65 (58)	1 (1)	- -	- -	- -	- -	31 (1)	22 (10)	- -
Circular Saw (hand-held)	23 (5)	3 (2)	- -	- -	72 (4)	26 (24)	25 (42)	183 (1)	1 (1)	- -	3 (1)	- -	31 (1)	165 (4)	- -
Power Hacksaw	16 (43)	5 (4)	4 (4)	6 (25)	17 (3)	64 (194)	45 (54)	3 (4)	- -	- -	27 (16)	1 (1)	- -	24 (4)	1 (1)
Nibbler (hand-held)	4 (6)	- -	33 (2)	3 (8)	- -	20 (95)	11 (34)	6 (3)	- -	- -	3 (5)	- -	- -	- -	- -
Sander	2 (2)	3 (2)	1 (1)	26 (2)	38 (1)	86 (1)	45 (14)	43 (4)	- -	- -	- -	- -	- -	- -	- -
Tube Expander	- -	- -	- -	- -	- -	107 (153)	- -	- -	- -	- -	- -	- -	- -	- -	- -
Pneumatic Pick	- -	- -	- -	- -	19 (4)	- -	- -	- -	- -	26 (1)	- -	- -	- -	- -	- -
Band Saw	- -	- -	- -	- -	193 (2)	20 (5)	28 (18)	- -	- -	- -	32 (6)	- -	- -	142 (4)	14 (5)
Kango Hammer	96 (1)	93 (2)	- -	25 (2)	66 (21)	53 (2)	16 (2)	26 (2)	99 (8)	365 (1)	16 (1)	- -	- -	19 (1)	1 (1)
Jack Hammer	96 (1)	13 (1)	- -	13 (2)	168 (67)	1 (2)	- -	31 (1)	47 (7)	- -	228 (1)	- -	24 (3)	10 (1)	19 (1)
Pedestal Grinder	- -	- -	- -	- -	12 (2)	92 (8)	46 (6)	- -	- -	- -	128 (32)	71 (6)	348 (1)	- -	21 (4)
Pedestal Nibbler	- -	- -	- -	- -	- -	36 (21)	2 (2)	- -	- -	- -	- -	- -	- -	- -	- -

Reported vibration exposure outside working hours consisted primarily of motorcycling, with 516 persons having been regular motorcyclists at some time. No effect of motorcycling on susceptibility to VWF was evident; the prevalence of blanching symptoms in past or current motorcyclists (19.6%) was lower than that for those who had never been regular motorcyclists (18.1%).

Power tools had been used extensively at home (more than two hours per week) by only 67 persons, and 20 persons had been regular users (more than two hours per week) of motor mowers.

4.7 THE EFFECTS OF SMOKING AND DRINKING

Since alcohol is known to be a vasodilator, and nicotine a vasoconstrictor, habitual smoking and/or drinking might be expected to affect the development of VWF symptoms in vibration-exposed workers. The evidence in the literature for an effect of smoking on susceptibility to VWF is mixed: Turtiainen (1974), Voss *et al.* (1978) and Lie (1980) observed an effect whereas Payne (1982), Wasserman *et al.* (1982), Brubaker *et al.* (1986) and Hayward and Griffin (1986) found no effect of smoking.

In order to test the hypotheses that alcohol consumption and tobacco consumption were statistically related to the prevalence of VWF, the 921 selected individuals were categorised according to their habits at the time of the survey as follows:

Smoking:
1. Non-smoker
2. Less than 20 cigarettes per day
3. 20 or more cigarettes per day

Drinking:
1. Not regular drinker
2. Drinking at least once a week but less than 28 units per week
3. 28 or more units per week

(One 'unit' of alcoholic drink is ½ pint of beer, 1 glass of wine or a single measure of spirits. Pipe and cigar smokers were excluded from this analysis.)

Chi-square independence tests were performed between the two ordinal variables described above and three binary variables representing the presence or absence of finger blanching, numbness and tingling respectively. The resultant values of χ^2, the degrees of freedom and the significance level *p* are tabulated in Table 4.8.

The smallest value of *p* was 0.063, indicating that no significant differences exist, at the 5% level, between the distributions for blanching, numbness and tingling due to smoking or drinking.

Table 4.8 *Chi-square independence tests on presence of VWF symptoms with current smoking and drinking habits*

	χ^2	d.o.f.	*p*
Drinking with blanching	3.02	2	0.221
Drinking with numbness	3.81	2	0.149
Drinking with tingling	5.52	2	0.063
Smoking with blanching	2.73	2	0.256
Smoking with numbness	2.29	2	0.317
Smoking with tingling	1.04	2	0.593

In the above analysis, smoking habits at the time of the survey were used (i.e. ex-smokers were classified as non-smokers). However, the questionnaire data also included details of the smoking habits of those who had previously been regular smokers but had ceased smoking at the time of interview. Table 4.9 shows the result of repeating the tests with the smoking variable re-coded to include all previous regular smoking habits.

Table 4.9 *Chi-square independence tests on presence of VWF symptoms with current/previous smoking habits*

	χ^2	d.o.f.	*p*
Smoking and blanching	12.53	2	0.002
Smoking and numbness	10.90	2	0.004
Smoking and tingling	0.92	2	0.630

Previous smoking habits appear to have a significant effect on the distributions of persons with and without symptoms of blanching and numbness. However, further analysis, summarised in Table 4.10, shows that there is a highly significant effect of age on the distribution of the smoking variable (i.e. older men are more likely to have smoked regularly at some time in their lives than are younger men). Significant relationships are also demonstrated between age and the numbers of men with blanching, numbness and tingling. (This is to be expected since accumulated vibration exposure, and hence likelihood of VWF, must increase with age.) Age would appear to be a confounding variable in this case.

Table 4.10 *Chi-square independence tests on age with presence of VWF symptoms and current or previous smoking habits*

	χ^2	d.o.f.	*p*
Smoking with age	46.74	20	0.001
Age with blanching	94.97	10	0.000
Age with numbness	52.67	10	0.000
Age with tingling	25.08	10	0.005

It was concluded that no significant relationship between smoking or drinking habits and the development of VWF had been demonstrated in this study group. Alcohol and tobacco consumption was not, therefore, considered in the further analysis of the questionnaire data, described in Chapter 5.

4.8 SUMMARY

Details of hand symptoms, other health information and history of tool use were collected from 1242 vibration-exposed dockyard workers. A selection procedure reduced the number of individuals in the study to 921, who were believed to be free of confounding medical conditions.

The population comprised 12 occupational groups. One of these groups, the combined trades, was subdivided for convenience into four subgroups: caulker/riveters, burners, drillers and (younger) combined trades. Table 4.5 showed that high prevalences of finger blanching existed in the following groups: caulker/riveters (81%), combined trades (33%), boilermakers (31%) and painters (16%). Other groups exhibited high prevalences but contained too few individuals for meaningful statistical analysis.

Table 4.7 showed that the pneumatic tools most used by the groups with VWF included chipping and riveting hammers, drilling machines, grinders, impact wrenches and scaling tools.

The majority of persons with finger blanching reported that attacks were triggered by cold. A small number reported blueness in the fingers. Most men with blanching also experienced numbness and/or tingling. Numbness and/or tingling were also present in approximately 17% of those men who had no blanching. However, there was no evidence that these symptoms indicate the early stages of VWF.

The severity of the condition was indicated by the scoring system and by the duration of attacks. There was some evidence that the duration increased with increased score (i.e. extent of blanching).

No effect on prevalence of symptoms was observed for those subjects who were regular smokers or drinkers or who were users of motorcycles.

The data produced by the questionnaire survey is further considered in Chapter 5, which describes an investigation into the relationship between exposure to hand-transmitted vibration and the development of VWF.

CHAPTER 5

INVESTIGATION OF DOSE-EFFECT RELATIONSHIPS

5.1 INTRODUCTION

The survey of vibration-exposed workers in Devonport Dockyard produced data describing the development of symptoms of vibration-induced white finger in 921 otherwise healthy individuals. The severity of VWF in individuals was described numerically using the blanching score system (Figure 2.2). The approximate dates of first vibration exposure and the onset of symptoms were obtained. This allowed the latent period to be calculated for each individual.

The questionnaire also provided information on the types of pneumatic tools used by each man, together with the relevant dates and exposure times. In conjunction with the vibration characteristics obtained from measurements on the commonly used tools (see Chapter 3) this provided the means for vibration 'doses', in terms of acceleration magnitudes, frequency content, direction of vibration and exposure duration, to be quantified for each individual.

This chapter describes an investigation of statistical relationships between variables representing the *dose* (vibration characteristics and exposure times for pneumatic tools used) and variables representing the *effect* (severity of VWF, latent period, etc.).

5.1.1 Computer Analysis

Statistical analysis of the data from the questionnaire survey was carried out using *SPSS* (Statistical Package for the Social Sciences) Release 4.0 running on Southampton University's IBM 3090 mainframe computer. In addition to the statistical procedures, *SPSS* provides a FORTRAN-like programming environment for the manipulation of data.

5.2 BLANCHING SCORE

5.2.1 Relation of Score to Vibration 'Dose'

A model for a lifetime vibration 'dose' may take the form:

$$\text{'dose'} \propto \left[\int_0^T a^m(t)\, dt \right]^n$$

where: $a(t)$ is the vibration acceleration magnitude;
T is the total lifetime duration of exposure;
m is a constant defining the time dependency (i.e. the relative importance of acceleration and time);
n is a constant defining the linearity of the dose measure.

The dose for an individual may be approximated by:

$$\text{'dose'} = \left[\sum_{i=1}^{N} (a_i^m \, t_i) \right]^n$$

where a_i is the average acceleration magnitude for tool i;
t_i is the total time (hours) spent using that tool;
N is the number of tools used.

This simple dose model assumes that the time-dependency is the same for daily and lifetime exposures. (The more complex model defined in the current standards, ISO 5349 (1986) and BS 6842 (1987) has values of $m = 2$, $n = ½$ for exposure accumulated during a working day, but $m = 1$, $n = 1$ over a lifetime.)

Lifetime vibration doses were computed for each of the 921 individuals in the study. The total tool use time, t_x, was obtained from the questionnaire data for each of the tools identified in Table 3.5 (the tools which were in most common use in the dockyard and for which vibration data were available). A single acceleration value was used to represent the vibration magnitude of each tool. This value was the mean from all repeat measurements made in the axis/position of greatest magnitude, as shown in Table 3.5 and summarised in Table 5.1. Dose calculations were made with both frequency-weighted and unweighted acceleration. The dominant axis was not always the same for weighted and unweighted acceleration.

(The use of the dominant axis follows the guidance in the current British and International Standards. It has been suggested that the vector sum of the magnitudes in three axes should be used (e.g. Price and Hewitt, 1989). It is unlikely that this approach would have altered the findings of the present study; this possibility is considered in Section 5.2.8.)

Vibration measurements could not be made on some tools identified in the survey of employees. The magnitudes assumed for these tools in Table 5.1 were measured on other similar tools. Riveting hammers and the chipping hammers used by painters for cement removal were given the magnitudes measured on the handle (not the chisel) of the caulkers' chipping hammer. Tube expanders, which had been used by many boilermakers, were given the values measured on the Morse drilling machine, which some boilermakers believed were similar. These assumed magnitudes, although unconfirmed, are likely to be of the correct order and allowed the inclusion in the investigation of widely used tools for which no vibration data could be obtained.

Table 5.1 Dominant axis r.m.s. acceleration magnitudes in ms^{-2} (weighted and unweighted) from vibration measurements described in Chapter 3

Tool	Weighted	Unweighted
Chipping Hammer (steel work)	8.38	114.82
Riveting Hammer	8.38	54.34
Vertical Grinder	3.57	16.64
Angle Grinder	1.40	14.17
End Grinder	2.14	25.21
Collet Grinder	2.24	76.85
Power Wire Brush	1.35	7.61
Disc Sander	5.46	23.20
Pistol Drill	3.64	23.77
Morse Drill	1.49	10.43
Nobbler	38.32	127.54
Needle Scaler	10.88	83.50
Pistol Needle Scaler	18.93	134.13
Chisel Scaler	19.14	126.79
Chipping Hammer (cement)	8.38	54.34
Impact Wrench	4.03	38.56
Power Hacksaw	5.16	30.20
Tube Expander	1.49	10.43

Vibration doses were first computed with values of $m = 2$ and $n = ½$. These are the values used in ISO 5349 and BS 6842 for the calculation of 'energy equivalent' daily vibration exposures. (These values for m and n are assumed if r.m.s. averaging is used for vibration measurement.)

As a preliminary attempt to produce a relationship between VWF and vibration exposure, linear regression of blanching score on this vibration dose was performed for the 921 selected subjects, producing the following results:

With frequency-weighted acceleration:

$$Score = 0.86 + (2.9 \times 10^{-3} \times dose)$$
$$r^2 = 0.08$$
$$\text{Standard error} = 9.45$$

With unweighted acceleration:

$$Score = -1.51 + (8.67 \times 10^{-4} \times dose)$$
$$r^2 = 0.23$$
$$\text{Standard error} = 8.63$$

The square of the Pearson correlation coefficient, r, is known as the coefficient of determination, and may be interpreted as the proportion of the variation in blanching score accounted for by the variation in dose. The use of unweighted acceleration magnitudes in the above dose-effect model therefore appears to give a slightly better fitting model than the use of weighted acceleration. However, the standard error of the estimate for blanching score is approximately nine in both cases; this indicates large uncertainties in the predicted blanching scores and shows that neither model would be of practical use as a predictive tool.

The above analysis was repeated, using various values of the exponents m and n in the dose definition. Table 5.2 shows the values obtained for the coefficient of determination and for the standard error of the estimate.

Table 5.2 Values for the coefficient of determination and the standard error of the estimate in linear regression of blanching score on measures of lifetime vibration 'dose' with different values for the constants m and n (921 subjects)

m	n	Dose	Acceleration	r^2	S.E.E.
0	1	$\sum t_i$	–	0.25	8.50
1	1	$\sum a_i t_i$	Weighted	0.17	8.97
2	1	$\sum a_i^2 t_i$	Weighted	0.05	9.61
2	½	$(\sum a_i^2 t_i)^{1/2}$	Weighted	0.08	9.44
4	1	$\sum a_i^4 t_i$	Weighted	0.02	9.75
4	¼	$(\sum a_i^4 t_i)^{1/4}$	Weighted	0.03	9.69
1	1	$\sum a_i t_i$	Unweighted	0.28	8.35
2	1	$\sum a_i^2 t_i$	Unweighted	0.26	8.47
2	½	$(\sum a_i^2 t_i)^{1/2}$	Unweighted	0.23	8.63
4	1	$\sum a_i^4 t_i$	Unweighted	0.23	8.61
4	¼	$(\sum a_i^4 t_i)^{1/4}$	Unweighted	0.16	9.04

In Table 5.2, the small values of r^2 and the large uncertainties in predicted values for blanching score are indications of poor models in all cases. However, these results show that the correlation between dose and score was greater, for all values of m and n, when the dose values were computed using unweighted acceleration magnitudes than when using the standard frequency weighting. The value of r^2 was smaller for all doses with weighted acceleration than for the doses based on time alone. Two of the five doses with unweighted acceleration (m = 1, n = 1 and m = 2, n = 1) gave larger r^2 values than the dose with exposure time alone (m = 0, n = 1) but the differences were small. This suggests that exposure time is of greater importance than acceleration magnitude in the prediction of blanching score (i.e. the true value of m may be small).

5.2.2 Limitations of Linear Regression Method

Although the scoring system for blanching provides a convenient numerical representation of the severity of the condition in an individual, it does not give a continuous ratio scale of allowable values. The range is bounded by 1 and 66 for persons who have blanching symptoms and is limited to a single value (zero) for individuals who are asymptomatic. Linear regression and correlation are not, therefore, ideal for the analysis of such data, since the assumption that residual values are normally distributed is not true.

The correlation between blanching score and the dose definitions shown in Table 5.2 was calculated a second time, using a nonparametric method (Kendall's τ). Unlike the linear regression method, this does not allow a numerical relationship between score and dose to be obtained. However, it may be considered to be a more appropriate test for the strength of such a relationship with data of this kind because it considers only ranks and makes no assumptions about the distribution of data. The values of τ are presented in Table 5.3.

Table 5.3 *Nonparametric correlation coefficients between blanching score and measures of lifetime vibration 'dose' with different values for the constant m (921 subjects)*

m	Dose	Acceleration	τ
0	$\sum t_i$	–	0.33
1	$\sum a_i t_i$	Weighted	0.33
2	$\sum a_i^2 t_i$	Weighted	0.27
4	$\sum a_i^4 t_i$	Weighted	0.18
1	$\sum a_i t_i$	Unweighted	0.34
2	$\sum a_i^2 t_i$	Unweighted	0.33
4	$\sum a_i^4 t_i$	Unweighted	0.31

Only seven different doses are included in Table 5.3; the value of n is unimportant for a nonparametric correlation because it affects only the linearity of the dose and not the ranking of the data.

All values of τ in Table 5.3 were significant at a level of $p < 0.0001$. As with the parametric correlations, the relationship between score and dose was found to be stronger for the dose with $m = 0$ (exposure time only) than for any of the doses which included frequency-weighted acceleration. A small increase in τ was obtained only for the dose with unweighted acceleration and $m = 1$.

5.2.3 Correlation of Score with Tool Use Time

In order to aid the identification of those pneumatic tools associated with VWF, rank order (nonparametric) correlation coefficients (Kendall's τ) relating total blanching score and total vibration exposure time in hours were calculated for each of the tools mentioned in the questionnaire responses. This procedure was performed separately within the three occupational groups in the dockyard for which the prevalence of VWF was found to be greatest; these were the combined trades (including caulker/riveters, burners and drillers), the painters and the boilermakers.

The coefficients have theoretically possible values in the range -1 to +1. Positive values of τ indicate an increase in blanching score with increasing use of the tool under consideration. Those values of τ which had a significance level of $p < 0.05$ are shown in Table 5.4.

Table 5.4 Rank order correlation coefficients (Kendall's τ, $p < 0.05$) between blanching score and total time exposed to vibration with each tool

Tool	Combined trades τ	Combined trades (N)	Painters τ	Painters (N)	Boilermakers τ	Boilermakers (N)
Chipping Hammer	0,48	(126)	0,20	(412)	0,34	(179)
Riveting Hammer	0,26	(126)	-	-	0,29	(179)
Pistol Drill	-0,22	(126)	-	-	-	-
Morse Drill	-0,11	(126)	-	-	0,18	(179)
Vertical Grinder	0,40	(126)	0,08	(412)	-	-
Angle Grinder	0,28	(126)	-	-	-	-
End Grinder	0,40	(126)	-	-	0,22	(179)
Collet Grinder	0,15	(126)	-	-	-	-
Power Hacksaw	0,17	(126)	-	-	-	-
Nobbler	-	-	0,26	(412)	-	-
Needle Scaler	-	-	0,18	(412)	-	-
Chisel Scaler	-	-	0,22	(412)	-	-
Power Wire Brush	-	-	0,11	(126)	-	-
Tube Expander	-	-	-	-	0,22	(179)

The tools identified are generally those which were most often used in these dockyard occupations (see Table 4.7). Because of the nature of the work, the exposure times for some *pairs* of tools were also highly correlated. (Matrices of Kendall correlation coefficients between exposure times for pairs of tools is presented in Appendix E.) For example, most caulkers used chipping hammers and vertical grinders as a regular part of their work and many boilermakers had used chipping hammers and tube expanders for similar periods of time. Therefore, if only one of the two tools was responsible for vibration injury, a significant correlation might still be observed between blanching score and the exposure time for the other tool. It is possible to calculate partial Kendall correlation coefficients (Siegal, 1956) using the following formula:

$$\tau_{xy.z} = \frac{\tau_{xy} - \tau_{xz}\tau_{yz}}{[(1 - \tau_{xz}^2)(1 - \tau_{yz}^2)]^{1/2}}$$

The following partial Kendall correlation coefficients illustrate the relationships between exposure times for different tools.

Combined trades:

Correlation between blanching score and chipping hammer exposure time: $\tau = 0.48$.

After controlling for vertical grinder exposure time: $\tau = 0.31$.

Correlation between blanching score and vertical grinder exposure time: $\tau = 0.40$.

After controlling for chipping hammer exposure time: $\tau = 0.14$.

Boilermakers:

Correlation between blanching score and chipping hammer exposure time: $\tau = 0.34$.

After controlling for tube expander exposure time: $\tau = 0.26$.

Correlation between blanching score and tube expander exposure time: $\tau = 0.22$.

After controlling for chipping hammer exposure time: $\tau = 0.01$.

In both of the above examples it is apparent that the principal effect arises from the use of chipping hammers. The high correlation coefficients between blanching score and the use of vertical grinders or tube expanders arise because, within the group, the exposure times for these tools are highly correlated with exposure times for chipping hammers.

Negative values of τ may indicate that an increase in the time spent using the tool in question results in reduced exposure time for tools having a greater effect. For example:

Combined trades:

Correlation between blanching score and exposure time using Morse drilling machines: $\tau = -0.11$.

After controlling for chipping hammer exposure time: $\tau = -0.03$.

This suggests that the actual effect on blanching score of exposure time for drilling machines is very small, but that increases in exposure to these tools result in decreased exposure to the more severe vibration from chipping hammers, and therefore in decreased hazard.

The above correlations included all individuals in the three groups. Most men had used some, but not all, of the tools; this resulted in a considerable number of zero values for exposure time for any one tool. An alternative approach is to include in the calculation only those individuals who had used the tool in question, thus reducing the number of tied ranks. This method produced the coefficients presented in Table 5.5. As before, only those with high significance ($p < 0.05$) are included.

Table 5.5 *Rank order correlation coefficients (Kendall's τ, $p < 0.05$) between blanching score and total time exposed to vibration for each tool (excluding zero exposure values)*

Tool	Combined trades τ	Combined trades (N)	Painters τ	Painters (N)	Boilermakers τ	Boilermakers (N)
Chipping Hammer	0,56	(113)	0,30	(204)	0,33	(168)
Riveting Hammer	0,40	(97)	-	-	0,38	(95)
Pistol Drill	-	-	-	-	0,13	(150)
Morse Drill	0,16	(95)	-	-	0,20	(161)
Vertical Grinder	0,47	(112)	-	-	-	-
Angle Grinder	0,46	(63)	-	-	-	-
End Grinder	0,30	(20)	-	-	-	-
Collet Grinder	0,48	(32)	-	-	-	-
Impact wrench	-	-	-	-	0,13	(139)
Nobbler	-	-	0,28	(325)	-	-
Needle Scaler	-	-	0,19	(303)	-	-
Chisel Scaler	-	-	0,23	(381)	-	-
Power Wire Brush	-	-	0,17	(202)	-	-
Tube Expander	-	-	-	-	0,34	(124)

It was not possible to produce partial correlation coefficients from these values, because each was calculated for a different group of individuals. This means that some coefficients will have excessively high values due to high correlations between the usage times for different tools (e.g. the value for the boilermakers' tube expander was shown above to be influenced by the effect of the chipping hammer; these tools were often used together in this occupation). However, some values of Kendall's τ in Table 5.5 may be considered to be more meaningful than those in Table 5.4, since the strength of the relationship between the two variables is not diluted by zero data values for persons who had not used the tool in question. For example, the riveting hammer (known to be associated with VWF in the past from anecdotal evidence), which had been used by relatively small numbers of young combined tradesmen and boilermakers, is now shown to be similar to the chipping hammer in the strength of its relationship to blanching score. Also, the negative coefficients previously obtained for combined tradesmen with the two types of drilling machine have been removed; a low positive value was obtained for the Morse machine and the significance of the correlation for the pistol drill was too low to be included in Table 5.5.

Although the actual values obtained are affected by the method of calculation, the tools identified by the two sets of significant correlation coefficients are, with minor exceptions, similar and provide an approximate means of establishing the relative severity of exposure to the vibration of pneumatic tools in regular dockyard use.

5.2.4 The Logistic Regression Method

In Section 5.2.2, problems with the use of blanching score as the outcome variable in a dose-effect relationship were discussed. An alternative measure of the effect is the probability, P, of a 'success' for a dichotomous variable. If a binary variable, Y, is used to express the 'outcome' (e.g. $Y = 0$ if $S = 0$, $Y = 1$ if $S \geq 1$, where S = blanching score), logistic regression may be used to predict the probability that $Y = 1$ (e.g. the probability that finger blanching will occur) for a given 'dose'. Because a probability must lie in the range 0 to +1, a graph of the probability as a function of the 'dose' (e.g. vibration exposure time) would be expected to give an 'S'-shaped curve or sigmoid.

An example of a sigmoid is the logistic curve:

$$P = \frac{\exp(a + bx)}{1 + \exp(a + bx)}$$

where: x is the dose variable;
a and b are constants.

This 'S'-shaped curve may be transformed into a straight line by replacing the probability (P) by the odds ($P/(1-P)$) and taking the natural logarithm. This link function is called the log-odds or logit.

$$\log_e(P/(1-P)) = \beta_0 + \sum(\beta_i X_i)$$

where: P = probability of ($Y = 1$)
β_i are regression coefficients
X_i are independent variables in the model

Logistic regression was performed using dose (computed with various values of the exponents m and n), as a single independent variable for three different binary outcome variables:

P(score > 0): probability of VWF;

P(score > 8): probability of reaching the current minimum score for prescription in the UK;

P(score > 20): probability of reaching what may arbitrarily be considered to be a high score.

When variables are entered or removed, the log-likelihood ratio statistic or deviance of the model is changed. This change is described by a variable which is distributed as chi-squared. This allows the significance of the improvement (or degradation) of fit to be observed. Table 5.6 shows the values of χ^2 for each of the fitted models.

Table 5.6 *Model χ^2 values (1 degree-of-freedom) from logistic regression analyses for three blanching score thresholds with eleven dose models (921 subjects)*

m	n	Dose	Acceleration	$P(S>0)$ χ^2_1	$P(S>8)$ χ^2_1	$P(S>20)$ χ^2_1
0	1	$\sum t_i$	-	185.3	180.8	88.2
1	1	$\sum a_i t_i$	Weighted	128.0	134.4	51.0
2	1	$\sum a_i^2 t_i$	Weighted	42.0	6.9	9.5
2	½	$(\sum a_i^2 t_i)^{1/2}$	Weighted	76.4	77.5	25.4
4	1	$\sum a_i^4 t_i$	Weighted	20.7	25.5	1.8
4	¼	$(\sum a_i^4 t_i)^{1/4}$	Weighted	35.6	34.5	9.9
1	1	$\sum a_i t_i$	Unweighted	185.3	183.4	94.6
2	1	$\sum a_i^2 t_i$	Unweighted	162.4	164.7	88.2
2	½	$(\sum a_i^2 t_i)^{1/2}$	Unweighted	189.1	184.3	98.7
4	1	$\sum a_i^4 t_i$	Unweighted	143.7	149.5	79.9
4	¼	$(\sum a_i^4 t_i)^{1/4}$	Unweighted	169.7	162.7	93.3

All of the values of χ^2_1 in Table 5.6 are highly significant ($p < 0.01$). It is apparent that when frequency-weighted vibration was included in the dose definition, the fit was less good than when dose was determined by exposure time alone.

With unweighted acceleration, the $\sum a_i t_i$ dose gave a small improvement for the prediction of $S > 8$ and $S > 20$, compared with the $\sum t_i$ dose (exposure time alone). The dose $(\sum a_i^2 t_i)^{1/2}$ gave improved fits for all three score outcome tests. The $(\sum a_i^4 t_i)^{1/4}$ dose gave an improved fit only for the prediction of high blanching scores ($S > 20$).

The dose models with $n = 1/m$ gave the best results. This may be because with $n = 1$ and $m > 1$, large exposure times (and possibly outliers) are emphasised while smaller values are condensed, reducing discrimination.

The dose $(\sum a_i^2 t_i)^{1/2}$ (i.e. $m = 2$, $n = ½$) gave the best fitting model in all three columns of Table 5.6. This dose model has the time-dependency given in the standards for evaluation of exposure during a working day, but not that given for lifetime exposures ($m = n = 1$).

5.2.5 Categorical Treatment of Dose

The distributions of the doses were not normal; large numbers of subjects had low or zero doses (50% below 4000 hours) while a small number had doses at the upper end of the range (10% above 25000 hours). An alternative method was used to fit the dose data to the logistic model, using binary independent variables. The 20th, 40th, 60th and 80th percentile dose values were calculated for each dose model. Five dose bands, bounded by these values, were thus created, with equal numbers of individuals in the bands. Five binary variables were defined such that, for each individual, four were set to zero, and one, depending on the band in which his dose lay, was set to unity. These five variables, X_1 to X_5, were used as independent variables in the logistic regression:

$$\log_e(P/(1-P)) = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5$$

The analyses summarised in Table 5.6 were repeated using this method. Table 5.7 contains the chi-square values from this exercise. (The value of *n* is unimportant here, since it has no effect on the rank orders of the doses and thus does not affect the categorisation of individuals by dose (i.e. the linearity of the dose measure is not important). Only seven different definitions of dose were therefore calculated.)

Table 5.7 *Model χ^2 values (4 degrees-of-freedom) from logistic regression analyses for three blanching score thresholds and seven dose models with dose represented by five binary variables. (921 subjects)*

m	Dose	Acceleration	*P(S>0)* χ^2_4	*P(S>8)* χ^2_4	*P(S>20)* χ^2_4
0	$\sum t_i$	-	166.9	157.0	81.1
1	$\sum a_i t_i$	Weighted	161.4	149.5	66.5
2	$\sum a_i^2 t_i$	Weighted	114.4	104.3	54.9
4	$\sum a_i^4 t_i$	Weighted	71.5	56.6	34.8
1	$\sum a_i t_i$	Unweighted	171.9	161.4	71.0
2	$\sum a_i^2 t_i$	Unweighted	169.7	148.4	75.6
4	$\sum a_i^4 t_i$	Unweighted	142.8	130.9	80.7

As before, the fit for dose computed from exposure time alone was better than that for the models which included frequency-weighted acceleration magnitudes. A small improvement was achieved using unweighted acceleration, but for only three of the nine analyses which used unweighted acceleration.

Tables 5.8, 5.9 and 5.10 show the numbers of individuals categorised by dose in five equally-sized groups and by blanching score in four categories. The doses were computed from the best three models in Tables 5.6 and 5.7: $\sum t_i$, $\sum a_i t_i$ (unweighted acceleration) and $(\sum a_i^2 t_i)^{1/2}$ (unweighted acceleration) respectively). It can be seen that the numbers of individuals affected increased with exposure time. However, for all three dose definitions, between 77% and 80% of the 168 individuals with blanching had doses greater than the 60th percentile value and between 55% and 56% had doses greater than the 80th percentile value. This indicates that the risk of developing vascular symptoms is similar for all three dose definitions.

Table 5.8 *Breakdown of 921 individuals by dose (total exposure time, five categories) and blanching score (four categories)*

Dose (hours)	Blanching score 0	1-8	9-20	> 20	Total
< 522	178	4	2	0	184
522 - 2329	172	7	1	4	184
2330 - 5822	165	9	5	6	185
5823 - 14643	147	20	10	7	184
> 14643	91	19	35	39	184
Total	753	59	53	56	921

Table 5.9 *Breakdown of 921 individuals by dose (unweighted acceleration × total exposure time, five categories) and blanching score (four categories)*

Dose (ms^{-2} hours)	Blanching score 0	1-8	9-20	> 20	Total
< 32356	176	5	2	1	184
32356 - 126159	173	6	3	2	184
126159 - 305790	169	11	0	5	185
305790 - 868880	145	16	11	12	184
> 868880	90	21	37	36	184
Total	753	59	53	56	921

Table 5.10 *Breakdown of 921 individuals by dose ($(a^2t)^{1/2}$ with unweighted acceleration, five categories) and blanching score (four categories)*

Dose (ms^{-2} hours$^{1/2}$)	Blanching score 0	1-8	9-20	> 20	Total
< 1389	178	4	1	1	184
1389 - 2938	174	6	2	2	184
2938 - 5061	163	10	8	4	185
5061 - 9014	147	17	8	12	184
> 9014	91	22	34	37	184
Total	753	59	53	56	921

In the logistic regression procedures described above, for any given individual dose only one of the five X values is unity and four are zero. The β value associated with that dose band is therefore equal to the log-odds value. For example, if an individual's dose lay in the 3rd dose band:

$$\log_e(P/(1-P)) = \beta_1 \times 0 + \beta_2 \times 0 + \beta_3 \times 1 + \beta_4 \times 0 + \beta_5 \times 0$$

The probability of a 'success' ($Y = 1$) for an individual with a dose value in the third band is therefore:

$$P(Y = 1) = \exp(\beta_3)/\exp(1 + \beta_3)$$

Confidence intervals for the odds ratios (and hence, the probabilities) may be calculated from the standard errors of the regression coefficients, which are given by the *SPSS* procedure LOGISTIC REGRESSION. The estimates may be assumed to be normally distributed (Healy, 1988) so the 95% confidence limits for each regression coefficient are:

$$\beta \pm (1.96 \times \text{S.E.}(\beta))$$

The nine graphs in Figure 5.1 show the probabilities, with 95% confidence limits, for $P(S > 0)$, $P(S > 8)$ and $P(S > 20)$ as functions of three definitions of dose: $\sum t_i$, $\sum a_i t_i$ (unweighted acceleration) and $(\sum a_i^2 t_i)^{1/2}$ (unweighted acceleration). The dose values plotted in the graphs are the median values for the five dose 'bands'.

It is apparent that the magnitudes of the probabilities and the associated confidence intervals are similar for all three definitions of dose. This suggests that, although the dose definitions which included unweighted acceleration magnitudes gave the better fitting models, there is little practical advantage in the use of these models, compared with the simpler (exposure time) model.

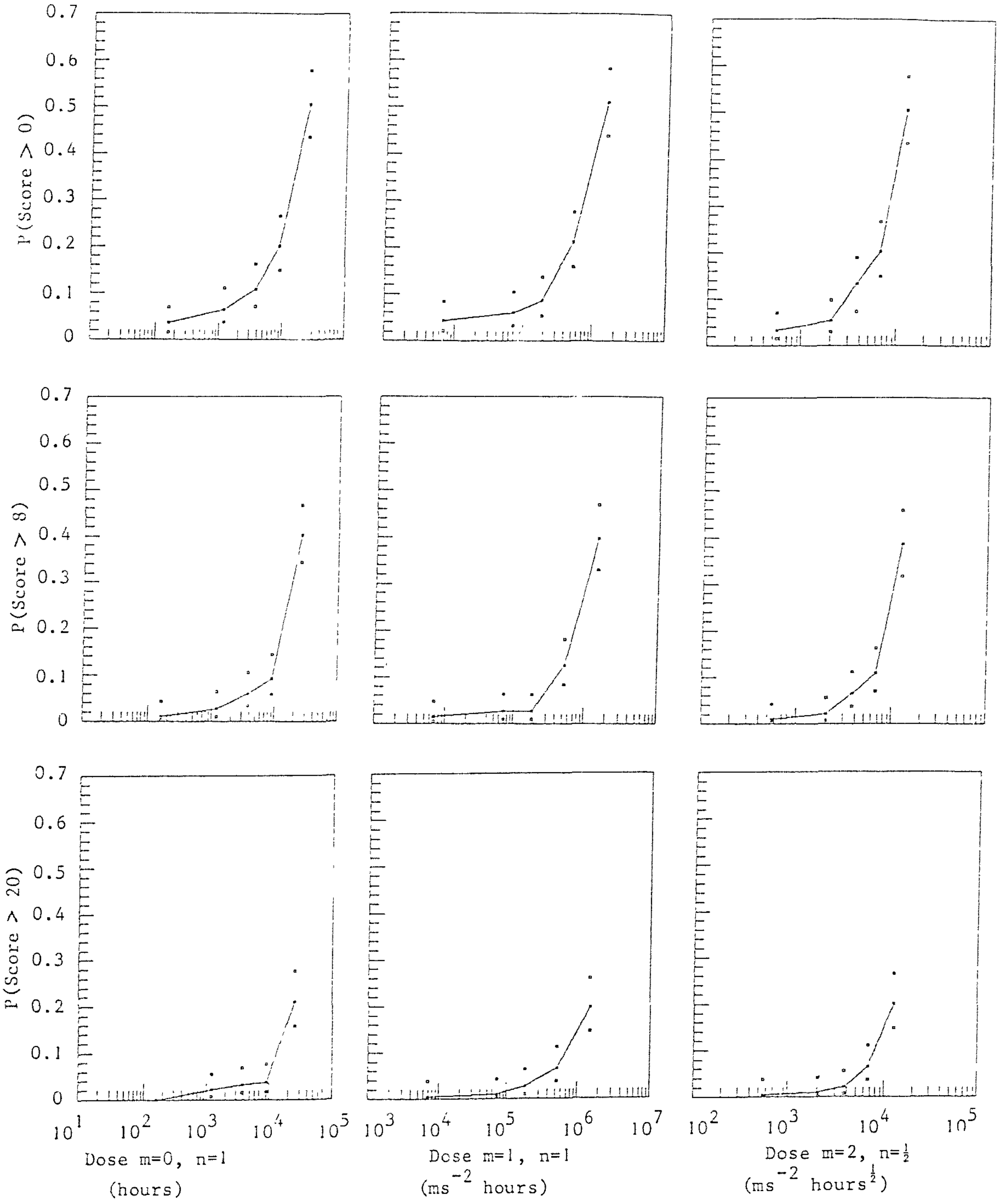


***Figure 5.1** Probabilities, with 95% confidence limits, for blanching scores greater than 0, 8 and 20 as a function of three definitions of vibration dose (921 subjects)*

5.2.6 Separate Effects of Magnitude and Time

The previous section was concerned with attempts to relate VWF (blanching score) to various measures of vibration dose. Since an acceleration magnitude can only have an effect when applied for a finite time, it was logical to define dose in terms of the vibration magnitude, raised to an appropriate power, integrated over time. The χ^2 values in Tables 5.6 and 5.7 suggested that the contribution of exposure time is greater than that of vibration magnitude.

In order to compare the individual contributions of acceleration magnitude and exposure time, further logistic regression analyses were carried out with 'nested' models in which acceleration and time were expressed as two independent variables. This approach gave a $\chi^2{}_1$ value (and thus a significance level) for the inclusion of each variable.

Since most individuals in the study had used a combination of different tools, for different periods of time, it was necessary to define a method for obtaining a single value to represent acceleration magnitude for each person. A 'dose' (i.e. acceleration integrated over time with a time-dependency exponent *m*) was computed and divided by the total exposure time, giving an average acceleration, *A*, which was independent of time:

$$A = \frac{\left(\sum_{i=1}^{N} a_i^m \, t_i\right)^{1/m}}{\sum_{i=1}^{N} (t_i)}$$

where: a_i is the measured r.m.s. acceleration for tool i;
t_i is the total time spent using tool i;
N is the number of tools used;
m is the time-dependency constant.

Average acceleration values (frequency-weighted and unweighted) were computed for each subject for exponents of $m = 1$, $m = 2$ and $m = 4$. Logistic regression analyses were carried out for the three binary outcome variables used before (blanching score S greater than 0, 8 and 20) with total exposure time and one of the six alternative values for average acceleration as the two independent variables. The variables were entered in the model using a forward stepwise entry procedure; a significance level of $p \leq 0.05$ was required for entry of each variable. The χ^2 values which describe the improvement in the model when each variable was entered are shown in Table 5.11.

Table 5.11 *Improvement χ^2 values (1 degree-of-freedom) for inclusion of time and acceleration variables in logistic regression analyses for three blanching score thresholds (921 subjects)*

m	Variable	$P(S > 0)$ χ^2_1	$P(S > 8)$ χ^2_1	$P(S > 20)$ χ^2_1
0	Time	185.3***	180.8***	88.2***
1	Weighted accel.	7.8*	10.5*	-
2	Weighted accel.	9.0*	11.3**	-
4	Weighted accel.	10.2*	16.7**	-
1	Unweighted accel.	14.3**	13.2**	5.2
2	Unweighted accel.	18.4***	15.9**	7.7*
4	Unweighted accel.	22.5***	18.3***	10.6*

* $p < 0.01$ ** $p < 0.001$ *** $p < 0.0001$

The χ^2_1 values for the time variable are the same as those obtained previously for the dose with $m = 0$ (see Table 5.6). All three have high significance levels ($p < 0.0001$). The χ^2_1 values for the inclusion of acceleration in the model are smaller, by an order of magnitude, than those for time, but are still highly significant ($p < 0.01$ for all but one of the χ^2_1 values computed).

As before, the better fitting models were those using unweighted acceleration. In the three models for the prediction of $P(S > 20)$ with weighted acceleration, the acceleration terms were not entered because the entry criterion was not met (i.e. the inclusion of the acceleration term in the model did not significantly improve the fit of the data).

The improvement in fit due to the inclusion of the acceleration term increased with increasing values of the exponent m; this was not always the case with the models based on a single dose variable (e.g. Table 5.6).

5.2.7 Effect of Vibration Frequency

In the previous section (5.2.6), acceleration magnitude was considered as a variable independent of exposure time in the dose-effect model. In order to investigate the effect of vibration frequency on the development of VWF, the same approach was adopted with separate variables to represent acceleration magnitudes for different frequency bands.

Mean acceleration magnitudes from the repeated measurements on the pneumatic tools are presented in Appendix B. In addition to the weighted and unweighted overall magnitudes, eight octave band magnitudes (centre frequencies from 8 Hz to 1000 Hz) are included. The octave band values for the axis with greatest unweighted overall r.m.s. magnitude were selected from the data for each of the 18 tools identified in Table 5.1. A set of eight octave band exposure variables A_8 to A_{1k} was computed for each subject:

$$A_i = \left(\sum_j (a_{ij}^2 \ t_j)/\sum_j t_j\right)^{1/2}$$

where: A_i is the average acceleration in octave band i;
a_{ij} is the acceleration of tool j in octave band i;
t_j is the time spent using tool j.

(A time-dependency exponent $m = 2$ was selected because this gave the best fit in the analysis in Section 5.2.4.)

Logistic regression analyses for the three blanching score outcome variables were carried out, with the eight octave band exposure variables and total exposure time as the independent variables. As before, a forward, stepwise variable entry procedure was employed. The entry criterion for each variable was a significance level of $p \leq 0.05$.

Table 5.12 shows the χ^2_1 values associated with the inclusion of the different variables. The exposure time was the only variable to be entered in all three analyses. In the first analysis ($P(S > 0)$) the 128 Hz and 256 Hz acceleration variables were entered. In the second analysis ($P(S > 8)$) the 32 Hz and 1024 Hz acceleration variables were entered and only the 1024 Hz variable was entered in the third analysis ($P(S > 20)$). With the entry criterion set at a significance level of $p \leq 0.05$, no other acceleration terms could be entered. As different components were identified as being significant in the three analyses, it was apparent that no clear effect of vibration frequency had been demonstrated.

These analyses were repeated, with forced entry of all variables, to obtain the values of the regression parameters. Table 5.13 shows the values of β for all variables from the logistic regression for the second analysis ($Y = 1$ if $S > 8$ as the binary outcome variable). Also included in this table are the standard errors of the β values, the Wald values and their significance levels.

(The Wald statistic is the square of the ratio of the regression coefficient β to its standard error $(\beta/S.E.(\beta))^2$.)

Table 5.12 Improvement χ^2 values (1 degree-of-freedom) for inclusion of time and octave band acceleration variables in logistic regression analyses for three blanching score outcomes (921 subjects)

Variable	$p(S > 0)$ χ^2_1	$p(S > 8)$ χ^2_1	$p(S > 20)$ χ^2_1
Time	185.3***	180.8***	88.2***
Acceleration (8 Hz)	-	-	-
Acceleration (16 Hz)	-	-	-
Acceleration (32 Hz)	-	13.1**	-
Acceleration (64 Hz)	-	-	-
Acceleration (128 Hz)	10.6*	-	-
Acceleration (256 Hz)	20.6***	-	-
Acceleration (512 Hz)	-	-	-
Acceleration (1024 Hz)	-	9.3*	13.4**

* $p < 0.01$ ** $p < 0.001$ *** $p < 0.0001$

Table 5.13 Logistic regression coefficients with their standard errors and Wald statistics for independent variables representing exposure time and acceleration in eight octave bands. Binary outcome variable Y = 1 if S > 8 (921 subjects)

Variable	β	S.E.	Wald	Sig.
Constant	-4.550	0.643	50.08	0.0000
Time	7.9E-5	9.0E-6	77.45	0.0000
Acceleration (8 Hz)	-0.884	1.188	0.55	0.4566
Acceleration (16 Hz)	-1.415	0.631	5.03	0.0249
Acceleration (32 Hz)	0.228	0.086	6.93	0.0085
Acceleration (64 Hz)	0.009	0.027	0.11	0.7398
Acceleration (128 Hz)	-0.010	0.021	0.22	0.6422
Acceleration (256 Hz)	0.033	0.072	0.21	0.6457
Acceleration (512 Hz)	0.058	0.027	4.55	0.0328
Acceleration (1024 Hz)	-0.004	0.024	0.03	0.8677

Although the constant and exposure time terms had β values with relatively small standard errors and therefore significant Wald values, all but three of the octave band acceleration terms were insignificant ($p > 0.05$) when forced into the model together. The three acceleration terms with the highest significance levels were the 16 Hz, 32 Hz and 512 Hz octave band components, whereas those entered in the stepwise entry were the 32 Hz and 1024 Hz components. It was not possible to determine any relative effects of vibration in different frequency ranges by comparing the β values.

It is likely that multicolinearity existed between the eight octave band variables. The vibration spectra in Appendix B show that all of the tools in the study had vibration components in all eight octave bands. Many vibration-exposed individuals had used similar combinations of tools. The average lifetime accelerations in different octave bands might then be highly correlated. To illustrate this, Pearson correlation coefficients were computed between all pairs of the eight acceleration values for all 921 selected subjects. These are shown in Table 5.14 below.

Table 5.14 *Pearson correlation matrix for eight octave band acceleration exposure components (921 subjects)*

	8	16	32	64	128	256	512	1024
8	1.00	0.94	0.90	0.76	0.28	0.44	0.26	0.33
16	-	1.00	0.97	0.85	0.43	0.51	0.14	0.21
32	-	-	1.00	0.89	0.46	0.51	-0.03	0.20
64	-	-	-	1.00	0.72	0.69	-0.13	0.27
128	-	-	-	-	1.00	0.84	-0.12	0.13
256	-	-	-	-	-	1.00	0.25	0.58
512	-	-	-	-	-	-	1.00	0.45
1024	-	-	-	-	-	-	-	1.00

(All significant ($p < 0.01$) except coefficient between 32 Hz and 512 Hz components.)

The high correlation between the aggregated vibration components in many pairs of eight octave bands, meant that no clear effect of vibration frequency could be found. This was not unexpected as the effects of vibration magnitude have been shown to be small compared with those of vibration exposure time. However, in all of the dose-effect models considered in the preceding sections, unweighted acceleration magnitudes (measured with an upper band limit of 1250 Hz) were better indicators of vibration severity than frequency-weighted magnitudes. This suggests that frequencies in the upper part of this range may be of greater importance in the development of VWF than the standard frequency weighting would imply. It is also possible that the inclusion of vibration frequencies above 1250 Hz would strengthen the relationship between acceleration magnitude and risk of VWF.

5.2.8 Effect of Vibration Direction

In the preceding sections, all acceleration magnitudes used in dose models were the mean values from repeated measurements in the axis of greatest severity. (Measurements were made in three axes at each hand position, giving a choice of three or six mean magnitudes for each tool.) This use of the 'worst axis' magnitude is advocated in the current measurement standards ISO 5349 (1986) and BS 6842 (1987). It has, however, been suggested (Price and Hewitt, 1989) that the vector sum (i.e. root-sum-of-squares) of the magnitudes measured in three orthogonal axes would be a more representative of severity. One argument for this is that many tools do not have an obvious 'dominant' axis of vibration; data in Table 3.5 and Appendix B show this to be true for some tools in this study.

The use of either the 'worst axis' magnitude or the 'vector sum' magnitude assumes that hand-transmitted vibration exposures in all directions are equally hazardous. It is reasonable, however, that the effects of vibration exposures with compressive action (i.e. normal to the skin surface) and shear action (i.e. parallel to the skin surface) on the flesh of the fingers might be different. With a typical cylindrical handle or tool body, the action on the fingers of vibration in the y-axis may be described as 'shear' while in the x- and z-axes the action of the vibration on part of the finger is 'compressive'.

To investigate the possibility of an effect of vibration axis, the following unweighted acceleration magnitudes were obtained from the data in Table 3.5.

1. Vector sum. The vector sum magnitude for each hand position was computed from the root-sum-of-squares of the mean unweighted magnitudes for the three components. The greater of the two vector sums (for two-handed tools) was then selected.

2. Greatest compressive component. The greatest of the two (or four for two-handed tools) unweighted x- and z-axis components was selected.

3. Greatest shear component. The unweighted y-axis component (or the greater of the two for two-handed tools) was selected.

These values are shown in Table 5.15, together with the 'dominant axis' values used previously.

In Section 5.2.4, the logistic regression analyses showed that, although the effects of including acceleration in the dose calculations were small, the best dose model contained unweighted acceleration and values of $m = 2$ and $n = ½$ for the two exponents. The four sets of acceleration magnitudes in Table 5.15 were used to construct four doses of this form. The logistic regression analyses with three binary outcome variables (blanching score S above or below zero, eight and twenty) were repeated with each of these doses as the independent variable. Table 5.16 shows the χ^2 values for the model.

Table 5.15 *Mean unweighted acceleration magnitudes (ms^{-2} r.m.s.) in various axes (from vibration measurements described in Chapter 3)*

Tool	Dominant axis	Greatest vector sum	Greatest compressive	Greatest shear
Chipping Hammer (steel work)	114,82	134,62	54,34	114,82
Riveting Hammer	54,34	70,70	54,34	34,50
Vertical Grinder	16,64	22,49	14,28	16,64
Angle Grinder	14,17	20,59	14,17	11,27
End Grinder	25,21	33,68	25,21	14,43
Collet Grinder	76,85	105,04	76,85	39,26
Power Wire Brush	7,61	10,33	7,23	7,61
Disc Sander	23,20	29,33	23,20	16,40
Pistol Drill	23,77	33,59	23,77	14,88
Morse Drill	10,43	16,71	10,43	9,31
Nobbler	127,54	131,60	127,54	35,35
Needle Scaler	83,50	124,45	69,88	83,50
Pistol Needle Scaler	134,13	204,21	134,13	121,70
Chisel Scaler	126,79	164,94	86,88	126,79
Chipping Hammer (cement)	54,34	70,70	54,34	34,50
Impact Wrench	38,56	59,33	38,56	34,34
Power Hacksaw	30,20	41,13	24,13	30,20
Tube Expander	10,43	16,71	10,43	9,31

Table 5.16 *Model χ^2 values (1 degree-of-freedom) from logistic regression analyses for three blanching score outcomes with four dose models containing acceleration magnitudes for different axes of vibration (921 subjects), dose = $(\sum a_i{}^2 t_i)^{1/2}$*

Acceleration	$P(S > 0)$ $\chi^2{}_1$	$P(S > 8)$ $\chi^2{}_1$	$P(S > 20)$ $\chi^2{}_1$
Dominant axis	189.1	184.3	98.7
Greatest vector sum	183.6	179.0	97.9
Greatest compressive component	136.7	135.4	58.3
Greatest shear component	186.6	177.0	106.4

All of the χ^2 values in Table 5.16 are significant at a level of $p < 0.0001$. The best fits (i.e. greatest values of χ^2) were for the model containing the 'dominant axis' acceleration data. The 'vector sum' acceleration gave χ^2 values which were close to, but not greater than, those obtained with 'dominant axis' magnitudes. It does not appear, therefore, that the use of 'vector sum' magnitudes in place of the 'dominant axis' values in the preceding analyses in this chapter would have given significantly different results for the fit of the data to the various dose models.

The model containing the 'greatest shear component' (y-axis) acceleration magnitudes produced greater values of χ^2 than that containing the 'greatest compressive component' (x- or z-axis) magnitudes. However, the reason for this may be that on several of the tools most used by groups with VWF (chipping hammer, vertical grinder, needle scaler, chisel scaler) the y-axis was dominant. On the chipping hammer in particular (shown in Tables 5.4 and 5.5 to be the tool most associated with high blanching scores) the y-axis magnitude was greater than the x/z-axis magnitude by a factor of two. Because of this, the fit of the data to the model containing y-axis magnitudes is similar to those for the 'dominant axis' and 'vector sum' models and better than that for the x/z-axis model. Any true difference between the effects of compressive and shear vibration may have been masked by this effect.

No conclusion was reached regarding differences between the effects of vibration in different directions. The dominant axis vibration gave the best fit to the dose-effect model, although similar results were obtained with the vector sum. This suggests that assessment of vibration severity based on the dominant axis of vibration, as recommended in ISO 5349 (1986) and BS 6842 (1987), is adequate for tools of this kind; measurement in three axes where the dominant axis is known may not be considered necessary.

5.3 LATENT PERIOD

The latent period, or latent interval, has been defined as 'the time during which an injury is manifest but not discernible': in practical terms, for VWF, this is the period of time between the start of vibration exposure and the first occurrence of finger blanching. Some previous studies of VWF have included reports of the mean latent period for those individuals affected (e.g. Taylor *et al.*, 1975; Starck *et al.*, 1983; James *et al.*, 1989). A mean latent period obtained from a cross-sectional study can be misleading because it is dependent on the prevalence of the condition within the group and therefore on the average period of vibration exposure. As exposure continues and more persons in the group develop symptoms, so the mean latency is reduced. The mean latent period in a group can also be influenced by the rate at which people have joined or left the group. If, for example, individuals have moved to alternative employment *because* of the onset of VWF symptoms, then the observed prevalence and mean latent period would be biased low and high respectively.

In this study, an analysis of the rate of development of VWF (i.e. the incidence rate) was made. This enabled latency values for different percentiles of exposed groups of workers to be evaluated. The *median* latency (i.e. the latency for the 50th percentile of the exposed population) is a more meaningful quantity than the *mean* latency for those affected at the time of the survey.

The biasing effects due to a changing population were assumed to be small, since most of the vibration-exposed employees were tradesmen and had remained in the same kind of employment throughout their working lives, following a five year apprenticeship. At Devonport, tradesmen with poor health were generally moved to 'light duties' but retained their trade status and, although no longer exposed to vibration, were included in the survey of employees in relevant occupations.

5.3.1 Survival Analysis

The 'survival analysis' procedure enabled rates of incidence to be calculated, while correcting for a changing sample size. This technique is used in medical research where a 'survival variable' represents the period between an initial event (e.g. diagnosis of disease or start of treatment) and a final event (e.g. recovery or death). In this study, the initial event was defined as the start of employment involving regular vibration exposure and the final event as the onset of finger blanching.

The individual latent period in years, for each person with blanching, was calculated by subtracting the date of first vibration exposure from the reported date on which blanching was first noticed. For those without symptoms, the number of years of regular exposure was calculated by subtracting the date of first exposure from the date of interview.

A survival function representing the cumulative proportion 'surviving' each 1-year period of vibration exposure was computed for each occupational group. The computations were performed by the SURVIVAL routine in the *SPSS* package which uses the following method (SPSS Inc., 1990):

For each year of vibration exposure, the proportion surviving, P_y, was calculated as follows:

$$P_y = 1 - \frac{b_y}{n_y}$$

where: b_y = number of persons first experiencing blanching during the yth year;
n_y = number of persons exposed to vibration for $(y - 1)$ years with no previous history of blanching.

The cumulative proportion remaining unaffected by blanching after each 1-year period y was then calculated:

$$C_y = \prod_{j=1}^{y} (P_j)$$

Figure 5.2 shows the proportion of persons remaining unaffected by blanching (i.e. the 'survivors') as a function of the number of years of vibration exposure, for caulker/riveters, combined tradesmen, painters and boilermakers. (The other occupations had very low prevalences or contained small numbers of individuals, making the resolution of their survival functions too low to be meaningful.)

The number of individuals included in these analyses decreases with increasing years of exposure because of the distribution of ages of subjects at the time of the survey. For this reason, the 'steps' in the survival functions increase in magnitude with increasing years of exposure. This is noticeable for exposures of more than approximately

25 years for the caulker/riveters, painters and boilermakers and approximately 10 years for the younger combined trades.

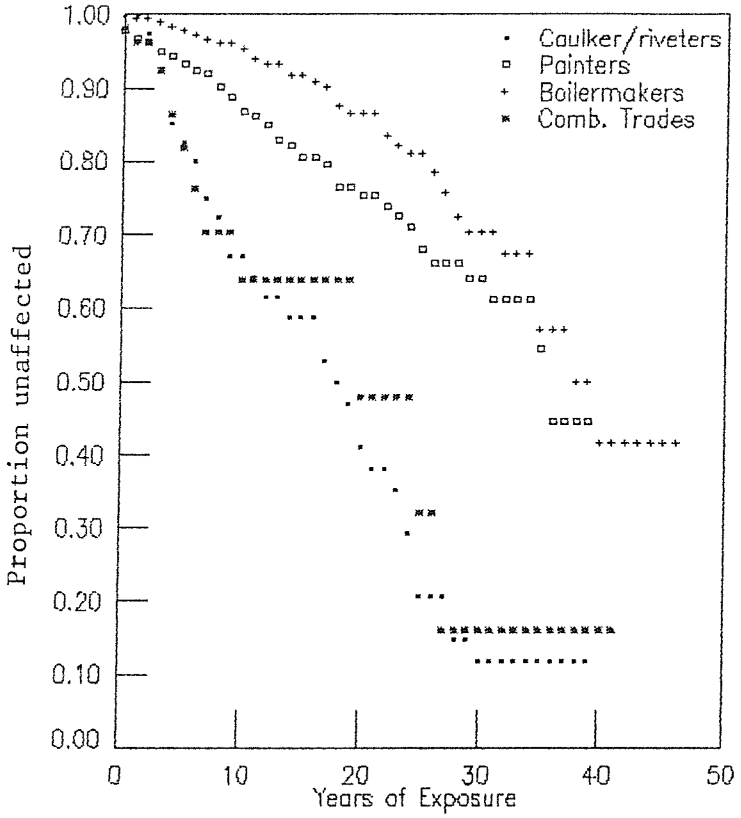


Figure 5.2 Blanching survival functions for four occupational groups

It can be seen that the blanching survival function for the caulker/riveters has a steeper gradient than the functions for the painters and for the boilermakers and shows the greatest final prevalence. This indicates that the regular vibration exposure experienced by caulker/riveters was more severe than for painters or boilermakers. (This was evident from the prevalence data from the questionnaire. However, the survival function shows the rates of *incidence* of VWF in the four groups, and contains more information about the development of the condition in the population than *prevalence* values from a cross-sectional study.)

The survival function for the combined trades follows that for the caulker/riveters very closely. The combined tradesmen performed similar work to the older caulker/riveters and it would appear that the effect of the vibration exposure in this occupation had not changed significantly over a period of approximately 30 years.

Figure 5.2 showed that the rates of development of VWF differed between occupational groups. This is an indication that differences existed between the severities of typical regular exposures to vibration in these groups. These differences may be due to variations between groups in the tools used and in the typical exposure durations.

Figure 5.3 shows a second set of survival functions for the same four occupational groups. Here, however, the proportion surviving is shown as a function of total tool use time (for the 18 tools identified in Table 5.1) in hours, instead of the number of years in the job. It is apparent that the differences in the gradients of the four survival functions have been generally reduced. This is because inter-group differences in regular exposure durations have been taken into account.

The differences between the four survival functions were reduced by replacing the number of years of vibration-exposure by tool use time in hours, a quantity which more accurately portrays the exposure. If the survival variable were to be replaced with a measure of 'dose' which exactly represented the severity of the exposure, then the survival functions for different groups of men would be identical. It is logical that a 'dose' should take account of the vibration magnitude, so the dose definition described in Section 5.2.1 was tested in the survival analysis.

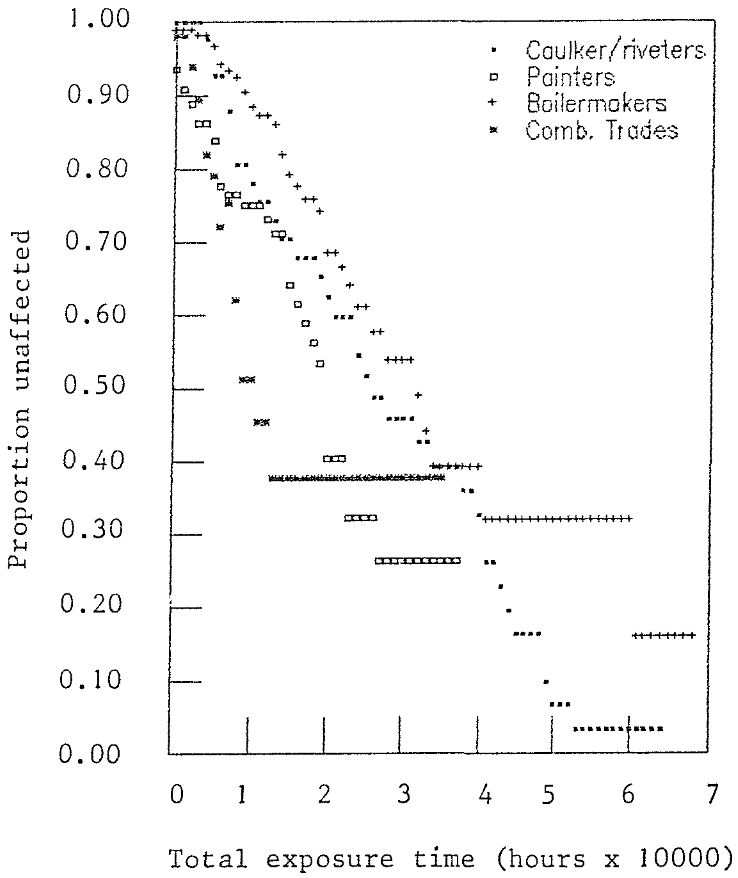


Figure 5.3 *Blanching survival for four occupational groups as a function of total tool exposure time*

Figures 5.4 and 5.5 show the results of repeating the survival analysis using doses with frequency-weighted and unweighted acceleration respectively. In each case, values of 1 and 2 were used for the time-dependency constant *m*.

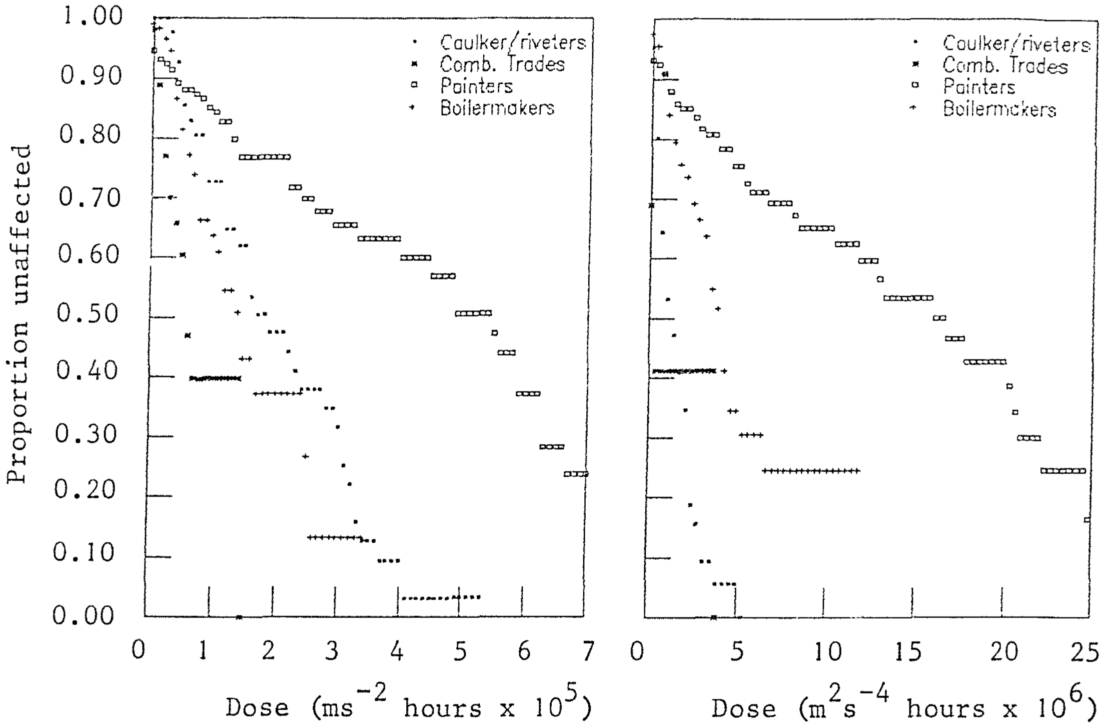


Figure 5.4 Blanching survival for four occupational groups as a function of two vibration doses: (a) $\int a\ dt$; (b) $\int a^2\ dt$ (frequency-weighted acceleration)

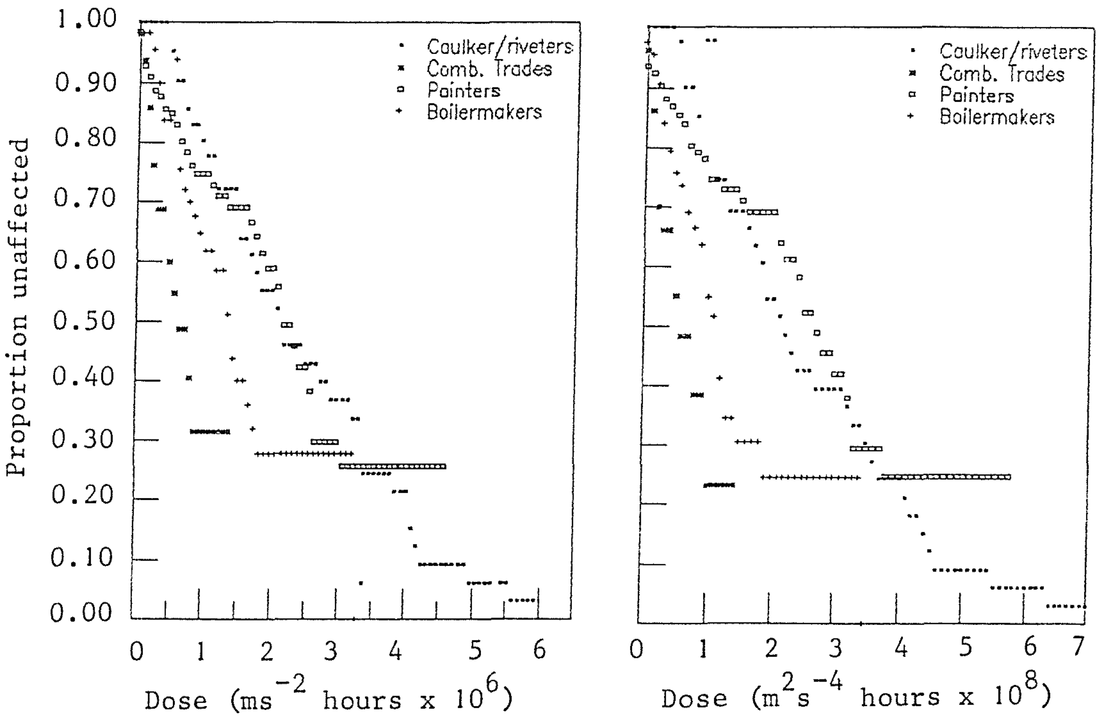


Figure 5.5 Blanching survival for four occupational groups as a function of two vibration doses: (a) $\int a\ dt$; (b) $\int a^2\ dt$ (unweighted acceleration)

The survival curves in Figure 5.4, where frequency-weighted acceleration magnitudes were used to produce the dose values, appear to be more diverse than those in Figure 5.3. The survival curves in Figure 5.5, where unweighted acceleration was used, show less scatter than those in Figure 5.4, but it is not clear whether these doses gave an improved measure of the hazard in different occupational groups compared with the 'time only' dose in Figure 5.3.

5.3.2 Relation of Latency to Exposure Rate

From inspection of the survival functions in Figure 5.2 it can be seen that the concept of a 'mean latent period' for those individuals with VWF has little meaning. As the symptoms could start at any time during an individual's working life, a mean latency value in a cross-sectional study would be dependent on the age distribution in the population at the time of the study. However, the latent period for any percentile of the *exposed* population may be determined directly from the survival function. The 50th percentile latent period (i.e. the time before 50% of exposed persons are affected) was obtained from each of the four survival functions in Figure 5.2:

caulker/riveters	-	19.0 years
combined trades	-	20.9 years
painters	-	36.5 years
boilermakers	-	39.0 years

The 50th percentile latent period for an occupational group may be expected to vary inversely with a suitable measure of the severity of regular vibration exposures in that occupation. Such a measure could take the 'dose' form:

$$\text{dose} \propto \left[\int_0^T a^m \, dt \right]^n$$

where: a is the vibration acceleration magnitude (suitably frequency and/or direction weighted);
T is the duration of regular exposure (e.g. hours per year);
m is a constant defining the relative importance of acceleration and time;
n is a constant defining the linearity of the relationship.

(This definition of 'dose' refers to a *regular* exposure to vibration: T is the average regular exposure time (e.g. daily, weekly, yearly) and not the 'lifetime' total exposure duration used in the 'lifetime dose' considered in Section 5.2.)

Each individual had reported a different combination of tool types and exposure durations. Individual average yearly vibration 'doses' were defined thus:

$$Yearly\ dose = \left[1/Y \sum_{i=1}^{N} (a_i^{m}\ t_i)\right]^{1/n}$$

where: a is the acceleration magnitude for tool i in ms^{-2} r.m.s.;
m and n are the time-dependency and linearity constants;
t_i is the individual's total time in hours using tool i;
N is the number of tools used by the individual;
Y is the number of years for which the individual had been working with vibrating tools.

An average yearly exposure was obtained for each occupational group by taking the median value of this quantity for all individuals.

If the value of the exponent m is zero, the rate of vibration exposure (hours/year) to the power of n will alone represent the severity of the exposure. For greater values of m, this exposure severity is 'acceleration-weighted' by multiplying each individual's total exposure time for a tool by the appropriate power of the measured acceleration magnitude for that tool; these values are then combined into a single dose.

Median yearly doses for the four occupational groups, were produced for m = 0, and for four combinations of m and n with frequency-weighted acceleration ($a_{h,w}$) and unweighted acceleration (a_{lin}). These values are shown in Table 5.17.

Table 5.17 *Median yearly vibration exposures for four occupational groups*

Dose	Unit	Caulker/ riveters	Combined trades	Painters	Boiler- makers
$m = 0$, $n = 1$	hours/year	1452	887	253	508
$m = 1$, $n = 1$, ($a_{h,w}$)	ms^{-2} h/year	10070	4104	4803	1962
$m = 2$, $n = 1$, ($a_{h,w}$)	m^2s^{-4} h/year	79603	24598	103409	10042
$m = 2$, $n = ½$, ($a_{h,w}$)	ms^{-2} $h^{½}$/year	47	55	103	22
$m = 1$, $n = 1$, (a_{lin})	ms^{-2} h/year	116714	38491	27271	16951
$m = 2$, $n = 1$, (a_{lin})	m^2s^{-4} h/year	12220757	3572568	3212161	996293
$m = 2$, $n = ½$, (a_{lin})	ms^{-2} $h^{½}$/year	590	648	536	220

The relationships between the median yearly doses for the four occupational groups and their latent periods (50th percentile) were investigated by calculating nonparametric correlation coefficients (Kendall's tau). These values are shown in Table 5.18.

An inverse relationship may be expected between measures of latency and the yearly dose in different occupational groups. Accordingly, the Kendall correlation coefficients in Table 5.18 are all negative (except for one zero value).

Table 5.18 Nonparametric correlation coefficients with one-tailed significance levels between 50th percentile latent period and median yearly vibration dose for four occupational groups

Dose	Kendall's τ	Significance (p)
$m = 0$, $n = 1$	-0.67	0.087
$m = 1$, $n = 1$, $a_{h,w}$	-0.67	0.087
$m = 2$, $n = 1$, $a_{h,w}$	-0.33	0.248
$m = 2$, $n = ½$, $a_{h,w}$	0.00	0.500
$m = 1$, $n = 1$, a_{lin}	-1.00	0.021
$m = 2$, $n = 1$, a_{lin}	-1.00	0.021
$m = 2$, $n = ½$, a_{lin}	-0.67	0.087

The yearly doses with unweighted acceleration gave the closest relationships: for $m = 1$, $n = 1$ and $m = 2$, $n = 1$ the coefficients were equal to −1. This indicates that the ranks of the four latent periods were exactly the inverse of the ranks of the yearly doses. The third dose with unweighted acceleration ($m = 2$, $n = ½$) gave the same correlation coefficient (−0.67) as the dose with no acceleration component.

With the yearly doses which used frequency-weighted acceleration values, the greatest negative coefficient was −0.67 ($m = 1$, $n = 1$). Poorer correlations were obtained with the other two dose definitions: for the dose with $m = 2$, $n = ½$ the correlation coefficient was zero. This means that no relationship existed between the ranks of the yearly doses and the latent periods (i.e. $p = 0.50$).

5.4 AN ALTERNATIVE DOSE-EFFECT MODEL

In this chapter, an investigation of the dose model (dose = $(\int a^m \, dt)^n$) has been investigated as a possible means of quantifying the severity of exposure to hand-transmitted vibration.

The logistic regression analyses in Section 5.2 linked dose with the probabilities of having a blanching score in excess of 0, 8 or 20. With $m = 0$ (i.e. dose based on exposure time only), highly significant relationships were shown. The 'goodness of fit' of the model was degraded when frequency-weighted acceleration magnitudes were included in the dose ($m = 1, 2, 4$). With unweighted acceleration magnitudes, an improved fit was obtained in some, but not all, calculations; however, no clear effect of varying m was found. When exposure time and acceleration were examined as separate variables, the improvement of the fit of the model due to the inclusion of the acceleration term was small compared with that for the exposure time term.

The inclusion of frequency-weighted vibration magnitude in the models describing the relationship between median (50th percentile) latent period and regular exposure duration for four occupational groups did not improve the fit of the data: the correlation coefficient was actually reduced. With unweighted magnitudes, small increases in correlation were obtained with some (but not all) values of m and n. From this evidence, vibration acceleration appears to be less useful than exposure time as a predictor of the group latent periods, and therefore as an indicator of the severity of the vibration hazards.

A possible explanation is that the variability of the vibration characteristics of the tools in normal use is so great that the vibration magnitudes obtained in the laboratory measurements were not representative; the use of a single value to represent the vibration severity of a tool (which may perform many different tasks in many different hands) may not be a realistic proposition. However, the data obtained in this study are more comprehensive than most. Even the inclusion of approximate acceleration magnitudes in a 'dose' model of the form $(\Sigma a_i^m t_i)^n$ might be expected to improve the fit by placing more weight on the exposure times for tools with the greatest vibration magnitudes.

Another possibility is that the probability of development of VWF is not directly related to vibration magnitude. There appear to be some tools with relatively low vibration severities which are not associated with vibration injury (such as many of the tools used by the shipwrights group in this study). It is possible that a 'threshold' effect exists, whereby it is primarily the exposure time which determines the risk of injury, if the vibration is of sufficient magnitude for VWF to occur. This leads to the following hypotheses:

1. The rate of development of blanching symptoms is related to the cumulative vibration exposure time and is independent of vibration magnitude, provided the magnitude of vibration is greater than some 'threshold' value.

2. Vibration exposures at magnitudes below the threshold value do not contribute to the development of VWF.

To investigate these hypotheses, further survival analyses were carried out.

Using the total vibration exposure times, in hours, for use of the 18 tool types identified in Table 5.1, VWF survival analysis for four occupational groups gave the results shown in Figure 5.3. The survival functions for the caulker/riveters, painters and boilermakers (although less scattered than those in Figure 5.2) have different gradients. The function for the combined trades has a steeper slope than the other three. The reason for this is not clear, as this group and the caulker/riveters have almost identical survival rates when expressed as functions of the number of years of exposure. It is possible that an additional and unidentified source of vibration exposure existed for this group. It may also be that because this group had a lower average age than the other three groups, their recollection of their tool use in the early years of exposure was generally better, resulting in lower doses and therefore a steeper survival gradient for the first 10 years of exposure.

The Comparison Statistic, D

When survival analysis of two or more subgroups is performed by the *SPSS* routine SURVIVAL, the comparison statistic, *D*, is computed. *D* is asymptotically distributed as chi-square with $(G - 1)$ degrees of freedom, where *G* is the number of subgroups, under the null hypothesis that the subgroups are samples from the same survival distribution. The larger the value of *D*, the greater the probability that the subgroups are from different survival distributions. The difference between any two survival functions may also be tested by a 'pairwise' comparison test which gives a value of *D* with one degree-of-freedom.

The overall comparison statistic for the analysis for Figure 5.3 had a value of $D_3 = 27.88$ ($p < 0.0001$), indicating that the four groups were not part of the same survival distribution.

If the 'vibration threshold' hypotheses were true, it might be expected that some, but not all, of the 18 tools would contribute to the development of VWF. By defining different 'threshold magnitudes' and selecting only tools with vibration magnitudes greater than this, it was possible to produce alternative groups of tools for inclusion in the exposure time survival analysis.

Four selection criteria were investigated. These were deliberately chosen so as to give four different selections of tools:

1. Weighted acceleration $a_{h,w} \geq 5.0$ ms^{-2} r.m.s.
2. Weighted acceleration $a_{h,w} \geq 3.0$ ms^{-2} r.m.s.
3. Unweighted acceleration $a_{lin} \geq 100$ ms^{-2} r.m.s.
4. Unweighted acceleration $a_{lin} \geq 50$ ms^{-2} r.m.s.

The tools selected by these criteria are listed in Table 5.19. The survival analysis on total exposure time was repeated for each selection of tools. The overall comparison statistic and significance level for the four occupational groups in each analysis is also included in this Table.

Table 5.19 *Tools selected by different vibration magnitude criteria and overall comparison statistic for survival analysis of four groups for each selection*

Pneumatic Tool	Minimum Vibration Magnitude (ms^{-2} r.m.s.)				
	All tools	$a_{h,w}$ ≥5	$a_{h,w}$ ≥3	a_{lin} ≥100	a_{lin} ≥50
Chipping Hammer (steel)	✓	✓	✓	✓	✓
Riveting Hammer	✓	✓	✓		✓
Vertical Grinder	✓		✓		
Angle Grinder	✓				
End Grinder	✓				
Collet Grinder	✓				✓
Power Wire Brush	✓				
Disc Sander	✓	✓	✓		
Pistol Drill	✓		✓		
Morse Drill	✓				
Nobbler	✓	✓	✓	✓	✓
Needle Scaler	✓	✓	✓		✓
Pistol Needle Scaler	✓	✓	✓		✓
Chisel Scaler	✓	✓	✓		✓
Chipping Hammer (cement)	✓	✓	✓		✓
Impact Wrench	✓		✓		
Power Hacksaw	✓	✓	✓		✓
Tube Expander	✓				
Statistic *D*	27.88	15.47	17.19	21.89	13.29
Significance	<0.0001	0.0015	0.0006	0.0001	0.0040

The smallest value for the overall comparison statistic in Table 5.19 was $D_3 = 13.29$ (3 degrees-of-freedom, $p = 0.004$). The survival variable in this case was total exposure time for tools with measured unweighted vibration magnitudes of 50 ms^{-2} r.m.s. or greater. The survival functions for this analysis are shown in Figure 5.6. The curves for the caulker/riveters and the painters are similar over much of the exposure time range, while the boilermakers' survival function has a steeper gradient.

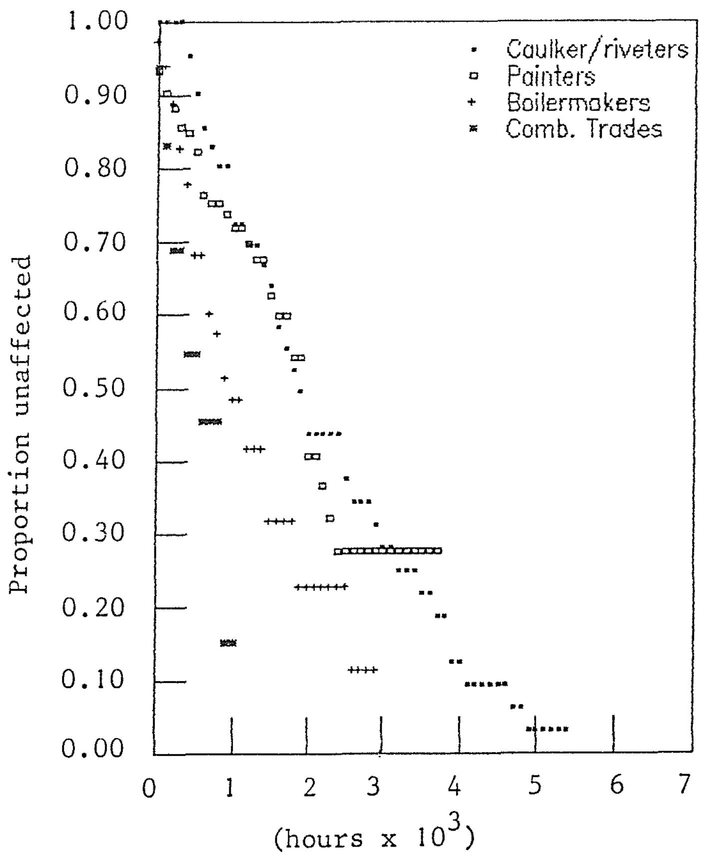


Figure 5.6 Blanching survival functions for four occupational groups, computed using exposure times for tools with $a_{1,n} \geq 50$ ms^{-2} r.m.s.

The comparison statistics for the survival functions in Figure 5.6 were as follows:

Caulker/riveters - painters:	$D_1 =\ \ 3.48\ (p = 0.062)$
Caulker/riveters - boilermakers:	$D_1 = 12.34\ (p = 0.0004)$
Caulker/riveters - comb. trades:	$D_1 = 14.96\ (p = 0.0001)$
Painters - boilermakers:	$D_1 =\ \ 0.27\ (p = 0.605)$
Painters - combined trades:	$D_1 =\ \ 3.21\ (p = 0.073)$
Boilermakers - combined trades:	$D_1 =\ \ 5.77\ (p = 0.016)$
Overall:	$D_3 = 13.29\ (p = 0.004)$

These values indicate that significant differences ($p < 0.05$) existed between the survival distributions for the caulker/riveters and the boilermakers, for the caulker/riveters and the combined trades and for the boilermakers and the combined trades. No differences (at this level of significance) were found between the survival distributions for the painters and any of the other three groups.

The tools used by the boilermakers, caulker/riveters and combined trades were generally of similar types (e.g. chipping hammers, grinders, drilling machines). If the criterion for the selection of tools included in the exposure time total (i.e. unweighted magnitude, $a_{lin} \geqslant 50$ ms^{-2} r.m.s.) was valid, similar survival functions would be expected for these three groups. It follows that closer agreement between the survival functions might be achieved by changing the selection of tools included.

Many of the boilermakers had used tube expanders for a considerable proportion of their work time (mean value 107 hours/year, see Table 4.7). It was not possible to make measurements of vibration on a tube expander, so the magnitude for this tool in Table 5.1 was estimated from measurements made on Morse drilling machines; these magnitudes were low, so tube expanders were not included in this survival analysis. On the assumption that their vibration severity had been underestimated, the analysis was repeated using total exposure time for the previous selection of tools (those with unweighted vibration, $a_{lin} \geqslant 50$ ms^{-2} r.m.s.) plus tube expanders. The resulting survival functions are shown in Figure 5.7.

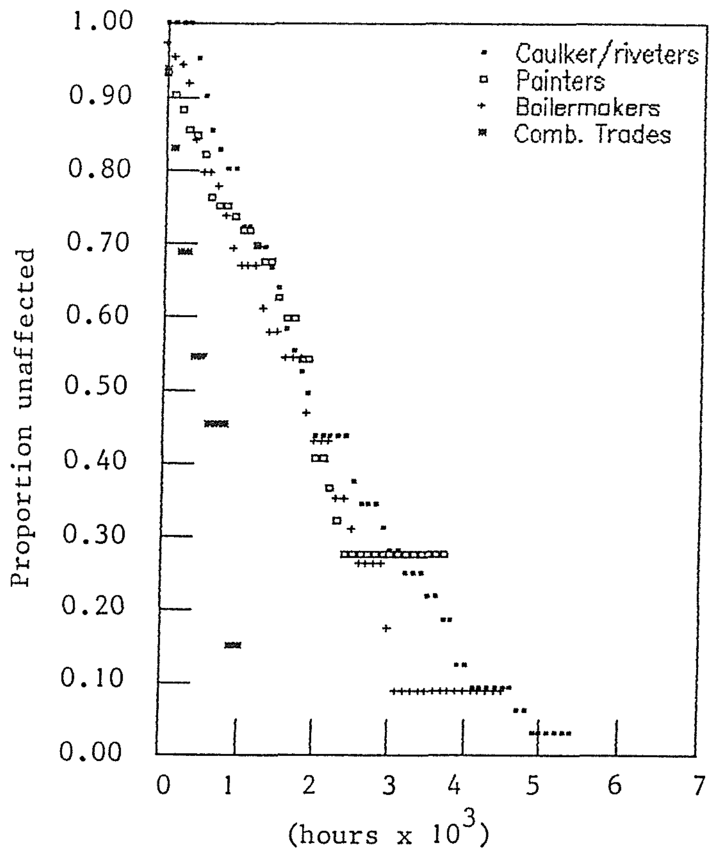


Figure 5.7 *Blanching survival functions for four occupational groups, computed using exposure times for tools with* $a_{lin} \geqslant 50$ *ms*$^{-2}$ *r.m.s. plus tube expanders*

Figure 5.7 shows that the survival function for the boilermakers was almost coincident with those for the caulker/riveters and the painters, following the inclusion of exposure time for tube expanders in the analysis.

The group comparison statistics for the survival functions in Figure 5.7 are shown below:

Caulker/riveters - painters:	D_1 = 3.48 (p = 0.062)
Caulker/riveters - boilermakers:	D_1 = 2.63 (p = 0.105)
Caulker/riveters - comb. trades:	D_1 = 14.96 (p = 0.0001)
Painters - boilermakers:	D_1 = 2.47 (p = 0.116)
Painters - combined trades:	D_1 = 3.21 (p = 0.073)
Boilermakers - combined trades:	D_1 = 11.56 (p = 0.0007)
Overall:	D_3 = 14.69 (p = 0.002)

Although the value of the overall statistic D_3 was slightly increased (14.69 compared with 13.29), the pairwise comparison statistics indicate that differences between the survival distributions for the caulker/riveters, painters and boilermakers were now small. Only the combined trades group had a survival function which was significantly different ($p < 0.05$) from those of the other three groups.

It appears that by selecting the tools which contribute to the dose based on total exposure time, the differences between the survival distributions for different occupational groups can be reduced. This supports the 'threshold' hypotheses. Identical survival distributions would not necessarily be expected for several reasons. Because the threshold vibration magnitude would be likely to vary between individuals, the tools contributing to the hazard might also vary between individuals. Also, because the vibration characteristics of many processes and tools are variable, some tools are likely to exceed the 'threshold' for an unknown proportion of the operating time, resulting in a complex time dependence.

While the 'threshold' concept is not confirmed by these findings, it has been shown to be a possibility in the absence of a clear effect of acceleration magnitude in dose models with 'conventional' time-dependencies (i.e. as defined in Section 5.2.1 and implied in current standards).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

The research described in this thesis has been concerned with the acquisition of epidemiological and vibration exposure data in a dockyard and the subsequent use of this information to investigate the relationships between exposure to hand-transmitted vibration and the development of vibration-induced white finger.

Measurements of the vibration characteristics of pneumatic tools used in the dockyard and exposure time information obtained from the tool users allowed models of vibration 'dose' to be constructed and fitted to the epidemiological data.

This chapter summarises the conclusions from the various parts of the research described in the thesis.

6.2 REVIEW OF LITERATURE

Tool vibration measurements reported in the literature were presented, where possible, in the form of octave band acceleration magnitudes, for ease of comparison. Large variations between the magnitudes obtained in different studies were apparent. In some cases, this was believed to be due to low-frequency measurement artifacts (e.g. d.c. shifts). However, data in the literature also showed that variability in magnitudes for similar tools can be highly variable due to differences in operating methods or techniques (e.g. European Committee of Manufacturers of Compressors, Vacuum Pumps and Pneumatic Tools, 1978, 1980; Scory *et al.*, 1990). This indicated the necessity for controlling the tool operating conditions when making repeatable vibration measurements.

Reports of VWF in industry have usually quoted the prevalence or the mean latent period for the condition. Both of these quantities are dependent on the average duration of exposure in the studied population. This source of bias is illustrated by the fact that prevalences ranging from zero to 100% have been reported for users of one type of pneumatic tool (riveting hammers). However, relationships between VWF prevalence and latent period and vibration magnitude have been suggested (e.g. Brammer, 1982b) and the dose-effect relationship suggested in the current standards ISO 5349 (1986) and BS 6842 (1987) is based on data of this kind.

Some other aspects of these standards are unsatisfactory. The frequency weighting is based on subjective and biodynamic findings, and not on epidemiological data. The time-dependency used for the assessment of daily vibration exposures (i.e. the 'equal energy' relationship) has its origin in the convenience of this method for analogue instrumentation with root-mean-square averaging. Several authors, writing since the publication of ISO 5349, have suggested that this method of evaluation underestimates the hazard for impulsive vibration. This may indicate a need to revise the frequency weighting, frequency range or time-dependency (averaging method) specified for vibration measurements.

In some studies (e.g. Miyashita *et al.*, 1983; Tominaga, 1982) relationships have been demonstrated between VWF and vibration exposure represented by total tool operating time in hours. This is an attractive approach because only one time-dependency is involved.

6.3 VIBRATION MEASUREMENTS

Methods for mounting accelerometers on vibrating tools were evaluated in the laboratory. The use of a block and hose clip for triaxially mounting three accelerometers at the hand position was found to be convenient in most situations. The frequency response of the mount was shown to be flat at frequencies below 1 kHz and it was demonstrated that the mass of the assembly did not significantly affect tool vibration.

A ring-shaped accelerometer mount, worn on the operator's finger, was developed for use on tools such as the chisel of a chipping hammer, where the hose clip method could not be used satisfactorily. A laser Doppler vibrometer was also evaluated for this application but was found to be time-consuming and inconvenient.

The vibration characteristics of sixteen pneumatic tools used in Devonport dockyard were measured. Repeated measurements were made with each tool in controlled but realistic conditions in the laboratory. These operating conditions were defined for each tool to achieve good repeatability; the coefficient of variation obtained for repeated measurements of frequency-weighted and unweighted acceleration on most tools was less than 0.25.

Spectral analysis was performed on all vibration signals. This was done to ensure that no data were affected by the low-frequency measurement artifact reported in the literature. Octave band acceleration magnitudes were also computed.

6.4 FINDINGS OF QUESTIONNAIRE SURVEY

Of 1242 individuals taking part in the questionnaire study, 921 were retained after a selection procedure to remove any subject with a possible non-vibration cause of relevant symptoms (primary Raynaud's disease, relevant injury or disease, etc.). The effect of this selection procedure on the age distribution was small and it was assumed that any relevant symptoms were related to vibration exposure in the remaining subjects.

Intermittent blanching of fingers was reported by 19.0% of selected subjects, numbness by 28.3% and tingling by 35.2%. Occasional blueness of the affected fingers was reported by 2.4%.

The prevalences of VWF in fifteen occupational groups ranged from zero to 81%. The prevalences for the four groups chosen for further study were:

Caulker/riveters:	81.0%
Combined trades:	32.7%
Painters:	15.8%
Boilermakers:	20.7%

(The large prevalence value for caulker/riveters is influenced by the fact that the average age, and therefore the total exposure duration, for this group was greater than for the other three groups.)

Attacks of blanching were reported to occur mainly in cold conditions, usually accompanied by numbness and often followed by tingling or discomfort on recovery. No evidence was found to support the suggestion that the neurological symptoms are an early indicator of VWF (Taylor and Pelmear, 1975) since most subjects with VWF recalled that numbness and tingling had started at about the same time as blanching, or later. This supports the more recent theory that the vascular and neurological components of the 'vibration syndrome' develop separately (Brammer *et al.*, 1986, 1987; Gemne *et al.*, 1987). Tingling of the fingers and hands was, however, experienced as a temporary phenomenon by many otherwise unaffected persons (mostly painters) immediately after using vibrating tools.

The effects of alcohol and tobacco consumption on the prevalences of blanching, numbness and tingling were investigated. No significant relationship was found between current drinking or smoking habits and any symptoms.

The questionnaire survey also identified the power tools which were in most common use by the occupational groups with the greatest prevalences of VWF. These are shown in Table 4.7 and included chipping and riveting hammers, various types of grinders and drilling machines, power hacksaws, impact wrenches and various types of scaling tool and power wire brushes.

6.5 DOSE-EFFECT RELATIONSHIPS

The severity of VWF in individuals was assessed using a scoring system. The scale of values given by this method does not include those who are affected but have not yet shown symptoms. The use of linear regression to model relationships between blanching score and various measures of vibration exposure was not, therefore, appropriate. These relationships were investigated using nonparametric statistics and logistic regression, in which the odds for a score greater than a chosen value were regressed on measures of dose.

Nonparametric correlation coefficients between blanching score and total tool operating time (hours) for different tools were used to identify the tools associated with VWF. The most significant correlations were obtained for chipping hammers, various grinders, drilling machines, scalers etc. However, the exposure durations for some tools were found to co-vary with those of others. By computing partial correlation coefficients, it was shown that the apparent relationships between blanching and operating time for some tools were due to the use of other tools.

Logistic regression analysis was used to investigate the frequency-dependency and the time-dependency of VWF in models of lifetime dose. The probability of blanching (i.e. score > 0) and the probabilities of exceeding higher blanching scores (8 and 20) were investigated as functions of 'dose' for all 921 selected subjects. When dose was defined as the total (lifetime) operating time with the tools listed in Table 5.1, a highly significant reduction in the deviance of the model (i.e. improvement of fit) was obtained. However, when frequency-weighted root-mean-square acceleration magnitudes (obtained using the frequency weighting in the current standards) were included in the dose, with first, second and fourth power time-dependencies, this reduction in deviance, while still highly significant, was smaller for all dose models. Using unweighted r.m.s. acceleration magnitudes, small improvements in fit were obtained for some, but not all, of these time-dependencies.

It was concluded that the standard frequency weighting is inadequate. The degradation in the fit of the dose-effect models with weighted acceleration indicates that the frequencies at the lower part of the range 6.3 to 1250 Hz, which are given the most weight but may not be important for vascular injuries, may have added 'noise' to the dose. The improved fit with unweighted acceleration indicates that frequencies in the upper part of the range may be of more relative importance than is suggested by the standards. Frequencies above 1250 Hz may also be important for evaluation of vibration with respect to vascular injuries.

The effect of the (unweighted) acceleration term in every dose model investigated was small compared with the effect of exposure time. No clear effect of varying the time-dependency exponent was found.

By computing survival functions for the four occupational groups identified above, the rates of development of VWF were demonstrated. The 50th percentile latent period (survival time for the 50th percentile of the exposed population) was obtained from each survival function. These values are corrected for changing population size and are a more appropriate measure than the prevalence of the hazard, or the *mean* latent period, in each group:

Caulker/riveters:	19.0 years
Combined trades:	20.9 years
Painters:	36.5 years
Boilermakers:	39.0 years

Using the total tool operating time (in hours) as the survival variable, in place of the number of years since the start of exposure, the differences between the gradients of the survival functions for the four groups were reduced. Attempts to further reduce these differences by using different measures of dose (time-dependency exponent $m = 1, 2$) as survival variables again failed to reveal an optimum value for m. If the form of the dose model assumed here is valid, it would be expected that a value of m could be found which gave a significantly better prediction of hazard than when m was equal to zero or another value.

It is possible that the rate of development of VWF is not directly related to vibration magnitude, but is determined by cumulative exposure time when the vibration is of sufficient severity. This would explain the apparent absence of a 'best fit' time-dependency. In an attempt to test this 'threshold' hypothesis, survival analyses were performed on exposure time for different selections of tools. Reduced differences between the survival functions for the four groups were obtained using this approach. This supports the threshold possibility, but does not confirm it. The threshold would be likely to vary between individuals, and would result in an apparently complex time-dependency, particularly for users of many different tools such as those in the present study.

6.6 RECOMMENDATIONS

The body of epidemiological data obtained in this study in Devonport dockyard is more comprehensive than those from most other studies of VWF, and may be further exploited in future investigations.

Longitudinal studies of VWF, in which the same population is studied on several occasions over a period of time are rare. The size of the studied population at Devonport may be sufficient to allow the condition of two subgroups of suitable subjects (with and without symptoms) to be studied over several years while vibration exposure continues. This may improve understanding of the development of VWF because the accuracy of the data obtained for vibration exposures, time of onset of any symptoms, etc. should be better than that for a cross-sectional study. The information obtained in the present study may also provide a rare opportunity to monitor the condition of persons with VWF symptoms after they cease to be exposed to vibration. It is recommended that three appropriate groups of subjects should be identified and studied annually: persons with VWF who continue to be exposed to vibration, persons with no symptoms who continue to be exposed and persons with VWF who are no longer exposed.

The vibration magnitudes used in all dose models in this study were obtained from repeated measurements of a single laboratory-based operation of each tool. It is recommended that the variability of the vibration characteristics of tools in real dockyard work should be investigated. This work should involve measurements made over long periods (preferably entire working days) and should include different tool operators. It may be necessary to develop a portable recording apparatus (i.e. a 'dosemeter') for this purpose. This equipment would require a facility to identify low frequency artifacts should they occur.

Some recent research, including the present study, has indicated that the frequency range normally used for measurements of hand-transmitted vibration (6.3 - 1250 Hz) and/or the averaging method (root-mean-square) may be insufficient to determine the hazard with respect to VWF. It is recommended that in further measurements made on pneumatic tools used at Devonport, a wider measurement bandwidth should be used. A bandwidth of 5 kHz has been suggested (National Institute for Occupational Safety and Health, 1989). This might require further careful consideration of the frequency response of the transducer mounting. Analysis of these vibration data using an alternative time-dependency (e.g. root-mean-quad averaging or vibration dose values (British Standards Institution, 1987b)) to give more weight to the peak acceleration magnitudes should also be considered. With the epidemiological data from the present study these vibration data may be used to further investigate the vibration frequency-dependency and the possibility of an optimum time-dependency in the dose model. Failure to obtain a value for the exponent m with improved vibration data would strengthen the evidence for the 'threshold' model, which should also be investigated further.

APPENDIX A

QUESTIONNAIRE USED IN SURVEY

Medical In Confidence

[Q101] (D)	Date: [ ][ ] 19[ ]		Serial Number SN [ ]
[Q102] (M)			
[Q103] (Y)			

ASSESSMENT OF THE EFFECTS OF HAND-ARM VIBRATION IN DEVONPORT DOCKYARD

	Name	....
[Q104]	Pay No	....
[Q105]	Grade	....
[Q106]	Centre	....

[Q107] (D) Date of birth [ ][ ] 19[ ]

[Q108] (M)

[Q109] (Y)

[Q110] Gender

M	F
[ ]	[ ]
1	2

[Q111] Ethnic Group

- Caucasian	[ ]	1
- Asian	[ ]	2
- Negroid	[ ]	3
- Mongoloid	[ ]	4

SOCIAL HISTORY

Smoking History

[Q201] Do you smoke or have you ever smoked? No 1 / Yes 2

If yes:

[Q202] How much did/do you smoke?

Cigarettes per day (including rolling tobacco) under 20	20 or more	cigars	pipe
1	2	3	4

[Q203] When did you start smoking regularly? 19

[Q204] Do you still smoke? No 1 / Yes 2

If no:

[Q205] When did you give up smoking? 19

Alcohol Consumption

[Q206] Do you drink alcohol? No 1 / Yes 2

If yes:

[Q207] do you drink regularly (at least once a week)? No 1 / Yes 2

If yes:

[Q208] units per week

(1 unit = 1/2 pint beer
= single spirit
= glass wine)

MEDICAL HISTORY

Present Medical History

[Q301] Are you under medical supervision at present?

No	Yes
1	2

If yes:

What is the condition being treated?

[Q302] Are you taking any tablets at the present time?

No	Yes
1	2

If yes:

a) What is the condition being treated?

b) What tablets are you taking?

[Q303) Have you had any serious illness or injury requiring hospital attendance as an Outpatient?

No	Yes
1	2

If yes:

What clinic did you attend and when?

[Q304] Any aspect of medical history considered relevant?

No	Yes
1	2

Injury to Fingers, Hand, Arm, Shoulders or Neck

Have you ever injured any of the following?

Nature and location of injury	Date of injury	Treatment received	Specify any after effects
a) Fingers			
b) Hand			
c) Arm			
d) Shoulders			
e) Neck			

[Q401] Any of the above? No 1 / Yes 2

[Q402] Any of above considered relevant? No 1 / Yes 2

Related Medical Conditions

Have you ever suffered from any of the following (give details)?	No	Yes	Date of first occurrence Month	Year	Still receiving treatment No	Yes	Details (after effects, location)
a) Heart or circulation trouble?							
eg 1 Coronary thrombosis							
2 Angina							
3 Pain in calves of legs when walking							
4 High blood pressure							
5 Cold injury (eg frostbite)							
6 Other ( )							
b) Neurological disease (that is problems with nervous system)							
eg 1 Polio							
2 Stroke							
3 Carpal Tunnel Syndrome							
4 Other ( )							
c) Connective Tissue Disease							
eg 1 Dupuytrens Contracture							
2 Arthritis							
3 Other ( )							
d) Degenerative Disease							
eg 1 Arthritis of hands, arms and neck							
2 Other ( )							
e) Endocrine Disease							
eg 1 Diabetes							
2 Other ( )							

[Q501] Any of the above? No [ ] 1 Yes [ ] 2

[Q502] Any of above considered relevant? No [ ] 1 Yes [ ] 2

[Q601] Have cold hands been more of a problem for you than for other people (those not using vibrating hand tools)?

No	Yes	Uncertain
1	2	3

[Q602] Have cold feet been more of a problem for you than for other people?

No	Yes	Uncertain
1	2	3

[Q603] Have you had chilblains in the last ten years?

No	Yes
1	2

[Q604] Do any members of your family experience white fingers or Raynaud's phenomenon?

(Answer 'yes' only for blood relatives, ie not wife/husband).

No	Yes	Uncertain
1	2	3

If yes:

[Q605] Do they use vibrating tools?

No	Yes
1	2

[Q606] May I see your hands?

No Significant Presence	Possibly Significant Presence
1	2

BLANCHING

	No	Yes
[Q701] Do any of your fingers ever go white?		
	1	2

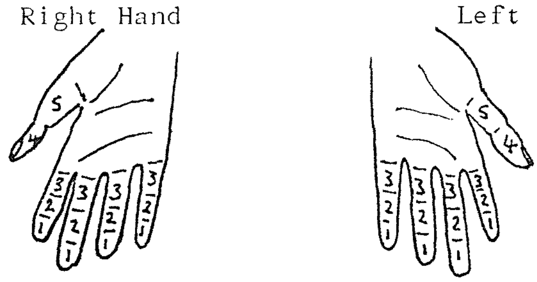
If no:

Go to next page.

		Month	Year
[Q702](M) [Q703](Y)	When did you first notice this?		
[Q724](M) [Q725](Y)	When did you last notice this?		
		1	2

Please indicate those areas on your fingers that go white.

Right Hand Left Hand



[Q704-Q715] (Across page)

Right Hand	Th	1	2	3	4	Total

Left Hand	4	3	2	1	Th	Total

(Shade in parts of fingers affected and enter score for each finger)

	Minutes
[Q716] What is the longest period your fingers have appeared white?	

Are your fingers made to go white:

		No	Yes
[Q717]	by cold conditions		
[Q718]	by handling cold objects		
[Q719]	when feeling the vibration from vibrating tools		
		1	2

		No	Yes
[Q720]	Do attacks occur only in cold conditions?		
		1	2

	0	1-10	11-30	31-100	>100
[Q726] How many attacks did you have last winter?					
[Q727] How many attacks did you have last summer?					
	0	1	2	3	4

		Summer	Winter	Both
[Q721]	Do the attacks occur in the Summer, Winter or both?			
		1	2	3

		No	Yes
[Q722]	Does the condition interfere with any leisure activities?		
		1	2

Specify which:

		No	Yes
[Q723]	Does the condition interfere with any work activities?		
		1	2

Specify which:

BLUENESS

[Q801] Do any of your fingers ever go blue?

No	Yes
1	2

If no:

Go to next page.

[Q802](M) [Q803](Y) When did you first notice this?

Month	Year
	19

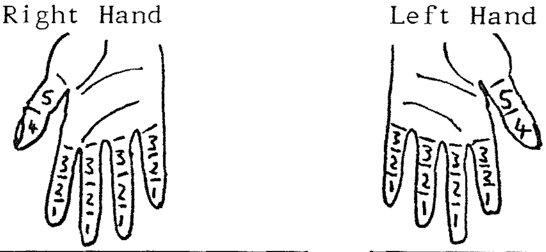
[Q804] For those with blanching:

Was this before or after they first went white?

Before	After	Same Time
1	2	3

Please indicate those areas on your fingers that go blue

Right Hand   Left Hand



[Q805-Q816] (across page)

Right Hand

Th	1	2	3	4	Total

Left Hand

4	3	2	1	Th	Total

(Shade in parts of fingers affected and enter score for each finger).

[Q817] What is the longest period your hands have appeared blue? Minutes [ ]

For those with blanching:

Do your fingers go blue:

		No	Yes
[Q818]	only before they go white?		
[Q819]	only after they go white?		
[Q820]	without going white?		
		1	2

[Q821] Does blueness only occur in cold conditions?

No	Yes
1	2

[Q822] Does blueness occur in the Summer, Winter or both?

Summer	Winter	Both
1	2	3

NUMBNESS

[Q901] Do you ever get numbness (that is, loss of feeling) in the fingers? — No 1 / Yes 2

If no:

Go to next page.

[Q902] Does numbness occur only at night? — No 1 / Yes 2

If yes:

Go to next page.

[Q903] Does numbness occur immediately after using vibrating tools? — No 1 / Yes 2

[Q904] *For those with blanching:*

Does numbness occur together with whitening of the fingers? — No 1 / Yes 2

[Q905] Does numbness occur at other times? — No 1 / Yes 2

(ie *other than* at night, immediately after using vibrating tools *and without* whitening of the fingers)

If yes:

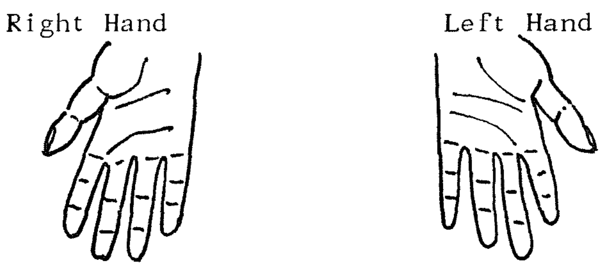
[Q906] (M) [Q907] (Y) When did you first notice this? — Month 1 / Year 2

[Q908] *For those with blanching:*

Was this before or after they first went white? — Before 1 / After 2 / Same Time 3

[Q909] Does numbness occur *only* in cold conditions? — No 1 / Yes 2

Please indicate those areas on your fingers that are affected by numbness.



[Q910-Q919] (across page)

Right Hand	Th	1	2	3	4		4	3	2	1	Th	Left Hand

(Shade in parts of fingers affected and enter 0 or 1 in appropriate boxes)

TINGLING

[Q1001] Do you ever get tingling in the fingers?

No	Yes
1	2

If no:

Go to next page.

[Q1002] Does tingling occur only at night?

No	Yes
1	2

If yes:
Go to next page.

[Q1003] Does tingling occur immediately after using vibrating tools?

No	Yes
1	2

[Q1004] For those with blanching:

Does tingling occur together with whitening of the fingers?

No	Yes
1	2

[Q1005] Does tingling occur at other times?

No	Yes
1	2

(ie other than at night, immediately after using vibration tools and without whitening of the fingers)

If yes:

[Q1006] (M)
[Q1007] (Y) When did you first notice this?

Month	Year
1	2

[Q1008] For those with blanching:

Was this before or after they first went white?

Before	After	Same Time
1	2	3

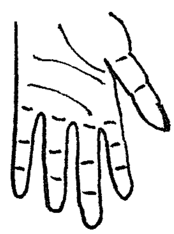
[Q1009] Does tingling occur only in cold conditions?

No	Yes
1	2

Please indicate those areas on your fingers that are affected by tingling.

Right Hand

Left Hand



[Q1010-Q1019] (across page)

Right Hand

Th	1	2	3	4

4	3	2	1	Th

Left Hand

(Shade in parts of fingers affected and enter 0 or 1 in appropriate boxes)

OTHER SIGNS

[Q1101] Do you have problems with your grip?

No	Yes
1	2

If yes give details:

[Q1102] Do you have any other problems with your fingers or hands?

No	Yes
1	2

If yes:

Sign	Location	Other Details

VIBRATION EXPOSURE

Where have you worked with vibrating tools since leaving school?

Employer and Trade	Starting Date	Finishing Date

		Month	Year
[Q1201] (M)	When did you first start working with		19
[Q1202] (Y)	vibrating tools?	1	2

Have you in the course of your work, used any of the following tools?
(Please include tools used in any previous jobs).

Caulking hammers	☐	Grinders	☐
Scalers/nobblers	☐	Sanders	☐
Riveting hammers/holderons	☐	Nailers/staplers	☐
Drilling machines	☐	Saws	☐
Impact wrenches	☐	Nibblers	☐

Have you ever used any other type of pneumatic or vibrating tools at work? No ☐ Yes ☐

Details: ....

....

Please indicate in as much detail as possible, your periods of use of the tools indicated previously.

Tn 1	Tn 2	Tn 3	Tn 4	Tn 5	Tn 6	Tn 7
Tool Type	Start Date	Finish Date	Hours/Day Holding Tool	Days/Week	Weeks/Year	Total Exposure (Hours)

Have you used any of the following regularly, for more than two hours per week when not at work?

		No	Yes
[Q1401]	Power tools		
[Q1402]	Motor cycle		
[Q1403]	Motor mower		
		1	2

HTn 1	HTn 2	HTn 3	HTn 4	HTn 5	HTn 6	HTn 7
Tool Type	Start Date	Finish Date	Hours/Day Holding Tool	Days/Week	Weeks/Year	Total Exposure (Hours)

APPENDIX B

DATA FROM LABORATORY VIBRATION MEASURENTS ON 16 PNEUMATIC TOOLS

Table B1 *Vibration acceleration magnitudes for chipping hammer type CPT Boyer Superior No 1 (handle)*

Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
	r.m.s. acceleration (ms^{-2})									
x-axis, mean	0,43	0,70	2,78	4,77	5,11	8,01	19,23	18,83	2,08	29,25
std. dev.	0,49	0,19	0,60	0,98	0,97	1,66	3,79	3,12	0,42	5,13
y-axis, mean	0,60	1,17	5,10	9,92	11,92	17,05	22,09	11,27	3,83	34,50
std. dev.	0,21	0,28	0,98	0,76	2,41	3,02	2,81	1,75	0,27	4,58
z-axis, mean	1,36	2,46	17,62	8,47	10,50	18,68	40,12	21,09	8,38	54,34
std. dev.	0,95	0,65	1,01	0,70	1,67	1,68	8,63	3,98	0,60	8,26

Number of runs ; 10

Table B2 *Vibration acceleration magnitudes for chipping hammer type CPT Boyer Superior No 1 (chisel)*

Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
	r.m.s. acceleration (ms^{-2})									
x-axis, mean	0,84	1,29	10,20	10,75	11,77	20,12	30,93	46,13	5,65	62,53
std. dev.	1,01	0,73	1,73	2,00	1,40	1,64	10,27	15,39	0,81	17,46
y-axis, mean	0,78	1,85	6,77	7,62	15,14	36,23	66,17	82,52	5,35	114,82
std. dev.	0,08	0,22	1,15	1,95	1,36	4,46	11,87	30,62	0,47	29,04
z-axis, mean	0,99	2,45	16,06	11,05	14,77	11,61	12,09	9,12	8,01	32,06
std. dev.	0,20	0,69	2,89	1,00	2,24	3,57	6,75	4,61	1,20	6,09

Number of runs ; 10

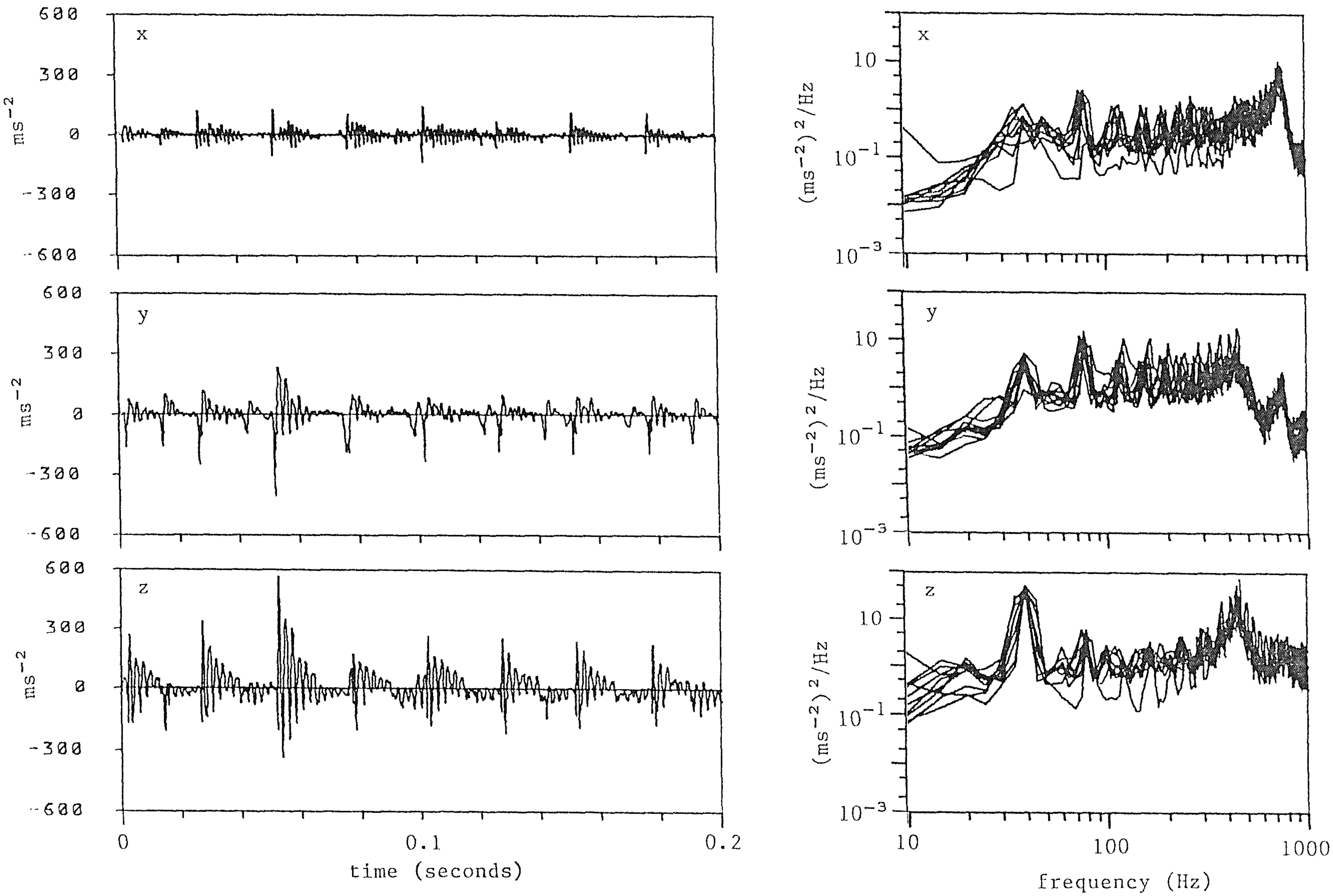


Figure B1 *Example acceleration time histories and ten power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the handle of a chipping hammer, CPT type Boyer Superior No. 1*

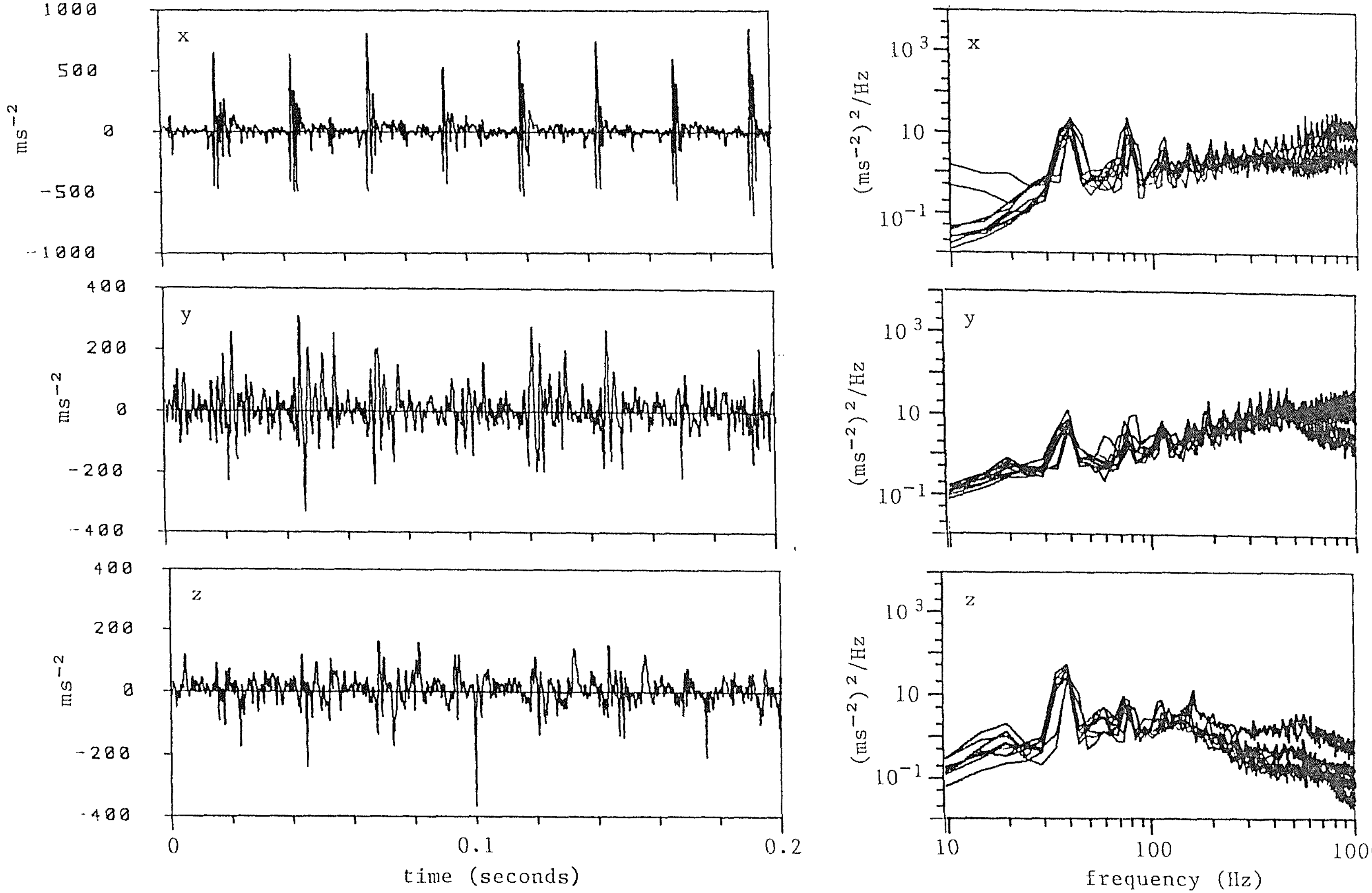


Figure B2 *Example acceleration time histories and ten power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the chisel of a chipping hammer, type CPT Boyer Superior No. 1*

Table B3 *Vibration acceleration magnitudes for vertical grinder, type Thor 5VL 40962T (left handle)*

Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
	r.m.s. acceleration (ms^{-2})									
x-axis, mean	0,09	0,33	1,30	4,93	1,46	1,61	1,83	2,67	1,34	6,53
std. dev.	0,02	0,22	0,64	0,56	0,60	0,17	0,25	0,46	0,15	0,54
y-axis, mean	0,13	0,36	1,39	4,38	1,44	1,44	3,93	8,47	1,25	10,73
std. dev.	0,12	0,17	0,45	0,50	0,30	0,19	1,04	2,21	0,15	1,93
z-axis, mean	0,15	0,38	1,30	4,44	1,25	1,26	1,75	2,82	1,24	6,40
std. dev.	0,02	0,16	0,49	0,44	0,30	0,44	0,36	1,01	0,15	0,55

Number of runs ; 10

Table B4 *Vibration acceleration magnitudes for vertical grinder, type Thor 5VL 40962T (right handle)*

Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
	r.m.s. acceleration (ms^{-2})									
x-axis, mean	0,06	0,21	1,03	3,14	2,09	2,10	4,36	2,78	0,94	6,90
std. dev.	0,02	0,20	0,63	0,26	0,68	0,36	0,86	0,36	0,15	0,93
y-axis, mean	0,11	0,15	0,54	16,53	1,19	0,46	1,11	1,38	3,57	16,64
std. dev.	0,01	0,02	0,06	4,16	0,19	0,03	0,26	0,28	0,74	4,01
z-axis, mean	0,13	0,18	0,59	13,76	1,44	0,56	1,54	0,73	3,02	14,28
std. dev.	0,02	0,03	0,35	2,38	0,88	0,48	1,98	0,51	0,49	2,00

Number of runs ; 10

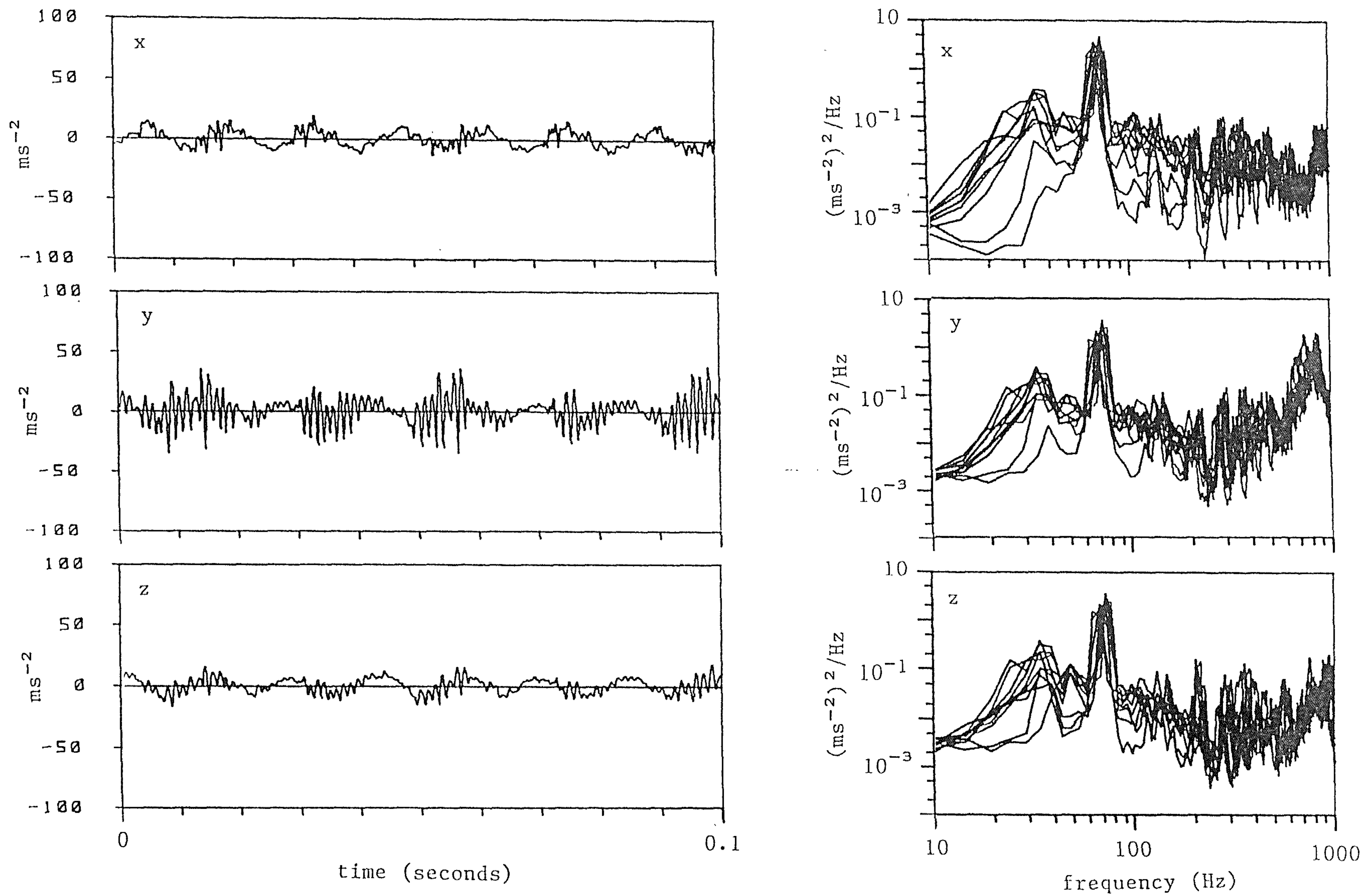


Figure B3 Example acceleration time histories and ten power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the left handle of a vertical grinder, type Thor 5VL

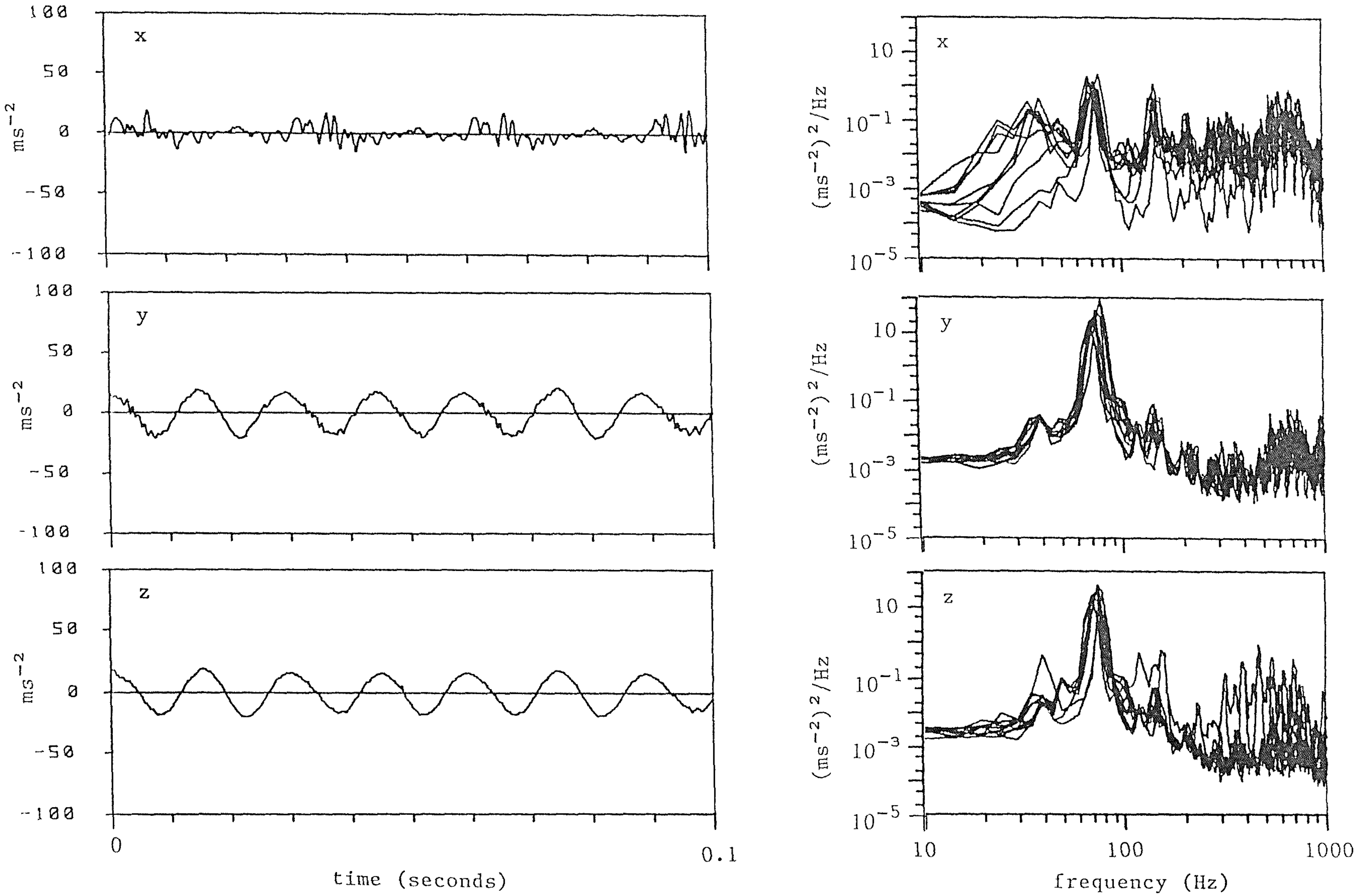


Figure B4 *Example acceleration time histories and ten power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the right handle of a vertical grinder, type Thor 5VL*

Table B5 Vibration acceleration magnitudes for vertical grinder with cutting disc, type Thor 5VL 8211 (left handle with trigger)

	r.m.s. acceleration (ms^{-2})									
Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis, mean	0,27	0,63	1,21	1,37	1,65	3,18	16,30	8,93	1,11	19,04
std. dev.	0,10	0,16	0,38	0,37	0,53	0,67	1,90	1,99	0,21	2,61
y-axis, mean	0,20	0,29	1,41	2,93	2,36	0,96	3,03	1,82	1,11	5,69
std. dev.	0,07	0,04	0,35	1,62	1,04	0,29	0,23	0,32	0,24	0,82
z-axis, mean	0,21	0,54	2,81	4,36	8,79	3,89	12,03	2,72	2,04	16,57
std. dev.	0,03	0,22	0,30	0,36	1,37	0,95	1,38	0,56	0,15	1,06

Number of runs ; 5

Table B6 Vibration acceleration magnitudes for vertical grinder with cutting disc, type Thor 5VL 8211 (right handle)

	r.m.s. acceleration (ms^{-2})									
Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis, mean	0,30	0,83	2,18	6,03	7,30	11,82	10,71	8,24	2,23	20,39
std. dev.	0,08	0,14	0,31	0,67	0,27	0,82	0,81	0,74	0,12	1,14
y-axis, mean	0,41	1,10	2,69	3,96	5,90	9,17	29,97	15,02	2,27	35,45
std. dev.	0,11	0,26	0,24	0,26	0,33	0,98	1,79	1,07	0,13	2,07
z-axis, mean	0,18	0,65	2,54	2,47	1,45	5,16	11,06	8,63	1,54	15,47
std. dev.	0,02	0,36	0,44	0,38	0,27	0,74	0,65	0,82	0,23	0,75

Number of runs ; 5

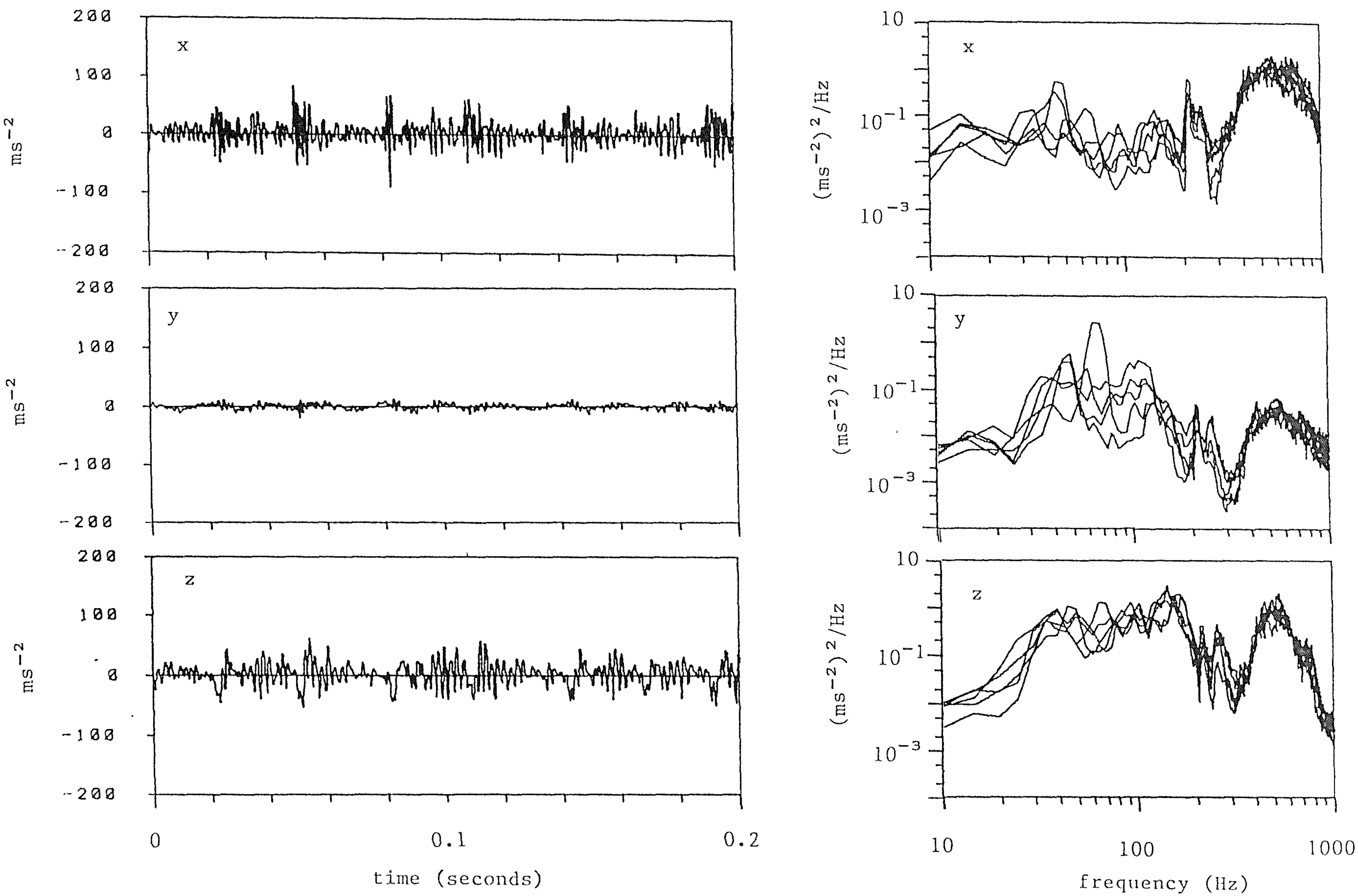


Figure B5 *Example acceleration time histories and five power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the left (trigger) handle of a vertical grinder, type Thore 5VL, fitted with a cutting disc*

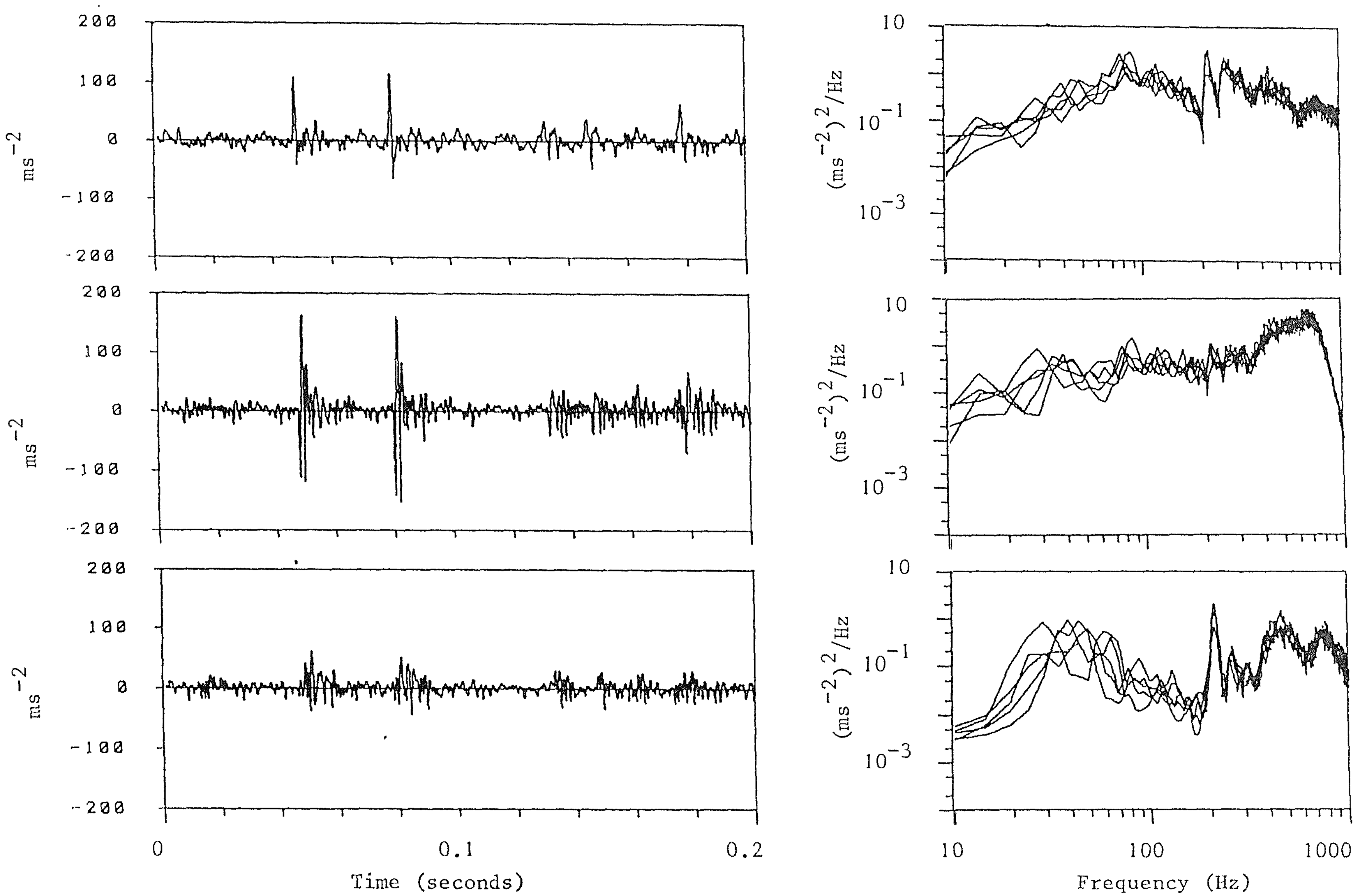


Figure B6 Example acceleration time histories and five power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the right handle of a vertical grinder, type Thor 5VL, fitted with a cutting disc

Table B7 *Vibration acceleration magnitudes for small angle grinder, type Thor 3S*

Octave band centre freq.		r.m.s. acceleration (ms^{-2})									
		8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis,	mean	0,11	0,10	0,21	0,98	2,68	1,57	3,48	3,87	0,51	9,80
	std. dev.	0,01	0,06	0,19	0,56	0,22	0,26	0,23	0,60	0,09	0,52
y-axis,	mean	0,14	0,18	0,92	3,18	6,70	4,16	5,43	4,53	1,40	11,27
	std. dev.	0,01	0,10	0,72	2,02	0,85	0,99	0,64	0,57	0,47	1,39
z-axis,	mean	0,17	0,25	0,66	1,49	3,75	2,01	5,03	12,35	0,83	14,17
	std. dev.	0,03	0,13	0,42	0,95	1,33	0,55	0,68	1,31	0,26	1,65

Number of runs ; 5

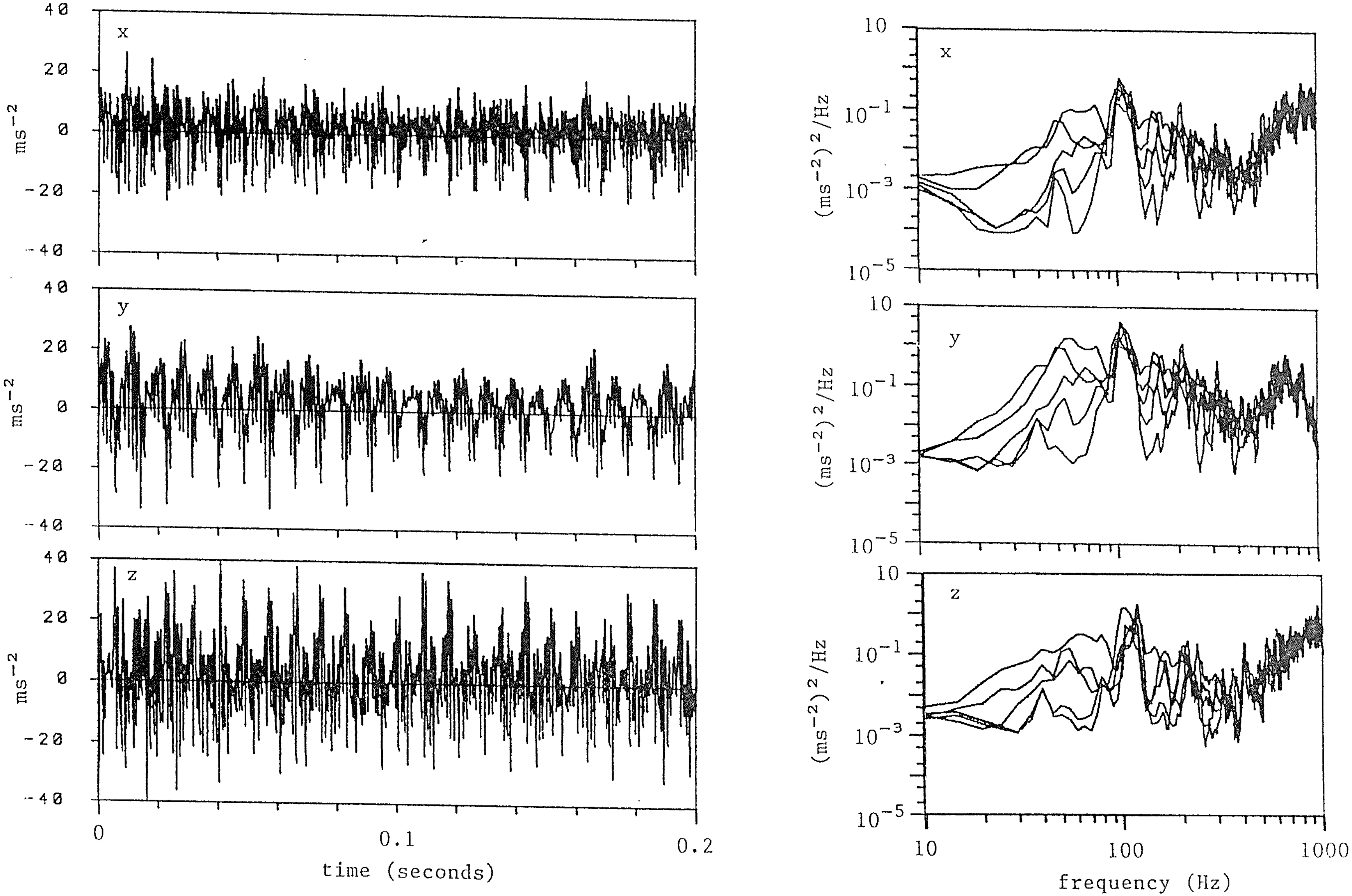


Figure B7 *Example acceleration time histories and five power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the handle of an angle grinder, type Thor 3S*

Table B8 Vibration acceleration magnitudes for end grinder, type Thor 301G (trigger end)

Octave band centre freq.		r.m.s. acceleration (ms^{-2}) 8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis,	mean	0,09	0,08	0,17	2,13	5,91	3,01	11,09	13,14	1,24	19,12
	std. dev.	0,01	0,00	0,04	0,64	0,49	0,36	0,76	0,00	0,51	0,50
y-axis,	mean	0,12	0,09	0,17	0,70	2,83	2,35	8,24	10,96	0,52	14,43
	std. dev.	0,01	0,00	0,01	0,17	0,28	0,18	0,09	3,43	0,00	2,79
z-axis,	mean	0,14	0,13	0,28	1,95	4,49	2,22	7,22	9,55	0,79	12,59
	std. dev.	0,03	0,02	0,08	0,60	0,03	0,70	0,76	1,32	0,08	3,08

Number of runs : 2

Table B9 Vibration acceleration magnitudes for end grinder, type Thor 301G (wheel end)

Octave band centre freq.		r.m.s. acceleration (ms^{-2}) 8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis,	mean	0,12	0,19	1,23	4,01	13,90	7,99	9,76	12,72	2,14	25,21
	std. dev.	0,01	0,08	0,91	1,58	2,88	0,52	0,52	1,60	0,00	0,01
y-axis,	mean	0,10	0,12	0,45	0,63	2,95	2,56	5,19	8,30	0,52	11,28
	std. dev.	0,00	0,01	0,02	0,00	0,66	0,97	1,05	0,93	0,02	1,23
z-axis,	mean	0,15	0,18	0,65	1,56	10,66	3,84	5,85	11,31	1,44	19,28
	std. dev.	0,03	0,00	0,06	0,28	2,50	1,78	1,67	1,47	0,28	0,88

Number of runs : 2

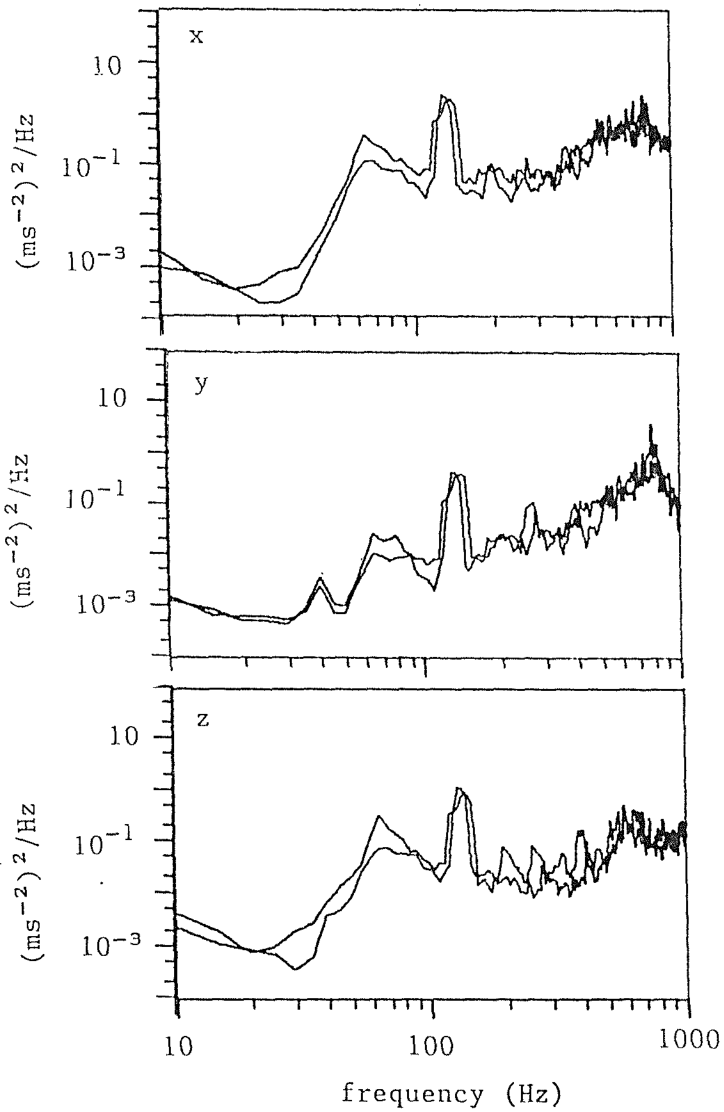


Figure B8 Two acceleration power spectral density functions (resolution = 4.88 Hz) for three axes of vibration at the trigger end of an end grinder, type Thor 301G

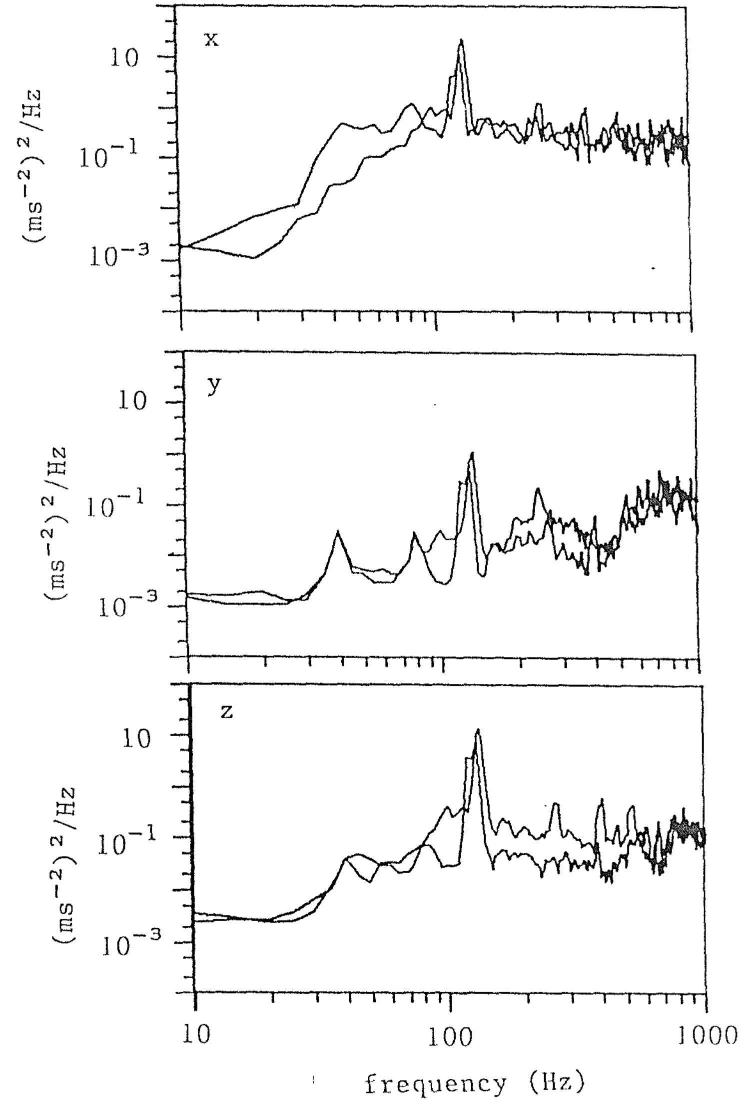


Figure B9 Two acceleration power spectral density functions (resolution = 4.88 Hz) for three axes of vibration at the wheel end of an end grinder, type Thor 301G

Table B10 Vibration acceleration magnitudes for collet grinder type ATA STR18

Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
	r.m.s. acceleration (ms^{-2})									
x-axis, mean	0,22	0,33	0,81	2,64	12,20	20,03	18,41	69,96	2,24	76,85
std. dev.	0,06	0,08	0,26	1,15	4,58	6,60	7,07	28,67	0,71	29,58
y-axis, mean	0,16	0,25	0,65	2,02	9,52	15,92	20,13	27,53	1,81	39,26
std. dev.	0,01	0,06	0,19	0,96	3,52	5,30	7,58	11,25	0,58	14,09
z-axis, mean	0,26	0,40	0,76	2,22	9,22	15,54	13,27	54,38	1,76	59,88
std. dev.	0,06	0,09	0,24	0,46	2,16	2,93	2,80	25,92	0,25	24,19

Number of runs : 10

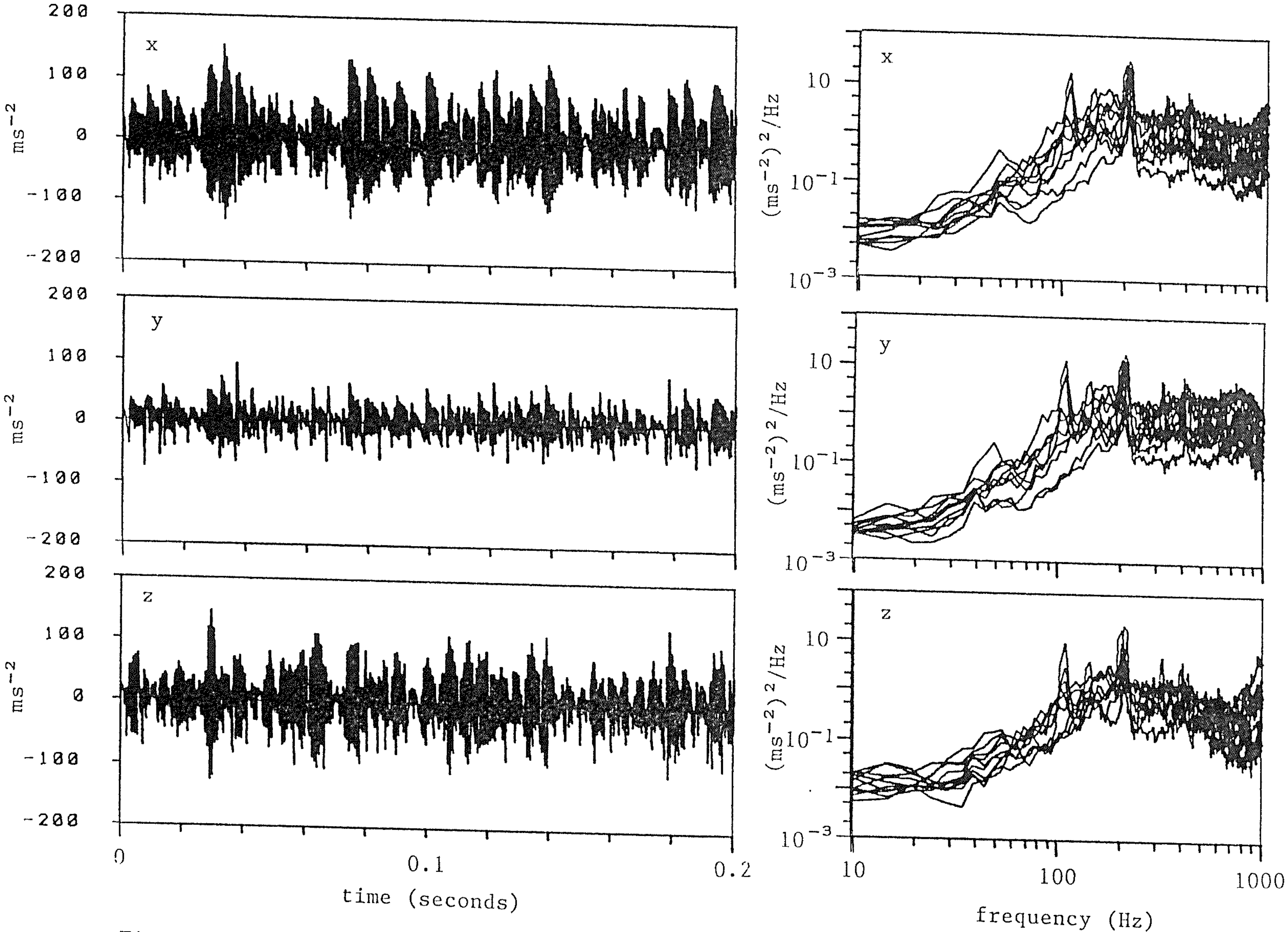


Figure B10 *Example acceleration time histories and ten power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on a collet grinder, type ATA STR18*

Table B11 Vibration acceleration magnitudes for power wire brush, type CPT 3320A (left handle)

Octave band centre freq.		r.m.s. acceleration (ms^{-2}) 8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis,	mean	0,03	0,09	3,02	0,70	0,60	1,85	3,62	3,60	1,25	3,69
	std. dev.	0,00	0,01	0,18	0,06	0,12	0,02	0,73	0,15	0,07	0,43
y-axis,	mean	0,05	0,10	3,23	0,89	0,79	2,34	1,42	5,92	1,35	7,61
	std. dev.	0,01	0,01	0,89	0,03	0,12	0,42	0,38	0,05	0,35	0,35
z-axis,	mean	0,07	0,07	1,47	0,78	0,73	1,45	1,08	2,67	0,65	3,83
	std. dev.	0,03	0,01	0,63	0,06	0,25	0,57	0,08	0,15	0,22	0,05

Number of runs : 2

Table B12 Vibration acceleration magnitudes for power wire brush, type CPT 3320A (right handle)

Octave band centre freq.		r.m.s. acceleration (ms^{-2}) 8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis,	mean	0,04	0,06	2,66	0,84	0,61	1,91	1,37	3,41	1,12	5,21
	std. dev.	0,01	0,01	0,23	0,16	0,20	0,90	0,06	0,52	0,08	0,83
y-axis,	mean	0,05	0,05	1,45	0,49	0,84	2,58	2,19	2,76	0,64	5,23
	std. dev.	0,01	0,01	0,15	0,19	0,19	0,98	0,03	0,66	0,06	0,51
z-axis,	mean	0,08	0,08	2,71	0,80	0,72	1,34	2,07	6,01	1,14	7,23
	std. dev.	0,04	0,01	0,57	0,21	0,35	0,25	0,01	0,16	0,21	0,42

Number of runs : 2

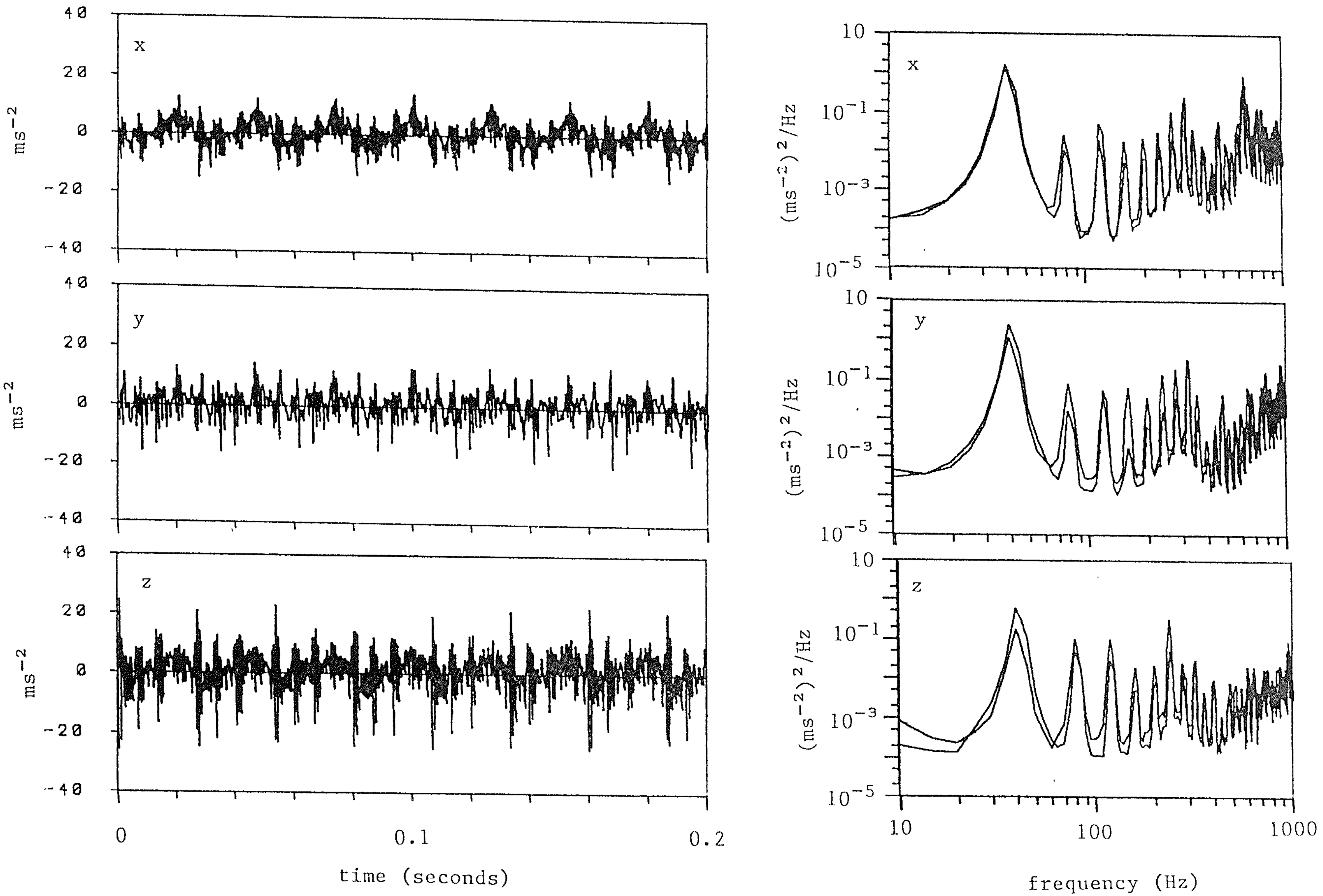


Figure B11 *Example acceleration time histories and two power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the left handle of a power wire brush, type CPT 3320A*

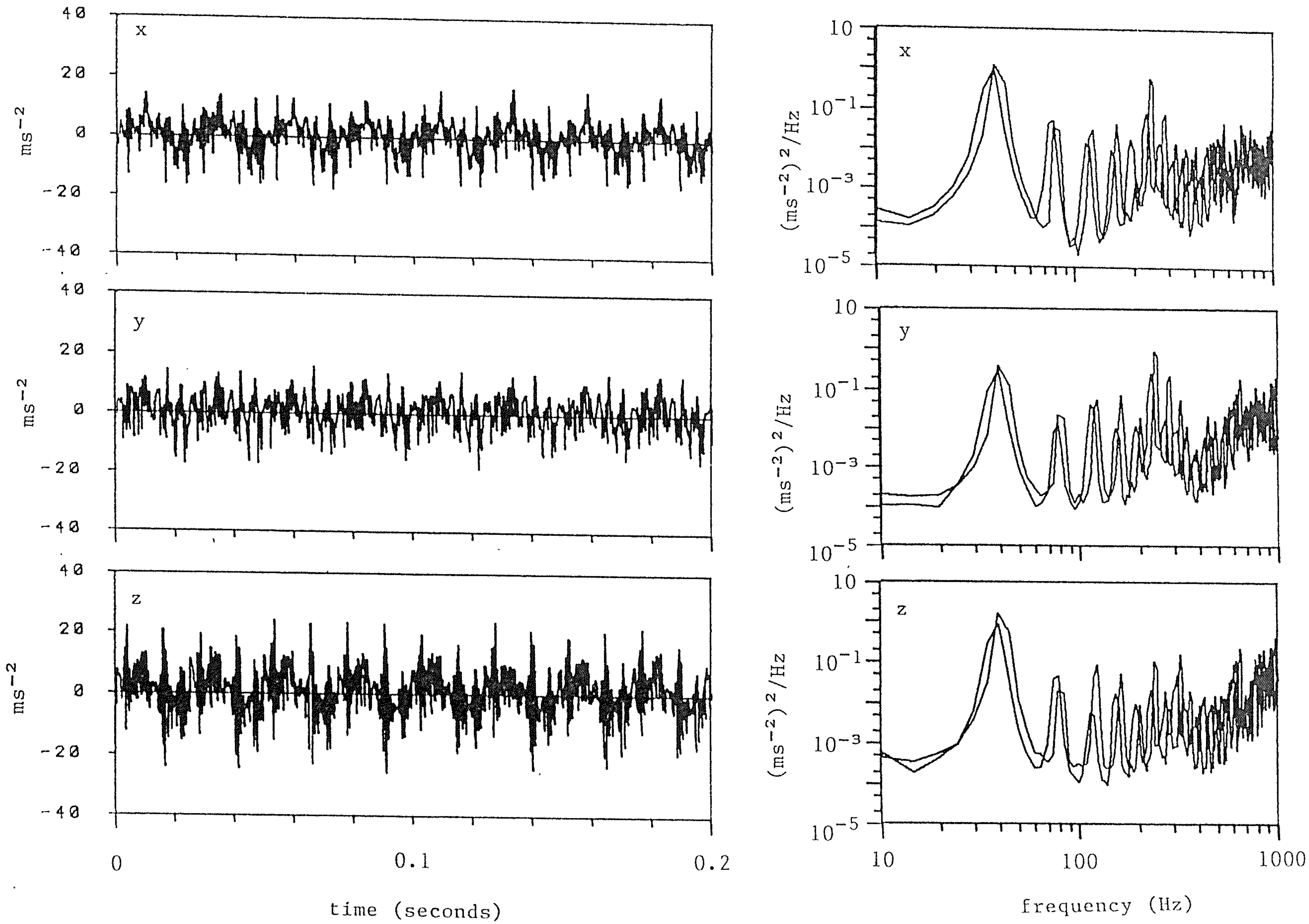


Figure B12 Example acceleration time histories and two power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the right handle of a power wire brush, type CPT 3320A

Table B13 *Vibration acceleration magnitudes for disc sander type Thor 5VL 40016T (left handle)*

Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
	r.m.s. acceleration (ms^{-2})									
x-axis, mean	0,10	0,11	0,34	22,96	1,07	1,66	2,59	1,47	5,46	23,20
std. dev.	0,02	0,02	0,19	4,33	0,37	0,81	1,55	0,24	0,25	4,52
y-axis, mean	0,08	0,08	0,27	16,07	0,44	0,44	2,48	1,20	3,81	16,40
std. dev.	0,03	0,00	0,10	3,90	0,05	0,21	1,04	0,51	0,38	4,05
z-axis, mean	0,10	0,09	0,16	6,70	0,95	0,85	1,73	1,59	1,61	7,28
std. dev.	0,00	0,02	0,01	1,19	0,16	0,31	0,81	0,30	0,05	1,39

Number of runs : 2

Table B14 *Vibration acceleration magnitudes for disc sander type Thor 5VL 40016T (right handle)*

Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
	r.m.s. acceleration (ms^{-2})									
x-axis, mean	0,08	0,09	0,07	7,29	0,60	0,71	1,44	2,10	1,51	7,87
std. dev.	0,04	0,06	0,02	1,13	0,21	0,28	0,29	0,00	0,16	1,11
y-axis, mean	0,10	0,08	0,16	15,12	0,52	0,91	1,30	2,07	3,14	15,39
std. dev.	0,00	0,02	0,10	1,46	0,17	0,06	0,21	0,13	0,13	1,46
z-axis, mean	0,19	0,13	0,20	15,95	1,05	0,82	2,14	2,00	3,31	16,30
std. dev.	0,03	0,04	0,04	1,82	0,23	0,13	0,35	0,06	0,20	1,83

Number of runs : 2

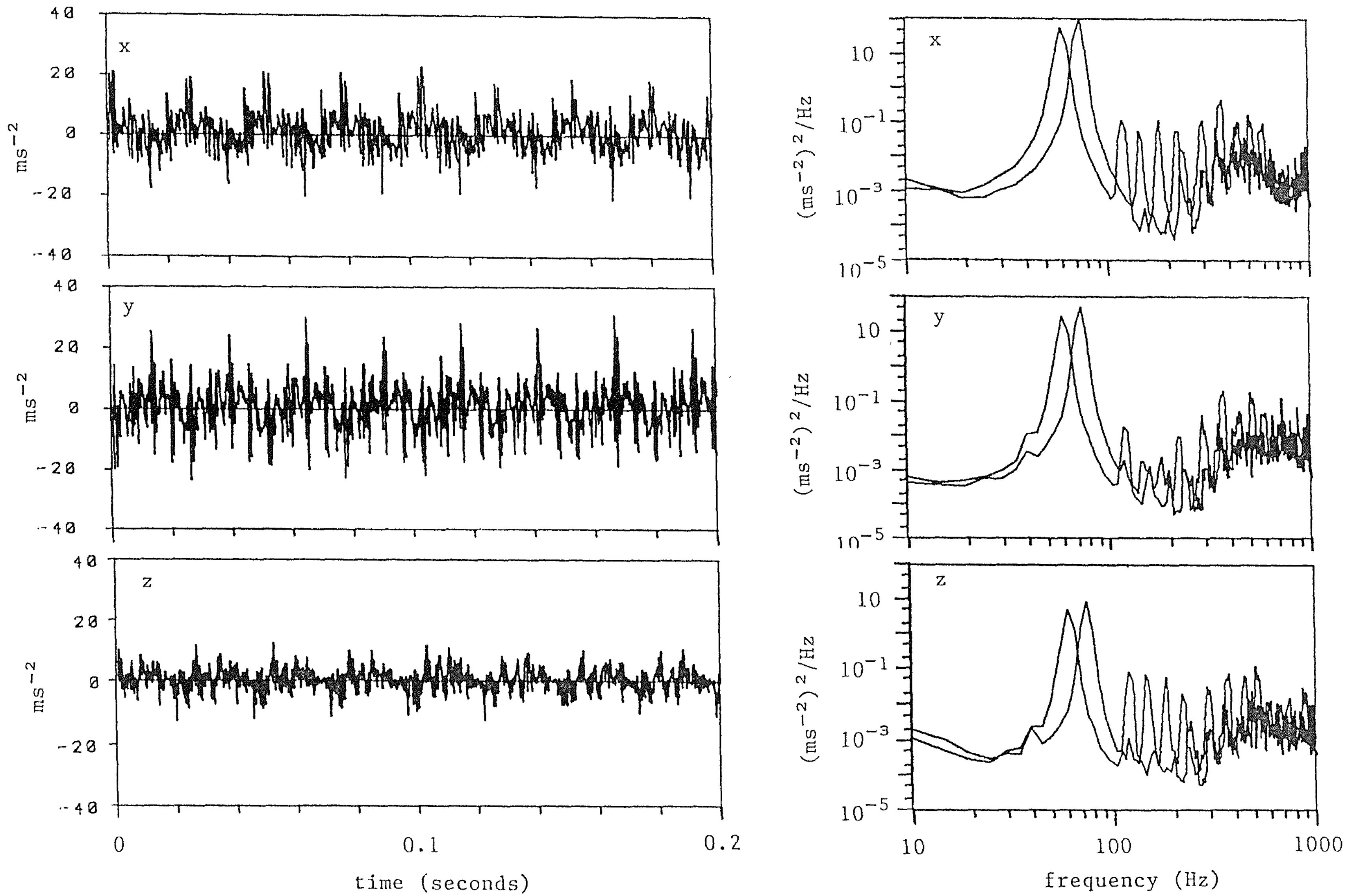


Figure B13 *Example acceleration time histories and two power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the left handle of a rotary sander, type Thor 5VL 40016T*

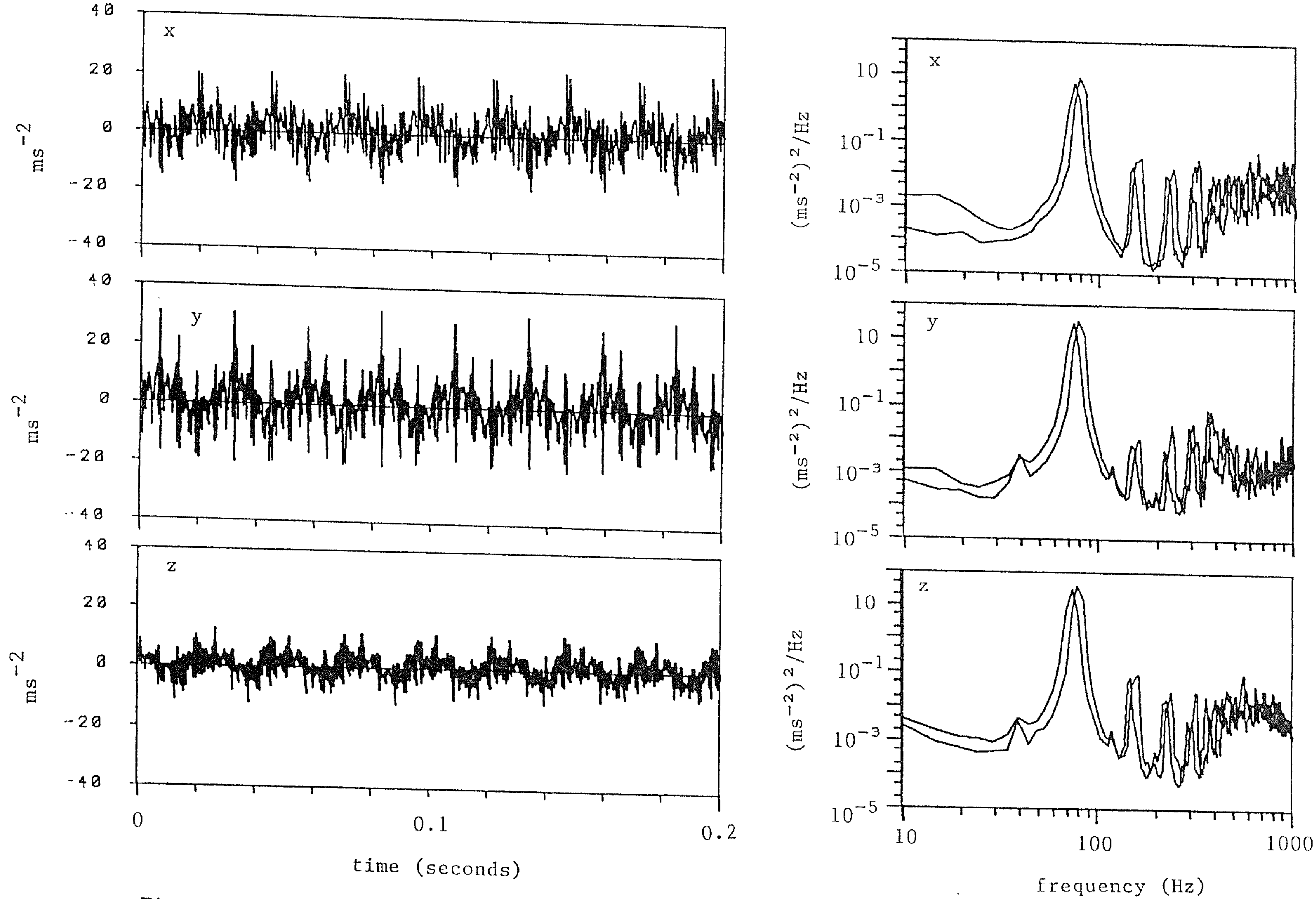


Figure B14 *Example acceleration time histories and two power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the right handle of a rotary sander, type Thor 5VL 40016T*

Table B15 Vibration acceleration magnitudes for pistol drilling machine, type Atlas Copco LBB 22 HO 22

					r.m.s. acceleration (ms^{-2})					
Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis, mean	0,19	0,92	1,41	1,42	9,55	1,76	9,34	11,49	1,78	18,49
std. dev.	0,01	0,11	0,06	0,13	1,15	0,98	1,58	0,34	0,20	0,57
y-axis, mean	0,16	1,10	1,71	2,01	8,58	10,44	3,23	2,12	1,74	14,88
std. dev.	0,04	0,00	0,12	0,34	4,45	2,28	0,47	0,27	0,38	4,40
z-axis, mean	0,65	1,95	3,05	3,65	19,45	8,67	5,97	4,10	3,64	23,77
std. dev.	0,40	0,38	0,80	0,47	0,65	1,68	1,38	0,21	0,25	1,75

Number of runs : 2

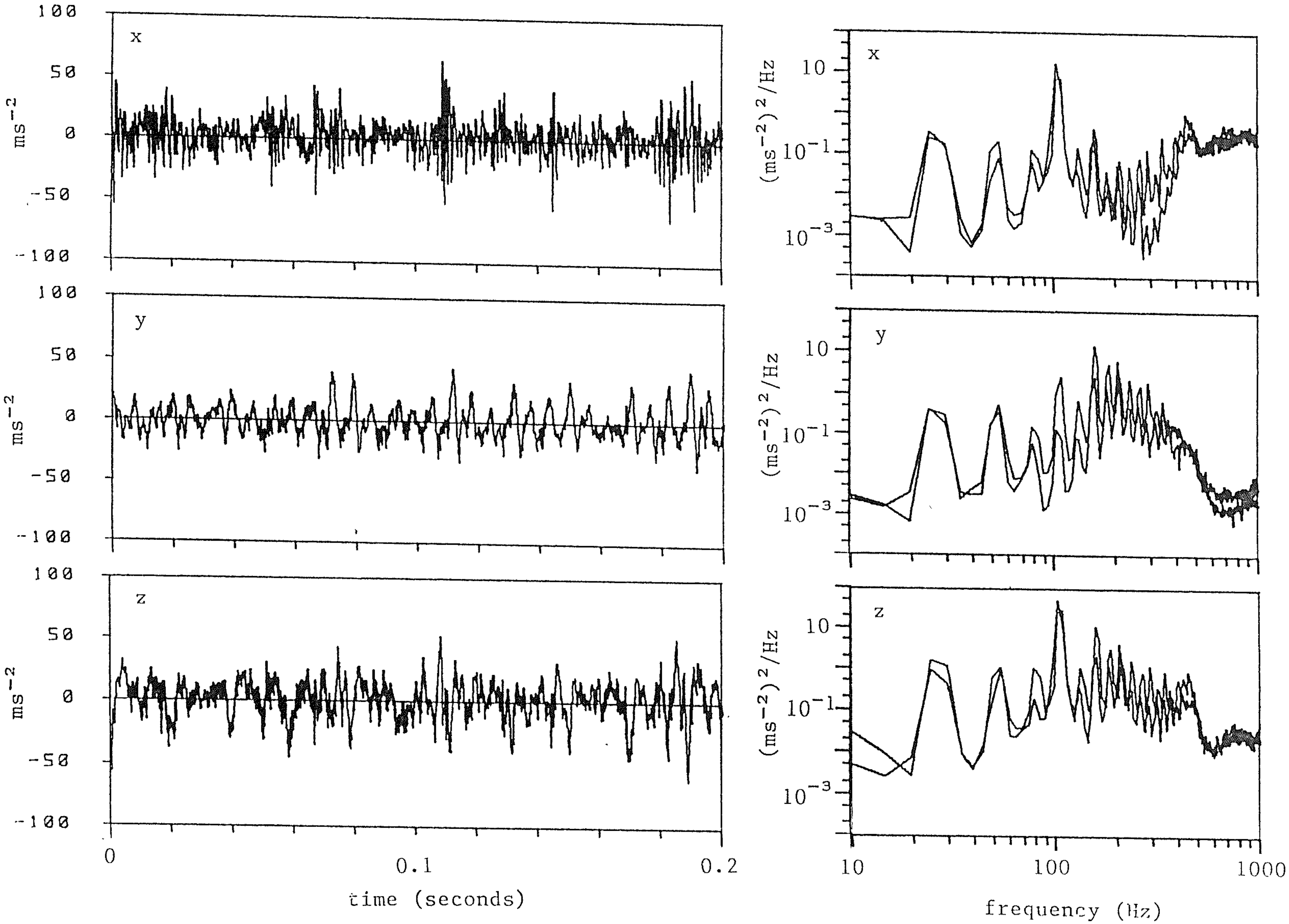


Figure B15 Example acceleration time histories and two power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the handle of a pistol drill, type Atlas Copco LBB 22 HO 22

Table B16 Vibration acceleration magnitudes for Morse drilling machine, type CPT 315 (left, throttle handle)

Octave band centre freq.	r.m.s. acceleration (ms^{-2}) 8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis, mean	0,20	0,33	0,80	1,26	1,33	3,76	3,39	8,69	0,69	10,43
std. dev.	0,07	0,21	0,60	0,86	0,77	0,99	0,90	1,76	0,37	2,27
y-axis, mean	0,31	0,55	1,02	1,47	1,06	1,58	4,62	7,18	0,88	9,05
std. dev.	0,05	0,25	0,56	1,06	0,66	0,42	0,52	2,32	0,42	2,25
z-axis, mean	0,29	0,44	1,11	2,22	1,98	4,59	4,26	5,96	0,99	9,41
std. dev.	0,10	0,18	0,65	1,58	1,22	1,45	1,09	0,99	0,46	2,18

Number of runs : 5

Table B17 Vibration acceleration magnitudes for Morse drilling machine, type CPT 315 (right, plain handle)

Octave band centre freq.	r.m.s. acceleration (ms^{-2}) 8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis, mean	0,30	0,68	1,50	2,82	6,52	3,35	2,39	3,09	1,49	9,91
std. dev.	0,11	0,54	1,62	4,68	11,00	4,65	1,54	0,43	1,99	12,02
y-axis, mean	0,39	0,53	0,71	0,97	1,09	2,07	6,56	5,67	0,80	9,31
std. dev.	0,25	0,37	0,57	1,17	1,22	1,02	0,81	1,08	0,58	1,12
z-axis, mean	0,47	0,72	1,14	2,88	5,06	2,98	2,04	3,47	1,37	8,44
std. dev.	0,28	0,48	1,18	3,60	7,75	3,78	1,84	0,32	1,46	8,75

Number of runs : 5

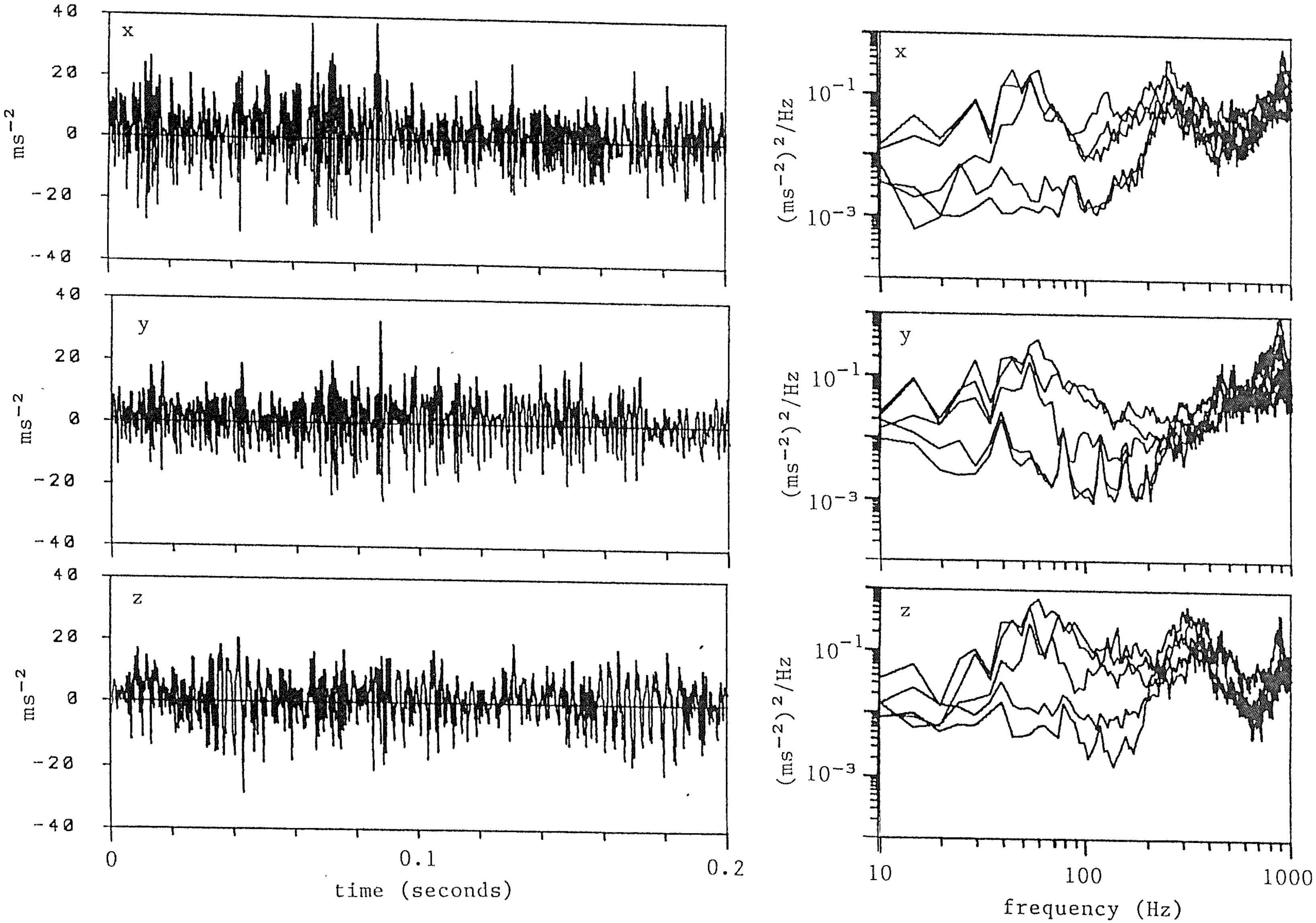


Figure B16 *Example acceleration time histories and five power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the throttle of a size 2 Morse drilling machine, type CPT 315*

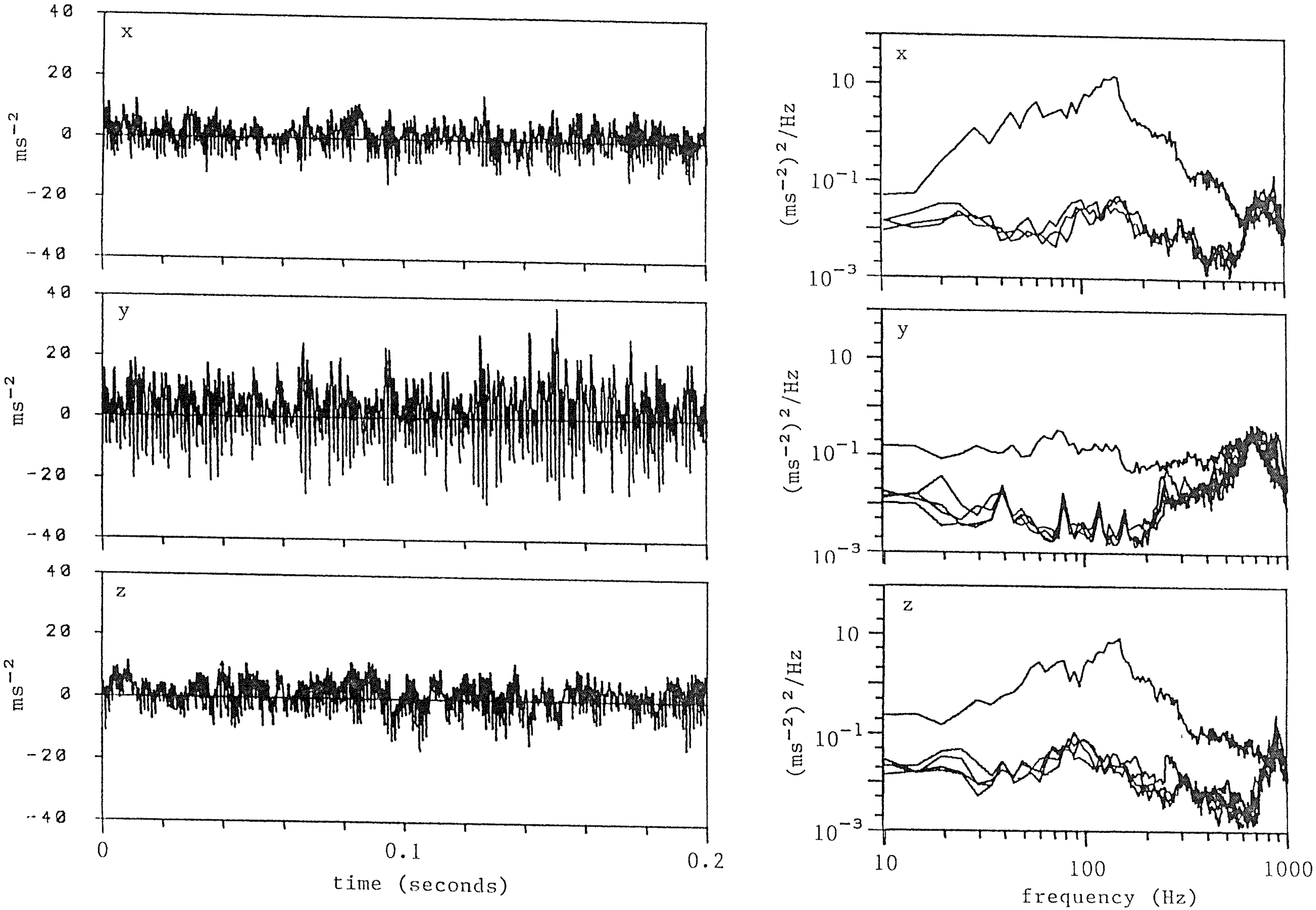


Figure B17 Example acceleration time histories and five power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the plain handle of a size 2 Morse drilling machine, type CPT 315

Table B18 *Vibration acceleration magnitudes for nobbler, type CPT no. 5 (trigger end)*

Octave band centre freq.		8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
		r.m.s. acceleration (ms^{-2})									
x-axis,	mean	0,43	1,21	1,70	3,33	1,94	5,36	18,10	8,38	1,86	21,50
	std. dev.	0,08	0,30	0,41	0,75	0,16	0,59	2,12	1,27	0,26	2,40
y-axis,	mean	0,99	1,92	5,95	13,25	6,27	7,76	13,76	26,76	5,32	35,35
	std. dev.	0,12	0,21	0,94	1,63	0,25	0,40	1,40	3,58	0,35	3,63
z-axis,	mean	1,20	2,34	6,28	15,51	7,99	21,78	38,92	27,87	6,36	56,33
	std. dev.	0,12	0,33	1,27	1,76	0,80	2,64	4,59	2,99	0,44	5,62

Number of runs : 10

Table B19 *Vibration acceleration magnitudes for nobbler, type CPT no. 5 (piston end)*

Octave band centre freq.		8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
		r.m.s. acceleration (ms^{-2})									
x-axis,	mean	0,68	1,29	4,78	6,82	2,51	3,94	12,07	13,56	3,24	20,91
	std. dev.	0,28	0,18	1,15	1,34	0,64	0,81	2,41	4,48	0,42	4,67
y-axis,	mean	0,90	1,40	4,32	4,68	4,56	4,47	10,44	20,04	2,75	24,80
	std. dev.	0,19	0,24	0,24	0,40	0,76	0,54	2,12	5,52	0,25	5,47
z-axis,	mean	2,32	8,04	56,88	93,29	29,56	26,31	27,18	37,99	38,32	127,54
	std. dev.	0,39	0,87	10,74	13,40	2,47	3,94	9,97	12,46	1,91	12,15

Number of runs : 10

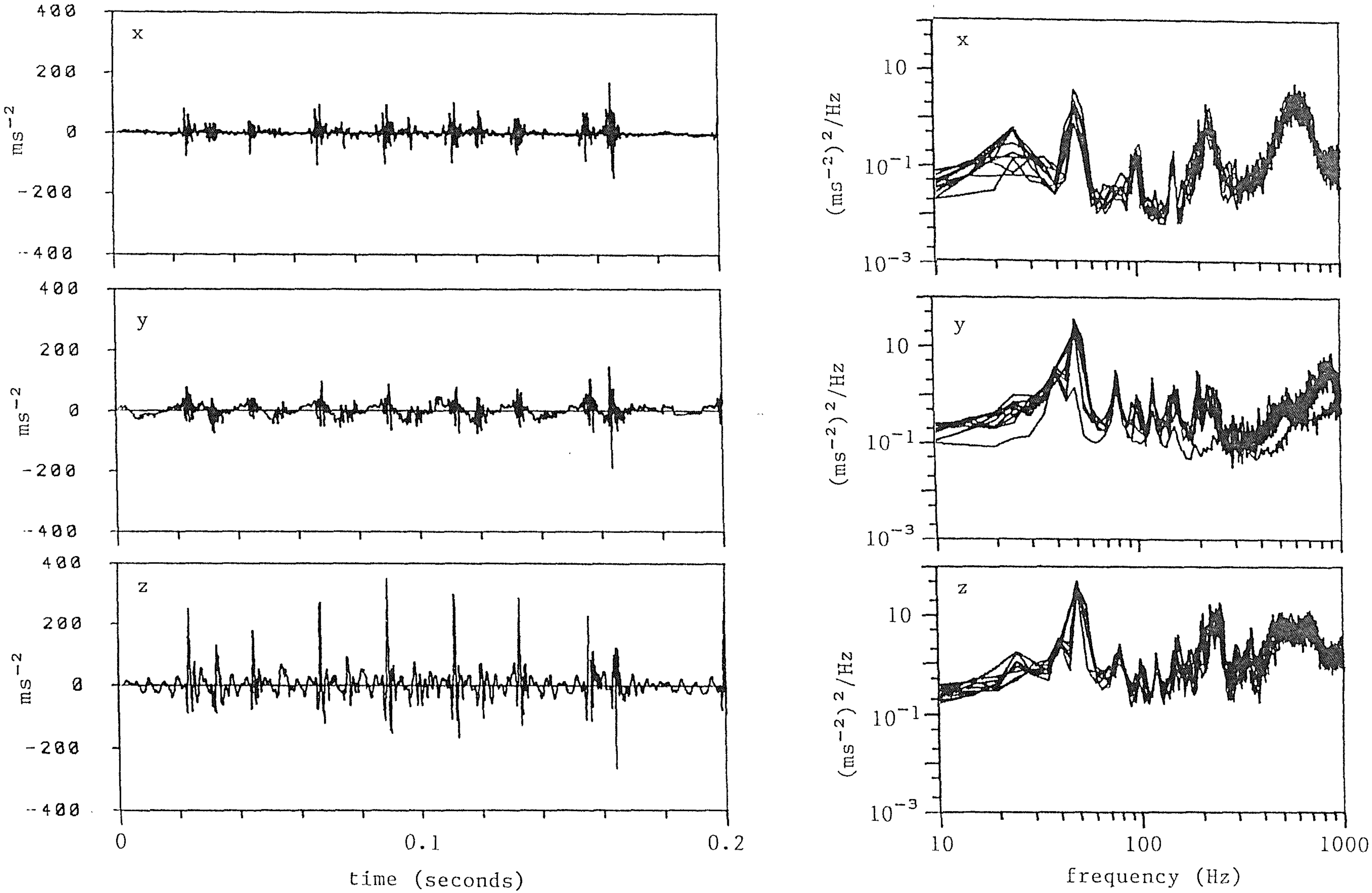


Figure B18 Example acceleration time histories and ten power spectral density functions (resolution = 4.88 Hz) for three axes of vibration at the trigger end of a nobbler, type CPT No. 5

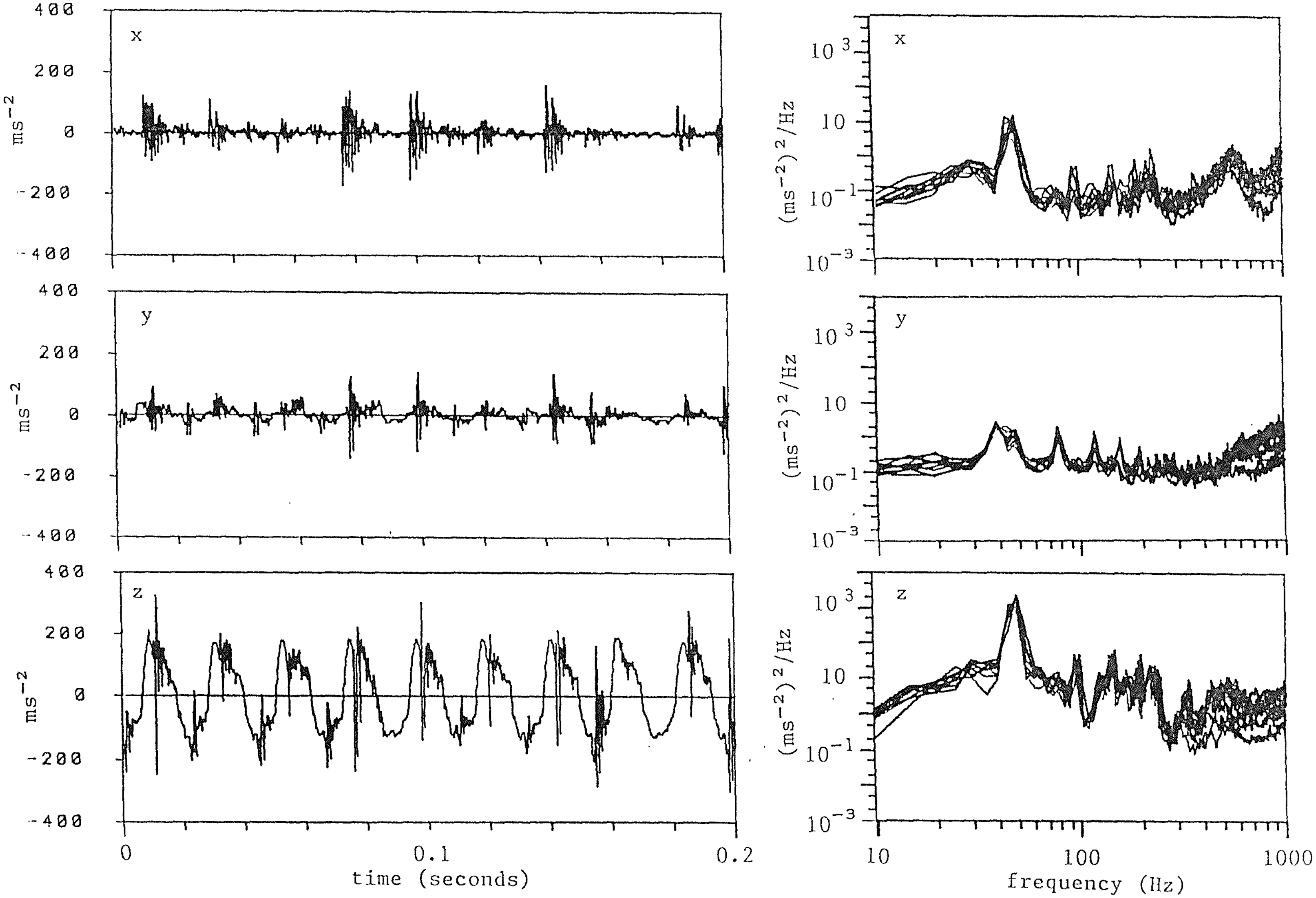


Figure B19 Example acceleration time histories and ten power spectral density functions (resolution = 4.88 Hz) for three axes of vibration at the piston end of a nobbler, type CPT No. 5

Table B20 Vibration acceleration magnitudes for needle scaler, type Trelawney 2BS (trigger end)

Octave band centre freq.		r.m.s. acceleration (ms^{-2}) 8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis,	mean	0,40	0,68	2,23	4,81	6,49	16,69	17,97	26,09	2,18	38,60
	std. dev.	0,05	0,07	0,17	0,69	0,26	1,55	1,36	1,09	0,11	2,00
y-axis,	mean	1,13	2,20	9,64	41,02	18,85	22,84	37,84	28,18	10,88	70,28
	std. dev.	0,05	0,10	0,47	2,58	1,26	1,06	1,82	5,12	0,48	4,06
z-axis,	mean	1,16	1,68	4,34	6,81	7,16	14,90	18,93	39,64	3,41	48,40
	std. dev.	0,10	0,14	0,23	0,53	0,24	1,11	1,10	1,39	0,18	1,52

Number of runs ; 10

Table B21 Vibration acceleration magnitudes for needle scaler, type Trelawney 2BS (needle end)

Octave band centre freq.		r.m.s. acceleration (ms^{-2}) 8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis,	mean	0,47	0,75	1,42	4,10	11,95	29,78	36,92	49,31	2,95	69,88
	std. dev.	0,09	0,06	0,18	0,53	0,32	2,97	2,09	2,08	0,14	3,50
y-axis,	mean	1,05	1,99	8,74	39,60	17,97	21,95	40,94	53,23	10,39	83,50
	std. dev.	0,10	0,18	0,97	2,14	0,93	1,07	1,88	2,70	0,45	3,56
z-axis,	mean	1,31	1,77	4,36	9,17	12,07	25,67	36,34	36,85	4,19	60,27
	std. dev.	0,17	0,15	0,32	0,50	0,90	2,73	2,33	2,79	0,13	4,15

Number of runs ; 10

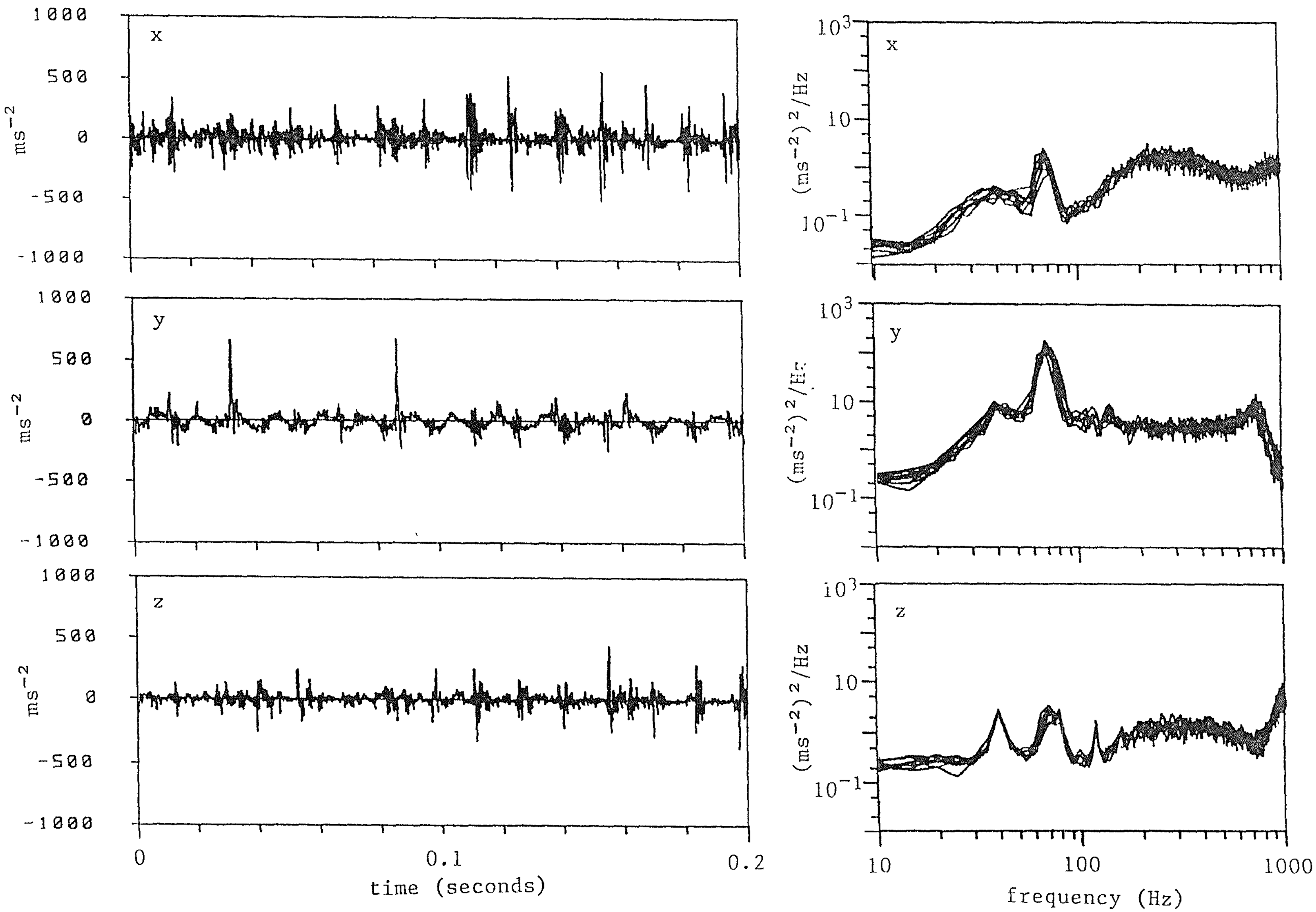


Figure B20 *Example acceleration time histories and ten power spectral density functions (resolution = 4.88 Hz) for three axes of vibration at the trigger end of a straight needle scaler, type Trelawney 2BS*

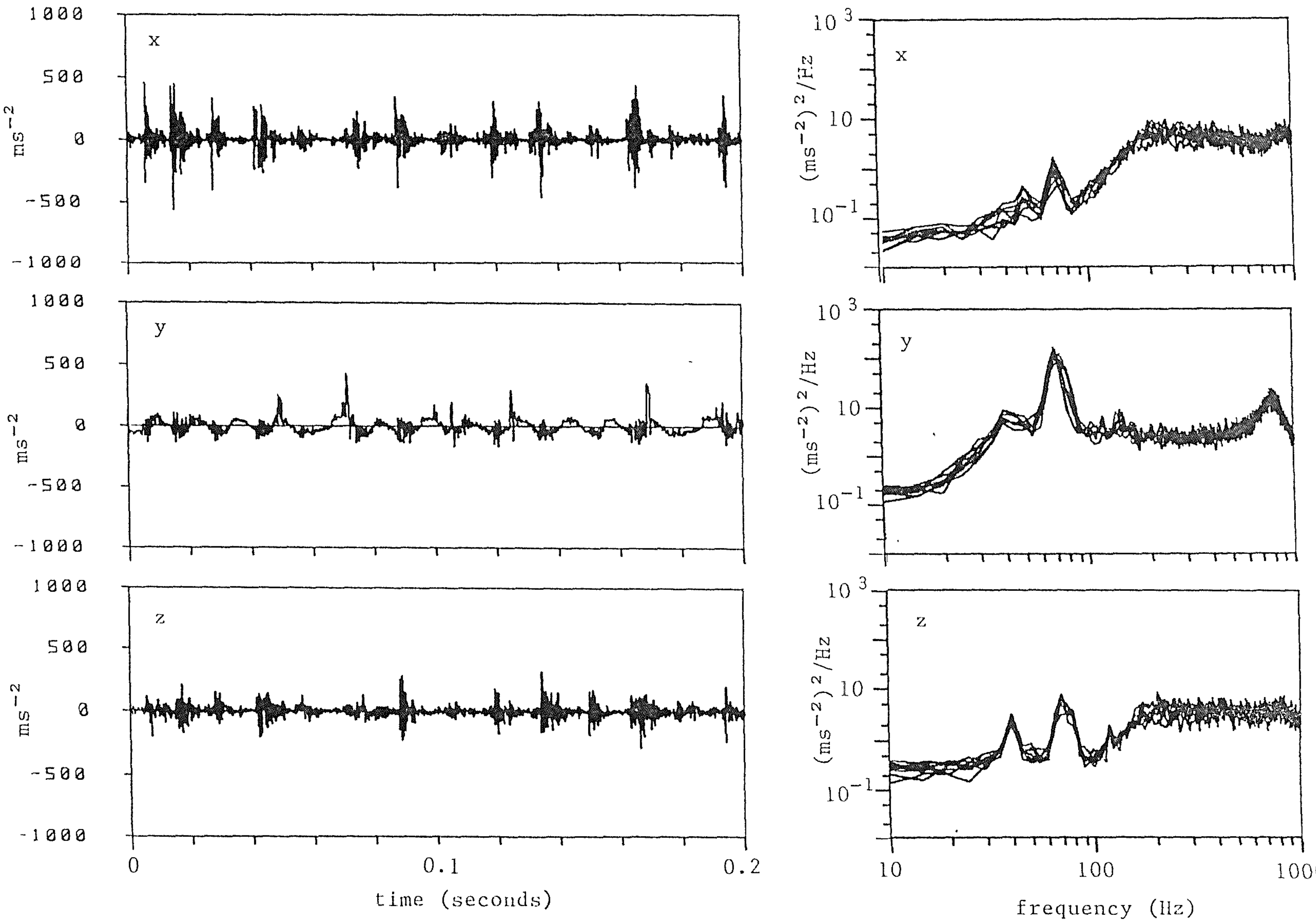


Figure B21 Example acceleration time histories and ten power spectral density functions (resolution = 4.88 Hz) for three axes of vibration at the needle end of a straight needle scaler, type Trelawney 2BS

Table B22 Vibration acceleration magnitudes for pistol needle scaler, type Von Arx 23-B (handle)

Octave band centre freq.	r.m.s. acceleration (ms^{-2}) 8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis, mean	1,17	1,07	3,00	48,97	12,91	21,87	55,68	105,05	13,43	134,13
std. dev.	0,18	0,00	0,15	2,40	0,54	0,96	3,97	3,23	0,49	3,78
y-axis, mean	0,93	1,48	4,78	20,66	8,50	45,01	37,73	29,10	6,69	67,45
std. dev.	0,11	0,13	0,19	1,87	0,38	1,79	0,07	9,99	0,37	0,47
z-axis, mean	1,09	1,60	3,48	4,58	5,15	13,55	23,17	22,88	2,86	39,16
std. dev.	0,13	0,01	0,13	0,13	0,09	0,25	0,62	2,33	0,04	1,58

Number of runs : 2

Table B23 Vibration acceleration magnitudes for needle scaler, type Von Arx 23-B (barrel)

Octave band centre freq.	r.m.s. acceleration (ms^{-2}) 8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis, mean	0,80	1,34	2,93	34,13	12,38	35,02	55,37	50,37	9,69	100,30
std. dev.	0,10	0,17	0,37	3,49	0,45	2,82	4,23	4,40	0,70	5,77
y-axis, mean	1,35	1,93	5,83	69,76	17,18	24,32	57,72	71,04	18,93	121,70
std. dev.	0,40	0,32	0,32	8,31	1,07	0,91	1,22	1,93	1,75	6,33
z-axis, mean	1,01	1,58	4,38	14,59	8,16	15,18	46,76	84,21	5,06	129,74
std. dev.	0,44	0,36	0,13	1,82	0,58	1,37	3,21	3,10	0,26	7,90

Number of runs : 3

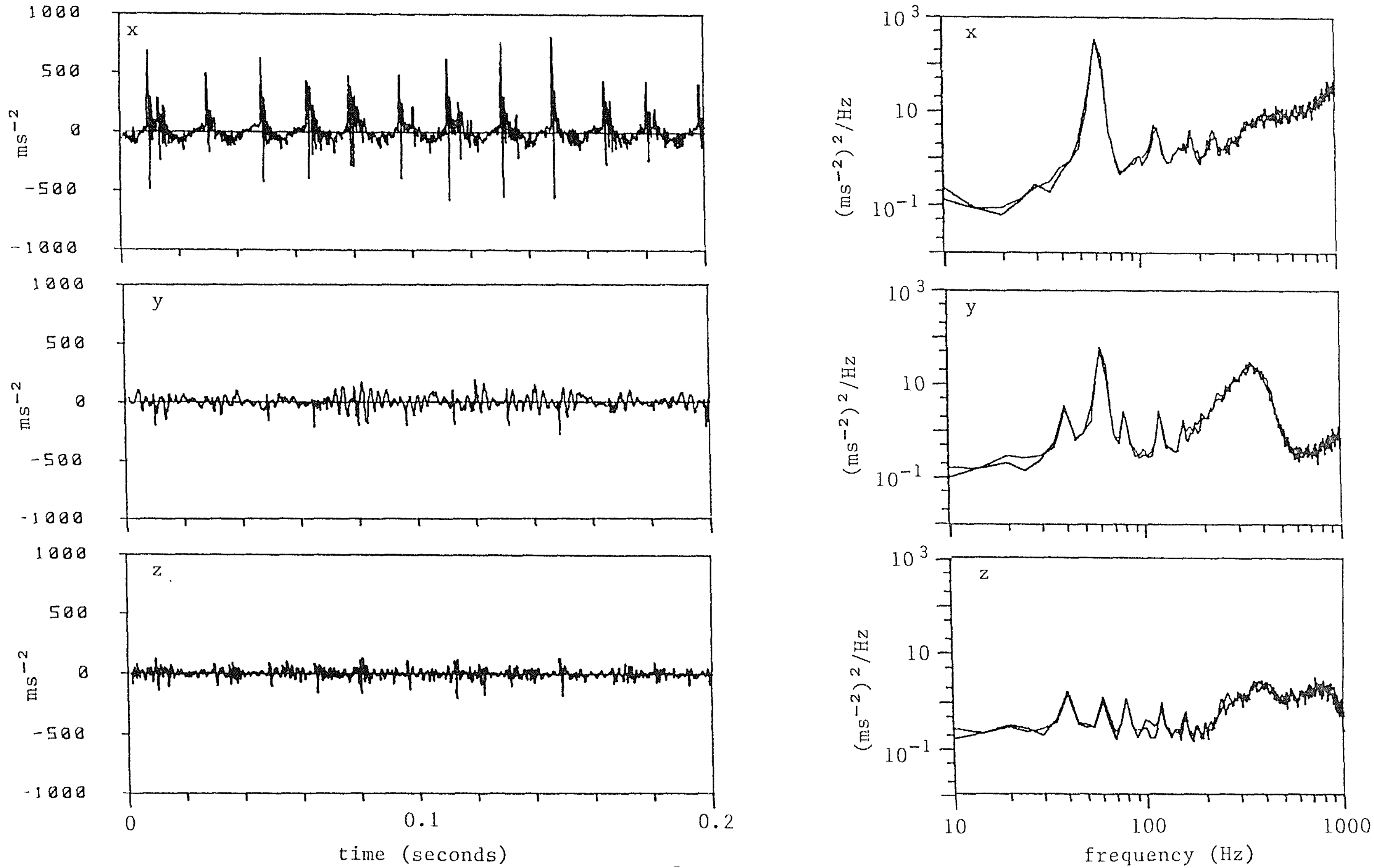


Figure B22 *Example acceleration time histories and two power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the handle of a pistol needle scaler, type Von Arx 23-B*

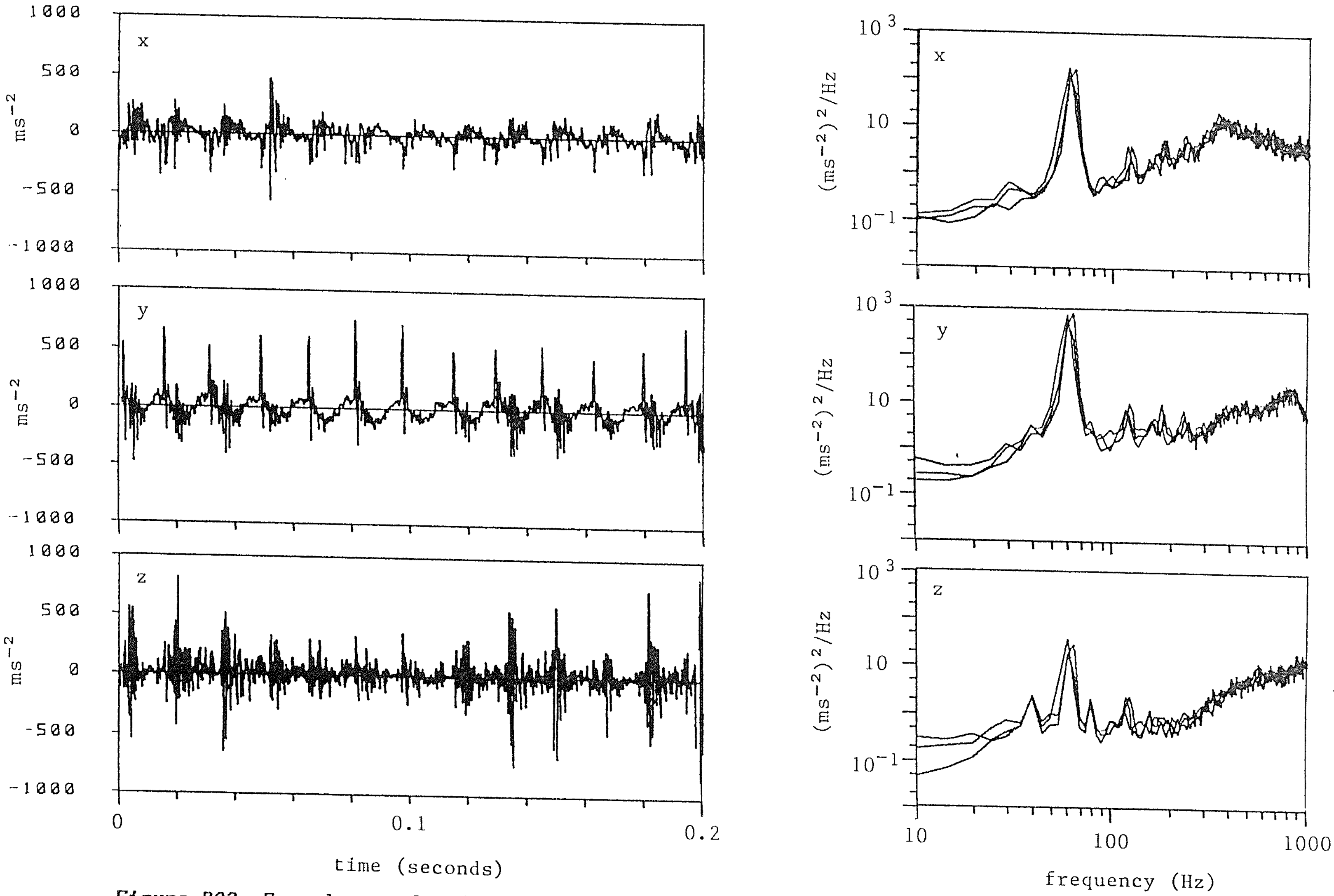


Figure B23 *Example acceleration time histories and three power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the barrel of a pistol needle scaler, type Von Arx 23-B*

Table B24 *Vibration acceleration magnitudes for chisel scaler, type CPT CP75 (trigger end)*

Octave band centre freq.		r.m.s. acceleration (ms^{-2})									
		8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis,	mean	0,28	0,36	0,96	3,79	5,13	6,55	15,94	24,90	1,63	46,40
	std. dev.	0,00	0,05	0,78	0,69	0,13	1,42	5,97	0,96	0,20	10,59
y-axis,	mean	0,91	1,39	5,43	42,31	109,53	39,01	23,06	27,59	19,14	126,79
	std. dev.	0,06	0,30	0,68	34,38	6,82	4,84	3,66	5,36	0,42	0,94
z-axis,	mean	1,20	1,73	4,79	7,23	10,30	7,51	12,19	22,29	3,73	38,60
	std. dev.	0,23	0,42	0,98	1,09	1,27	0,09	0,14	2,60	0,09	1,91

Number of runs : 2

Table B25 *Vibration acceleration magnitudes for chisel scaler, type CPT CP75 (chisel end)*

Octave band centre freq.		r.m.s. acceleration (ms^{-2})									
		8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis,	mean	0,36	1,41	6,53	12,18	17,04	19,92	27,87	56,14	5,24	86,88
	std. dev.	0,02	0,30	4,55	3,46	4,20	0,29	1,63	12,70	1,11	11,98
y-axis,	mean	1,11	1,52	4,88	58,10	103,43	33,56	17,68	18,35	19,05	120,28
	std. dev.	0,13	0,04	0,71	16,06	13,40	4,55	0,69	2,02	0,61	7,41
z-axis,	mean	1,20	1,79	8,86	17,83	17,40	15,82	23,63	45,69	6,95	72,05
	std. dev.	0,20	0,13	0,14	1,16	4,70	3,37	2,64	2,00	0,64	0,15

Number of runs : 2

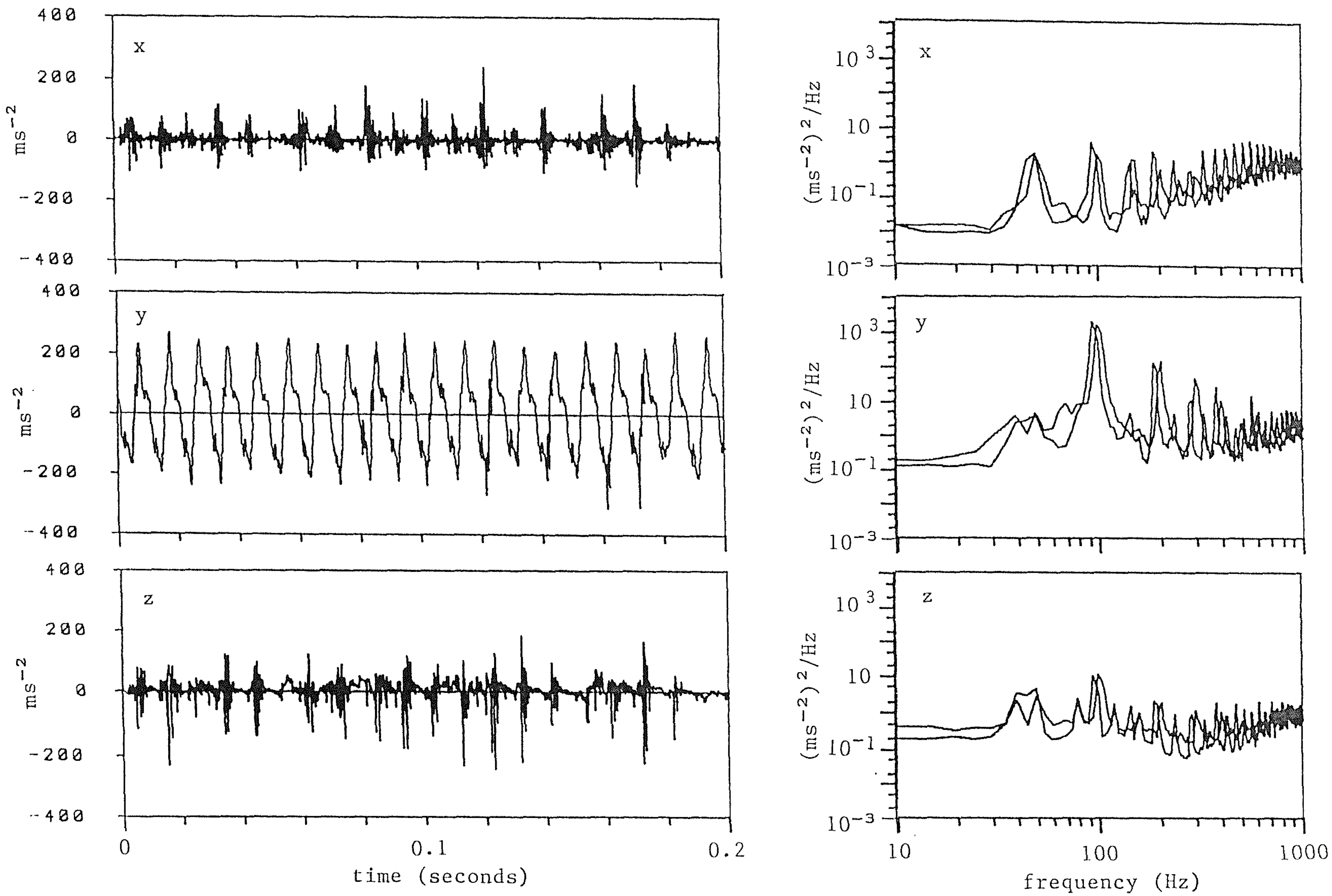


Figure B24 Example acceleration time histories and two power spectral density functions (resolution = 4.88 Hz) for three axes of vibration at the triger end of a chisel scaler, type CPT CP75

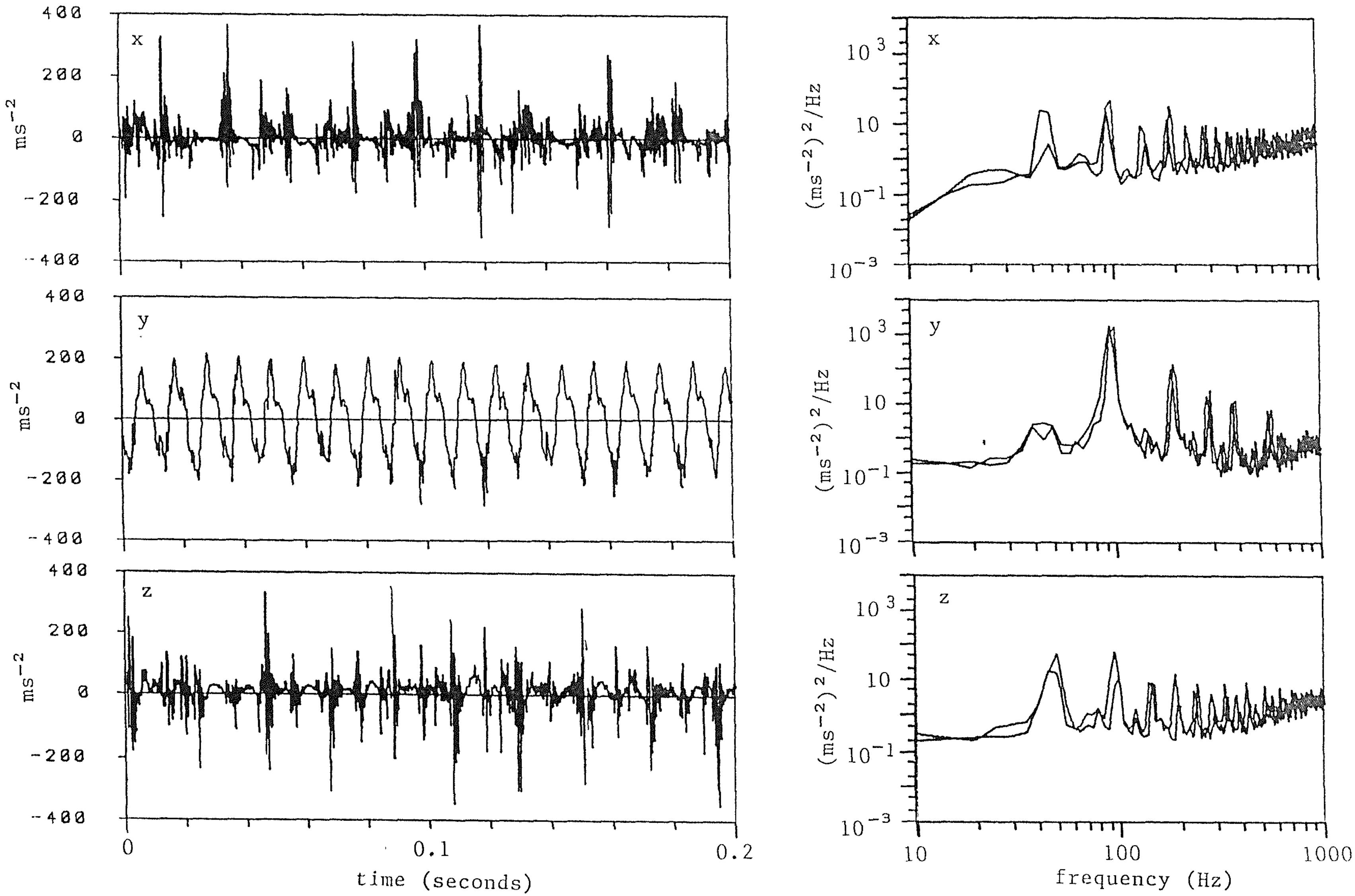


Figure B25 *Example acceleration time histories and two power spectral density functions (resolution = 4.88 Hz) for three axes of vibration at the chisel end of a chisel scaler, type CPT CP75*

Table B26 Vibration acceleration magnitudes for impact wrench type Atlas Copco LMS 36 HR 13

Octave band centre freq.		r.m.s. acceleration (ms^{-2})									
		8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis,	mean	0,50	1,48	0,95	1,04	1,58	5,74	8,88	21,71	1,68	29,23
	std. dev.	0,16	0,07	0,11	0,16	0,02	0,69	0,17	3,25	0,11	2,33
y-axis,	mean	0,70	2,09	3,25	4,71	7,26	29,83	7,91	9,02	3,36	34,34
	std. dev.	0,22	0,21	0,66	0,18	0,17	4,73	1,03	1,41	0,13	4,45
z-axis,	mean	1,14	2,21	4,97	7,07	12,00	13,74	17,06	21,81	4,03	38,56
	std. dev.	0,10	0,16	0,17	0,31	0,16	0,42	1,56	1,73	0,10	0,23

Number of runs : 2

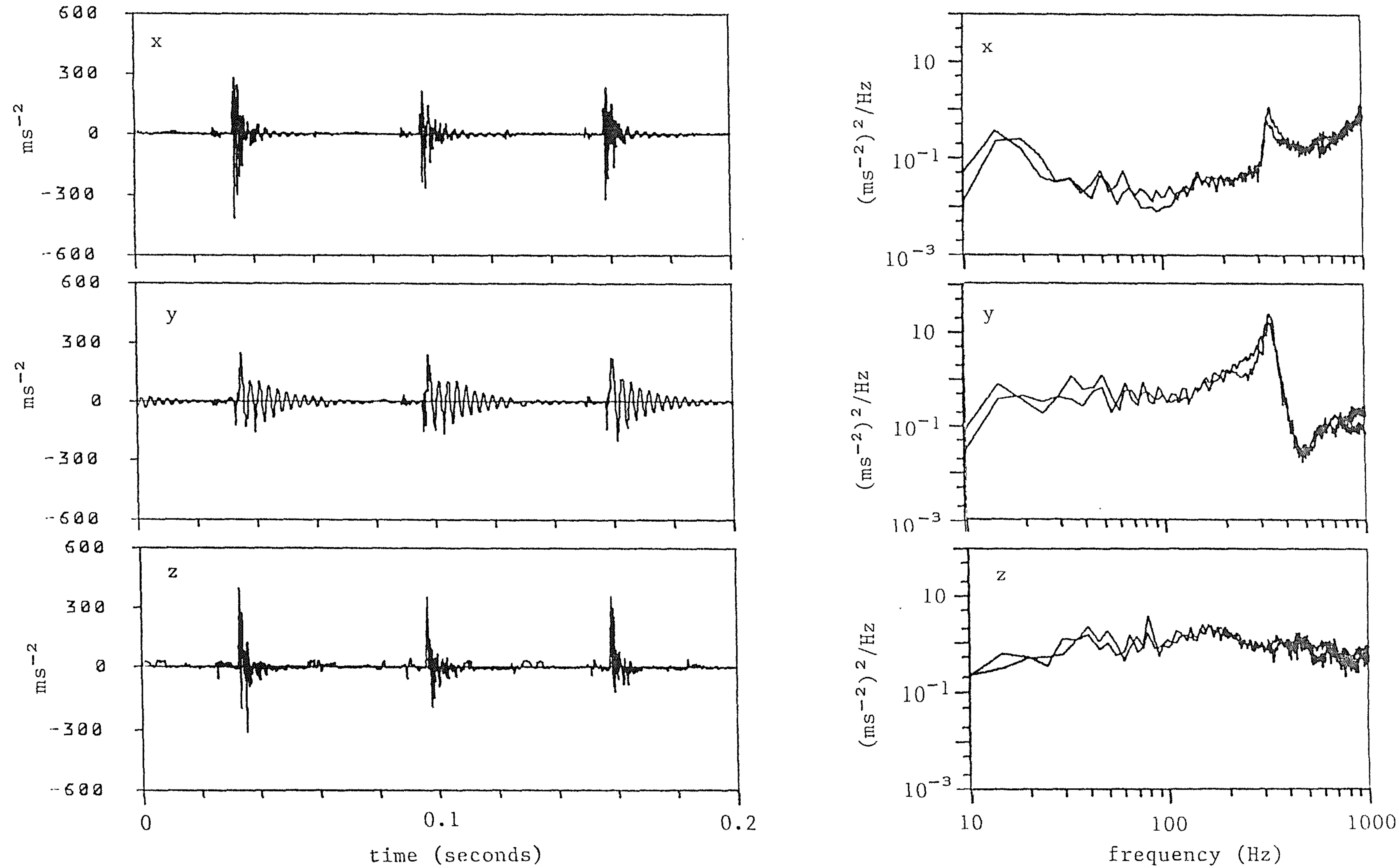


Figure B26 Example acceleration time histories and two power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the handle of an impact wrench type Atlas Copco LMS 36 HR 13

Table B27 Vibration acceleration magnitudes for power hacksaw type Cengar (trigger end)

	r.m.s. acceleration (ms^{-2})									
Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis, mean	1,62	3,80	4,87	8,08	4,41	7,00	12,67	11,06	5,16	24,13
std. dev.	0,21	0,42	0,04	0,06	0,42	0,16	1,52	1,47	0,21	1,20
y-axis, mean	1,36	3,18	2,36	5,77	7,02	13,15	17,23	16,31	4,06	30,20
std. dev.	0,07	0,83	0,42	1,10	1,63	1,30	2,52	0,35	0,81	2,64
z-axis, mean	1,13	2,31	1,88	1,34	1,05	2,05	10,61	6,23	2,74	14,05
std. dev.	0,62	0,35	0,30	0,15	0,02	0,02	2,20	0,55	0,54	1,36

Number of runs ; 2

Table B28 Vibration acceleration magnitudes for power hacksaw type Cengar (barrel)

	r.m.s. acceleration (ms^{-2})									
Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
x-axis, mean	0,49	1,54	1,01	0,98	1,32	2,51	4,65	6,98	1,73	10,46
std. dev.	0,13	0,45	0,18	0,10	0,21	0,59	0,94	2,01	0,40	1,39
y-axis, mean	0,99	3,32	3,49	8,03	5,27	4,75	7,73	4,55	4,37	15,73
std. dev.	0,28	0,98	0,12	0,08	0,56	0,73	1,68	0,73	0,79	0,59
z-axis, mean	0,33	1,18	1,76	5,86	7,33	6,30	7,34	4,01	2,22	14,48
std. dev.	0,01	0,10	0,45	2,72	1,94	1,93	1,74	0,54	0,61	3,85

Number of runs ; 2

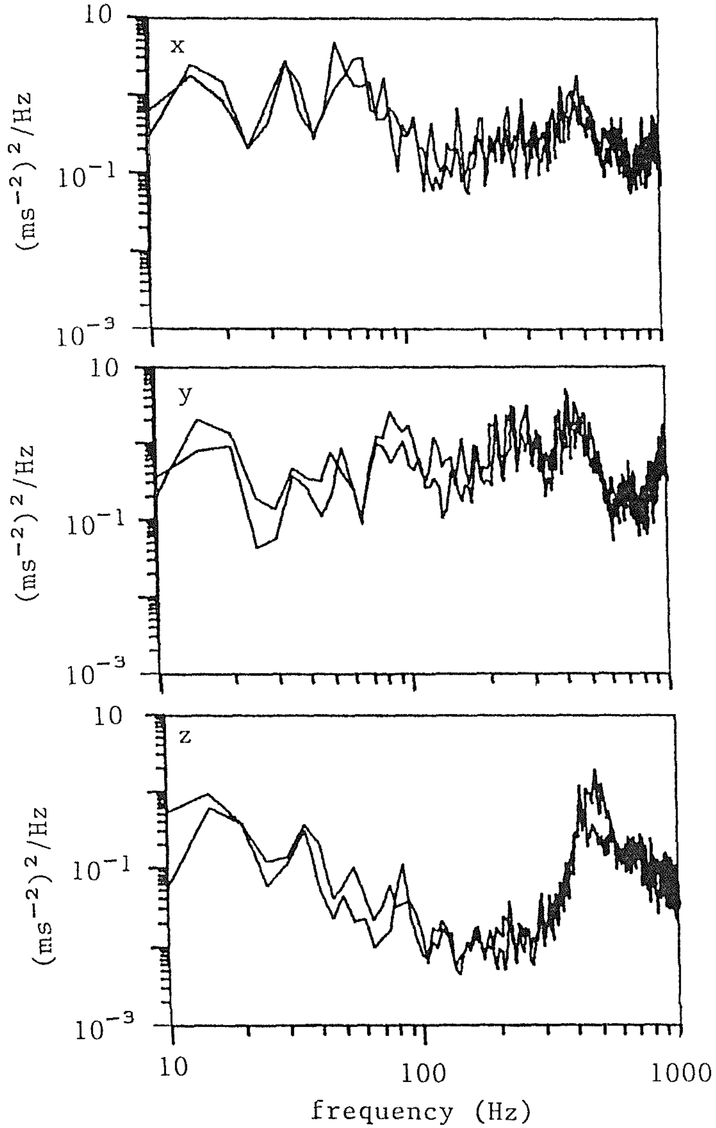


Figure B27 Two acceleration power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the handle of a Cengar power hacksaw

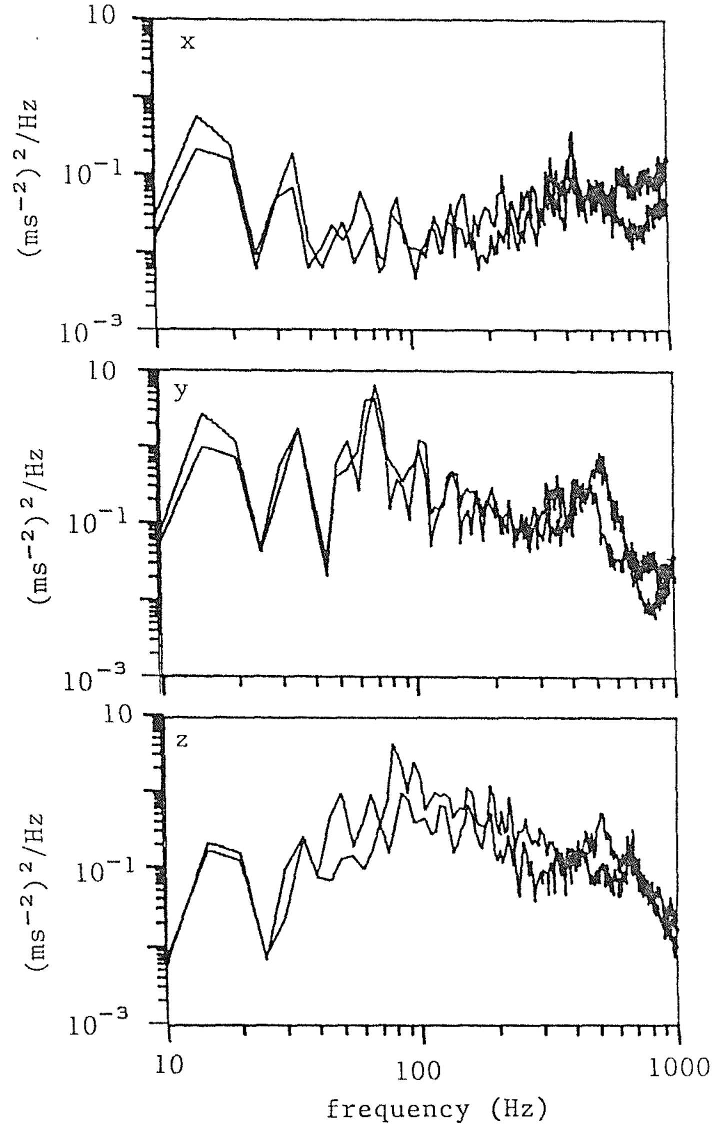


Figure B28 Two acceleration power spectral density functions (resolution = 4.88 Hz) for three axes of vibration on the barrel of a Cengar power hacksaw

APPENDIX C

ADDITIONAL VIBRATION DATA

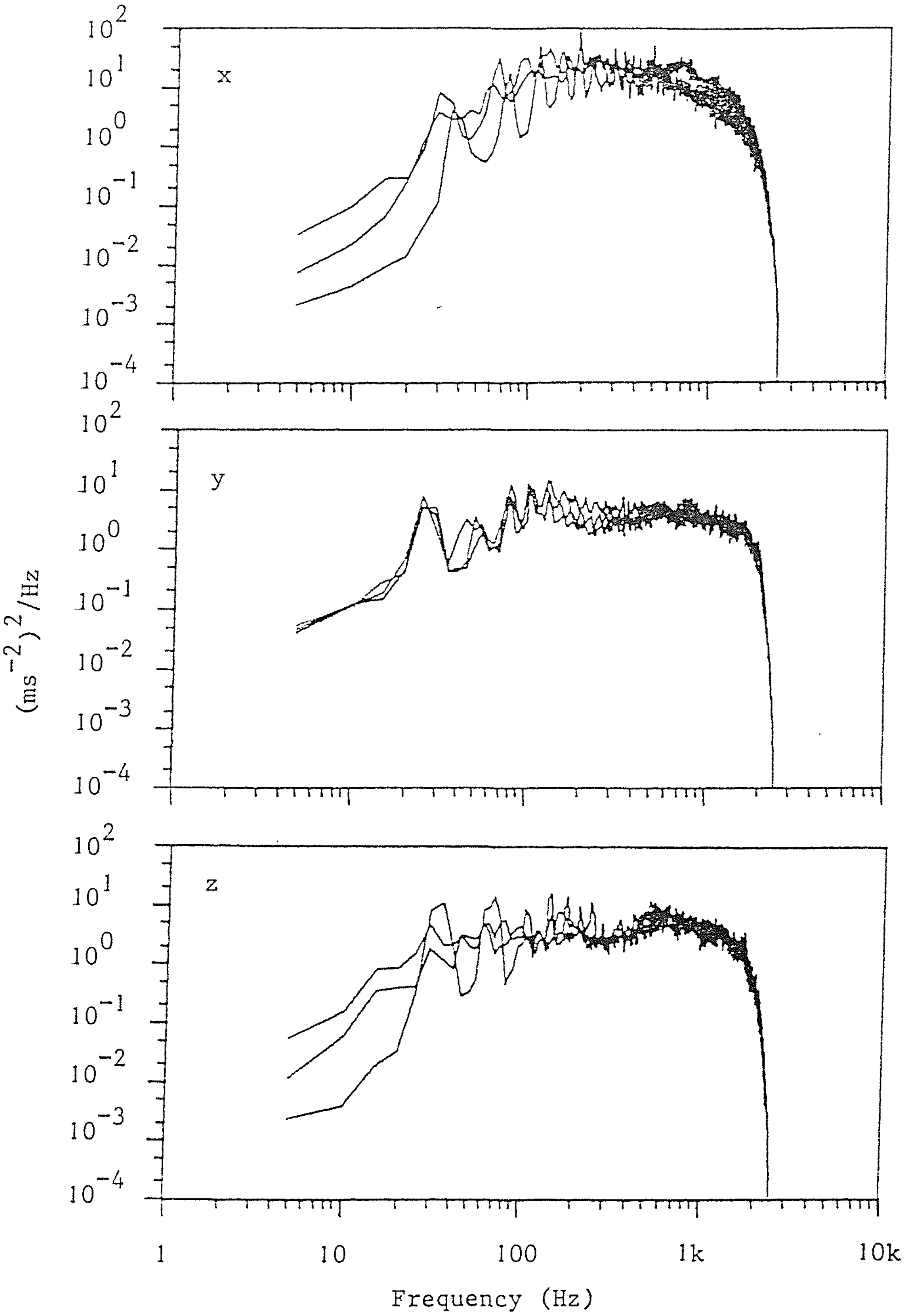


Figure C1 Acceleration power spectral density functions for vibration measured in three axes on the chisel of a chipping hammer using a laser doppler vibrometer. (Resolution = 4.88 Hz.)

Table C1 *Weighted and unweighted acceleration magnitudes (ms^{-2} r.m.s.) measured on the chisel of a chipping hammer with a laser doppler vibrometer*

Axis		Weighted	Unweighted
x-axis	Run 1	7.31	114.33
	Run 2	9.28	126.44
	Run 3	10.27	153.96
	Mean	8.95	131.58
	Std Dev.	1.51	20.31
y-axis	Run 1	6.57	76.80
	Run 2	5.99	71.44
	Run 3	7.03	83.09
	Mean	6.53	77.11
	Std Dev.	0.52	5.83
z-axis	Run 1	6.27	79.25
	Run 2	6.93	82.42
	Run 3	5.55	85.70
	Mean	6.25	82.46
	Std Dev.	0.69	3.23

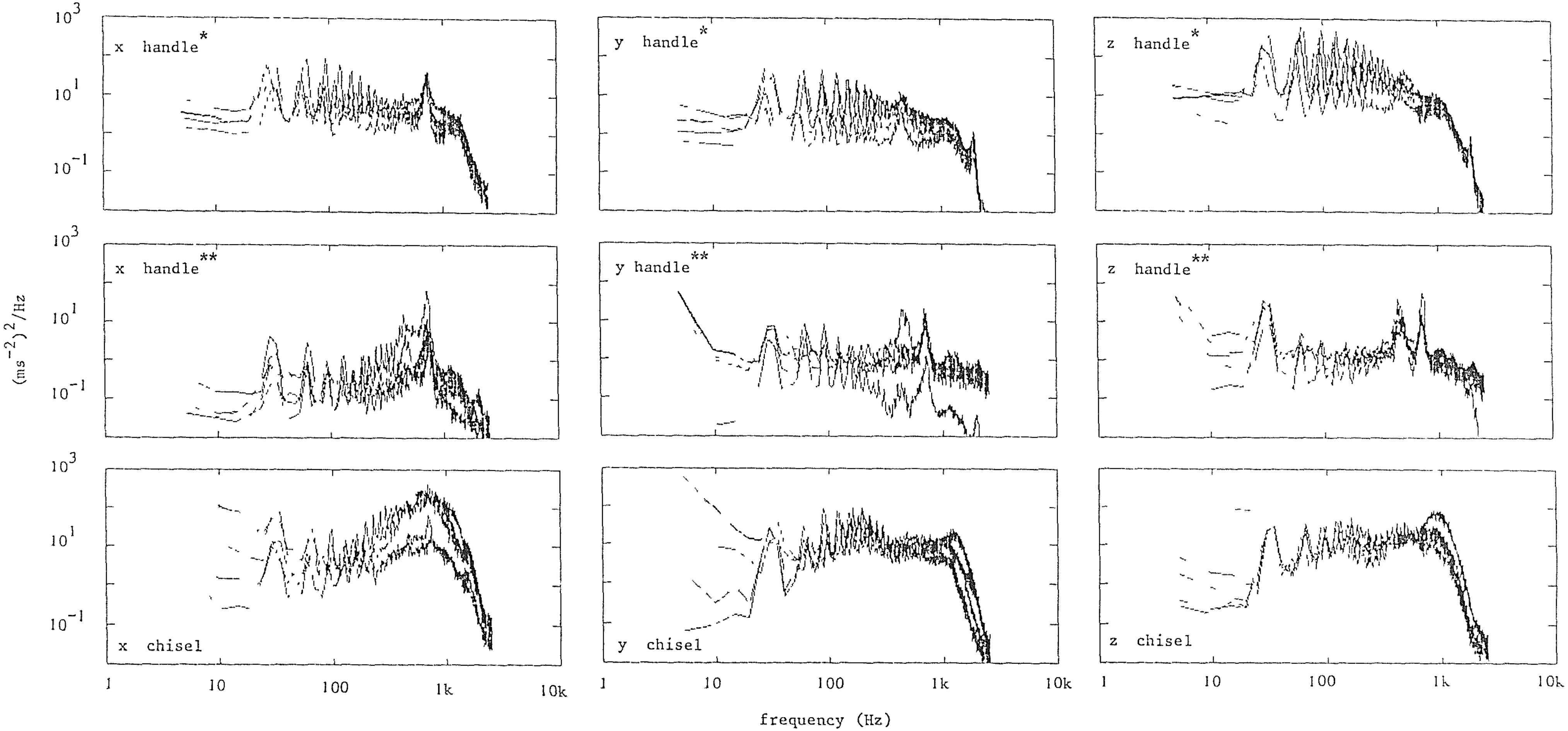


Figure C2 *Accceleration power spectral density functions (resolution = 4.88 Hz) from additional measurements on a chipping hammer type CPT Boyer Superior No. 1*
** Piezoelectric accelerometers/mechanical filters*
*** Piezoresistive accelerometers*

Table C2 *Acceleration magnitudes (ms^{-2} r.m.s.) from additional vibration measurements on a chipping hammer type CPT Boyer No. 1 operating on the PNEUROP test rig*

	Weighted		Unweighted	
	Mean	S. Dev.	Mean	S. Dev.
Handle*				
x-axis	13.13	4.71	86.35	21.96
y-axis	10.56	3.84	64.02	17.48
z-axis	28.68	8.81	161.89	46.64
Handle**				
x-axis	2.53	0.89	38.93	21.36
y-axis	6.12	1.27	51.03	18.05
z-axis	9.75	1.83	70.99	8.41
Chisel				
x-axis	21.51	15.78	245.73	134.07
y-axis	19.39	9.48	127.61	23.30
z-axis	22.38	24.65	167.29	48.41

Number of runs: 5

* Piezoelectric accelerometers/mechanical filters
** Piezoresistive accelerometers

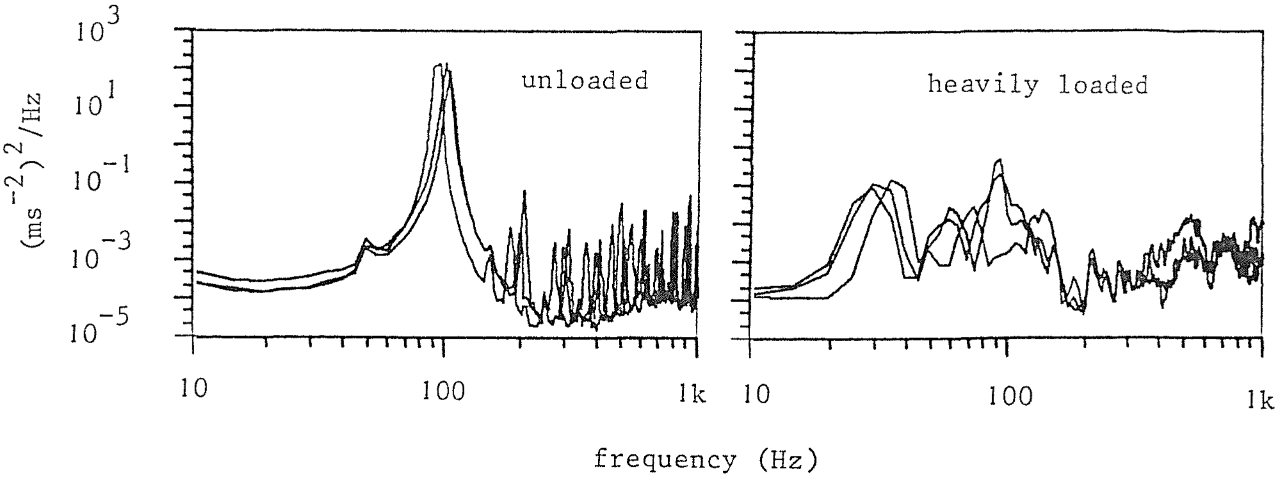


Figure C3 Acceleration power spectral density functions for y-axis vibration on the right handle of a vertical grinder with small and large loading forces (Resolution = 4.88 Hz)

Table C3 *Vibration acceleration magnitudes for a vertical grinder type Thor 5VL 40962T showing the effect of loading force*

	r.m.s. acceleration (ms^{-2})									
Octave band centre freq.	8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
Free running, speed approx. 6000 r.p.m.										
mean	0.06	0.05	0.09	10.50	26.99	0.43	0.60	0.90	4.99	30.49
std. dev.	0.00	0.00	0.02	13.31	3.24	0.26	0.07	0.32	1.24	5.69
Heavily loaded, speed approx. 1200 r.p.m.										
mean	0.06	0.20	0.99	1.09	1.22	0.27	0.84	1.00	0.59	2.43
std. dev.	0.01	0.14	0.17	0.51	0.46	0.04	0.37	0.45	0.07	0.26

Number of runs : 3 in each condition

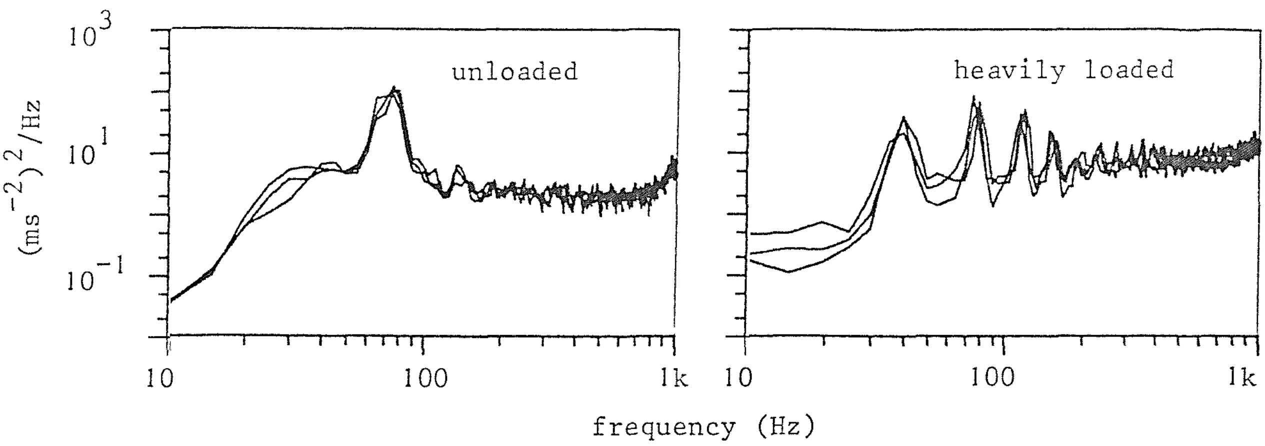


Figure C4 Acceleration power spectral density functions for y-axis vibration at the trigger end of a needle scaler with large and small loading forces (Resolution = 4.88 Hz)

Table C4 Vibration acceleration magnitudes for needle scaler type Trelawney showing the effects of loading force

Octave band centre freq.	r.m.s. acceleration (ms^{-2}) 8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
Free running, unloaded ;										
mean	0,45	2,72	9,55	40,26	16,76	19,99	26,23	56,38	10,57	79,82
std. dev.	0,02	0,52	0,70	0,53	0,35	0,72	1,65	2,75	0,12	1,97
Heavily loaded ;										
mean	1,14	1,88	15,71	24,18	29,06	35,68	52,81	78,16	9,83	109,21
std. dev.	0,30	0,55	1,08	1,89	0,87	2,99	4,82	7,29	0,27	8,63

Number of runs ; 3 in each condition

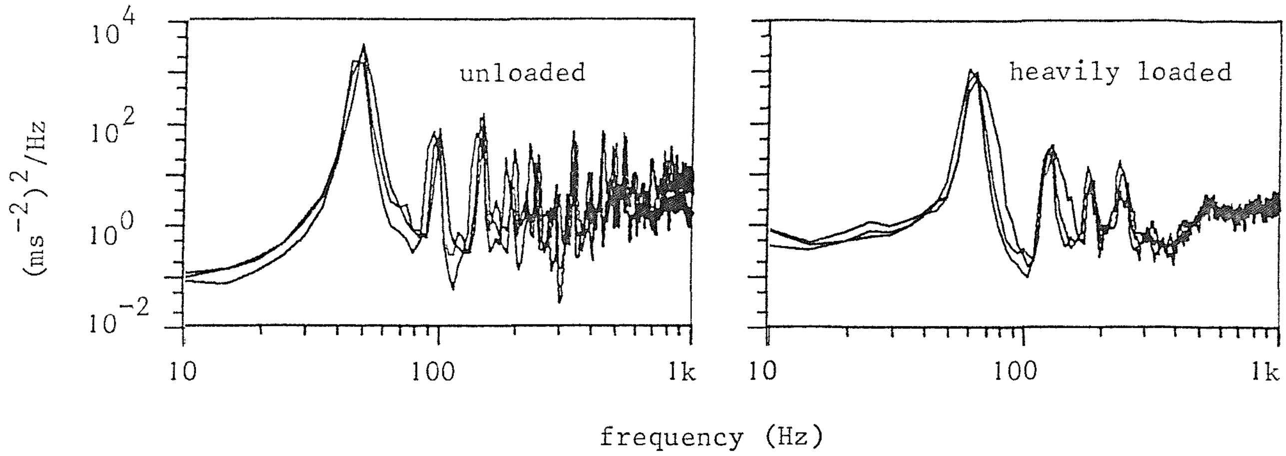


Figure C5 Acceleration power spectral density functions for z-axis vibration at the piston end of a nobbler with large and small loading forces (Resolution = 4.88 Hz)

Table C5 Vibration acceleration magnitudes for nobbler type CPT no. 5 showing the effects of loading force

Octave band centre freq.	r.m.s. acceleration (ms^{-2}) 8	16	32	64	128	256	512	1024	$a_{h,w}$	a_{lin}
Free running, unloaded ;										
mean	0,73	1,44	53,24	115,17	37,21	28,12	41,31	56,59	43,30	155,65
std. dev.	0,07	0,23	22,63	20,11	3,58	2,62	13,98	18,87	1,86	18,69
Heavily loaded ;										
mean	2,16	2,52	5,41	94,83	22,20	18,17	23,68	37,76	24,69	109,14
std. dev.	0,58	0,34	0,41	3,61	0,91	2,60	1,23	2,59	1,55	2,51

Number of runs ; 3 in each condition

APPENDIX D

POWER TOOLS IDENTIFIED BY VIBRATION-EXPOSED DOCKYARD EMPLOYEES

POWER TOOLS IDENTIFIED BY DOCKYARD EMPLOYEES

‡ = Vibration measurements made on tool (Chapter 3)

† = Tool considered in dose-effect relationhips (Chapter 5)

	Reference Number	Tool Description	Number of Individuals
† ‡	1	Chipping hammer (for steel)	453
†	2	Riveting hammer	301
† ‡	3	Pistol drilling machine	446
† ‡	4	Morse drilling machine	392
† ‡	5	Vertical grinder	498
† ‡	6	Angle grinder	298
† ‡	7	End grinder	70
† ‡	8	Collet grinder	122
† ‡	9	Nobbler (scaling hammer)	466
† ‡	10	Needle scaler	418
† ‡	11	Chisel scaler	507
† ‡	12	Chipping hammer (for cement)	307
† ‡	13	Impact wrench	275
	14	Chain saw	79
	15	Jig saw	116
	16	Circular (Skill) saw	85
† ‡	17	Cengar saw (power hack saw)	353
	18	Nibbler	153
†	19	Sander	28
	20	Pistol saw	3
	21	(Not allocated)	-
	22	Stapler	10
† ‡	23	Vertical sander	154
	24	Vibrating (orbital) sander	36
	25	Belt sander	27
	26	Planer	4

	Reference Number	Tool Description	Number of Individuals
	27	(Not allocated)	–
† ‡	28	Power wire brush	340
	29	Flap wheel	1
	30	Drum scaler	2
	31	Flail scaler	2
	32	Roll pick	24
† ‡	33	Pistol needle scaler	30
	34	Pistol sander	4
†	35	Tube expander	154
	36	Nutsert	1
	37	Large rotating sander	4
	38	Router	2
	39	Spindle moulder	1
	40	Nailer	2
	41	Laminate cutter	3
	42	(Not allocated)	–
	43	Shoe polisher	1
	44	Engraver	2
	45	McDonald gun	2
	46	3-headed nobbler	1
	47	Press	1
	48	Salt drill	1
	49	Hole cleaner	1
	50	Wood drill	1
	51	(Not allocated)	–
	52	(Not allocated)	–
	53	Rivet buster	1
	54	(Not allocated)	–
	55	Jumping jack	9
	56	Band saw	40
	57	Wood lather	7

Reference Number	Tool Description	Number of Individuals
58	Rotary pump	2
59	Testing various tools in store	6
60	Kango hammer	44
61	Scriber	1
62	Power float	2
63	Huckbolt	1
64	Power vane	1
65	Floor polisher	3
66	Jack hammer	88
67	Concrete vibrator	11
68	Paint stirrer	3
69	Hilti nailer	6
70	(Not allocated)	-
71	Road roller	2
72	Fork lift truck	1
73	Plate cutter	1
74	Scabbling gun	2
75	Machine gun (military service)	2
76	Wall nobbler	2
77	Rock drill	1
78	Tube cutter	1
79	Car polisher	3
80	Power screwdriver	6
81	Hammer drill	14
82	Pedestal grinder	82
83	Large nibbling machine	23
84	Forging hammer	18
85	Hot saw	7
86	Chipping hammer (sand packing)	5
87	Fret saw	1
88	Car panel chisel gun	6

Reference Number	Tool Description	Number of Individuals
89	Bench circular saw	4
90	DIY power tools	67
91	Motor cycle	516
92	Motor mower	20
93	Outboard motor	6
94	(Not allocated)	-
95	Inflatable sander	1
96	Disc cutter	1
97	Hand press	
98	(Not allocated)	-
99	Power file	1

APPENDIX E

NONPARAMETRIC CORRELATION MATRICES
FOR TOTAL EXPOSURE TIMES
FOR DIFFERENT PNEUMATIC TOOLS

Table E1 *Kendall correlation coefficients (and significance levels) for total exposure times for ten pneumatic tools used by combined trades (including caulker/riveters, burners and drillers), N = 126*

	CH	RH	PD	MD	VG	AG	EG	CG	IW	HS
CH	1,00 (0,00)	0,50 (0,00)	-0,27 (0,00)	-0,17 (0,00)	0,65 (0,00)	0,39 (0,00)	0,38 (0,00)	0,21 (0,00)	0,15 (0,20)	0,37 (0,00)
RH	- -	1,00 (0,00)	-0,11 (0,04)	-0,04 (0,29)	0,38 (0,00)	0,27 (0,00)	0,21 (0,00)	0,09 (0,09)	0,22 (0,00)	0,34 (0,00)
PD	- -	- -	1,00 (0,00)	0,60 (0,00)	-0,22 (0,00)	-0,10 (0,08)	-0,21 (0,00)	-0,06 (0,19)	-0,10 (0,08)	-0,08 (0,14)
MD	- -	- -	- -	1,00 (0,00)	-0,13 (0,02)	-0,11 (0,05)	-0,22 (0,00)	-0,04 (0,30)	-0,01 (0,44)	-0,11 (0,05)
VG	- -	- -	- -	- -	1,00 (0,00)	0,38 (0,00)	0,25 (0,00)	0,27 (0,00)	0,01 (0,42)	0,25 (0,00)
AG	- -	- -	- -	- -	- -	1,00 (0,00)	0,23 (0,00)	0,44 (0,00)	0,05 (0,27)	0,16 (0,01)
EG	- -	- -	- -	- -	- -	- -	1,00 (0,00)	-0,09 (0,13)	0,16 (0,03)	0,26 (0,00)
CG	- -	- -	- -	- -	- -	- -	- -	1,00 (0,00)	0,01 (0,43)	0,03 (0,34)
IW	- -	- -	- -	- -	- -	- -	- -	- -	1,00 (0,00)	0,16 (0,02)
HS	- -	- -	- -	- -	- -	- -	- -	- -	- -	1,00 (0,00)

Key:

CH Chipping hammer
RH Riveting hammer
PD Pistol drilling machine
MD Morse drilling machine
VG Vertical grinder
AG Angle grinder
EG End grinder
CG Collet grinder
IW Impact wrench
HS Power hacksaw

Table E2 Kendall correlation coefficients (and significance levels) for total exposure times for eleven pneumatic tools used by boilermakers, N = 179

	CH	RH	PD	MD	VG	AG	EG	CG	IW	HS	TE
CH	1,00 (0,00)	0,26 (0,00)	-0,09 (0,13)	0,41 (0,00)	0,15 (0,03)	-0,18 (0,01)	0,27 (0,00)	0,05 (0,27)	0,20 (0,00)	0,18 (0,01)	0,73 (0,00)
RH	- -	1,00 (0,00)	0,05 (0,24)	0,29 (0,00)	-0,02 (0,41)	0,03 (0,35)	0,11 (0,08)	-0,05 (0,26)	0,01 (0,44)	0,07 (0,16)	0,20 (0,00)
PD	- -	- -	1,00 (0,00)	0,28 (0,00)	0,24 (0,00)	0,26 (0,00)	-0,31 (0,00)	0,09 (0,11)	0,25 (0,00)	0,35 (0,00)	-0,04 (0,32)
MD	- -	- -	- -	1,00 (0,00)	0,24 (0,00)	-0,05 (0,25)	0,13 (0,04)	-0,01 (0,43)	0,34 (0,00)	0,39 (0,00)	0,28 (0,00)
VG	- -	- -	- -	- -	1,00 (0,00)	0,10 (0,08)	-0,19 (0,01)	0,06 (0,21)	0,38 (0,00)	0,29 (0,00)	0,09 (0,40)
AG	- -	- -	- -	- -	- -	1,00 (0,00)	-0,27 (0,00)	0,22 (0,00)	0,17 (0,01)	0,16 (0,01)	-0,08 (0,14)
EG	- -	- -	- -	- -	- -	- -	1,00 (0,00)	-0,13 (0,04)	-0,22 (0,00)	-0,16 (0,02)	0,12 (0,05)
CG	- -	- -	- -	- -	- -	- -	- -	1,00 (0,00)	0,06 (0,20)	0,07 (0,19)	0,04 (0,28)
IW	- -	- -	- -	- -	- -	- -	- -	- -	1,00 (0,00)	0,43 (0,00)	0,25 (0,00)
HS	- -	- -	- -	- -	- -	- -	- -	- -	- -	1,00 (0,00)	0,27 (0,00)
TE	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	1,00 (0,00)

Key:

CH Chipping hammer
PD Pistol drilling machine
VG Vertical grinder
EG End grinder
IW Impact wrench
TE Tube expander
RH Riveting hammer
MD Morse drilling machine
AG Angle grinder
CG Collet grinder
HS Power hacksaw

Table E1 *Kendall correlation coefficients (and significance levels) for total exposure times for five pneumatic tools used by painters, N = 412*

	N	CS	NS	CH	WB
N	1.00	0.27	0.62	0.54	0.40
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
CS	-	1.00	0.25	0.27	0.40
	-	(0.00)	(0.00)	(0.00)	(0.00)
NS	-	-	1.00	0.50	0.29
	-	-	(0.00)	(0.00)	(0.00)
CH	-	-	-	1.00	0.43
	-	-	-	(0.00)	(0.00)
WB	-	-	-	-	1.00
	-	-	-	-	(0.00)

Key:

N Nobbler

CS Chisel scaler

NS Needle scaler

CH Chipping hammer

WB Power wire brush

REFERENCES

Agate, J.N. (1949) An outbreak of Raynaud's phenomenon of occupational origin. *British Journal of Industrial Medicine*, **6**, 144-163.

Agate, J.N., Druett, H.A. (1946) A method for studying vibrations transmitted to the hands. *British Journal of Industrial Medicine*, **3** (3), 159-166.

Agate, J.N., Druett, H.A. (1947) A study of portable vibrating tools in relation to the clinical effects which they produce. *British Journal of Industrial Medicine*, **4** (3), 141-163.

Asanova, T.P. (1975) Vibration disease among workers using portable power tools in Finnish shipyards. Vibration and Work. *Proceedings of the Finnish-Soviet-Scandinavian Vibration Symposium, Helsinki, 10-13 March*, 52-62.

Auerbach, E.I. (1982) An investigation of chipping hammer vibration. In *Vibration Effects on the Hand and Arm in Industry*, eds. Brammer, A.J. and Taylor, W., Wiley, 311-315.

Barber, A.D. (1982) Standard methods of measurement of vibration in pneumatic tools. Paper presented at the United Kingdom Informal Group Meeting on Human Response to Vibration held at the Health and Safety Executive, Cricklewood, London, 16-17 September 1982.

Behrens, D., Taylor, W., Wasserman, D. (1982) Vibration syndrome in workers using chipping and grinding tools. In *Vibration Effects on the Hand and Arm in Industry*, eds. Brammer, A.J. and Taylor, W., Wiley, 147-155.

Behrens, V., Taylor, W., Wilcox, T., Miday, R., Spaeth, S., Burg, J., Wasserman, D., Reynolds, D., Doyle, T., Carlson, W., Smith, R., Samueloff, S., Howie, G., Rappaport, M. (1984) Vibration syndrome in chipping and grinding workers. *Journal of Occupational Medicine*, **26**, 765-788.

Bovenzi, M., Giansante, C., Fiorito, A., Calabrese, S. (1985) Relation of haemostatic function, neurovascular impairment and vibration exposure in workers with different stages of vibration-induced white finger. *British Journal of Industrial Medicine*, **42**, 253-259.

Bovenzi, M., Petronio, L., DiMarino, F. (1980) Epidemiological survey of shipyard workers exposed to hand-arm vibration. *International Archives of Occupational Environmental Health*, **46**, 251-266.

Brammer, A.J. (1977) Vibration-induced disorders of the hand: symptoms and their control. Paper presented to the Canadian Acoustical Association, 26 October 1977.

Brammer, A.J. (1982a) Relations between vibration exposure and the development of the vibration syndrome. In *Vibration Effects on the Hand and Arm in Industry*, eds. Brammer, A.J. and Taylor, W., Wiley, 283-290.

Brammer, A.J. (1982b) Threshold limit for hand-arm vibration exposure throughout the workday. In *Vibration Effects on the Hand and Arm in Industry*, eds. Brammer, A.J. and Taylor, W., Wiley, 291-301.

Brammer, A.J. (1983) Dose-response relationships for the hand-arm vibration syndrome, with reference to neuro-vegetative effects. *Journal of Low Frequency Noise and Vibration*, **1** (1983): special issue, 151-162.

Brammer, A.J. (1986) Dose-response relationships for hand-transmitted vibration. *Scandinavian Journal of Work, Environment and Health*, **12** (4), 284-288.

Brammer, A.J., Taylor, W., Piercy, J.E. (1986) Assessing the deverity of the neurological component of the hand-arm vibration syndrome. *Scandinavian Journal of Work, Environment and Health*, **12** (4), 428-431.

Brammer, A.J., Taylor, W., Lundborg, G. (1987) Sensorineural stages of the hand-arm vibration syndrome. *Scandinavian Journal of Work, Environment and Health*, **13**, 297-283.

British Standards Institution (1975) *Draft for Development: Guide to the evaluation of exposure of the human hand-arm system to vibration*. DD43 (1975).

British Standards Institution (1987a) *British Standard Guide to Measurement and evaluation of human exposure to vibration transmitted to the hand*. BS 6842:1987.

British Standards Institution (1987b) *British Standard Guide to Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock*. BS 6841:1987.

Brocklehurst, T. (1945) Pseudo-Raynaud's disease due to electric vibratory tools. *The Medical Press and Circular*, **213**, 10-11.

Brückner, L., Eisler, L., Rosmanith, J., Volf, J. (1964) Die Folgen der Vibrationseinwirkungen auf die oberen Gliedmassen der Gussputzer (The result of the effect of vibration on the limbs of casting cleaners). *Int. Archiv für Gewerbepathologie und Gewerbehygiene*, **21**, 50-59.

Brubaker, R.L., Mackenzie, C.J.G., Hutton, S.G. (1986) Vibration-induced white finger among selected underground rock drillers in British Columbia. *Scandinavian Journal of Work, Environment and Health*, **12**, 296-300.

Brüel & Kjær (1978) *Piezoelectric accelerometers and vibration preamplifiers. Theory and Application Handbook.* Brüel & Kjær, Nærum, Denmark.

Brusl, H. (1978) Vibration assessment on pneumatic picks. *Sichere Arbeit*, **3**, 31-33.

Burström, L., Landstrom, U., Hagberg, M., Oberg, R. (1987) *Vibrationsexponering bland plastslagare inom tyngre verkstadsindustri. (Exposure to vibrations among sheet metal workers.)* Undersokningsrapport 1987:28, Arbetskyddsstyrelsen, Solna, ISSN 0347-2248.

Chatterjee, D.S., Barwick, D.D., Petrie, A. (1982) Exploratory electromyography in the study of vibration induced white finger in rock drillers. *British Journal of Industrial Medicine*, **39**, 89-97.

Cherchi, P., Cotza, R., Cao, C. (1968) Study of the vibrations produced by pneumatic hammers. *Securitas*, **53** (7), 65-90.

Chu, A. (1987) Zeroshift of piezoelectric accelerometers in pyroshock measurements. *The Shock and Vibration Bulletin*, **57** (Part 1), 71-80.

Clarke, J.B., Dalby, W., Gunn, J.F. (1986) Chipping hammer vibration. *Scandinavian Journal of Work, Environment and Health*, **12**, 351-354.

Clarke, J. B., Dalby, W. (1987) The sources and control of vibration from hand-held grinders. Paper presented at the United Kingdom Informal Group Meeting on Human Response to Vibration. Royal Military College of Science, Shrivenham, 21-22 September 1987.

Crosetti, L., Casalone, E., Meda, E. (1974) *An ergonomic evaluation of several modified pneumatic hammers.* European Coal and Steel Community Technical Report No. 16 Community Ergonomic Research Document 1522/74 e RCE.

Dandanell, R., Engström, K. (1984) Vibration measurements and analysis of percussion tools such as riveting hammers and bucking bars. Paper presented at United Kingdom Informal Group Meeting on Human Response to Vibration held at Heriot-Watt University, Edinburgh, 21-22 September 1984.

Dandanell, R., Engström, K. (1986) Vibration from riveting tools in the frequency range 6 Hz - 10 MHz and Raynaud's phenomenon. *Scandivanian Journal of Work, Environment and Health*, **12** (4), 338-342.

Department of Health and Social Security (1970) Industrial Injuries Advisory Council. Vibration syndrome - Interim Report. National Insurance (Industrial Injuries) Act 1965. Cmnd 5965. London, HMSO.

Department of Health and Social Security (1985) The social security (industrial injuries) (prescribed diseases) Amendment Regulation 1985. Statutory Instruments 1985 No. 159. London, HMSO. ISBN 0-11-056159-7.

Dart, E.E. (1946) Effects of high speed vibration tools on operators engaged in the airplane industry. *Occupational Medicine*, **1** (6), 515-550.

Dupuis, H., Schäffer, N. (1986) Effects of impulse vibration on the hand-arm system. *Scandivanian Journal of Work, Environment and Health*, **12** (4), 320-322.

Eklund, L., Hansson, J-E., Kihlberg, S. (1986) *The influence of the grinding wheel on the vibration level of grinders.* Undersokningsrapport 1986:36, Arbetarskyddsstyrelsen, Solna.

Eklund, L., Hansson, J-E., Kihlberg, S. (1987) Grinding wheels can affect health. *Noise and Vibration Control Worldwide*, **18** (3), 102-104.

Engström, K., Dandanell, R. (1986) Exposure conditions and Raynaud's phenomenpon among riveters in the aircraft industry. *Scandivanian Journal of Work, Environment and Health*, **12** (4), 293-295.

Eskenasy, J-J. (1972) Peripheral syncope due to vibrations. *Archives des Maladies Professionelles de Médecine du Travail et Sécurité Sociale*, **33**, 31-44.

European Committee of Manufacturers of Compressors, Vacuum Pumps and Pneumatic Tools (1978) *Vibrations in pneumatic hand-held tools - investigations on hand-held grinding machines.* PNEUROP Committee 17 "Vibrations".

European Committee of Manufacturers of Compressors, Vacuum Pumps and Pneumatic Tools (1980) *Vibrations in pneumatic hand-held tools - investigations on hand-held percussive tools.* PNEUROP Committee 17 "Vibrations".

European Committee of Manufacturers of Compressors, Vacuum Pumps and Pneumatic Tools (1983) *Test procedure for the measurement of vibration from hand-held (portable) power driven grinding machines.* PNEUROP report 6610.

European Committee of Manufacturers of Compressors, Vacuum Pumps and Pneumatic Tools (1985) *Test procedure for the measurement of vibration from chipping hammers.* PNEUROP report 661600.

Fawer, R. (1976) Occupational pathology due to vibrations of pneumatic hammers and pneumatic drills. *Arch. Mal. Prof.*, **37**, 739-760.

Fright, E. (1991) *A task analysis of operations involving the use of selected hand tools associated with vibration-induced white finger.* M.Sc. thesis, Loughborough University of Technology.

Frood, A.D.M. (1977) Test methods and some of the problems involved in measuring the vibration of hand-held pneumatic tools. *Proceedings of the International Occupational Hand-arm Vibration Conference, Cincinnati.* DHEW (NIOSH) Publication 77-170, 146-152.

Futatsuka, M. Safurai, T., Ariizumi, M. (1984) Preliminary evaluation of dose-effect relationships for vibration-induced white finger in Japan. *Int. Arch. Occup. Environ. Health*, **54**, 201-221.

Futatsuka, M., Yasutake, N., Sakurai, T., Matsumoto, T. (1985) Compatative study of vibration disease among operators of vibrating tools by factor analysis. *British Journal of Industrial Medicine*, **42**, 260-266.

Gemne, G., Pykkö, I., Taylor, W., Pelmear, P.L. (1987) The Stockholm Workshop Scale for the classification of cold-induced Raynaud's phenomenon in the hand-arm vibration syndrome (revision of the Taylor-Pelmear scale). *Scandivanian Journal of Work, Environment and Health, **13**, 275-278.*

Glass, S. W. (1979) Vibration analysis of high-cycle 5400 hand grinders used on flat steel plates. Arbete Och Halsa, Vetenskaplig Skriftserie, 1979: 32.

Griffin, M. J. (1980) *Vibration injuries of the hand and arm: their occurrence and the evolution of standards and limits.* Health and Safety Executive Research Paper 9. HMSO. ISBM 011 883271 9.

Griffin, M. J. (1981) Dose-effect relationships for vibration-induced white finger. *Proceedings of United Kingdom Informal Group Meeting on Human Response to Vibration*, Heriot-Watt University, Edinburgh, 9-11 September 1981, 112-127.

Griffin, M. J. (1982a) Hand-arm vibration standards and dose-effect relationships. In *Vibration Effects on the Hand and Arm in Industry*, eds. Brammer, A. J., Taylor, W., Wiley, 259-268.

Griffin, M. J. (1982b) *The effects of vibration on health.* Report prepared for the Health and Safety Directorate of the Commission of the European Communities, June 1982 (also I. S. V. R. Memorandum 632, Institute of Sound and Vibration Research, University of Southampton).

Griffin, M. J. (1990) *Handbook of Human Vibration.* Academic Press, London. ISBN 0-12-303040-4.

Griffin, M. J., Macfarlane, C. R., Norman, C. D. (1982) The transmission of vibration to the hand and the influence of gloves. In *Vibration Effects on the Hand and Arm in Industry*, eds. Brammer, A. J., Taylor, W., Wiley, .

Gurdjian, E. S., Walker, L. W. (1945) Traumatic vasospastic disease of the hand (white finger). *Journal of the American Medical Association*, **129** (10), 668-672.

Halliwell, N.A. (1979) Laser-Doppler measurement of vibratory surfaces: a portable instrument. *Journal of Sound and Vibration*, **62** (2), 312-315.

Hancock, D.M. (1989) A two step prcedure for the assessment of the vascular component of the hand-arm vibration syndrome (vibration white finger). *Proceedings of the Institute of Acoustics*, **11** (9), 435-454.

Hansson, J-E., Eklund, L., Kihlberg, S., Ostergren, C-E. (1987) Vibration in car repair work. *Applied Ergonomics*, **18. 1**, 57-63.

Harada, N., Matsumoto, T. (1979) Vibration disease in an iron foundry. *Proceedings of 9th Asian conference on Occupational Health, Seoul, Korea*, 253-257.

Harada, T., Fukuhara, K. (1958) On the hazards of upper extremities caused by portable pneumatic tools - especially on X-ray findings of workers' elbows. *Kobe Journal of Medical Sciences*, **4**, 179-184.

Harris, C.M., Crede, C.E. (1976) *Shock and Vibration Handbook*. Second Edition. McGraw-Hill, New York. ISBN 0-07-026799-5.

Hayward, R.A., Griffin, M.J. (1986) Measures of vibrotactile sensitivity in persons exposed to hand-arm vibration. *Scandivanian Journal of Work, Environment and Health*, **12** (4), 423-427.

Healy, M.J.R. (1988) *GLIM: an introduction*. Clarendon Press, Oxford. ISBN 0918522134.

Hempstock, T.I., O'Connor, D.E. (1974) The vibration characteristics of several processes which produce white finger. In *The Vibration Syndrome*, Academic Press, 51-60.

Hempstock, T.I., O'Connor, D.E. (1975a) The measurement of hand-transmitted vibration. In *Vibration White Finger in Industry*, eds. Taylor, W., Pelmear, P.L., Academic Press, ISBN 0 12 684550, 111–122.

Hempstock, T.I., O'Connor, D.E. (1975b) Evaluation of human exposure to hand-transmitted vibration. *Applied Acoustics*, **8**, 87–99.

Hempstock, T.I., O'Connor, D.E. (1977) Evaluation of human exposure to hand-transmitted vibration. *Proceedings of the International Occupational Hand-arm Vibration Conference, Cincinnati*. DHEW (NIOSH) Publication 77-170, 129–135.

Hempstock, T.I., O'Connor, D.E. (1978) Assessment of hand-transmitted vibration. *Annals of Occupational Hygiene*, **21**, 57–67.

Heslop, J., Coggon, D., Acheson, E.D. (1983) The prevalence of intermittent digital ischaemia (Raynaud's phenomenon) in a general practice. *Journal of the Royal College of General Practicioners*, **33**, 85–89.

Hodges, J.P. (1985) Examples of on-site hand transmitted vibration measurements. *Proceedings of United Kingdom Informal Group Meeting on Human Response to Vibration, British Rail Technical Centre, Derby, 17-19 September 1985.*

Hunt, J.H. (1936) Reynaud's phenomenon in workers using vibrating instruments. *Proceedings of the Royal Society of Medicine*, **30**, 171–178.

Hunter, D., McLaughlin, A.I.G., Perry, K.M.A. (1945) Clinical effects of the use of pneumatic tools. *British Journal of Industrial Medicine*, **2** (1), 10–16.

International Electrotechnical Commission (1966) *Octave, half-octave and third-octave band filters intended for the analysis of sounds and vibrations.* Publication 225.

International Organization for Standardization (1979) *Principles for the measurement and the evaluation of human exposure to vibration transmitted to the hand.* Draft International Standard ISO/DIS 5349 (1979).

International Organization for Standardization (1984) *Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration.* Draft International Standard ISO/DIS 5349.2 (1984).

International Organization for Standardization (1986) *Mechanical Vibration - Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration.* International Standard ISO/DIS 5349:1986.

International Organization for Standardization (1988) *Hand-held portable power tools - Measurements of vibration at the handles - Part 1: General.* International Standard ISO 8662-1:1988.

Ishida, K., Ishida, H., Ohno, T., Saito, K., Nasu, Y., Habu, K., Matoba, T., Mishima, Y. (1986) *Report on treatment of vibration disease.* Report of the Ad Hoc Committee on Treatment of Vibration Disease. Japan: Labor Standards Bureau of the Ministry of Labor.

James, C.A., Aw, T.C., Harrington, J.M., Trethowan, W.N. (1989) A review of 132 consecutive patients referred for assessment of vibration white finger. *Journal of the Society of Occupational Medicine*, **39**, 61-64.

Jorulf, L. (1986) Vibration-induced effects caused by impact wrenches used in truck assembly. *Scandinavian Journal of Work, Environment and Health*, **12** (4), 269-271.

Kimura, S. (1943) On the peripheral vascular disturbance by riveting. *Ijikoron*, **1605**, 1217-1220.

Kitchener, R. (1977) The measurement of hand-arm vibration in industry. *Proceedings of the International Occupational Hand-arm Vibration Conference, Cincinnati*. DHEW (NIOSH) Publication 77-170, 153-159.

Kovshilo, V.E., Kodyskina, J.N. (1975) Work conditions of workers using portable power tools in Finnish shipyards. Vibration and Work. *Proceedings of the Finnish-Soviet-Scandinavian Vibration Symposium, Helsinki*. ISBN 951-801-030-7, 30-45.

Landrgot, B., Hüzl, F., Koudela, K., Potmesil, K., Sykora, J. (1975) Incidence of Dupuytren's contracture in workers occupationally exposed to vibration. *Pracovni Letarstvi*, **27** (10), 331-335.

Last J.M. (1988) *A Dictionary of Epidemiology*. Second Edition. Oxford University Press, New York. ISBN 0-19-505481-4.

Leonida, D. (1977) Ecological elements of vibration (chippers) syndrome. *Proceedings of the International Occupational Hand-arm Vibration Conference, Cincinnati*. DHEW (NIOSH) Publication 77-170, 89-96.

Lidström, I-M. (1975) Vibration injury among rockdrillers, chiselers and grinders. Vibration and Work. *Proceedings of the Finnish-Soviet-Scandinavian Vibration Symposium, Helsinki*. ISBN 951-801-030-7, 81-88.

Lie, A. (1980) *Articular changes in construction workers*. HD 815/791 220. Yrkeshygienisk Institut Arbeidsforskingsinstituttene, Oslo.

Lindqvist, T., Flemberg, T. (1945) Raynaud's phenomenon in riveters. *Acta Medica Scandinavica*, **121** (4), 309-318.

Lloyd Davies, T.A., Glaser, E.M., Collins, C.P. (1957) Absence of Raynaud's phenomenon in workers using vibrating tools in a warm climate. *The Lancet*, 1957, 1014-1016.

Loriga, G. (1911) Il lavoro con i martelli pneumatici (The use of pneumatic hammers). *Boll. Ispett. Lavoro*, **2**, 35-60.

Lundström, R. (1990) Health effects of hand-arm percussive tools. An Overview. *Proceedings of the 5th International Conference on Hand-Arm Vibration, Kanazawa, 23-26 May 1989*. Eds. A. Okada, W. Taylor, H. Dupuis. Kyoei Press Company Ltd, Kanazawa, 113-116.

Lundström, R., Burström, L. (1984) *Vibrationer i handverktyg. Vibration in hand held tools*. Undersokningsrapport 1984:24, Arbetarskyddsstyrelsen, Umea, Sweden.

Magos, L., Okos, G. (1963) Raynaud's phenomenon: the situation in the Hungarian iron, steel and engineering industry. *Archives of Environmental Health*, **7**, 341-345.

Malinskaya, N.N., Filin, A.P., Shkarinov, L.N. (1964) Problems of occupational hygiene in operating mechanized tools. *Vestnik Academy of Medical Science, USSR*, **19** (7), 31-36. (English translation by United States Department of Commerce JPRS Translation 27032 41-49.)

Marshall, J., Poole, E.W., Reynard, W.A. (1954) Raynaud's phenomenon due to vibrating tools: neurological observations. *The Lancet*, 5 June 1954, 1151-1156.

Matsumoto, T., Iwata, H., Ozasa, K., Shibata, T., Ohara, S. (1969) On the health status of workers using vibrating tools in a steelworks. *Japanese Journal of Industrial Health*, **11**, 9-19.

Matsumoto, T., Harada, N., Yamada, S., Kobayashi, F. (1981) On vibration hazards of chipping hammer operators in an iron foundry. Part 1. Results of the first investigation. *Japanese Journal of Industrial Health*, **23**, 51-60.

Mikulinsky, A.m., Sudonina, L.T., Laschenco, N.S., Kossovsky, N.N., Azovskaya, I.I. (1971) Clinico-physiological peculiarities of vibration disease in workers handling high-frequency rotating tools and means of preventing it. *Gigiena i Sanitarya*, **8**, 59-62.

Miura, T., Morioka, M., Kimura, K. (1956) On the occupational hazards by vibrating tools. *Reports of the Institute for the Science of Labour*, **50**, 7-10.

Miura, T., Morioka, M., Kimura, K., Atuku, A. (1959) On the occupational hazards by vibrating tools (Report IV) - On the vibration of vibrating tools and the tentative threshold limit of vibration. *Journal of Science of Labour*, **35**, 760-767.

Miura, T., Morioka, M., Kimura, K., Isdia, N. (1957) On the occupational hazards by vibrating tools (Report III). *Reports of the Institute for the Science of Labour*, **52**, 12-23.

Miwa, T. (1967) Evaluation methods for vibration effect. Part 3. Measurements of threshold and equal sensation contours on hand for vertical and horizontal sinusoidal vibrations. *Industrial Health*, **5**, 213-220.

Miwa, T., Yonekawa, Y. (1974) Measurement of vibrations generated from portable vibrating tools. *Industrial Health*, **12** (1), 1-21.

Miwa, T., Yonekawa, Y., Nara, A., Kanada, K. (1979) Vibration isolators for portable vibration tools. Part 3 - a pneumatic baby-riveting hammer. *Industrial Health*, **17**, 131-139.

Miwa, T., Yonekawa, Y., Nara, A., Kanada, K., Baba, K. (1979) Vibration isolators for portable vibration tools. Part 1 - a grinder. *Industrial Health*, **17**, 85-101.

Miyashita, K., Shiomi, S., Itoh, N., Kasamatsu, T., Iwata, H. (1983) Epidemiological study of vibration syndrome in response to total hand-tool operating time. *British Journal of Industrial Medicine*, **40**, 92-98.

Musson, Y., Burdorf, A., Drimmelen, D. van, (1989) Exposure to shock and vibration and symptoms in workers using impact power tools. *Ann. occup. Hyg.*, **33** (1), 85-96.

McKinnon, C.R., Kemp, W.N. (1946) Vibration syndrome. *Canadian Medical Association Journal*, **54**, 472-477.

McLaren, J.W. (1937) Disability of workers using pneumatic drills. *The Lancet*, 4 December 1937, 1296-1299.

National Institute for Occupational Safety and Health (1989) *Criteria for a recommended standard: occupational exposure to hand-arm vibration.* U.S. Department of Health and Human Services, National Institute for Safety and Health, DHHS (NIOSH) Publication No. 89-106.

O'Connor, D.E. (1989) The EEC Machinery Safety Directive and its implications in the field of hand-arm vibration. *Proceedings of the Institute of Acoustics* **11** (9), 465-469.

O'Connor, D.E., Frood, A.D.N. (1983) Methodologies of the vibration measurement of pneumatic tools. *Noise Control: The International Scene. Internoise 83* II 1035-1038.

O'Connor, D.E., Lindqvist, B. (1982) Methods for measuring the vibration of impact pneumatic tools. In *Vibration Effects on the Hand and Arm in Industry*, eds. Brammer, A.J., Taylor, W., Wiley,. ISBN 0-471-88954-7.

Oliver, T.P., Pethybridge, R.J., Lumley, K.P.S. (1979) Vibration white finger in dockyard workers. *Arh. Hig. Rada Toksikol*, **30**, 683-693.

Olsen, N., Nielson, S.L., Voss, P. (1982) Diagnosis and prevalences of vibration-induced white finger in Denmark. *International Symposium on the Protection of Workers against Vibration, NIS, Yugoslavia, 21-24 September*, 22.

Payne, R.A. (1982) *Vibration white finger and noise induced hearing loss in caulkers*. M.Sc. thesis, London School of Hygiene and Tropical Medicine, University of London.

Pelmear, P.L., Taylor, W. (1975) The results of long-term vibration exposure with a review of special cases of vibration white finger. In *Vibration White Finger in Industry*, eds. Taylor, W., Pelmear, P.L., Academic Press, ISBN 0 12 684550, 83-110.

Pelmear, P.L., Taylor, W., Pearson, J.C.G. (1975) Raynaud's phenomenon in grinders. In *Vibration White Finger in Industry*, eds. Taylor, W., Pelmear, P.L., Academic Press, ISBN 0 12 684550.

Pheasant, S. (1988) *Bodyspace. Anthropometry, ergonomics and design*. Taylor and Francis, London. ISBN 0-85066-352-0.

Price, I.R., Hewitt, S.M. (1989) Problems in interpreting the British and ISO standards for assessing hand transmitted vibration exposure. *Proceedings of the Institute of Acoustics*, **11** (9), 471–478.

Pyykkö, I., Starck, J. (1986) Pathophysiological and hygienic aspects of hand-arm vibration. *Scandinavian Journal of Work, Environment and Health*, **12**, 237-241.

Rasmussen, G. (1982) Measurement of vibration coupled to the hand-arm system. In *Vibration Effects on the Hand and Arm in Industry*, eds. Brammer, A.J., Taylor, W., Wiley, ISBN 0-471-88954-7, 89-96.

Raynaud, M. (1888) *On local asphyxia and symmetrical gangrene of the extremities*. Selected monographs: The New Sydenham Society, London.

Redwood, R.A., Beale, K.P., Wiseman, A.S. (1977) Measurement of hand-arm vibration levels caused by chipping hammers of two designs. *Annals of Occupational Hygiene*, **20**, 369-373.

Reider, W. (1938) Zur Frage der Traumatischen Enstehung der Endangitis obliterens. *Arch. Klin. Chir.*, **193**, 737.

Reynolds, D.D., Wasserman, D.E., Basel, R., Taylor, W., Doyle, T.E., Asburry, W. 1982 Vibration acceleration measured on pneumatic tools used in chipping and grinding operations. In *Vibration Effects on the Hand and Arm in Industry*, eds. Brammer, A.J., Taylor, W., Wiley, ISBN 0-471-88954-7, 225-238.

Reynolds, D.D., Basel, R., Wasserman, D.E., Taylor, W. (1984) A study of hand vibration on chipping and grinding operators, Part I: Vibration acceleration levels measured on pneumatic tools used in chipping and grinding operations. *Journal of Sound and Vibration* **95** (4), 479–497.

Rigby, T.A., Cornish, D. (1984) *Vibration Syndrome Research Panel*, Guest, Keen and Nettlefolds Ltd (GKN Forgings Ltd) and Rolls Royce, Derby (England).

Rosa, E. de, Saia, B. (1970) Rapporti fra morbo di Dupuytren e tecnopatia da strumenti vibranti (Relations between Dupuytren's disease and technopathy for quivering tools.) *Lavoro Umano*, **22**, 304-310.

Seyring, M. (1930) Erkrankungen durch Arbeit mit Pressluftwerkzeugen (Diseases caused by working with pneumatic tools). *Archiv für Gewerbepathologie und Gewerbehygiene*, **1** (3), 359-375.

Scory, H., Boileau, P.-E., Boutin, J. (1990) Development of a computerised test bench for the comparison of vibration from hand-held grinding machines. *Proceedings of the 5th International Conference on Hand-Arm Vibration, Kanazawa, 23-26 May 1989*, Eds. A. Okada, W. Taylor, H. Dupuis. Kyoei Press Company Ltd, Kanazawa. 59-62.

Siegal, S. (1956) *Nonparametric statistics for the behavioral sciences*. McGraw-Hill.

SPSS Inc. (1988) *SPSS® Reference Guide*, Release 4.0. SPSS Inc., Chicago, ISBN 0-918469-62-7.

Starck, J. (1975) Measurements of the noise and vibration of portable power tools and some general comments about workplace noise. *Vibration and Work. Proceedings of the Finnish-Soviet-Scandinavian Vibration Symposium, Helsinki*, ISBN 951-801-030-7 30-44, 46-51.

Starck, J., Färkkilä, M., Aatola, S., Pyykkö, I., Korhonen, O. (1983) Vibration syndrome and vibration in pedestal grinding. *British Journal of Industrial Medicine*, **40**, 426-433.

Starck, J., Pekkarinen, J., Pyykkö, I. (1990) Physical characteristics of vibration in relation to vibration-induced white finger. *American Industrial Hygiene Association Journal*, **51** (4), 179-184.

Starck, J., Pyykkö, I. (1986) Impulsiveness of vibration as an additional factor in the hazards associated with hand-arm vibration. *Scandinavian Journal of Work, Environment and Health*, **12** (4), 323-326.

Stewart, A. (1968) Vibration syndrome. *British Journal of Occupational Safety*, **7** (85), 454-455.

Stewart, A.M., Goda, D.F. (1970) Vibration syndrome. *British Journal of Industrial Medicine*, **27**, 19-27.

Stýblová, V. (1959) Neurologische Erscheinungen bei Werktätigen, die Vibrationen ausgesetzt sind (Neurological appearances in people involved in industrial vibration). *Archiv für Gewerbepathologie und Gewerbehygiene*, **17**, 485–503.

Suggs, C.W., Hanks, J.M., Roberson, G.T. (1982) Vibration of power tool handles. In *Vibration Effects on the Hand and Arm in Industry*, eds. Brammer, A.J., Taylor, W., Wiley, ISBN 0-471-88954-7, 245-251.

Suzuki, H. (1978) Vibration syndrome of vibrating tool users in a factory of steel foundry, (Part 1) Complained symptoms. *Japanese Journal of Industrial Health* **20** (5), 261-268.

Takagi, S. (1968) Raynaud's phenomenon due to chain saw and chipping machine. *Japanese Circulation Journal*, **32**, 32–33, 99–110.

Takamatsu, M., Futatsuka, M., Sakurai, T., Matoba, T., Gotoh, M., Aoyama, H., Osaka, J., Ishida, K., Nasu, Y., Watonabe, S., Hosokawa, M., Iwata, H., Yamada, S., Matsumoto, T., Kaneda, K., Okada, A., Nohara, S., Miura, T., Miwa, T., Uehata, T., Yamazaki, K., Suzuki, H., Usutani, S., Honma, H., Koschichi, H., Wakaba, K. (1982) A study of the extent and scope of local vibration hazards in Japan. *Industrial Health*, **20**, 177–190.

Taylor, W., Ogston, S.A., Brammer, A.J. (1986) A clinical assessment of seventy-eight cases of hand-arm vibration syndrome. *Scandinavian Journal of Work, Environment and Health*, **12** (4), 265-268.

Taylor, W., Pelmear, P.L. (1975) Introduction to: *Vibration White Finger in Industry*, eds. Taylor, W., Pelmear, P.L., Academic Press, ISBN 0 12 684550.

Taylor, W., Pelmear, P.L., Pearson, J.C.G. (1975a) Vibration-induced white finger epidemiology. In *Vibration White Finger in Industry*, eds. Taylor, W., Pelmear, P.L., Academic Press, ISBN 0 12 684550, 2-14.

Taylor, W., Pelmear, P.L. (1976) Raynaud's phenomenon of occupational origin. An epidemiological study. *Acta Chirurgica Scandanavica*, Supplement, **465**, 27–33.

Taylor, W., Pelmear, P.L., Hempstock, T.I., O'Connor, D.E., Kitchener, R. (1975b) Correlation of epidemiological data and the measured vibration. In *Vibration White Finger in Industry*, eds. Taylor, W., Pelmear, P.L., Academic Press, ISBN 0 12 684550, 123–183.

Tominaga, Y. (1982) Dose-response relation for the vibration syndrome. In *Vibration Effects on the Hand and Arm in Industry*, eds. Brammer, A.J., Taylor, W., Wiley, ISBN 0-471-88954-7. 277–281.

Trickovic, K., Milijic, B., Stojiljkovic, M., Savic, N. (1969) Quelques manifestations de la maladie de vibration (Some manifestations of vibration disease). In *The 16th International Congress of Occupational Health, Tokyo*, 144–147.

Turtiainen, K. (1974) Chain saw operators' opinions of chain saw vibration. A questionnaire study. *Work, Environment, Health*, **11** (2), 132–135.

Voss, P., Olsen, N., Nielsen, S.L. (1978) *Vibrationsskader fra håndvaerktøjer.* Hovedrapport Lydteknik Teknologist Institut (Denmark).

Walker, L.W., Gurdjian, E.S. (1948) Types and pathogenesis of diseases produced by vibrating tools. *The Grace Hospital Bulletin*, **26** (2), 87–99.

Wasserman, D.E. (1989) To weight or not to weight ... that is the question. *Journal of Occupational Medicine*, **31** (11), 909.

Wasserman, D.E., Taylor, W., Behrens, V., Samueloff, S., Reynolds, D. (1982) *Vibration white finger disease in U.S. workers using pneumatic chipping and grinding hand tools. I: Epidemiology*, DHHS (NIOSH) Publication No. 82–118.

Wasserman, D., Reynolds, D., Behrens, V., Taylor, W., Samueloff, S., Basel, R. (1981) *Vibration white finger disease in U.S. workers using pneumatic chipping and grinding hand tools. II: Engineering Testing*, DHHS (NIOSH) Publication No. 82–101.

Welsh, C.L. (1986) Digital rewarming time in the assessment of vibration-induced white finger. *Scandinavian Journal of Work, Environment and Health*, **12**, 249–250.

Wilcox, T. (1983) Epidemiological design of studies on the hand-arm vibration syndrome. *Journal of Low Frequency Noise and Vibration*, 1983: special issue, 163–170.

Xu, Z., Ding, M.P. (1990) The characteristic of vibration on grind and the prevalence of VWF among grinders. *Proceedings of the 5th International Conference on Hand-Arm Vibration, Kanazawa, 23-26 May 1989*, Eds. A. Okada, W. Taylor, H. Dupuis, Kyoei Press Company Ltd, Kanazawa, 315–317.

Yamada. S. (1969) Vibration hazards in Japan. In *The 16th International Congress on Occupational Health, Tokyo*, 139–140.

Yu, Z-S., Chao, H., Qian, D-S., Ye, Y-H. (1986) Epidemiologic survey of vibration syndrome among riveters, chippers and grinders in the railroad system of the People's Republic of China. *Scandinavian Journal of Work, Environment and Health*, **12** (4), 289–292.

Zhou, D., Chen, L. (1990) Research on the hygienic standard for hand-arm transmitted vibration in People's Republic of China. *Proceedings of the 5th International Conference on Hand-Arm Vibration, Kanazawa, 23-26 May 1989.* Eds. A. Okada, W. Taylor, H. Dupuis, Kyoei Press Company Ltd, Kanazawa, 309-311.