UNIVERSITY OF SOUTHAMPTON

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HELMET-MOUNTED DISPLAYS:
VISUAL PERFORMANCE WITH IMAGE STABILISATION DURING EXPOSURE TO VIBRATION

by

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ABSTRACT

Helmet-mounted displays (HMDs) can present information to the operator regardless of head orientation. This is a substantial benefit compared with panel-mounted displays which can only be viewed with a limited range of head orientation angles. A consequence of mounting the display on the head, however, is that legibility of the displayed information can be degraded under conditions of whole-body vibration. This is because of the relative movement between eyes and the HMD. The eyes are space stabilised by the vestibulo-ocular reflex (VOR) which deflects them in the opposite direction to head motion. The VOR enables people to see a stationary image of the outside world throughout many human activities such as walking and running. HMDs are fixed to the head and therefore movement of the eyes within the head due to the VOR produces motion of the displayed image on the retina. Image motion degrades legibility and, therefore, makes the HMD less effective. This problem is acute in conditions where the VOR is particularly active, such as vibrating environments in rotary and fixed wing aircraft.

This thesis describes the application of an electronic image stabilisation system which improves HMD legibility under conditions of whole-body vibration. Stabilisation works by moving the displayed image in a way that matches some of the eye motion, thereby reducing retinal image motion. The eight experimental phases in the thesis describe the programme to assess the effectiveness of the system in different conditions. Factors analysed were vibration type, vibration frequency, image type and electronic system design. Vibration types included sinusoidal, random, fixed and rotary wing. Frequencies ranged from 0.4 Hz to 10 Hz. Image types included digits, pictures of vehicles and a reticle for helmet-mounted sight (HMS) applications. The electronic stabilisation system was tested with successive developments which enabled legibility to be improved during vibration with a mix of voluntary and involuntary head motion.

HMD legibility was degraded by sinusoidal, random and rotary wing vibration. The range of frequencies which produced the effect was 2.5 Hz to 10 Hz. The stabilisation system improved digit reading performance. Neither vehicle identification performance nor HMS aiming performance were found to be improved by stabilisation in the experiments.

The finding that whole-body vibration reduces the effectiveness of HMDs is consistent with the effects of the VOR. This means that designers should be aware of the additional sensitivity of HMDs to vibration. If vibration cannot be reduced, electronic image stabilisation designed to counter the VOR effects should be considered. Although vehicle identification was not improved by stabilisation, this was considered to be due to difficulties in measuring an effect, rather than lack of a benefit. HMS aiming performance may have been degraded because reticle motion due to stabilisation was translated into aiming error. Additional research should focus on these two areas

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

The performance of military aircraft is limited by the capabilities of the human operator. A characteristic of aircrew tasks is the large demand for information processing, most of the information that the aircrew receive is visual. If the presentation of information can be improved, then this could improve the ability of the aircrew to perform tasks.

Information about the external world and the aircraft flight is obtained by looking through the the canopy. Information about the state of the aircraft and systems is obtained by looking at displays inside the cockpit (head-down displays). The configuration of head-down displays and canopy is illustrated in Figure 1.1 A form of display which allows the operator to see information superimposed on the outside world has become common in recent years. This is called the head-up display. However, the position of the head-up display is fixed and therefore the line of sight or gaze must be aligned in a predetermined direction. There are occasions where this is not helpful, for example combat pilots continuously change gaze over a range which is an order of magnitude larger than the field of view of the head-up display. A different type of display has been developed for this and other applications - the helmet-mounted display. By fixing the display to the helmet, this type of display can allow the operator to view information regardless of head orientation.

Helmet-mounted systems can be divided into two categories:

- Helmet-mounted displays.

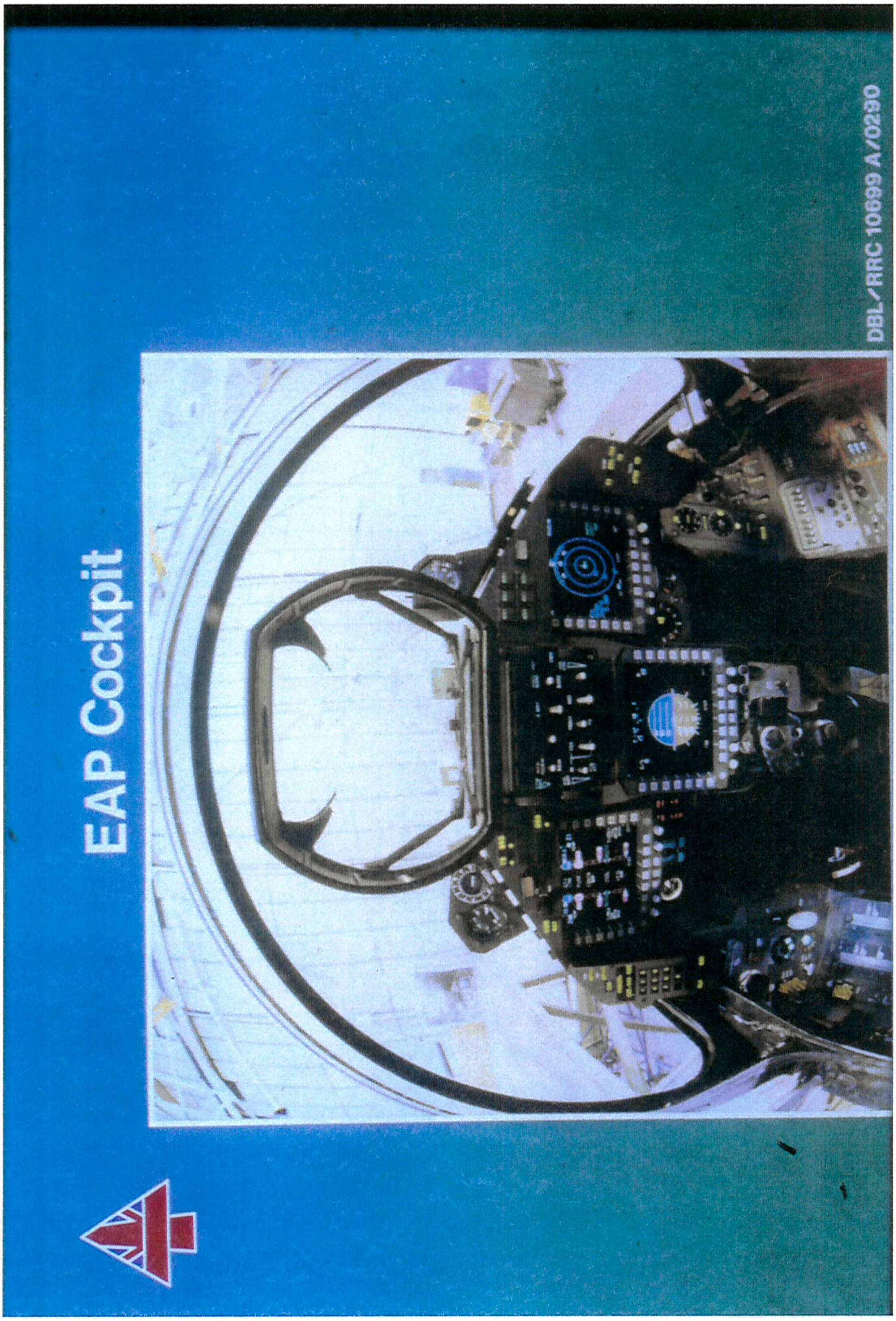


Figure 1.1 The cockpit of a prototype for the European Fighter

- Helmet-mounted sights.

The helmet-mounted display provides the operator with a visual image in front of the eye irrespective of head position. An example of such a system is shown in Figure 1.2.

It consists of a small cathode ray tube with lenses and mirrors attached to the helmet. The wearer sees a virtual image at optical infinity which is superimposed on the outside world.

The helmet-mounted sight allows the operator to designate targets by pointing the head. A helmet-mounted sight typically consists of a helmet position sensing system, and a helmet-mounted reticle. The operator places the reticle over the target and the system measures the line of sight from the position of the helmet. Certain types of raster scanned helmet-mounted displays may be used to present the reticle, in which case additional information may be made available to the operator.

Proposed uses of helmet-mounted systems include:

- Allowing task-relevant information to be monitored while viewing the outside world (e.g. status of the aircraft attack, navigation, and flight systems).

- Providing information without requiring large cockpit-mounted displays, for example a 30 degree field of view provided by a helmet-mounted display subtends the same visual angle as a 127 mm cockpit-mounted display at a distance of 600 mm.

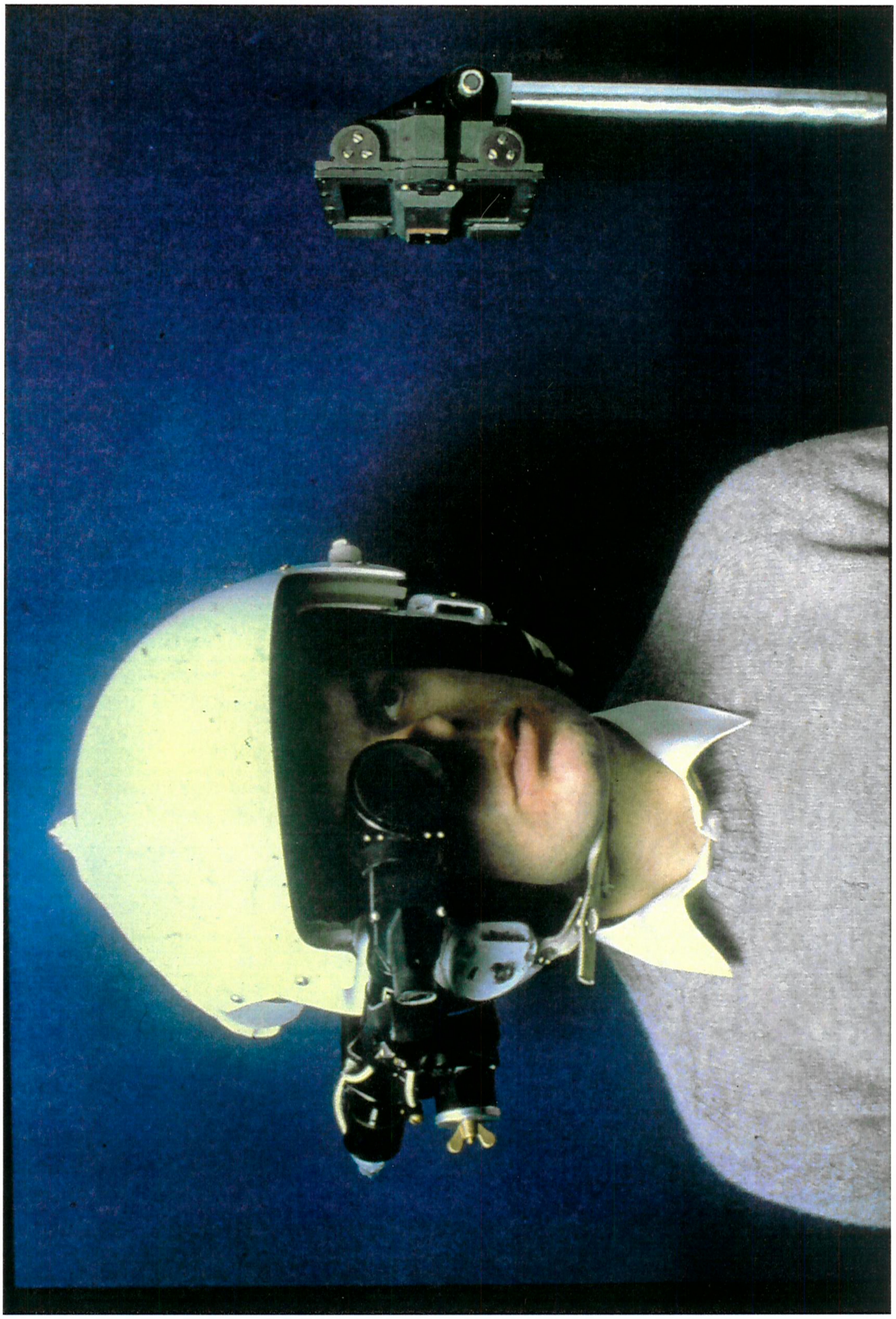


Figure 1.2 The Hughes helmet-mounted display mounted on the side of a United States Air Force Helmet

- The helmet-mounted sight can use the tracking ability of the head to improve target acquisition performance.

- The position of electro-optical sensors may be slaved to head position by using helmet position sensing systems. If the sensor output is displayed on a helmet-mounted display, it provides the operator with the ability to operate under low visibility conditions (e.g. night, fog, smoke).

- In conjunction with head position sensing and computer generated imagery, two helmet-mounted displays have been used to produce a wide field of view (100 to 140 degree total horizontal) flight simulation. The advantages of such a system include potential low cost and the ability to dispense with the spherical domes and projection systems used in some flight simulators (Furness et al (1982)).

1.2 A MODEL OF THE FACTORS AFFECTING HEAD-COUPLED SYSTEMS

A model has been developed to show how the various factors and their relationships affect head-coupled sight aiming error. Figure 1.3 shows this model.

The box at the top left indicates that motion is input to the system at the seat. The motion can be complex and in six axes (horizontal, lateral, vertical, roll, pitch and yaw) as in aircraft. The type of seat will change the nature of the motion (Lewis (1979)). Posture is constrained by the seat and harness and maintained by the stretch reflex (Rack (1973)). Vibration is transmitted through the body to the head in a manner that is affected by posture (Griffin (1975)). Magnitude of vibration at the head can be increased by a factor of 6 with a change in posture.

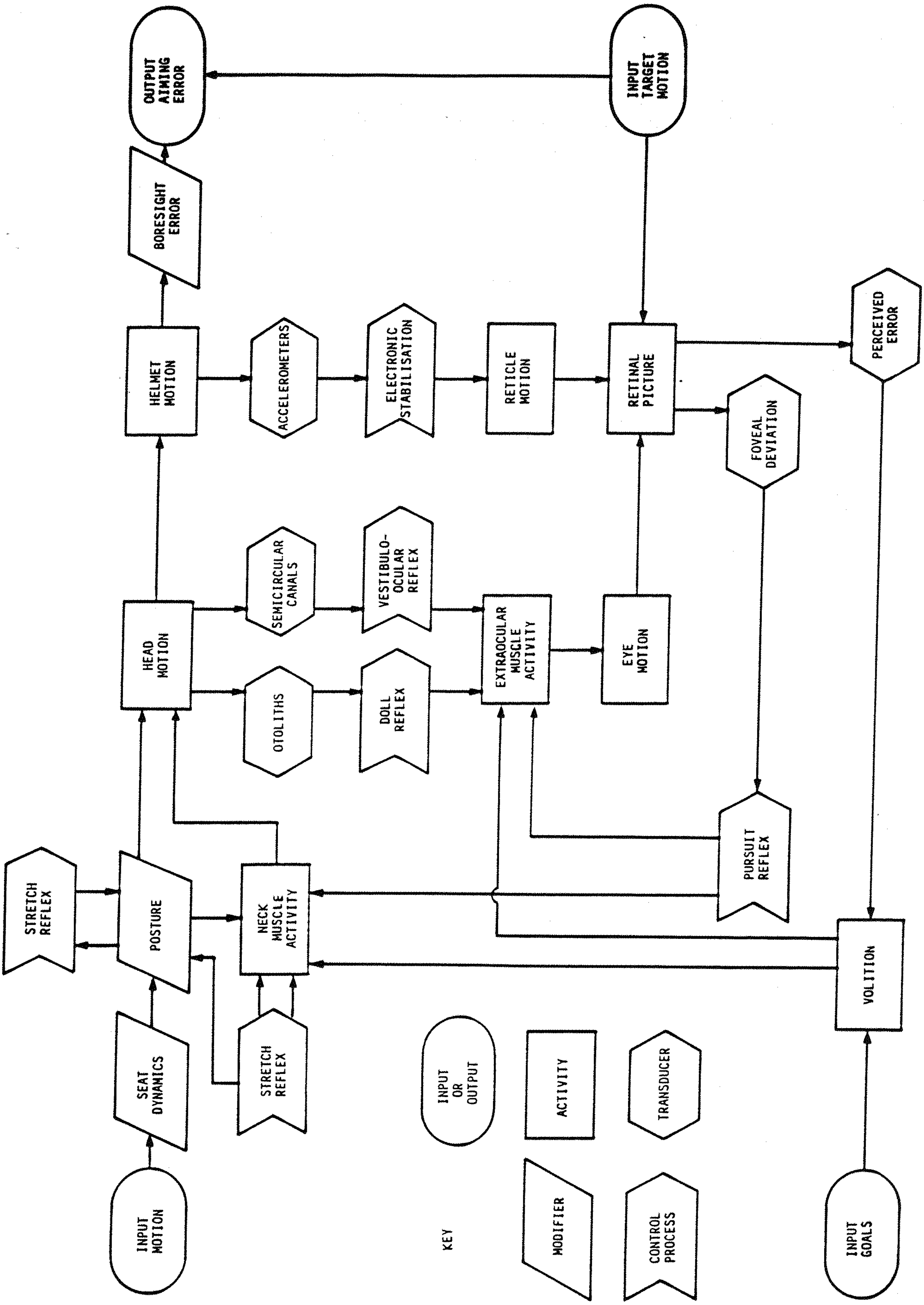


Figure 1.3 Head and eye tracking model

Helmets fitted tightly on the head do not vibrate in exactly the same manner as the head. Furness (1981) has shown that in certain conditions loose helmets can exhibit more than twice as much vibration as exists on the head.

The current form of helmet-mounted sight uses sensors of helmet position to indicate helmet pointing angle. The system requires a boresight calibration. This involves the participant pointing the reticle at a target which is in a known position and matching the helmet-mounted sight output to the target position. Clearly this calibration may be subject to error in the original setting. Another kind of boresight error can arise from reticle motion. Accelerometers on the helmet transduce angular displacements to the reticle so that it stays aligned with gaze. This motion of the reticle means that if the participant aims at the target, then the system will err by at least the amount of reticle deflection. This will then contribute to the output aiming error.

Head motion can produce nervous discharge from a combination of three sources: otoliths, which are sensitive to head translation; semicircular canals, which are sensitive to head rotation; and the retina, which is sensitive to changes in image position which may be due to translation or rotation of the eye in space (Davson (1980)).

The otoliths detect the tension in hair cells produced by the force of gravity. A change in the orientation of the head will produce a change in the vector component of gravity normal to the membrane. This is responsible for the doll-like reflex which will rotate the eyes upwards in response to downwards rotations of the head in the median plane and vice versa in order to maintain a gaze stable in space (Ebenholtz and Shebilske (1975)). Acceleration will produce the same effect as orientation in a gravity field due to the additional component of force exerted on the otolith membrane. The hair cells will then be under a tension which is due to the addition of the vector component of centrifugal force. Since no distinction can be made between the sources of the force, disorientation may result if a pilot has no other cues to indicate position relative to gravity.

Rotational acceleration of the head is detected in the semicircular canals. The acceleration signals are used as inputs for the vestibulo-ocular reflex. This serves to produce an image on the retina that is stable in space. Benson (1972) proposed that it was adapted to preserve vision only where normal body movements were likely to disturb vision, i.e. up to 10 Hz. Experiments with the helmet-mounted display tend to confirm this (Furness and Lewis (1978)).

Viewing an object which appears to move on the retina evokes the pursuit reflex. Laycock (1974) provides a survey of research on the pursuit reflex. This is essentially a velocity related mechanism. The upper limit for smooth pursuit is about 28 degrees per second. With oscillating targets, velocity is changing continuously, and the pursuit reflex cannot change velocity fast enough to maintain visual performance above about 2 Hz. Indeed reduced gain can be seen at 0,5 Hz (Benson and Barnes (1978)).

Since the eyes are limited in their displacement (e.g. plus or minus 45 degrees laterally) head motion is necessary to centralise the eyes in the head. During search or target pursuit, continuous head movements can be used to increase the area covered visually.

The co-ordination of head and eye movement is achieved by signals from the semicircular canals modifying eye movement control. In this manner targets can be acquired by the eyes before the head has finished moving.

The stimulation and inhibition of eye muscles and neck muscles are clearly linked very closely. Barnes (1979) shows that in acquiring a visual target, the eyes make an initial movement, with a slow return as the head moves towards the target.

Input target motion type has been investigated by Laycock (1974) who measured the frequency response of the eye in pursuit of square, sinusoidal, and triangular waves. The eye could pursue targets moving at frequencies below about 2 Hz. This effect was similar for all wave types studied. However, the important parameter of target motion is its predictability. Gain can be increased and phase can be improved even to the extent of leading the target when predictable targets are used. Prediction of sinusoidal motion can be achieved within the first four cycles.

Voluntary control can be exerted over the system in that operators can choose whether to follow a target or the outside world. The reflex mechanism itself is considered to use central resources (neural pathways in the brain) for neuromuscular control (Young and Stark (1965)).

There must be some element of modification, however, to allow for differences in inertia and friction in different muscle groups. Presumably the gain can be altered in response to changes in their dynamics. Thus the empathy that is experienced by a skilled controller is a function of adopting the correct gain for the system as a whole, rather than just muscular control.

1.3 HUMAN FACTORS PROBLEMS WITH THE USE OF HEAD-COUPLED SYSTEMS

Helmet-mounted displays have many potential uses, but their effectiveness has been reduced by the type of vibration occurring in many of the environments in which they would be used. Furness and Lewis (1978) showed that at frequencies of whole-body vibration below 10 Hz reading performance was more severely degraded with helmet-mounted than panel-mounted displays (Figure 1.4).

At some frequencies, the magnitude of vibration required to induce 10% reading error on a helmet-mounted display was one-tenth the magnitude required to produce the same error rate on a panel-mounted display at 0.75 m in front of the operator. Investigations by Laycock (1978) and Barnes et al (1978) with head-fixed displays during head and body rotation have also indicated that performance can be degraded by motion.

The vibration-induced performance decrement experienced with helmet-mounted displays is caused by relative motion between the display image and the retina as a result of vibration occurring in the body, head, and helmet. Vertical, z-axis, translational vibration at the seat results in vibration at the head in the six orthogonal axes (x, y, z, translational axes and roll, pitch, yaw, rotational axes). There are also movements of the helmet, the display and the eyes in some or all of the six axes. Because the display image is collimated and, therefore, at optical infinity, the relative translational movements of the eye and the display are of lesser importance than the relative movements in the three rotational axes.

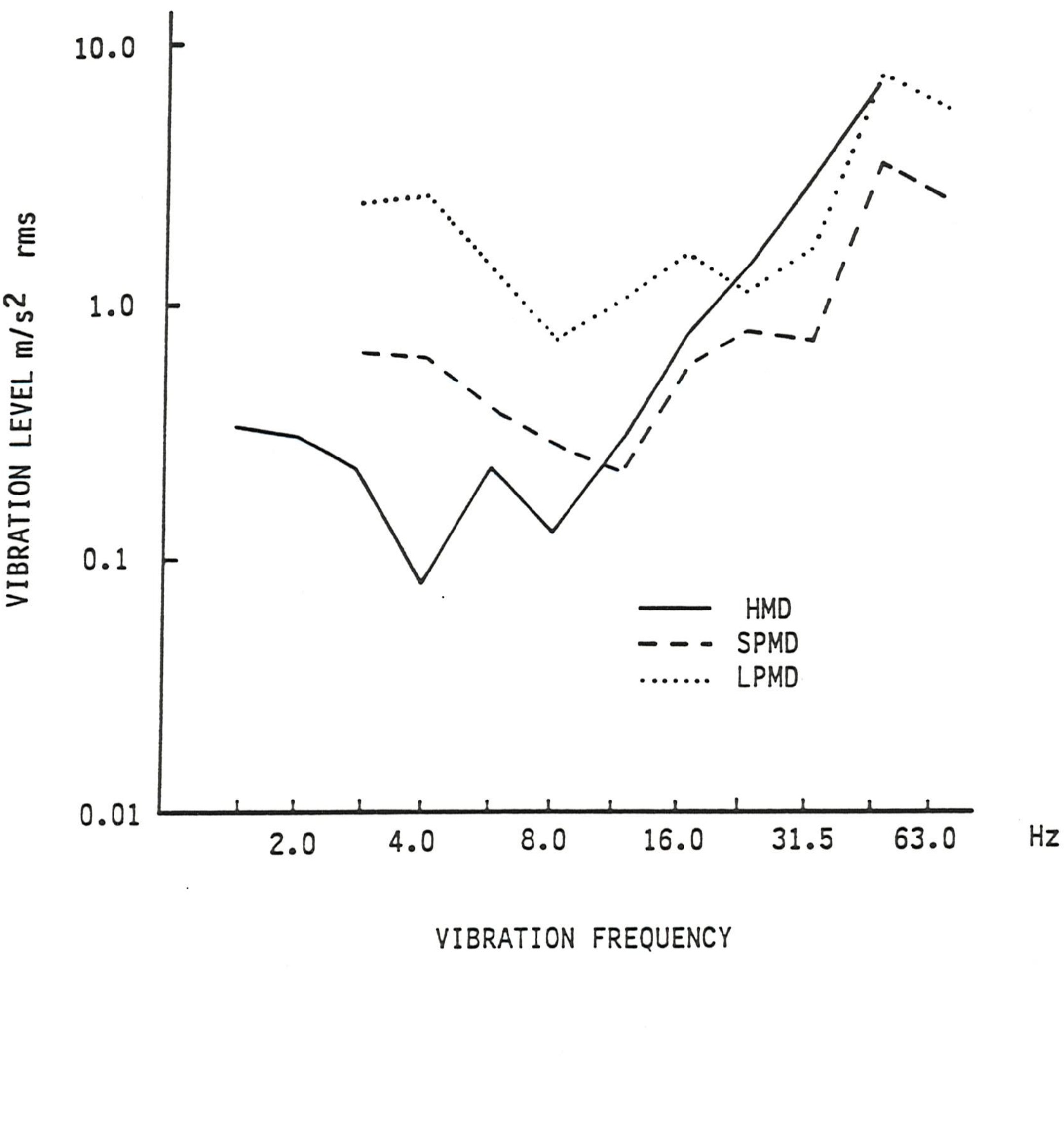


Figure 1.4 Combinations of frequencies and amplitudes of whole-body vibration required to produce 10% reading error on a helmet-mounted display (HMD), a small panel-mounted display (SPMD), and a large panel-mounted display (LPMD). After Furness and Lewis (1978).

Relative movements between the image and the retina in the roll, pitch and yaw axes result in movements of the image on the retina in the roll, z, and y axes respectively. These movements result in retinal image motion and a blurred visual percept. Furness (1981) reported transfer functions from the vertical seat axis to several axes of the head to determine the relative magnitude and importance of these axes in producing image blur. His studies indicated that pitch and yaw head motion are the major contributors to relative image motion due to vertical seat vibration.

There is much data on the transfer of pitch and yaw axis rotational vibration from the head to the eyes at frequencies up to about 6 Hz. For example Benson (1970), Atkin and Bender (1968), and Hixson (1974). These workers suggest that under most conditions a transfer function of close to unity and a phase lag of approximately 180 degrees may be expected. The implications of this are that the eyes maintain a constant line of sight while the head, helmet and display are vibrating with respect to space. Thus a head to eye transfer function appropriate and necessary for viewing distant, stationary, panel-mounted displays under conditions of whole-body vibration, becomes inappropriate for viewing the helmet-mounted display under the same vibration conditions. Even if the transfer function was such that the eyes moved with the head, the problem would still exist since the helmet and the display may be expected to move relative to the head due to slippage.

Helmet-mounted sights also encounter problems under conditions of whole-body vibration. Vibration-induced head movements will cause errors in head aiming and head position sensing. In addition, if the reticle cannot be seen as a single, unblurred image by the operator, then judgement of its true position may not be reliable.

Solutions to the effects of whole-body vibration on helmet-mounted displays

There are two possible solutions:

- Isolation of the vibration at source.
- Deflection of the image on the display to coincide with the line of sight of the eye.

1.3.1 ISOLATION AT SOURCE

As far as the operator is concerned, the source of vibration includes all the vibrating parts of the aircraft and the interface between the aircraft and the operator.

In both rotary and fixed wing aircraft there exists great potential for vibration isolation by the redesign of rotors, transmission systems, aerodynamic surfaces, and airframes. Effort is also being invested in seat design in order to reduce the transmission of vibration from the aircraft to the operator.

Improvements in these areas involve a multitude of conflicting requirements and progress has not resulted in significantly lower magnitudes of vibration in all new aircraft. Vibration isolation at source may be considered to be an ideal solution which appears to have practical limitations.

1.3.2 IMAGE DEFLECTION

The effects of vibration may be reduced by moving the image on the display to match the motion of the eye. This would remove relative image motion and produce a stable image on the retina. This could be done by direct measurements of eye motion and using the information to drive an image displacement system. This method has serious practical problems associated with it and may be unacceptable in an operational environment (Young and Sheena (1975)). For a more extensive discussion of approaches, see Storey and Wells (1980).

Another approach is to measure display-in-space vibration and predict eye-in-space vibration. The display image may then be deflected to remove any relative movement. This will be required for both pitch and yaw axis head vibration, since these have been identified as major contributors to the vibration induced decrement. Existing data suggest that eye in space movements may be predictable. For example the eyes have been reported as being approximately space stable up to 5 Hz (Benson (1970)) and the results of reading performance studies implied that this stabilisation existed up to 9 to 10 Hz (Benson and Barnes (1978)).

Vibration of the display can either be predicted or measured. Vibration may be measured at any point along the vibration pathway of floor, seat, head, helmet, display. Each point has advantages and disadvantages. Measurement of vibration at the floor or seat has the advantages of ease of transducer mounting and freedom from damage in an operational environment, but the prediction of display vibration is made more difficult by the modification of the vibration as it passes through the operator's body. Seat to head transfer functions are prone to significant inter-participant and intra-participant variability (Griffin (1975)). Measurement of head vibration is accomplished in the laboratory with bite-bars, but this technique is unacceptable for operations. Furthermore, the head to helmet transfer function is likely to exhibit large inter-subject variability. The measurement of helmet vibration has the disadvantage of requiring transducers to be placed on the helmet. However there is the considerable advantage of obtaining directly the relevant movement needed for image stabilisation (at low frequencies the helmet to display coupling can be considered rigid).

The research described in this thesis demonstrates the effective use of accelerometers on the display for image stabilisation. The system has been shown to be able to operate under a wide range of vibration conditions. An experiment using the system for reticle stabilisation in a helmet-mounted sight is also presented.

The purpose of this thesis is to explain the progression of research which led to the existence of a functional display stabilisation system.

1.3.3 APPARATUS

Figure 1.5 shows the display assembly as mounted on the helmet.

A CRT was mounted on a modified large size United States Air Force flying helmet model HGU-2A/P. A series of optics was used to present the image of the CRT in front of the user's right eye.

The cathode ray tube (CRT) was 25 mm in diameter with P43 phosphor. The decay time was approximately 1 millisecond to 1%. The short persistence was necessary to allow rapid image deflections without smear.

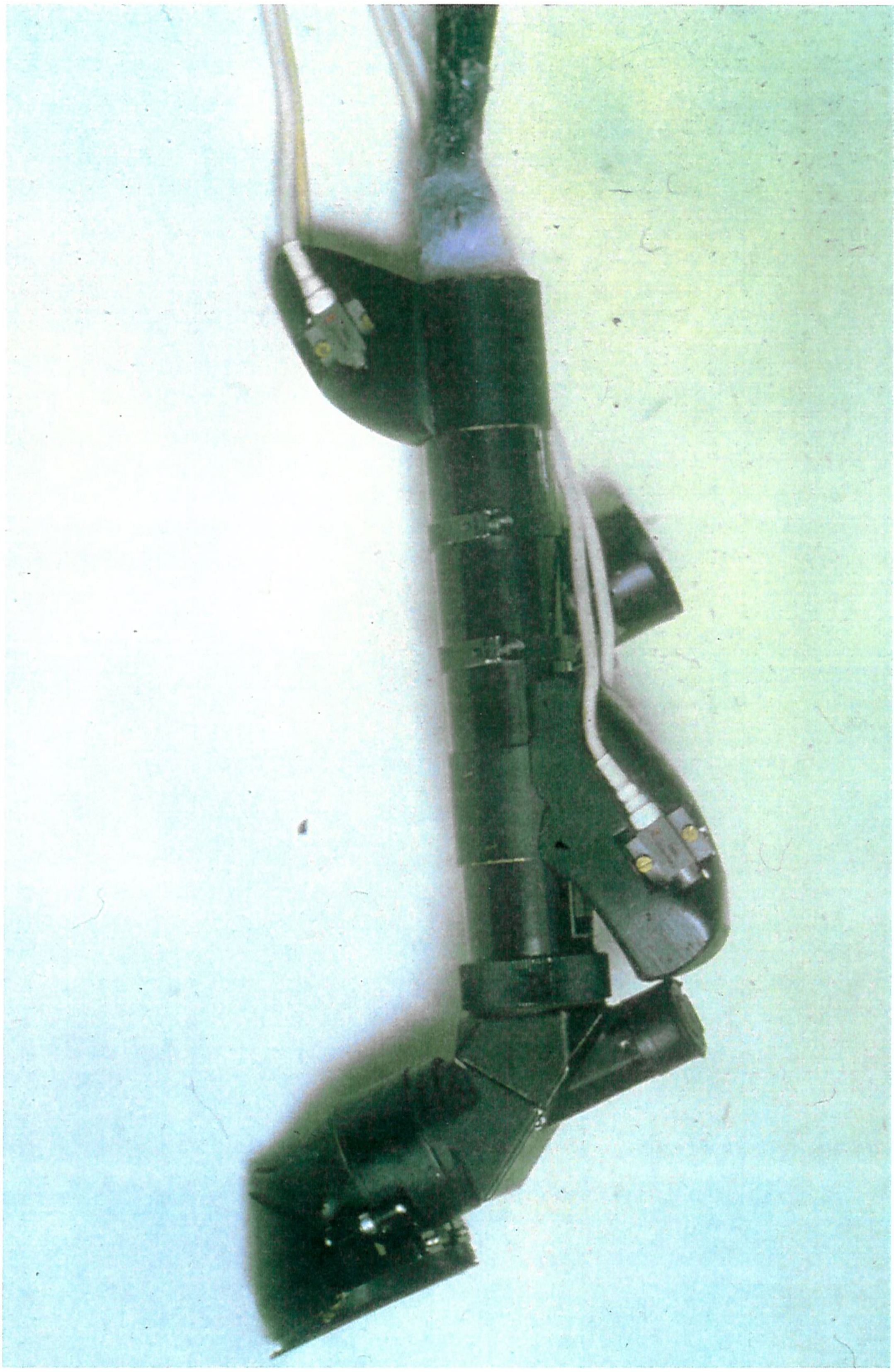


Figure 1.5 The display assembly

The functional screen diameter of the CRT was 19 mm. This provided a field of view of approximately 30 degrees. The image was focussed at optical infinity for all experiments.

The last element in the optical assembly was a semi-silvered mirror which allowed a view of the outside world with the CRT image superimposed. However all experiments were conducted in the dark. This prevented visual distractions and ensured high image contrast.

In addition to the CRT mounted on the helmet, four translational accelerometers (Endevco model 2265-20) were fixed in a rigid mount on the display. These were placed in positions where the signals could be used to provide display pitch and display yaw. Two accelerometers being required for each axis.

Relative displacement between translational accelerometers can be used to calculate rotational acceleration. The technique is shown in Figure 1.6 and 1.7.

Vibration was provided by one of two machines. One was a Derritron VP180LS electrodynamic vibrator. The other was a Servotest vertical 1 metre stroke hydraulic vibrator. This is shown in Figure 1.8.

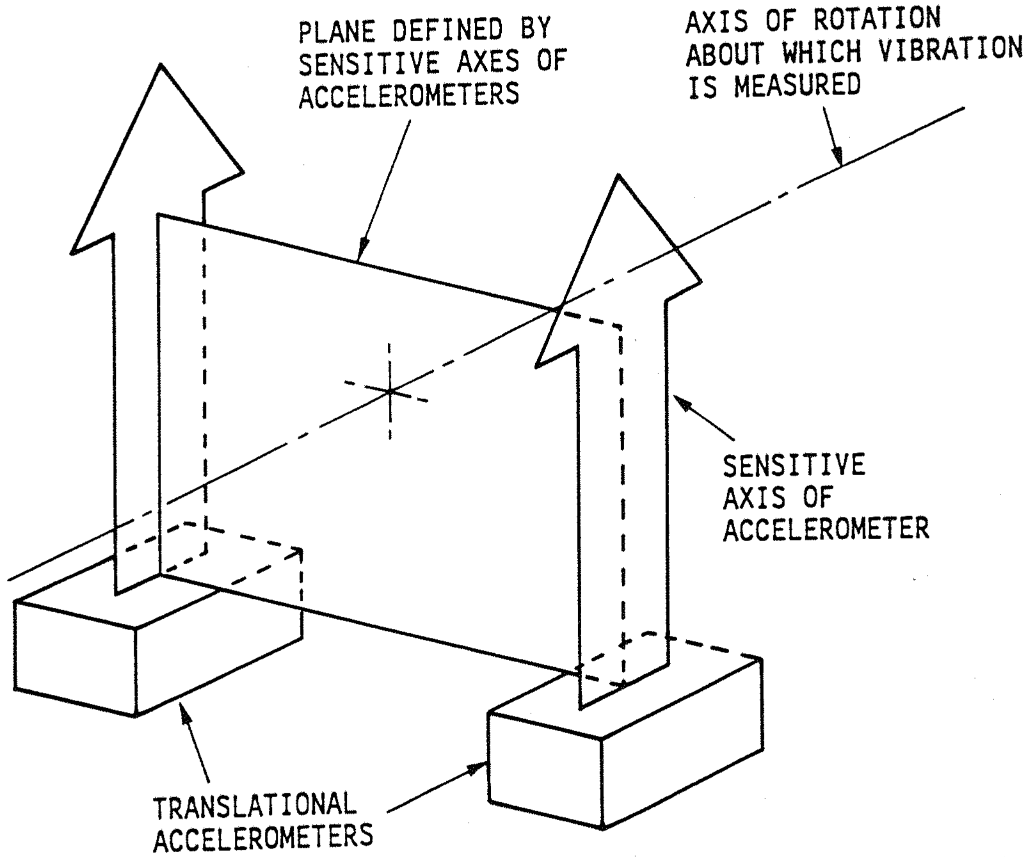


Figure 1.6 The linking of two translational accelerometers to produce information about rotational motion within a plane (After Wells 1983)

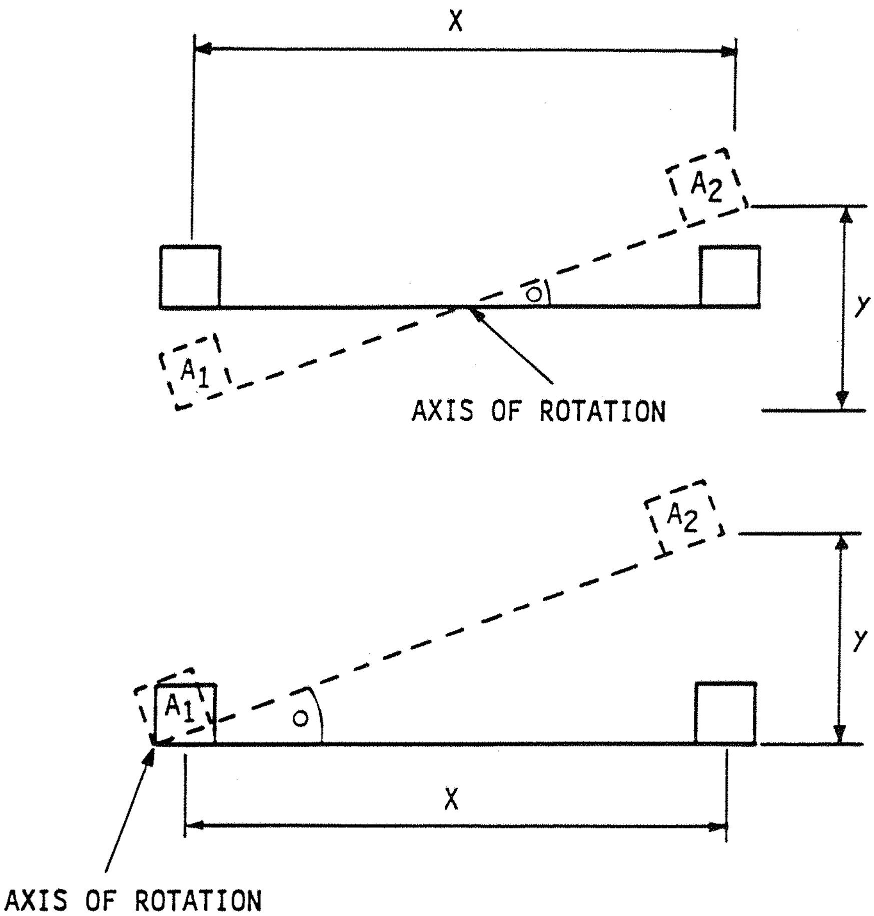


Figure 1.7 How the difference in translational acceleration is used to produce rotational information (After Wells 1983)

Figure 1.8 The 1 metre stroke vertical vibrator at the University of Southampton

CHAPTER 2 : HELMET-MOUNTED DISPLAY IMAGE STABILISATION UNDER DIFFERENT TYPES OF WHOLE-BODY VIBRATION

2.1 INTRODUCTION

Space stabilisation of the image on the helmet-mounted display has been shown to result in improvements in helmet-mounted display reading performance under conditions of vertical, z-axis, whole-body vibration (Wells and Griffin (1984)). Single axis vertical stabilisation improved reading performance and dual axis vertical and horizontal stabilisation further enhanced performance.

The stabilisation algorithm used in the performance studies was limited in its application to anything other than an experimental environment. The main limitation was caused by the frequency response of the double integrator during voluntary head movements.

The stabilisation system worked by measuring the rotational acceleration of the display, double integrating the acceleration to obtain rotational displacement and using the displacement signal to deflect the display image in antiphase to the displacement of the display. Double integration is appropriate at frequencies above 1 to 2 Hz, where the vestibulo-ocular reflex tends to stabilise the line of sight of the eye. However, at frequencies below 1 Hz the line of sight of the eye is under voluntary control and double integration results in a large inappropriate amplification of rotational display acceleration which is perceived as drift in the position of the image on the display. High pass filtering was incorporated in the double integrator electronics but in order to minimise the phase error incurred at frequencies above 1 to 2 Hz, the filtering was kept to a minimum.

The filtering produced good image stabilisation over the range of vibration frequencies investigated. However, although the participants attempted to maintain a constant line of sight, small intermittent involuntary head movements caused the image to drift noticeably on the display. Large or rapid head movements would cause the integrator electronics to saturate, resulting in a temporary loss of stabilisation and large displacements of the image from the line of sight. This would make the performance of the system unacceptable in an operational environment where it would be necessary to make voluntary head movements or where vibration was present at frequencies below 1-2 Hz.

The filter characteristics which result in optimum display visibility will be a compromise between a high resonance frequency, resulting in good rejection of low frequency head movements at the expense of phase error, and a high selectivity, resulting in less phase error at the expense of transient response. The best compromise is likely to be somewhat dependent upon the vibration waveform. A more random waveform, due to its transient nature, will have a greater propensity to excite ringing in the filter output. Rapid voluntary head movements will also result in oscillatory behaviour of the filter output if the selectivity is too high.

The following experiment was performed to compare the effects of sinusoidal and random vibration waveforms on helmet-mounted display reading performance, and to test the image stabilisation algorithm in sinusoidal and random vibration environments.

2.2 APPARATUS AND PROCEDURE

A Hughes helmet-mounted display model RL/202 was mounted on a United States Air Force flying helmet. Fifty digits (five of each numeral from 0 to 9) were presented in a random arrangement in a 5 row by 10 column array on the display. The digits were made up from a 7 by 9 dot matrix on the raster display. Each digit subtended 15 minutes of arc vertically. Luminance was approximately 150 cd m^{-2}. They were presented against a black background. One set of digits was used for each condition. The arrangement of the digits is illustrated in Figure 2.1.

Participants sat on a rigid, flat seat with no backrest and stationary footrest. A Derritron VP180LS electrodynamic vibrator produced vertical (z axis) motion.

The vibration conditions are shown in Table 2.1:

TABLE 2.1 VIBRATION CONDITIONS USED IN THE EXPERIMENT

Vibration type	Centre frequency (Hz)	Amplitude (ms $^{-2}$ rms)
sinusoidal	4	1.5
1/3 octave band random	4	1.5
1 octave band random	4	1.5

There were two viewing conditions:

- no stabilisation

- stabilisation

Twelve male participants, selected from students and staff of the University of Southampton, were used each with Snellen acuity of at least 6/4 in each eye.

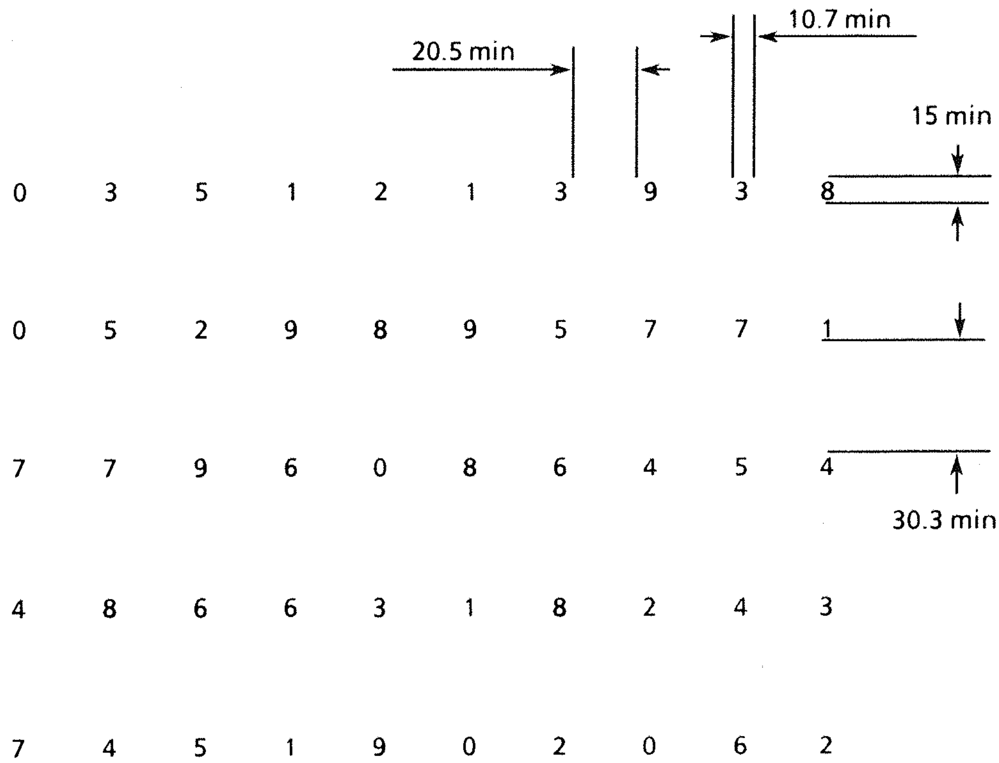


Figure 2.1 A typical array as used in the experiment

Each participant read four sets of fifty numerals under each condition. They were instructed to read as quickly and accurately as possible. A fixed sum of money was paid for participation. A control condition was presented at the beginning and end of the experimental session. The control condition consisted of four sets of fifty numerals presented without vibration.

The order of the main conditions was balanced.

Reading time was recorded as the duration from the initial presentation of a set of 50 digits to the moment when the last digit had been read. Incorrect and omitted digits were classed as errors.

2.3 RESULTS

Two factor mixed effects randomised block analyses of variance were carried out on error and time scores.

The results are summarised in Table 2.1 and Table 2.2.

It can be seen that there were significant effects of vibration type and of image stabilisation on both reading time and reading error.

Time scores were converted to percentage increase in reading time (compared with static time) per unit acceleration. Errors were converted to increase in percentage reading error (compared with the static percentage error). This transformation was used to allow comparison of results with a previous study in which a different form of electronic image stabilisation was used.

TABLE 2.1 ANALYSIS OF VARIANCE SUMMARY TABLE FOR READING TIME

	Time				
Source	Sum of squares	df	Mean square	F ratio	Sig
Vibration	6899.6	2	3449.8	3.68	*
Stabilisation	84769.0	1	84769.0	13.70	**
Vib x Stab	6795.1	2	3397.6	3.20	
Vib x Participants	20621.0	22	937.3		
Stab x Participants	68032.1	11	6184.7		
Vib x Stab x Par	23331.1	22	1060.5		

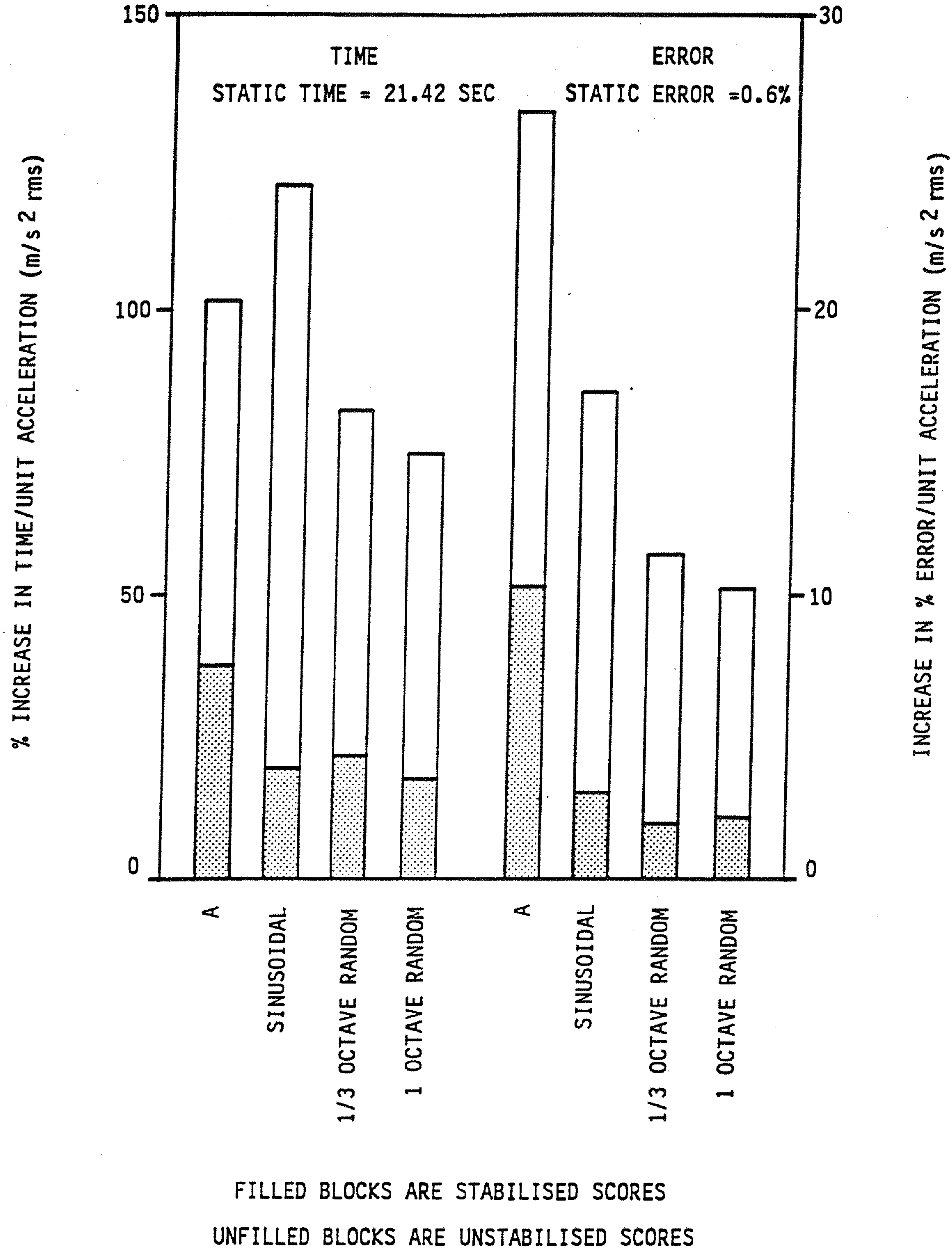
Significance levels: ** 1%
* 5%

TABLE 2.2 ANALYSIS OF VARIANCE SUMMARY TABLE FOR READING ERROR

	Error				
Source	Sum of squares	df	Mean square	F ratio	Sig
Vibration	184.33	2	92.17	4.54	*
Stabilisation	1750.35	1	1750.35	21.05	**
Vib x Stab	98.78	2	49.39	2.10	
Vib x Participants	446.67	22	20.30		
Stab x Participants	914.82	11	83.17		
Vib x Stab x Par	514.55	22	23.53		

Significance levels: ** 1%
* 5%

The mean scores for the twelve participants are presented in Figure 2.2.



A = Results from Wells and Griffin (1984) 4 Hz data

Figure 2.2 Mean time and error scores from the dual-axis stabilisation performance study with 4 Hz sinusoidal and random vibration

TABLE 2.3 SIMPLE MAIN EFFECTS TABLE FOR READING TIME

Simple main effects	Time				
	Sum of squares	df	Mean square	F ratio	Sig
No stab, vib	13605.7	2	6802.8	7.26	**
Stab, vib	89.1	2	44.5	0.05	-
Stab, sinusoidal vib	55344.0	1	55344.0	8.95	*
Stab, 1/3 octave vib	19153.5	1	19153.5	3.10	-
Stab, 1 octave vib	17066.7	1	17066.7	2.76	-

Significance levels: ** 1%
* 5%

TABLE 2.4 SIMPLE MAIN EFFECTS TABLE FOR READING ERROR

Simple main effects	Error				
	Sum of squares	df	Mean square	F ratio	Sig
No stab, vib	275.39	2	137.69	6.78	**
Stab, vib	7.72	2	3.86	0.19	-
Stab, sinusoidal vib	1027.04	1	1027.04	12.3	**
Stab, 1/3 octave vib	477.04	1	477.04	5.74	*
Stab, 1 octave vib	345.05	1	345.05	4.15	-

Significance levels: ** 1%
* 5%

2.4 DISCUSSION

It can be seen that sinusoidal vibration had a greater effect on unstabilised reading performance than either of the random vibration conditions presented at the same rms acceleration magnitude. This is consistent with the work of Moseley et al (1982) with panel mounted displays. The latter authors showed that for a wide range of frequencies, reading performance on a static display was impaired more by sinusoidal z axis whole-body vibration than by 1/3 octave band random z axis whole-body vibration at the same centre frequency and magnitude. The results were explained by showing that there is a higher proportion of low differential velocity between the image and the eye in random vibration conditions. The results of the current experiment also indicate a slightly lower effect on unstabilised reading performance by the 1 octave band random motion compared with the 1/3 octave band random motion. This may be explained the smaller proportion of energy which would be present in the immediate vicinity of 4 Hz, which has been shown in previous experiments to have the greatest effect on helmet-mounted display reading performance (Furness and Lewis (1978)).

Image stabilisation can be seen to result in a marked reduction in both reading time and reading errors for all vibration conditions. There was no clear effect of vibration condition on performance when the image was stabilised. There was a slight reduction in errors during 1/3 octave band random vibration compared to the other two vibration conditions, but this was mirrored by a slight increase in reading time. Although the vibration by stabilisation interaction terms were not significant, the interaction F ratio for reading time was only marginally short of that required for significance at the 5% level. In view of this, and to obtain a greater understanding of the benefits of stabilisation, tests of simple main effects were carried out. These are summarised in Table 2.3 and 2.4.

It can be seen that although the effect of vibration was highly significant for the unstabilised conditions, it did not approach significance for the stabilised conditions. Consequently, it can be seen from Figure 2.2 that the proportional improvement resulting from image stabilisation is not quite as great for random vibration as for sinusoidal vibration. This is confirmed by the tests of simple main effects which indicate that the effect of stabilisation is not significant for reading time with 1/3 octave band random vibration, and is not significant for either time or errors with 1 octave band random vibration.

CHAPTER 3 : HELMET-MOUNTED DISPLAY IMAGE STABILISATION AND TARGET IDENTIFICATION UNDER CONDITIONS OF WHOLE-BODY VIBRATION

3.1 INTRODUCTION

A study by Furness (1981) showed that the ability to identify targets was reduced under conditions of sinusoidal whole-body vibration. The study tested an early form of stabilisation using head pitch acceleration signals to deflect the image on the display. This method produced no significant improvement in performance.

The image stabilisation system has been much developed since then. It showed its value in improving digit legibility under conditions of whole-body vibration. It was considered that it would be useful to conduct a target identification experiment to see if the latest form of stabilisation would improve performance under conditions of whole-body vibration.

3.2 APPARATUS AND PROCEDURE

Target images consisted of six static military vehicles (truck, jeep, tank, etc.) in each of four orientations. For each of these 24 images the visual angle was increased linearly from 0.64 degrees to 6.4 degrees over a period of 20 seconds.

Twelve male participants with Snellen visual acuity better than 6/4 in both eyes took part in the experiment.

The vibrator was a VP180LS with a rigid flat seat moving in the vertical, z axis. A stationary footrest was provided. Motion was 4 Hz sinusoidal at 1.0 ms^{-2} rms.

Participants were shown photographs of the images until they could identify the vehicles without error. The experimental session then commenced with a measurement of performance under static conditions.

Participants were then exposed to vibration and performance was measured with a set of images with or without stabilisation. The stabilisation condition was balanced and alternated between presentation of images. The experiment ended with a static condition.

3.3 RESULTS

Table 3.1 shows the results of an analysis of variance on the time scores.

TABLE 3.1. ANALYSIS OF VARIANCE SUMMARY TABLE FOR TIME SCORES

Source	Time				
	Sum of squares	df	Mean square	F ratio	Sig
Participants(P)	5180.01562	11	470.91052	55.05231	**
Orientation (A)	369.03125	3	123.01041	5.24029	**
Vehicles (B)	2540.12500	5	508.02499	24.04238	**
Vibr/Stab (C)	975.46875	3	325.15625	11.86124	**
AB	778.34375	15	51.88958	4.43849	-
AC	135.26563	9	15.02951	2.37125	-
BC	158.34375	15	10.55625	1.68525	-
ABC	615.90625	45	13.68681	2.70207	-
RESIDUAL	8938.79687	1045	8.55387		
AP	774.64062	33	23.47396		
BP	1162.17187	55	21.13040		
CP	904.64063	33	27.41335		
ABP	1928.98438	165	11.69081		
ACP	627.48437	99	6.33823		
BCP	1033.54688	165	6.26392		
ABCP	2507.32812	495	5.06531		
TOTAL	19691.31250	1151	17.10800		

Significance level: **1%

The most important factor to consider is the vibration/stabilisation factor. This is significant and for more information a simple main effects test was carried out.

Table 3.2 shows the mean time and Table 3.3 shows the mean errors for the four conditions.

TABLE 3.2 MEAN TIME SCORES

Condition	Time
Static	14.01
Vibration, no stabilisation	15.48
Vibration, stabilisation	15.46
Static	13.34

TABLE 3.3 MEAN ERROR SCORES

Condition	Errors (out of 288)
Static	53
Vibration, no stabilisation	61
Vibration, stabilisation	55
Static	69

Tukey's t test shows that the identification time is significantly increased in the presence of vibration. However no significant difference was found between the image identification time with and without stabilisation.

Error scores showed no significant difference across conditions. The stabilisation condition did produce a lower error score, which indicates that there may be some benefit from the use of the system.

The results are consistent with an error minimisation strategy. The presence of vibration increases time compared with the mean static score, but not errors. Participants may delay responding in order to ensure a correct response. Such a delay would enable more time looking at the image and also would allow the image size to increase.

Stabilisation does not improve time scores, but does improve error scores. This is also consistent with an error minimisation strategy.

Participants reported that they used major features to identify vehicles. Examples of such features are tracks versus wheels and large versus small. These features can be identified in the presence of vibration by their spatial frequency components.

3.4 DISCUSSION

The nature of the experimental design varied visual angle and time together. This may have meant that the task was not very sensitive to the differences between the conditions. It was also reported by participants that they used low spatial frequency components for identification, thereby reducing the susceptibility to vibration.

Vibration has been shown to significantly increase identification time. Image stabilisation has not been shown to reduce significantly either identification time or identification errors, although a positive decrease in errors was noted.

CHAPTER 4 : ASSESSMENT OF AN ADAPTIVE INTEGRATOR SYSTEM FOR IMAGE STABILISATION IN THE PRESENCE OF VOLUNTARY HEAD MOVEMENTS

4.1 INTRODUCTION

The experiment described in Chapter 2 showed that for helmet-mounted display viewing with a constant line of sight it is possible to realise a double integrator filter function with a good compromise between integrator stabilisation performance and attenuation of very low frequency head activity. However a problem still exists with respect to gross voluntary head movements. With the filter parameters which were set up for the first experiment, large or rapid voluntary head movements caused the image to divert by up to 10 degrees from the line of sight of the eye. After completion of the head movement there would be a slight delay while the image returned to the line of sight before the participant could fixate upon it adequately for reading to recommence.

In order to adequately maintain the image within the line of sight during large or rapid voluntary head movements the natural frequency of the system would need to be increased to the order of 1 Hz. This would generate an unacceptable integrator phase error at frequencies within the stabilisation bandwidth of the system. However, it is not necessary to maintain stabilisation performance while the head is engaged in a gross voluntary movement, provided that stabilisation performance returns immediately after the cessation of movement. A possible solution to the voluntary head movement problem would therefore be to increase the natural frequency of the system for the duration of gross head movements. In order to realise such a system it would be necessary to find a means of distinguishing between low frequency, voluntary head movements and higher frequency, vibration induced head motion. Possible candidates for this are the magnitudes of head velocity or displacement, both of which are available as outputs from the previously developed double integrator system.

A new stabilisation system model with voltage controlled filter parameters, was developed on a VIDAC 336 analogue computer. An adaptive feedback system was incorporated to vary the resonance frequency of one of the complex pole pairs in response to either the rotational velocity or displacement of the display. The response of the model was investigated with an extensive range of parameters using simulated helmet rotational acceleration inputs. The final form of the model is described in Figure 4.1. The principles of operation of this model are shown in Figure 4.2 and 4.3. Image deflection feedback was found to give a slightly more consistent and stable result than velocity, so this was used. A further advantage of image deflection feedback is that it is more compatible with alternative methods of transducing rotational motion of the helmet such as are used in helmet-mounted sight systems.

In its non-adapted state the response of the system is similar to that of the previous double integrator system. When a large or rapid enough head movement is made to cause the deflection (displacement) signal to exceed a preset threshold the natural frequency of one complex pole pair is increased. The increase in natural frequency is proportional to the deflection signal up to a maximum value. This opposes the tendency of the image to divert from the line of sight. In order to maintain stability, and to ensure that the imaging returns quickly and completely to the line of sight it is necessary to incorporate a small lag in the return of the natural frequency to its minimum value following the cessation of gross head movement. The amplitude and phase response of the system in its fully adapted and non-adapted states are given in Figure 4.4.

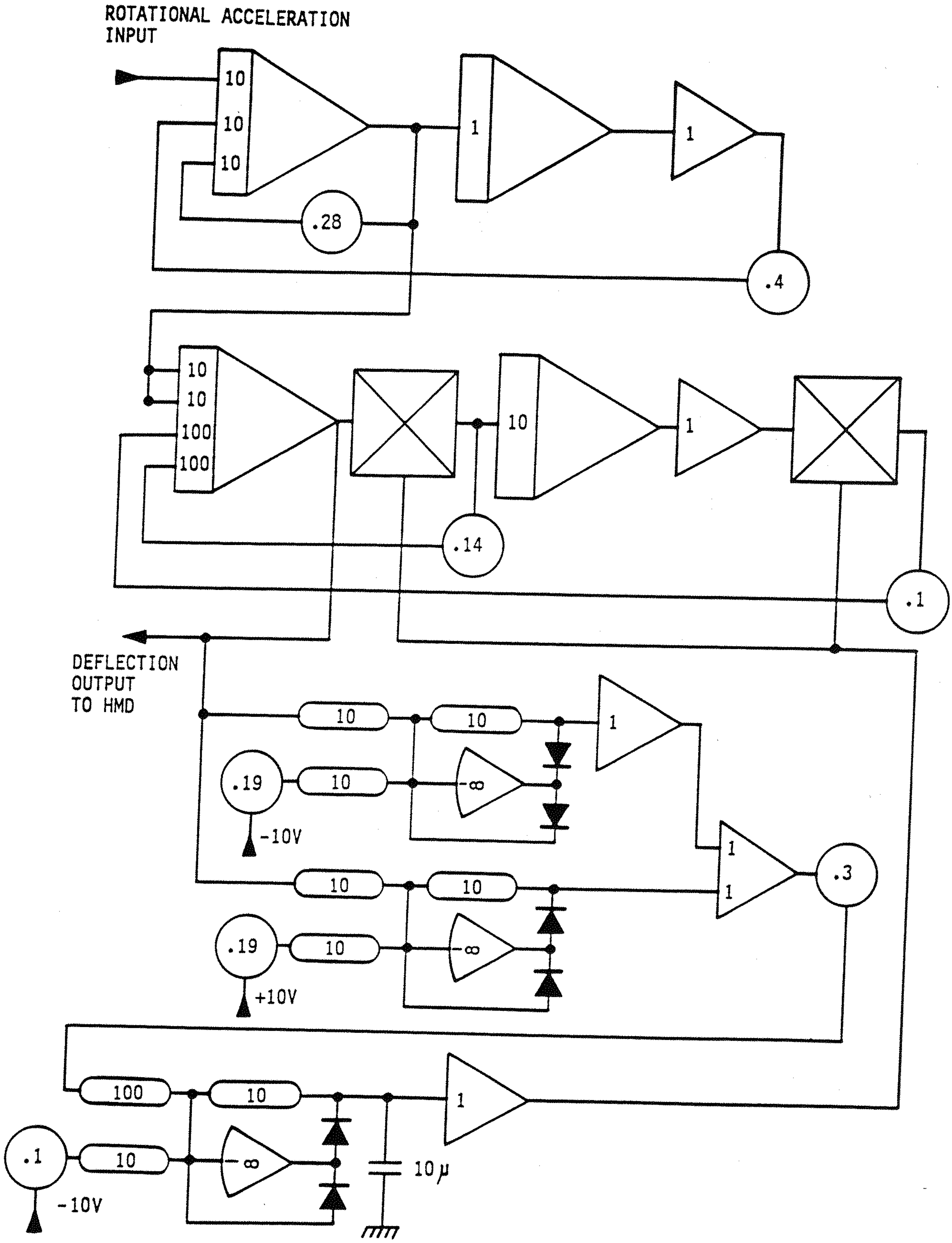


Figure 4.1 The analogue computer patch diagram for the adaptive double integrator used in the experiment. Vertical channel only shown. Circuit designed by Dr C. Lewis.

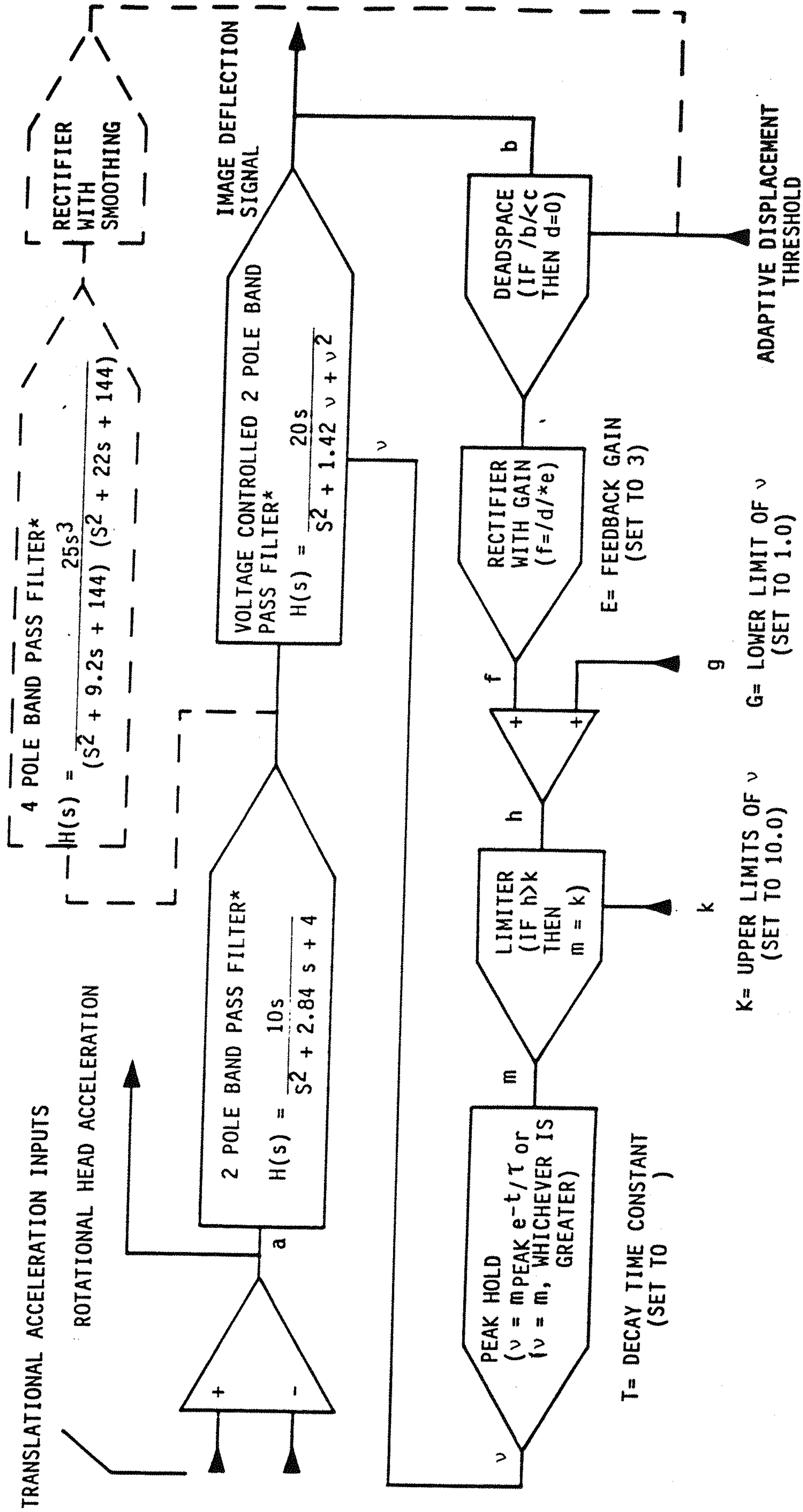


Figure 4.2 Schematic diagram of the adaptive image deflection system. Dashed components show modifications made to automatically vary the adaptive displacement threshold. (* the band pass filters combine the characteristics of integrators and high pass filters). Circuit designed by Dr C. Lewis.

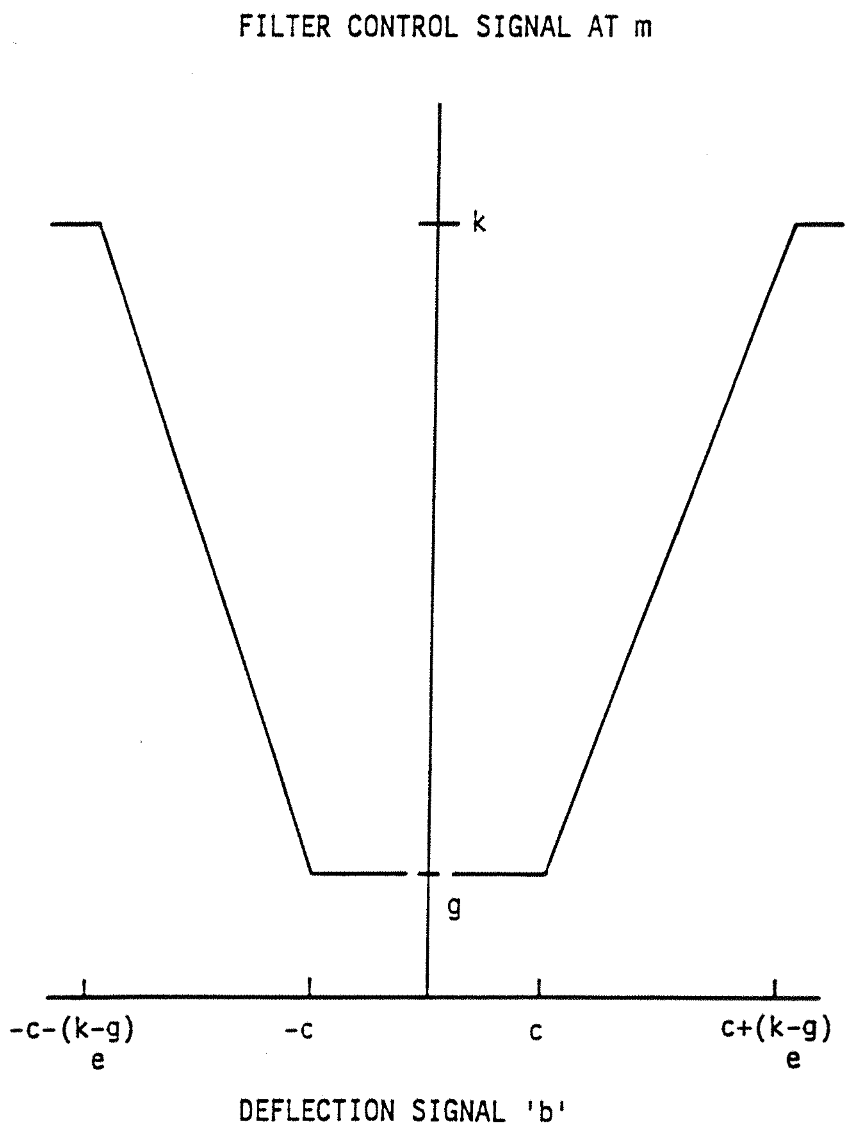


Figure 4.3 The variation of the filter control signal in the adaptive double integrator, at point 'm' in Figure 4.2, with the magnitude of the reflection signal 'b' and other circuit parameters.

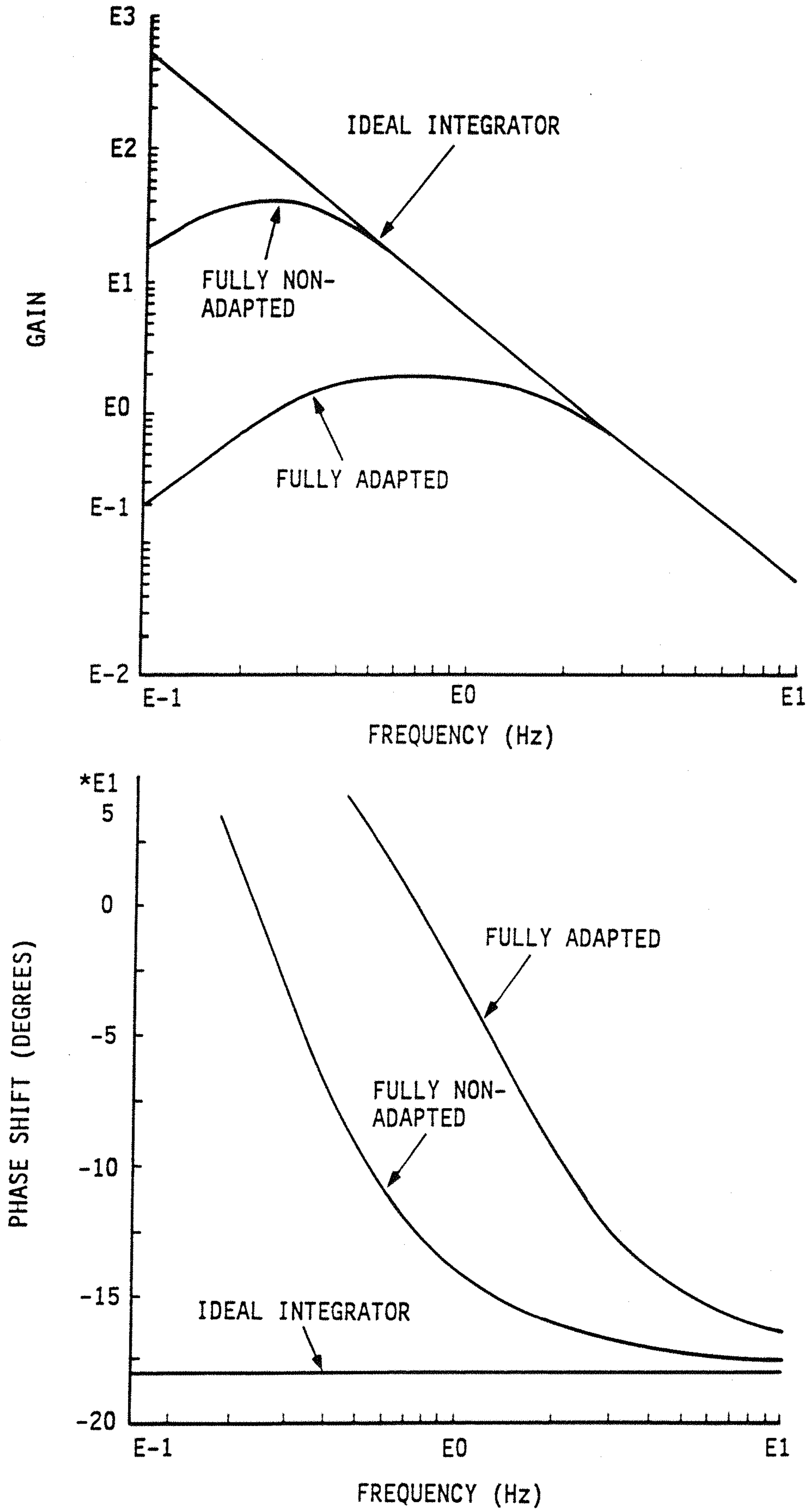


Figure 4.4 The response of the adaptive stabilisation system in its fully adapted and fully non-adapted states, compared to an ideal double integrator

The experiment described below was performed to test the performance benefits of the adaptively filtered stabilisation system, compared to the fixed filtering, when performing a helmet-mounted display reading task in the presence of large and rapid voluntary head movements.

4.2 APPARATUS AND PROCEDURE

This experiment was performed with a Hughes helmet-mounted display system. The two axis stabilisation was set up in each axis similarly to the experiment described earlier. The two identical analogue computer circuits were set up on separate VIDAC 336 analogue computers. The analogue computer patch diagrams are reproduced in Figure 4.1. The gain of the system was adjusted to give a space stable image at frequencies above 2 Hz.

As in previous experiments the visual material presented on the display consisted of sets of 50 numerals (0 to 9 presented 5 times each in random order) in a rectangular array of five rows by ten columns. The character size, font and luminance conditions were the same as in the previous experiments. The only difference in the presentation of the image was that a double width gap was left between columns 5 and 6. This additional gap helped participants find their position again after voluntary head movements.

Participants sat on a Derritron VP180LS electrodynamic vibrator with a hard flat seat, no backrest and a stationary footrest. Motion was vertical in the z axis. Experiment conditions are summarised below.

(a) Vibration conditions

v1 stationary
v2 4 Hz sinusoidal motion at 1.4 ms^{-2} rms

(b) Image stabilisation conditions

s1 adaptive stabilisation

s2 stabilisation fixed in unadapted state

s3 stabilisation fixed in fully adapted state

The experiment was performed by twelve male participants with Snellen visual acuities of at least 6/4 in each eye as tested on a Keystone oculometer. Two point sources of light were mounted in front of the participant, subtending 30 degrees diagonal at the participants eye from bottom left to top right. The mid point was 1.5 metres in front of the participants eyes as the participant looked straight ahead. The task was to position the centre of the display over one of the lights, read 5 digits, move the display rapidly along the diagonal to the other light, then read another five digits. This continued until the participant had read all fifty digits presented on the display thereby having made nine rapid head movements.

The participants read four complete arrays of fifty digits under each of the eight possible combinations of stabilisation and vibration conditions. These were presented in a balanced order. The participants were instructed to read 'as quickly and accurately as possible, but speed is twice as important as accuracy'. Payments made for taking part in the experiment consisted of a fixed sum with bonus additions. Bonuses were calculated on a 2:1 ratio between speed and accuracy. The experiment was run by two experimenters, one of whom continuously monitored head rotational acceleration. If peak acceleration in either axis during the voluntary movement along the diagonal fell below 60 radians per second, the participants were encouraged to increase the rapidity of their movements. Performance was measured by recording reading errors of omission and incorrect digits. Reading time for each array of fifty digits was also measured.

4.3 RESULTS

Separate two factor, mixed effects, randomised block analyses of variance were carried out on both reading time and reading error data. The results are summarised in Table 4.1 and 4.2.

TABLE 4.1 ANALYSIS OF VARIANCE SUMMARY TABLE FOR READING TIME

	Time				
Source	Sum of squares	df	Mean square	F ratio	Sig
Stabilisation	980.1	3	326.7	14.7	***
Vibration	4799.0	1	4799.0	185.9	***
Stab x Vib	1265.6	3	421.9	18.3	***
Stab x Participants	733.5	33	22.2		
Vib x Participants	284.0	11	25.8		
Vib x Stab x Par	759.9	33	23.0		

Significance level: *** 0.1%

TABLE 4.2 ANALYSIS OF VARIANCE SUMMARY TABLE FOR READING ERROR

	Error				
Source	Sum of squares	df	Mean square	F ratio	Sig
Stabilisation	1047.5	3	349.2	32.9	***
Vibration	2989.9	1	2989.9	73.3	***
Stab x Vib	1224.3	3	408.1	37.8	***
Stab x Participants	349.9	33	10.6		
Vib x Participants	448.6	11	40.8		
Vib x Stab x Par	356.4	33	10.8		

Significance level: *** 0.1%

It can be seen that there were highly significant effects of vibration and stabilisation on reading time and error ($p < 0.001$). Highly significant interactions between vibration and stabilisation are also apparent in both cases. Due to the nature of the interactions, Tukey's honestly significant difference test was performed on the differences between all possible pairs of means. The results are reported in Table 4.3.

TABLE 4.3 RESULTS OF TUKEY'S TEST OF HONESTLY SIGNIFICANT DIFFERENCES BETWEEN PAIRS OF EXPERIMENTAL CONDITIONS, FOR READING TIME

		Time							
		No vibration				Vibration			
		A1	A2	A3	A4	A1	A2	A3	A4
no vibration	A1								
	A2	-							
	A3	*	*						
	A4	-	-	*					
vibration	A1	*	*	*	*				
	A2	*	*	-	*	*			
	A3	*	*	-	*	-	-		
	A4	*	*	*	*	-	*	*	

TABLE 4.4 RESULTS OF TUKEY'S TEST OF HONESTLY SIGNIFICANT DIFFERENCES BETWEEN PAIRS OF EXPERIMENTAL CONDITIONS, FOR READING ERROR

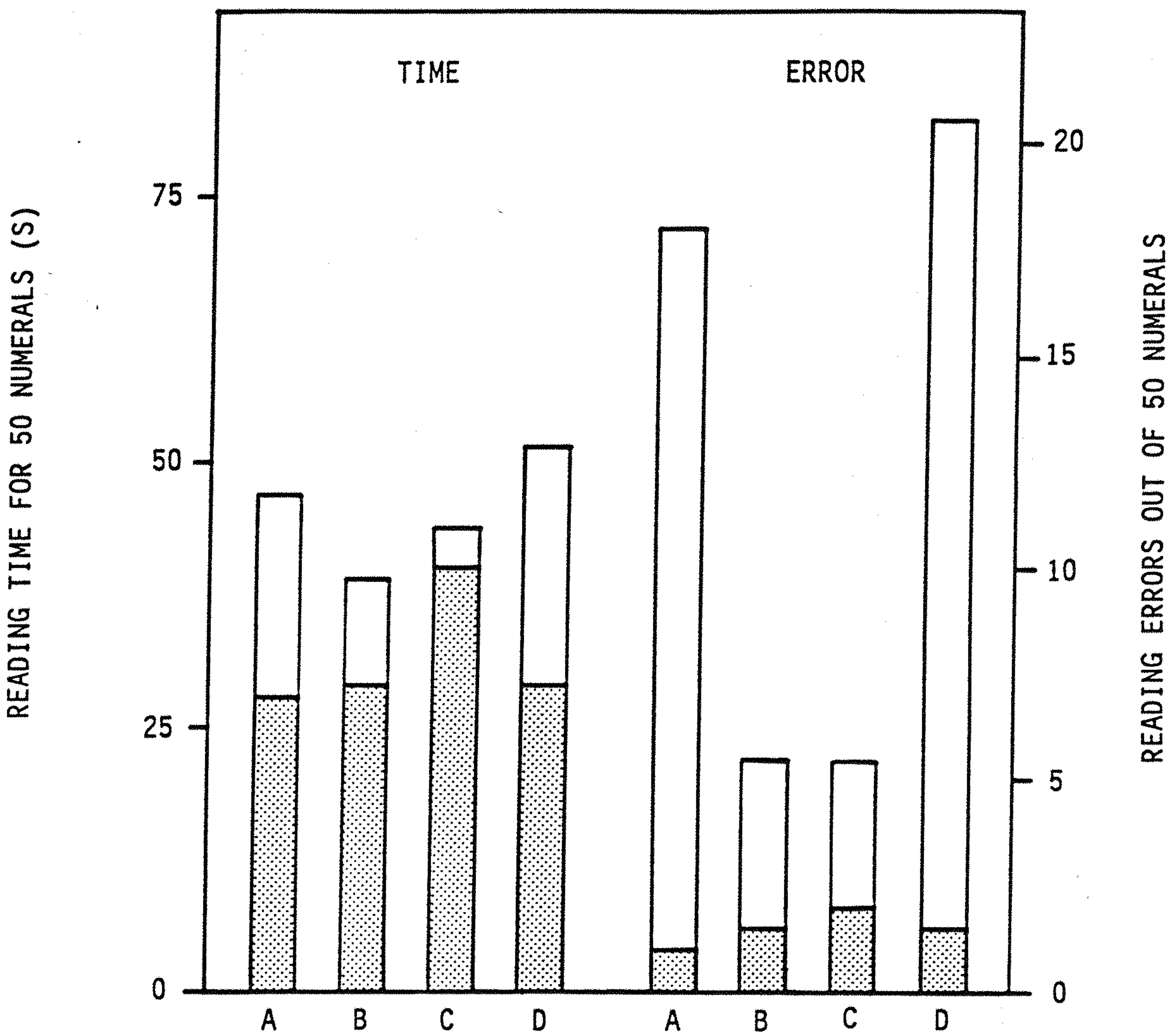
		Error							
		No vibration				Vibration			
		A1	A2	A3	A4	A1	A2	A3	A4
no vibration	A1								
	A2	-							
	A3	-	-						
	A4	-	-	-					
vibration	A1	*	*	*	*				
	A2	-	-	-	-	*			
	A3	-	-	-	-	*	-		
	A4	*	*	*	*	-	*	*	

Significance level: * 5%
A1 = no stablisation
A2 = adaptive stabilisation
A3 = fixed non-adapted stabilisation
A4 = fixed fully-adapted stabilisation

Mean reading times and errors for all the combinations of experimental conditions are plotted in histogram form in Figure 4.5.

Both the adaptive and the fixed non-adapted image stabilisation resulted in large and significant reductions in reading errors during 4 Hz vibration. The error performance during the fixed adapted stabilisation condition was slightly worse than that with no stabilisation, although the difference was not statistically significant. This confirms that a permanent increase in the high pass cut-off frequency, sufficient to effectively reduce apparent image motion during voluntary head movements, will result in an unacceptable integrator phase error for good stabilisation performance.

The reading time measures show that with no vibration, the fixed non-adapted stabilisation resulted in a significant reduction in performance. This was probably due to the time taken for the image to return to the line of sight after the cessation of head movements. A similar reduction in performance is apparent in reading error data, although not statistically significant. The comparable reduction in performance with adaptive stabilisation is very small in each case, showing that the adaptive filter does effectively maintain the image in the line of sight during rapid voluntary head movements. This was confirmed by the subjective impressions of the adaptive stabilisation system. Significant reductions in reading time with adaptive stabilisation are also apparent with 4 Hz vibration, compared with the other stabilisation conditions.



A = NO STABILISATION

B = ADAPTIVE STABILISATION

C = FIXED NON-ADAPTED STABILISATION (ω_2 = 1 RAD S^{-1})

D = FIXED FULLY-ADAPTED STABILISATION(ω_2 = 10 RAD S^{-1})

FILLED BLOCKS ARE SCORES WITH NO VIBRATION

UNFILLED BLOCKS ARE SCORES WITH 4 Hz SINUSOIDAL VIBRATION

Figure 4.5 Mean reading time and error scores from the adaptive stabilisation performance study

4.4 DISCUSSION

The results of the above experiment indicate that the implementation of adaptive high pass filtering has resulted in a system which can produce good image stabilisation at vibration frequencies encountered in aviation. It effectively reduces large unwanted amplifications of low frequency head motion, with the associated reading time penalties. Comments by experimental participants confirm that the adaptive stabilisation is subjectively more acceptable than a system with fixed high pass filtering. The adaptive stabilisation algorithm used in the experiment was therefore adopted as the basis of a flightworthy system to be tested in a helicopter. The circuit diagram for this is shown in Figure 4.6 and 4.7.

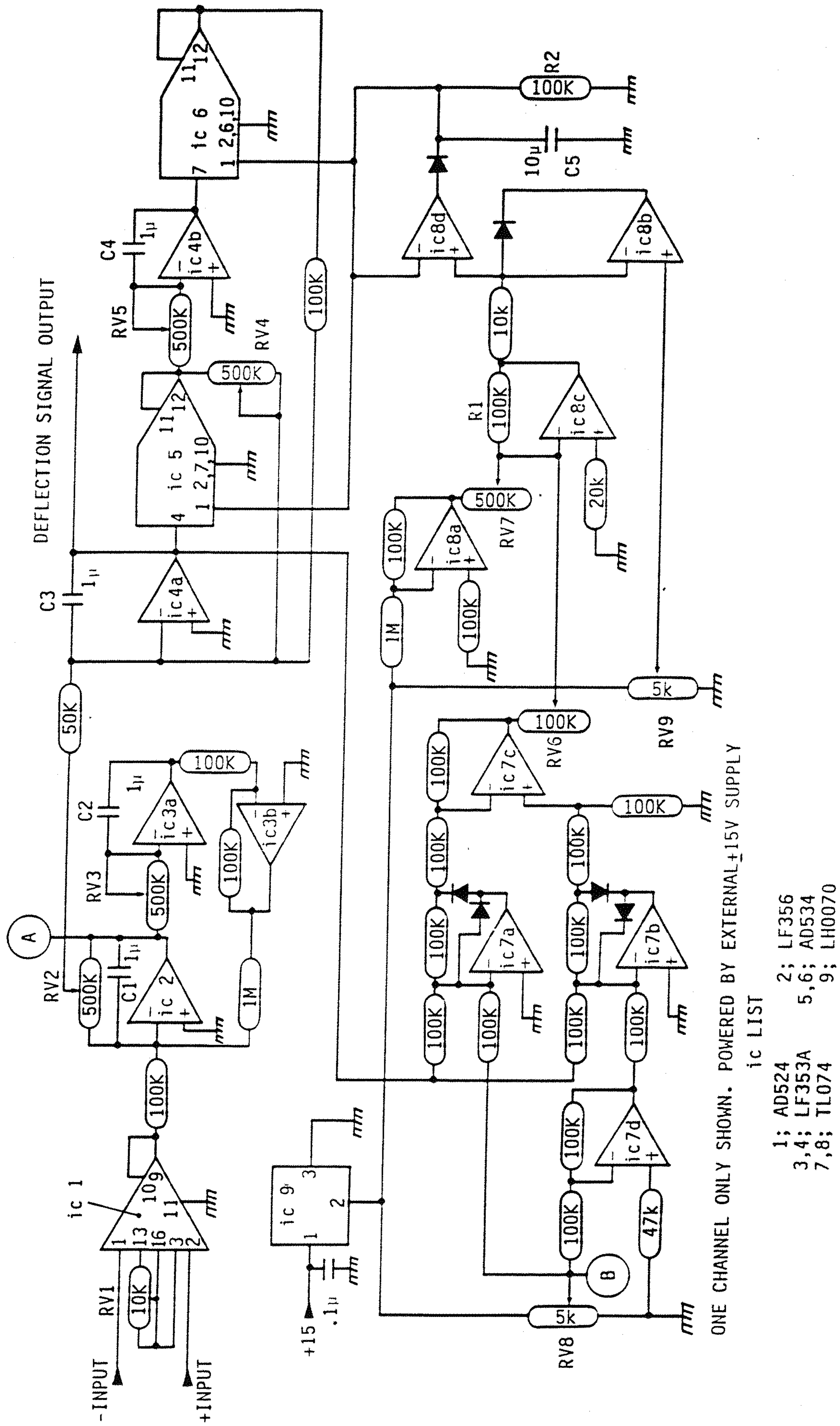


Figure 4.6 Main part of adaptive stabilisation circuit. Circuit designed by Dr C. Lewis

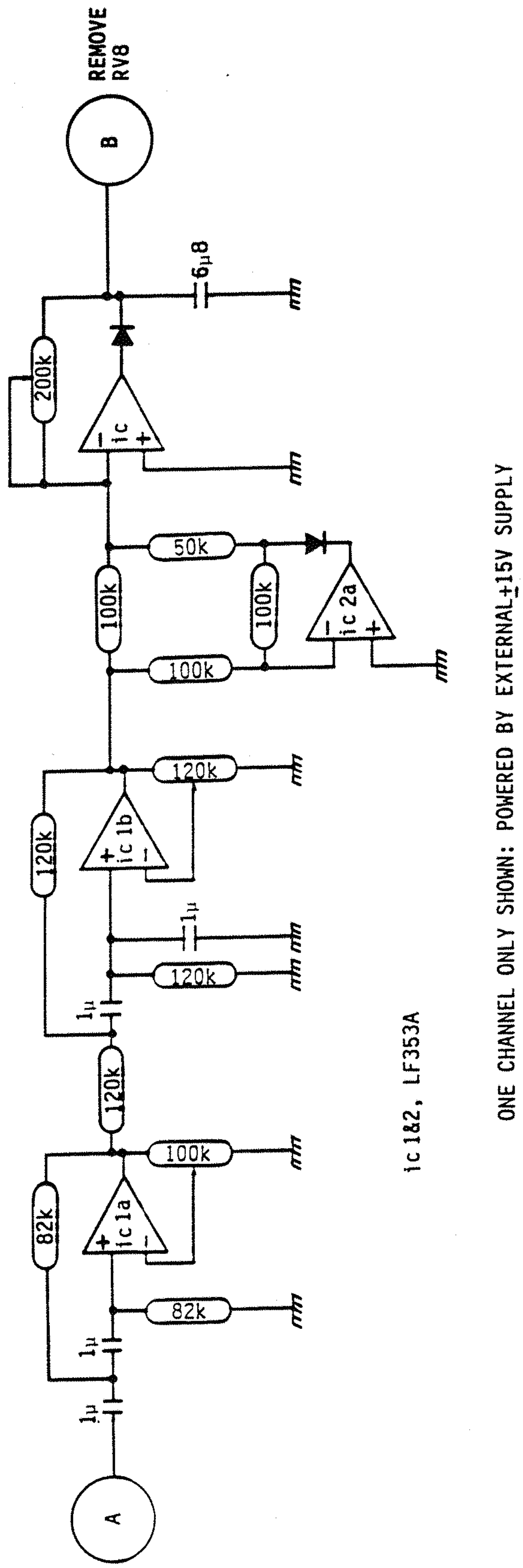


Figure 4.7 Sub-section adaptive stabilisation circuit. Circuit designed by Dr C Lewis

CHAPTER 5 : OPTIMISATION OF THE ADAPTIVE STABILISATION SYSTEM

5.1 INTRODUCTION

An adaptive stabilisation system, with its greater complexity of operation, inevitably generates more parameters which need to be optimised for a particular application. The system which was used in the previous experiment was set up largely on the basis of tests with simulated rotational acceleration inputs. Although good results were obtained in the experiment, it was considered important to investigate the possible benefits of fine tuning the parameters of the adaptive feedback system. The non-adapted natural frequency of the system was set up on the basis of the previous experiments, and was considered to be near optimum. The size of the deadspace determines the magnitude of the deflection signal which causes the system to begin to adapt. The optimum deadspace depends on the nature of the vibration environment and is not considered here. The two parameters investigated in this experiment are the fully adapted natural frequency and its exponential decay time constant. The fully adapted natural frequency affects the extent of the attenuation of voluntary head movements. The natural frequency decay time constant affects the speed with which the natural frequency returns to its non-adapted value.

5.2 APPARATUS AND PROCEDURE

The helmet-mounted display and seating conditions were identical to those in the previous experiment. Seven values of ω_k, the maximum natural frequency of the variable complex pole pair, and three values of τ, the exponential decay time constant, were used. Thirteen combinations of these parameters were used. Table 5.1 shows the exact values.

TABLE 5.1 VALUES OF ω_k and τ USED IN THE EXPERIMENT

		ω_k (rad s^{-1})						
		5	6.3	8	10	12.5	16	20
τ(s)	1.0	1	2	3	4†	5	6	7
	0.5		8		9		10	
	0.25		11		12		13	

(Only the numbered combinations were presented)
† The combination used in the previous experiment

The variation in gain and phase response of the system as ω_k is changed is shown in Figure 5.1.

The task was performed under 4Hz vertical, sinusoidal, z axis vibration at 1.4 ms^{-2} rms. Four participants with Snellen visual acuity of at least 6/4 in both eyes were used. The participants read one complete array of fifty numbers for each combination of experimental conditions.

5.3 RESULTS

The results are presented in Figures 5.2 and 5.3.

In view of the limited nature of the experiment, the form of the results obtained, and the few participants, no formal statistical tests were applied to the data. The data as presented in graphical form reveal sufficient trend information to be of use.

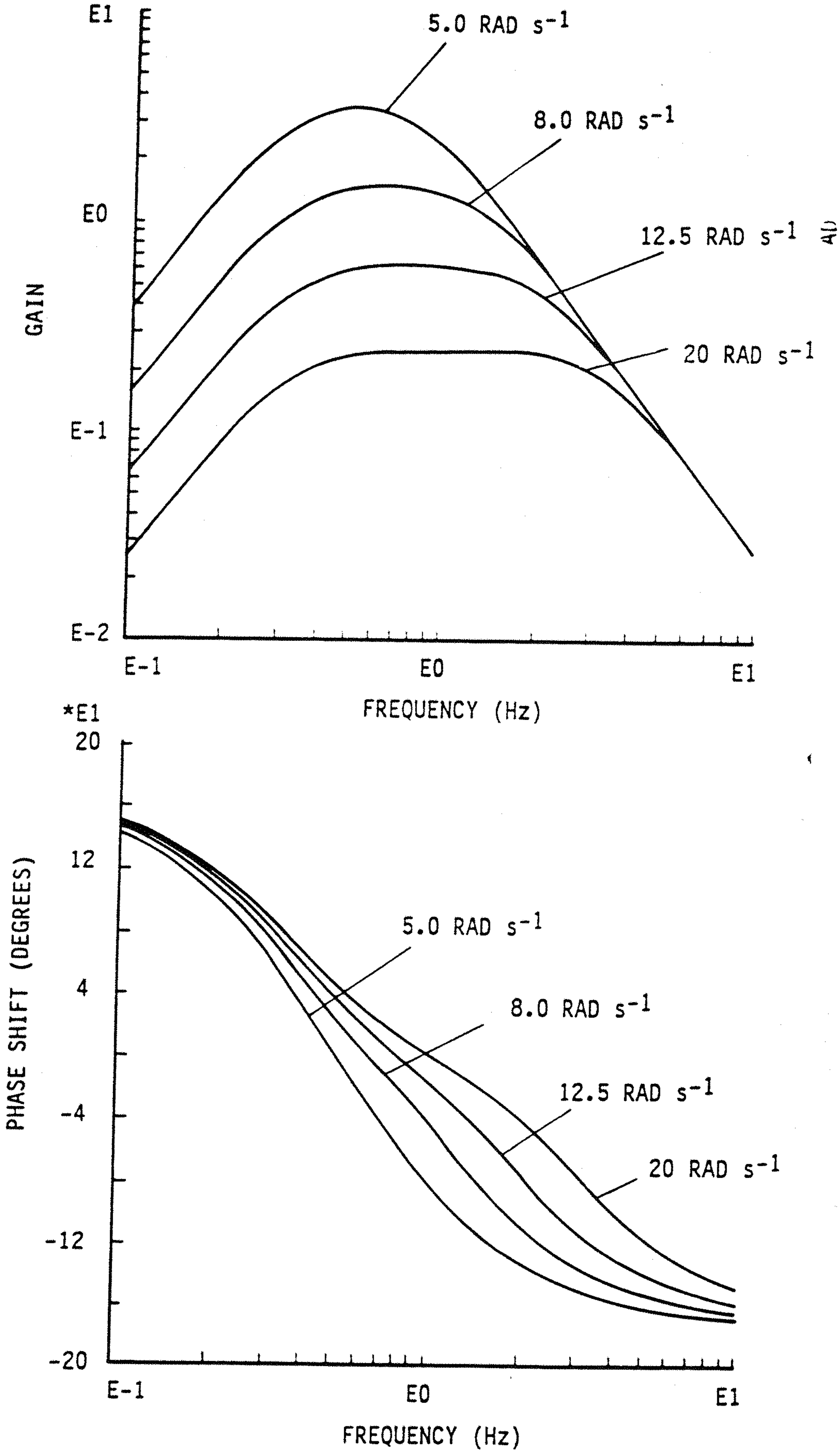


Figure 5.1 Variation in response of adaptive stabilisation system in its fully adapted state, with variations in maximum value of ω_{n2} or ω_k

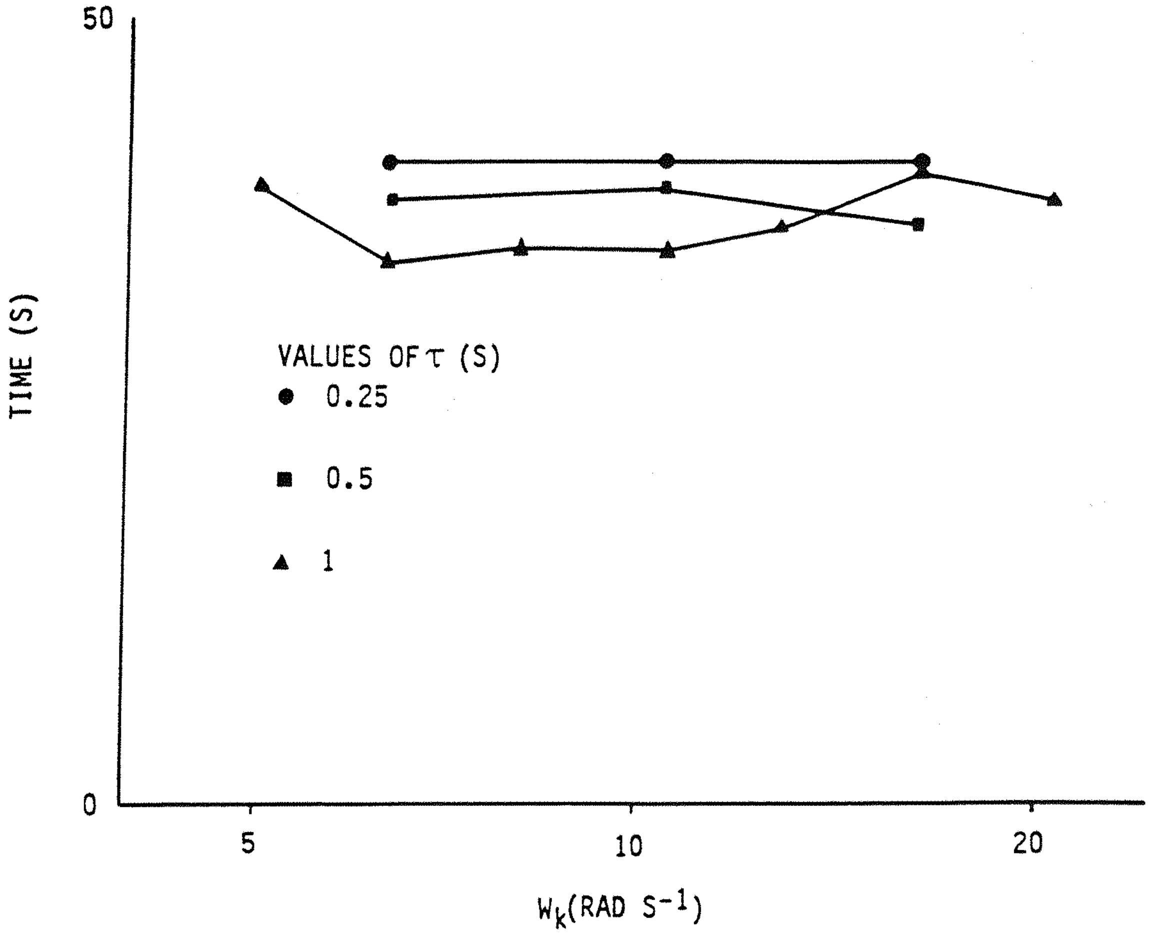


Figure 5.2 Mean reading time under conditions of whole-body vibration with different combinations of ι and ω_k in the stabilisation algorithm.

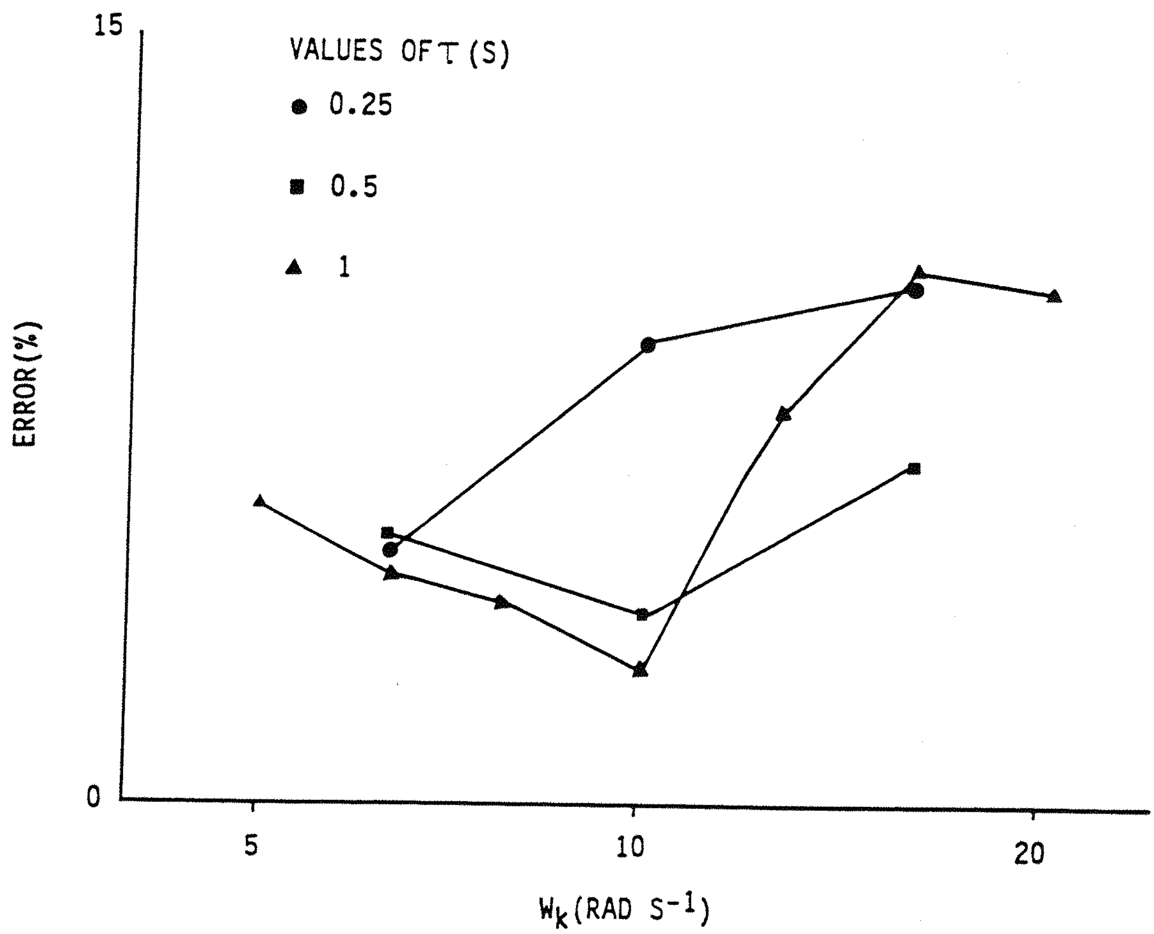


Figure 5.3 Mean reading error under conditions of whole-body vibration with different combinations of ι and ω_k in the stabilisation algorithm.

5.4 DISCUSSION

There was little effect of ω_k on reading time, particularly with the lower time constants. However, a time constant of 1.0 second produced a lower mean ω_k between 6.3 and 12.5 radians per second. The variations in reading error are more marked. The higher two values of ι both favour an ω_k of 10 radians per second. A ι of 0.25 second seems to favour a much lower value of ω_k. With the lower time constants, and particularly with ι = 0.25 second, the participants reported symptoms of image instability. The instability was particularly marked at the higher values of ω_k. It would appear that the shorter time constants do not give sufficient lag in the natural frequency of the filter to allow the image to settle sufficiently in the line of sight after the cessation of a head movement. Consequently the deflection signal varies about the edge of the deadspace, continually oscillating between an adapted and a non-adapted state.

On the basis of the results reported above, it was concluded that the values of ω_k (maximum natural frequency) and ι (naturally frequency decay time constant) used in the previous experiment represented near optimum settings. These allowed a stable transition between adapted and non-adapted states, and would be included in a flightworthy system.

CHAPTER 6 : ASSESSMENT OF RETICLE STABILISATION FOR HELMET-MOUNTED SIGHTS

6.1 INTRODUCTION

A helmet-mounted sight utilises the ability of the head to acquire and track targets. The equipment includes a helmet position sensing system to give information about head pointing angle. A reticle is included to give the operator enhanced feedback of head orientation.

The reticle may be generated by dedicated hardware or by drawing an electronic image on the screen of a helmet-mounted display. The latter provides the advantages of the helmet-mounted display and helmet-mounted sight in one system.

Because of their proposed use in high vibration airborne environments, it is important to understand the effects of vibration on tasks involving helmet-mounted sights. It should also be known to what extent performance may be changed by the use of image stabilisation techniques.

The helmet-mounted sight encounters certain problems when operated in vibrating environments. Vibration-induced head movement appears as an error signal at the output of the system. In addition, as with the helmet-mounted display, the eye remains approximately space stable, whilst the reticle moves with the head and helmet. The relative motion between reticle and eye results in a blurred or moving image. Lewis and Griffin (1979) showed that target and reticle blur may be the primary cause of increased tracking error in manual displacement tracking tasks under vibration. Stabilisation of the reticle may therefore be expected to reduce vibration induced performance decrements in head aiming performance.

The precision of the feedback provided by the reticle about head pointing angle will be reduced if inappropriate image deflection occurs with stabilisation. Image drift, due to low frequency and voluntary head movements, is therefore likely to offset the performance benefits obtained by reducing image blur. Voluntary head movements are an essential feature of tasks involving helmet-mounted sights. The early versions of the image stabilisation system produced large image deflection in response to voluntary movement. This made it clearly unsuitable for use in sights. The development of the adaptive stabilisation system which suppresses deflection in response to voluntary movement appeared to have the right qualities for image stabilisation in sights.

The adaptive stabilisation system operates by comparing the image deflection with a preset displacement threshold. When the deflection exceeds the threshold, the high pass filtering of the signal is progressively increased. Thus, the low frequency image deflection activity, seen as image drift, is reduced. The amount of image drift observed with the system is dependant on the displacement threshold. The magnitude of the threshold is a compromise between a high value to ensure stabilisation during high magnitude vibration, and a low value to reduce drift. This becomes a matter of reticle blur at high values or reticle drift at low values.

The experiment described below was performed to determine the optimum displacement threshold.

6.2 APPARATUS

A reticle was drawn on the CRT of the helmet-mounted display. The reticle consisted of a '+' five degrees in diameter. Head position was measured using a Honeywell

MOVTAS III. This system projects contra-rotating beams of infra red light which are detected by sensors fixed to the helmet. The times that the beams strike the sensors are used to compute head angular displacement in space. The system used two sensor assemblies to determine head roll, pitch and yaw. However the addition of the helmet-mounted display hardware prevented the use of one of the sensors. The single sensor system could only compute head pitch and yaw, any head roll added to the error in the two outputs. It was therefore necessary to ensure that participants controlled any tendency to roll their heads. The system required boresight calibration to align the output with a known position in space.

A semi-rigid simulated Sea King seat was mounted on a Derritron VP180LS vibrator. A perspex sheet 1.5 metres in front of the seat held a rectangular array of 9 light emitting diodes. The central diode was in the participant's line of sight whilst looking straight ahead. The top row was 15 degrees up, and the bottom row 15 degrees down. The left column was 15 degrees left, and the right column was 15 degrees right.

During the experiment, head pitch and yaw outputs were digitised and stored for analysis.

Twelve male participants carried out a task which required acquiring targets and aiming at them. One of the diodes was used as a cue. The participant aimed the reticle at the cue, when the cue light was extinguished a target light was illuminated. This provided the signal for the participant to move the reticle to the target and hold it on position until ten seconds after the signal. Participants were instructed to be as quick and accurate as possible. They were also asked to minimise head roll as there is a tendency to roll the head when moving it along diagonals.

The experimental conditions are listed below.

(a) Movement

Vertical	15 degrees up to 15 degrees down
Horizontal	15 degrees left to 15 degrees right
Diagonal	15 degrees up, 15 degrees left to 15 degrees down, 15 degrees right

(b) Vibration

No vibration
z axis vertical sinusoidal 4 Hz 1.4 ms^{-2}
z axis vertical random 4 Hz 1.4 ms^{-2} rms 1 octave band

(c) Stabilisation

No stabilisation
1 degree window
2 degree window
3 degree window

All combinations of the above conditions were presented in a random order.

Head pitch and yaw were measured from the moment the experimenter switched the target light on to ten seconds later.

The stored measures of head pitch and yaw displacement were used to calculate the radial deviation of the line of sight from the target. The time histories were then analysed and scored in the following four ways:

- Fast phase — Time to reach the target position

▪	Settling time	Time until the cross is continuously on target for at least 0.5 second
▪	Proportion of time on target	Measured from the settling time until the end of the time history
▪	Mean radial error	Measured from settling time until the end of the time history

6.3 RESULTS

Figure 6.1 shows how head pitch angle varies without vibration for a vertical movement from 15 degrees up to 15 degrees down.

Figure 6.2 shows how head pitch angle varies with 4 Hz sinusoidal vibration for a vertical movement from 15 degrees up to 15 degrees down.

Figure 6.3 shows how head pitch and yaw angles vary with 4 Hz octave band random vibration for a diagonal movement from 15 degrees up, 15 degrees left to 15 degrees down, 15 degrees right.

Although the light emitting diode was virtually a point source, the analysis of angular deviations from the target classed 'on target' as any point within a 3 degree diameter circle centred upon the position of the light emitting diode. Several analyses of variance were performed and Table 6.1 provides a summary of results.

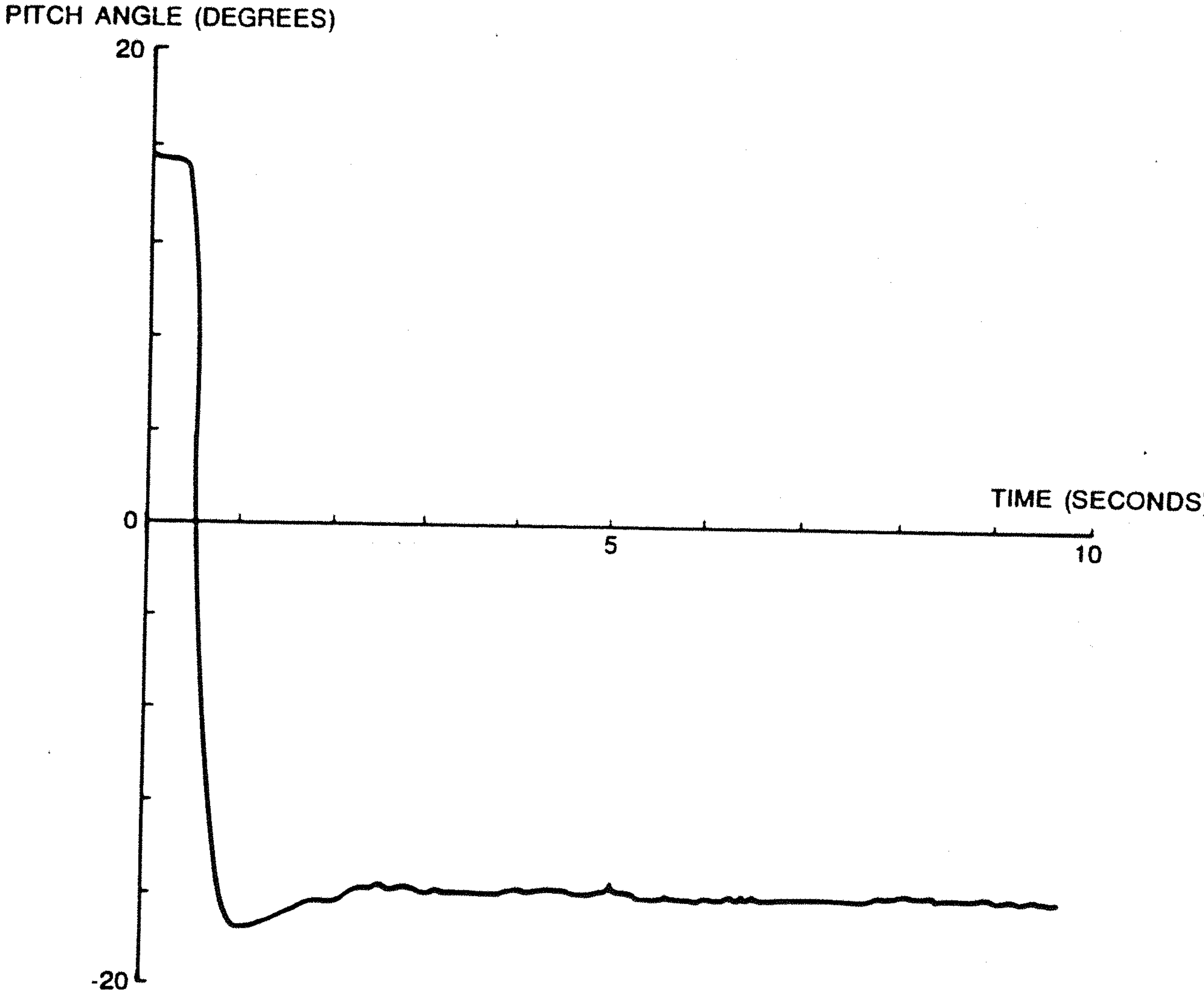


Figure 6.1 Head pitch angle during target acquisition

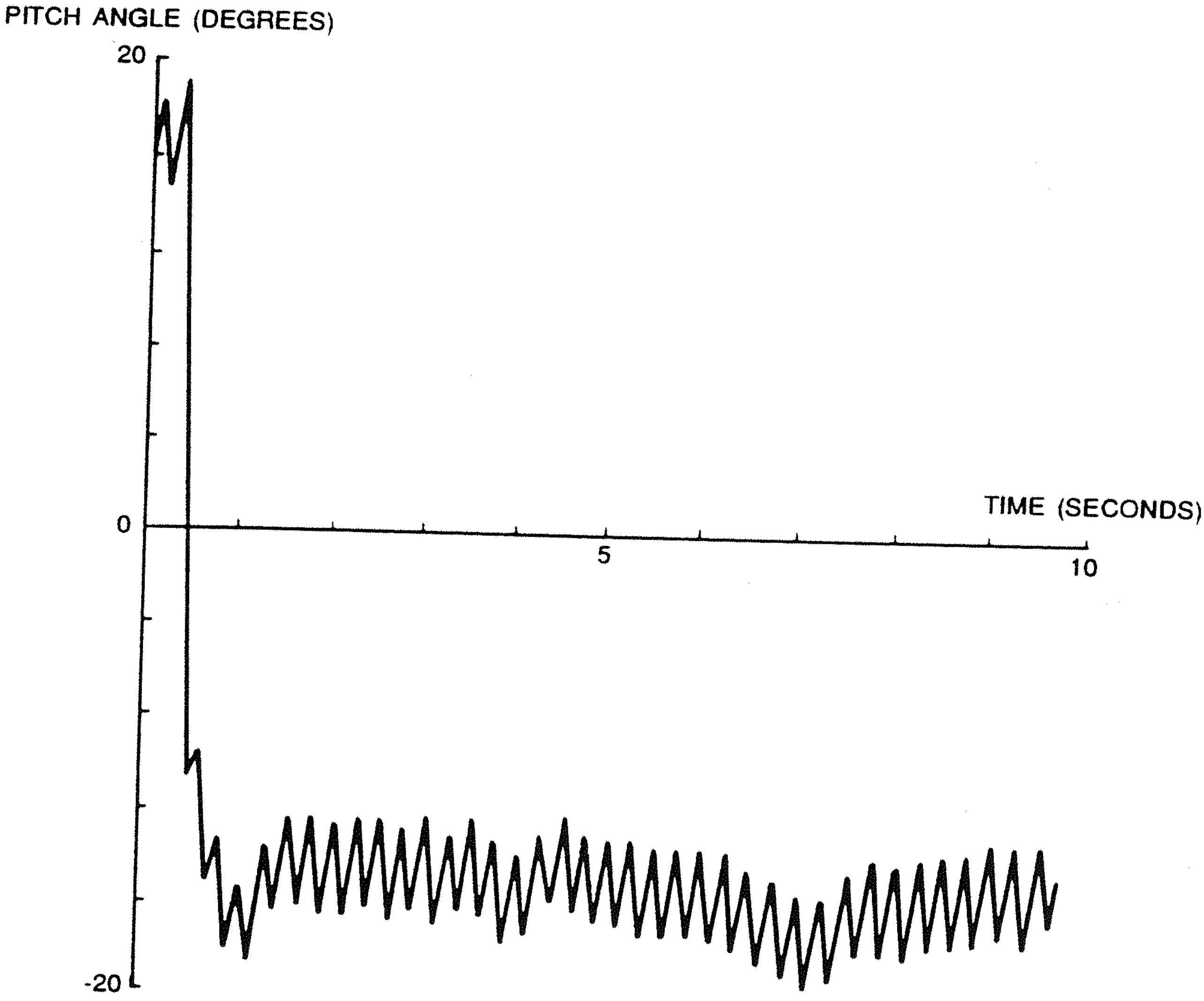


Figure 6.2 Head pitch angle during target acquisition under whole-body vibration (4 Hz sinusoidal 1.4 ms^{-2} rms)

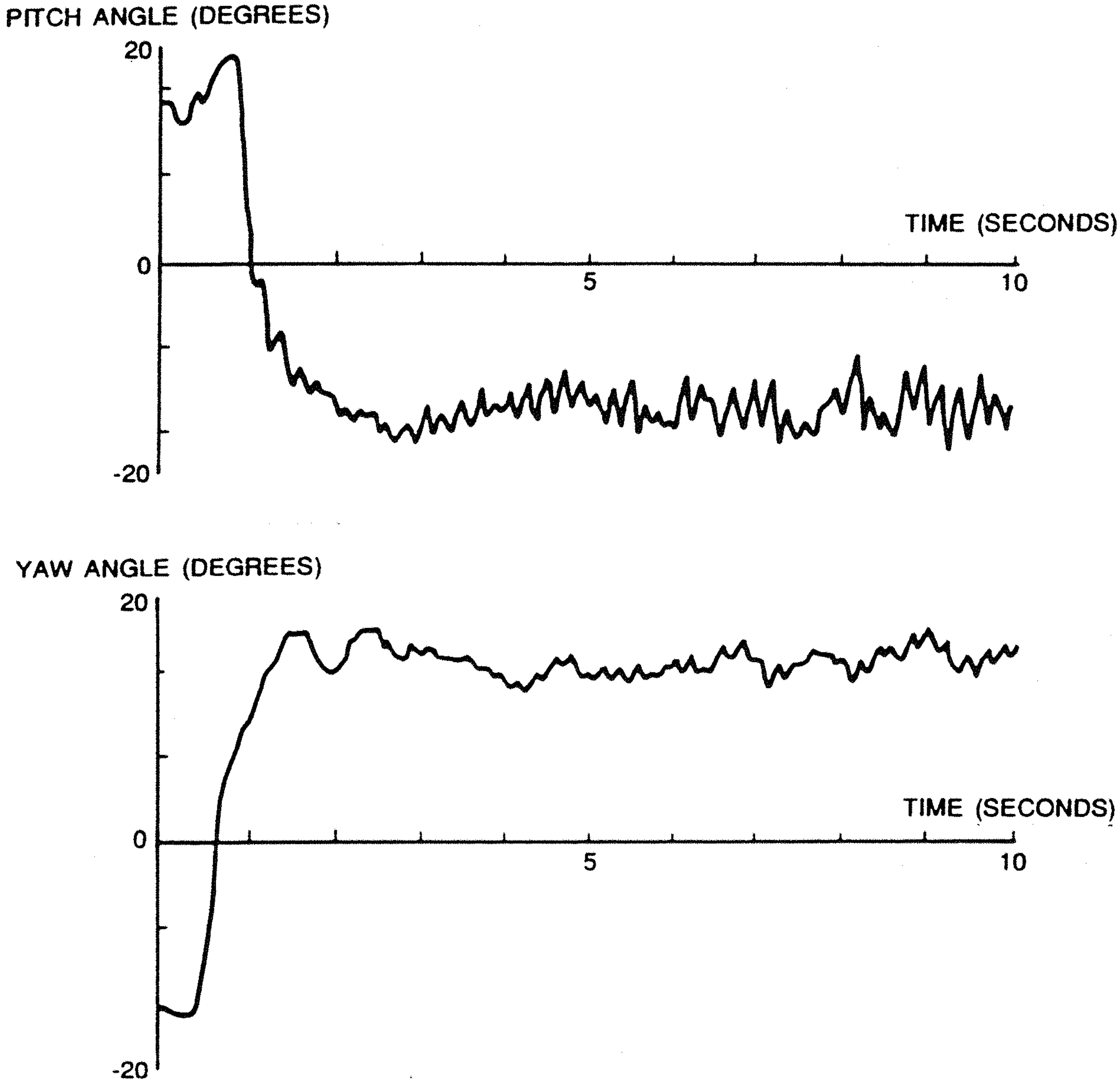


Figure 6.3 Head angle during target acquisition under whole-body vibration (4 Hz Random 1 octave band 1.4 ms^{-2} rms)

TABLE 6.1 RESULTS OF AN ANALYSIS OF VARIANCE OF DATA FOR A VERTICAL MOVEMENT

Source	Fast phase	Settling time	Proportion on target	Mean radial error
Participants	***	***	***	***
Movement (A)	***	***	*	**
Vibration (B)	**	-	**	***
Stabilisation (C)	***	***	-	**
AB	-	-	-	-
AC	-	-	-	-
BC	*	-	-	*
ABC	-	-	-	-

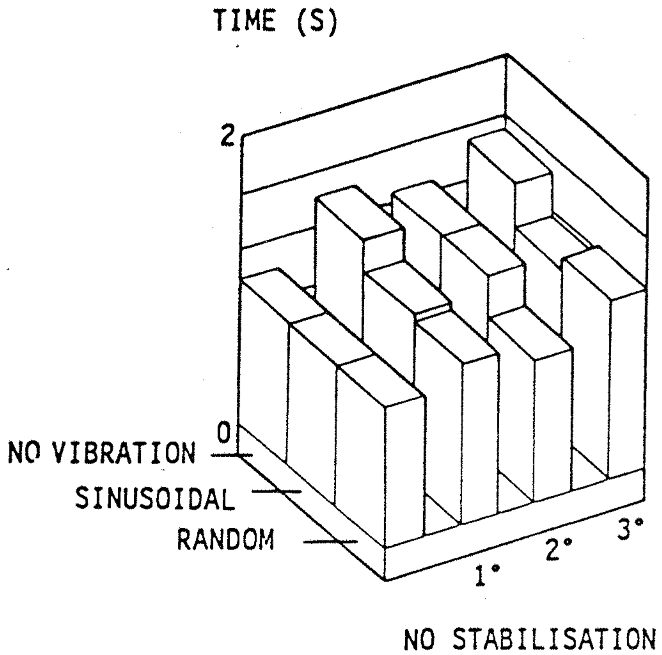
Significance levels: *** 0.1%
** 1%
* 5%

The histograms in Figure 6.4 show results for vertical movements where the cue light was 15 degrees up and the target was 15 degrees down. The other conditions showed similar trends.

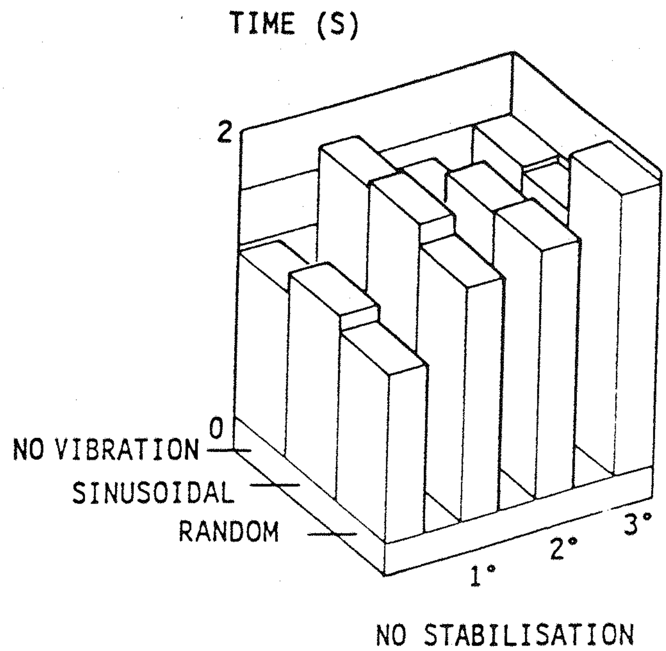
6.4 DISCUSSION

Since an arbitrary target size of 3 degrees was chosen during analysis, there may be more merit in studying the mean radial error, than the other measures. However, the other measures may be useful to indicate trends.

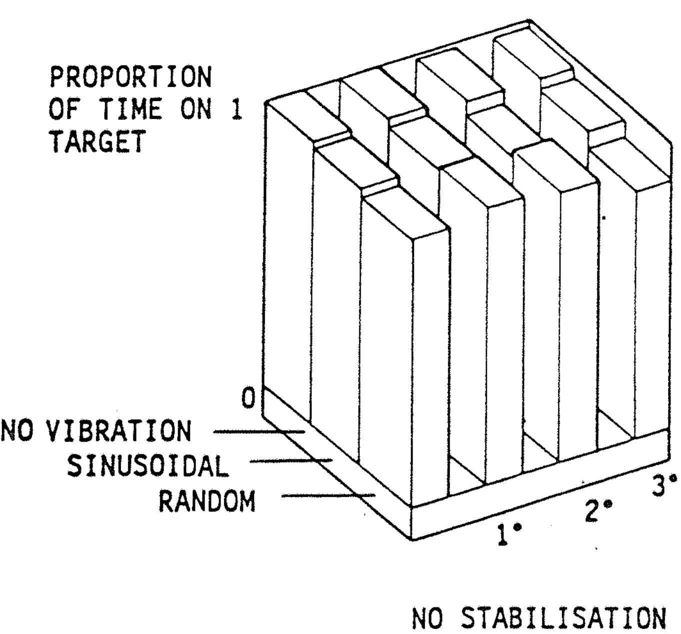
The mean radial error after settling time can be seen generally to increase with the magnitude of the adaptive displacement threshold. The proportion of time on target follows a similar trend.



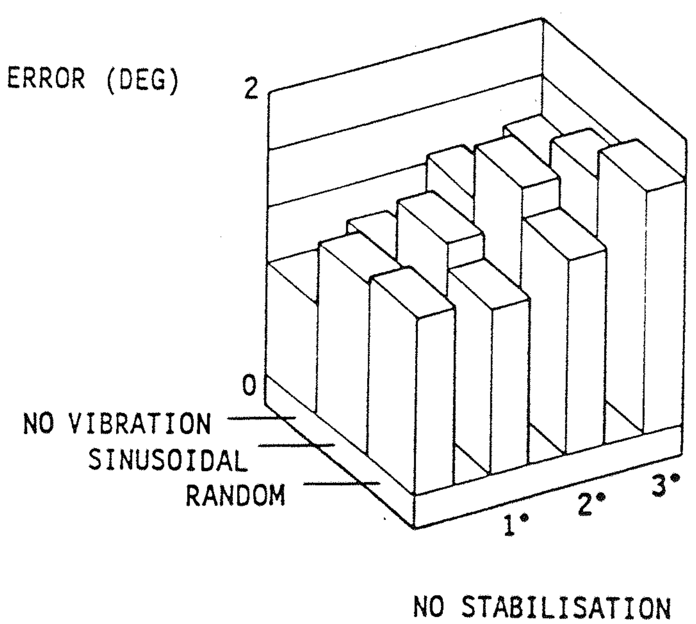
FAST PHASE



SETTLING TIME



PROPORTION OF TIME ON TARGET



MEAN RADIAL ERROR

Figure 6.4 Head aiming performance scores

There was a general increase in the fast phase time with stabilisation and increasing window size. Under stabilisation conditions, with fast head movements, the dynamics of the deflection system cause the reticle to lead head position. This tendency becomes more exaggerated as window size increases. The consequence is that participants apparently decelerate head movements too early resulting in an increase in fast phase time. This tendency is less marked when vibration is present as the image deflection due to vibration induced head movement causes the displacement threshold to be exceeded earlier, thus decreasing the lead in reticle position. Similar trends can be observed in settling time where the larger displacement thresholds resulted in greater uncertainty in helmet pointing angle.

A similar process is observed in the settling time, the increasing window size causing greater uncertainty in the target position.

The only condition where stabilisation improved aiming performance was under random vibration with the smallest window size. This showed increased time on target and decreased mean radial error. However the improvements were small. With the larger displacement thresholds the stabilisation system allows a greater amount of low frequency reticle drift. The decrement in aiming performance due to reticle drift is clearly greater than the performance benefit due to the reduction of reticle blur by image stabilisation. There is an indication that with smaller displacement thresholds and random vibration the benefits of stabilisation may equal the degradation due to image drift. Although it is unlikely that reticle stabilisation could significantly improve static aiming performance with the system used in this experiment.

The degradation of aiming performance by the image stabilisation system is due to the low frequency image deflection which causes the reticle to depart from the helmet pointing angle. This means that the reticle no longer gives reliable feedback to the operator of where the helmet is pointing. The image deflection signal could be fed into the output for weapons and sensors and the output of helmet sensing system would therefore indicate the line of sight of the reticle and the reticle would provide precise feedback to the operator of the aiming angle of the sensors or weapons.

6.5 CONCLUSIONS

An experiment is described which measures the effects of varying the displacement threshold of a reticle stabilisation system on aiming performance with a helmet-mounted sight under conditions of whole-body vibration. It was shown that with sinusoidal vibration, irrespective of displacement threshold, stabilisation did not improve performance. With random vibration, a 1 degree displacement threshold produced a small increase in the proportion of time on target and a small reduction in mean radial error. The decrement in performance produced by reticle stabilisation was caused by low frequency reticle deflection which resulted in the operator being given false information about helmet pointing angle. A scheme is suggested which may allow the advantages of reticle stabilisation to be realised without introducing the disadvantages of reticle drift.

CHAPTER 7 : HELMET-MOUNTED DISPLAY READING PERFORMANCE DURING LOW FREQUENCY WHOLE-BODY VIBRATION

7.1 INTRODUCTION

The purpose of this experiment was to investigate helmet-mounted display performance at low frequencies of vertical vibration. Although major problems were not expected in the effective range of the pursuit reflex i.e. up to about 2 Hz (see Chapter 1), it was considered important to conduct an experiment to confirm this. It was important because aircraft vibration spectra often have large amounts of low frequency vibration.

7.2 APPARATUS AND PROCEDURE

Fourteen male participants from students and staff of the University of Southampton were used in the experiment. They had visual acuities better than 6/6 in each eye.

Participants were trained by presentation of 3 arrays of digits without vibration. This was followed by 3 arrays with sinusoidal vibration. The vibration frequency during training was chosen at random from each of three ranges, low (0.4 to 1.0 Hz), medium (1.25 to 3.15), and high (4.0 to 10.0 Hz). Vibration magnitude was 1.4 ms^{-2} rms.

A semi-rigid simulated Sea King seat was mounted on the 1 metre stroke hydraulic vibrator. Participants were secured by a five point harness. They were instructed to 'look straight ahead and read as quickly and accurately as possible'. Reading time was measured from the first appearance of the digits on the display to the moment the participants had read the 50th digit. Reading errors were recorded for incorrect and omitted digits.

Sixteen vibration conditions were presented to participants in a random order. They consisted of a static conditions and sinusoidal vibration at each of the fifteen preferred third-octave frequencies from 0.4 to 10 Hz (0.4, 0.5, 0.63, 0.8, 1.0, 1.25, 1.6, 2.0, 2.5, 3.15, 4.0, 5.0, 6.3, 8.0, 10.0). At all frequencies the vibration magnitude was 1.4 ms^{-2} rms.

7.3 RESULTS

Time and error scores were tested by analysis of variance. Tables 7.1 and 7.2 summarise the results.

TABLE 7.1 SUMMARY TABLE OF ANALYSIS OF VARIANCE FOR TIME SCORES

TIME

Source	Sum of squares	df	Mean square	F ratio	Sig
Blocks	4224.34	13	324.95		
Treatments	11543	15	769.53	20.00	***
Error	7504.37	195	38.48		
Total	23271.71	223	104.36		

Significance level: *** 0.1%

TABLE 7.2 SUMMARY TABLE OF ANALYSIS OF VARIANCE FOR ERRORS

ERROR

Source	Sum of squares	df	Mean square	F ratio	Sig
Blocks	1061.81	13	81.68		
Treatments	88626.53	15	5908.44	220.49	***
Error	5225.41	195	26.80		
Total	10711.75	223	48.03		

Significance level: *** 0.1%

Figure 7.1 shows reading time scores as a function of vibration frequency. All time scores from 2.5 to 10Hz inclusive were found to be significantly different at the 5% level from the static condition according to Dunnets t test. Percentage error scores are shown in Figure 7.2, where a score of 100% represents 50 errors. All error scores from 3.15 to 8 Hz were found to be significantly different at the 5% level from the static error according to Dunnets t test.

The frequency of worst effect for reading errors was 5 Hz. This was not significantly different at the 5% level from the error scores at 3.15, 4 and 6.3 Hz, but it was significantly different from those at all other frequencies (Tukey's t test).

The reading time and error scores were divided by 1.4 ms^{-2} to normalise them with respect to an acceleration magnitude of 1.0 ms^{-2} rms. The time scores of each participant were then converted to percentage increase in reading time relative to the static time of that participant. The error scores of each participant were converted into increase in percentage error relative to the static error of that participant.

Figure 7.3 shows the converted time scores compared with data from Wells and Griffin (1983), who treated their data in the same manner. Figure 7.4 shows the converted error scores. An important difference between the two experiments is that Wells and Griffin varied vibration magnitude with frequency whereas the current experiment did not.

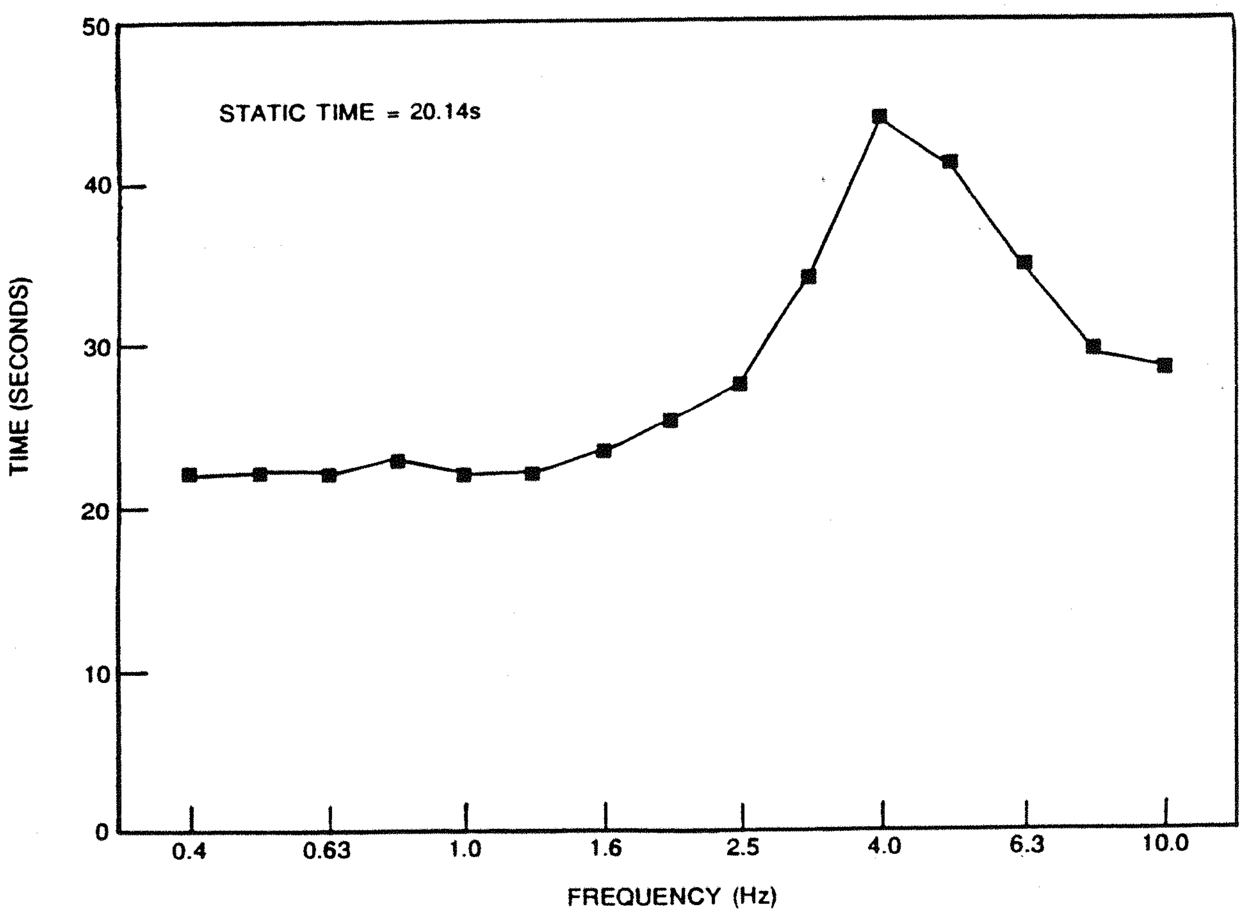


Figure 7.1 Mean reading time against frequency for 50 digits

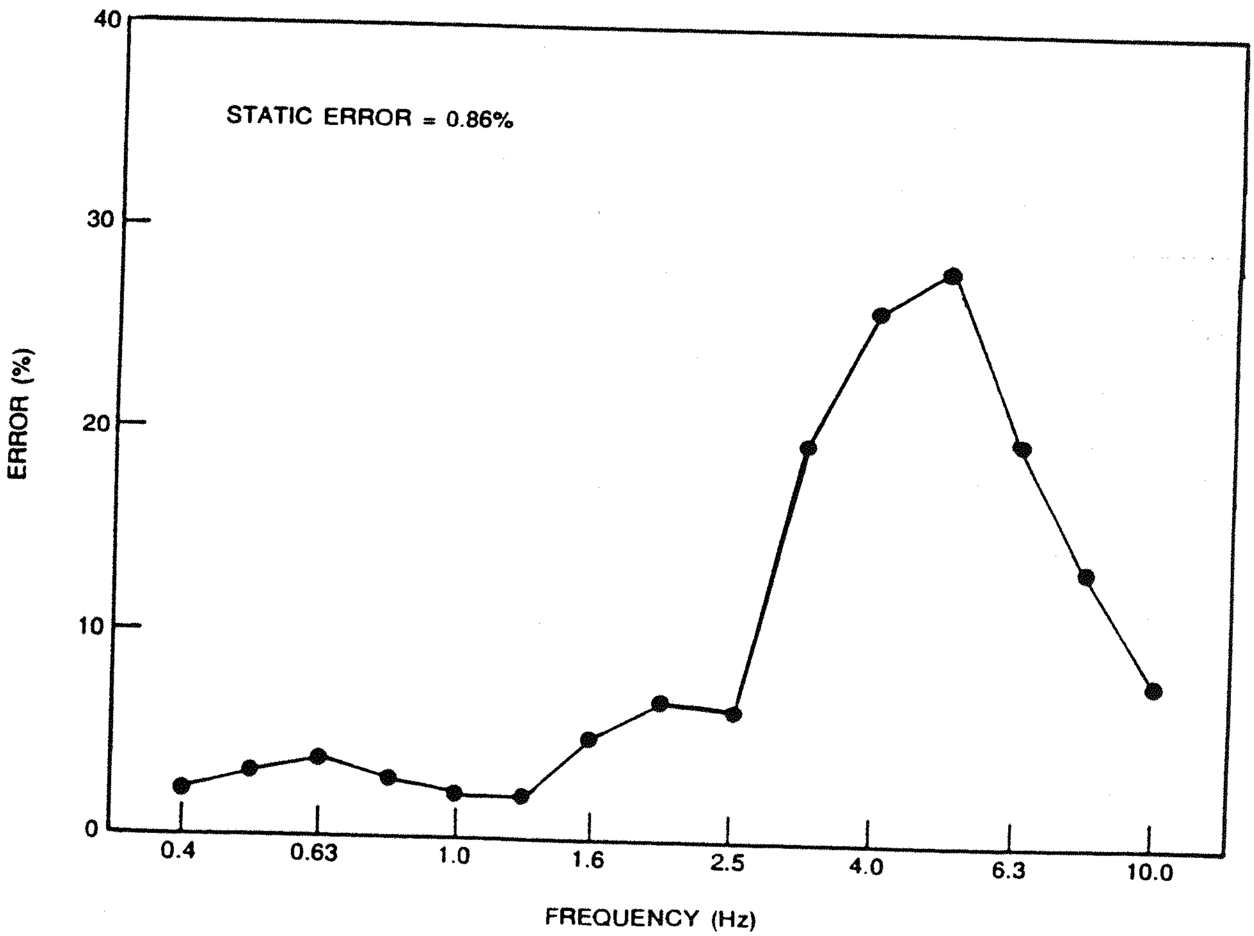


Figure 7.2 Mean reading error against frequency for 50 digits

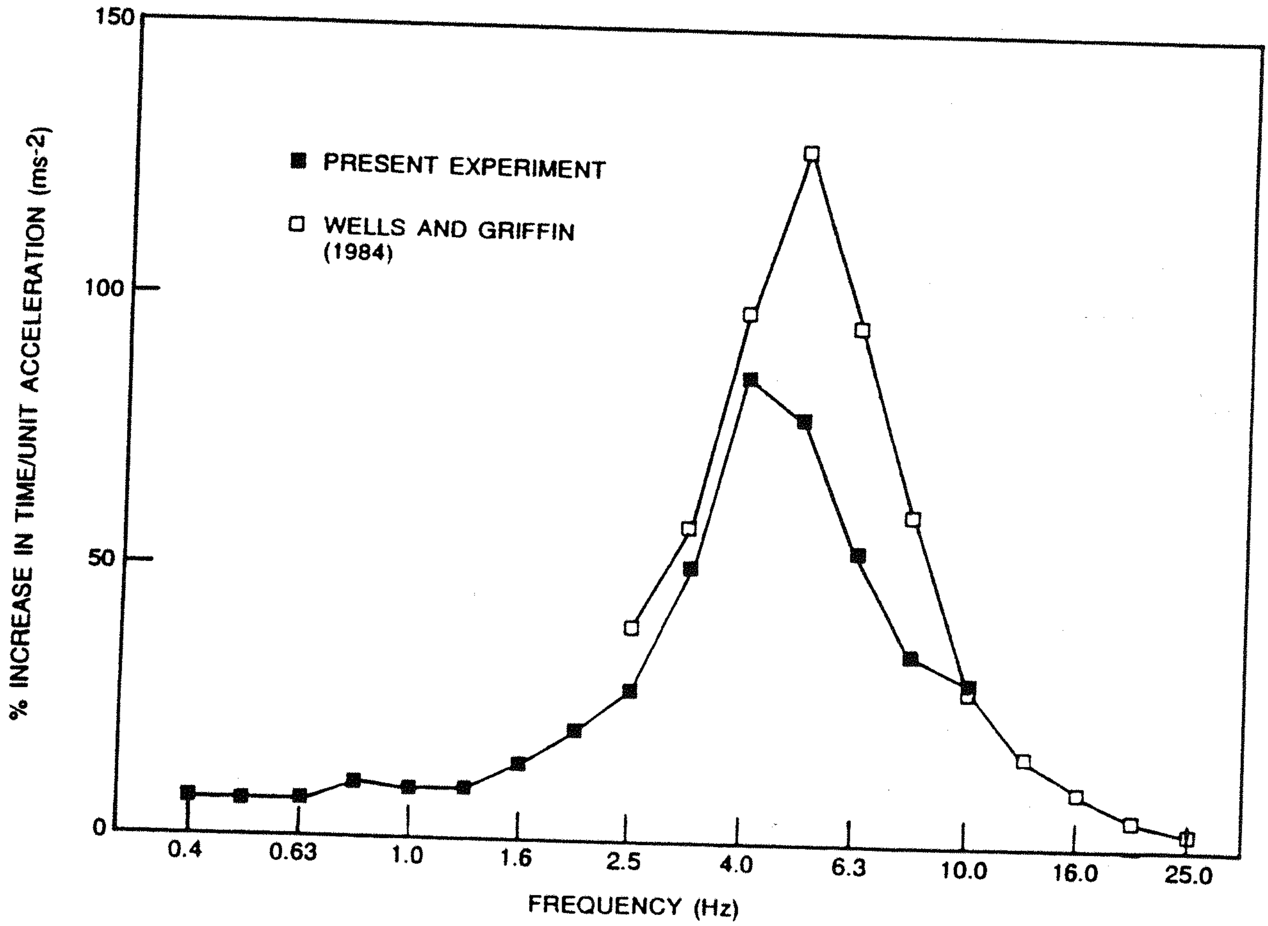


Figure 7.3 Mean reading time against frequency for 50 digits with data from Wells and Griffin (1984)

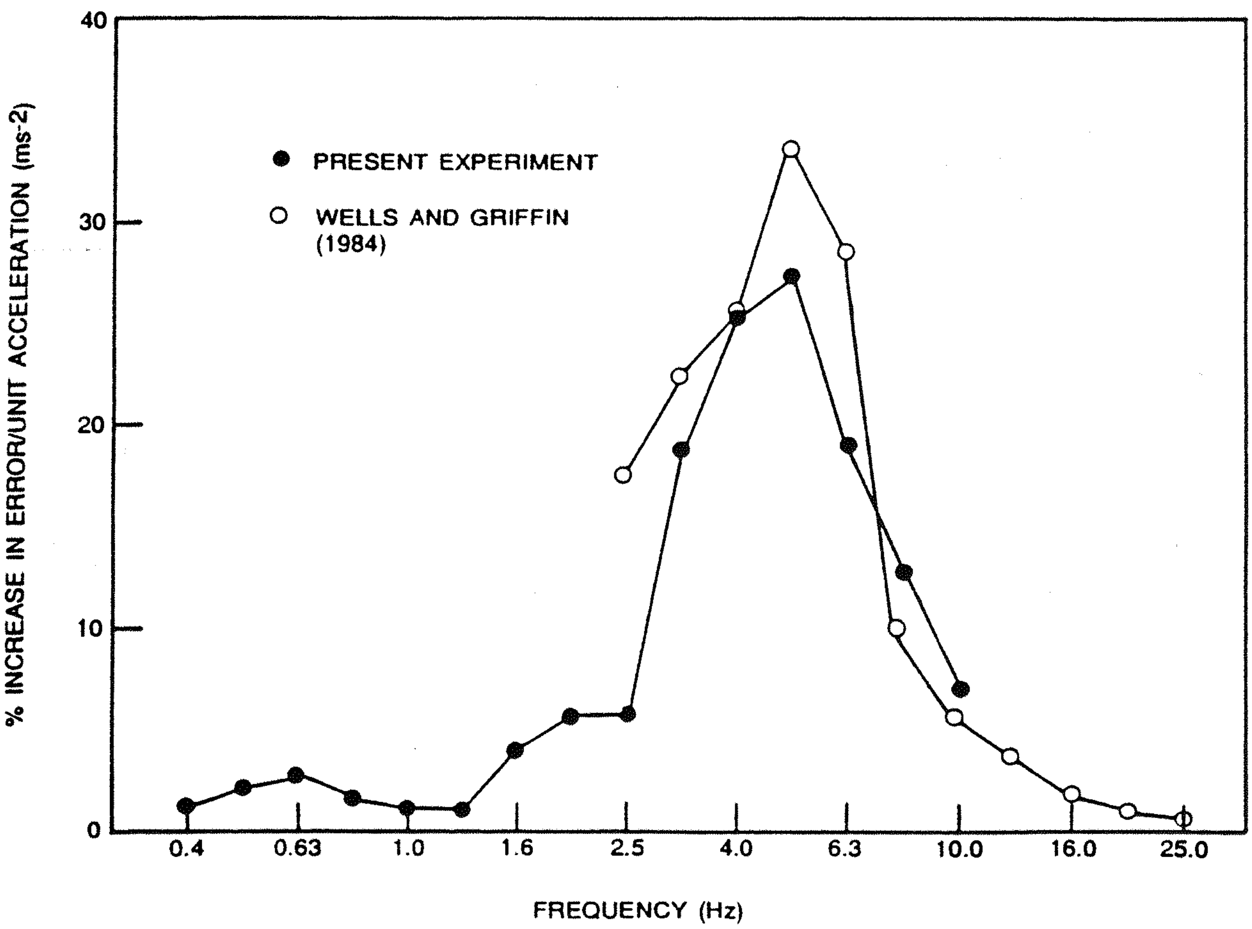


Figure 7.4 Mean reading error against frequency for 50 digits with data from Wells and Griffin (1984)

7.4 DISCUSSION

Figures 7.1 and 7.2 show that most performance decrement lies in a particular frequency range. Time and error scores give slightly different lower frequency limits, but 3.15 to 8 Hz certainly produce most decrement. These results are consistent with the theory that the vestibulo-ocular reflex is operating to reduce reading performance. The suppression of this reflex by the pursuit reflex up to 2 Hz is also consistent with the results. Time scores show no difference between the static and vibration conditions below and including 2 Hz.

The estimated error variances in Wells and Griffin (1983) are 59.42 for time and 59.10 for errors. These were obtained by dividing the published treatment mean square by its F ratio. Dunnetś t test at 5% gives a significant difference from the static condition in the range 3.15 to 8 Hz for time and 2.5 to 6.3 Hz for error.

The results found were similar to the present experiment. The frequency of worst effect is similar in that they found it to be 4 Hz for time and errors. However, the time score at 4 Hz was not significantly different from 3.15 or 5 Hz and the error score at 4 Hz was not significantly different from 2.5, 3.15 or 5 Hz (Tukeyś t test at 5%). Thus the data on head motion recorded by Furness (1981) showing a peak at 5 Hz would explain the poor performance around that frequency because head motion would translate into retinal image movement.

Figures 7.3 and 7.4 show that the present experiment and the previous one by Wells and Griffin (1984) have similar but not identical results. The sizes of the peak decrements are different. This may be due to the different experimenter and the vibration used. Although changes in the participant posture may also have affected transmission of vibration to the head and hence to the display. Seating conditions, and regular checks of posture were made, but posture is considered the factor most likely to have caused differences in peak decrement between the two experiments.

7.5 CONCLUSIONS

Digit reading performance with the helmet-mounted display under whole-body vertical vibration performance can be maintained below 2 Hz. Between 3.15 and 8 Hz digit reading performance under whole-body vibration is worse than under static conditions. The results show good agreement over the range of matching frequencies with those of Wells and Griffin (1984).

CHAPTER 8 : HELMET-MOUNTED DISPLAY STABILISATION
THE EFFECTS OF PHASE ERROR ON PERFORMANCE

8.1 INTRODUCTION

Low frequency head motions cause the double integrator in the stabilisation system to deflect the image on the screen to large displacements. This is due to the high gain at low frequencies. The consequences are that the image reaches the edge of the screen and remains there until the deflection signal reduces below a given value. This does not provide a stabilised image for good legibility. Secondly, image stabilisation is not required at low frequencies, and is even detrimental below 2 Hz. This is because the pursuit reflex maintains the line of sight on the moving image at low frequencies. Voluntary head movements produce low frequency energy at displacements larger than the display screen. Therefore a low frequency filter has been added to the stabilisation to reduce these problems. The filter has introduced phase error which is perceived by the operator either as reduced stabilisation, or as the image moving in the wrong direction.

It was essential to understand how the phase error affected legibility for operators. The following experiment was conducted to elicit the relevant information.

8.2 APPARATUS AND PROCEDURE

Fifteen male participants from students and staff at the University of Southampton were used in the experiment. They had visual acuities better than 6/6 in each eye.

A semi-rigid simulated Sea King seat was mounted on the Human Factors Research Unit 1 metre stroke hydraulic vibrator. Participants were instructed to 'look straight ahead and read as quickly and accurately as possible'. Vibration was sinusoidal at 4 Hz, 1.0 ms^{-2} rms.

Thirteen stabilisation conditions were included during vibration in the randomised block factorial design. One of these was a no stabilisation condition. The others were generated by adjusting the 2 pole high pass filter in the double integrator. The filter was adjusted to produce different phase errors. The adjustment involved holding one pole constant at 2 radians per second, while the other pole was varied in the experiment to hold one of the following values: 0.25, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 radians per second.

Performance without vibration or stabilisation was assessed before and after the experiment.

8.3 RESULTS

Figure 8.1 shows reading time and Figure 8.2 shows reading error scores.

8.4 DISCUSSION

These data show (by inspection) that there is a linear relationship between reading time and phase error, and also between reading error and phase error at least to 40 degrees. Therefore optimum stabilisation performance will be achieved by reducing phase error to a minimum. Clearly the reduction of phase error can be made by lowering the filter frequency, but this will be at the expense of low frequency rejection.

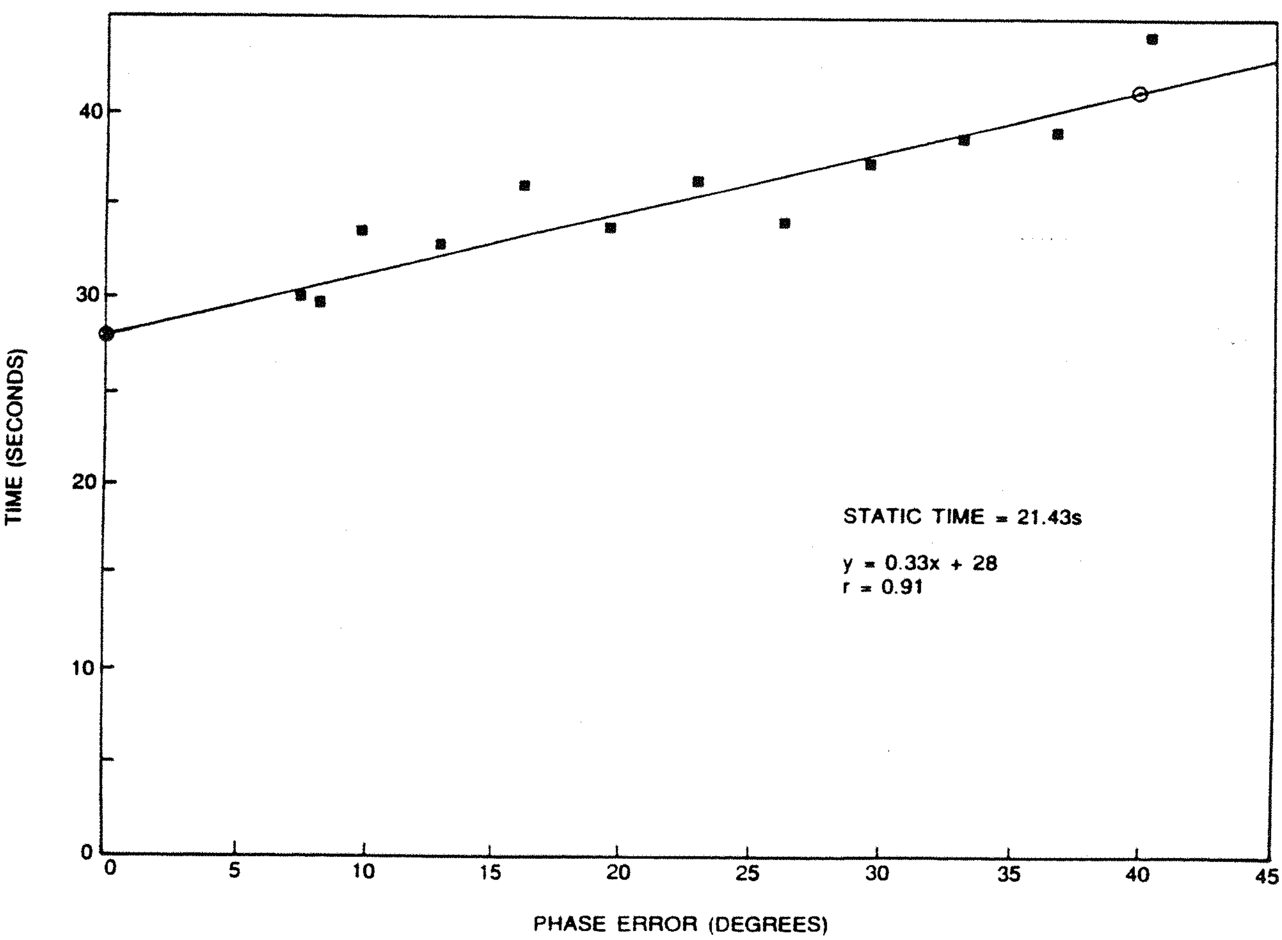


Figure 8.1 Mean reading time against phase error for 50 digits

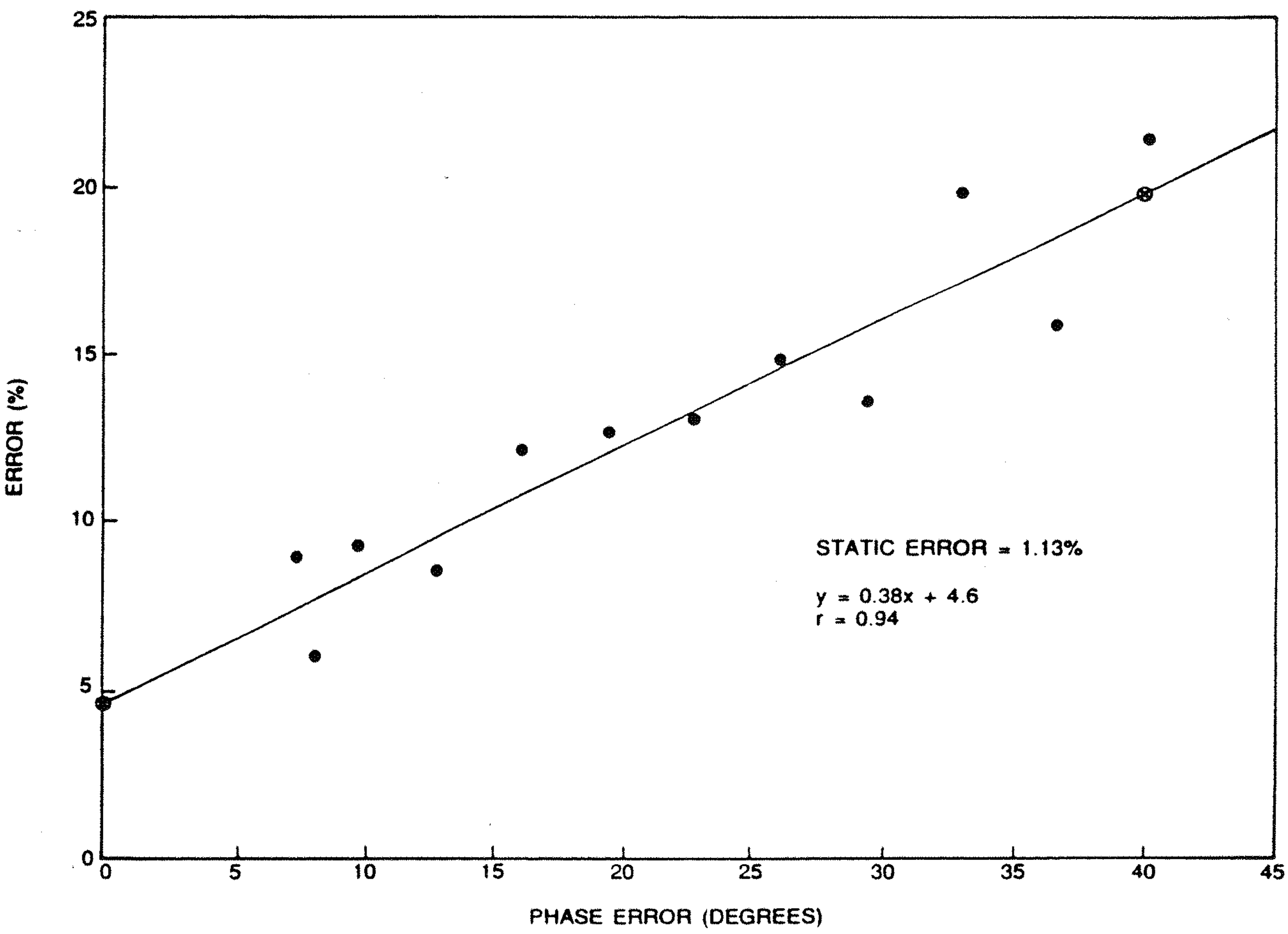


Figure 8.2 Mean reading error against phase error for 50 digits

CHAPTER 9 : EXPERIMENTAL EVALUATION OF AN ADAPTIVE STABILISATION SYSTEM FOR HELMET-MOUNTED DISPLAYS

9.1 INTRODUCTION

Twelve seated participants took part in an experiment to assess reading performance with a helmet-mounted display. Vertical vibration recorded in a Sea King helicopter and a Phantom fixed wing aircraft and 1.0 ms^{-2} rms sinusoidal and random motion in one third octave steps from 0.5 Hz to 8 Hz were used as experimental conditions. Reading time and reading errors were measured and found to be significantly worse with Sea King motion and with frequencies between 2 Hz and 8 Hz compared to static conditions. An image stabilisation system reduced reading performance decrements to insignificant amounts. Random vibration produced less decrement than sinusoidal vibration and encouraged a different reading strategy.

The following experiment was designed to assess the latest adaptive stabilisation system. The system was evaluated with both sinusoidal and random vibration known to cause problems.

9.2 APPARATUS AND PROCEDURE

Vertical vibration of participants was provided by the Human Factors Research Unit 1 metre stroke hydraulic vibrator fitted with a rigid flat seat and no backrest.

The following stimuli were presented:

(a) Sinusoidal vibration

0.5, 0.63, 0.8, 1.0, 1.25, 1.6, 2.0, 2.5, 3.15, 4.0, 5.0, 6.3, 8.0 Hz at 1.0 ms^{-2} rms

One third octave band random vibration
Centred on the above frequencies at 1.0 ms^{-2} rms.

(b) Fast jet vibration

z axis floor vibration recorded in a Phantom aircraft flying at 200 knots at 250 ft, high pass filtered 0.5 Hz 48 dB per octave reproduced at 0.56 ms^{-2} rms. See Figure 9.1.

(c) Helicopter vibration

z axis floor vibration recorded in a Sea King helicopter flying at 100 knots at 100 ft and reproduced at 0.94 ms^{-2} rms. See Figure 9.2.

Twelve male participants took part in the experiment each with Snellen visual acuity better than 6/6 in each eye.

Each vibration condition was presented twice: once with stabilisation; and once without. In addition a single static condition was presented without stabilisation.

Participants were instructed to read the numerals on the display as quickly and accurately as possible. Reading time was measured for each array. Errors were counted for incorrect and omitted digits.

The order of presentation of conditions was completely randomised.

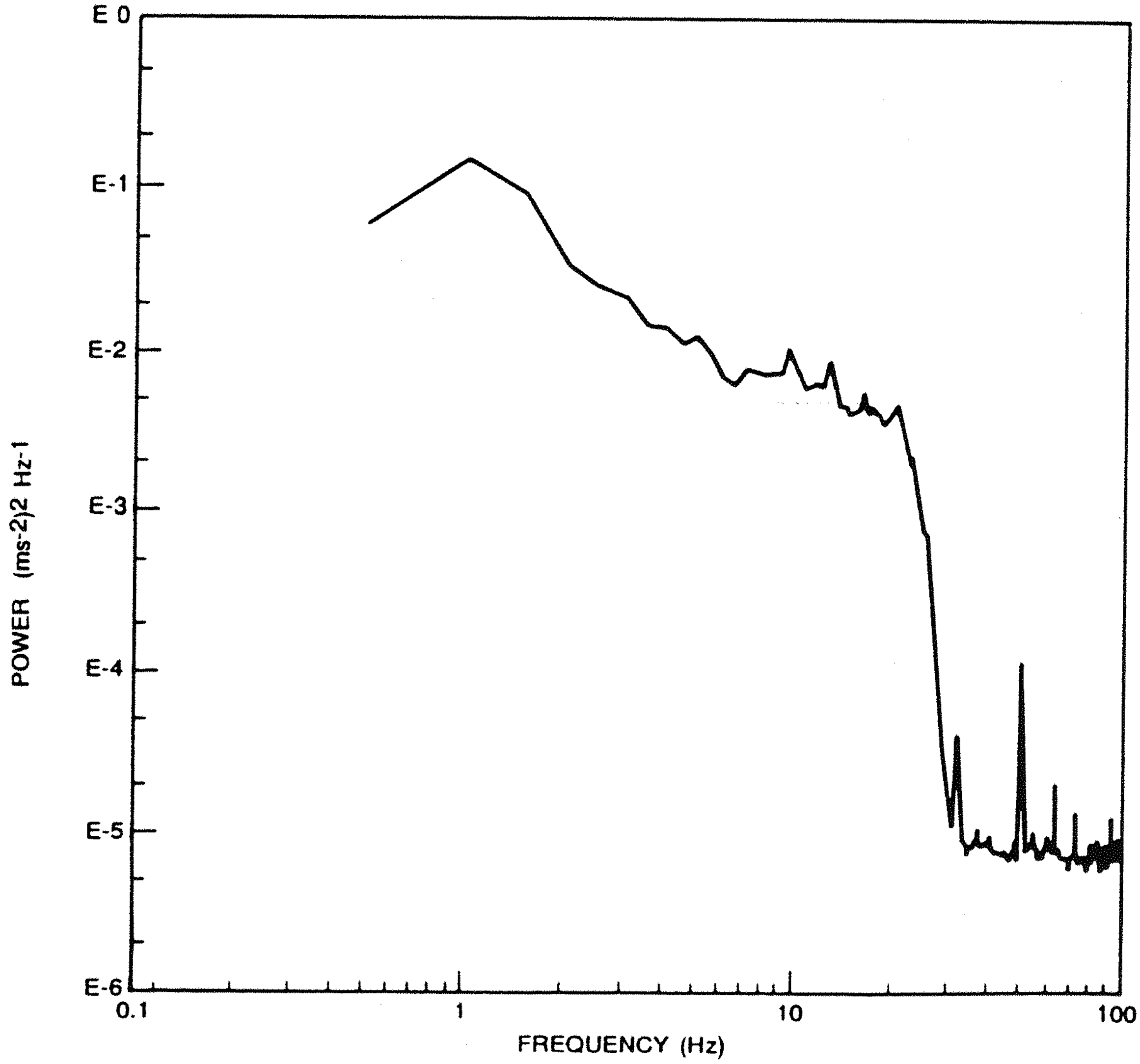


Figure 9.1 Power spectral density (0.5 Hz resolution) for a Phantom aircraft flying at 200 knots at 250 ft

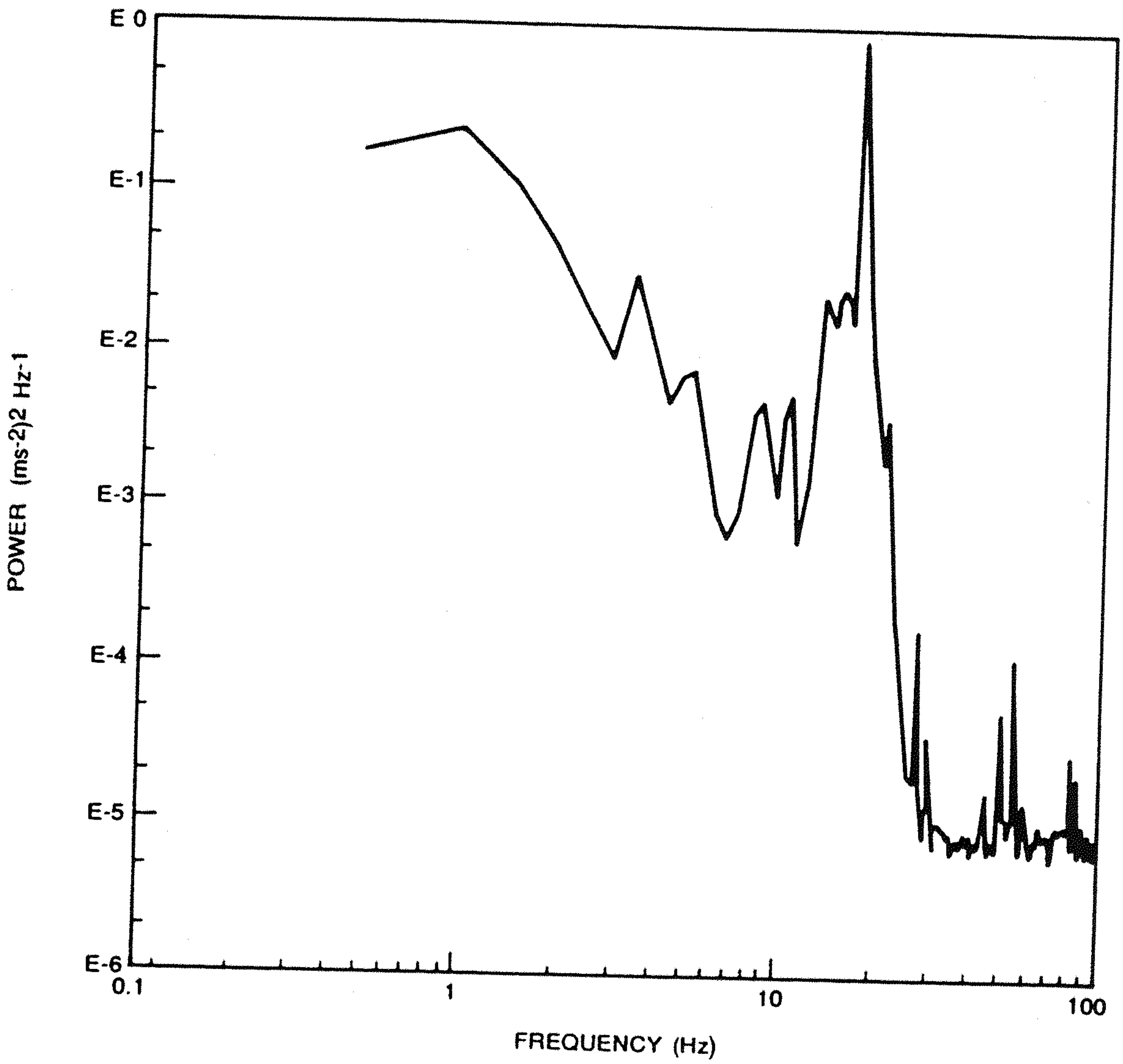


Figure 9.2 Power spectral density (0.5 Hz resolution) for a Sea King flying at 100 knots at 100 ft

9.3 RESULTS

Tables 9.1 and 9.2 shows the mean reading times and errors for the aircraft vibration conditions. Figures 9.3 and 9.4 show the mean time and mean errors across the twelve participants for the sinusoidal and random vibration conditions.

Dunnett's t test was used to determine which conditions were significantly different at the 5% level from the static condition. These conditions are marked with an asterisk for the aircraft vibration results in Tables 9.1 and 9.2.

TABLE 9.1 READING TIME FOR AIRCRAFT VIBRATION WITH AND WITHOUT STABILISATION

	Condition	No stabilisation	Stabilisation
Mean Time (s)	Static	20.75	
	Fast Jet	22.58	21.17
n = 12	Helicopter	24.92*	21.58

Significance level: *5%

TABLE 9.2 READING ERROR FOR AIRCRAFT VIBRATION WITH AND WITHOUT STABILISATION

	Condition	No stabilisation	Stabilisation
Mean Error (%)	Static	0.00	
	Fast Jet	1.67	0.17
n = 12	Helicopter	3.17*	1.17

Significance level: *5%

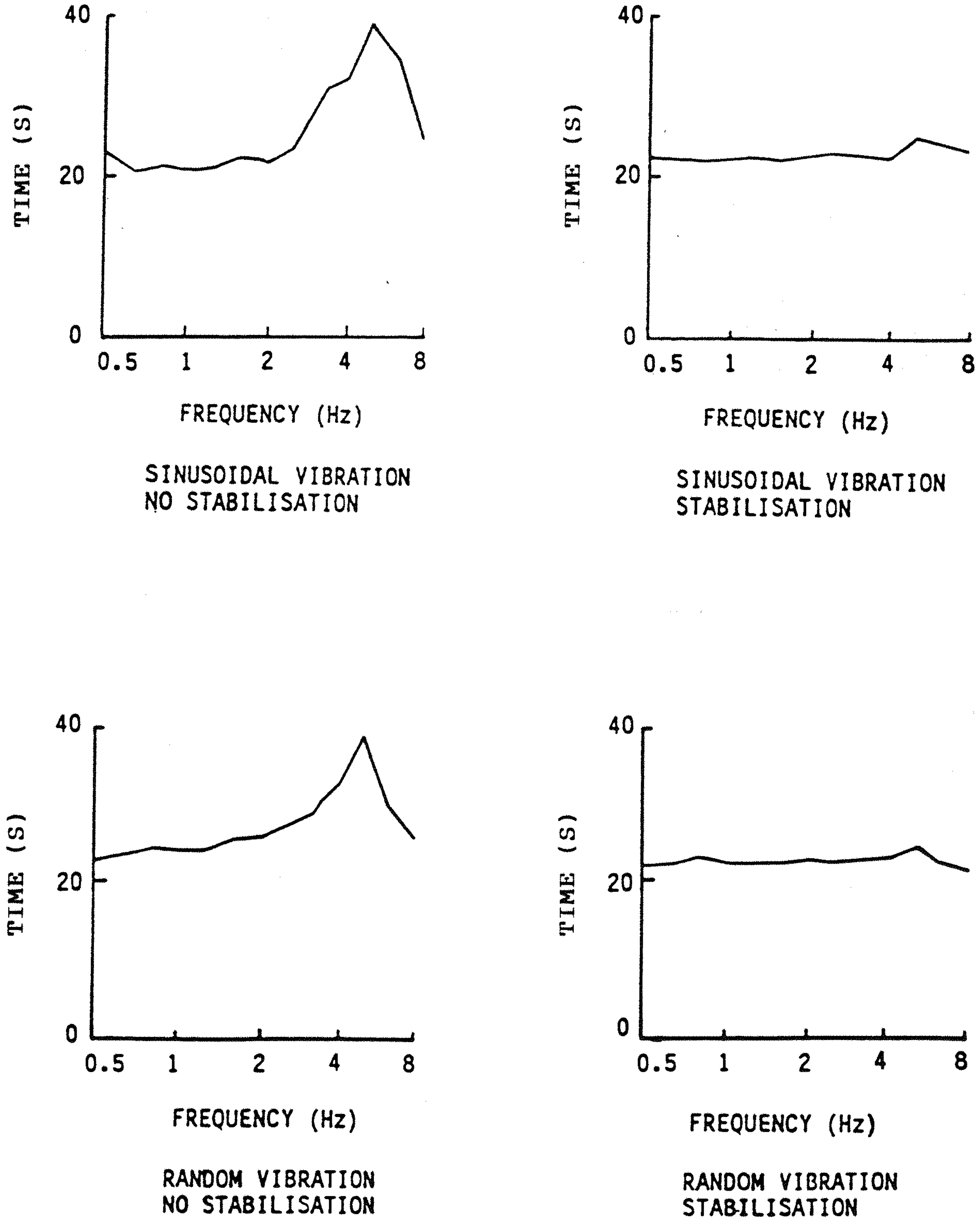


Figure 9.3 Reading time data with sinusoidal and random vibration with and without stabilisation

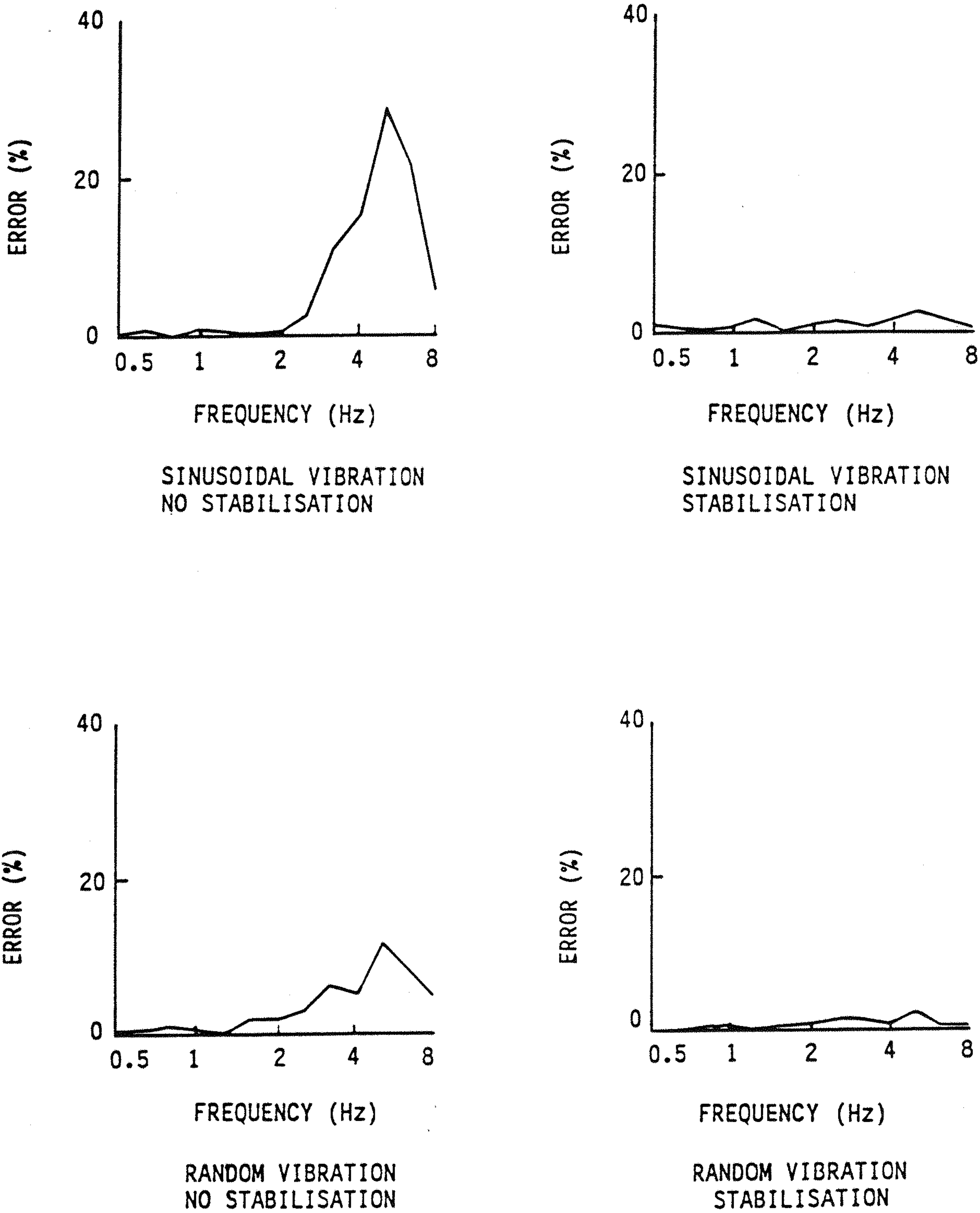


Figure 9.4 Reading error data with sinusoidal and random vibration with and without stabilisation

Without stabilisation the sinusoidal vibration produced significant increases in reading time and error at 3.15, 4.0, 5.0, and 6.3 Hz. Without stabilisation the random vibration produced significant increases in time between 2.5 and 6.3 Hz inclusive, and in error at 3.15, 4.0, and 6.3 Hz. None of the conditions which included stabilisation produced reading times or reading errors significantly different from the static condition.

Mixed effects randomised block analyses of variance were performed on the random and sinusoidal vibration time and error scores. These are summarised in Tables 9.3 and 9.4.

TABLE 9.3 ANALYSIS OF VARIANCE SUMMARY TABLE FOR READING TIME

Source	Sum of squares	df	Mean square	F ratio	Sig
Participants (P)	13512.96	11	1228.45	82.81	***
Frequency (A)	4569.09	12	380.75	18.65	***
Vibration type (B)	2.84	1	2.84	0.40	-
Stabilisation state (C)	1827.93	1	1827.93	31.53	***
AB	360.62	12	30.05	2.68	**
AC	2948.40	12	245.70	17.18	***
BC	25.40	1	25.40	6.20	-
ABC	192.0	12	16.0	1.40	-
RES	8722.15	561	14.83		
AP	2694.87	132	20.41		
BP	76.87	11	6.98		
CP	637.68	11	57.97		
ABP	1475.15	132	11.17		
ACP	1887.43	132	14.29		
BCP	45.06	11	4.09		
ABCP	1505.06	132	11.40		
TOTAL	31761.43	623	50.98		

Significance levels: *** 0.1%
** 1%
* 5%

TABLE 9.4 ANALYSIS OF VARIANCE SUMMARY TABLE FOR READING ERROR

Source	Sum of squares	df	Mean square	F ratio	Sig
Participants (P)	528.95	11	48.08	4.88	***
Frequency (A)	1676.26	12	139.68	13.27	***
Vibration type (B)	105.02	1	105.02	11.86	**
Stabilisation state (C)	685.44	1	685.44	17.60	**
AB	351.14	12	29.26	3.64	***
AC	1301.55	12	108.46	9.97	***
BC	83.30	1	83.30	6.70	*
ABC	323.11	12	26.92	3.64	***
RES	5522.87	561	9.84		
AP	1388.96	132	10.52		
BP	97.39	11	8.85		
CP	428.36	11	38.94		
ABP	1060.93	132	8.03		
ACP	1435.13	132	10.87		
BCP	136.73	11	12.43		
ABCP	975.34	132	7.38		
TOTAL	10577.68	623	16.97		

Significance levels: *** 0.1%
** 1%
* 5%

9.4 DISCUSSION

The range of vibration frequencies which produced decrements in reading performance was found to be similar to that in previous experiments. It is above 2 Hz where the eye cannot follow a moving image, but does not extend to 8 Hz where the rotational displacements produced at the head are usually very small.

Fast jet vibration did not produce problems with legibility for the low magnitude example reproduced in the experiment. However, the example of helicopter vibration produced a decrement in reading performance.

The power spectrum in Figure 9.2 shows that Sea King vibration produced large amounts of energy at 3.5, 5.3, and 17.5 Hz. These correspond to the revolution rate of moving parts such as rotors and planets. The first two of these frequencies are in the range where helmet-mounted display reading performance is most sensitive to vibration (see Figures 7.3 and 7.4). The power spectrum of Phantom aircraft vibration in Figure 9.1 shows no such peaks and this may explain the better performance obtained with the Phantom motion although it also had a lower root-mean-square acceleration.

In order to illustrate this the head pitch acceleration power spectra for one participant in response to these motions are shown in Figures 9.5 and 9.6.

The stabilisation produced reading times and errors in all conditions which did not differ significantly from the static (no vibration) condition. That this is true at low frequencies (0.5 Hz to 2 Hz) shows that the stabilisation system can operate in conditions where the stimulus energy is below the cut off frequency of the high pass filter. This implies that the low frequency gain and the phase errors produced by the variable cut off frequency can be compensated by the pursuit eye tracking movement.

At 8 Hz the head rotational displacement produced by z axis seat vibration was so small that reading performance was not degraded. This reduction in performance decrement has been shown to continue at least as high as 25 Hz.

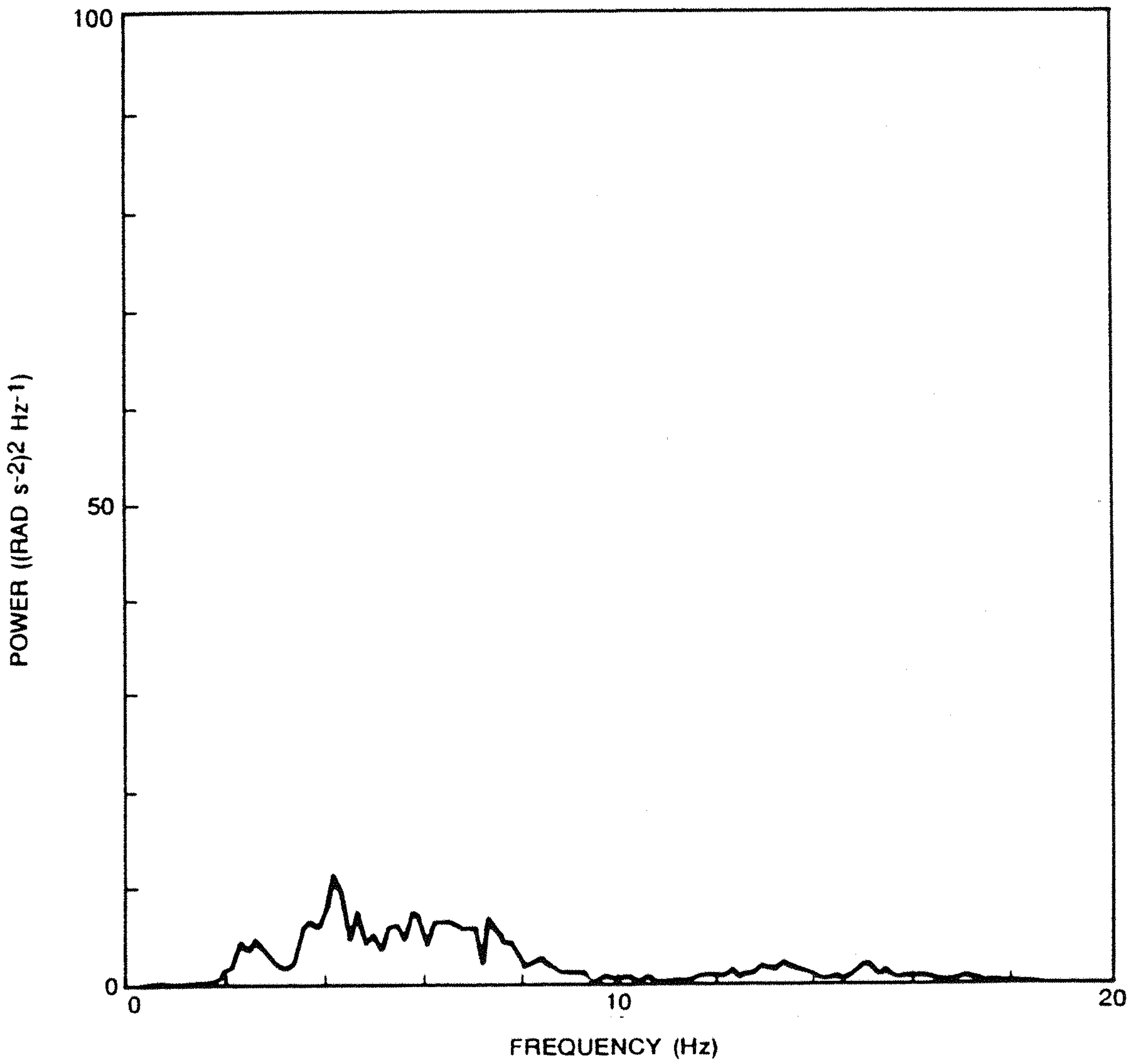


Figure 9.5 Head pitch acceleration power spectral density (0.2 Hz resolution) for one subject in response to Phantom motion shown in Figure 9.1

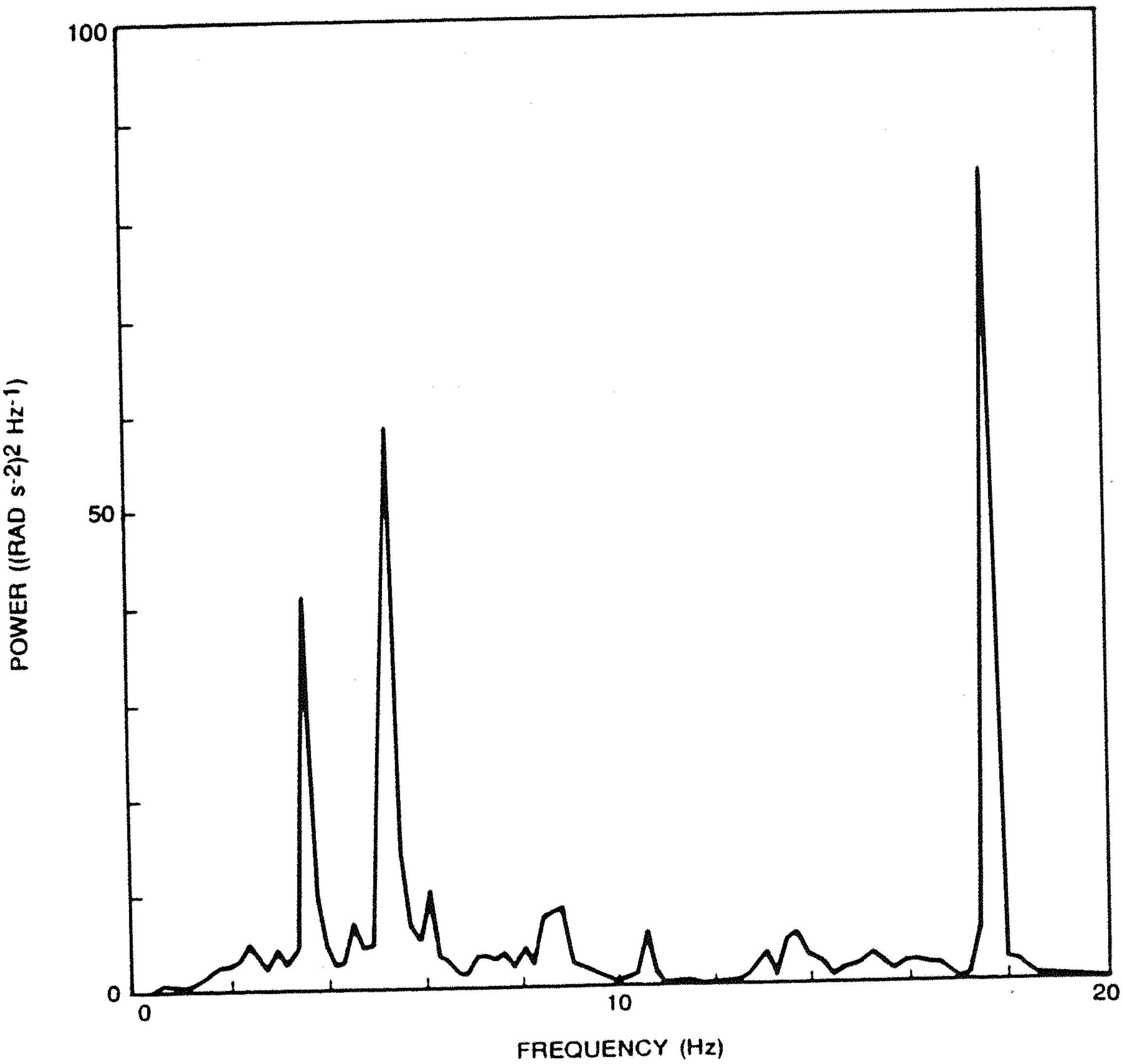


Figure 9.6 Head pitch acceleration power spectral density (0.2 Hz resolution) for one subject in response to Sea King motion shown in Figure 9.2

Reading strategies appear to differ between sinusoidal and random vibration. In Figure 9.7 it can be seen that, without stabilisation, errors with random vibration were much lower than the errors obtained with sinusoidal vibration. However, in Figure 9.8 the scores under random vibration are seen to be only slightly less than the time scores under sinusoidal vibration. This result may be explained by the differences in the distributions of head vibration under the random and sinusoidal conditions. Fewer errors are made when participants are able to view a vibrating display which has a high probability of producing a low image velocity. With random vibration the fluctuations in image velocity encourage the participant to wait for a period of low image velocity before attempting to read the digit. The waiting produces a time penalty which is reflected in the time scores. Sinusoidal vibration does not produce long term fluctuations in image velocity, only within the period (0.25 second at 4 Hz). Thus there is no advantage to the participant to wait before reading the digit. In a complex motion environment, operator response may be expected to be delayed during periods of high image velocity. If there is a premium on immediate response, there would be more errors. The use of image stabilisation in such an environment would remove the image velocity and thereby increase the time during which error free reading could be accomplished.

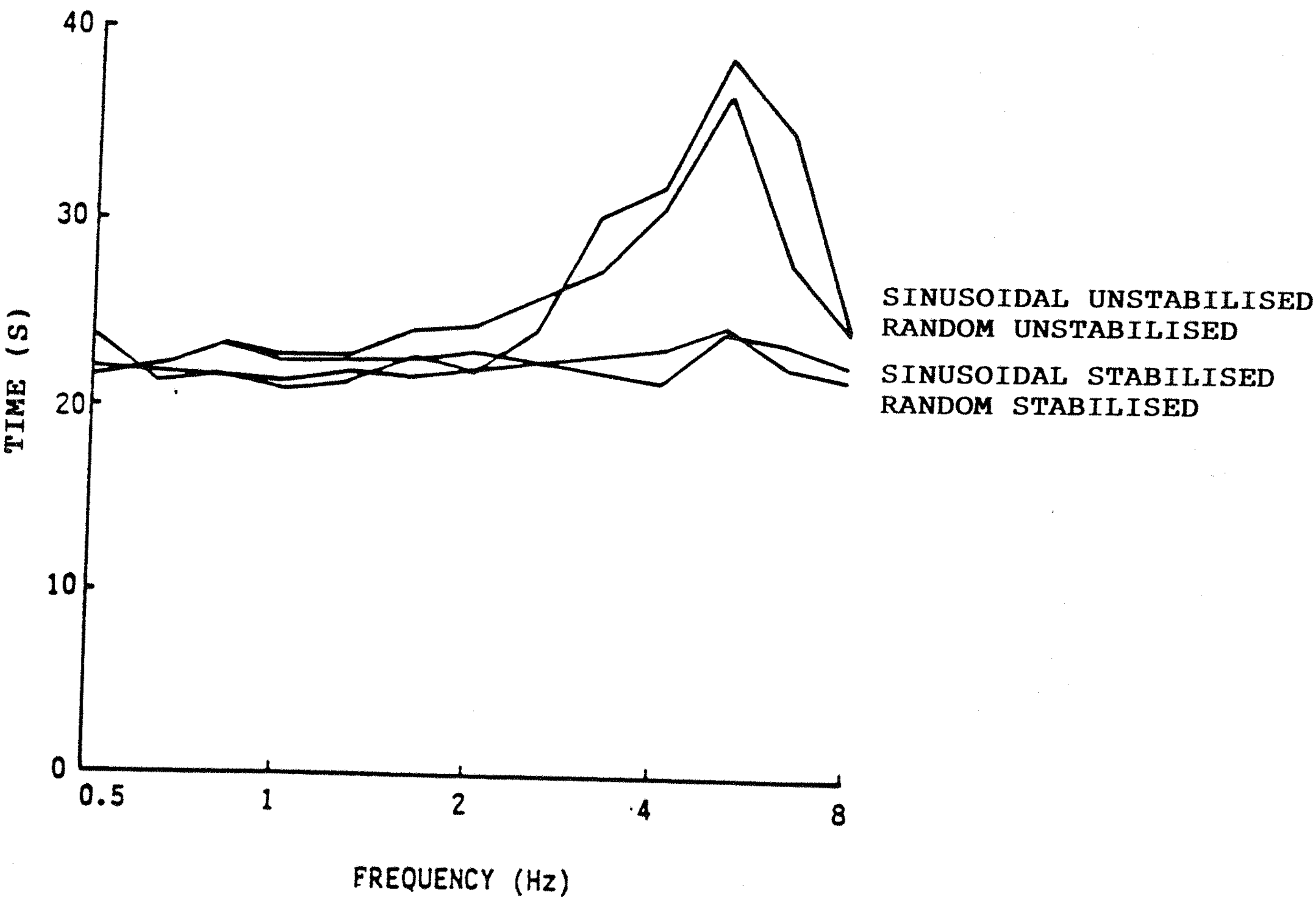


Figure 9.7 Mean reading time (n=12) with sinusoidal and random vibration with and without stabilisation

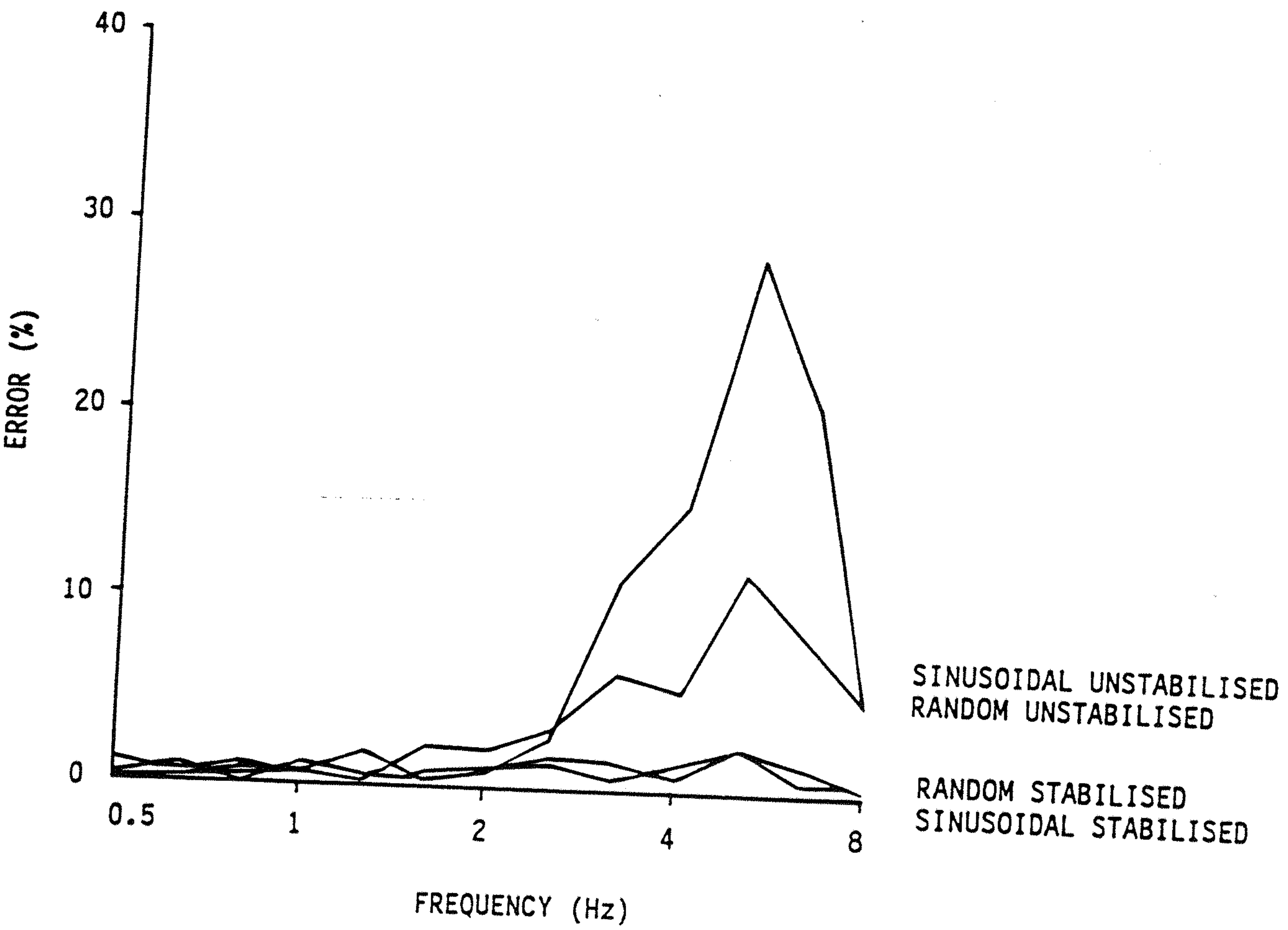


Figure 9.8 Mean reading error (n=12) with sinusoidal and random vibration with and without stabilisation

9.5 CONCLUSIONS

At 8 Hz and at frequencies below 2 Hz whole - body sinusoidal and random vertical vibration at moderate levels produced no significant decrement in helmet - mounted display reading performance. Between these frequencies reading performance was degraded.

Image stabilisation was found to reduce reading performance decrements to insignificant levels during sinusoidal, random, and aircraft vibration conditions.

Sinusoidal vibration produced a greater decrement in reading performance than random vibration. Random vibration can encourage a participant response strategy which reduces errors at the expense of reading time.

CHAPTER 10 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

10.1 GENERAL DISCUSSION

The experimental image stabilisation systems have all been implemented using analogue circuits. A comparable digital system could be implemented using a microprocessor to realise the filters and integrators by either recursive or finite impulse response techniques. However, the sampling rate would need to be high enough and processing delays short enough to ensure that they did not incur significant additional phase errors at frequencies of 10 Hz and below. Some phase compensation for system delays may be feasible if finite impulse response techniques were employed. However, the resolution of the system would need to be small enough to ensure sufficiently linear operation with large ranges of inputs and outputs. In view of these considerations it is doubtful whether the greater flexibility of a digital system would currently justify its much greater complexity for the applications so far considered.

All of the image stabilisation systems employed in the experiments described in this report have worked by transducing the rotational acceleration of the display by means of accelerometers, then double integrating the acceleration signal to give head angular displacement. This signal is then used to displace the image in the opposite direction to the displacement of the display. The first experiments used rotational servo-accelerometers mounted on the helmet but these were later superseded by pairs of miniature piezo-resistive translational accelerometers which are small and light enough to mount directly onto the display tube. In the latter case the rotational acceleration of the display was derived from the difference in acceleration between the two accelerometers as described in Chapter 1. Mounting accelerometers on the display avoids possible measurement inaccuracies due to differential movement between the display and helmet. For good stabilisation performance it is important to ensure that the accelerometers and their associated signal conditioning have an appropriate amplitude and phase performance over the frequency limit; amplitude and phase errors in the accelerometers will add to the errors incurred by high pass filtering the integrator response.

Helmet-mounted sight systems have been developed for sensing the angular position of the head in the cockpit, for the purposes of head aiming and target designation. Where the output from such a system is available it could provide an attractive source of stabilisation signals. As with accelerometer inputs, good amplitude and phase performance is essential over the operating frequency range of the system. Currently available systems include the Honeywell MOVTAS, which is based on the radiation and sensing of infra-red light, and the electromagnetic helmet-mounted sights produced by Polhemus and Ferranti. All of these are sampled data systems, with sample rates between 25 and 60 samples s^{-1}. The minimum processing delay is equal to the reciprocal of the sampling rate, and with the above systems this would result in phase error of between 36° and 72° at 5 Hz. This would be unacceptable for good stabilisation performance. Anti-aliasing filters may have to be provided, particularly with the low sampling rates, and these would further increase the phase error. It may be possible to obtain some benefit with phase correction networks, provided that the head motion was constrained within a narrow band of frequencies. Head position would need to be measured with a resolution of about 1 minute of arc - the current helmet-mounted sights can only achieve about 10 minutes of arc.

If a suitable high resolution, fast, head position sensing device became available it could be used to provide the forcing function for the adaptive image stabilisation system. In this case it would be necessary to modify the integrating filters to give high pass rather than band-pass responses, as the integration function would not be required.

The adaptive filter algorithms employed in the final version of the experimental image stabilisation system can be seen to reduce image movement during voluntary head movements to proportions which are likely to be subjectively acceptable in most applications. The results of the experiment reported in Chapter 9 show that these reductions have been achieved without sacrificing stabilisation performance. Further reductions in image movement may be possible, but these would probably result in reduced stabilisation performance in some situations. Large amplitude voluntary head movements are frequently initiated by an acceleration step which contains some high frequency activity. This causes a momentary increase in the adaptive displacement threshold, or acceptance window, which leads the image deflection signal and allows the image to 'flick' in the opposite direction to the head movement. Such a tendency could be reduced by delaying the displacement threshold so that it lags behind the image deflection signal. This could be achieved by low-pass filtering the threshold signal. The displacement threshold would then increase more gradually than the image deflection and would more effectively restrain the image on the display. However the initiation of involuntary head movements which are caused by impulsive or random vibration may also be characterised by similar acceleration patterns. In this case it is more appropriate for the displacement threshold to lead the image displacement, allowing the image to remain fully stabilised.

It may not be possible to further reduce image movement during voluntary head movement and still maintain stabilisation performance in environments where there is impulsive or low frequency random motion, such as in high performance fixed-wing aircraft. However, if the vibration environment is periodic or relatively time invariant, such as in a rotary wing aircraft, the modification suggested above may give some additional benefit.

10.2 HELMET-MOUNTED SIGHT RETICLE STABILISATION

The results of the experiment reported in Chapter 6 showed that any improvement in helmet-mounted sight aiming performance due to the reduction in reticle blur with a stabilised reticle, was offset by the effect of low frequency image drift. The drift was caused by the response of the image stabilisation system to voluntary head movements and resulted in errors in the position of the aiming reticle relative to the output of the head position sensor. Hence, the reticle did not give the operator accurate feedback of where the sighting system was pointing. Subsequent to the experiment reported in Chapter 6 the image drift has been further reduced by modifications to the adaptive stabilisation system. However the magnitude of the problem indicated by the experiment suggests that further system developments will be necessary to make reticle stabilisation a practical proposition for the improvement of head aiming accuracy.

It is feasible to electronically correct the outputs of the head position sensor, using the image deflection signal, so that they represent the angular position indicated by the reticle rather than the position of the helmet. This scheme is illustrated in Figure 10.1. The head position outputs would be space-stabilised at vibration frequencies and there would be cancellation of vibration-correlated noise as well as low frequency position errors.

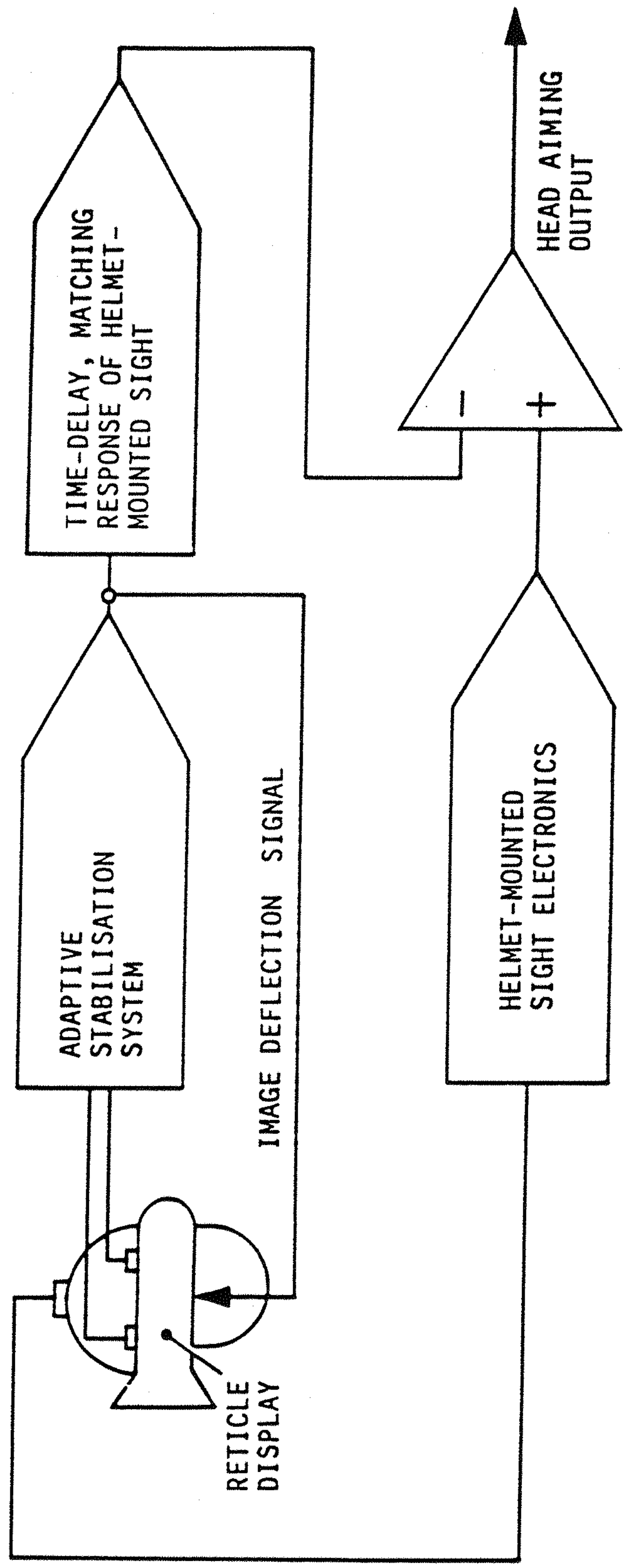


Figure 10.1 Active cancellation of reticle drift and vibration-induced noise in a helmet-mounted sight aiming system

A disadvantage of using helmet-mounted sight output stabilisation with this scheme is that a small variable lag would be introduced between the reticle and head position and this would present the operator with a higher order tracking task. As the image displacements are restrained by the modified adaptive stabilisation system this is not expected to result in significant aiming performance decrements when compared with the likely performance benefits of reducing reticle blur and vibration-induced output noise.

10.3 CONCLUSIONS

The eyes remain approximately space-stabilised during vibration-induced angular head movements at frequencies above about 2 Hz. This induces relative movement between the eye and images on a display. Additional motion between the display and the head (caused by helmet slip) will also contribute to this relative movement. At frequencies above 16 Hz the head angular displacement produced by whole-body vibration is small and produces little effective performance decrement. Consequently, under vertical whole-body vibration at frequencies between about 2 Hz and 16 Hz reading performance is more severely degraded with the helmet-mounted display than with comparable panel-mounted displays.

Space stabilisation of images on the helmet-mounted display at frequencies above 2 Hz cancels the relative image movement between the eyes and the display and results in large improvements in reading performance during vertical whole-body vibration. Space stabilisation of the image can be effected on a short persistence CRT type helmet-mounted display by transducing the rotational acceleration of the display, double integrating to obtain rotational displacement and using this signal to electronically deflect the display image in the opposite direction to the display displacement. Angular accelerations of the head at frequencies less than about 2 Hz must be rejected by the system so that voluntary head movements do not cause large drifts in the position of the image on the display, however the filtering employed should not result in significant phase shifts of the displacement signal at frequencies above about 2 Hz or the effectiveness of the image stabilisation will be reduced. An adaptive filter has been developed and has been shown to reduce image drifts due to voluntary and other low frequency head motion whilst maintaining stabilisation performance above 2 Hz.

An experiment performed during helicopter flight has shown that the vibration levels encountered in the helicopter environment are sufficient to cause a reading performance problem with the helmet-mounted display. However the large reading performance decrements induced by the helicopter vibration were considerably reduced by image stabilisation using the adaptive system.

Simply stabilising the aiming reticle in a helmet-mounted sight system has been shown to be ineffective in reducing head aiming errors because of the residual drift in the position of the reticle. A potentially more effective system had been suggested for stabilising the helmet position sensor outputs. The helmet position sensor may provide a source of the image deflection signal for use in stabilising the helmet-mounted display or reticle, however current systems do not have adequate speed or resolution to make them a practical alternative to accelerometers.

10.4 RECOMMENDATIONS

The aircrew in helicopters and high performance fixed-wing aircraft are exposed to vibration acceleration amplitudes and frequencies which are likely to significantly degrade the reading of information from helmet-mounted displays. If helmet-mounted displays are to be used in these and other high vibration environments it is recommended that the displays should be capable of being stabilised and that image stabilisation techniques described in this report should be available to counter the effects of vibration on reading performance.

Displays which include reticles for helmet-mounted sight aiming should not be stabilised unless additional measures are taken to cancel reticle position errors due to image drift. Development and testing should continue on techniques for effectively stabilising the outputs of a helmet-mounted sight to reduce the effects of reticle blur and vibration-induced output noise.

REFERENCES

Atkin A.J. and Bender M.B. (1968) Ocular stabilisation during oscillatory head movements. Arch Neurol 19 559-566.

Barnes G.R. (1979) Vestibulo ocular function during co-ordinated head and eye movements to acquire visual targets. J Physiol 287 127-147.

Barnes G.R., Benson A.J. and Prior A.R.J. (1978) Visual-vestibular interaction in the control of eye movements. Aviation Space and Environmental Medicine 49(4) 557-564.

Benson A.J. (1970) Interactions between semicircular canals and gravoreceptors. In Recent advances in aerospace medicine Busby D.E. (ed) Reidel.

Benson A.J. (1972) Effect of angular oscillation in yaw on vision. Aerospace Medical Association Annual Scientific Meeting Bal Harbour Florida 43-44.

Benson A.J. and Barnes G.R. (1978) Vision during angular oscillation: the dynamic interaction of visual and vestibular mechanisms. Aviation Space and Environmental Medicine 49(1) 340-345.

Davson H. (1980) Physiology of the eye. 4th edition. Churchill Livingstone.

Ebenholtz S.M. and Shebilske W. (1975) The doll reflex and ocular counterrolling with head-body tilt in the median plane. Vision Research 15 713-717.

Furness T.A. (1981) The effects of whole-body vibration on the perception of the helmet-mounted display. PhD Thesis University of Southampton.

Furness T.A., Haas M.W. and Boff K.R. (1982) Visually-coupled airborne systems simulator. An application of visually-coupled systems technology. Air Force Medical Research Laboratory. Wright Patterson AFB.

Furness T.A. and Lewis C.H. (1978) Helmet-mounted display reading performance under whole-body vibration. UK Informal Group Meeting on Human Response to vibration. NIAE Silsoe Bedfordshire.

Griffin M.J. (1975) Vertical vibration of seated subjects. Effects of posture, vibration level and frequency. Aviation Space and Environmental Medicine 46(8) 1033-1040.

Hixson W.C. (1974) Frequency response of the oculovestibular system during yaw oscillation. NAMRL 1212.

Laycock J. (1974) Prediction in the human eye movement control system PhD Thesis University of Southampton.

Laycock J. (1978) A preliminary investigation of the legibility of alphanumeric characters on a helmet-mounted display. RAE Technical Memo FS155.

Lewis C.H. (1979) The interaction of the effects of vibration in three axes and seating conditions on the reading of numeric displays UK Informal Group Meeting on Human Response to vibration. RAE/IAM Farnborough.

Lewis C.H. and Griffin M.J. (1979) Mechanisms of the effects of vibration frequency level and duration in continuous manual control performance. Ergonomics 22(7) 855-889.

Moseley M.J., Lewis C.H. and Griffin M.J. (1982) Sinusoidal and random vibration: comparative effects on visual performance. Aviation Space and Environmental Medicine 53(10) 1000-1005).

Rack P.M.H. (1973) The stretch reflex response to movement of the human elbow joint. In Stein R.B., Pearson K.G., Smith R.S. and Redford J.B. Control of posture and locomotion Plenum Press.

Storey N. and Wells M.J. (1980) Stabilisation of helmet-mounted display images during conditions of whole-body vibration. UK Informal Group Meeting on Human Response to Vibration. Swansea University.

Wells M.J. (1983) Vibration-induced eye movements and reading performance with the helmet-mounted display. PhD Thesis University of Southampton.

Wells M.J. and Griffin M.J. (1984) Benefits of helmet-mounted display image stabilisation under whole-body vibration. Aviation Space and Environmental Medicine 55(1) 13-18.

Young L.R. and Sheena D. (1975) Survey of eye movement recording methods. Behaviour Research Methods and Instrumentation 7(5) 397-429.

Young L.R.and Stark L. (1965) Biological control systems - a critical review and evaluation NASA CR-190.