UNIVERSITY OF SOUTHAMPTON

INSTITUTE OF SOUND AND VIBRATION RESEARCH

# RAILWAY TRACTION TYPE AND NOISE ANNOYANCE

by

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To my Parents,

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UNIVERSITY OF SOUTHAMPTON

## ABSTRACT

FACULTY OF ENGINEERING AND APPLIED SCIENCE
INSTITUTE OF SOUND AND VIBRATION RESEARCH

Master of Philosophy

# RAILWAY TRACTION TYPE AND NOISE ANNOYANCE

by Christos Kantarelis

This study was designed to investigate the relationship between railway traction type and human response (annoyance) under controlled laboratory conditions. Three types of motive power were considered: diesel, overhead electric and third-rail electric power. In the initial part of the study, recordings of train pass-bys of all three types were rated by listeners in the laboratory. The diesel trains were judged to be more annoying than either the third-rail or overhead electric trains, even though the spectrum of the diesel and third-rail electric trains was similar. Changes in the low frequency content of the sounds affected the subjective response, annoyance increasing with increased levels of low frequency noise.

A further experiment examined the acoustical characteristics that influence annoyance. It included recordings of diesel and third-rail electric trains as above (real), together with synthesized signals that reproduced the time history and spectral content of the two types of train (synthesized).

More detailed examination of the characteristics of the diesel locomotive noise identified two factors which were worthy of further investigation. Firstly, there was a low frequency modulation of around 6-8 Hz; secondly, a 34 Hz component was always present in the particular type of train studied. The use of synthesized sounds provided a method of controlling the levels of these sounds and a third experiment was conducted. The major conclusion was that a reduction in the diesel engine noise of 10 dB was required for the diesel train to be judged subjectively equal to an electric train.

In the final part of the study the source of the low frequency modulation which is present in diesel locomotive noise was identified. Using signal analysis the exhaust noise waveform and the effect of the silencer were studied. It was found that the existing arrangement of the exhaust manifold, for the particular engine considered, produces a highly amplitude modulated waveform of "pulsing" character. In Chapter 7 an alternative design of exhaust manifold is proposed, which will reduce the amplitude modulation in the exhaust noise waveform thus making diesel trains 5 dB quieter.

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## ACKNOWLEDGEMENTS

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# 1. INTRODUCTION

Environmental noise pollution has been recognised in recent years as a serious threat to the quality of life enjoyed by the people in most industrialised nations. One of the main sources of environmental noise is transportation noise. It is in the last thirty years or so that all of us have experienced the transport revolution. Roads have become crowded with cars and heavy lorries. The development of the jet engine in aircraft has affected those living anywhere near the major airports. On the railways the old steam locomotive has now been replaced by powerful diesel and electric traction which is faster but often much noisier. The Noise Advisory Council was formed in 1970 (but no longer in existence) to consider the problem of noise and provide the Department of the Environment with invaluable advice on all aspects of the noise problem.

In addition, the Department of the Environment and the motor industry have jointly sponsored projects to develop heavy commercial vehicles which will be at least 10 dB quieter than comparable current types. Some of the bus manufacturers have also been working on quieter vehicles. In the aircraft industry quieter aircraft are now coming into service. The Lokheed Tristar and the European Airbus are two successful examples of the new generation of the wide body type of aircraft using quieter turbo fan engines.

In contrast to the growth of road and air traffic, railways have not developed significantly. In many countries the railway system has been in a state of decline. However, following the success of high speed trains in Japan, many European countries have increased the speed and number of their passenger services so that they can be competitive with air travel. These include the HST (High Speed Train) and APT (Advanced Passenger Train) in Britain and the TGV (Train a Grande Vitesse) in France, the latter running at speeds up to 300 km/h.

However, the increased traffic and speed resulted in increased noise levels. In Japan since the opening of the New Tokaido Line in 1964, the noise produced by the high speed train has given the inhabitants along the railway a less favourable living environment [1.1]. In contrast to the extensive research on reactions to aircraft and road traffic noise, relatively little has been done on reactions to railway noise. Nevertheless, railway noise has not been totally neglected. Studies in Japan [1.2], France [1.3] and the UK [1.4] have created a firm basis for the understanding of reactions to railway noise.

A major field study of the response to railway noise was carried out in 1975/76 in Great Britain by the Institute of Sound and Vibration Research at the University of Southampton [1.5]. A combined social survey and noise survey recorded residents' reactions and measured the railway noise levels. Major findings about reactions of people to trains operated with different types of traction included the conclusion that people were less annoyed by noise if they lived alongside overhead electrified routes than if they lived alongside diesel (non-electrified) or third-rail electrified routes. In general the difference in annoyance is equivalent to a least 10 dB(A) difference in noise levels. This difference cannot be explained by differences in noise levels, presence of jointed rail, proportion of freight traffic, ambient noise level, population density, train speed, number of trains, region of country, visibility of railway structures, fear of the electrified third-rail, annoyance with fumes, or annoyance with dirt from the railway. However, when the noise levels were expressed in dB(linear) rather than dB(A), the differences between the responses to the traction types were very considerably reduced. Therefore there was some evidence to suggest that the difference was, at least in part, due to acoustical characteristics which are better represented by a linear rather than an A-weighting. The puzzling similarity in the reactions for the third-rail electrified routes and diesel routes led to speculation that there may be generally more positive reaction towards the more modern appearance of the overhead electrification programme. This could not be explored further in the field study analyses. There was therefore a clear finding but no equally clear explanation.

This thesis reports laboratory studies designed to investigate the reasons for these differences in reactions and the influence of changes in the acoustical factors under carefully controlled conditions.

Laboratory studies have a particular value in that they allow examination of the effect of purely acoustical factors in the formulation of response. If a thorough understanding can be gained of the effect of changes in these factors on the subjective response then it would be possible to define the noise reductions necessary for diesel trains to be judged equal to overhead electric trains.

From the environmental point of view, this would be extremely valuable to British Rail as well as to other railway operators. In particular, it would help to formulate guidelines on locomotive exhaust and silencer design and it would also be valuable if regulatory noise emission levels are to be set.

The objectives of the work were:

1. To determine the reasons for the different annoyance reactions to diesel, third-rail electric and overhead electric trains and routes;

2. To examine the acoustical characteristics of the train noise which may be responsible for these differences.

These objectives were achieved by a series of laboratory experiments which were carried out in order to investigate the annoyance reactions to different types of traction.

Random signal theory was used to identify the subjectively important acoustical factors of the different noises considered.

In Chapter 7, suggestions are made about reducing the annoyance to noise produced by diesel trains. It is proposed that by modifying the existing exhaust manifold of the diesel engine, diesel trains could become subjectively quieter.

## 2. LABORATORY INVESTIGATION OF THE ANNOYANCE DUE TO THREE TYPES OF TRACTION (DIESEL, THIRD-RAIL ELECTRIC AND OVERHEAD ELECTRIC)

### 2.1 Introduction

In this chapter a general description of train noise in Britain is presented initially, together with a consideration of its sources and prediction.

A series of noise measurements are reported for three different types of traction (diesel, third-rail electric and overhead electric trains). The purpose of these measurements was to identify acoustical differences between the types, which could be subjectively important. A description of the frequency analysis techniques used is given.

A laboratory study followed which investigated the annoyance due to the three different types of traction mentioned above. Special attention was given to the effect of the high level of low frequency noise (below 250 Hz) on subjective response.

### 2.2 The Railway Network in Britain

The British railway network includes extensive sections of railway routes which utilize a variety of different types of electric traction as well as sections which are only used by diesel trains.

The modernisation plan of railways started in 1955, when the British Transport Commission ordered the formulation of a comprehensive programme for the modernisation and re-equipment of British Rail [2.1]. Four different types of traction are found in Great Britain. These are: diesel, electrified third-rail direct current (d.c.), electrified overhead d.c. and electrified overhead alternating current (a.c.). Diesel only routes are much more widely spread.

The decision to electrify the lines was made as part of the British Rail modernisation plan. Electricity in many ways is the ideal means of traction, reliability in operation and technical efficiency both being of a high order. Furthermore, there is a substantial overload capacity giving good performance when starting from rest and when tackling stiff gradients [2.2].

It was decided in 1955 that the electrification should be on the 25 kV, 50-cycle single phase a.c. system, after a detailed comparison of the costs had revealed a saving of about 5 percent compared with 1500 volt direct current. The third-rail electrification of the Southern Region, which started in 1959, was a continuation of the early electrification programme [2.3].

The primary benefits of high-voltage a.c. electrification are these. The higher the voltage used the smaller the amount of current that needs to be supplied to the traction unit; and since the size of the conductor is governed by the amount of current it has to carry, with a high voltage system the overhead supply wires can be much lighter. In a typical high voltage a.c. installation these contact wires are nearly half the size in cross section of those in an average 1500 volts d.c. overhead supply system. Since the wires are copper, an expensive metal, the saving in cost is considerable [2.3].

## 2.3 Sources and Prediction of Noise

In this study train noise is considered to be the noise generated by the running trains. The major sources are:

(a) rail-wheel interaction
(b) power unit noise.

The speed of the trains determines which is dominant. While differences in noise levels from different electric train pass-bys at a particular location are dependent almost exclusively on speed, the noise from diesel trains can vary considerably from one pass-by to another, depending upon whether or not the engine is under power. Diesel locomotives and most diesel multiple units use the diesel engines to generate electricity. This is fed to electric motors which drive the wheels. The frequency spectrum of diesel engines depends mainly upon the engine r.p.m. and could be different for each locomotive.

Various models have been developed to predict the noise level produced at a specified distance from the track. They assume a moving line source made up from a number of dipole sources [2.4, 2.5]. For example, in the United Kingdom, British Rail have developed their own method of predicting noise levels in terms of peak pass-by noise expressed in dB(A). They assumed rail/wheel noise to be the predominant source of noise beyond 20 m from the track. The model which they currently use is a modified version of the model derived by Peters [2.5]. The model derived by Peters predicted the peak ($SPL_p$) measured in dB(A) at a given distance from the track in terms of the train make-up and speed. $SPL_p$ is calculated from the equation:

$$SPL_p + SPL_G + 10 \log \frac{A}{4N} - 20 \log \frac{\ell_v}{20} + 25 \log \frac{v}{120} \pm 5.5 \text{ dB(A)}$$

where $SPL_G$ is a normalised peak sound pressure level in dB(A)

$A$ is the mean number of axles per vehicle

$N$ is the number of vehicles

$\ell_v$ is the vehicle length in metres

and $v$ is the train speed in km/h.

The modified predicted levels for existing trains, which takes into account ground absorption, compare well with measurements reported from several sources [2.6, 2.7].

Another method has been developed by Walker, Allen and Large [2.8] for predicting the noise climate for existing and future railway operation. This method is based on measurements reported by Allen

[2.9] and is summarized in Figure 2.1. Tubby [2.10], Figure 2.2, examined in detail the way in which noise levels at different distances from the track depend on the particular wheel configuration in the trains. His data compare well with Rathe's [2.4] theoretical studies if the train is considered as an array of point sources with spacing corresponding to the axle spacing on the train. Lotz [2.11] has studied the relationship of noise level with speed for passenger cars on continuous welded rail, and for passenger cars on jointed rail. The data from British Rail, Walker and Lotz, as well as data from other sources, suggest that the change in level ($\Delta L_A$) with speed is given by:

$$\Delta L_A = n \log \; v_1/v_2$$

where $\Delta L_A$ is the change in level in dB(A) for a change in speed from $v_1$ to $v_2$. n is quoted as being between 20 and 40 for a variety of rolling stock and track. Thus, a doubling of train speed would change the level by between 6 and 12 dB(A).

## 2.4 Noise Measurements

Examination of previously recorded noise data indicated that the frequency spectra for the different types of trains exhibited marked individual characteristics [2.5]. The recordings obtained during previous studies were unsuitable for analysis and for use in the laboratory study (insufficient signal-to-noise ratio or no low frequency information below 60 Hz, not stereophonic recordings). Hence a programme of noise measurements was planned, as shown in Table 2.1 below.

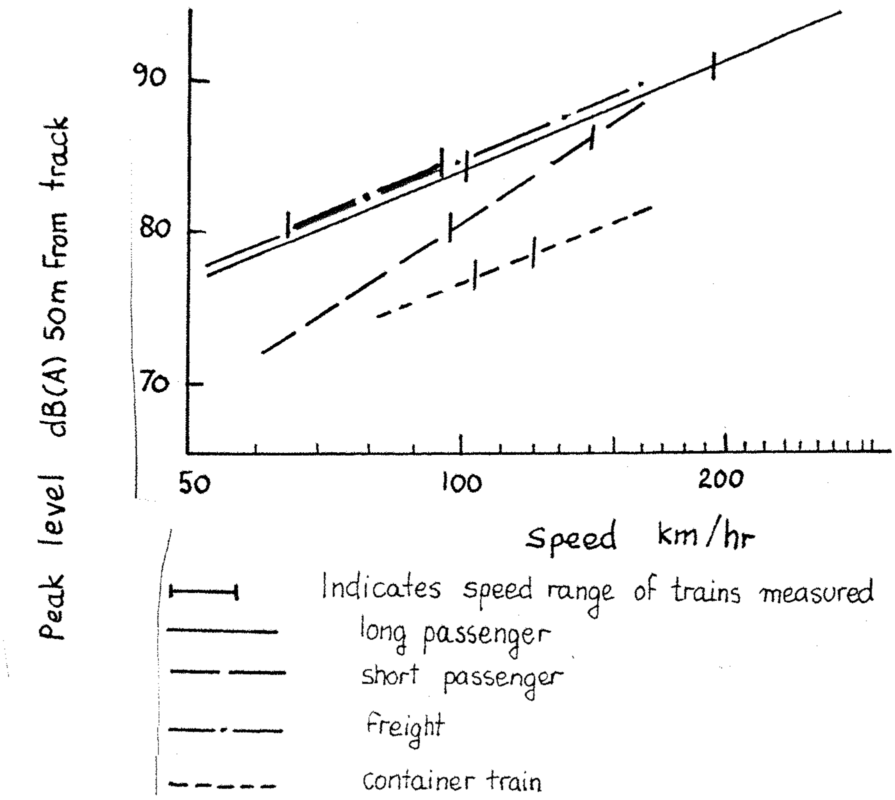



**Figure 2.1 Relationship between train speed and peak level, dB(A) (From Walker, Allen, Large, 1974)**

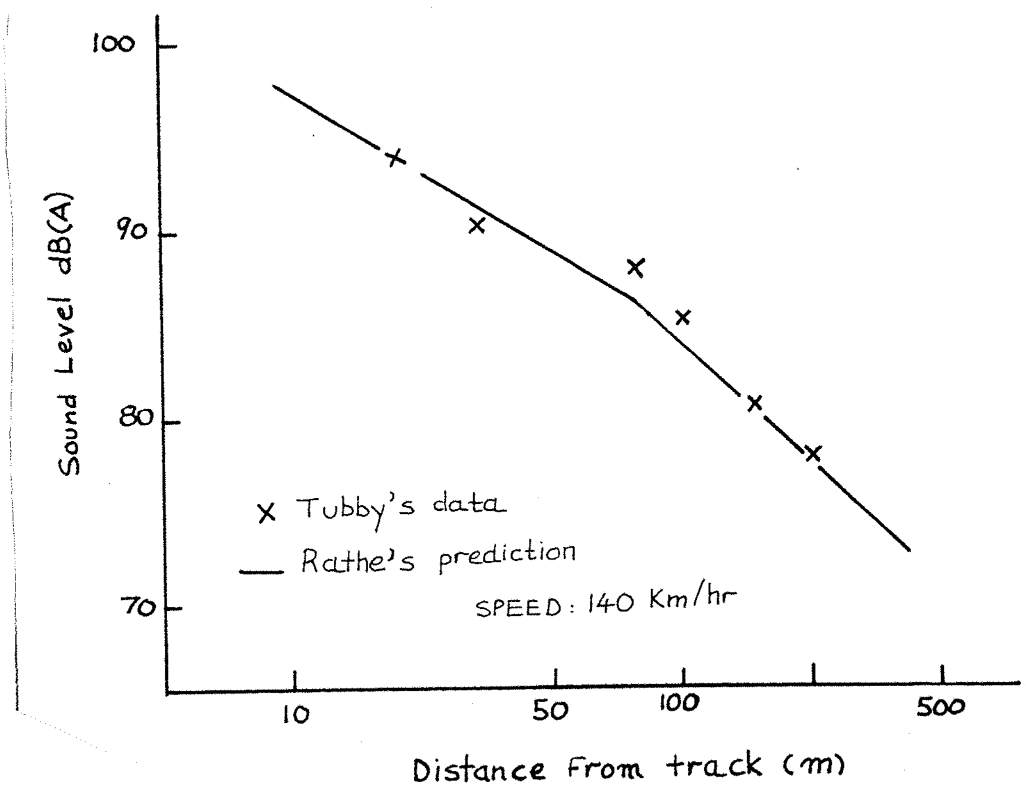



**Figure 2.2 A-weighted sound level for 12-car passenger train (From Tubby, 1975)**

Table 2.1 Summary of noise measurement and subsequent noise data analysis.

| Train type | No. of cars | Distance from track (m) | Approx. speed (km/h) | Route | Analysis |
|---|---|---|---|---|---|
| Diesel-passenger | 8-10 | 25, 50, 100 | 110 | Waterloo-Bournemouth | Time history 1/3 oct. analysis |
| Third-rail electric passenger | 8-12 | 25, 50, 100 | 110 | " | " |
| Overhead electric passenger | 12 | 25, 50, 100 | 110 | West Coast main line | " |

In order to get uniformity between the train recordings it was decided that only main line trains were to be recorded, i.e., trains with at least 8 coaches and travelling at speeds greater than 90-100 km/h. The trains would have to be recorded on a stretch of line in a non-built up area in order to eliminate noise from other sources such as traffic and construction noise. When selecting a location for recording trains, the following points were considered:

(a) the location should not be near a main road or any other source of noise

(b) there should be a good view of track in both directions

(c) the track should be a continuous welded rail

(d) the track should be on a slight embankment (not more than 3 m)

(e) the track should not pass over any bridges in the immediate vicinity of the recording area.

Suitable locations were selected from local maps of the areas. The diesel and third-rail electric trains were recorded at two locations north of Winchester. For the overhead electric trains, the recordings were made in Paroff Elsace's farm in Cheddington, near Aylesbury. Depending on whether the recordings were needed for analysis purposes or for use in the laboratory study, two different sets of recording gear were used, see Appendix 2. It is known that the character of the noise from passing trains changes with the distance from the track. This is due to propagation effects [2.4]. The recordings of train pass-bys used in the laboratory for the experiments were therefore made at three distances from the track.

## 2.5 Analysis of the Noise Measurements

### 2.5.1 Frequency analysis techniques

We were interested in the amplitude of the signal at a particular frequency and also in a range of frequencies.

In general, two types of frequency analysis are used in the analysis of noise signals: constant percentage bandwidth and constant bandwidth. In the first analysis method the filter bandwidth is a constant percentage of the centre frequency of the pass-band, whatever its absolute value, and therefore increases as the frequency increases. In the second method, the filters have a constant bandwidth, say 100 Hz, completely independent of the centre frequency to which the filter is tuned. This technique permits very detailed analysis of the spectrum. Acoustic noise measurements for purposes of estimating loudness, annoyance and subjective response generally do not require such detailed knowledge of the spectrum of the noise source. This is because the ear responds in a way similar to a constant percentage band analyzer with a 1/3 octave bandwidth, and loudness determination procedures have been largely based on this fact. Constant percentage bandwidth analysis is also normally used in procedures for the estimation of the subjective response of people to environmental noise. Aircraft noise is generally analysed in 1/3 octave bands, from which the perceived noise level is calculated.

The values which result from normal frequency analysis are obtained from a finite length of time record, giving rise to errors in the averaged values. The rms value of the signal is given by

$$A_{rms} = \sqrt{\frac{1}{T}\int_{0}^{T} a^2(t)\, dt}$$

where T is the averaging time used to determine the rms value of the signal, and a is the instantaneous amplitude. For noise which is statistically varying, the rms value obtained will only approach the true rms value if this period T is infinitely long. This, of course, can never be the case so we always have to accept an error in our measured values. However, by selecting a large enough value of T, the magnitude of these error fluctuations can be reduced. The second factor which affects the error superimposed on the true rms value is the passband width, and it can be shown that the relation between the error, the bandwidth B, and the length of the analysis record, T, is

$$\epsilon = 1/2\sqrt{BT}.$$

This is an extremely important result. To obtain results of certain accuracy, it is necessary to increase the time over which the data is averaged as the bandwidth.

In this work we were mainly interested in measuring the lower frequencies of our noises accurately enough. Therefore it was essential in the analysis to estimate the averaging time for measuring the low frequencies below 100 Hz. This was done as explained below.

It can be proved that:

$$\frac{\text{variance of o/p}}{\text{variance of i/p}} = \frac{\sigma^2 y}{\sigma^2 x} = \frac{1}{4RCf_c}$$

for an input of random nature.

For good accuracy, we want this to be $\rightarrow 0$, i.e., we need large RC. ($f_c$ is the upper cut-off of our signal.) Therefore,

$$\frac{\sigma^2 y}{\sigma^2 x} = \frac{1}{2f_c T}$$

$T = 2RC$ = integration time.

It can be shown that if the input is band limited of bandwidth B, then

$$\frac{\sigma_y^2}{r_x^2} = \frac{1}{BT}$$

This equation can be used to assess the accuracy of a band spectra. The rule of thumb for measurements is that BT 100.

For example, in our case, if we have a one-third octave band at 31.5 Hz, then the bandwidth B is given by:

$$B = 0.23 \times 31.5 = 7.245 \text{ Hz}$$

Therefore $T \quad 100/7.245 = 13$ seconds,

i.e., 13 seconds integration time is required. This would lead to an accuracy of about 10% or 1 dB.

For a full description of the determination of the accuracy of measurements, see reference [2.12].

To obtain the one-third octave frequency spectra which are shown here in this chapter, a Bruel and Kjaer frequency analyser type 2131 was used. It was possible to adjust the appropriate time constant for the noises. Exponential averaging was used which, in contrast to linear averaging, gives weight to recent samples rather than to previous ones.

It must be appreciated that trains are moving sources of noise and talking about the frequency spectrum of a train pass-by is not strictly correct. One has to take into account the variation of spectrum caused by the movement of the train. There are various methods that could be applied in order to eliminate the Doppler effect and obtain a stationary spectrum. One method that achieves this is by continuously varying the tape recorder's speed during the recording. Other methods involve complicated signal analysis theory applied to a non-stationary spectrum in order to obtain stationary spectra [2.14]. None of the above methods was applied here. It was assumed that there was very little variation in the spectrum of the noise during the pass-by. This assumption was found to be accurate enough as will be seen later in Chapter 3. Therefore the frequency spectra shown in Figures 2.3, 2.4 and 2.5 of the three types of traction are "composite" spectra, made up of the maximum rms level which occurred in each frequency band during the train pass-by.

### 2.5.2 Level-time histories

The level time histories were obtained using a B & K level recorder type 2307 . Typical time histories of the three different types of traction can be seen in Figure 2.6a,b,c.

### 2.5.3 Results of the Analysis

(a) Differences in frequency spectra

Frequency analysis showed that both the diesel and third-rail electric trains contained high levels of noise in the low frequency region below 100 Hz, which were not present in the overhead electric noise spectrum. This low frequency peak in the spectrum is expected to make a significant contribution to the overall annoyance because of its high level [2.14, 2.15, 2.16]. Therefore it will be worthy of investigation under controlled conditions in the laboratory. The spectra for the diesel and third-rail electric trains can be seen to be roughly similar except in the mid-frequency range.

(b) Differences in the time histories

From the time histories of the three different types of traction it can be seen that in the case of the diesel there is a peak associated with the diesel locomotive. It was found from measurements that the level depends upon the operating conditions of the engine and typically is approximately 5 to 10 dB higher than the level of rail wheel noise. If the time history of the diesel train is A-weighted, then the peak disappears. Thus it means that low frequencies are associated with the peak and the source is most likely to be exhaust noise [2.17].

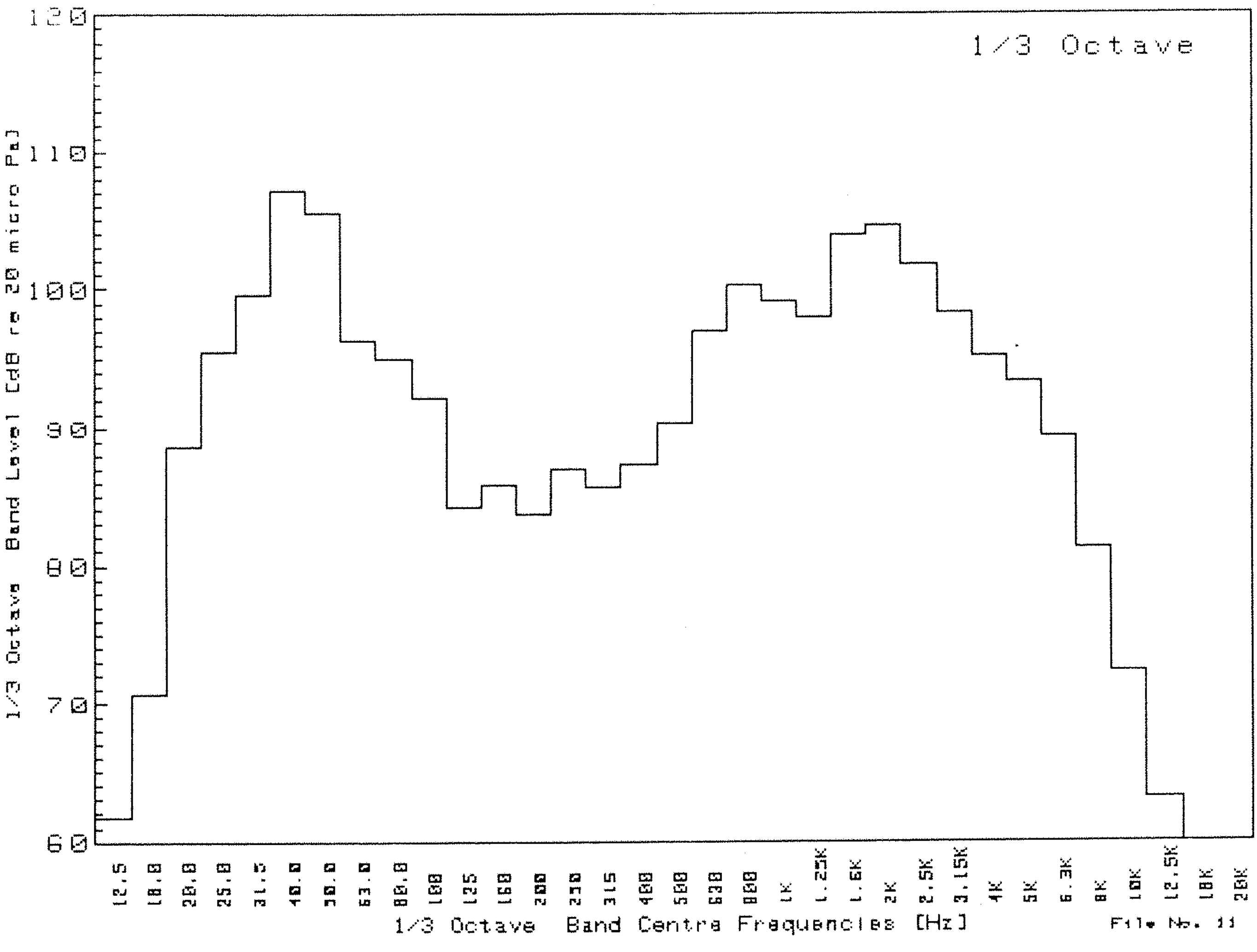



Figure 2.3 Composite frequency spectrum of a third-rail electric train pass by (11 coaches) 20 metres.

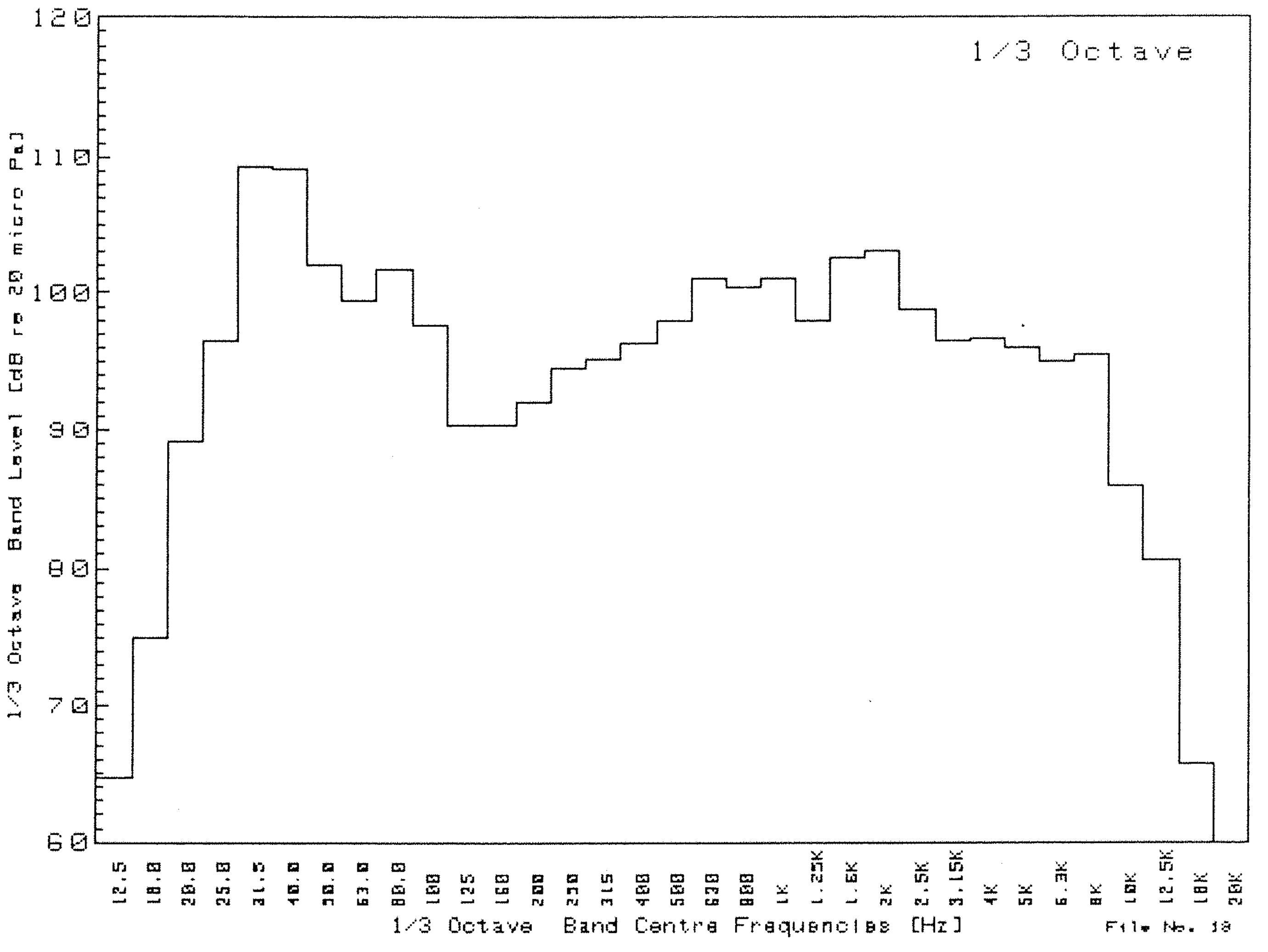



**Figure 2.4** **Composite frequency spectrum of a diesel (Class 47) train pass by (8 coaches) 20 metres from the track**

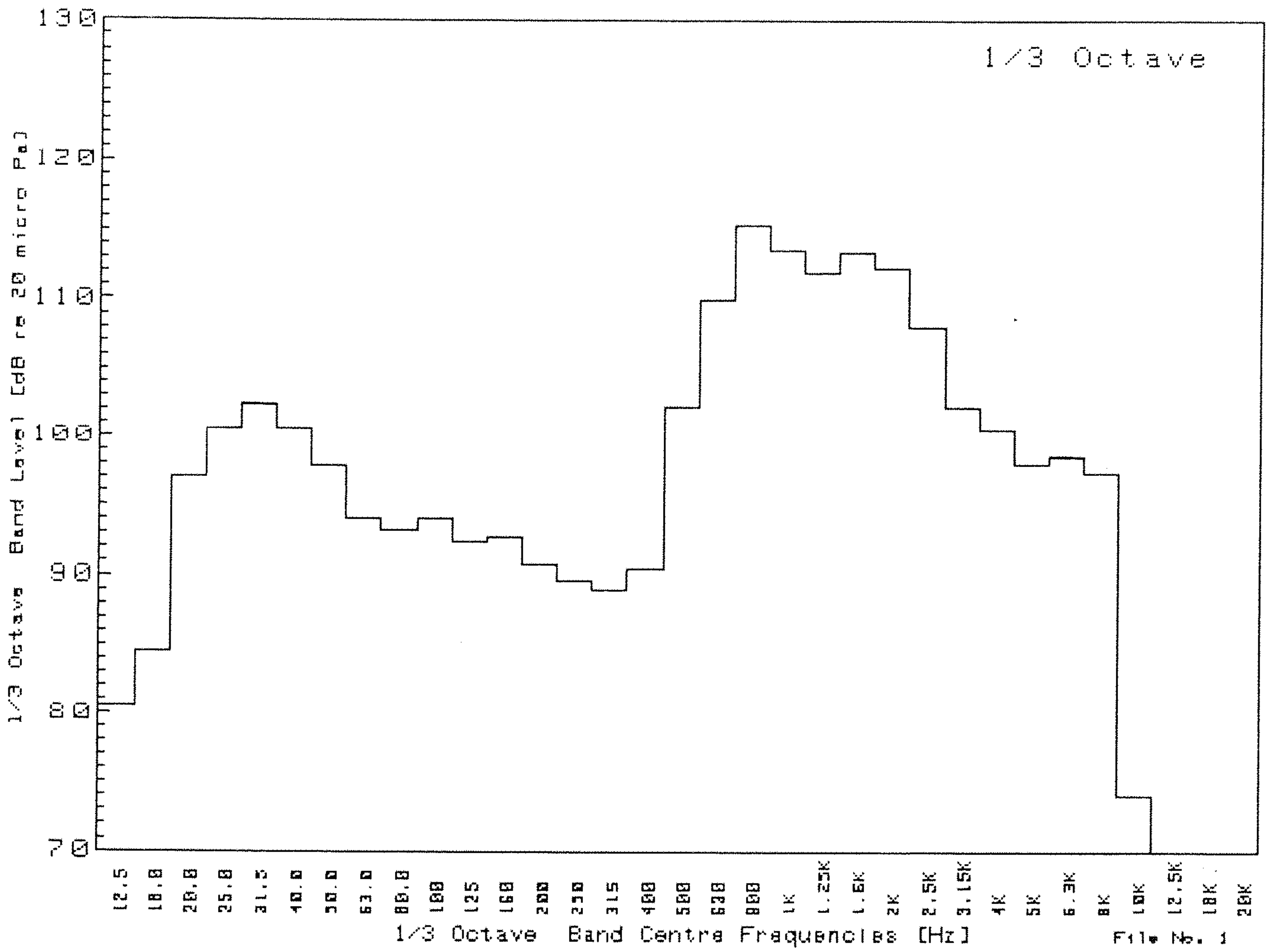



**Figure 2.5** Composite frequency spectrum of an overhead electric train pass by (12 coaches) 20 metres from the track

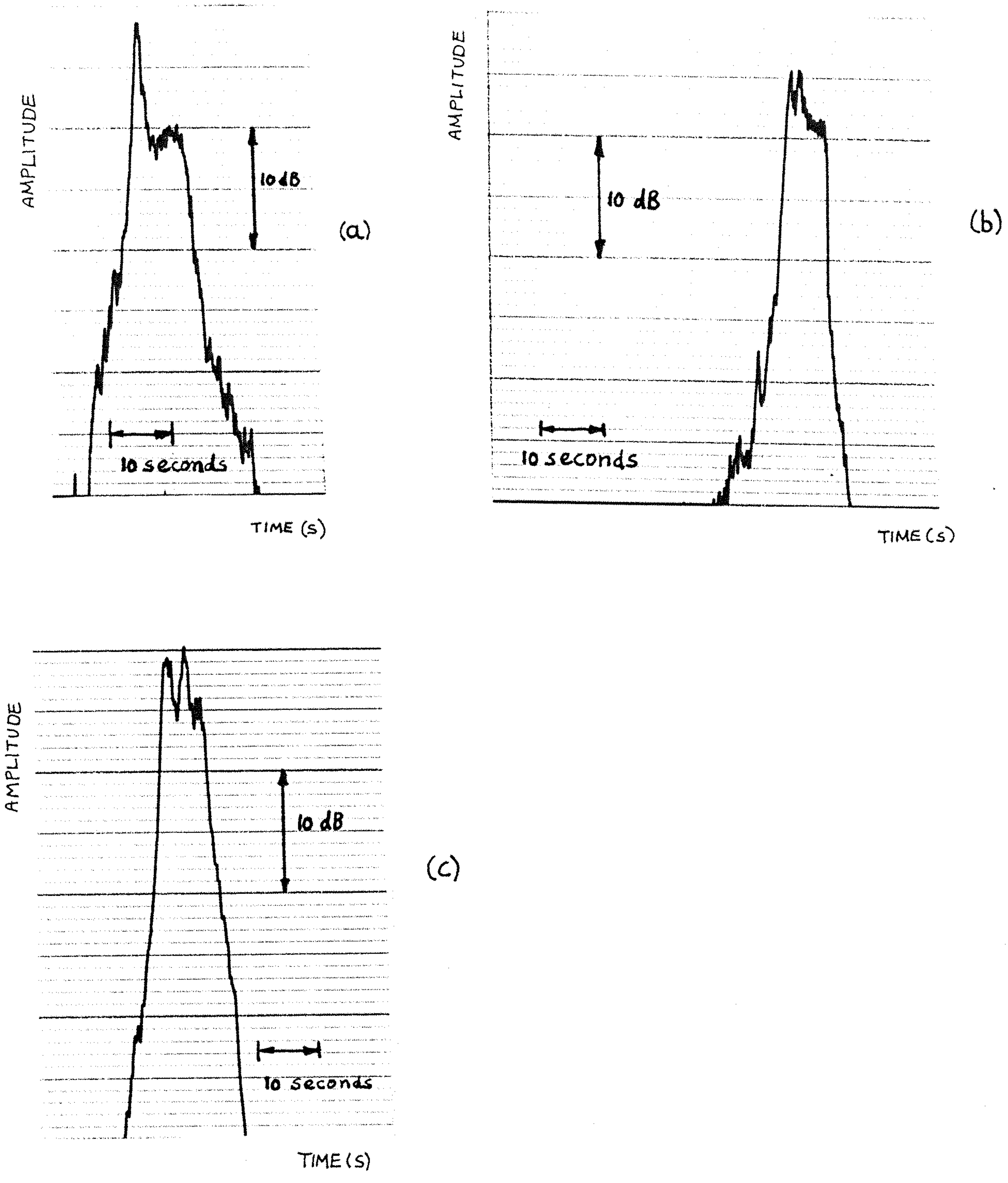



Figure 2.6 Time histories of the three traction types
(a) Diesel
(b) Third-rail electric
(c) Overhead electric

## 2.6 The Experiment

### 2.6.1 Designing an experiment

In general an experiment is set up to test one or more hypotheses or predictions. In this context an experiment is defined as a procedure in which at least two different conditions are presented to subjects and the differential influence (if any) on behaviour is measured [2.18] and a prediction is a statement that a change in one variable (the independent variable) will produce a change in another variable (the dependent variable). In this work, noise produced by moving trains is the independent variable, and the subject's reaction (annoyance) is the dependent variable.

In precise terms an experiment is a means of collecting evidence to show the effect of one variable upon another. In the ideal case the experimenter manipulates the independent variable, holds all other variables constant, and then observes the changes in the dependent variable. In this case, any changes in the dependent variable must be caused by the manipulation of the independent variable only. Unfortunately, many of the variables one would like to investigate cannot be brought under complete experimental control. When conducting an experiment there are many variables that could influence behaviour apart from the independent variable. These other variables are known as "irrelevant variables". They can be subdivided into "subject" variables (e.g., personality characteristics) and "situational" variables (e.g., background noise level). It is impossible to hold all irrelevant variables constant throughout an experiment. Some factors are bound to change randomly from time to time. However, it is essential that no variable is allowed to change "systematically" with the independent variable.

#### (a) Repeated measures design

The major purpose of "experimental control" is to avoid confounding factors. The only way one can be sure that two groups of subjects will have identical characteristics is to use the same subjects in each group. That is, each subject performs under both conditions of the experiment so that the effect of subject variables will balance out exactly. This type of design is prone to error due to "order effects" which may lead to confounding. We must therefore ensure that the order in which the tasks are performed is "counterbalanced" across the subjects. Throughout this thesis, repeated measures design was used as a method to control subject variables.

(b) Latin squares

One of the main uses of Latin squares is to counterbalance the order of treatment effects. If one has, say, one independent variable with levels A and B, then the result may be affected by the order in which the levels are presented. Hence, one should attempt to give half the subjects the level in order A, B and half in the order B, A. This effectively balances the order or any order effect.

With three or more levels of the variable complete counterbalancing becomes more difficult. With three treatment levels there are six possible orders, with four treatments there are twenty-four possible orders, etc.

A Latin square design allows each level (treatment) to occur equally often in each position. The basic format for the design of the Latin square is as follows:

| Subject no. | Order of presentation of levels (treatments) | | | | | |
|---|---|---|---|---|---|---|
| 1 | 1 | 2 | n | 3 | n-1 | 4 |
| 2 | 2 | 3 | 1 | 4 | n | 5 |
| 3 | 3 | 4 | 2 | 5 | 1 | 6 |
| 4 | 4 | 5 | 3 | 6 | 2 | 7 |
| ⋮ | | | | | | |

where n = number of treatments.

Using this design, residual effects are minimized; that is, the effects of a subject's judgement of a noise being influenced by the noise heard before is minimized.

Since each presentation occurs once in each row and column, row (subject), column (presentation order) and treatment effects are orthogonal. This allows the variation in subjective response due to these effects to be independently estimated and so a better estimation of the experimental error can be obtained.

For the above reasons throughout this thesis Latin square design was used for presenting the different treatments to the subjects.

(c) Subjects

In general there are two decisions to be made about subjects. First is the number of subjects to be used so that the experimental effect can be detected with reasonable confidence, and secondly, how the subjects should be selected [2.19]. Unfortunately, the variability of the scores, or the probable difference in population means, is unlikely to be known before the experiment. Thus the actual number cannot be calculated. All that can be said is that the prospects of detecting significance grow better as the sample increases. In practice one should run as many samples as time and resources allow; a pilot study in this case can be very useful.

In theoretical terms subjects should be selected randomly from the population to which the generalization of the experimental findings is intended. The subjects for the laboratory studies in this work were chosen from students and people working in the University of Southampton

All laboratory studies in this work were carried out in the simulated living room in ISVR. A description of the room and the equipment used for the reproduction of the noises is given in Appendix 1.

### 2.6.2 Experimental design

In order to make a preliminary study of the relationship between railway noise and annoyance in the laboratory, an experiment was designed to examine the effect of high levels of low frequency noise (below 250 Hz) for the three different types of traction - diesel, third-rail electric and overhead electric - at different overall levels. The variables included in the experimental design were: (a) type of train; (b) frequency content; and (c) noise level. The conditions at which each variable was presented are listed below.

1. Three train types: diesel, third-rail electric and overhead electric.

2. Two frequency conditions: (a) linear; (b) high pass at 250 Hz, (24 dB/oct.)

3. Four noise levels. In order to investigate the annoyance level relationship it was decided that each noise should be presented at four different levels. With the outdoor/indoor attenuation taken into account [2.20], the levels were: 80, 75, 68 and 62 dB(A), which corresponded to 15, 50, 100 and 200 metres from the track.

The experiment, therefore, contained 24 treatments ($3 \times 2 \times 4 = 24$). There was one pass-by per treatment. A balanced $24 \times 24$ Latin square design was used to present the 24 treatments to an equal number of subjects. The instructions given to the subjects and the response sheets are shown in Appendix 3. For each noise heard the subjects answered on a ten step scale, choosing a digit ranging from 0 ("not at all annoying") to 9 ("extremely annoying"). Each subject was tested for normal hearing (± 20 dB i.s.o.) using a self-recording Bekesy audiometer. The total time for the 24 treatments including the hearing test was 1 hour.

Preparation of the noises

A set of four recordings of train pass-bys was prepared for each type of traction to cover the range of noise levels from 62 dB(A) to 80 dB(A), containing the whole range of frequencies. Similarly, another set of four recordings was prepared, but this time the low frequency region below 250 Hz was removed by using a high pass filter set. The cut-off frequency was set at 250 Hz and the rate of decay was 24 dB/octave. Frequency spectra of the noises used in the experiment, as they were actually heard by the subjects, are shown in Figures 2.7, 2.8 and 2.9. Each noise treatment was recorded on a separate reel of tape, and numbers were allocated randomly to each tape. The tapes were then played in order according to the Latin square design.

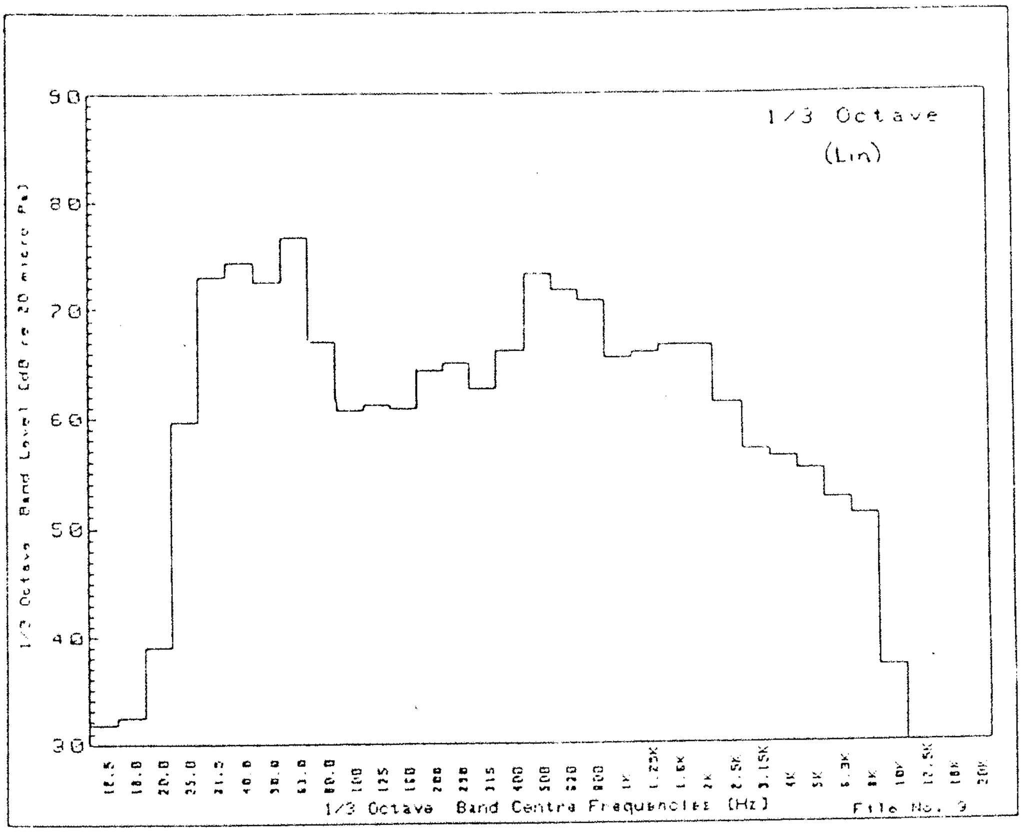



Figure 2.7a  Diesel with the low frequencies

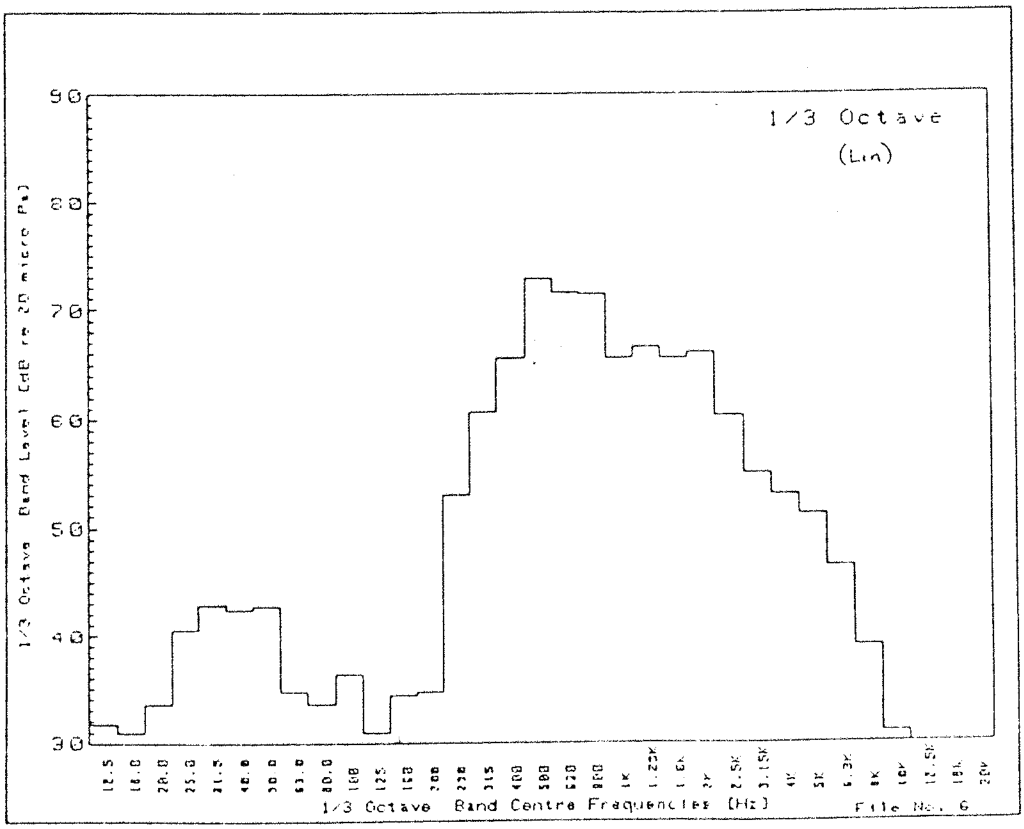



Figure 2.7b  Diesel without the low frequencies

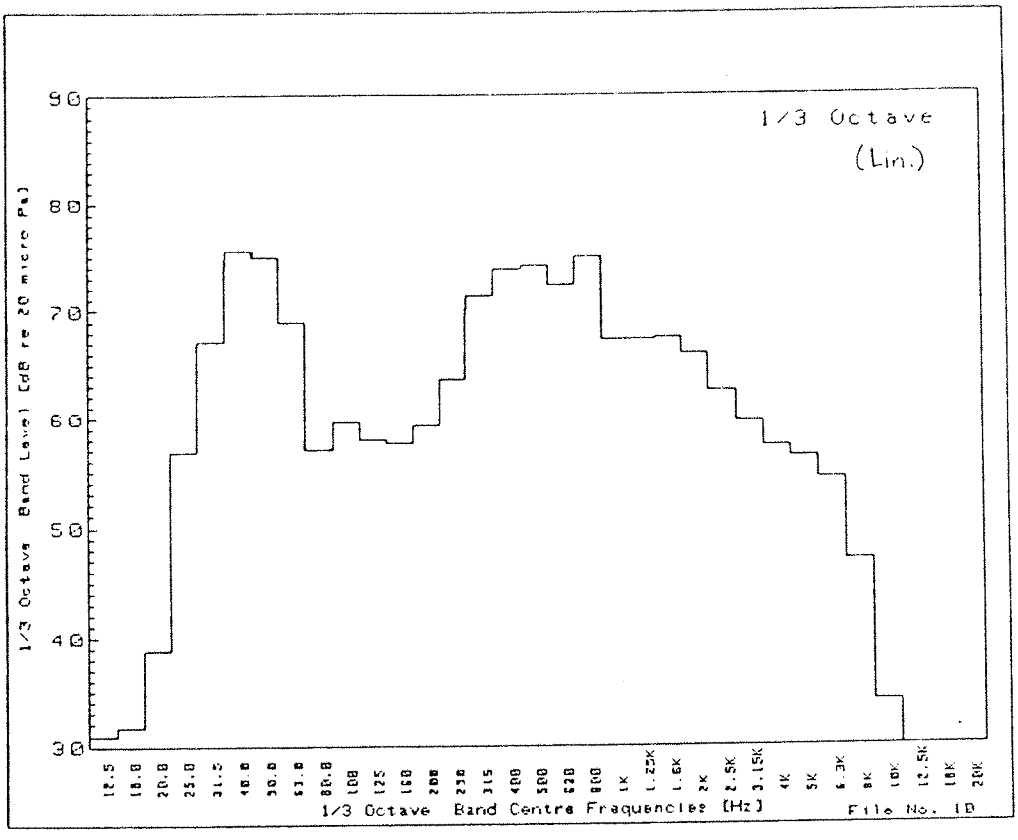



**Figure 2.8a Third-rail electric with the low frequencies**

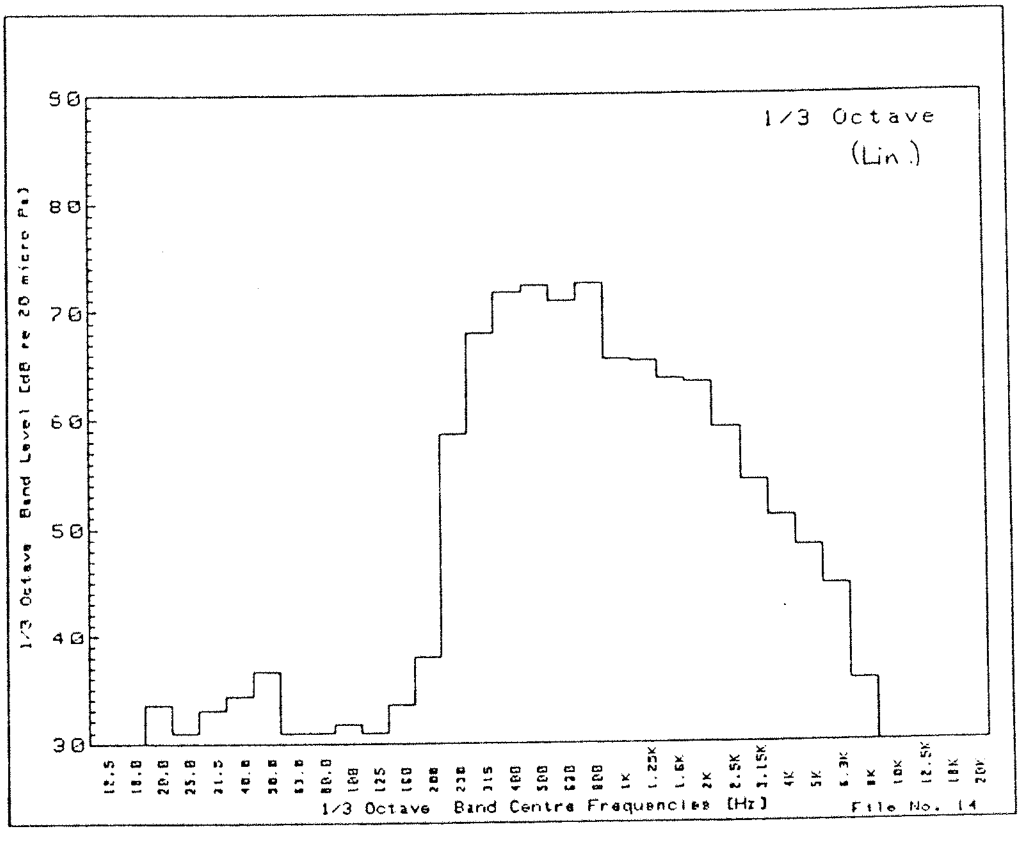



**Figure 2.8b Third-rail electric without the low frequencies**

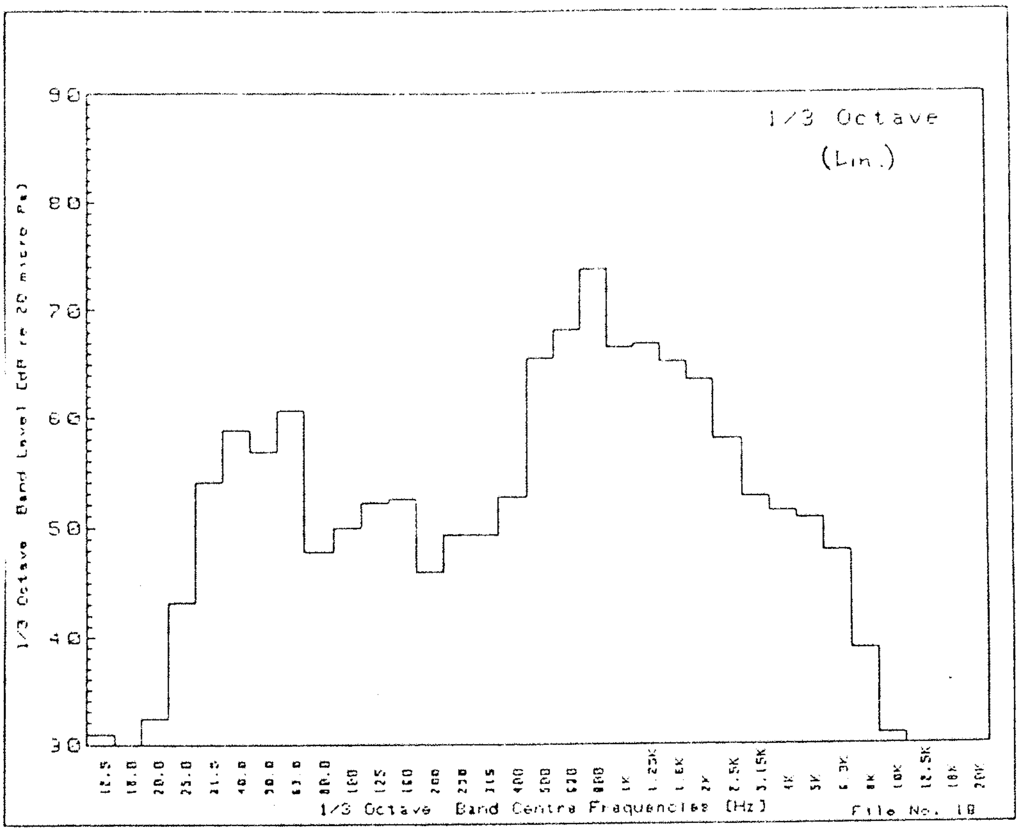



**Figure 2.9a Overhead electric with the low frequencies**

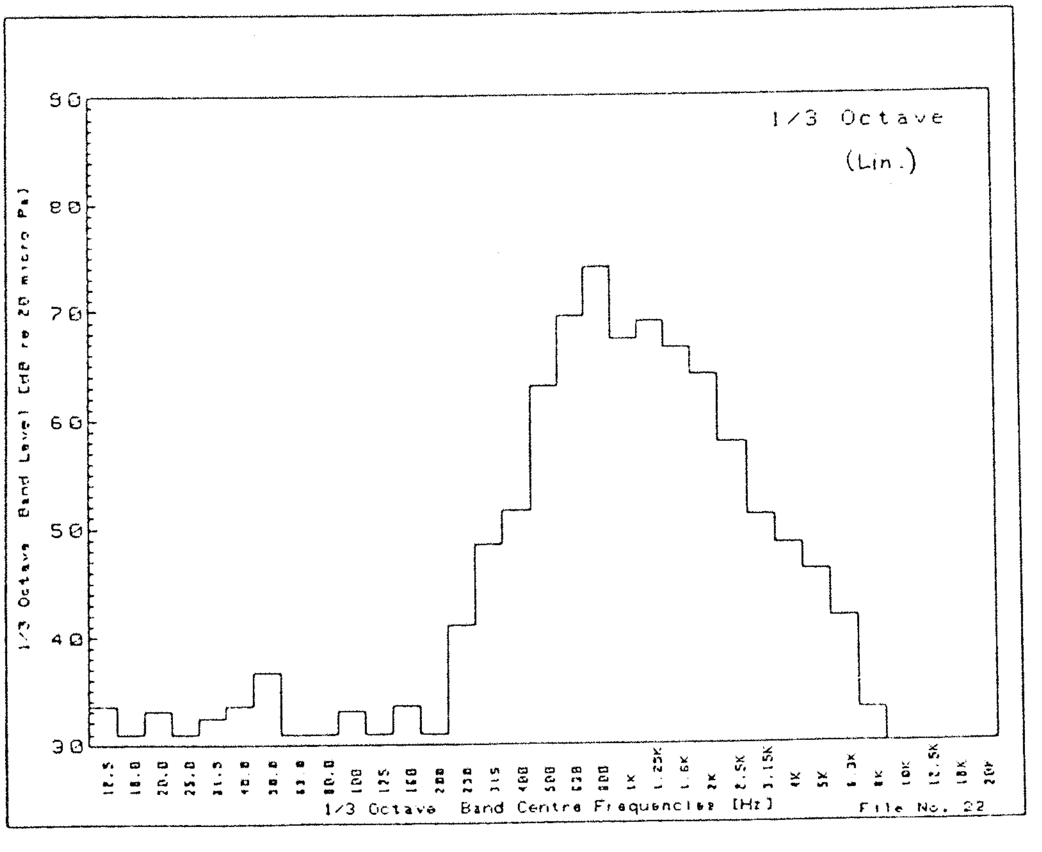
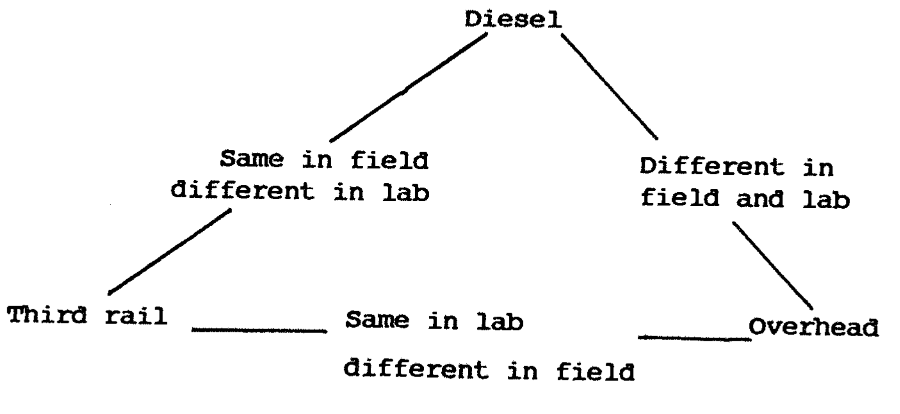


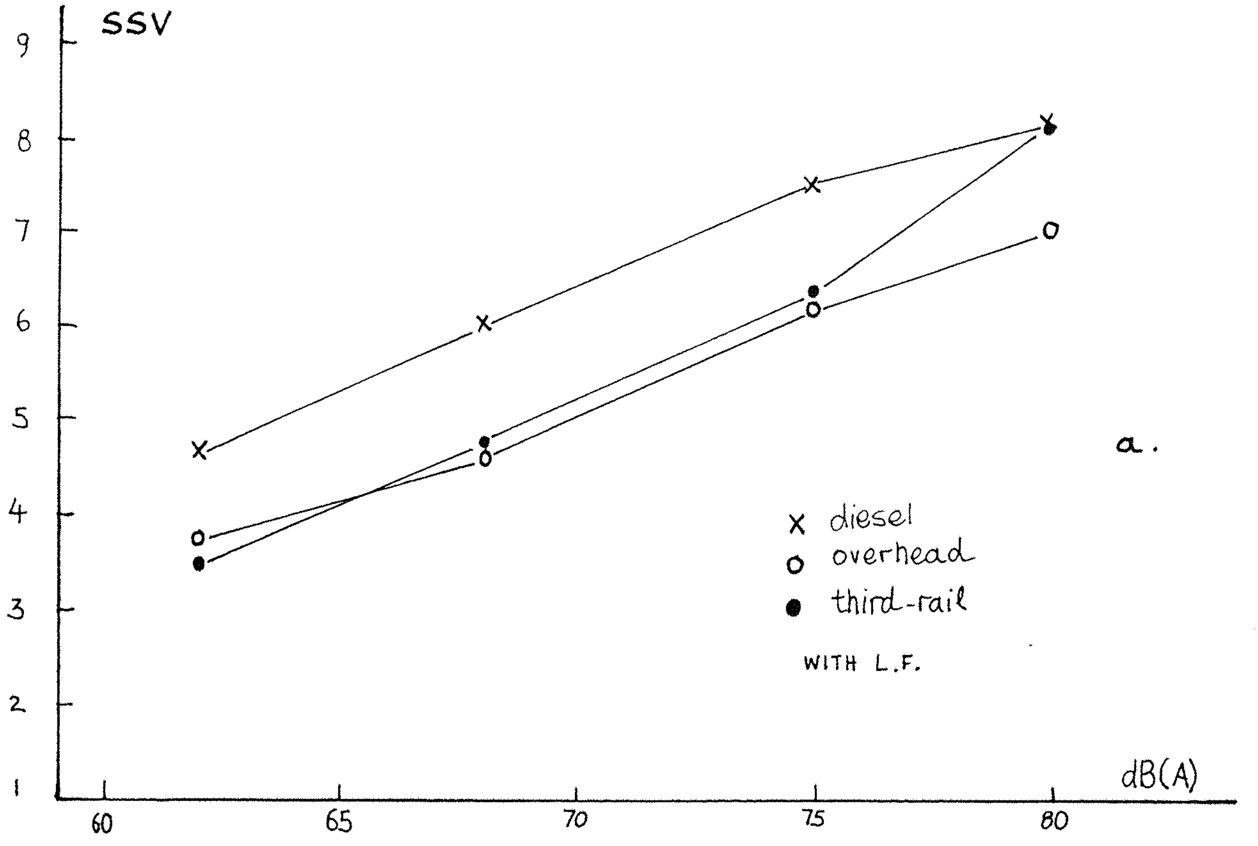

**Figure 2.9b Overhead electric without the low frequencies**

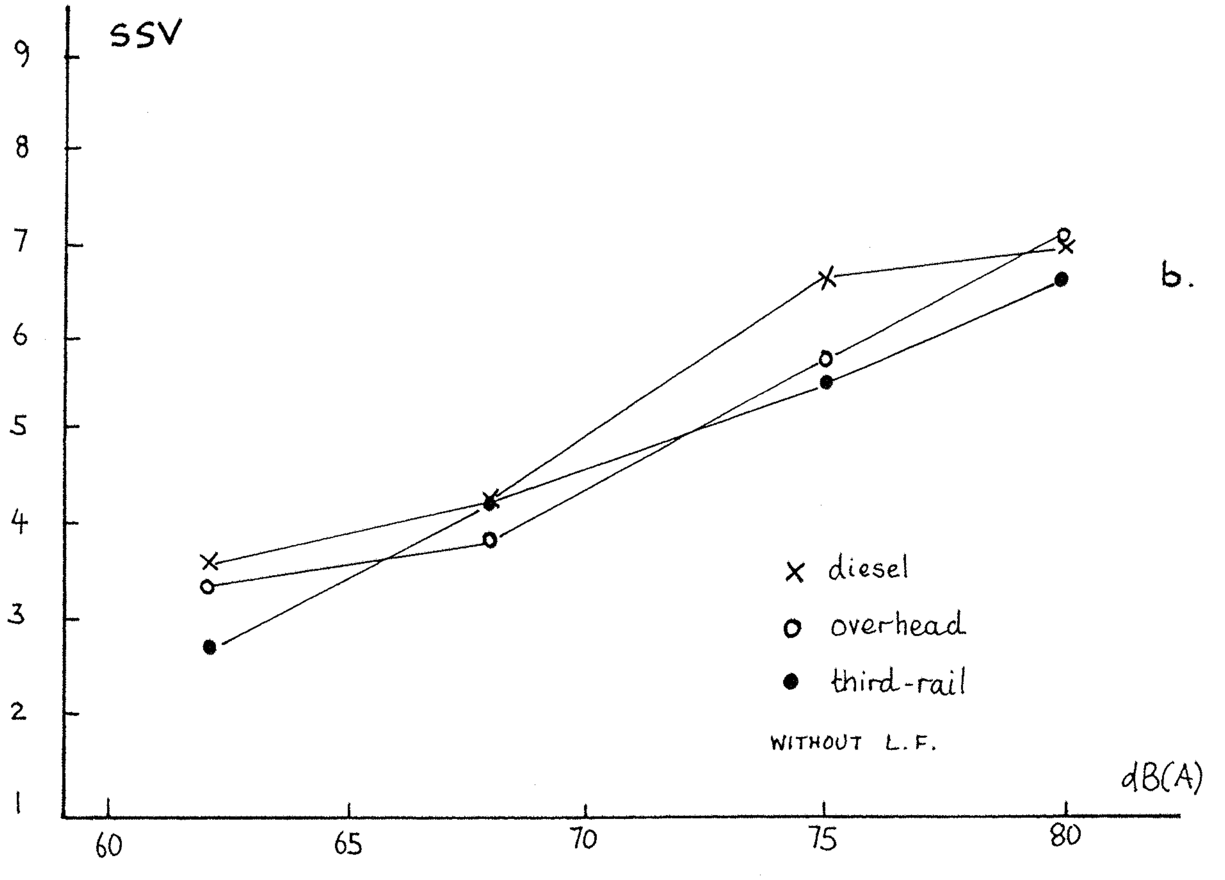
## 2.7 Results and Analysis

The subjective response scores of each subject were recorded and can be seen in Appendix 3. The response scorers were averaged between the number of subjects so that an average response score was obtained for each treatment. The mean response score was then calculated and plotted (see Figures 2.10, 2.11, 2.12 and 2.13).

The graphs show subjective response rating against maximum noise level in dB(A) reached during the pass-by for the different types of traction. The results were analysed using the analysis of variance method. Details of the analysis of variance are shown in Tables 2.2 and 2.3. The variance ratio tests revealed that the differences in type, level and frequency content were significant. Also significant at the 1% level was found to be the type-frequency interaction. This implies that the differences recorded beween the three types of traction with frequency content are significant and that the diesel with the low frequency noise present was the most annoying combination. Overhead electric type was found to be the least annoying. This finding contradicts Fields and Walker's finding concerned with the relationship between traction type and annoyance. According to the results of that study, overhead electric trains were less annoying than diesel and third-rail electric trains. The difference found in annoyance between diesel and third-rail was quite small but in the direction of third rail being less annoying.
The diagram below summarizes the differences in the findings of the laboratory study and the field study concerned with the difference in annoyance due to traction type. The important interactions were plotted and the graphs are shown in Figure 2.14.






**2.10a, b Relationship between subjective response and noise level**
(WITH and WITHOUT LOW FREQUENCY).

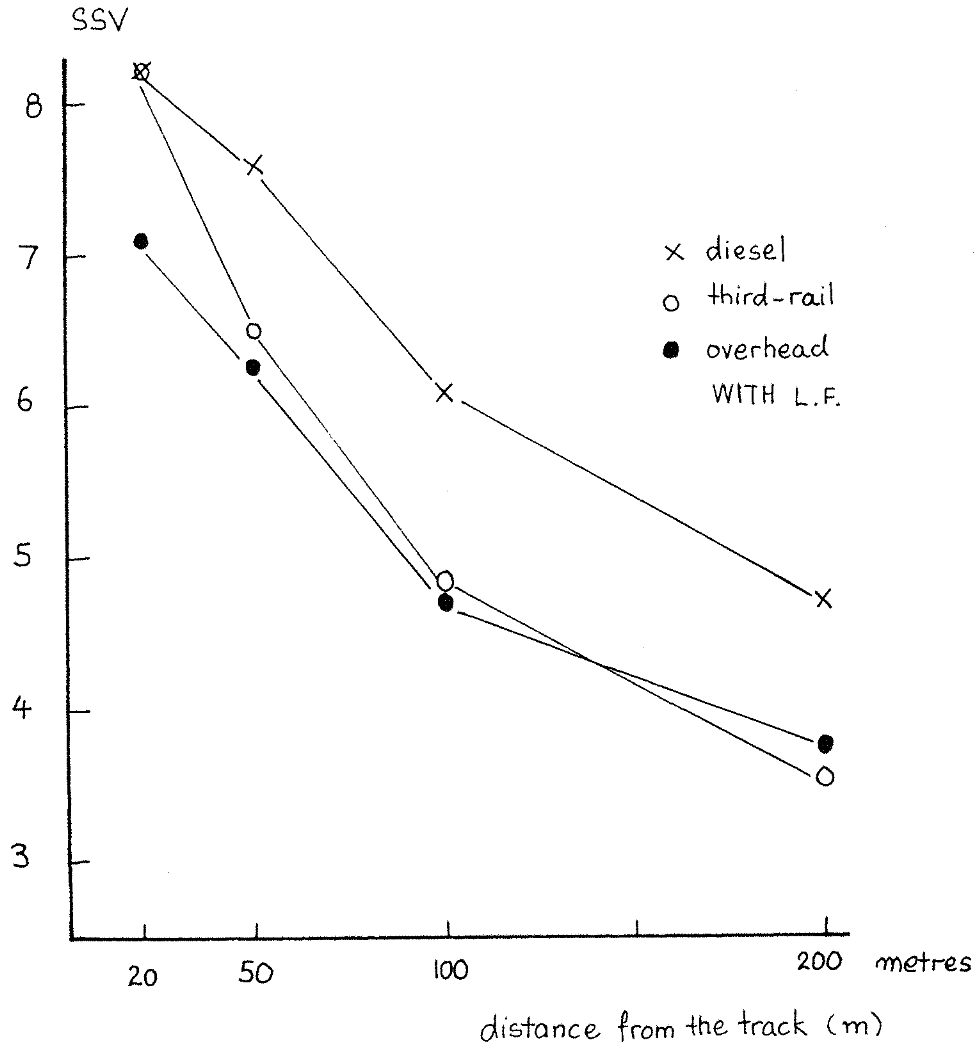



**Figure 2.10c Relationship between subjective response and distance from the track**

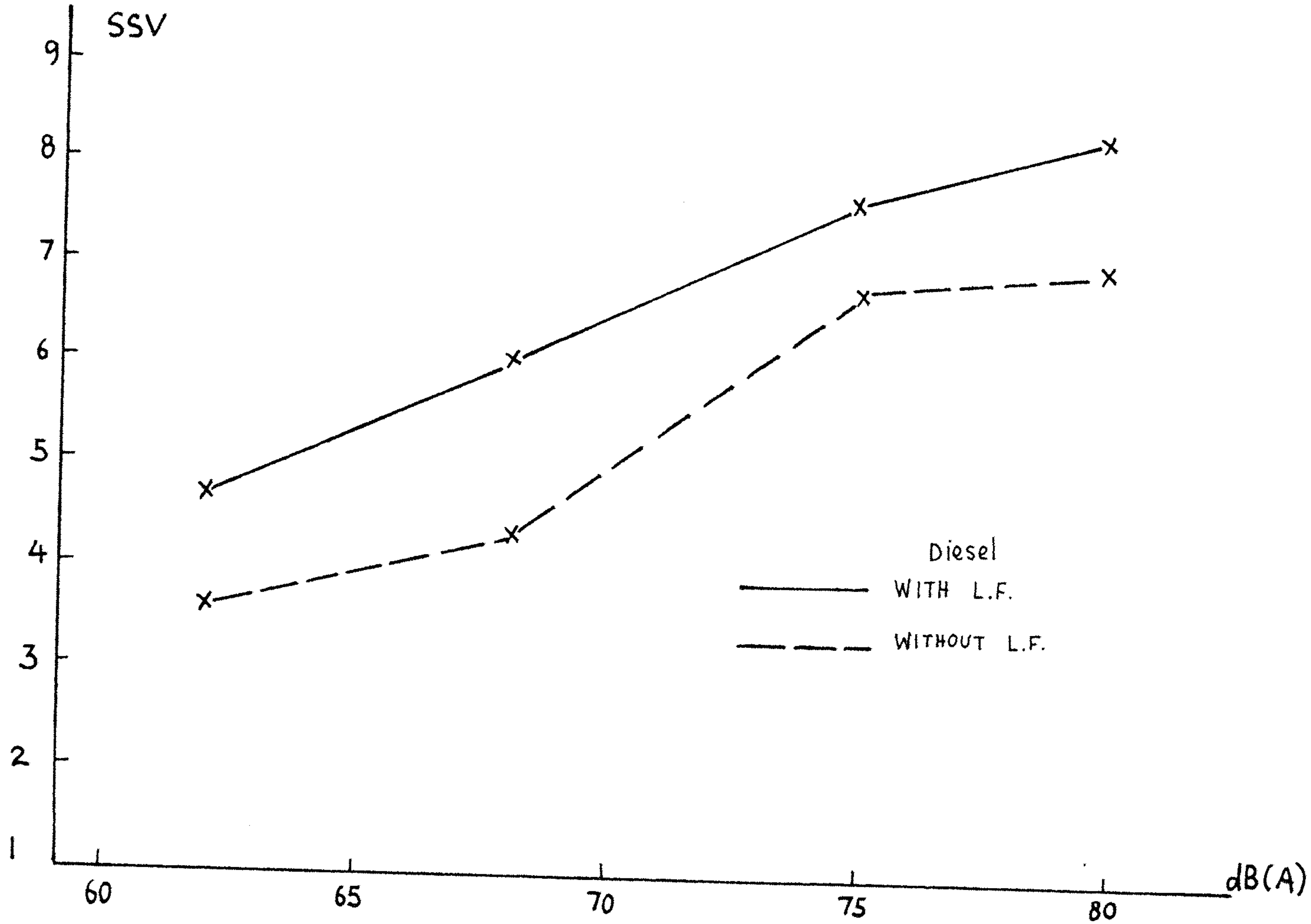



Figure 2.11 Relationship between subjective response and noise level

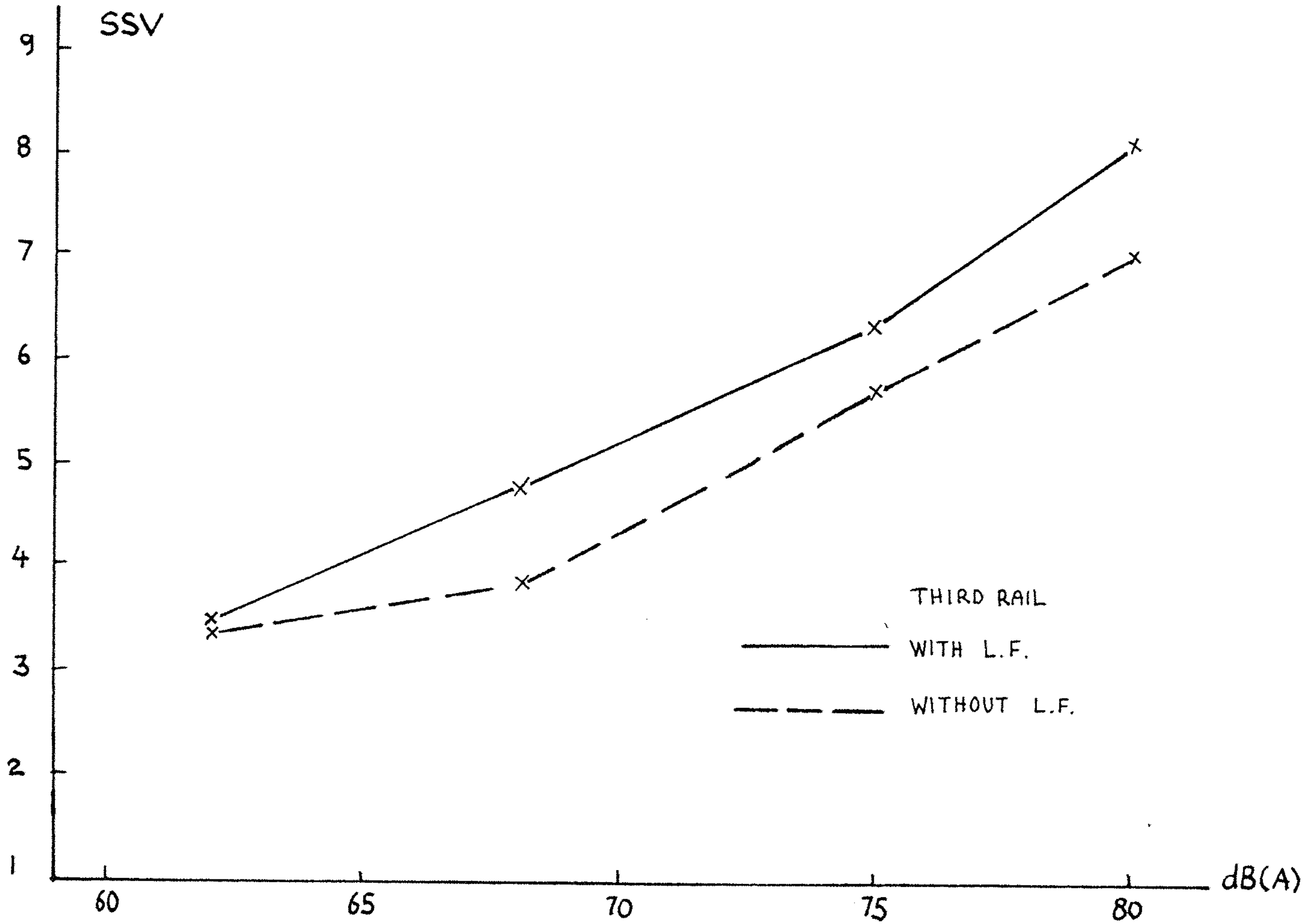



Figure 2.12 Relationship between subjective response and noise level

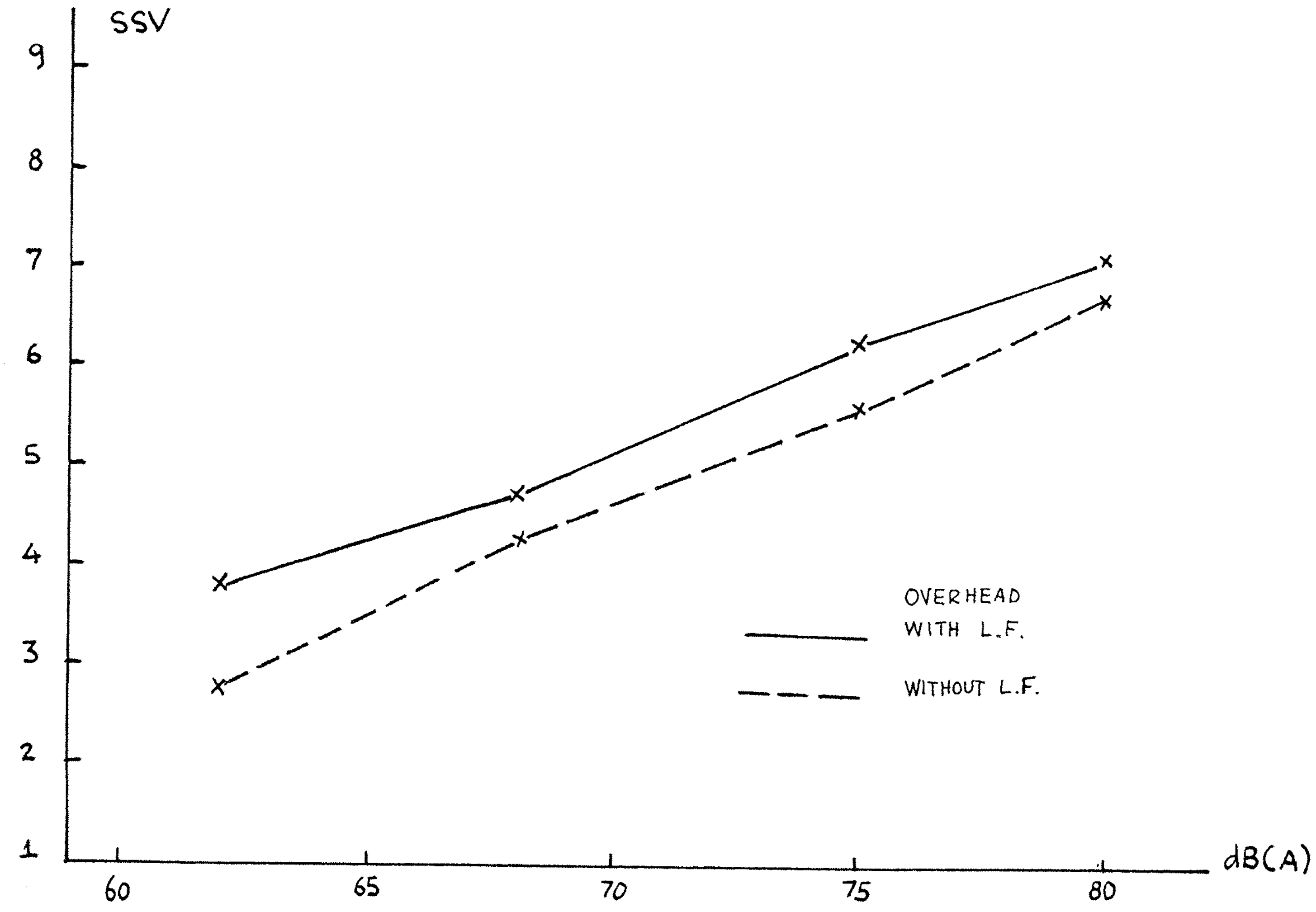



Figure 2.13 Relationship between subjective response and noise level

Table 2.2 Analysis of variance (Laboratory study I)

| Source of variation | D.F. | S.S. | M.S. | V.R. F ratio |
|---|---|---|---|---|
| Type | 2 | 76.260 | 38.130 | 32.078*** |
| Level | 3 | 1226.768 | 408.923 | 344.018*** |
| Frequency | 1 | 105.918 | 105.918 | 89.107*** |
| Type-level | 6 | 19.934 | 3.322 | 2.795* |
| Type-frequency | 2 | 11.212 | 5.606 | 4.716*** |
| Level-frequency | 3 | 2.602 | 0.867 | 0.730 NS |
| Type-level-frequency | 6 | 13.205 | 2.201 | 1.851 NS |
| Residual | 529 | 628.805 | 1.189 | |
| Total | 552 | 2084.705 | 3.777 | |
| Grand total | 575 | 2753.855 | 100.000 | |

Grand mean: 5.516

Total number of observations: 576

*** : Significant at 1% level
* : Significant at 5% level
NS : Non-significant

The means

| Type | 80 dB(A) With L.F. | 80 dB(A) Without L.F. | 75 dB(A) With L.F. | 75 dB(A) Without L.F. | 65 dB(A) With L.F. | 65 dB(A) Without L.F. | 62 dB(A) With L.F. | 62 dB(A) Without L.F. |
|---|---|---|---|---|---|---|---|---|
| Diesel | 8.208 | 6.958 | 7.583 | 6.667 | 6.083 | 4.292 | 4.667 | 3.625 |
| Third rail | 8.208 | 7.083 | 6.458 | 5.792 | 4.833 | 3.917 | 3.458 | 3.375 |
| Over-head | 7.083 | 6.667 | 6.250 | 5.625 | 4.708 | 4.292 | 3.792 | 2.740 |

L.F.: low frequencies.

Linear regressions

| | Slope | Intercept | S.E. | r |
|---|---|---|---|---|
| Diesel with L.F. | 0.199 | -7.598 | 0.213 | 0.994 |
| Diesel without L.F. | 0.206 | -9.296 | 0.524 | 0.967 |
| Third rail with L.F. | 0.257 | -12.597 | 0.255 | 0.995 |
| Third rail without L.F. | 0.212 | -10.087 | 0.395 | 0.982 |
| Overhead with L.F. | 0.188 | -7.905 | 0.126 | 0.998 |
| Overhead without L.F. | 0.215 | -10.462 | 0.133 | 0.998 |

Table 2.3 Table of means and interactions (Laboratory study I)

Grand mean: 5.516

| | | | | |
|---|---|---|---|---|
| Type | 1 (Diesel) | 2 (Third-rail) | 3 (Overhead) | |
| | 6.010 | 5.391 | 5.146 | |
| Level | 1 (80 dB(A)) | 2 (75 dB(A)) | 3 (68 dB(A)) | 4 (62 dB(A)) |
| | 7.368 | 6.396 | 4.688 | 3.611 |
| Frequency | with L.F. | without L.F. | | |
| | 5.944 | 5.087 | | |

Interactions

| Level<br>Type | (1) 8) dB(A) | (2) 75 dB(A) | (3) 65 dB(A) | (4) 62 dB(A) |
|---|---|---|---|---|
| (1) Diesel | 7.583 | 7.125 | 5.187 | 4.146 |
| (2) Third-rail | 7.646 | 6.125 | 4.375 | 3.417 |
| (3) Overhead | 6.875 | 5.937 | 4.500 | 3.271 |

| Frequency<br>Type | (1) with L.F. | (2) without L.F. |
|---|---|---|
| (1) Diesel | 6.635 | 5.385 |
| (2) Third-rail | 5.740 | 5.042 |
| (3) Overhead | 5.458 | 4.833 |

| Frequency<br>Level | (1) with L.F. | (2) without L.F. |
|---|---|---|
| (1) 80 dB(A) | 7.833 | 6.903 |
| (2) 75 dB(A) | 6.764 | 6.028 |
| (3) 68 dB(A) | 5.208 | 4.167 |
| (4) 62 dB(A) | 5.972 | 3.250 |

Standard error of differences of means

| | Type | Level | Freq. | Type<br>Level | Type<br>Freq. | Level<br>Freq. | Type<br>Level<br>Freq. |
|---|---|---|---|---|---|---|---|
| Rep. | 192 | 144 | 288 | 48 | 96 | 72 | 24 |
| Sed. | 0.1113 | 0.1285 | 0.0909 | 0.2225 | 0.1574 | 0.1817 | 0.3147 |

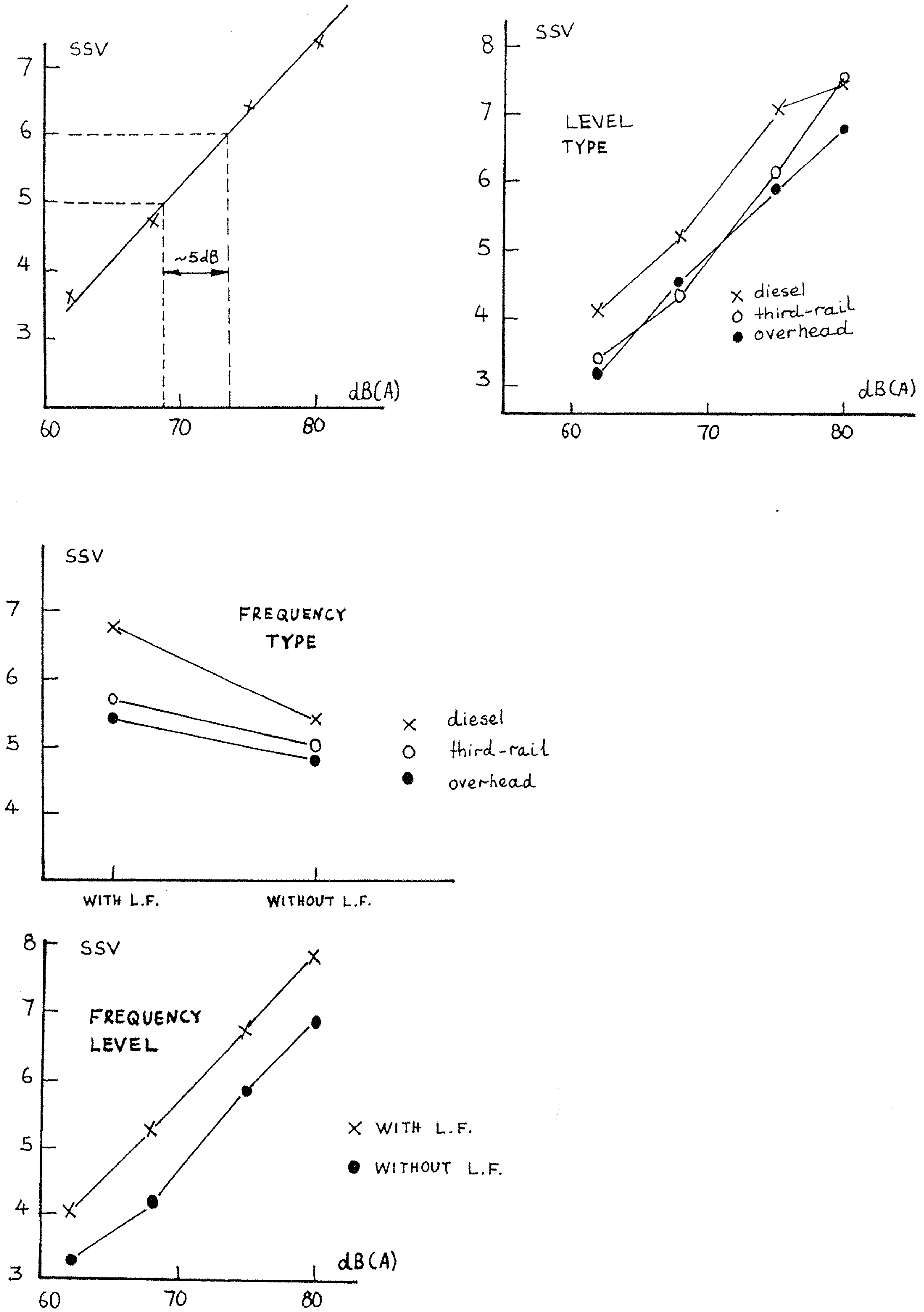



Figure 2.14 Graphs of the interactions of laboratory study I

In the laboratory study the difference found in the reaction between the diesel and the overhead electric is due to the spectral differences of the two noises. However, when comparing the diesel and the third-rail, one would expect both types of cause similar reaction due to their similarity in the noise spectra. But the diesel was found to be more annoying than the third-rail electric by a significant amount. The difference in terms of subjective scale value was approximately 5 dB. Perhaps the best way to grasp the significance of the difference is to take a single annoyance level and to determine the noise level at which each of the traction types causes the same amount of annoyance. This was done for an annoyance score of 7. This annoyance score is reached for a diesel at 74 dB(A) and for the third rail and overhead at 78 and 79 dB(A) respectively, some 5 dB higher than for the diesel trains. The fact that the diesel was more annoying than the third rail cannot be explained in terms of the low frequency noise which is present. There must be an additional factor associated with the diesel trains which caused the difference in the response.

## 2.8 Linear against A-weighting

### Noise index

An ideal noise index would give the same subjective response for a given level of noise from any source, no matter what the tempmoral and frequency characteristics. It has been found that peak dB(A) correlates well with subjective response to railway noise [2.21, 2.22]. Therefore it was decided that the peak dB(A) associated with the train pass-by should be used here to describe the physical stimulus.

However, an investigation was also carried out to examine how the A-weighting compares with the un-weighted (linear) maximum level in describing the subjective response.

Graphs were plotted showing the relationship between subjective response and noise level for both A-weighting and linear measures (see Figures 2.15, 2.16).

It can be observed that when the noise levels are expressed in linear terms, both the diesel and third rail electric have moved to the right towards the higher levels, while the overhead electric has remained constant. This was expected due to the high levels of low frequency noise associated with the diesel and third-rail electric which were ignored by the A-weighting.

Perhaps the most important observation is that expressing the noise in A-weighting and linear level had no effect on the difference between the diesel and third-rail electric, which has remained constant.

Estimates of the correlation coefficient for all three types of trains for each case were compared. It was found that A-weighting resulted in a correlation coefficient $r = 0.934$, where the linear resulted in a higher coefficient of correlation, $r = 0.974$.

If one has two independent estimates of a correlation coefficient, and wishes to test whether they differ significantly, it is very difficult to get a reliable answer when the size of the sample is small (< 100). However, for most practical applications it is safe to transform to z values ($z = 1.15 \log (1 + r/1 - r)$) [2.23], and refer the difference of these values to the standard error of their difference, namely,

$$\sqrt{\frac{1}{N_1 - 3} + \frac{1}{N_2 - 3}}$$

For the A-weighting $r$ is 0.934 and $z$ is 1.687, where for the linear, $r$ is 0.974 and $z$ is 2.162.

The difference between the z values is $2.162 - 1.687 = 0.475$. The standard error of the difference is

$$\sqrt{\frac{1}{9} + \frac{1}{9}} = 0.471.$$

Since the difference is almost equal to one standard error, it could be significant. However, due to the small size of the sample it is difficult to state whether this difference in the correlation coefficients of A-weighting and linear is important.

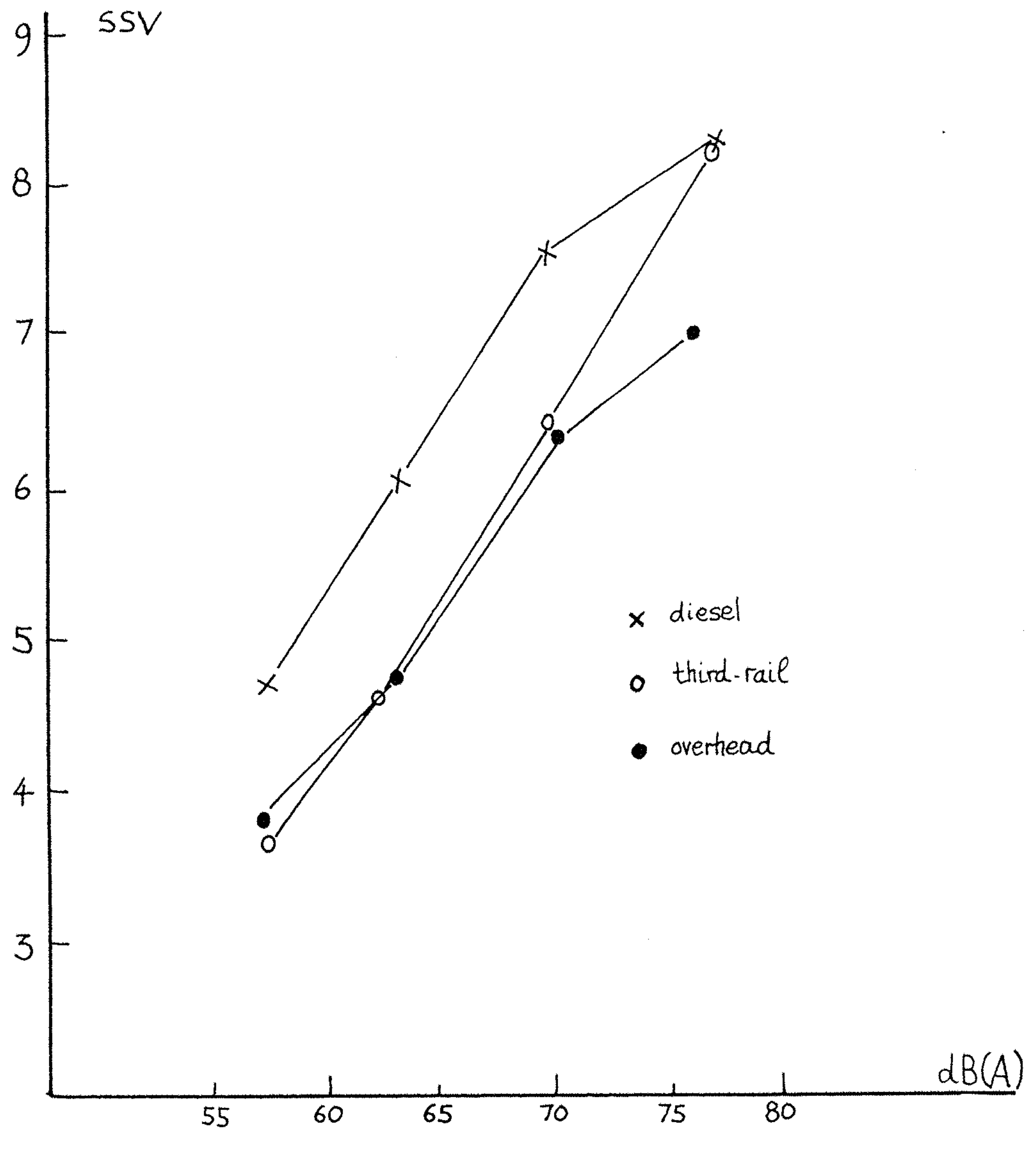



Figure 2.15 Relationship between subjective response and noise level

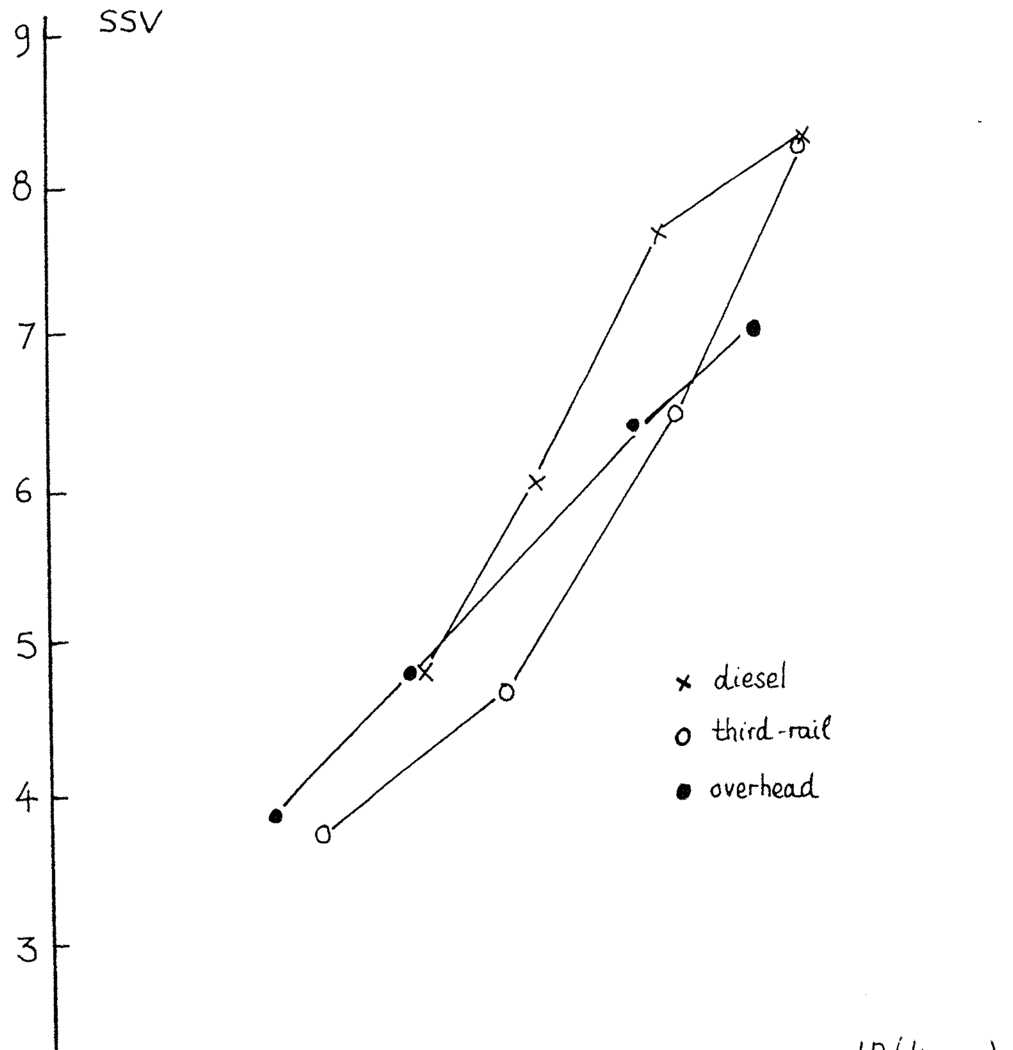



**Figure 2.16 Relationship between subjective response and noise level**

From the results of this laboratory study it was found that the diesel trains were subjectively more annoying than third-rail electric trains, both at the same dB(A) and dB(linear) levels. As far as the frequency content of the two noises is concerned, it was found that both have similar one-third octave band frequency spectra. This implied that the shape and the level of the frequency spectrum did not include the acoustical factors which were responsible for the difference in the subjective response. Thus there was nothing to be gained from using a different frequency weighting other than dB(A) for expressing the noise levels.

Also it was desirable throughout the study for the descriptor of the physical stimuli to remain constant, to enable more meaningful comparison between subjective responses.

It was for these reasons that the dB(A) scale was used for expressing the noise levels throughout this study.

## 2.9 Conclusions

The main conclusions from this part of the study are:

1. The noise from diesel trains is more annoying than noise from electric trains. The difference in terms of subjective scale value was approximately 5 dB.

2. The annoyance of all three types of train investigated was greatest with high levels of low frequency noise below 250 Hz present.

Although the diesel was more annoying than the third-rail electric, both types display a remarkable similarity as far as the one-third octave spectra is concerned. This was to be the subject of the next laboratory study.

# 3. LABORATORY INVESTIGATION OF THE DIFFERENCE IN ANNOYANCE BETWEEN DIESEL AND THIRD-RAIL ELECTRIC TRAINS

## 3.1 Introduction

It has been found in the work described in the earlier chapters that the level of the low frequency noise below 250 Hz failed to correlate with subjective response in attempting to establish the annoyance due to diesel and third-rail electric trains. Possible explanations could be: (a) the engine peak in the time history of the diesel train, (b) the fine structure of the low frequency region of the noise not observable in the one-third octave spectra.

In the laboratory study which followed it was decided that this time the subject's attention was going to be drawn to two aspects of the noise, i.e., (a) the time history and (b) the overall frequency spectrum. This was achieved by using synthesized sounds. Tests were carried out to ascertain whether the spectrum of the noise is constant during a pass-by (see Section 3.3). The synthesized sounds used in the laboratory were designed in line with these findings. In the laboratory study synthesized train noises matched in overall spectrum and in time history with the real trains, and real trains of both traction types were judged by subjects for annoyance.

## 3.2 Narrow Band Analysis (0-200 Hz) of the Noise of the Two Types - Diesel and Third-rail Electric

It was thought that the fine structure of the low frequency noise of the two types of trains might contain acoustical information which could be significant in judging the annoyance.

An analysis was carried out in order to investigate this hypothesis. The low frequency region (0-200 Hz), which was previously identified as the part of the spectrum of the noise which correlated with subjective response, was investigated.

Recordings from the field data were acquired using the B & K narrow band analyser (type 2031) and plots of the 0-200 Hz region were made. The time constant and bandwidth were adjusted accordingly as explained in the previous chapter. The frequency spectra are shown in Figures 3.1, 3.2, 3.3 and 3.4. Two spectra are shown for each type; the first being just before the maximum level during the pass-by and the second during the maximum level. As can be observed, both types are similar. In the case of the diesel there is a peak at 35 Hz and one can also see the harmonic components. This could be related to the firing frequency of the engine. However, due to its relatively low level compared with the rest of the spectrum, its effect was thought at that time to be unimportant.

### 3.3 3-D Frequency Analysis

An investigation of the variation in the spectrum of the noise was carried out for the two types of traction, diesel and third-rail electric.

This was done by using a special algorithm for converting non-stationary spectra to stationary spectra [3.1]. The analysis was made using the computer in the Data Analysis Centre (DAC) at ISVR.

Due to limitations of the computer memory it was not possible to acquire the total length of the pass-by; instead, only 10 seconds were acquired. Plots of the variation of the spectrum with time are shown in Figures 3.5 and 3.6 for the two types of traction. The frequency range examined was from 25 Hz to 8 kHz.

It can be seen from the plots that for both types of train there is no significant variation of the spectrum of the noise with time during the pass-by. Thus it can be safely assumed that the spectrum of the noise remains constant throughout the whole pass-by.

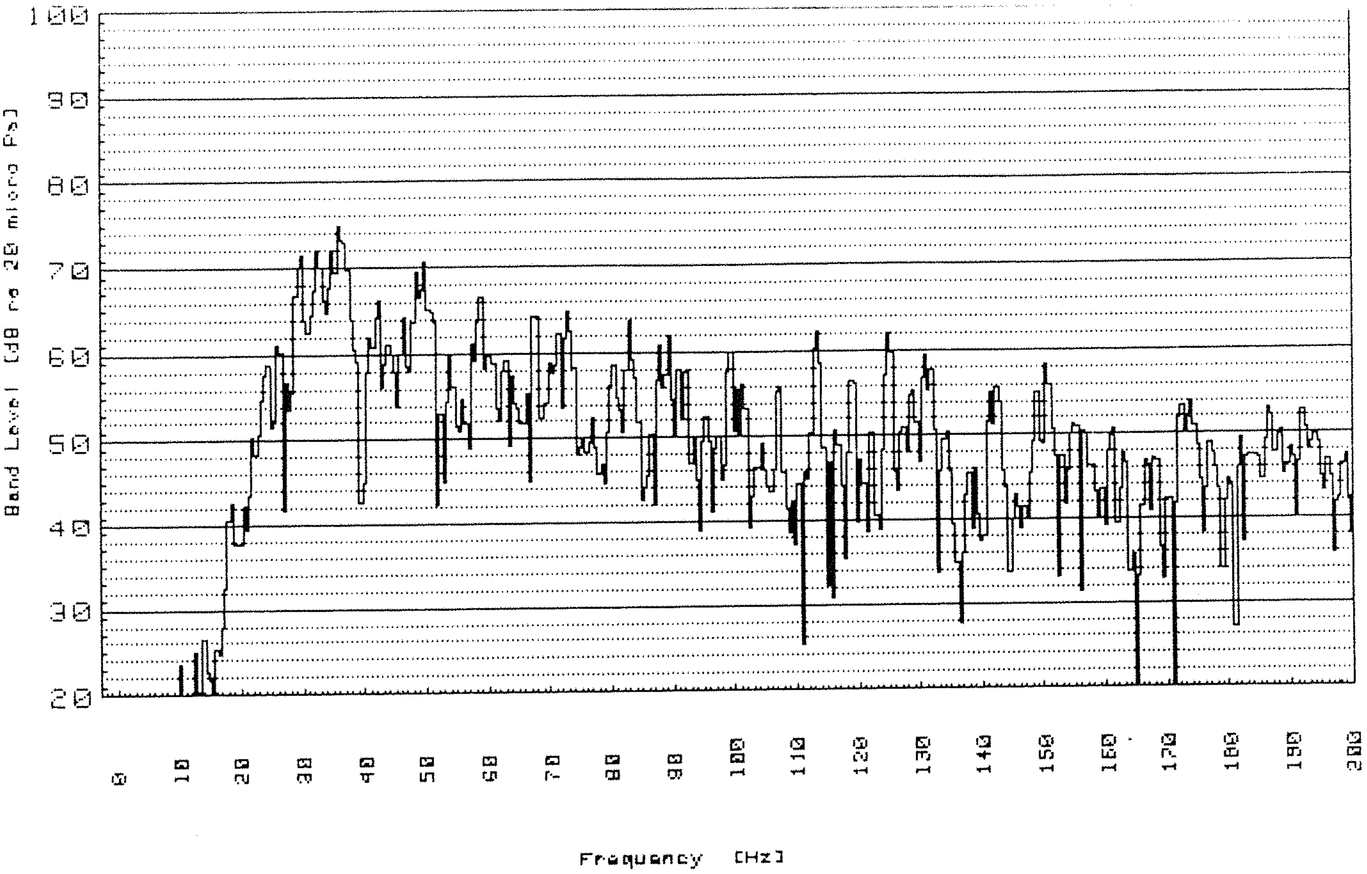



**Figure 3.1 Frequency spectrum just before maximum level (diesel)**

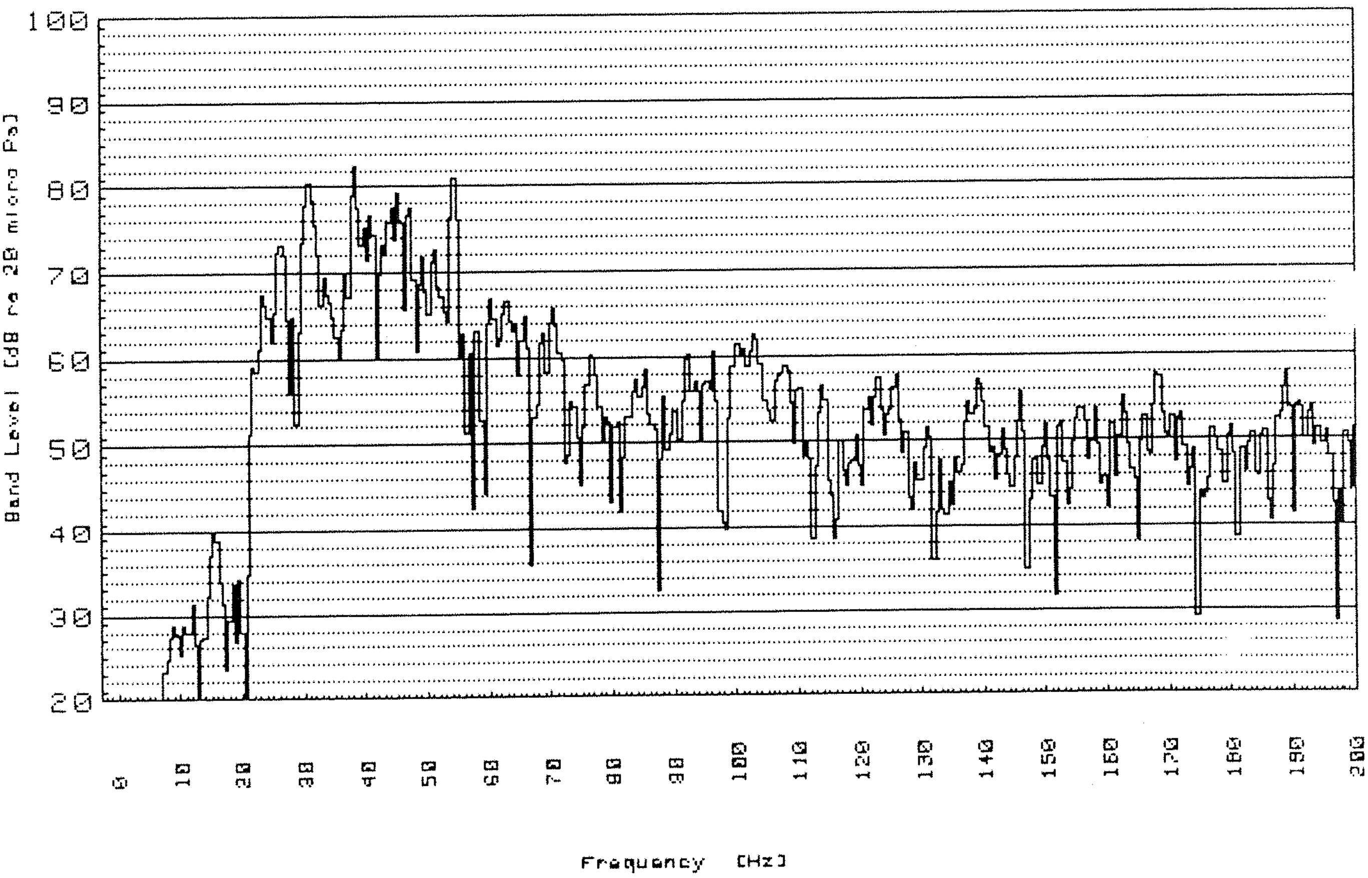



**Figure 3.2 Frequency spectrum just before maximum level (third-rail)**

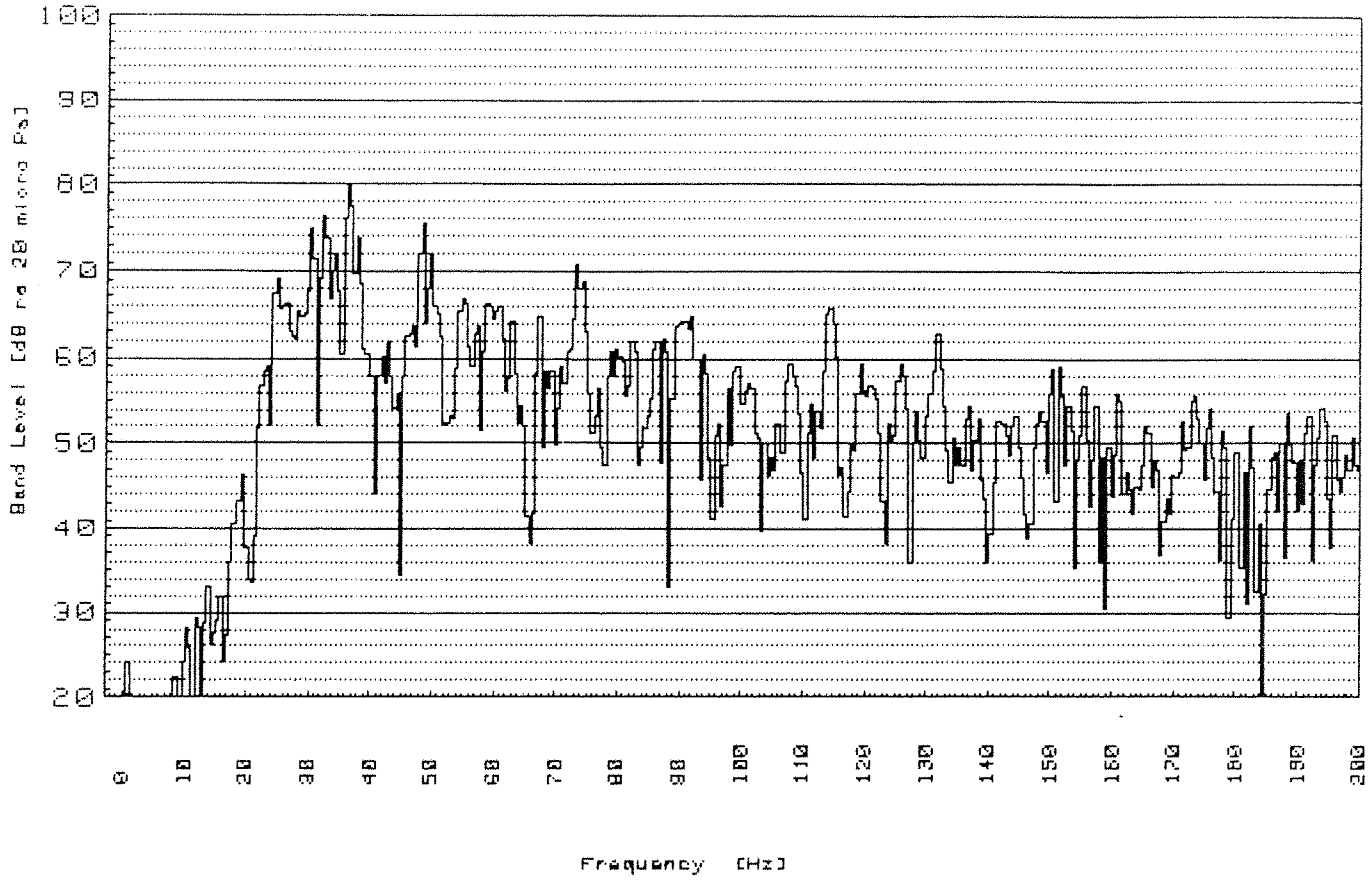



**Figure 3.3 Frequency spectrum at maximum level (diesel)**

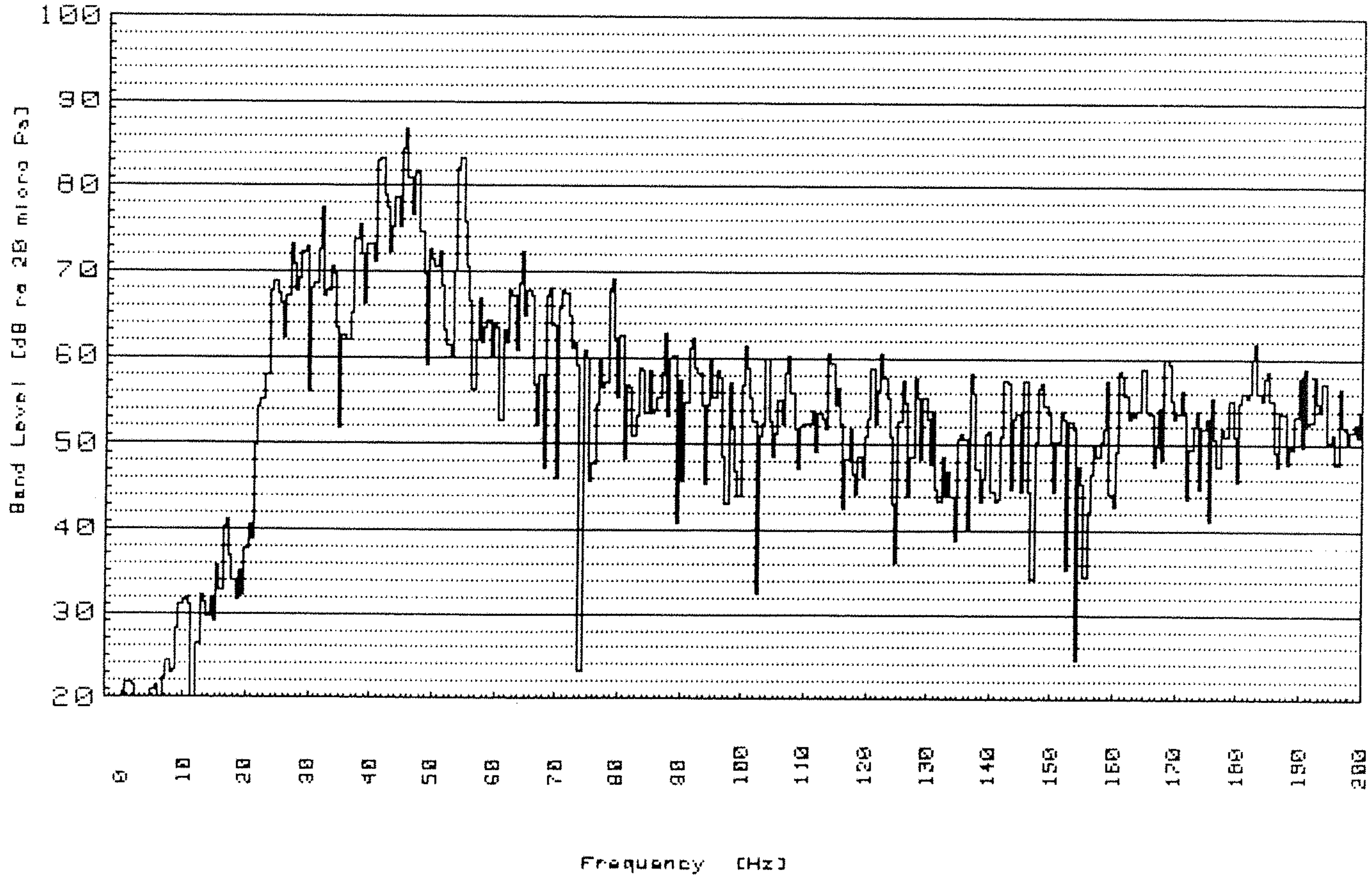



**Figure 3.4 Frequency spectrum at maximum level (third-rail)**

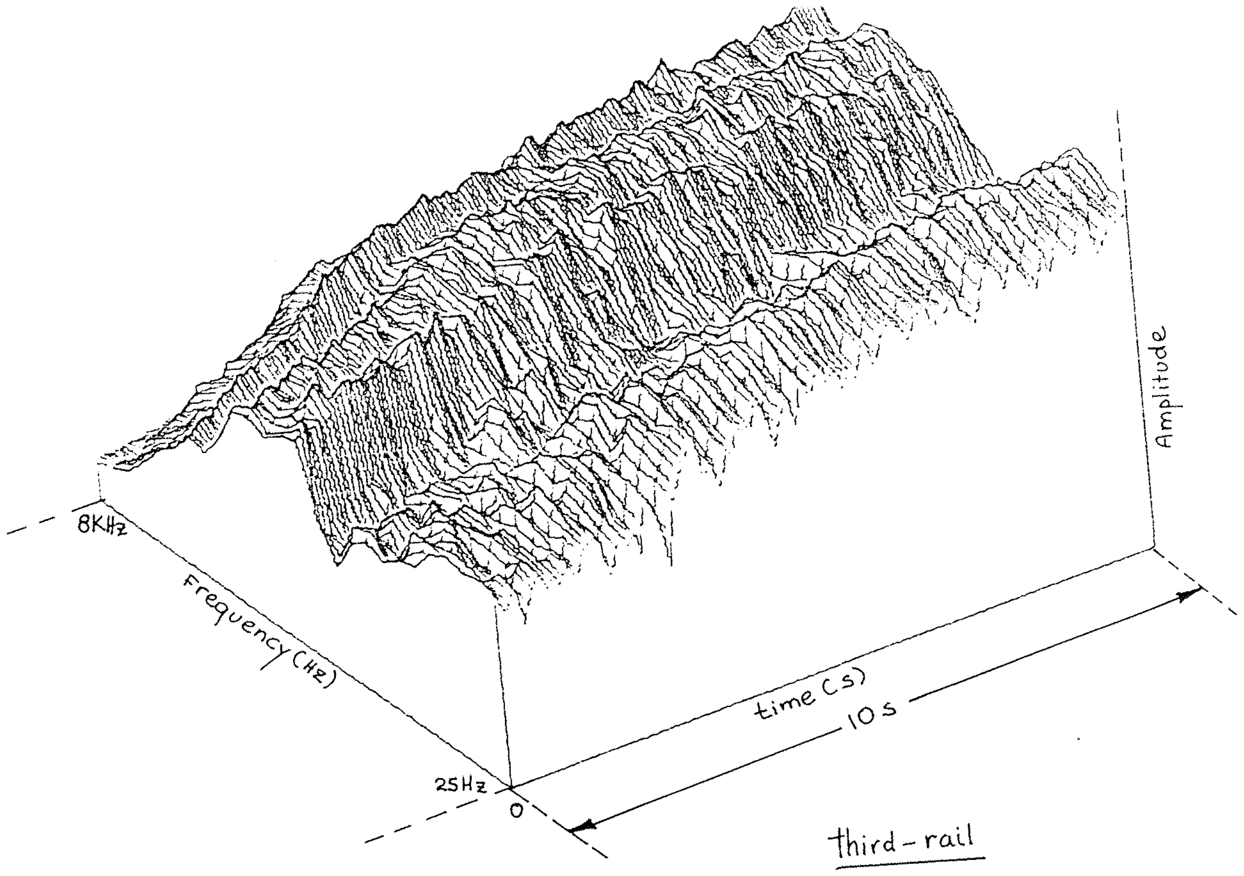



**Figure 3.5  Variation of spectrum with time - third rail electric**

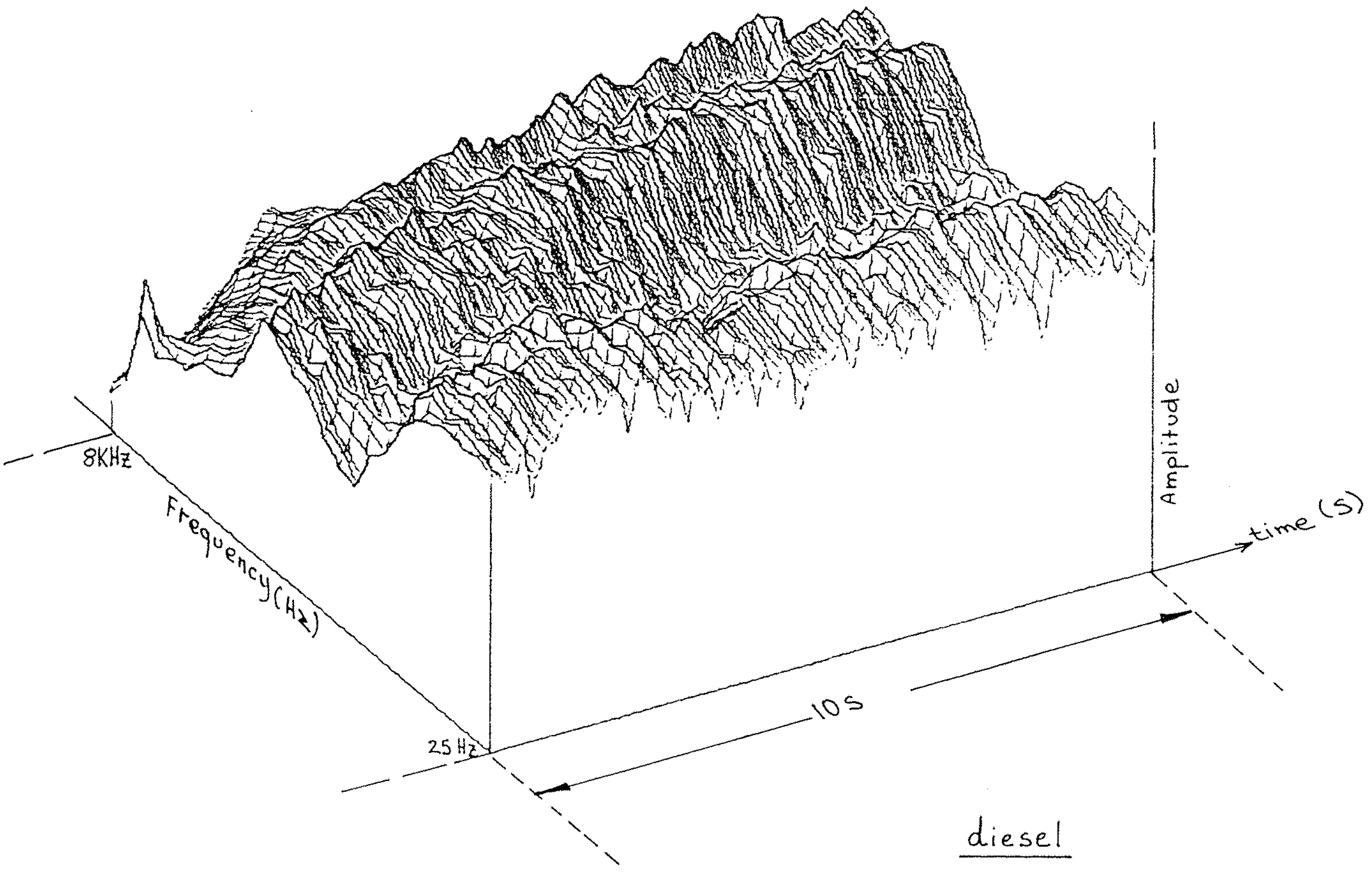



**Figure 3.6  Variation of spectrum with time - diesel**

### 3.4 Why Use Synthesized Noises?

Previously, various attempts were made in order to find acoustical differences between the two noises, which could correlate with the subjective differences found. So far the noises were examined in the frequency domain.,

The time domain should be the next area to be investigated. A difference concerning the time histories of the noises has already been found. In the case of the diesel trains, there was a peak in the time history associated with the diesel engine. which is typically 5-10 dB higher than the level of rail wheel noise. If the A-weighted time history were obtained, the peak would be greatly reduced. In order to examine the effect of the engine peak on the subjective response, a way of controlling the level of the peak should be devised. At this point it was desirable to think of a method to control the potentially important acoustical factors of the noises. Only then could the reasons for the subjective difference be identified. One way in which this could be done would be by using synthesized sounds [3.1].

As a first step it was decided to reproduce the time history and the one-third octave frequency spectra of the two types of train. This ensured that another possible difference in the subjective response could only be due to either the differences in the time history or the small variations in the frequency spectrum of the two noises.

### 3.5 Synthesizing the Noises

The synthesized train noise was obtained by varying the shaped output of a random noise generator using the time history of a real train pass-by. The shape of the output was according to the spectrum of the real noise.

An electronic circuit which could follow the envelope of the time history of the real train during the pass-by was required. The circuit used is known as "peak detector" and is shown in Figure 3.7. The simple circuit will detect peaks of increasing and decreasing amplitude. The R-C combination determines the time constant of the circuit. It was found that

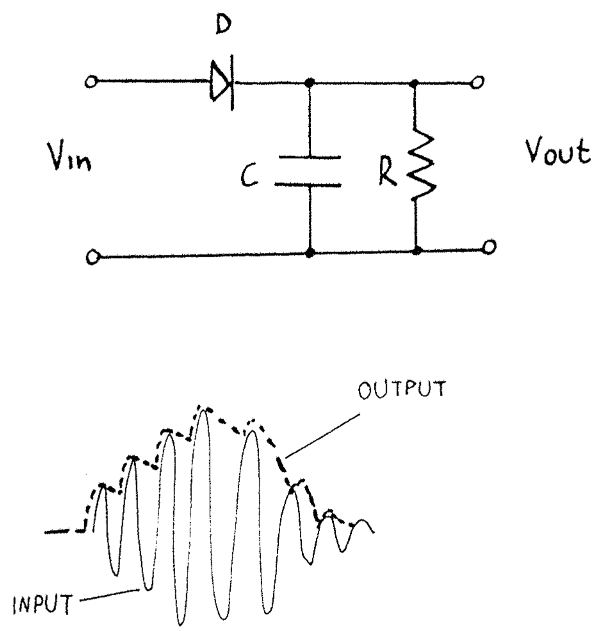



Figure 3.7 Simple diode detector

for accurate reproduction of the time history of the noise a time constant of approximately 40 ms was needed.

In order to make the output of the random noise generator vary according to the time history of the real train, an analogue multiplier was used. Figure 3.8 shows in block diagram the equipment used to produce the synthesized noises. Figure 3.9 shows the time histories of both types for real and synthesized noises. In the case of the diesel, the engine peak was greatly reduced when the electrical signal was passed through an A-weighted filter.

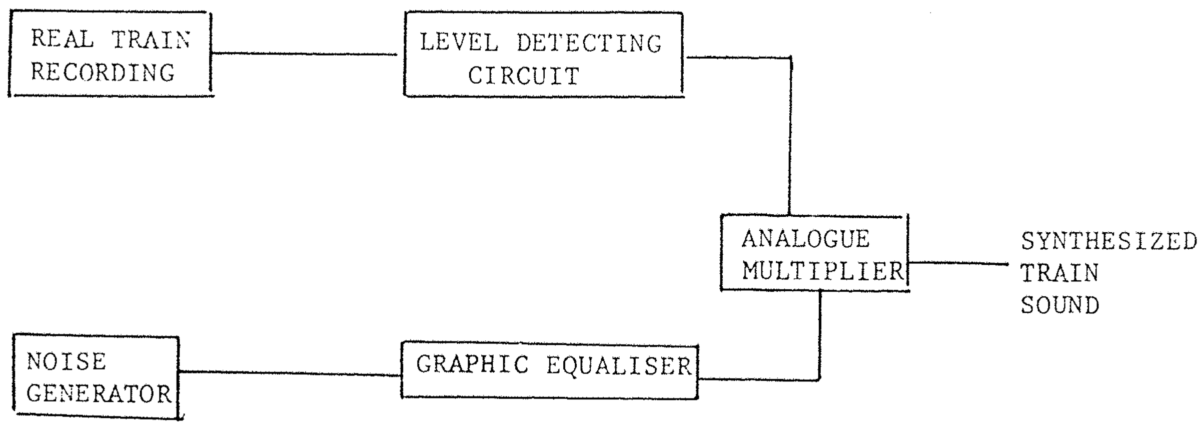



Figure 3.8 Synthesis of train noise

## 3.6 Laboratory Investigation II

### The experiment

The aim of this experiment was to investigate whether the differences in the time history and the frequency spectra between the two types of trains (diesel and third-rail electric) were subjectively important. By using synthesized sounds it was possible to examine these two aspects of the noise in isolation. Actual train recordings of the two types, (denoted as 'real' trains) were also used in the experiment for comparison. In order to investigate the low frequency part of the spectrum of the two noises in more detail, three frequency contents were examined. The following conditions were investigated:

1. 2 types of noise (real, synthesized)
2. 2 types of train (diesel, third-rail electric)
3. 3 frequency contents (linear and using a high pass filter with cut-off frequencies at 160 Hz and 50 Hz with rate of attenuation

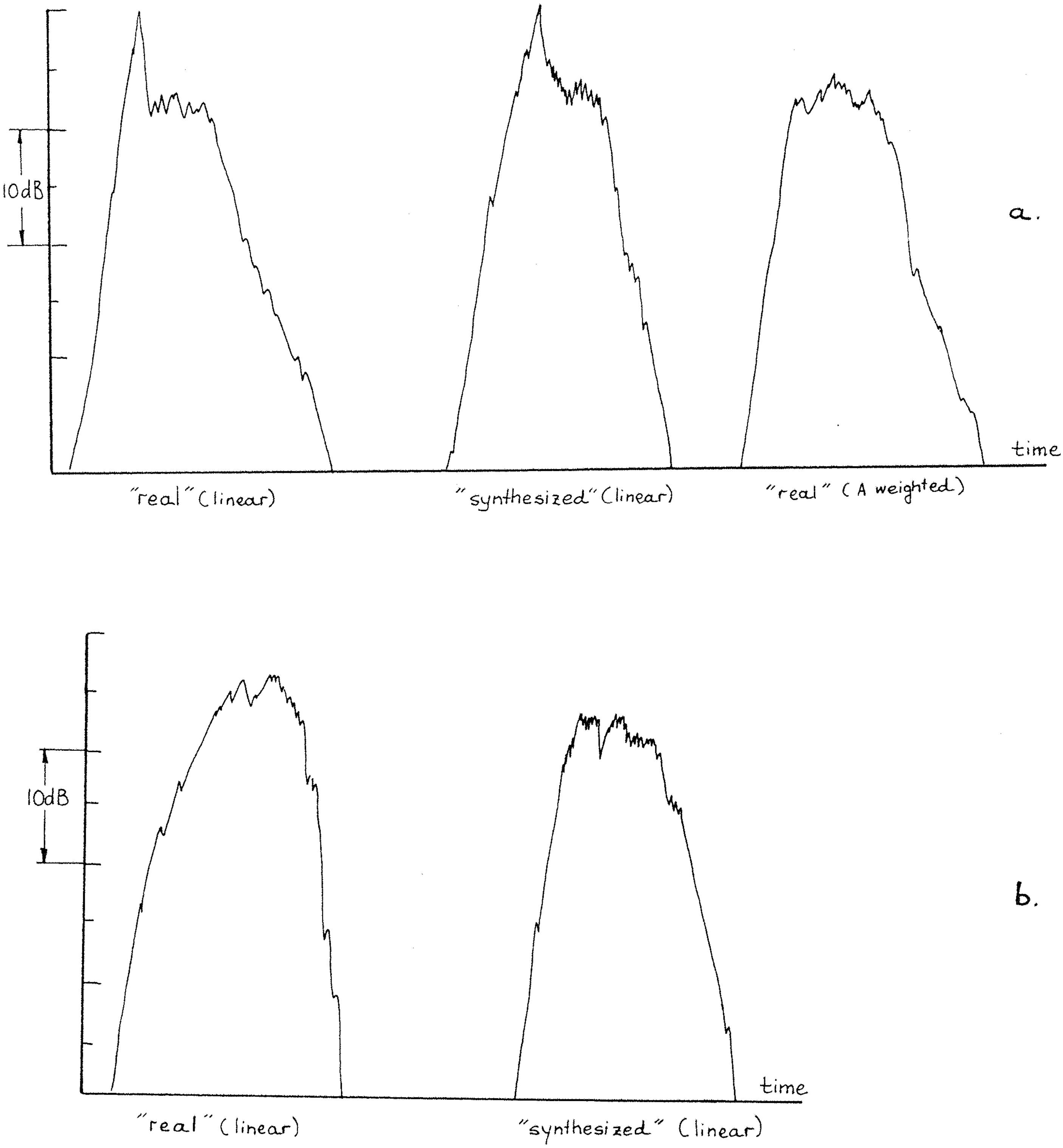



Figure 3.9 Time histories of real and synthesized sounds
(a) diesel (b) third-rail

24 dB/octave). Figure 3.10 shows the effect of the three frequency contents in the spectrum of a diesel train as it was actually heard in the laboratory.

4. 4 noise levels (75, 70, 65, 60 dB(A)).

These factors resulted in a 48 × 48 factorial design (2 × 2 × 3 × 4 = 48). In a normal factorial experiment the number of conditions should equal the number of subjects. In this experiment 24 subjects were used with each subject listening to all 48 conditions. 24 tapes were prepared containing pairs of pass-bys. The pairs were randomised and a 24 × 24 balanced Latin square design was used to present the 24 different pairs of noises to 24 subjects. It was decided that the order of the two conditions contained in a single pair was not important. The total time taken for the 24 pairs of noises to be presented was 1.5 hours.

## 3.7 Analysis of Results

The subjective response scores of each subject were recorded and can be seen in Appendix 5. An average response score was obtained for each presentation and the results were plotted (see Figures 3.11, 3.12 and 3.13). The graphs show subjective response against noise level measured in dB(A). The results were analysed by an analysis of variance method (see Tables 3.1 and 3.2).

Variance ratio tests revealed that the differences observed between class, type, frequency and level were highly significant. Also highly significant at 1% level were the interactions of level with class and type with class. The important interactions were plotted and are shown in Figures 3.14 and 3.15.

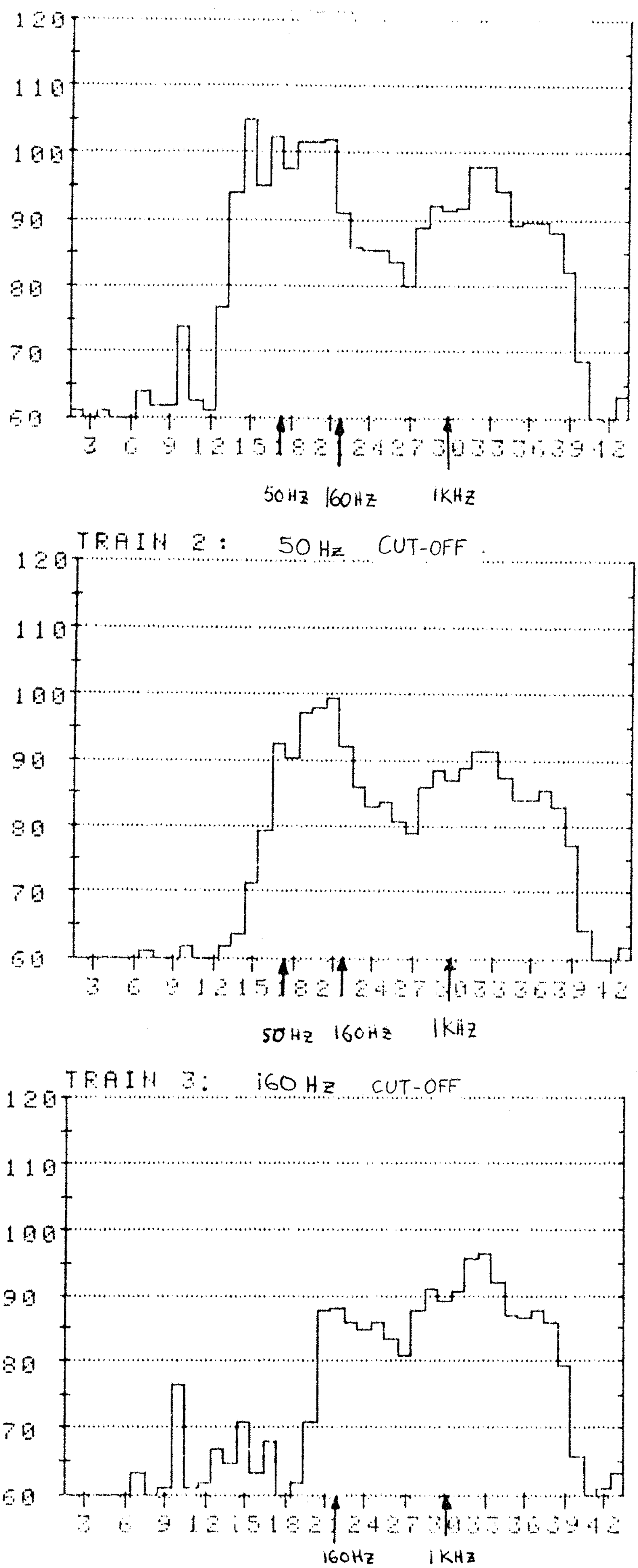
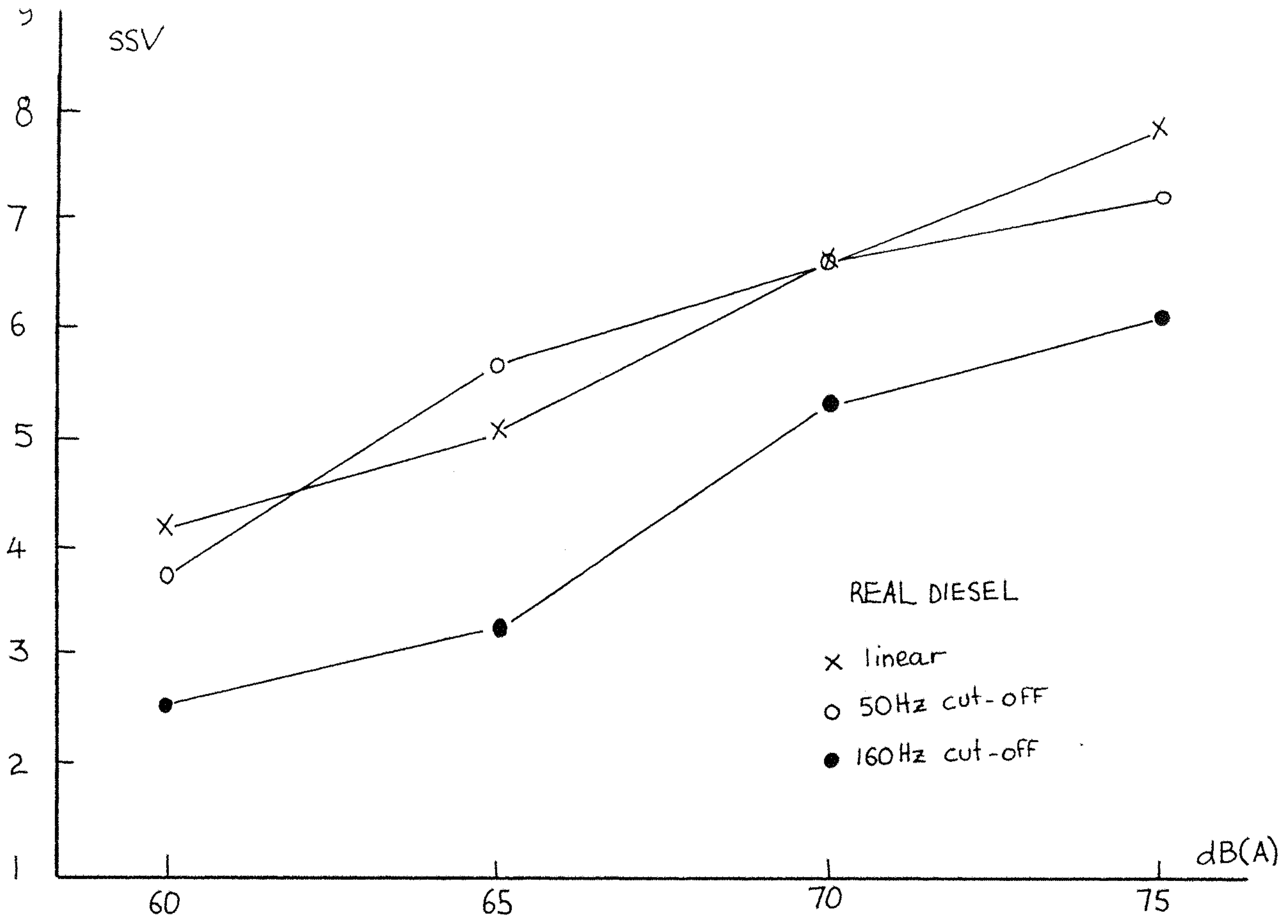



**Figure 3.10 Frequency spectrum of a diesel at linear, 50 Hz cut-off and 160 Hz cut-off**



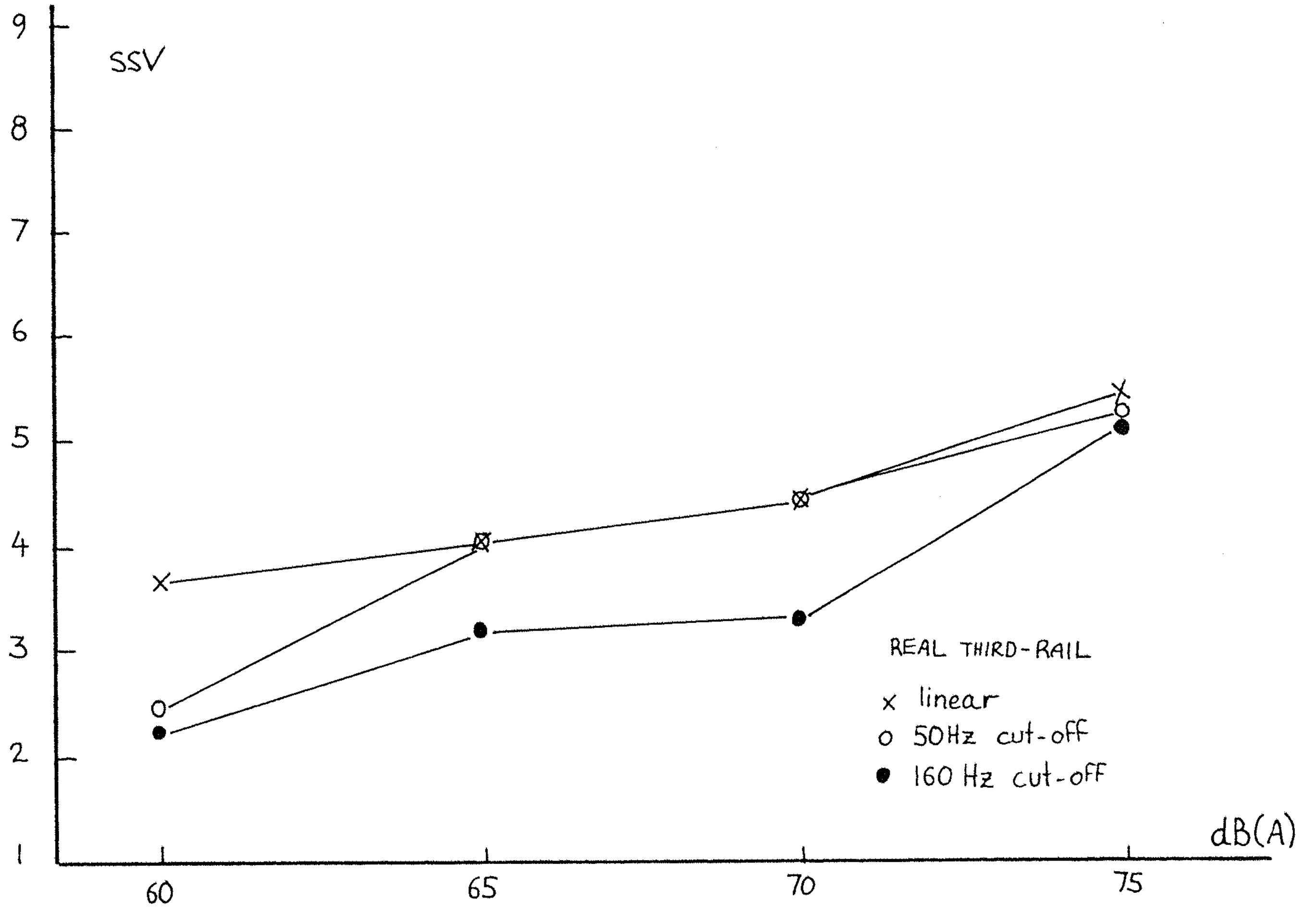
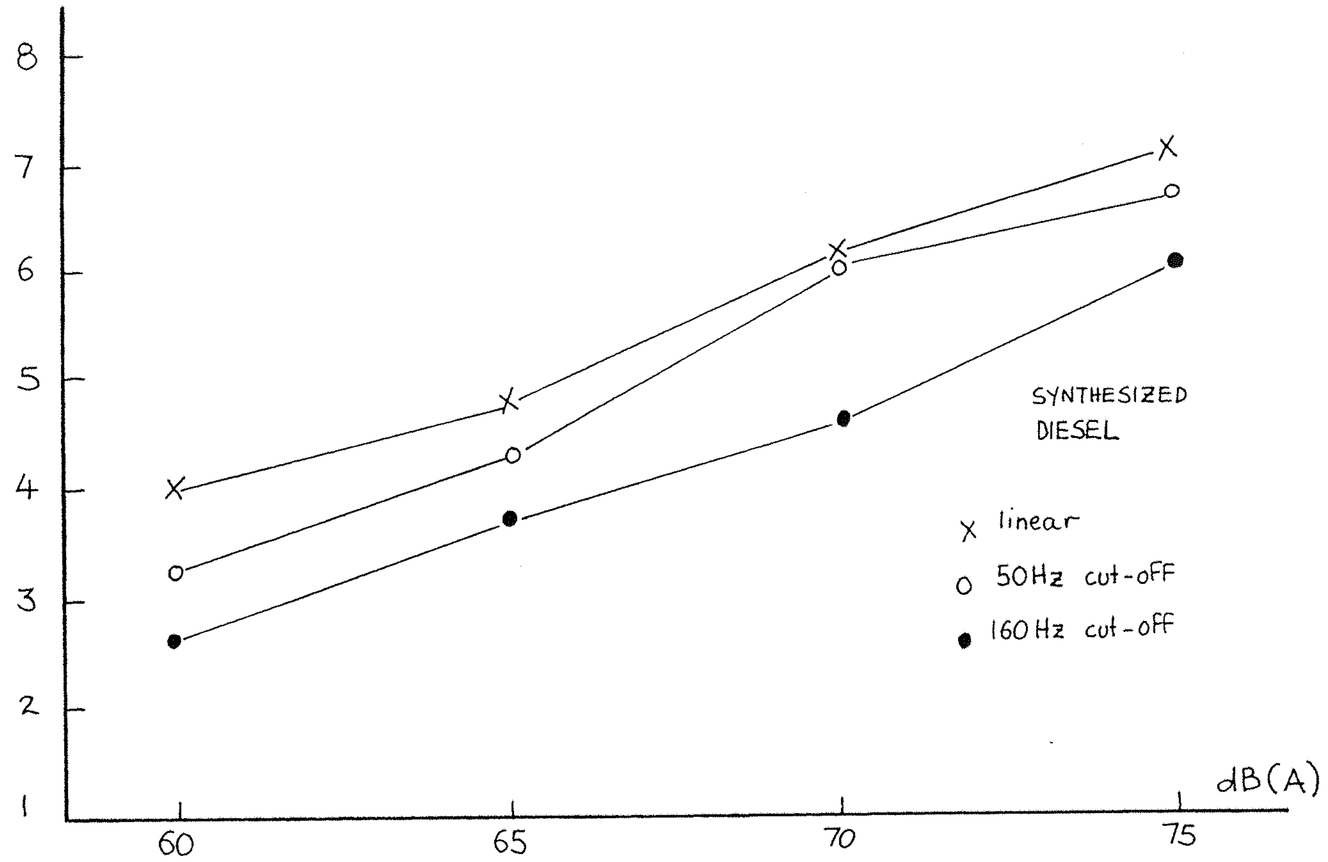




**Figure 3.11 Relationship between subjective response and noise level**



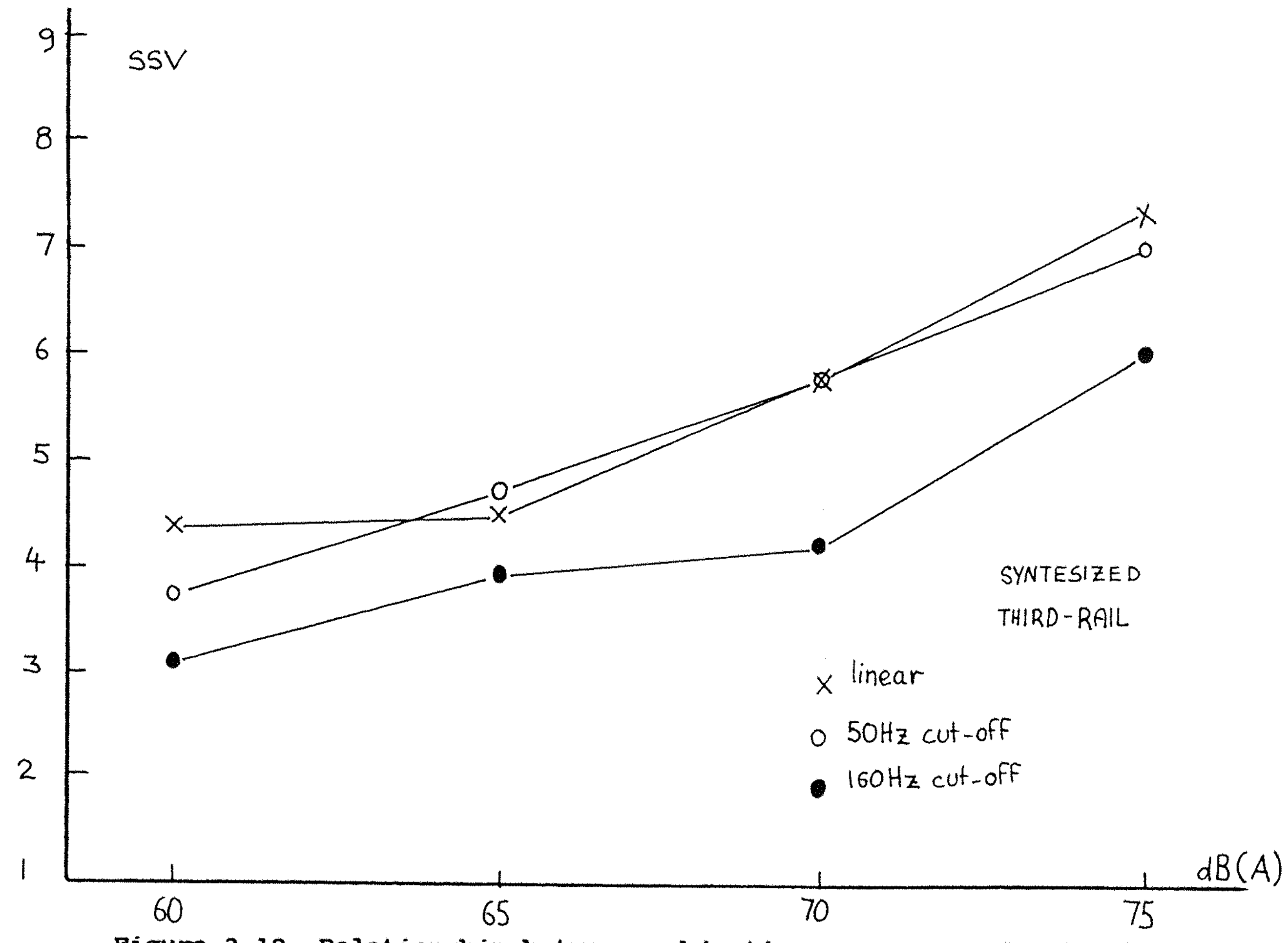




**Figure 3.12 Relationship between subjective response and noise level**

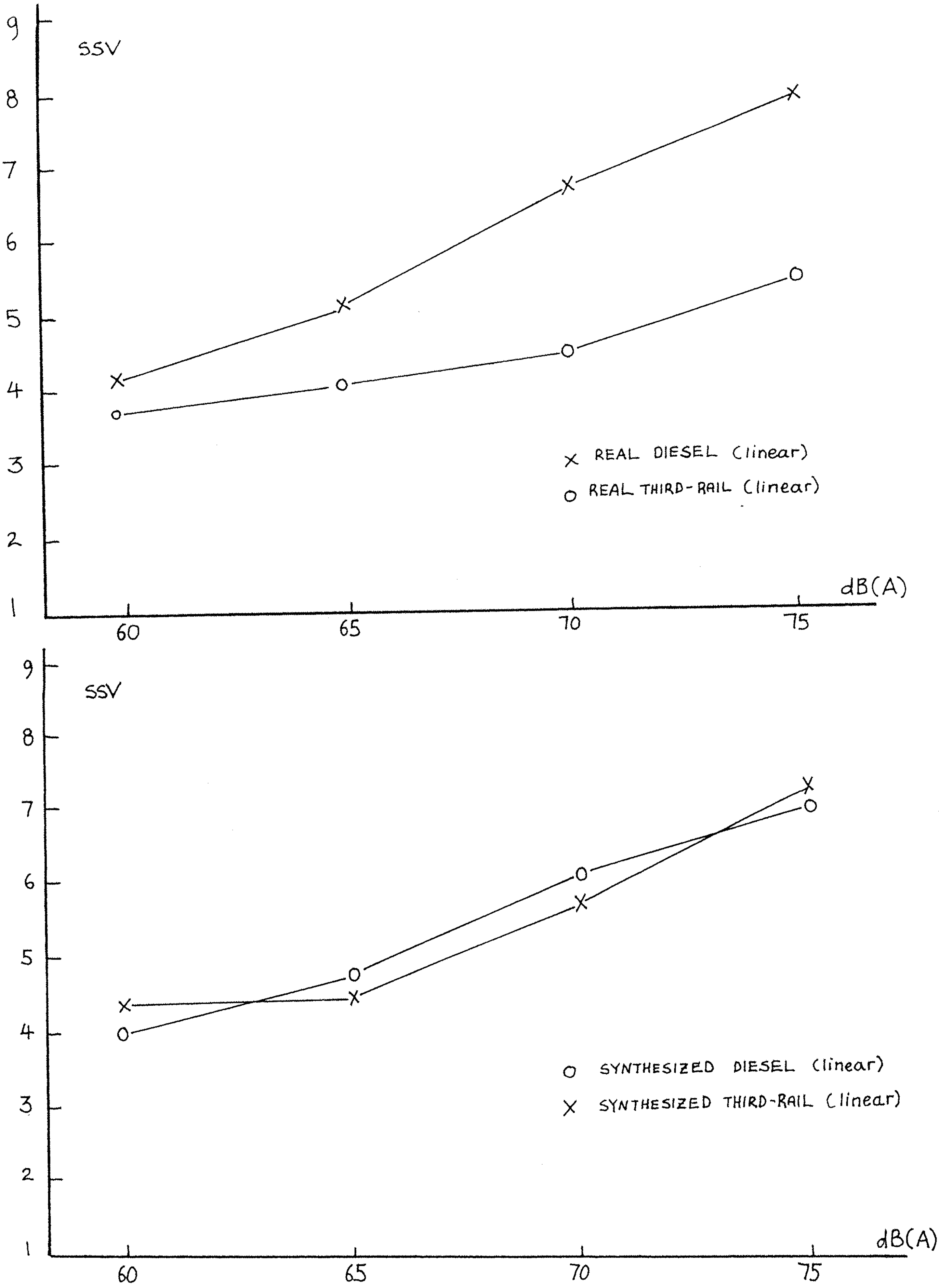



**Figure 3.13 Relationship between subjective response and noise level**

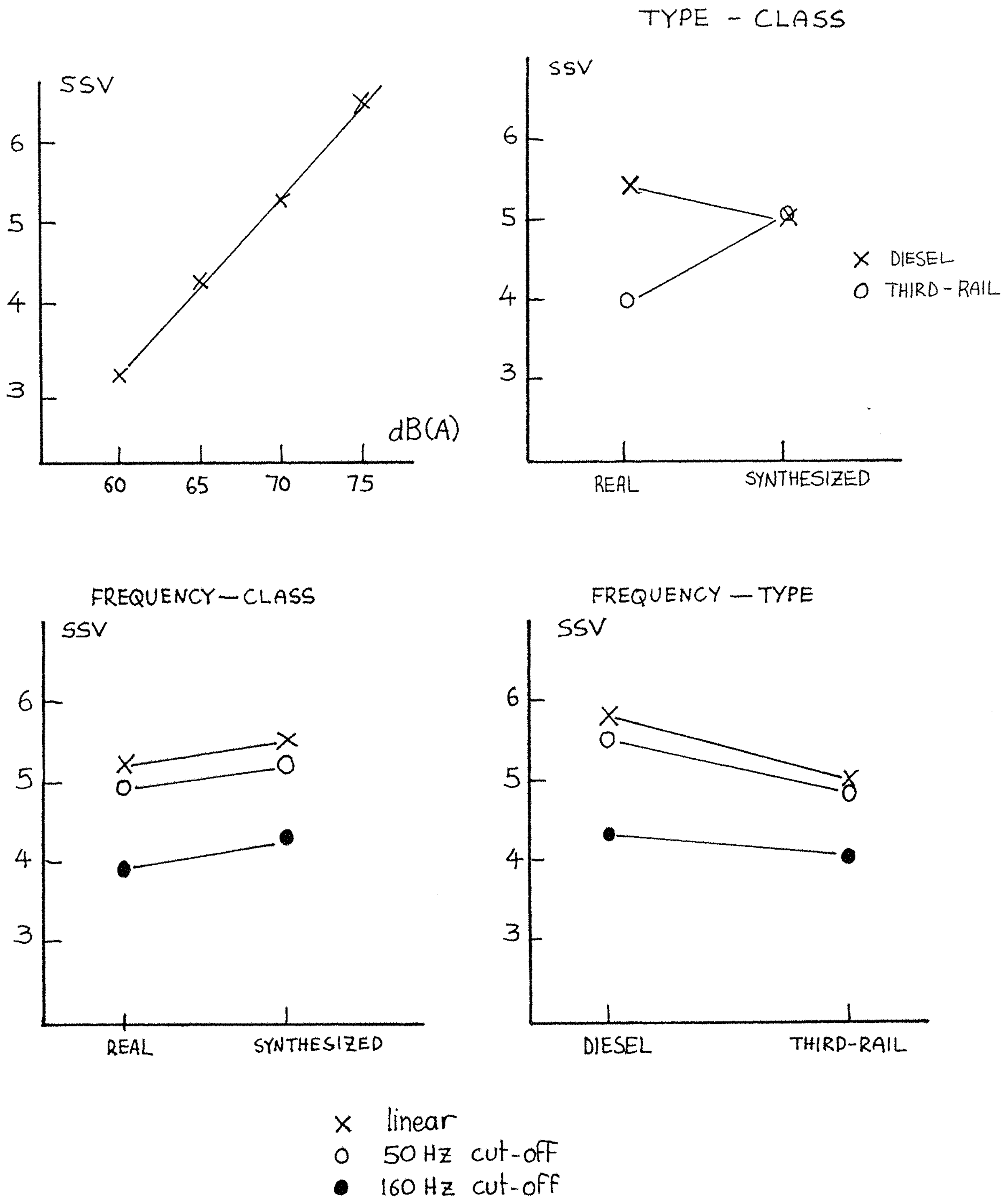



**Figure 3.14 Interactions of laboratory study II**

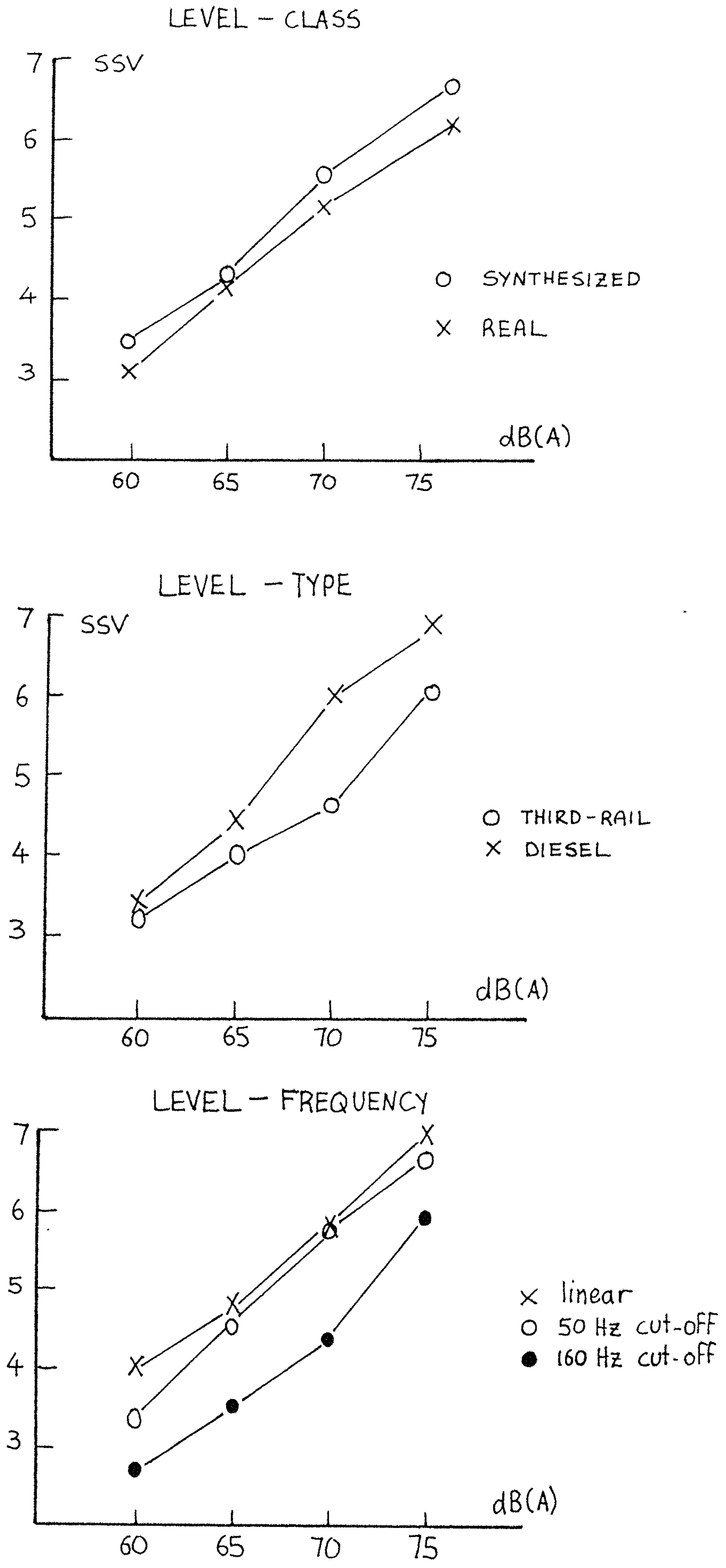



**Figure 3.15 Interactions of laboratory study II**

Table 3.1 Analysis of variance – Laboratory study II

| Source of variation | D.F. | S.S. | M.S. | V.R. |
|---|---|---|---|---|
| Subject | 23 | 1378.596 | 59.939 | 45.052 *** |
| Class | 1 | 27.813 | 27.813 | 20.905 *** |
| Type | 1 | 126.008 | 126.008 | 94.712 *** |
| Frequency | 2 | 330.671 | 165.336 | 124.272 *** |
| Level | 3 | 1566.896 | 522.299 | 392.578 *** |
| Class-type | 1 | 156.792 | 156.792 | 117.850 *** |
| Class-frequency | 2 | 0.273 | 0.136 | 0.102 N.S. |
| Type-frequency | 2 | 11.849 | 5.924 | 4.453 |
| Class-level | 3 | 4.496 | 1.499 | 1.126 N.S. |
| Type-level | 3 | 54.301 | 18.100 | 13.605 *** |
| Frequency-level | 6 | 19.516 | 3.253 | 2.445 * |
| Class-type-frequency | 2 | 14.970 | 7.485 | 5.626 *** |
| Class-type-level | 3 | 11.628 | 3.876 | 2.913 N.S. |
| Class-frequency-level | 6 | 11.637 | 1.940 | 1.458 N.S. |
| Type-frequency-level | 6 | 19.977 | 3.330 | 2.503 * |
| Residual | 1087 | 1446.182 | 1.330 | |
| Total | 1128 | 3803.008 | 3.371 | |
| Grand total | 1151 | 5181.602 | | |

*** : Significant at 1% level
* : Significant at 5% level
N.S.: Non-significant

Table 3.2 Interactions - Laboratory study II

Grand mean: 4.582

| | | | | |
|---|---|---|---|---|
| Class | 1 (real) | 2 (synthesized) | | |
| | 4.696 | 5.007 | | |
| type | 1 (diesel) | 2 (third-rail) | | |
| | 5.182 | 4.521 | | |
| Frequency | 1 (linear) | 2 (50 Hz HP) | 3 (160 Hz HP) | |
| | 5.372 | 5.068 | 4.115 | |
| Level | 1 | 2 | 3 | 4 |
| | 6.472 | 5.306 | 4.292 | 3.337 |

| Type | 1 (diesel) | 2 (third-rail) |
|---|---|---|
| Class | | |
| 1 (real) | 5.396 | 3.997 |
| 2 (synthesized) | 4.969 | 5.045 |

| Frequency | 1 (linear) | 2 (50 Hz HP) | 3 (160 Hz HP) |
|---|---|---|---|
| Class | | | |
| 1 (real) | 5.229 | 4.922 | 3.937 |
| 2 (synthesized) | 5.516 | 5.214 | 4.292 |

| Frequency | 1 (linear) | 2 (50 Hz HP) | 3 (160 Hz HP) |
|---|---|---|---|
| Type | | | |
| 1 (diesel) | 5.781 | 5.464 | 4.302 |
| 2 (third-rail) | 4.964 | 4.672 | 3.927 |

| Level | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Class | | | | |
| 1 (real) | 6.243 | 5.167 | 4.229 | 3.146 |
| 2 (synthesized) | 6.701 | 5.444 | 4.354 | 3.528 |

| Level | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Type | | | | |
| 1 (diesel) | 6.861 | 5.958 | 4.500 | 3.410 |
| 2 (third-rail) | 6.083 | 4.653 | 4.083 | 3.264 |

| Level | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Frequency | | | | |
| 1 (linear) | 6.979 | 5.781 | 4.781 | 3.948 |
| 2 (50 Hz HP) | 6.583 | 5.781 | 4.552 | 3.354 |
| 3 (160 Hz HP) | 5.854 | 4.354 | 3.542 | 2.708 |

| Type | 1 (diesel) | | | 2 (third-rail) | | |
|---|---|---|---|---|---|---|
| Freq. | 1 (lin.) | 2 (50Hz HP) | 3(160Hz HP) | 1 (lin.) | 2 (50Hz HP) | 3 (160 Hz HP) |
| Class | | | | | | |
| 1 (real) | 6.031 | 5.812 | 4.344 | 4.427 | 4.031 | 3.531 |
| 2 (syn) | 5.531 | 5.115 | 4.260 | 5.500 | 5.312 | 4.323 |

| Type | 1 (diesel) | | | | 2 (third-rail) | | | |
|---|---|---|---|---|---|---|---|---|
| Level | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Class | | | | | | | | |
| 1 (real) | 7.111 | 6.278 | 4.694 | 3.500 | 5.375 | 4.056 | 3.764 | 2.792 |
| 2 (synth.) | 6.611 | 5.639 | 4.306 | 3.319 | 5.250 | 5.250 | 4.403 | 3.736 |

| | Level | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Class | Frequency | | | | |
| 1 (real) | 1 (linear) | 6.729 | 5.583 | 4.896 | 3.708 |
| | 2 (50 Hz HP) | 6.312 | 5.604 | 4.562 | 3.208 |
| | 3 (160 Hz HP) | 5.678 | 4.312 | 3.229 | 2.521 |
| 2 (synthesized) | 1 (linear) | 7.229 | 5.979 | 4.667 | 4.187 |
| | 2 (50 Hz HP) | 6.854 | 5.958 | 4.542 | 3.500 |
| | 3 (160 Hz HP) | 6.021 | 4.396 | 3.854 | 2.896 |

| | Level | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Class | Frequency | | | | |
| 1 (diesel) | 1 (linear) | 7.500 | 6.458 | 5.292 | 3.875 |
| | 2 (50 Hz HP) | 6.979 | 6.437 | 4.708 | 3.729 |
| | 3 (160 Hz HP) | 6.104 | 4.979 | 3.500 | 2.625 |
| 2 (third-rail) | 1 (linear) | 6.458 | 5.104 | 4.271 | 4.021 |
| | 2 (50 Hz HP) | 6.187 | 5.125 | 4.396 | 2.979 |
| | 3 (160 Hz HP) | 5.604 | 3.729 | 3.583 | 2.792 |

STANDARD ERROR OF DIFFERENCES OF MEANS

| | Class | Type | Frequency | Level | Class Type | Class Frequency | Type Frequency |
|---|---|---|---|---|---|---|---|
| Rep. | 576 | 576 | 384 | 288 | 288 | 192 | 192 |
| Sed. | 0.0680 | 0.0680 | 0.0832 | 0.0961 | 0.0961 | 0.1177 | 0.1177 |

| | Class Level | Type Level | Frequency Level | Class Type Frequency | Class Type Level | Class Frequency Level | Type Frequency Level |
|---|---|---|---|---|---|---|---|
| Rep. | 144 | 144 | 96 | 96 | 72 | 48 | 48 |
| Sed. | 0.1359 | 0.1359 | 0.1665 | 0.1665 | 0.1922 | 0.2354 | 0.2354 |

3.8 Discussion of Results

The major results and implications of the experiment are summarized below:

1. The "real" diesel was again more annoying than the "real" third-rail electric.

2. From the interaction between level and frequency, one could come to the conclusion that the subjective response and the frequency content varied in a similar way for both types and classes of noise. Annoyance increased when low frequency noise was present, as was found previously. Linear and 50 Hz cut-off were more annoying than the 160 Hz cut-off condition.

3. Perhaps the most important implications can be derived from the significance of the interaction between type and class. It was found that there was no significant difference between "synthesized" diesel and third-rail electric trains. However, there was significant difference between the "real" diesel and third-rail electric trains. This finding signified that: (a) the differences in the time history and the spectral characteristics were not subjectively important and (b) the "synthesized" diesel noise did not contain the subjectively important acoustical characteristic which should increase its annoyance against the third-rail as it was with the "real" noises. This particular parameter of the diesel noise, which correlates with subjective response, was not included in the synthesis of the sounds. In particular, the characteristic "pulsing" sound of the diesel engine was missing, indicating that neither in the overall frequency spectrum of the noise nor in the envelope of the time dhistory during the pass-by, was this characteristic obvious.

It would therefore be important to identify the acoustical factor which is responsible for the characteristic sound of the diesel engine.

# 4. LABORATORY STUDY OF THE EFFECT OF THE DIESEL ENGINE NOISE LEVEL ON THE SUBJECTIVE RESPONSE

## 4.1 Introduction

Previous experiments have shown that the differences in time history and in frequency spectra between the two types of noise were not subjectively important for the type of noises synthesized.

From listening to the noise of the two types of trains, it was clear that there was a special characteristic in the noise of the diesel which discriminated it from the third-rail electric train. This could be described as "pulsing" or "thumping" and it could be the sound to which people responded. It was not reproduced in the synthesis of the noises described in the previous chapter, because the acoustical factors associated with it had not yet been identified.

In this chapter an investigation was carried out to examine the waveform of the noise of the two types of train. A further laboratory experiment examined the effect on the subjective response of varying the noise level of a synthesized diesel locomotive in a synthesized diesel train pass-by.

## 4.2 Waveform Investigation

The noise signals have so far been analysed by using one-third octave frequency analysis, (0-200 Hz) narrow band analysis and variation of the frequency spectrum with time during the pass-by. All these methods failed to identify differences which were subjectively important in determining the human response due to noise from diesel and third-rail electric trains. One-third octave spectra were not showing convincing differences which could have explained the difference in the reaction between the two types.

Generally it is possible for two noises to have a similar frequency spectrum and yet to sound different. However, the shape of the waveform can enclose information concerning the nature of the noise. For example, a simple case could be where two pure tones close together, if presented simultaneously to the ear, may give rise to a beating sensation, the frequency of beating being equal to the separation of the two pure tones in Hz. Frequency analysis will reveal the two pure tones but there will be no sign of the beat frequency. However, if one examines the waveform of the resulting signal then the beating frequency may be easily identified.

Hence in our case the shape of the waveform of the noises could provide valuable information about strong amplitude variations with time in the signal, which could be subjectively important. The term "waveform" here is used to describe instantaneous variations of the amplitude with time. Thus the noise waveforms of Class 33 and Class 47 locomotives were examined. For comparison the noise waveform of third-rail electric trains was also examined. Typical waveforms of the diesel and third-rail electric trains are shown in Figures 4.1 and 4.2.

The waveform of the diesel train indicated the presence of a low frequency modulation of around 6-8 Hz. This modulation is the probable source of the characteristic "pulsing" sound associated with diesel locomotives. It is important therefore to reproduce this factor in any synthesis of the sound. Also, a low frequency component (about 34 Hz) was present in the noise waveform of the diesel trains examined which could be related to the firing frequency of the engine.

The waveform of the third-rail electric train, as can be observed, was more random in nature without any specific pattern associated with it.

Therefore, by examining the noise waveform it was possible to identify the difference between the two types of noise. The modulation may be important in accounting for the difference in the subjective response that exists between the two noises in the real life situation. This is therefore worthy of further research with a view to:

(a) describing the process analytically
(b) investigating its subjective effect by including it in the synthesis of the sounds.

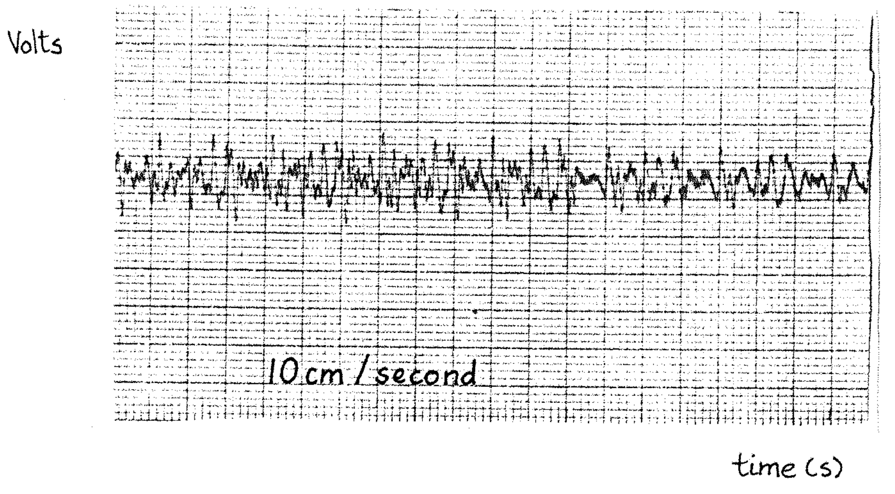



**Figure 4.1 Noise waveform of a diesel**

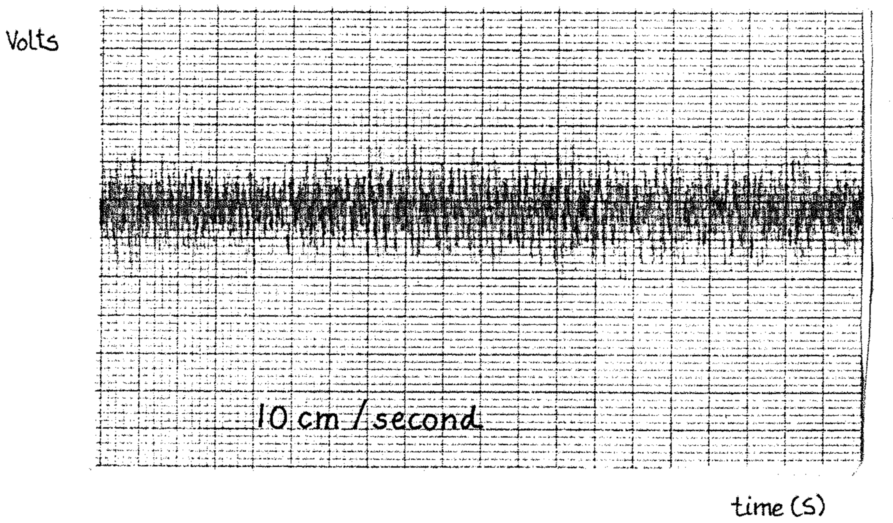



**Figure 4.2 Noise waveform of a third-rail electric**

4.3 Laboratory Study III

Synthesis of the noises

The three elements used in the synthesis of the diesel train were: (a) a low frequency modulation of around 8 Hz; (b) a 34 Hz frequency component; and (c) shaped random noise. The noise from the locomotive was synthesized separately from the rail wheel noise, so that its level could be caried independently. The complete train was then produced by mixing the synthesized diesel locomotive noise with synthesized rail-wheel noise. Figure 4.3 shows how this was done.

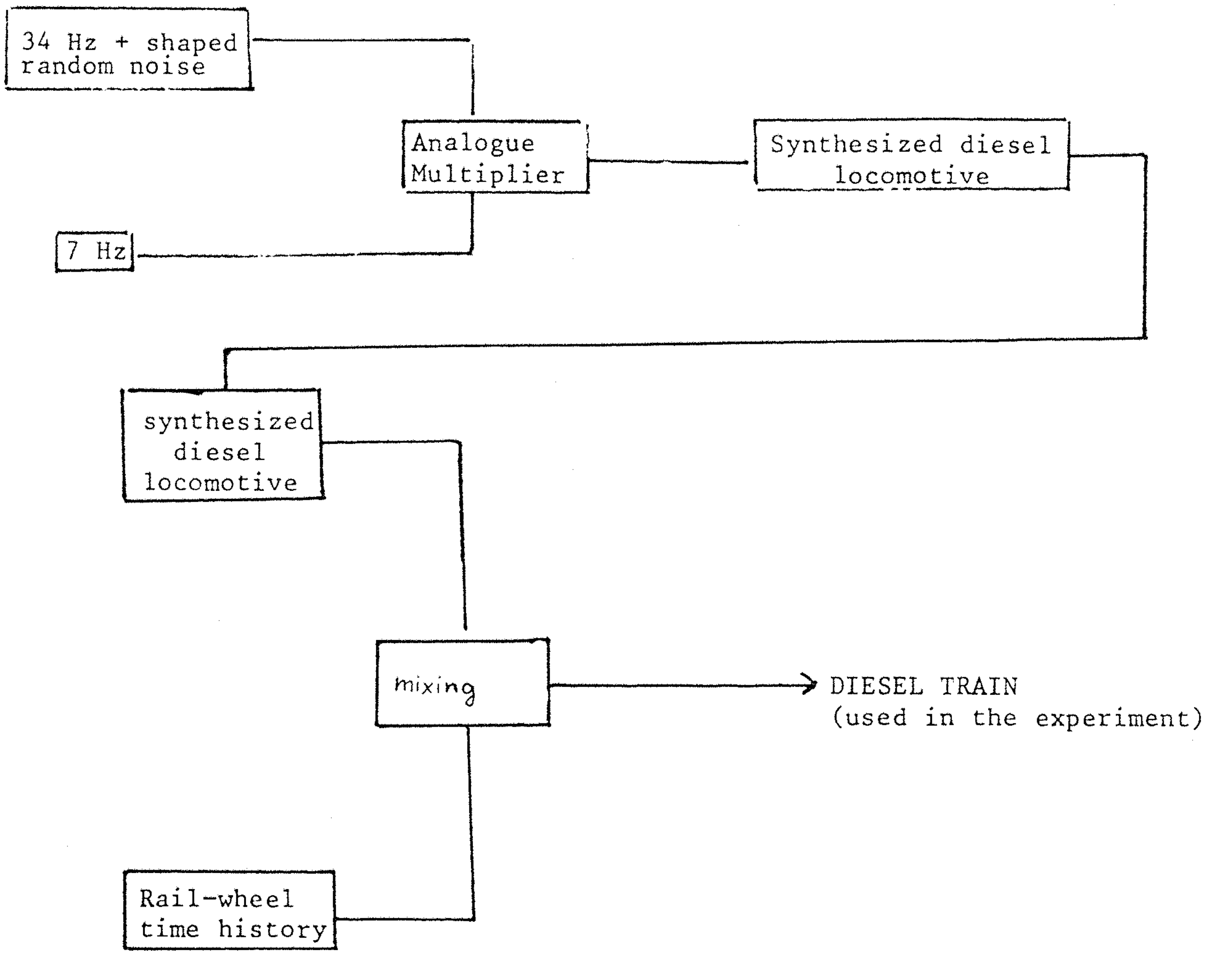



Figure 4.3 Production of synthesized sound

Figure 4.4 shows the synthesized noise waveform of the complete train. Listening to the waveforms showed that the similarity between "real" and "synthesized" sounds was now very encouraging. The synthesized diesel sounded very similar to a typical real diesel train. At the end of each session of the experiment the subjects were asked to make comments about the noises they had just heard. None of the 16 subjects who had taken part in the experiment had realised that the noises were not real.

Experimental design

The experiment was designed to investigate the effect on the subject of varying the noise level of the diesel locomotive.

The noise from the diesel locomotive was presented at four conditions at each train noise level; the first three conditions were attenuated from the typical noise level measured on a real train by:

(a) 0 dB, representing the typical measured level for the real train,

(b) 5 dB below level (a),

(c) 10 dB below level (a),

whilst in the fourth,

(d) the synthesized locomotive noise was not present.

This last condition was effectively equivalent to an electric train (i.e., only rail-wheel noise was present).

The time histories for these four conditions are shown in Figure 4.5. The train noises were presented at four levels (60, 65, 70 and 75 dB(A)).

These conditions resulted in a 16 × 16 factorial design (4 × 4 = 16). 16 subjects were used with each subject judging all 16 different treatments for annoyance. Each treatment was allocated a number randomly and as in previous studies a Latin square design was used to present the treatments.

## 4.4 Results - Analysis

The results were plotted and are shown in Figure 4.6. Statistical analysis showed that there was a significant difference between the 10 dB and the 0 dB attenuation conditions ((a) and (c)) (see Appendix 6), but there was no significant difference between the 10 dB attenuation and the "no noise" conditions ((c) and (d)). Also, there is no significant difference between the 0 dB and 5 dB attenuation conditions ((a) and (b)). At low levels (60 and 65 dB(A)) there is a significant difference between the 5 dB and the "no noise" conditions (b) and (d)), but at high levels (70 and 75 dB(A)) there is no significant difference.

From these findings it is evident that reducing the synthesized diesel engine noise by approximately 10 dB results in the synthesized diesel train becoming subjectively equal to a synthesized electric train.

Therefore, the real difference which exists between the two types of train was reproduced by including the modulation component in the noise waveform of the diesel. This is illustrated in Figure 4.7 which shows the relationship between the subjective response and noise level for synthesized and real noises. The regression lines in the figure were calculated from data in Chapter 3 and in this chapter.

An analysis of variance was also carried out; the results are shown in Tables 4.1 and 4.2.

## 4.5 Conclusions

In this part of the study the effect of varying the noise level of a synthesized diesel locomotive on the subjective response was investigated. The major conclusion was that for the type of test carried out a 10 dB reduction in the diesel locomotive noise was necessary for the diesel train to be equivalent subjectively to an electric train. Therefore it was shown that the temporal character as well as the frequency content was important in determining the annoyance of diesel trains.

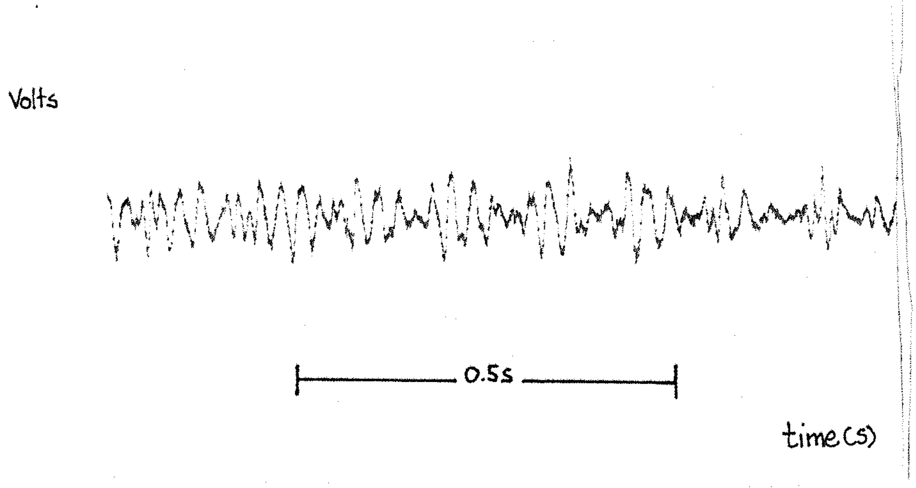



Figure 4.4 Waveform of synthesized diesel

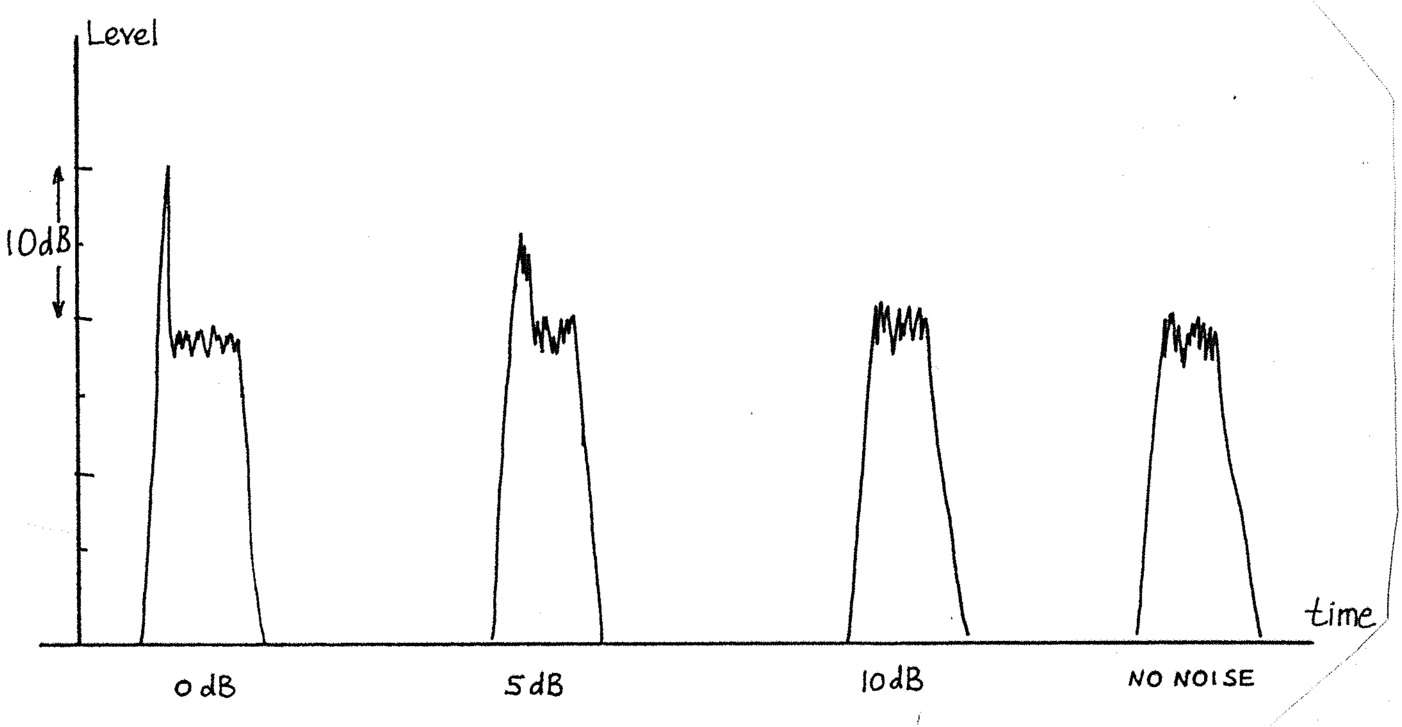



Figure 4.5 Time histories of the synthesized diesel train showing the four conditions at which the noise from the diesel locomotive was presented

Table 4.1 Analysis of variance, laboratory study III.

| | DF | SS | MS | VR |
|---|---|---|---|---|
| Subjects | 15 | 341.859 | 22.791 | 20.993 *** |
| Attenuation | 3 | 85.547 | 28.516 | 26.267 *** |
| Level | 3 | 423.922 | 141.307 | 130.162 *** |
| Attenuation - level | 9 | 13.266 | 1.474 | 1.358 N.S. |
| Residual | 225 | 244.266 | 1.086 | |
| Total | 240 | 767.000 | 3.196 | |
| Grand total | 255 | 1108.859 | | |
| Grand mean | 4.773 | | | |

Total number of observations: 256

Table 4.2 Table of means.

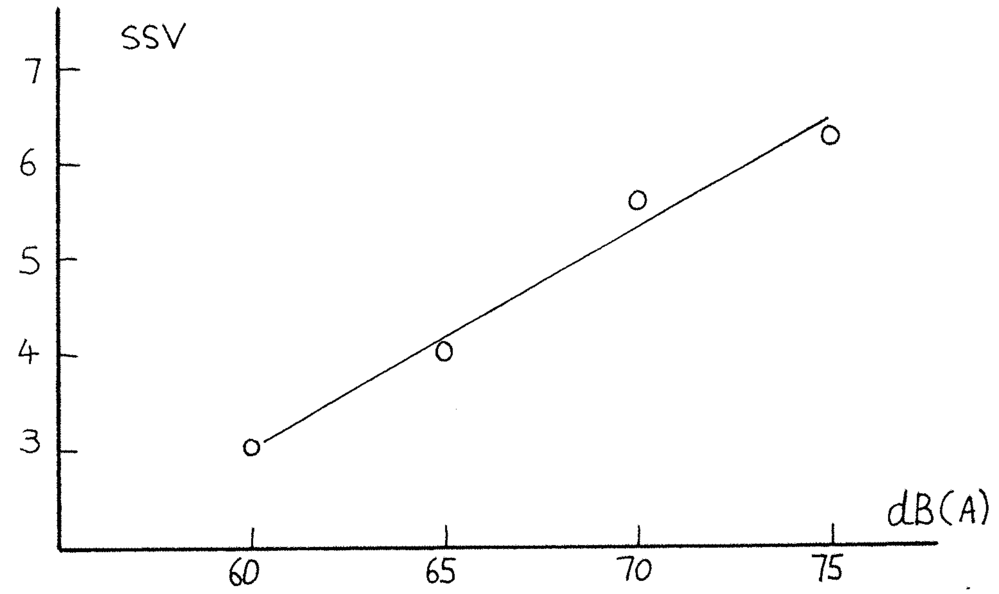
| Attenuation | 0 dB | 5 dB | 10 dB | No noise |
|---|---|---|---|---|
| | 5.641 | 4.953 | 4.203 | 4.297 |

| Noise level | 60 | 65 | 70 | 75 |
|---|---|---|---|---|
| | 3.063 | 4.063 | 5.625 | 6.344 |

| Noise level | 60 | 65 | 70 | 75 |
|---|---|---|---|---|
| Attenuation | | | | |
| 0 | 3.938 | 5.125 | 6.438 | 7.063 |
| 5 | 3.438 | 4.188 | 5.438 | 6.750 |
| 10 | 2.250 | 3.250 | 5.188 | 6.125 |
| No noise | 2.265 | 3.688 | 5.438 | 5.4438 |

<u>Standard error of differences of means</u>

| | Attenuation | Noise Level | Attenuation noise level |
|---|---|---|---|
| Rep. | 64 | 64 | 16 |
| Sed. | 0.1842 | 0.1842 | 0.3684 |



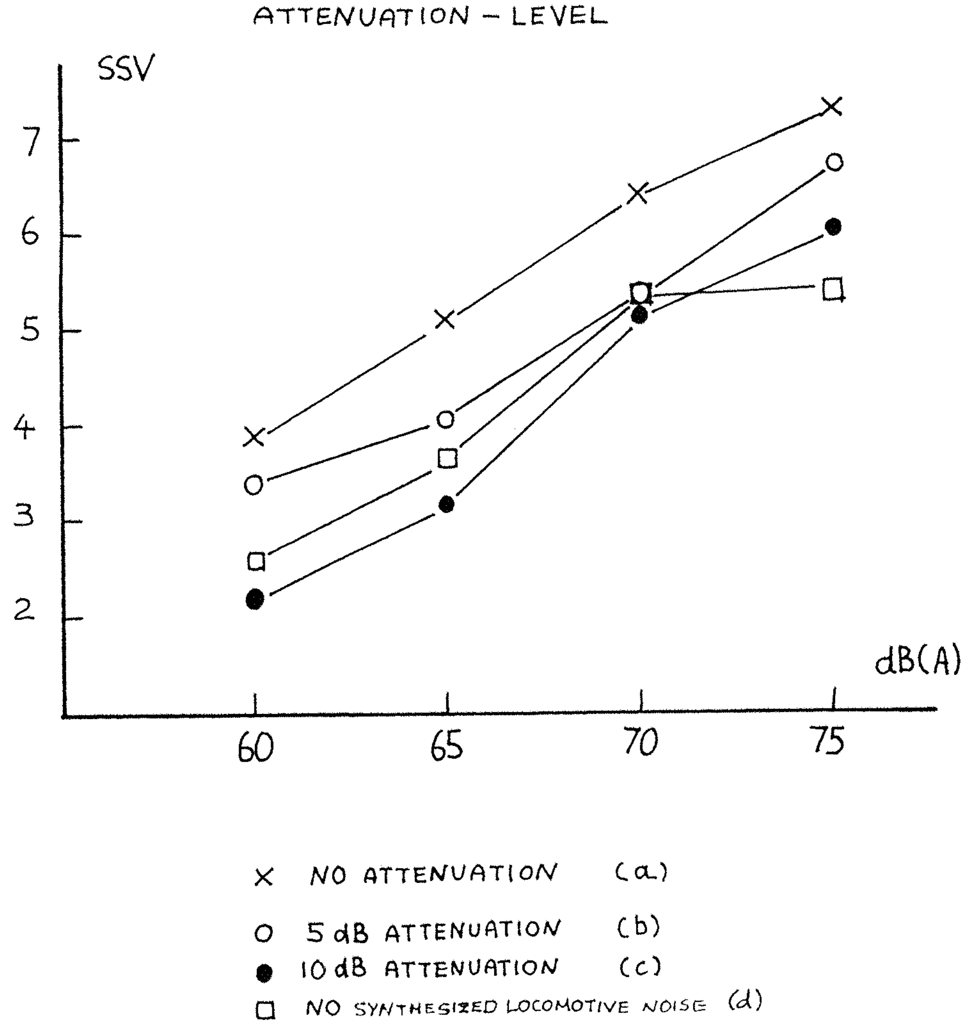




**Figure 4.6 Relationship between subjective response and noise level**

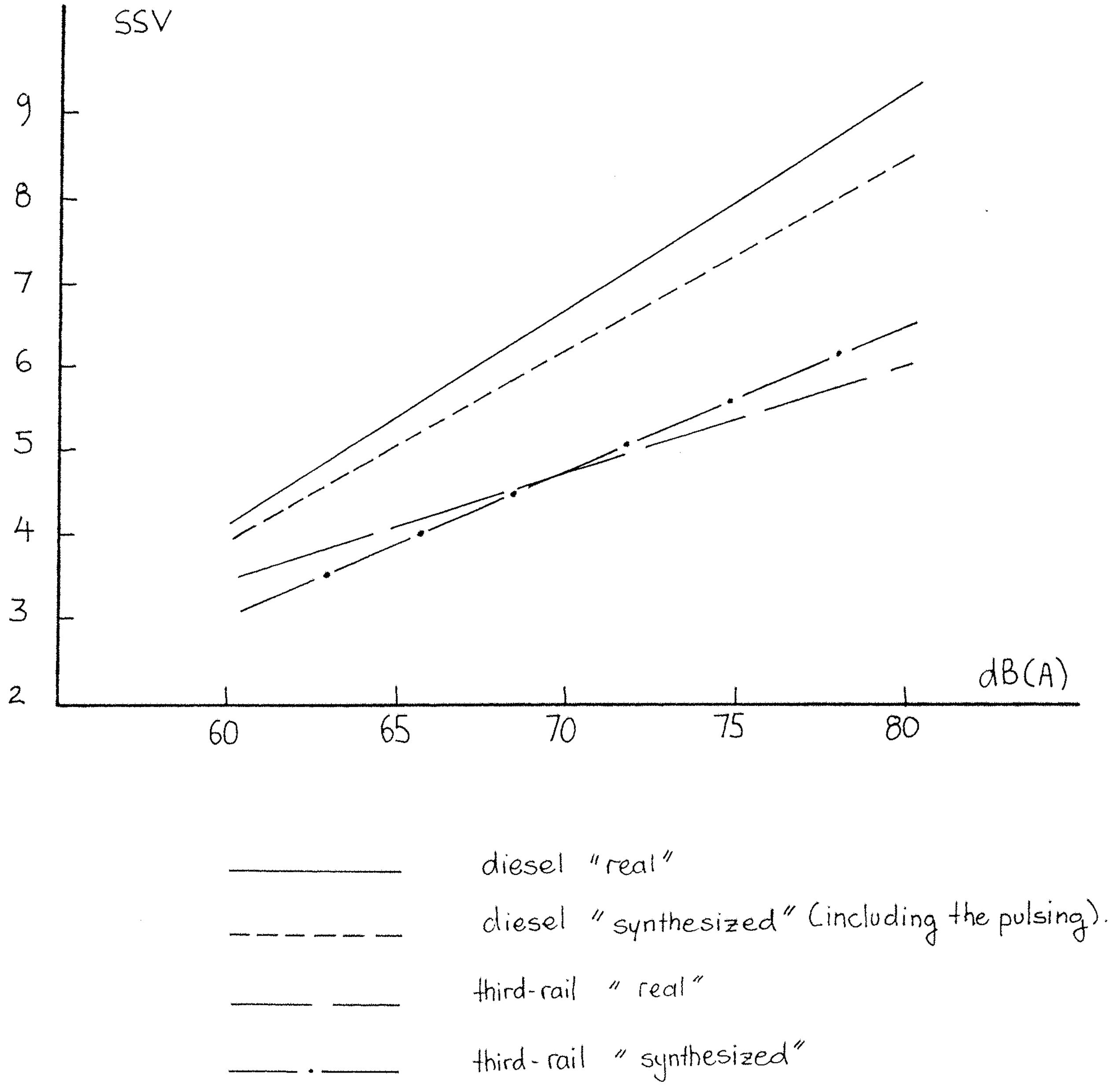



Figure 4.7 Relationship between subjective response and noise level for "real" and "synthesized" noises

# 5. INVESTIGATION OF THE EXHAUST NOISE PRODUCED BY A DIESEL ENGINE. THE EFFECT OF THE SILENCER.

## 5.1 Introduction

In this chapter a series of noise measurements are described of the exhaust noise produced by Class 47 and 58 diesel engines. These were carried out in order to investigate further the modulation component.

First, measurements were carried out of the noise produced by the Class 47 diesel engines. In order to have some control over the operational characteristics of the engine, recordings were made at two operating conditions: (a) idling while the train was stationary, and (b) at full-load while the train was moving away from the station.

In addition, noise measurements were carried out on a stationary Class 58 diesel engine set up on a test bed at British Rail's workshop in Derby. These were taken at a range of different speeds and loads.

The effect of a typical silencer was also investigated.

The recordings of the noise waveforms obtained were analysed using the Data Analysis Centre (DAC) at ISVR. A description of the system is given in this chapter.

## 5.2 Noise Measurements of a Class 47 Diesel Locomotive

The measurements were made at Eastleigh and Winchester railway stations. A Bruel and Kjaer FM tape recorder type 7003 was used to record the noise from the diesel locomotive at two operating conditions: (a) idling, and (b) full-load while moving away from the station. The recordings were made at a distance of about 4 metres from the engine.

The recordings were analysed using the DAC computer in ISVR. The waveforms and corresponding FFTs are shown in Figures 5.1-5.4. Both noise waveforms have a harmonic nature. They also appear to be modulated as it was found previously. The frequency of the envelope is 2.8 Hz for idling and 7.3 Hz for full-load conditions (see Figures 5.1 and 5.2). These values correspond to the fundamental firing frequency $f_o$ of the engine, given by

$$f_o = N/2 \times 60 \text{ (Hz) for a 4-stroke engine}$$

where N is the rotational speed of the engine in rpm.

The firing frequency $f_f$ of the engine is given by:

$$f_f = f_o \times \text{number of cylinders.}$$

From the manufacturer's specifications concerning the engine installed in the Class 47 locomotive (see Appendix 6 ), full-load is obtained at approximately 800 rpm and when idling at 325 rpm. These correspond to fundamental firing frequencies of 6.7 Hz and 2.7 Hz respectively. The FFTs obtained show line spectra with harmonic components related to the firing frequency of the engine. In both spectra shown, the separation of the harmonic components is equal to the fundamental firing frequency.

If a waveform has a periodic component, the autocorrelation function will show a periodic character [5.1]. Figure 5.5 shows the autocorrelation function of the noise waveform at full load; its periodic character confirms the periodicity of the waveforms.

Although there was consistency in the nature of the noise waveforms between different trains using the same locomotive, it was found that the frequency of modulation varied. This was due to the fact that during the measurements it was impossible to obtain control on the operating characteristics of the different engines. Therefore, measurements should be made on a stationary diesel engine which could be under completely controlled operating conditions.

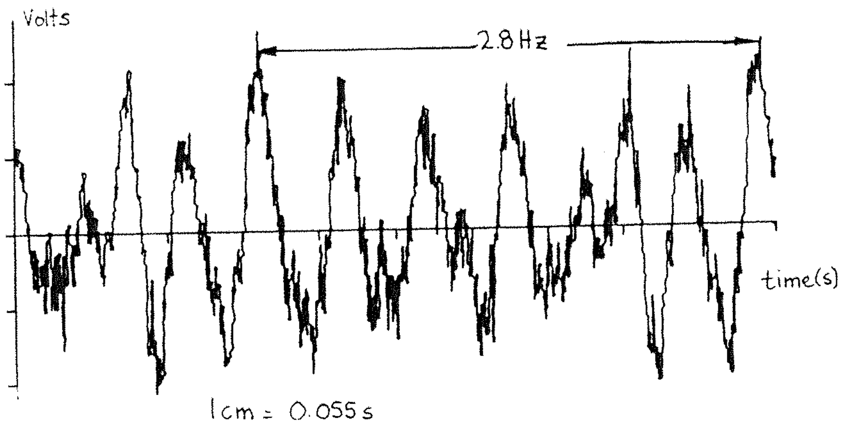



**Figure 5.1 Noise waveform at idling (Class 47)**

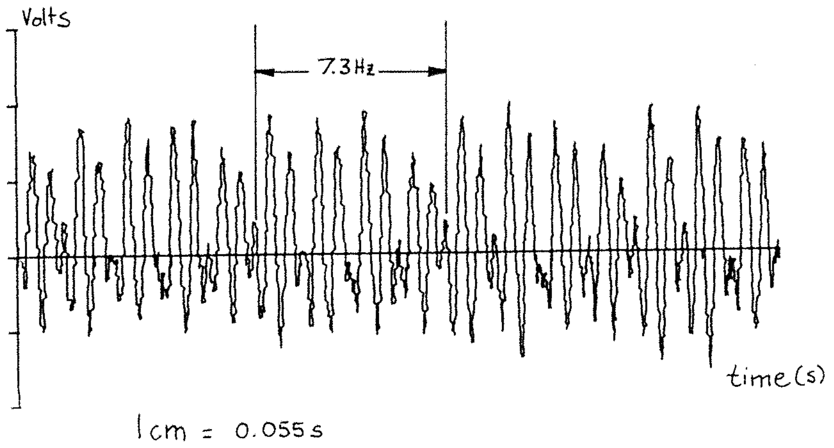



**Figure 5.2 Noise waveform at full load (Class 47)**

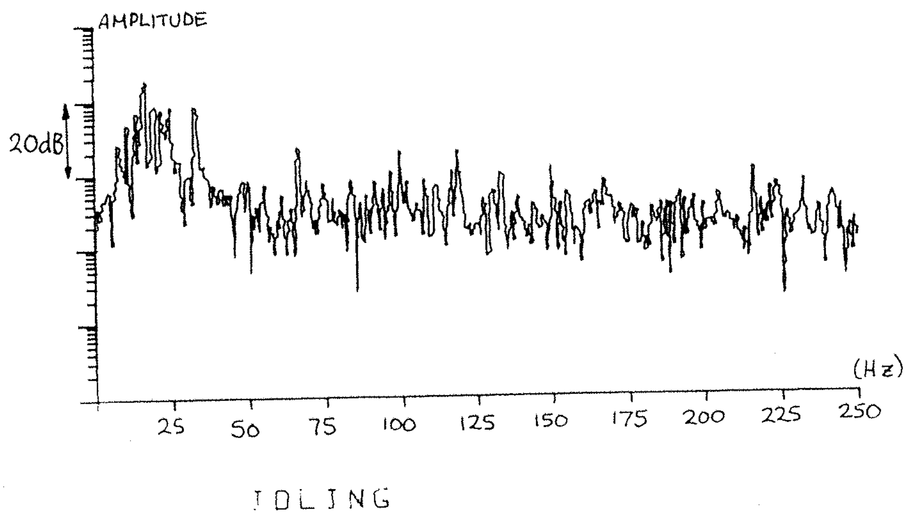



**Figure 5.3 Modulus of FFT at idling**

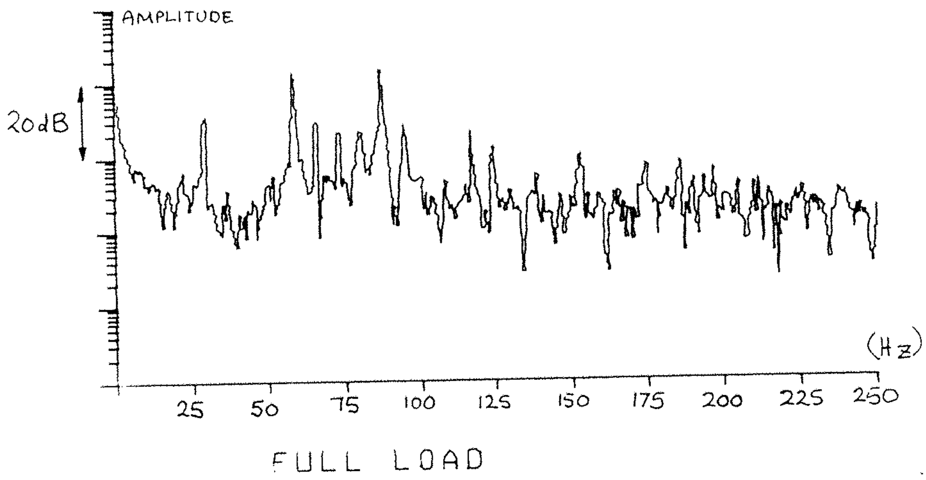



**Figure 5.4 Modulus of FFT at full-load**

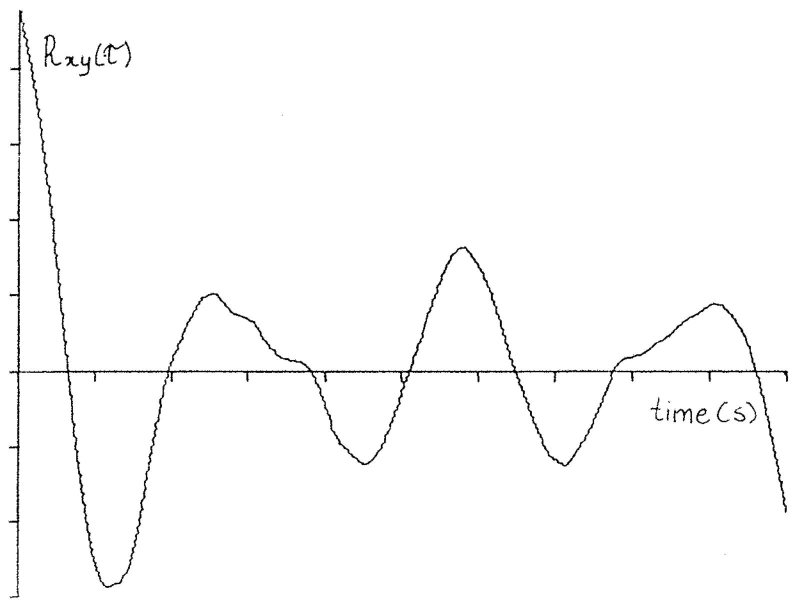



**Figure 5.5 Autocorrelation function of noise waveform at full load**

## 5.3 Digital Processing of Signals

### 5.3.1 Acquisition

Samples of the recordings made were acquired in the DAC computer. The system used is DATS 11. Due to the structure of the system a number of data files were created corresponding to particular cases of interest. The sampling rate used was twice the highest frequency component in the signal. A low pass filter was used as an "anti-aliasing filter" to limit the frequency range of the input data, and thus suppressing any extraneous frequency components generated by the system. The dynamic range of the system was limited by the dynamic range of the recording equipment. The data records acquired were assumed to be typical representatives of the original signals. A signal which was acquired for 5 seconds, with a highest frequency of interest being 1500 Hz, resulted in a data file consisting of 15,000 points.

Standard plotting packages were used to display the analysed data.

### 5.3.2 Analysis

**FFT**

A signal $x(t)$ representing a continuous record of data after digitizing becomes $x(nT)$, where $T$ is the sampling interval, which is

$$\text{sampling interval, } T = \frac{1}{\text{sampling rate}} \text{ (seconds),}$$

and $n = 1, \ldots, M$ data length.

For the transformation of this data a finite length transform can be implemented defined by $N$, the transform length.

In practice $N$ is a specified parameter and with the DAC system can vary from 126 to 8192.

For the transformation, the following relationship is implemented:

$$F(kT) = \frac{1}{N} \sum_{n=0}^{N-1} f(nT) \exp\left(-j \frac{2\pi nkT}{N}\right)$$

(see reference [5.2]).

Often in practice the transform length $N$ is shorter than the acquired data length $M$ for computational reasons.

For this a typical stationary section of data is obtained extracted using a windowing function to avoid distortions.

The $F(kT)$ is a complex signal (function) and therefore is expressed as

$$F(kT) = |F(kT)| \exp(\arg(F(kT))).$$

The modulus function $|F(kT)|$ was displayed (plotted) in all cases in order to obtain a frequency representation of the signal.

**Inverse FFT**

In some cases a time domain signal was required to be obtained from a frequency domain signal. For this an inverse FFT program was used based on the equation

$$f(nT) = \sum_{k=0}^{N-1} F(kT) \exp(j \frac{2\pi kT}{N})$$

In practice this is limited to 4096 complex points.

**Autocorrelation**

Generally correlation is a measure of the similarity of two time series or waveforms and it is a function of the time displacement between the two [5.3]. If a waveform is compared with itself by the correlation process it is called autocorrelation. To obtain the autocorrelation of a waveform a whole set of average products is calculated. If a waveform is shifted in time with respect to itself, an averaged product can be obtained and so on for many shifts in time. The average products as a function of time displacement, or delay (usually designed by $\tau$), are the autocorrelation functions. The fundamental equation for the auto-correlation for a stationary signal is

$$R_x(\tau) = \lim_{T\to\infty} - \int_{t}^{t+\tau} x(t)x(t + \tau)\, dt$$

$R_x(\tau)$ gives a complete statistical knowledge of the time domain. If a waveform has a periodic component, the autocorrelation function will show a periodic character.

**Convolution**

A digital operation called "convolution" is sometimes used in the time domain. If one waveform is convolved with another, one of them is reversed in time or folded back. The operation can also be looked upon as a filtering of the input waveform. In this process the second function is known as the impulse response of the filter. Convolution in this type of operation is also superposition. If an input waveform is assumed to be a collection of impulses occurring at successive instants in time, the output waveform can be obtained by superposition of the individual responses to the impulses [5.4].

In a linear system the output of the system is the convolution of the input signal and the impulse response of the system. This is a convolution of the time domain expressed as follows:

$$y(t) = \int_{-\infty}^{\infty} x(t')h(t - t')dt = x(t) * h(t)$$

where $y(t)$ is the output, $x(t)$ is the input and $h(t)$ is the impulse response of the system. In the frequency domain the above becomes:

$$Y(\omega) = X(\omega).H(\omega)$$

where $Y(\omega)$ is the Fourier transform of the output, $X(\omega)$ is the Fourier transform of the input and $H(\omega)$ is the frequency response of the system.

## 5.4 Diesel Engine Noise

Considering propulsion system noise, diesel engine noise is considered to be radiated as casing noise, inlet noise and exhaust noise [5.5]. Casing noise is generated by the combustion noises which are transmitted through the engine block and indirectly through the crankshaft, while inlet noise is produced by the opening and closing of the inlet valves on four cycle engines.

Exhaust noise is considered to be composed of broad-band and discrete elements. The discrete noise is produced by the pulsations in the exhaust system. Broad-band jet noise is produced by the passage of high velocity gas streams across the valve seat. In a study of the magnitude of transportation noise generation and potential abatement [5.6] the noise produced from the three different sources was predicted. The graphical representation taken from the report shown in Figure 5.6 shows that, over a major portion of the spectrum, unmuffled exhaust noise is dominant, casing noise is the next most important component and inlet noise is the least important. In the region above 1000 Hz which contributes most strongly to the A-weighted sound level, casing noise and exhaust noise are at approximately the same level.

## 5.5 Exhaust Noise Measurements on a Stationary (Class 58) Diesel Engine under Controlled Operating Conditions

A Class 58 diesel locomotive was available for noise measurements at the British Railway workshops in Derby. The noise measurements were intended to investigate the effect of the silencer on the noise waveform. Thus, recordings were obtained of both the silenced and unsilenced noise waveforms. Special care was taken to position the microphone, so that exhaust noise, which is the main contributor to the characteristic sound of the diesel engine, was recorded.

Samples of the noise were recorded for approximately 30 seconds at the following engine load settings: idling, 1/4 load, 1/2 load, 3/4 load and full-load. These settings corresponded to 450, 570, 795, 900 and 1000 rpm of the engine respectively. A chart shown in Figure 5.7 obtained from

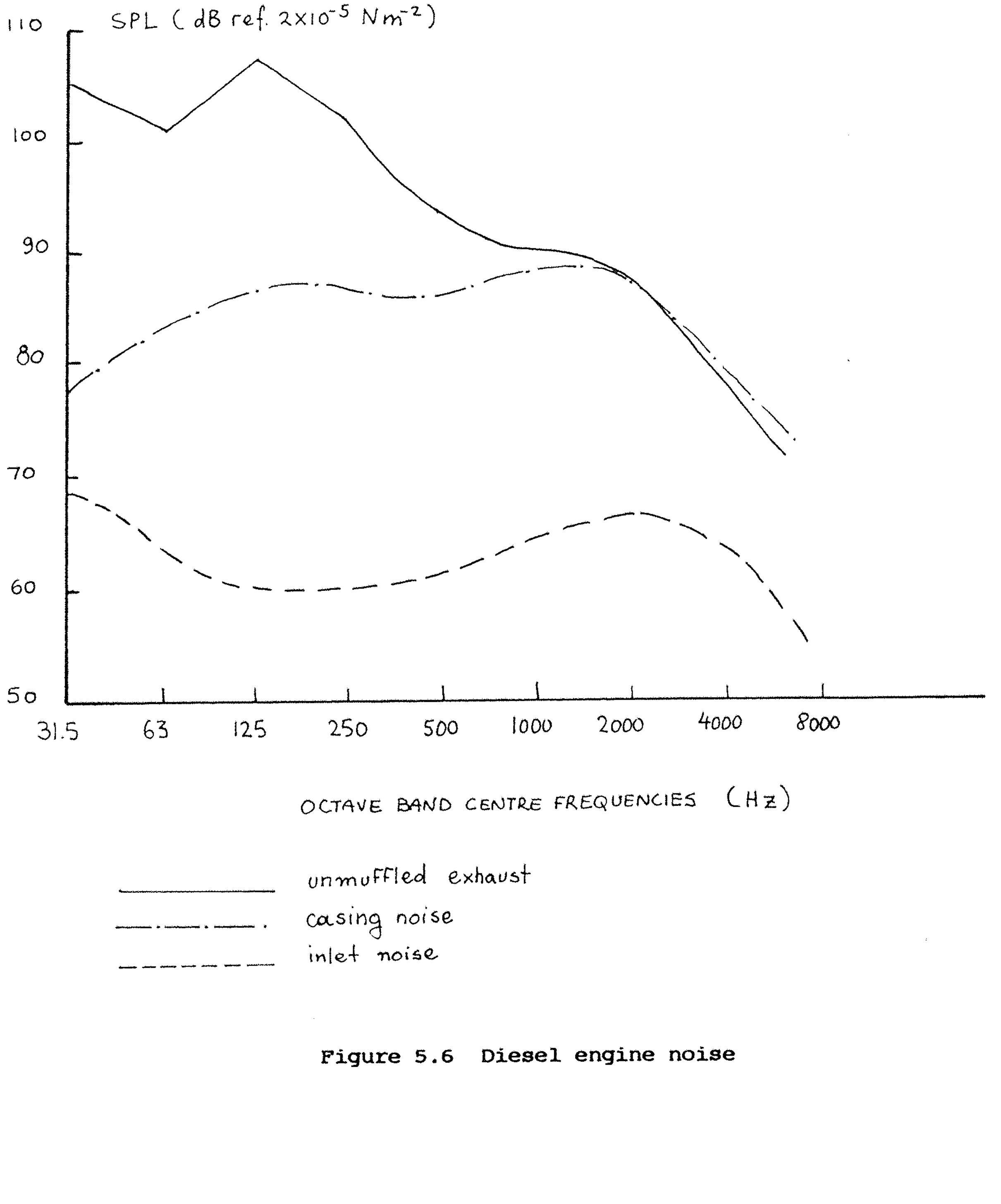



**Figure 5.6 Diesel engine noise**

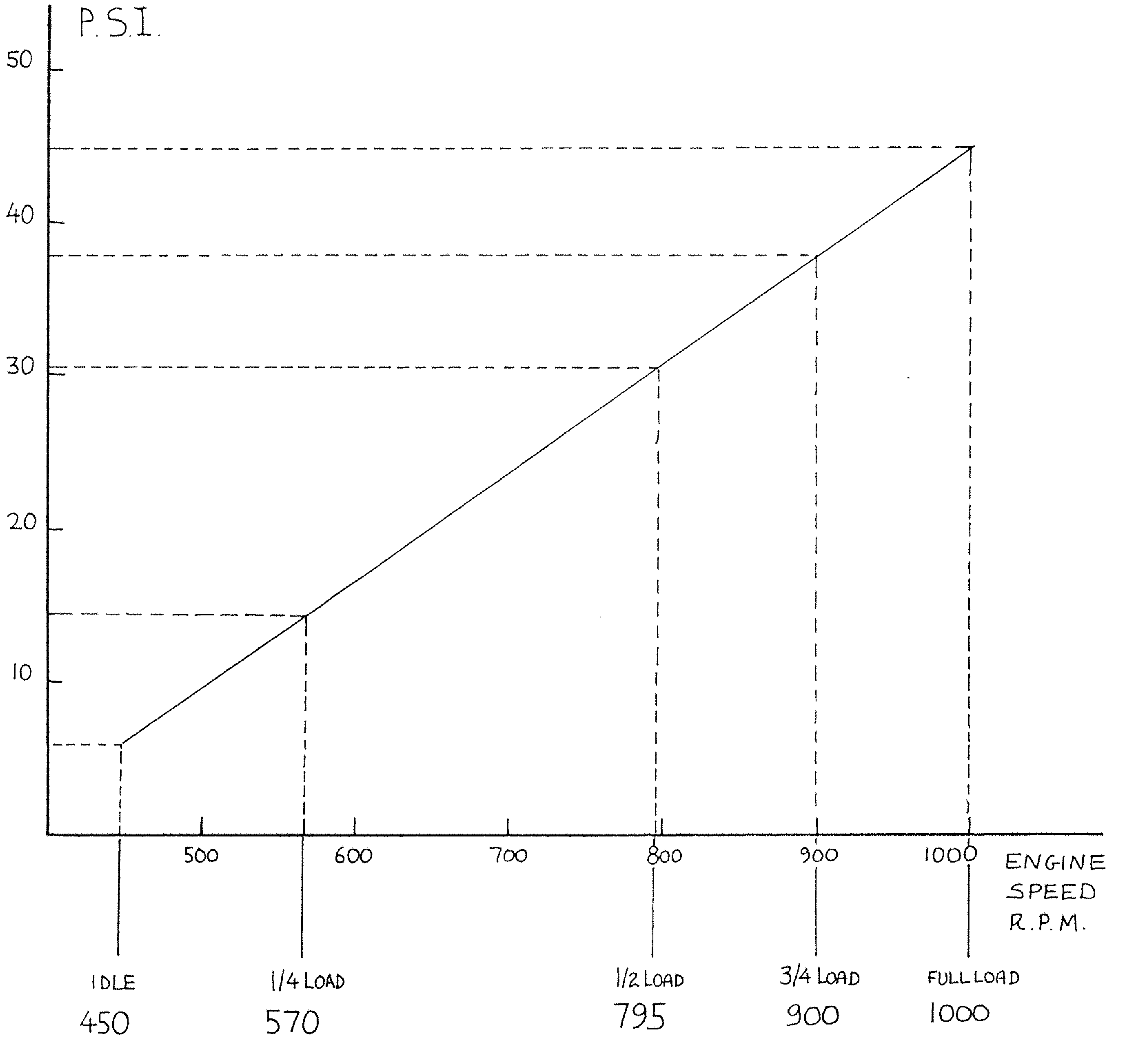



**Figure 5.7 Relationship between psi and speed of the engine rpm**

British Rail was used to estimate the rpm values from the linear relation which exists between psi values, recorded during the tests, and engine speed in rpm for the particular type of engine.

The recordings were analysed using the DAC computer. The noise waveforms and corresponding FFTs are shown in Figures 5.8 to 5.23 for both silenced and unsilenced cases.

## 5.6 Exhaust Noise Signature

The exhaust noise from an internal combustion engine normally consists of an irregular waveform, which is repeated at a frequency equal to the firing frequency of the engine [5.7], that is $n \times N/120$ for a four-stroke engine, where $N$ is the engine speed in rpm and $n$ is the number of cylinders. Therefore it may be assumed that the noise consists of a basic component equal to the engine firing frequency, plus a number of components having frequencies equal to the integral multiples of the basic one. From extensive research carried out by Davies [5.8], there is also the case where often some of the fundamental components are missing. Such behaviour is typical of all engine noise driving signals.

Attempts to predict theoretically the form of the exhaust noise signature [5.9] do not appear to be satisfactory at the present state of knowledge.

From the results of the measurements it can be observed that under all engine speeds and load conditions the noise waveforms are modulated. The frequency of modulation is equal to the fundamental firing frequency of the engine (see Figures 5.8 to 5.23). Table 5.1 shows the frequency of modulation and the corresponding engine speed. The firing frequency is also shown.

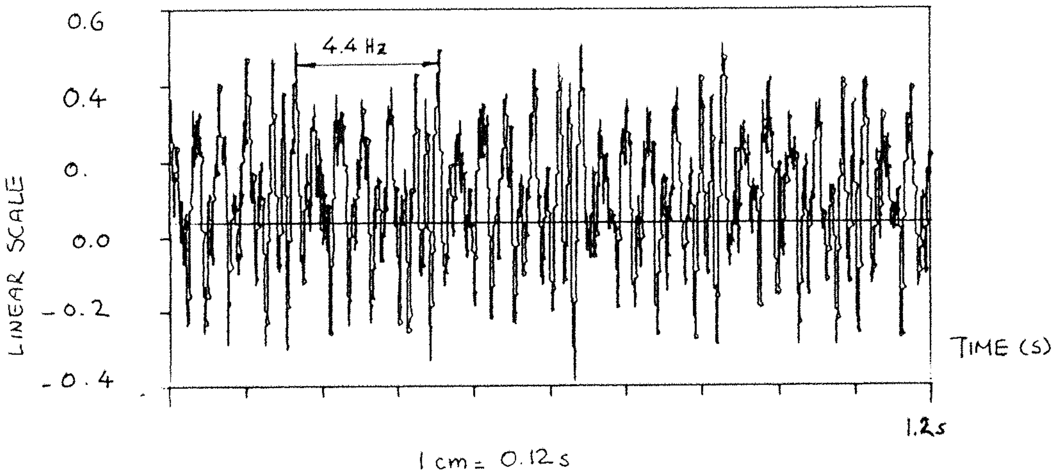



Figure 5.8 Silenced noise waveform at 1/4 load

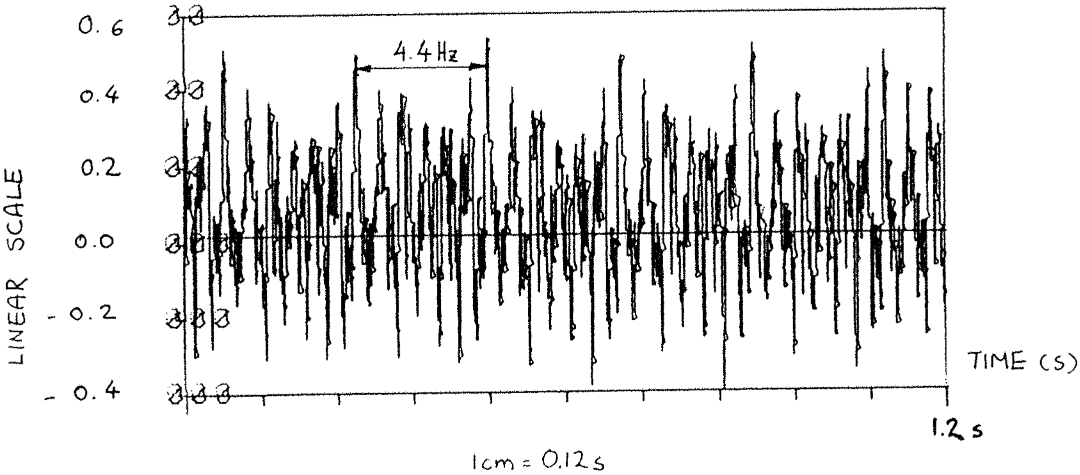



Figure 5.9 Unsilenced noise waveform at 1/4 load

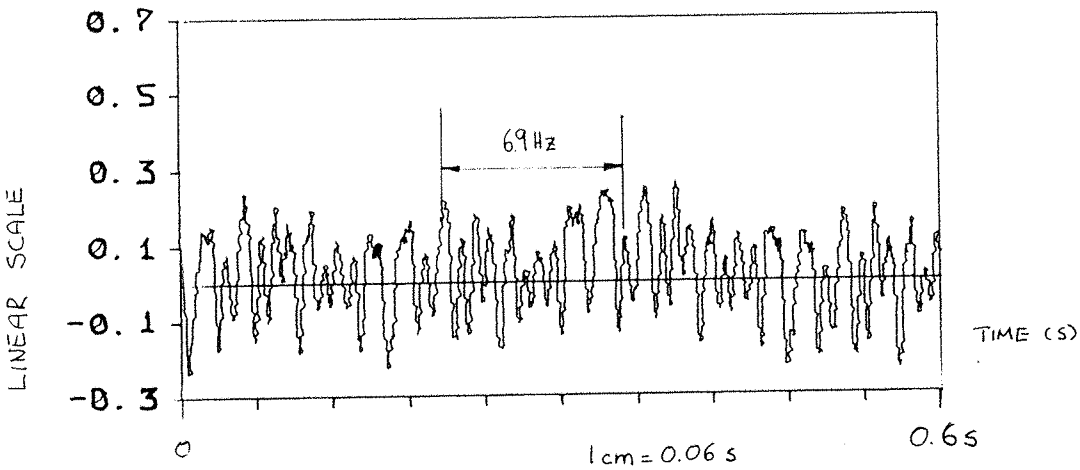



**Figure 5.10 Silenced noise waveform at 1/2 load**

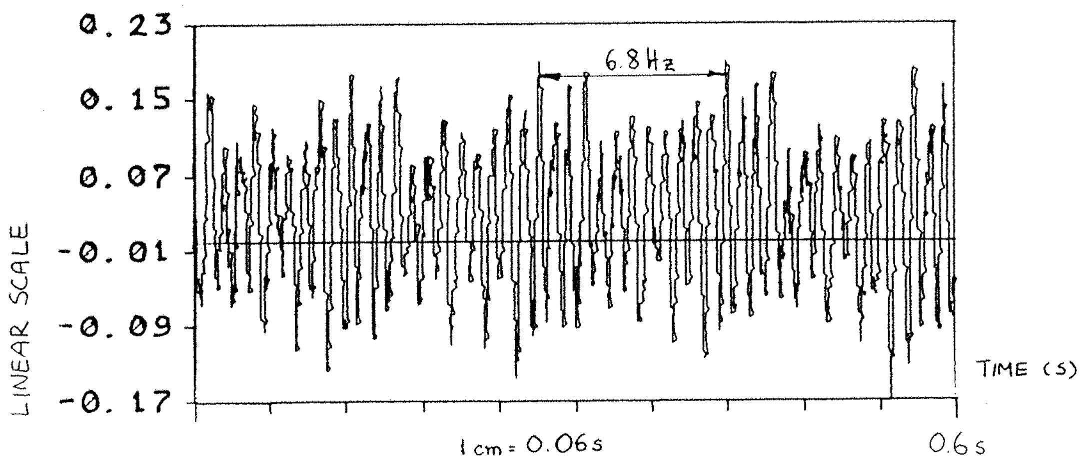



**Figure 5.11 Unsilenced noise waveform at 1/2 load**

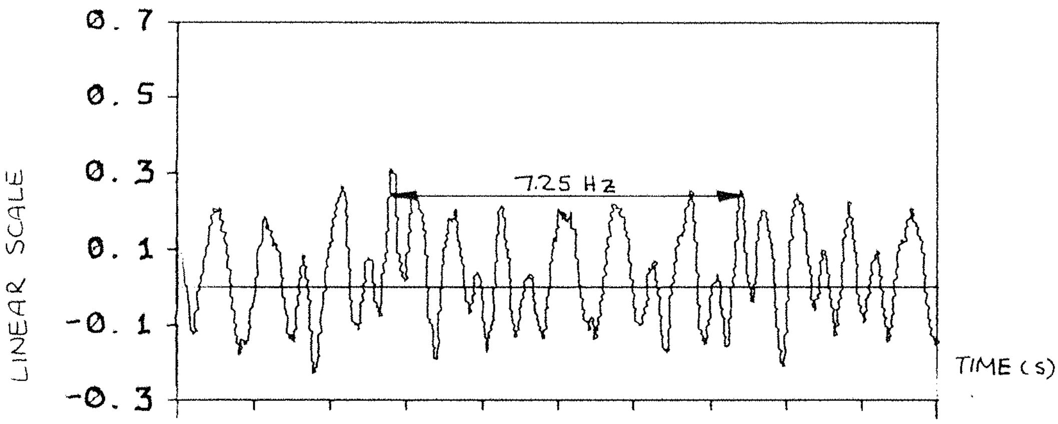



Figure 5.12 Silenced noise waveform at 3/4 load

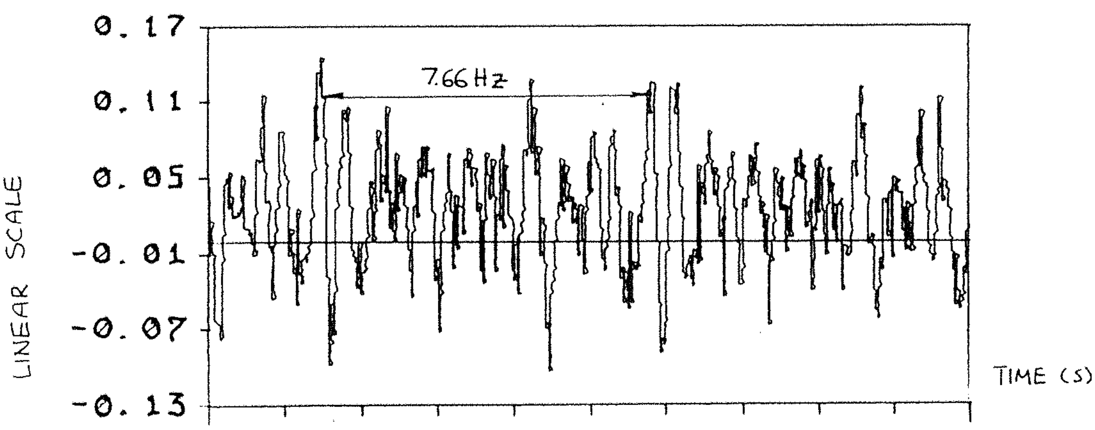



Figure 5.13 Unsilenced noise waveform at 3/4 load

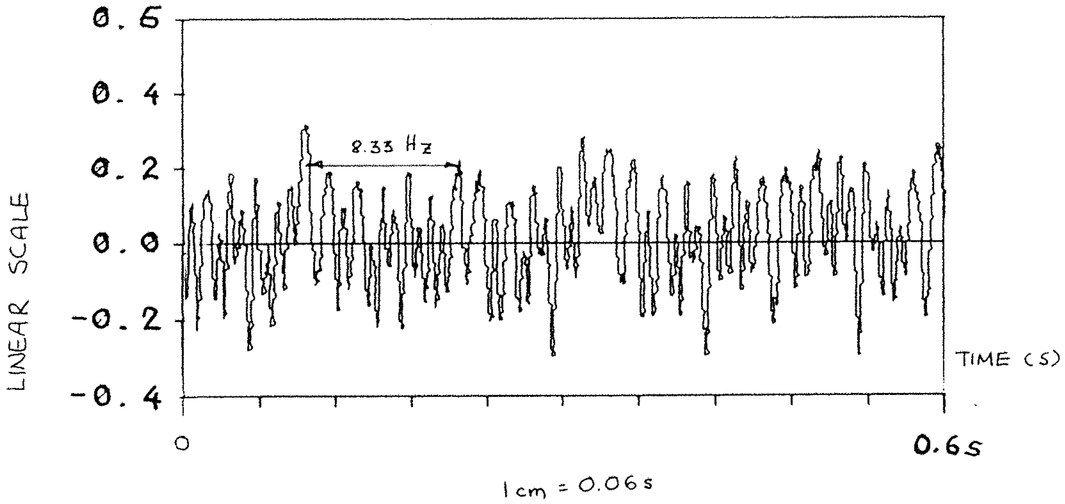



Figure 5.14 Silenced noise waveform at full-load

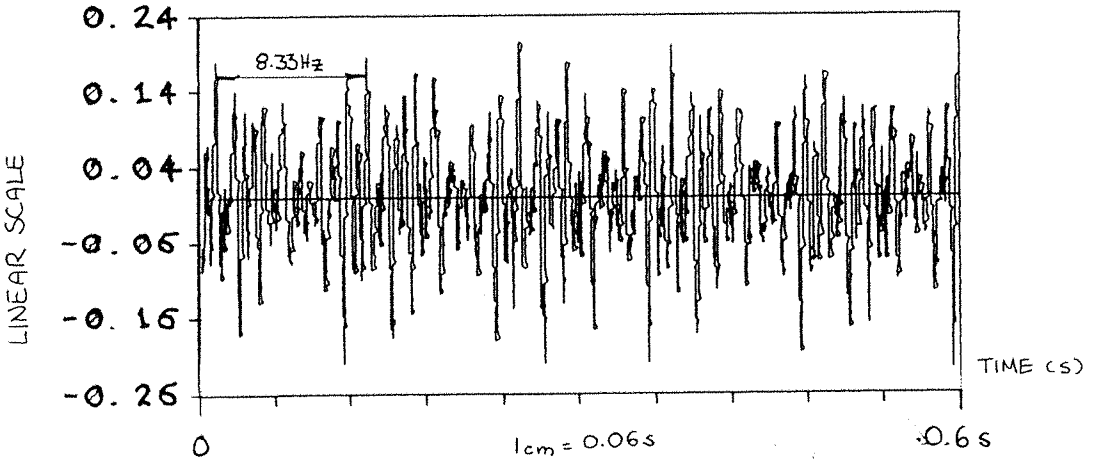



Figure 5.15 Unsilenced noise waveform at full-load

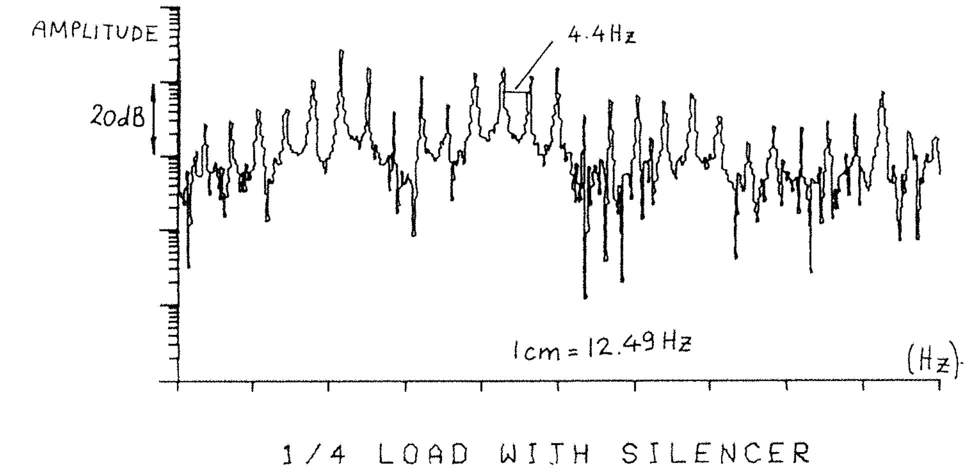



**Figure 5.16 |FFT| at 1/4 load (silenced)**

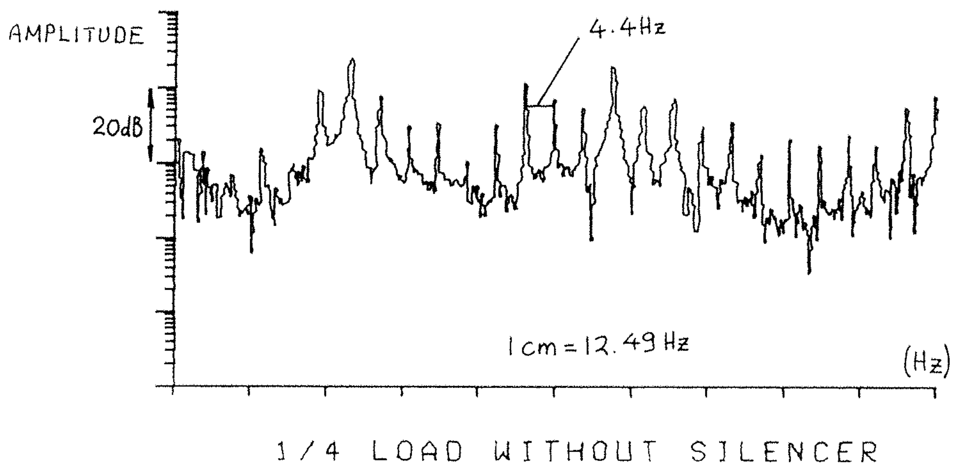



**Figure 5.17 |FFT| at 1/4 load (unsilenced)**

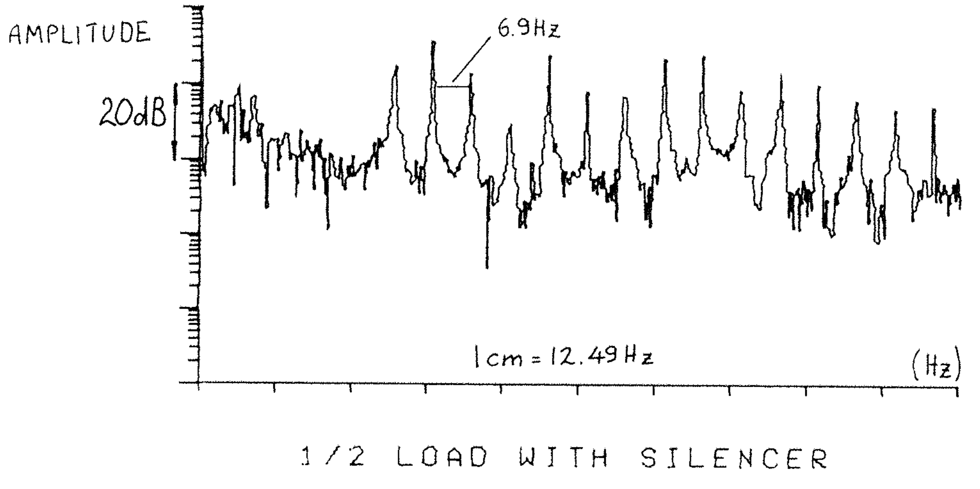



**Figure 5.18 |FFT| at 1/2 load (silenced)**

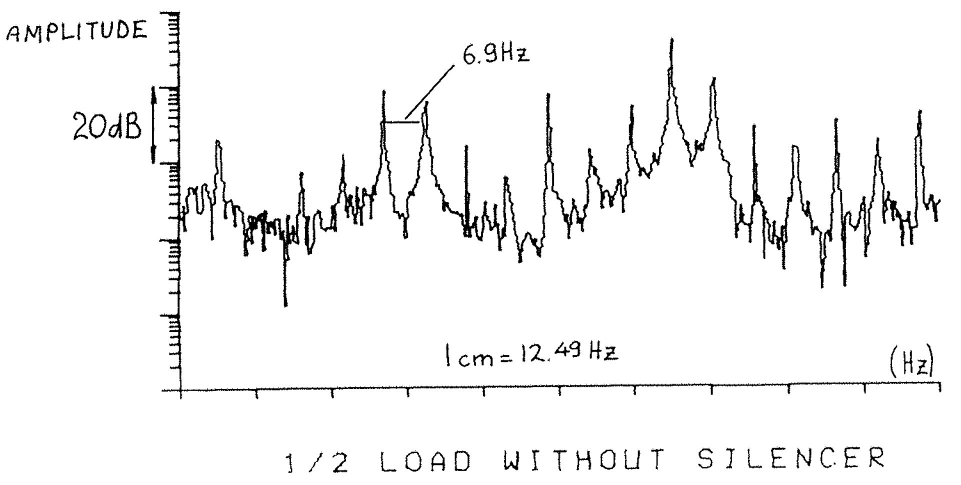



**Figure 5.19 |FFT| at 1/2 load (unsilenced)**

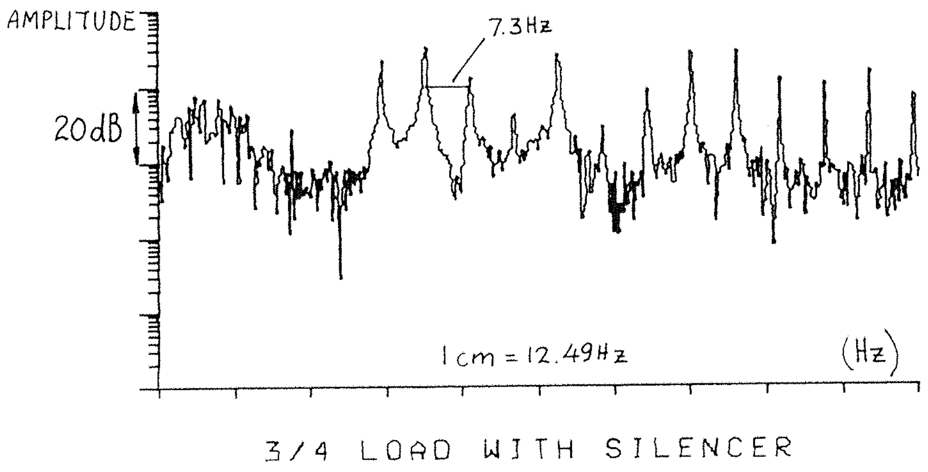



**Figure 5.20 |FFT| at 3/4 load (silenced)**

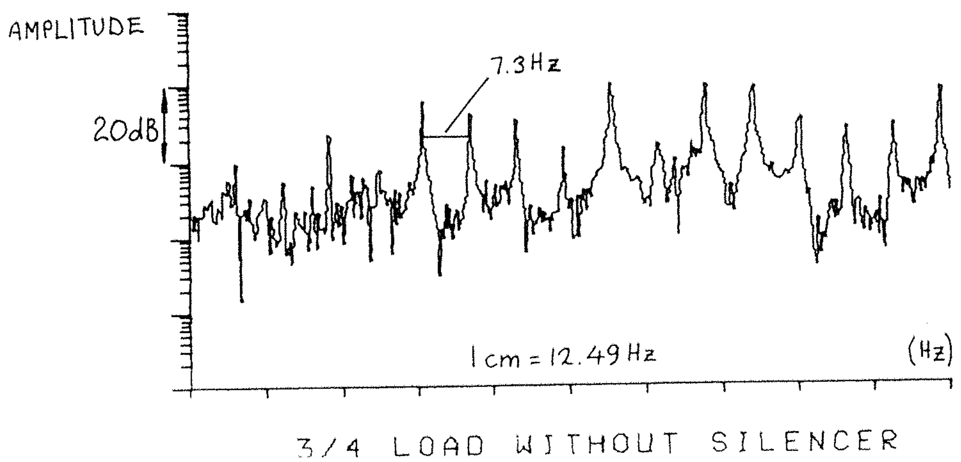



**Figure 5.21 |FFT| at 3/4 load (unsilenced)**

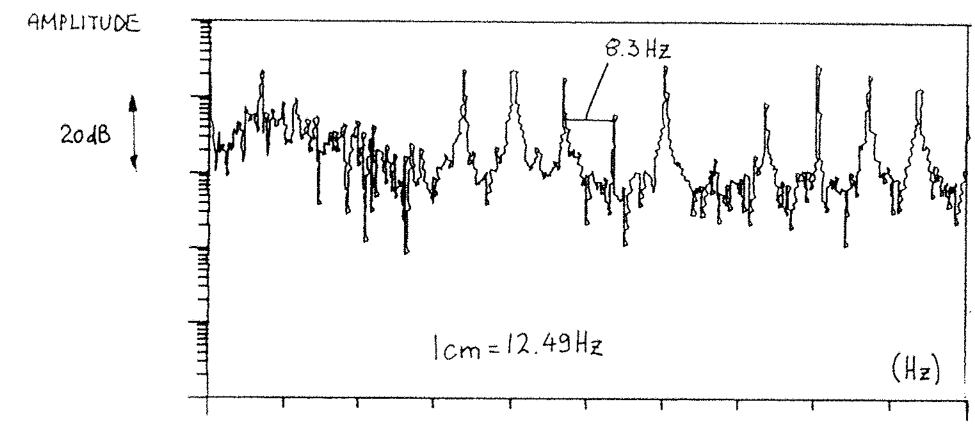



**Figure 5.22 |FFT| at full-load (silenced)**

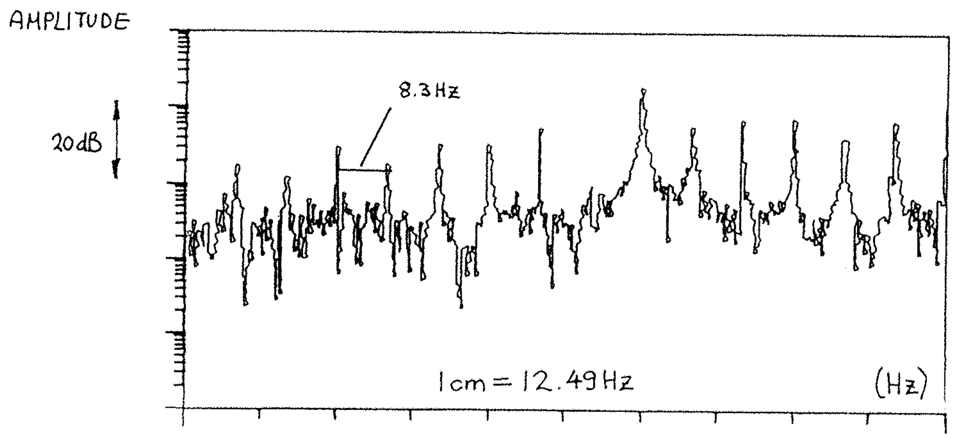



**Figure 5.23 |FFT| at full-load (unsilenced)**

Table 5.1

| Engine speed (rpm) | Modulation frequency (Hz) (same as fundamental firing frequency) | Firing frequency (Hz) |
|---|---|---|
| 450 | 3.75 | 45.0 |
| 570 | 4.75 | 57.0 |
| 795 | 6.63 | 79.5 |
| 900 | 7.50 | 90.0 |
| 1000 | 8.33 | 100.0 |

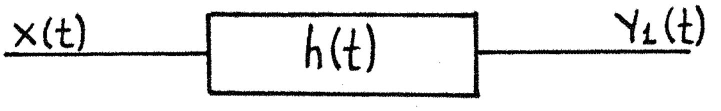
From the measurement it can also be observed that the modulation is also present in the unsilenced noise waveforms. This indicates that the silencer is not the source of modulation.

Suggestions that the source of modulation could be due to a panel resonance were soon abandoned after noise measurements carried out at various positions around a diesel engine showed an omnidirectional pattern of noise in the particular frequency range of interest. If a panel resonance was the reason for the modulation, then one should expect a figure of eight directional pattern [5.10]. Further noise measurements made on a smaller diesel engine in an anechoic chamber identified a similar modulation component to that of the Class 47 and 58 diesel engines. This indicates that the modulation in the Class 47 and 58 diesel engines could not have been created by the interaction of the engine and the structure in which it is installed.

## 5.7 Impulse Response of the Silencer

The impulse response, or frequency response, of the silencer is considered here to be the difference between silenced and unsilenced noise in the time or frequency domain respectively, as it was measured for that particular type of diesel engine.

The simple input/output relationships which follow explain the system which is considered here. In order to perform this type of analysis it was assumed that the system is linear, and the effect of the silencer interfering with the exhaust processes so as to modify the breathing characteristics of the engine was considered negligible. In the time domain the system can be considered as follows:




where $x(t)$ is the input function, $y_1(t)$ is the function describing the resulting noise waveform without the silencer, and $h(t)$ is the impulse response of the system. For a linear system in the time domain the output is given by the convolution of the input and the impulse response of the system.

$$y_1(t) = x(t) * h(t) \tag{1}$$

Expression (1) in the frequency domain is a much simpler relationship, given by:

$$Y_1(\omega) = H(\omega).X(\omega) \tag{2}$$

where $Y_1(\omega)$ is the frequency response of the output without the silencer, $X(\omega)$ is the frequency response of the input, and $H(\omega)$ is the frequency response of the system. Equations (1) and (2) describe the input/output relationships of the system without the silencer in the time and frequency domain, respectively. Similar expressions can be written relating the input and output of the system when the silencer is present. In the time domain we have

$$y_2(t) = h(t) * x(t) \tag{3}$$

where now $y_2(t)$ is the resulting waveform of the noise as modified by the silencer. In the frequency domain, equation (3) becomes:

$$Y_2(\omega) = H(\omega).X(\omega) \tag{4}$$

From equations (2) and (4) the frequency response of the silencer can now be obtained:

$$(2), (4) \qquad H(\omega) = \frac{Y_2(\omega)}{Y_1(\omega)} \qquad (5)$$

The frequency response of the silencer is shown in Figure 5.24, and it can be observed that it is very similar to a low pass filter with a cut-off at about 80 Hz and a rate of decay approximately 12 dB/octave. Figure 5.25 shows the impulse response of the silencer.

## 5.8 Exhaust Pulse - the Effect of the Silencer

The diagram in Figure 5.26 shows the theoretical shape of a typical exhaust pulse of a diesel engine. The first peak is associated with the steep pressure gradient which exists between points A and B before the exhaust valve opens. The second peak is due to the motion of the piston. An exhaust pulse was simulated using the D.A.C. computer and is shown in Figure 5.27 . This was then duplicated twelve times, corresponding to the twelve cylinder firings per cycle. The pattern of the twelve pulses was arranged so that it corresponded to the full-load condition of the engine running at 1000 rpm (see Figure 5.28). This was to be the excitation function, which will be the input to the system having as an impulse response that of the silencer which was previously calculated. In order to obtain the modelled waveform, the frequency response of the silencer was multiplied by the frequency response of the simulated exhaust pulses. By taking the inverse Fourier transform of the result of the product, the actual modelled waveform of the silenced noise was obtained, as shown in Figure 5.29.

It can be observed that there is no modulation present in the modelled waveform as it is with the actual waveform. This rules out the assumption that the silencer could be the source of the modulation.

## Conclusion

From the measurements in this chapter it was found that the modulation frequency in the noise waveform of the diesel is related to the fundamental firing frequency of the engine. Furthermore, there was no proof that the modulation was created by either a panel resonance or the interaction of the engine and the structure in which it was installed.

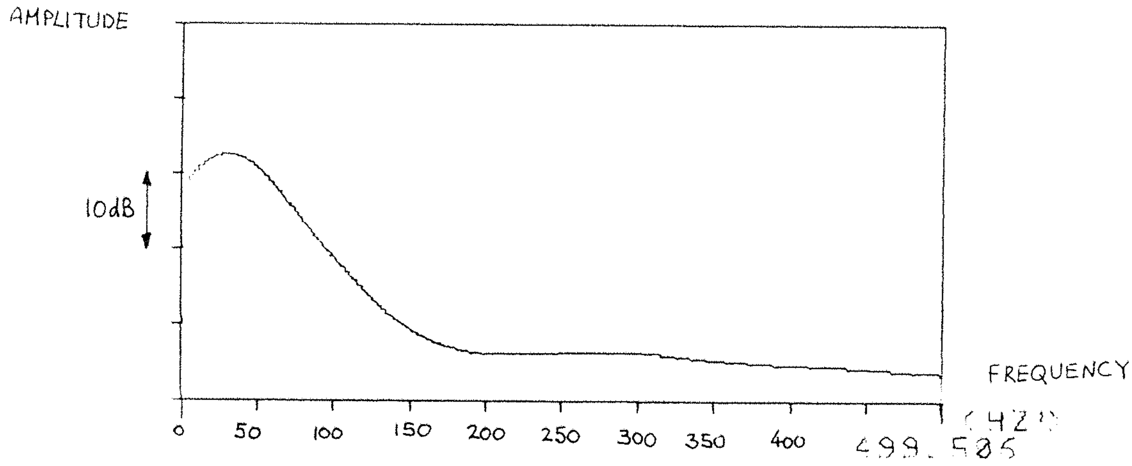



**Figure 5.24** Frequency response of the silencer fitted in the Class 56 diesel locomotive

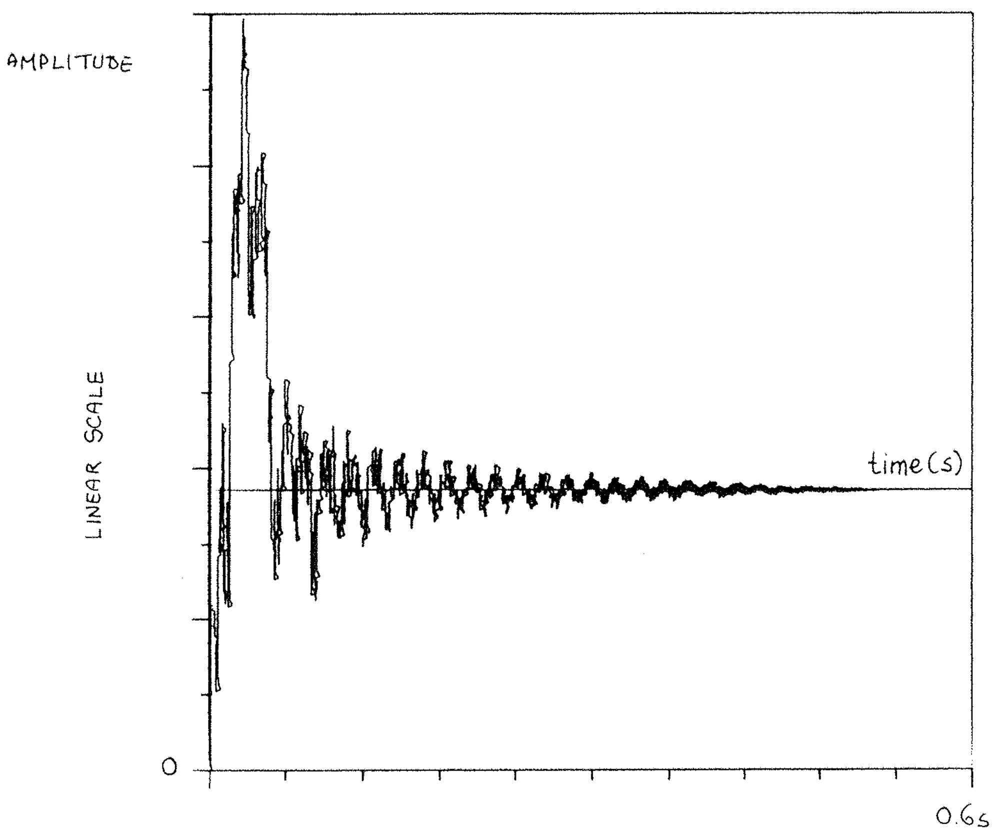
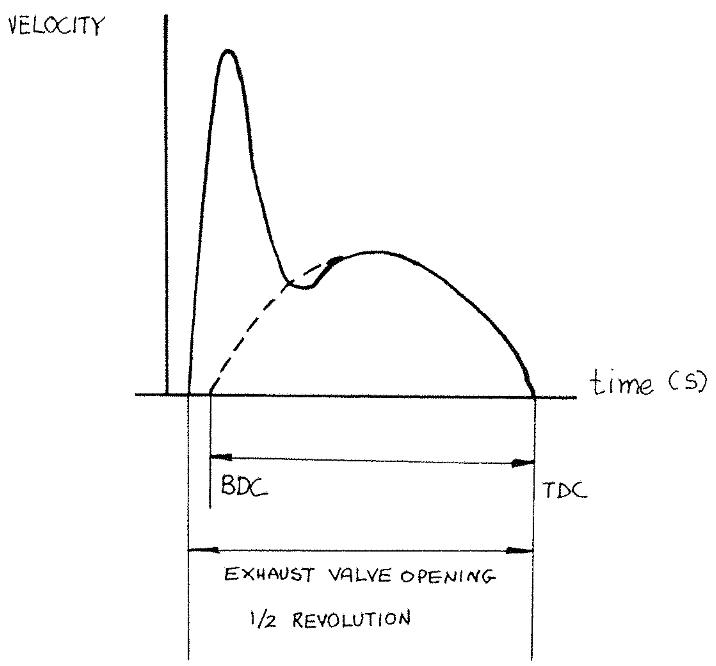



**Figure 5.25** Impulse response of the silencer fitted in the Class 56 diesel locomotive



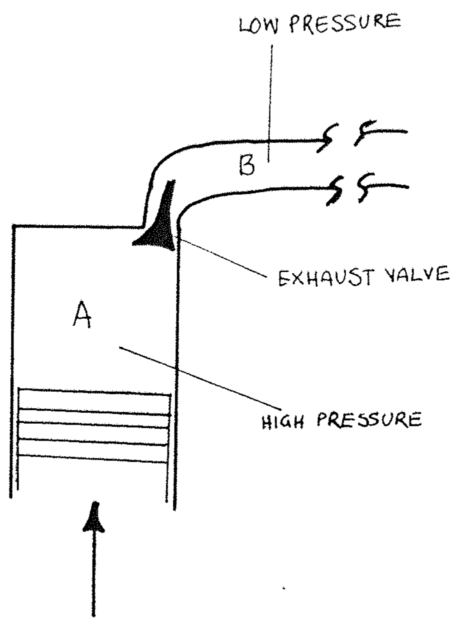




**Figure 5.26 Theoretical shape of the exhaust pulse**

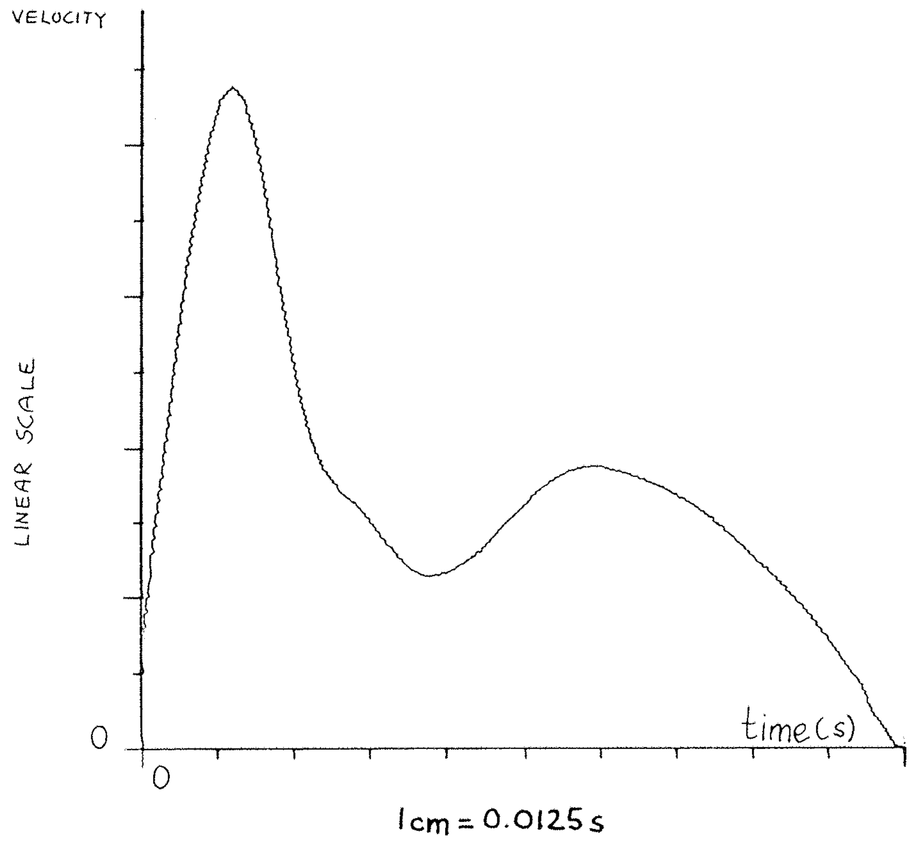



**Figure 5.27 Simulated exhaust pulse**

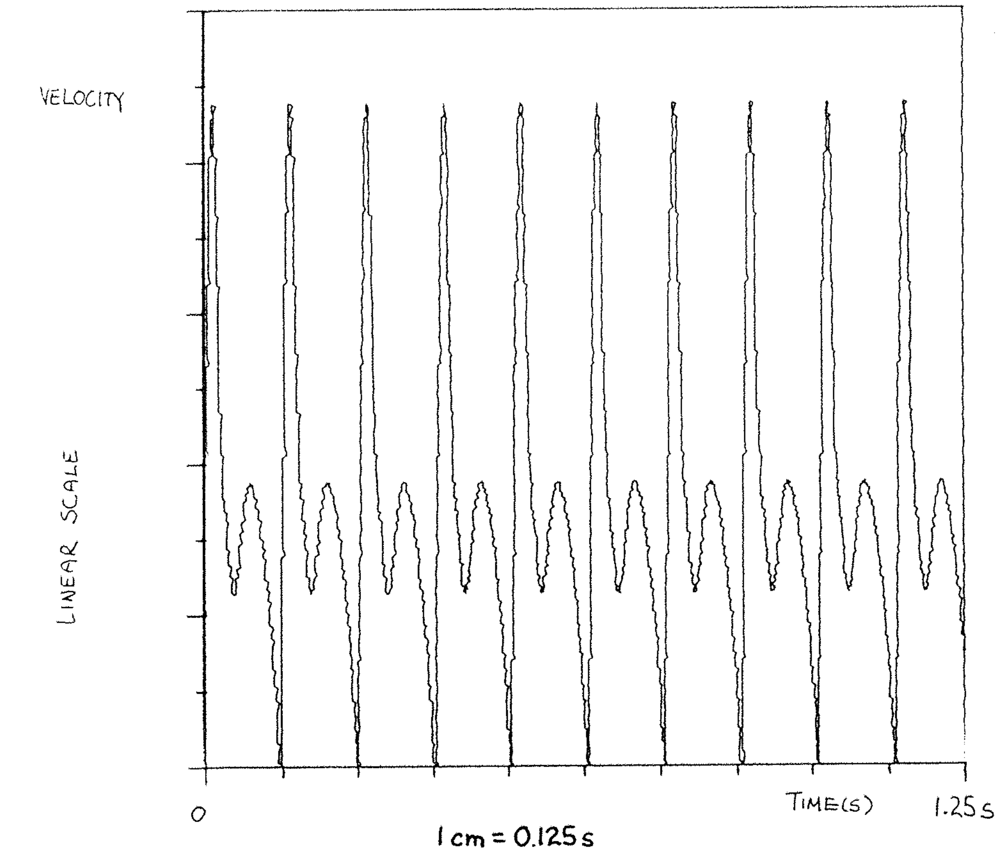



**Figure 5.28 Series of 12 exhaust pulses**

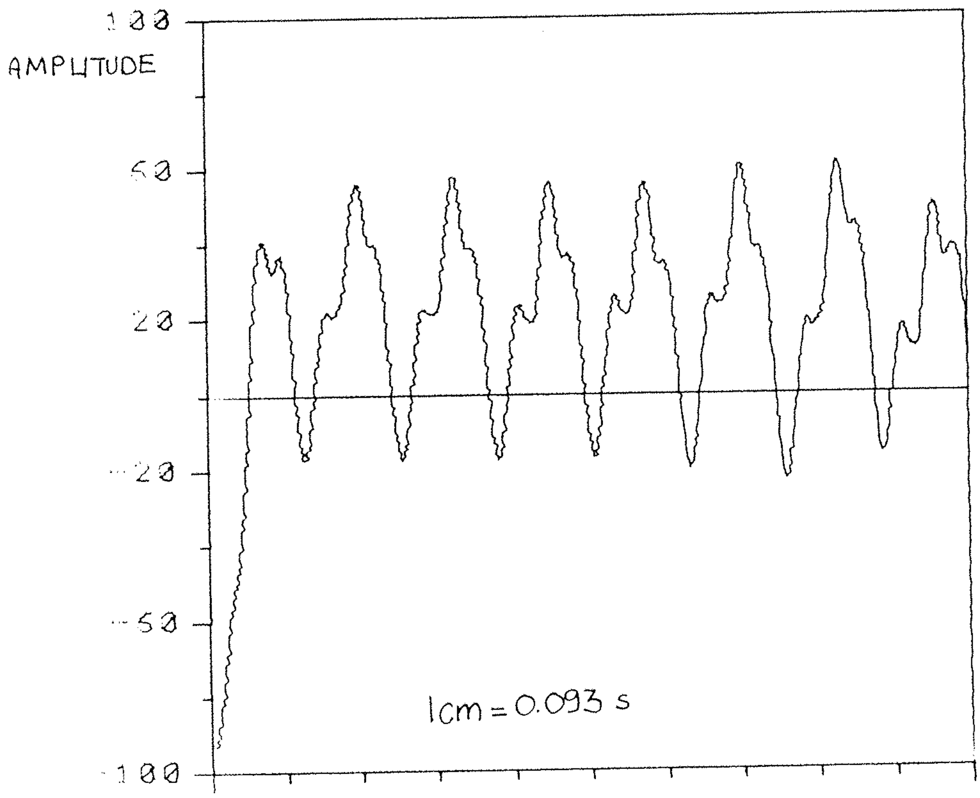



**Figure 5.29 Modelled waveform of the silenced exhaust noise**

# 6. DEMODULATION

## 6.1 Introduction

This chapter is concerned with the estimation of the modulation component in the noise waveform.

First, a literature survey was carried out to investigate the perception of amplitude modulated noise.

Using signal analysis theory, the envelope of the modulation was calculated. Having an expression for the modulation component an attempt was made to reduce the "pulsing" character of the noise by demodulation.

## 6.2 The Subjective Effect of Low Frequency (0–10 Hz) Amplitude Modulation

Modern research on the effect of modulated noise started with Miller and Taylor (1948) [6.1]. They observed that if a wide band noise is gated on and off regularly, observers hear a weak but distinct pitch, and furthermore, many observers can match the pitch to that of a sinusoid quite accurately. From the theory of amplitude modulation used extensively in communication systems a carrier tone with frequency $f_c$, amplitude modulated by another tone with frequency $f_m$, is given by

$$(1 + a \cos 2\pi f_m t) \cos 2\pi f_c t \qquad (1)$$

where $a$ is the modulation depth. For $a = 1$, the envelope varies sinusoidally between 0 and 2. Figure 6.1 shows the waveforms of some complex stimuli. Figure 6.1a illustrates the waveform for the case of two simple tones $f_1 = 9.5\ f$ and $f_2 = 10.5\ f$. Equation (1) can also be written as

$$\tfrac{1}{2}a \cos 2\pi(f_c - f_m)t + \cos 2\pi f_c t + \tfrac{1}{2}a \cos 2\pi(f_c + f_m)t \qquad (2)$$

demonstrating that the amplitude modulated stimulus can be interpreted as the sum of three tones with frequencies $f_c - f_m$, $f_c$, $f_c + f_m$ and specific amplitude and phase relations. Figure 6.1b gives the compound waveform for the case $f_c = 10\ f_m$. Shifting the phase of the middle component of equation (2) from 0° to ±90° has a strong influence on the signal's envelope. This is illustrated in Figure 6.1c where it can be observed that the envelope is nearly flat.

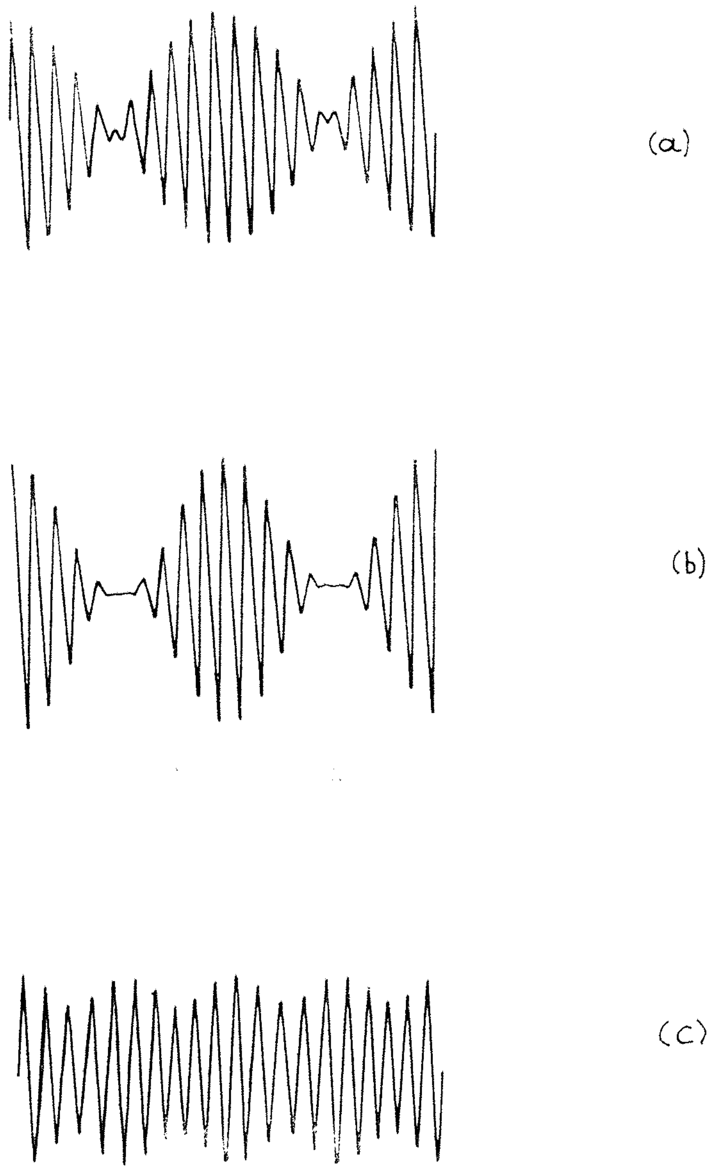



Figure 6.1 Waveforms of complex stimuli

Miller and Taylor also found that the roughness sensation produced by the amplitude modulation can be reduced by shifting the phase of the middle component in equation (2) over $90^o$. This demonstrates that periodic amplitude variations are clearly perceived as long as the ear is unable to analyse the complex stimulus into its sinusoidal components.

The degree to which the roughness of sinusoidally amplitude modulated tones depends upon the physical parameters of the stimulus was extensively studied by Terhardt [6.2]. Some of his results follow here.

The slow loudness variations audible for low modulation frequencies change into a "rattle" for faster modulations. The transition frequency appears to be nearly independent of carrier frequency. For 100% amplitude modulation, it varies from $f_m$ 20 Hz for $f_c = 250$ Hz up to $f_m$ 30 Hz for $f_c = 4000$ Hz. A further increase of modulation frequency results in a progressively rougher sensation which is maximal at $f_m$ 35 Hz for $f_c = 125$ Hz and $f_m$ 75 Hz for $f_c \geqslant 1000$ Hz. Roughness scaling showed that if $f_c$, $f_m$ and sensation level are kept constant, a factor of two in roughness corresponds rather well to $\sqrt{2}$ in modulation depth. This holds generally, almost independently of the other stimulus parameters. It means that every reduction of the levels of the components with frequencies $f_c - f_m$ and $f_c + f_m$ by 3 dB results in halving the amount of roughness.

These studies so far refrain from attempting to investigate low modulation frequencies below 20 Hz. Rather high modulation frequencies (in the order of 100 Hz) have normally been used [6.3, 6.4, 6.5].

Dubrovskii and Tumarkina conducted a study [6.6] which had as an objective the detailed investigation of the characteristic features of amplitude modulated noise and their associated subjective criteria by which people distinguish such noise from unmodulated noise. The perception was studied in the range of low audio and infrasonic modulation frequencies from 0.5 to 100 Hz. Also investigated was the role of conditioning of the subject to the perception of amplitude-modulated noise. Some of the findings and their implications are listed below.

The abrupt changes in the absolute values of the thresholds were not the same for different modulation frequencies. This fact fosters the notion that a human being's every day experience is such that he can only accommodate to the perception of low-frequency modulations falling in the range 0.5–10 Hz. The perception of amplitude modulation noise at infrasonic modulation frequencies could not be based on a change in the spectral characteristics, since the spectrum of amplitude modulated noise at such modulation frequencies is essentially undistinguishable from the spectrum of unmodulated noise. For low modulation frequencies below 10 Hz the ear manages to keep up with the variations in the noise level. With an increase in modulation frequency, the variations in the level become too rapid for the stimulus rise and fall processes in the auditory system to be able to keep pace with the level changes. In this case the variations in the stimulation in the ear will occur approximately as shown in Figure 6.2 by the dashed curve. It is clear that the difference between the maximum and minimum excitation diminishes.

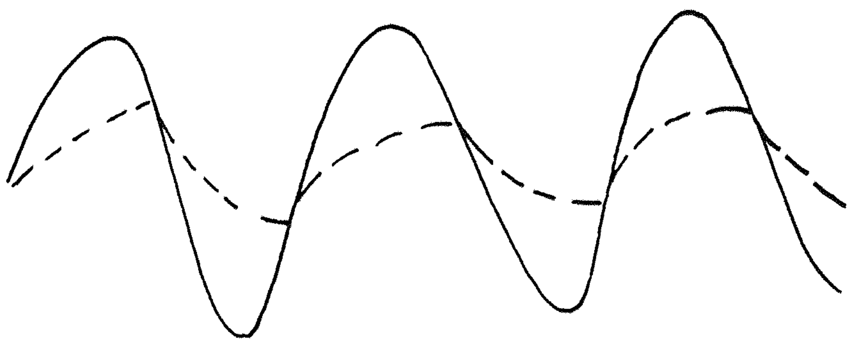


Figure 6.2 Envelope of amplitude modulated noise and the variations in stimulation in the ear.

According to Dubrovskii and Tumarkina, for rapid changes in the noise level the ear is no longer able to track these variations. Instead, the latter are summed or averaged. In other words, at modulation frequencies above 10 Hz the ear discloses integrating properties.

## 6.3 Amplitude Modulation

It is convenient to base the theoretical discussion of amplitude modulation on the assumption of a sinusoidal modulating signal. Figure 6.3 demonstrates this amplitude modulation [6.7].

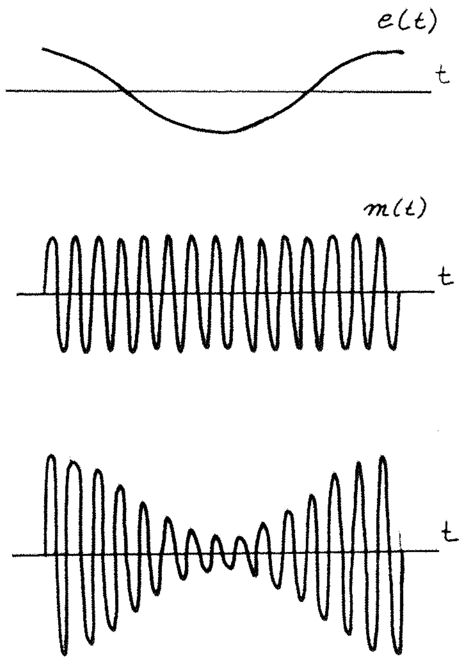



Figure 6.3 Amplitude modulation

Let us assume that e(t) is a sinusoidal signal expressed by $C \cos 2\pi f_c t$, while m(t) can be represented by $M \cos 2\pi f_m t$

$$e(t).m(t) = A_o C[1 + \frac{A_1 M}{A_o} \cos 2\pi f_m t] \cos 2\pi f_c t$$

In general, the above expression can be written

$$E_c[1 + \frac{E}{E_c} \cos 2\pi f_m t] \cos 2\pi f_c t$$

where $E_c$ is the amplitude of the unmodulated carrier, while the ratio

$E/E_C$ expresses the maximum fractional deviation of amplitude with respect to the unmodulated value, called index or depth of modulation. Figure 6.4 shows amplitude modulated waveforms for (a) 100% modulation, i.e., $E_C = E$ and (b) overmodulation, i.e., $E > E_C$.

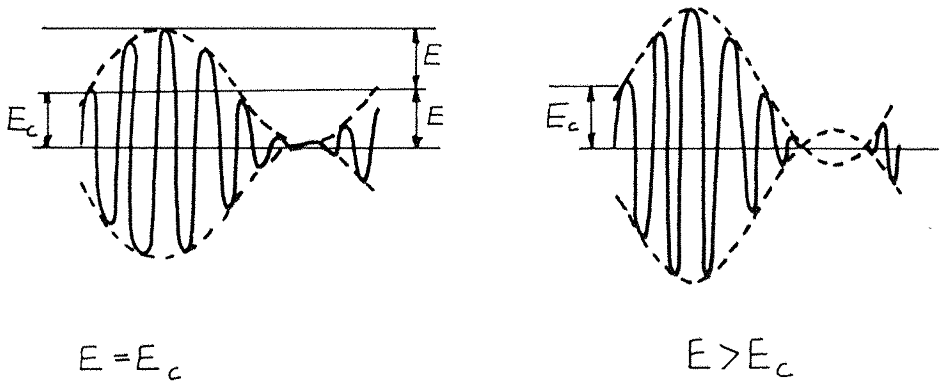



Figure 6.4 (a) 100% modulation; (b) overmodulation.

## 6.4 Envelope Analysis

### 6.4.1 Hilbert transform

The simplest non-mathematical way of describing the Hilbert transform of a time signal is to say that it gives all the frequency components of a signal a $-90^{o}$ shift, or in the time domain that it shifts each component by a quarter wavelength. This effect is similar to an integration of the signal [6.8]. As an example, the Hilbert transform of a sinusoid is shown in Figure 6.5. Using the letter $\mathcal{H}$ to denote the Hilbert transform, it is seen that

$$(\cos 2\pi ft) = \sin 2\pi ft,$$
$$(\sin 2\pi ft) = -\cos 2\pi ft, \quad \text{etc.}$$

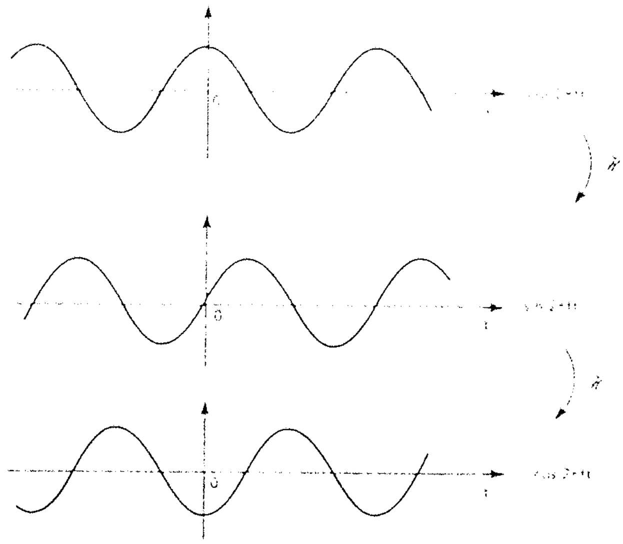


Figure 6.5 Hilbert transform of a sinusoid.

The Hilbert transform of a real valued signal, a(t), is defined as

$$[a(t)] = a(t) = -\int_{-\infty}^{+\infty} a(\tau)\ \frac{1}{t = \tau}\ d\tau.$$

### 6.4.2 Estimation of the envelope

In order to measure the amplitude modulation function of the signal f(nT) it is necessary to represent it as

$$f(nT) = m(nT).x(nT)$$

where m(nT) is the (discrete-time) envelope and x(nT) is the carrier signal.

In theory, such analysis is suitable for narrow band signals and will consider f(nT) to be a band limited signal since its frequency content was restricted during acquisition between 5 Hz and 1500 Hz [6.9].



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The envelope function $m(t)$ can be measured from the analytical signal [6.9] corresponding to $f(nT)$ where

$$f(nT) = f(nT) + jf_H(nT)$$

where $f_H(nT)$ is the Hilbert transform of $f(nT)$.

The envelope $m(nT)$ is the modulus of the analytical signal. Hence

$$m(nT) = \sqrt{(f(nT))^2 + (f_H(nT))^2}.$$

In the Data Analysis Centre there is a program which can be used to obtain the Hilbert transform of the signal and hence the envelope according to the equation above. This was employed for the estimation of the envelope of the signal.

Figure 6.6 shows the modulated signal of the exhaust noise of a Class 58 12-cylinder diesel engine running at 1000 rpm at full-load. The estimated envelope of the signal is shown in Figure 6.7.

## 6.5 Demodulation of the Diesel Engine Exhaust Noise

If the assumption that the modulation which is present in the diesel engine exhaust noise is amplitude modulation, then by performing demodulation it is possible to get back to the unmodulated noise signal. This in effect should minimise the "pulsing" character of the diesel.

Let us assume that $y(t)$ is the modulated noise. Then for amplitude modulation we can write:

$$y(t) = x(t).m(t)$$

where $x(t)$ is the unmodulated diesel engine exhaust noise, and $m(t)$ is the modulating function. Solving the above equation for $x(t)$ we get

$$x(t) = y(t)/m(t).$$

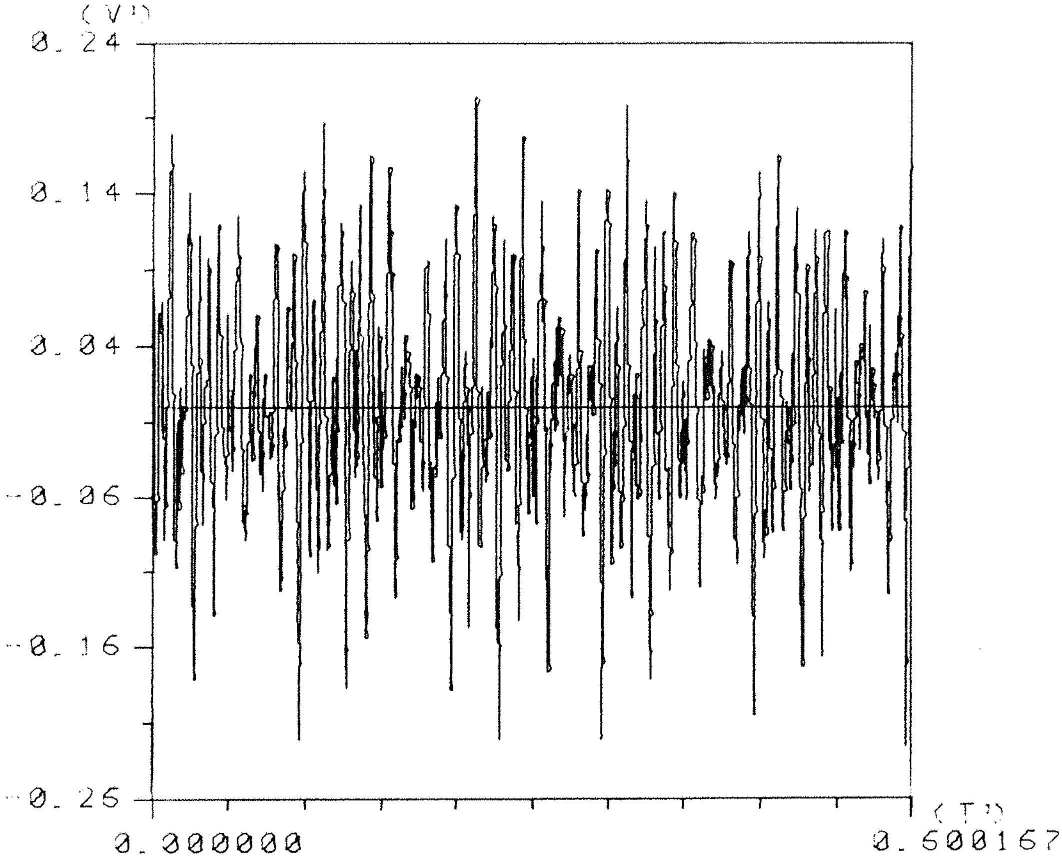



**Figure 6.6 Noise waveform at 1000 rpm full-load.**

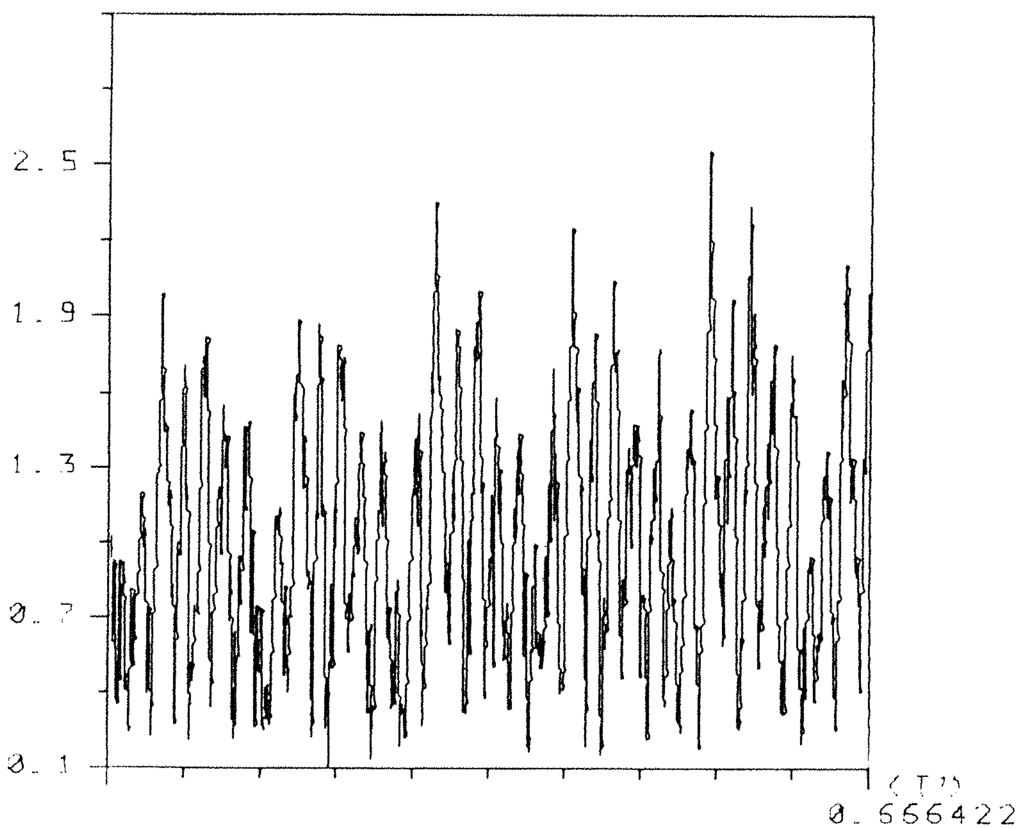



**Figure 6.7 Estimated envelope**

This was carried out using the DAC computer and x(t) was converted to analogue form through a digital-to-analogue conversion system. The demodulated signal is shown in Figure 6.8.

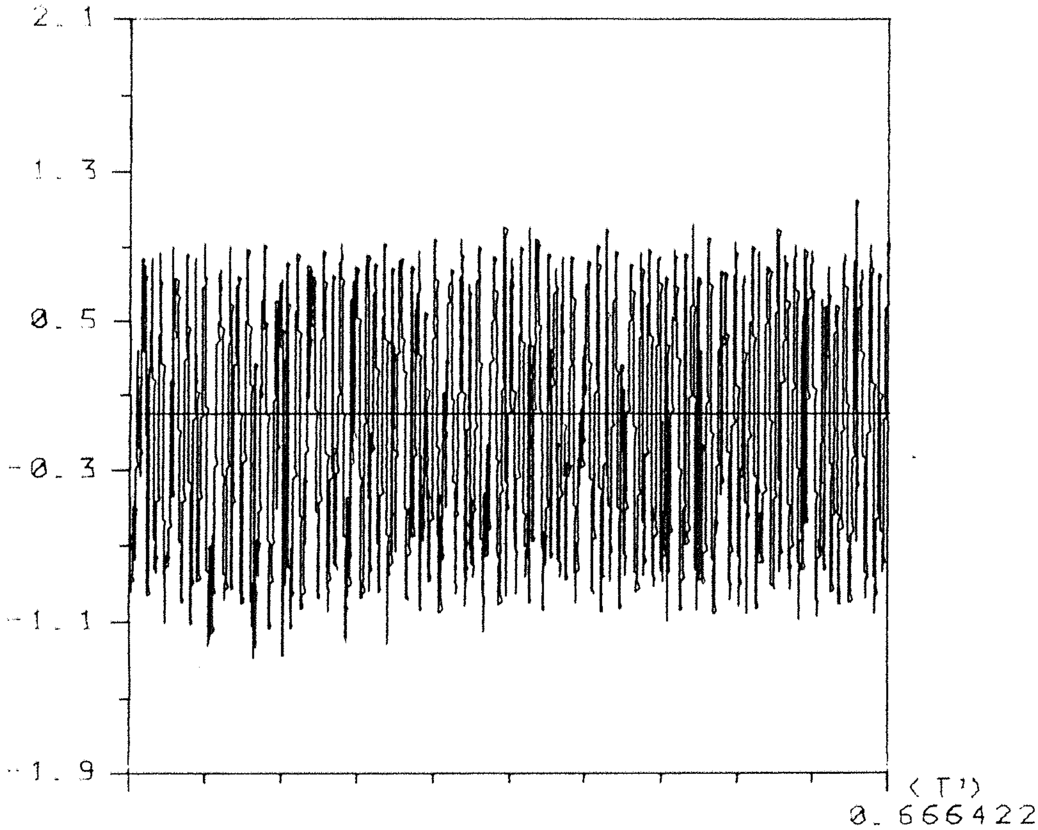



Figure 6.8 Demodulated noise waveform

# 7. SOURCES OF AMPLITUDE MODULATION

## 7.1 Introduction

In this chapter an attempt is made to explain the mechanism which generates the amplitude modulation in the noise waveform. The combustion noise and the exhaust pressure in a diesel engine are described first.

From the noise measurements in Chapter 5 it was found that the frequency of the modulation envelope was equal to the fundamental firing frequency of the engine. Thus the waveform of the noise can be regarded as a modulated waveform where the carrier frequency is the firing frequency of the engine, and the modulating frequency is the fundamental firing frequency.

It is suggested that the modulation must be created by the timing of the engine's firing in conjunction with the time delay introduced to each explosion by the exhaust manifold. In order to test this hypothesis the exhaust noise waveform was modelled taking into account the firing order, the time delay introduced by the manifold and the shape of the exhaust gas pressure.

Finally, a theory is described here which was developed in order to describe the maximum and minimum points in the envelope of the modulation.

## 7.2 Combustion-induced Noise

Combustion-induced noise is associated with unidirectional forces [7.1]. These are only important in the vicinity of TDC on the compression stroke, and are produced from compression and subsequent pressure rise which results from the combustion. In the engine equivalent system shown in Figure 7.1, the undirectional force excitation is shown. Since, during this period, the force does not change its direction, any significant vibration can only be produced if there is a rapid change in the magnitude of the force. This rapid change in the magnitude is produced by the onset of combustion in the engine cylinder and thus can be defined as combustion-induced noise. As can be seen, the gas force $P_g$ excites the

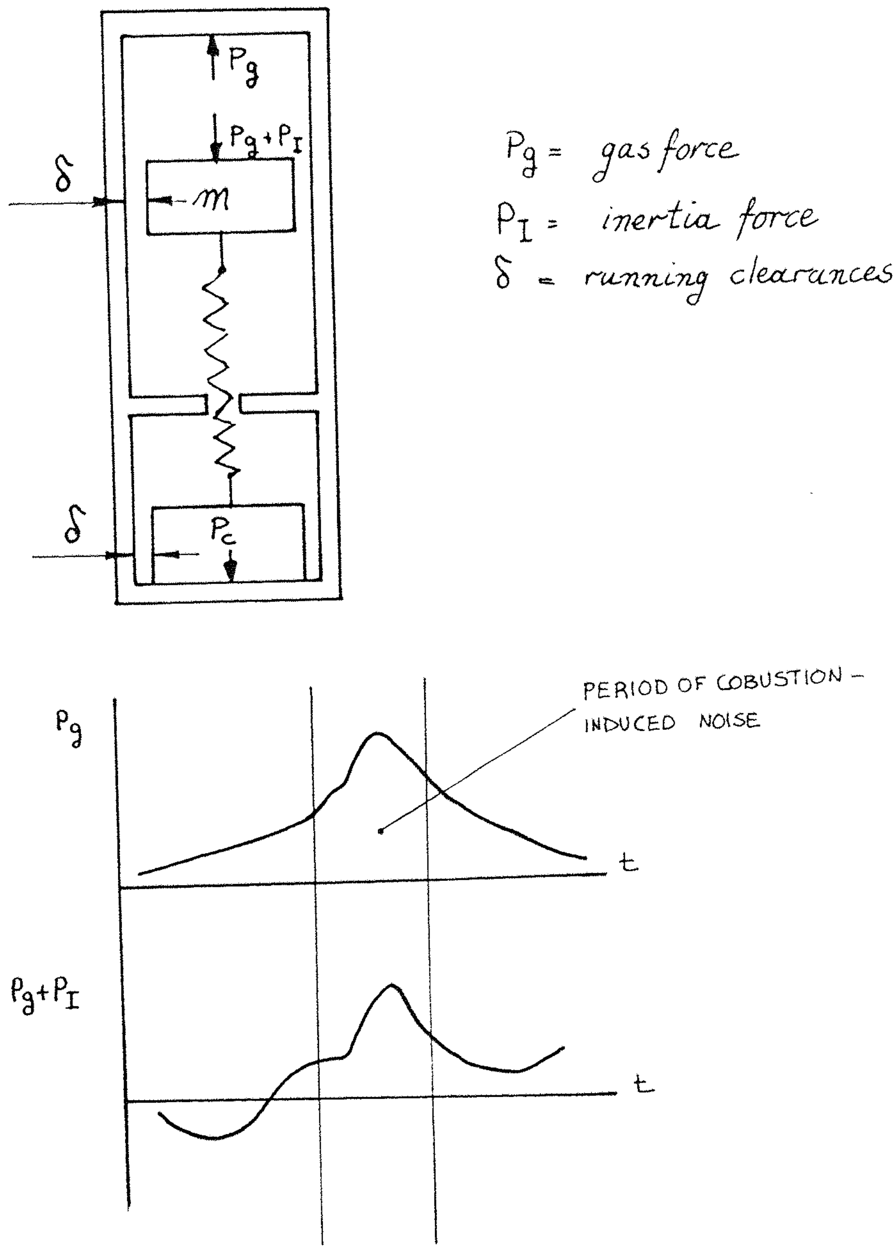



**Figure 7.1 Combustion induced noise**

combustion-induced noise. As can be seen, the gas force $P_g$ excites the top part of the engine structure, while the lower part of the structure is excited by the combined gas force and inertia force, $P_g + P_I$.

7.3 Exhaust Pressure

When the exhaust valve opens towards the end of the firing stroke, namely from about 45° to 55° before bottom dead centre, the pressures of the gases in the cylinder are much higher than atmospheric. The effect of this sudden release of high pressure hot gases upon the mass of cooler gases in the exhaust pipe and silencing systems is to set up a series of pressure waves, the amplitudes and frequencies of which depend upon several factors, including (a) the dimensions and design of the exhaust silencing system; (b) the number of cylinders; (c) the engine speed; (d) the inlet and exhaust valve timing; and (e) the compression ratio [7.2]. The pressure waves are actually sound waves of definite frequencies which can be calculated approximately for the cylinder and exhaust pipe combination, regarded as an acoustical resonator from the following equation

$$\text{Frequency} = \frac{V_s}{2\pi}\sqrt{\frac{A}{V(\ell + 0.89\sqrt{A})}}$$

where $V$ = cylinder volume, $V_s$ = velocity of sound, $A$ = cross-sectional area of pipe, $\ell$ = length of pipe.

In Figure 7.2, exhaust pressure diagrams are shown at 1000 rpm and 3400 rpm as measured by Dr. J.C. Morrison on a single cylinder engine. The base scale corresponds to 600 degrees of crank angle, i.e., less than a complete cycle. It will be observed that at the lowest speed the pressure waves are roughly of the damped sine wave form and almost die out before the exhaust valve opens again. A similar pulse shape to that shown in Figure 7.2 was used in modelling the exhaust noise waveform of the Class 58 diesel locomotive.

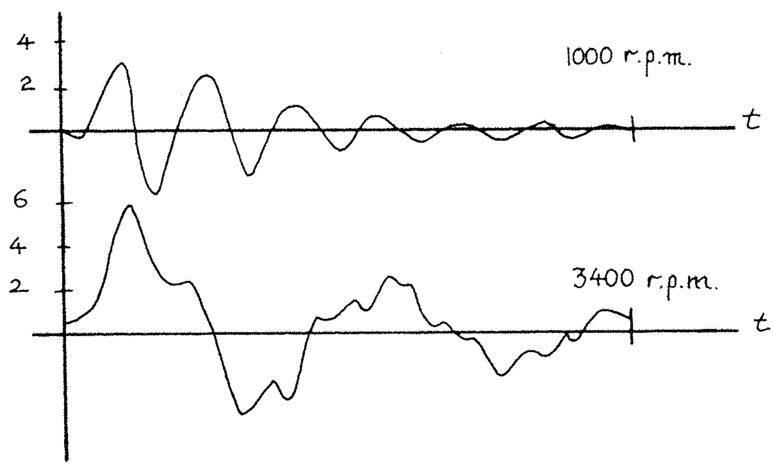



Figure 7.2 Exhaust pressure diagrams

## 7.4 Modelling of the Exhaust Noise Waveform

In Chapter 5 it was concluded that the amplitude modulation, which was present in the noise waveform of the diesel engine, was not caused by: (a) the silencer, (b) the interaction of the engine with the structure in which it was installed, or (c) panel resonances of the coachwork.

Examining the shape of the noise waveform at 1000 rpm for the Class 58 locomotive it can be observed that approximately every 1/8.34 second there is a group of twelve pulses which vary in amplitude. Therefore it seems that there is a mechanism which generates this variation in the amplitude of the twelve pulses. If this mechanism can be explained then we have identified the "source" of modulation. At this stage it appeared that a possible mechanism, which could generate the variation in the amplitude of the exhaust pulses, is the interaction of the engine's firing order with the time delay introduced by the exhaust manifold. This delay is due to the uneven nature of the pipe length that each pulse has to travel in the exhaust system.

In order to test this hypothesis a model was made to predict the noise waveform, which took into account: (a) the firing order of the engine, (b) the time delay introduced by the exhaust manifold and (c) the shape of the exhaust gas pressure. The model is based on the assumption that an exhaust pulse from cylinder B6 will reach point x more quickly than an exhaust pulse from cylinder B1 (see Figure 7.3). Taking into account the above-mentioned factors, the interaction of the twelve exhaust pulses at point x will produce a complicated waveform which will be repeated every cycle. Thus the ear, which is not able to analyse the complex waveform into its sinusoidal components, perceives the periodic amplitude variations instead [6.6]. These variations occur at a rate that the ear is able to perceive (0–10 Hz), as already mentioned in Chapter 6.

The model can be described analytically as follows.

Let the exhaust pressure pulse produced by each cylinder be described by the following expressions:

$w_1(t) = A_1 w(t - t_1)$ pulse from cylinder 1

$w_2(t) = A_2 w(t - t_2)$ pulse from cylinder 2

.

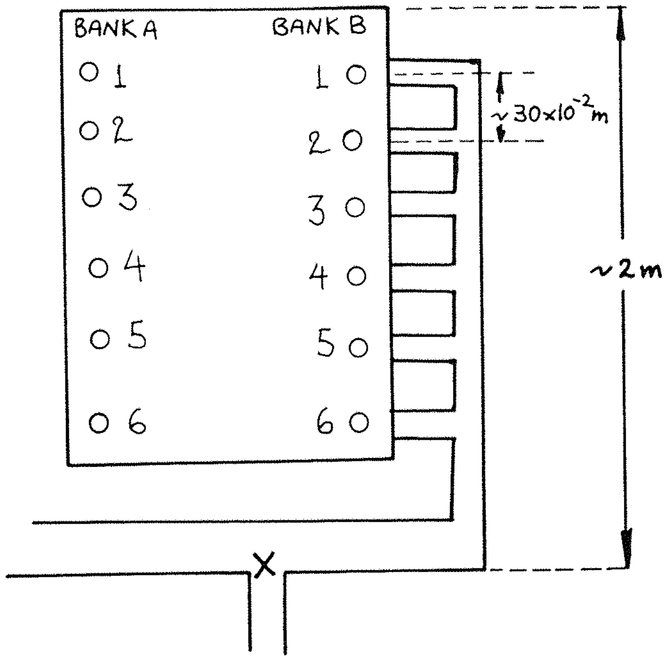
.

$w_{12}(t) = A_{12} w(t - t_{12})$ pulse from cylinder 12

where $t_1 \ldots t_{12}$ = time required for exhaust pulse to reach point x in seconds.

It was assumed that there is negligible attenuation travelling down the exhaust manifold due to friction and the reflected pulse is generated thus:

$A_1 = A_2 = \ldots. A_{12}$ (all pulses have equal amplitude)




FIRING ORDER: A 1 5 3 6 2 4
B 6 2 4 1 5 3

Figure 7.3 Engine and exhaust manifold arrangement

The resulting waveform will be

$$y(t) = \sum_{n=1}^{12} A_n w(t - t_n)$$

which is equivalent to

$$y(t) = \underbrace{w(t)}_{A} * \underbrace{\sum_{n=1}^{12} A_n \delta(t - t_n)}_{B}$$

where A is a function describing the shape of the exhaust pressure and B is a series of delta functions each placed at the time of arrival of each exhaust pulse at x. Table 7.1 shows the estimated time of arrival of the pulses from the twelve cylinders.

Table 7.1. Time delay for each exhaust pulse

| Cylinder | Time (s) |
|---|---|
| A1, B1 | 0.0044 |
| A2, B2 | 0.0038 |
| A3, B3 | 0.0031 |
| A4, B4 | 0.0024 |
| A5, B5 | 0.0018 |
| A6, B6 | 0.0011 |

The time was calculated from $t = s/v$ (s) where s is the distance of each cylinder from point x measured in metres and v is the speed of sound in $ms^{-1}$, which was assumed to be 450 $ms^{-1}$. At 1000 rpm a complete revolution takes 1/8.34 = 0.12 second. During that time, twelve exhaust pulses are generated, which implies that there is a pulse every 0.12/12 = 0.01 second. Table 7.2 shows the stimated time of arrival of each exhaust pulse at point x taking into account the order of firing of each cylinder.

Table 7.2 Time taken for each exhaust pulse to reach point x

| Cylinder | Time (s) | Difference (s) |
|---|---|---|
| A1 | 0.0044 | |
| | | 0.0076 |
| B6 | 0.011 | |
| | | 0.0110 |
| A5 | 0.022 | |
| | | 0.0120 |
| B2 | 0.034 | |
| | | 0.0090 |
| A3 | 0.043 | |
| | | 0.0090 |
| B4 | 0.052 | |
| | | 0.0090 |
| A6 | 0.061 | |
| | | 0.0130 |
| B1 | 0.074 | |
| | | 0.0100 |
| A2 | 0.084 | |
| | | 0.0080 |
| B5 | 0.092 | |
| | | 0.0100 |
| A4 | 0.102 | |
| | | 0.0110 |
| B3 | 0.113 | |

Using this information a series of delta functions was created in the DAC computer with each delta function placed at the time given in Table 7.1 as shown in Figure 7.4. As an exhaust pulse a damped sinewave was used, given by

$$w(t) = Ae^{\lambda t} \sin 2\pi ft$$

where $f = 130$ Hz and $\lambda = 25$, the decay ratio. This is shown in Figure 7.5.

The damped sinewave function was then convoluted with the series of the delta functions, thus givng us the combined waveform at point x. This is shown in Figure 7.6 and is repeated every complete cycle of the engine. The resulting waveform is shown in Figure 7.7 and shows great similarity to the original noise waveform of the Class 58 diesel engine at 1000 rpm, full-load condition, shown in Figure 7.8. When it was converted back to analogue form, for subjective evaluation, it was found to be

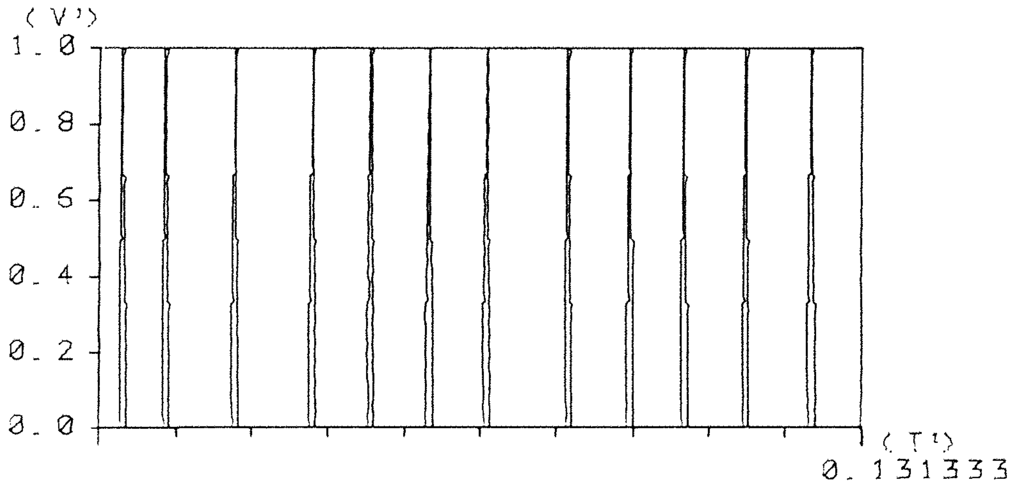



**Figure 7.4 Series of delta functions unequally spaced**

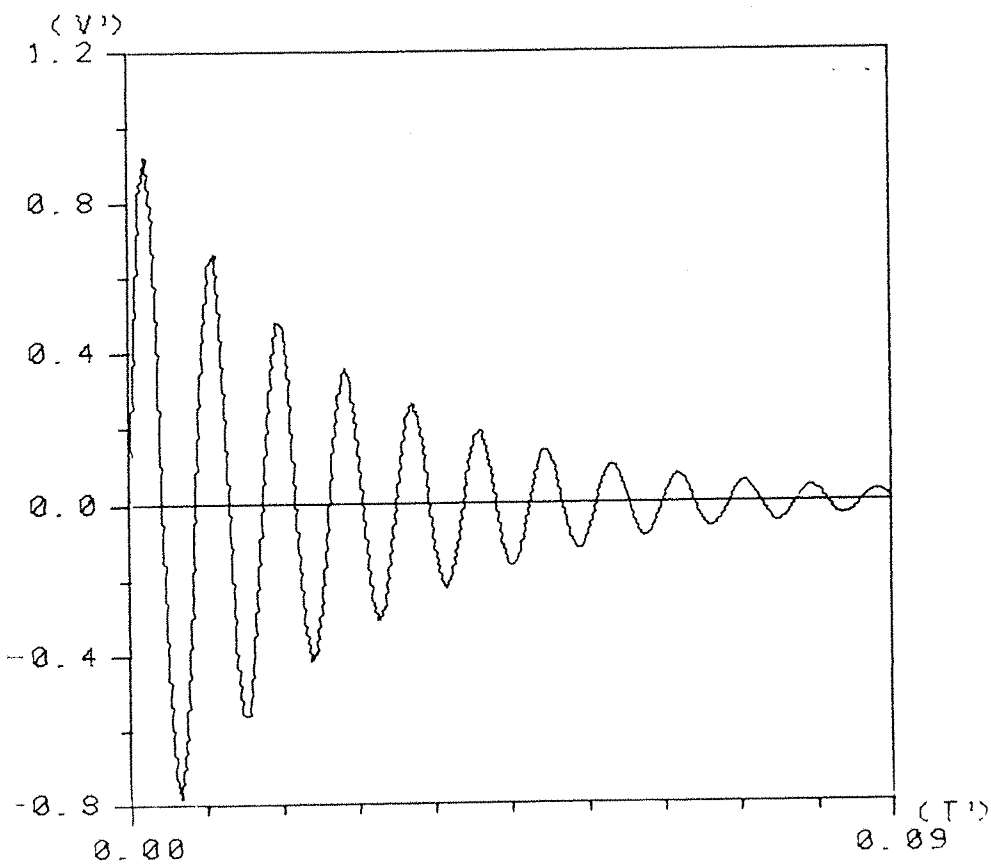



**Figure 7.5 Simulated exhaust pulse**

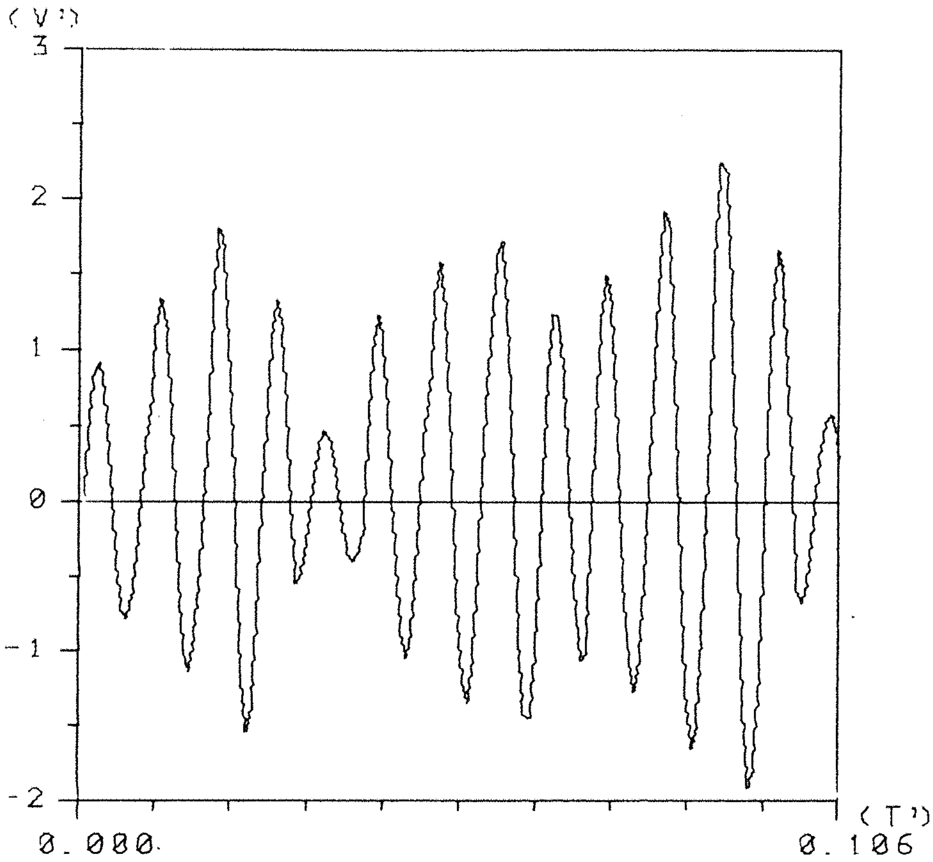



**Figure 7.6** **Convolution of simulated exhaust pulse with the series of delta functions**

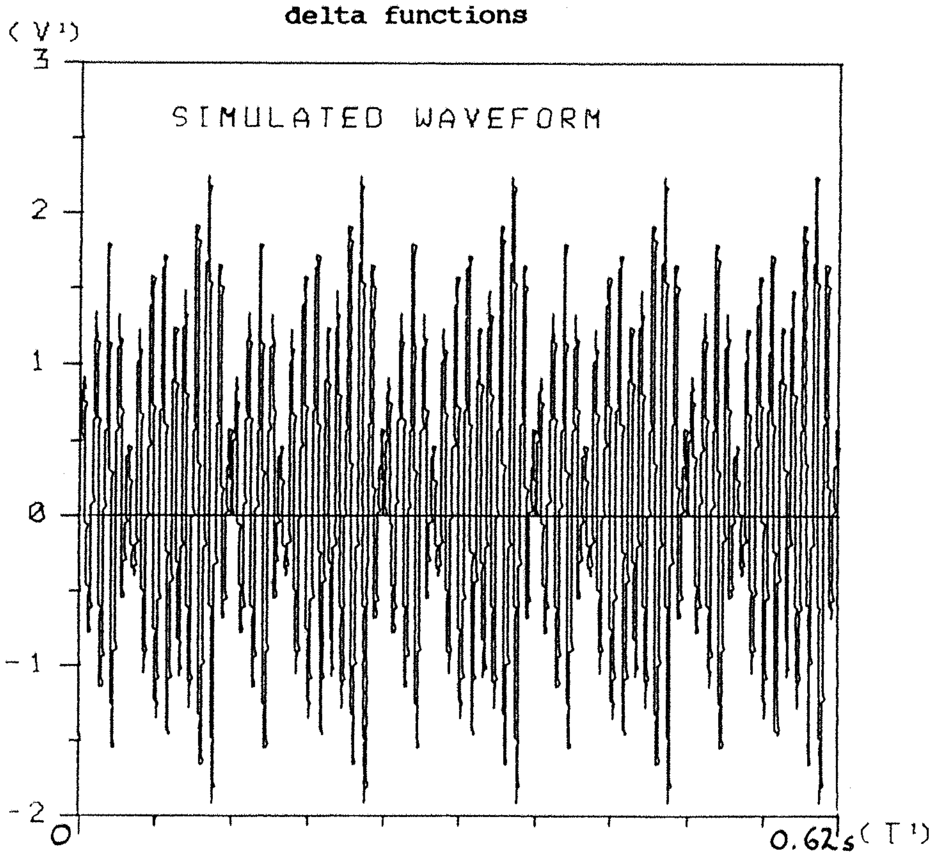



**Figure 7.7** **Simulated waveform at 1000 rpm full-load, resulting from the unequally spaced pulses**

similar to the real noise. This means that the simple model used here to describe the noise waveform is valid. This also identifies the source of amplitude modulation as being the unequal spacing of the exhaust pulses which is introduced by the exhaust manifold.

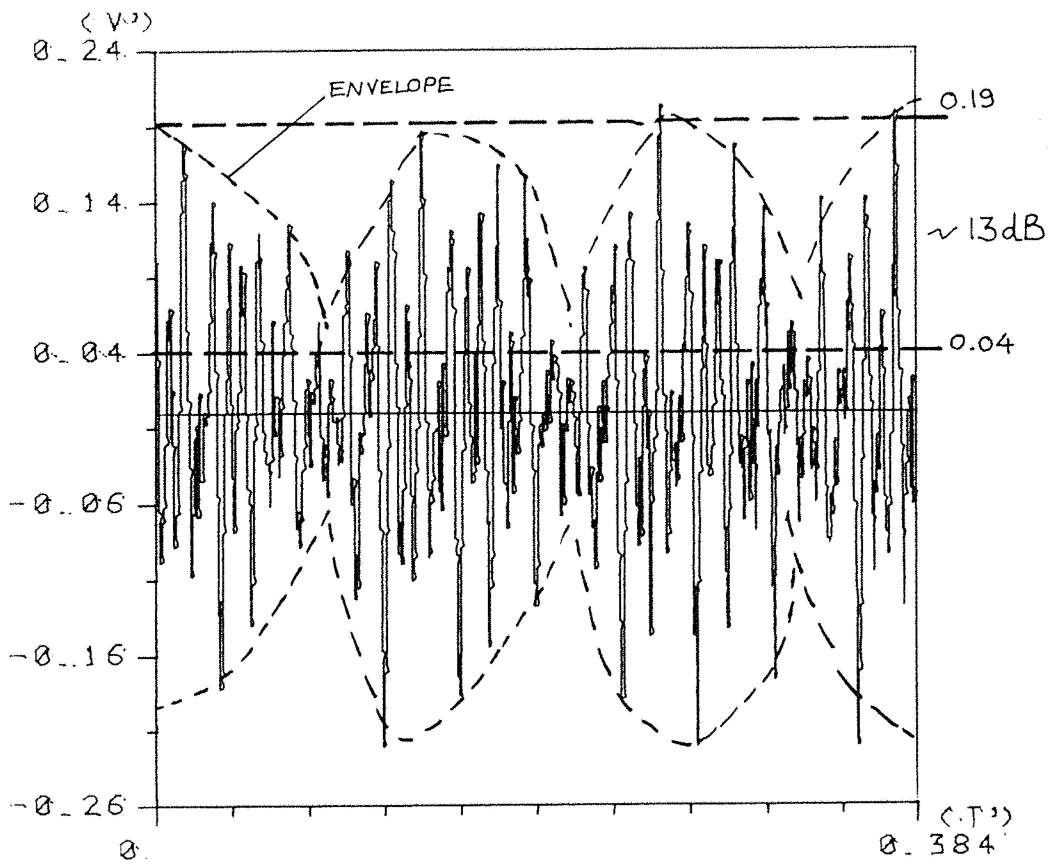



Figure 7.8 Real noise waveform at 1000 rpm full-load

## 7.5 Case for Minimum Modulation

The effect of the spacing of the pulses on the amplitude modulation was then investigated. The delaying effect of the exhaust manifold on the exhaust pulses was removed by creating a series of exhaust pulses which were spaced at 0.01 s intervals. Figure 7.9 shows a series of twelve delta functions which are equally spaced.

Using the same method as previously a new waveform was obtained by convoluting the damped sinewave in Figure 7.5 with the series of the equally spaced delta functions. The result is shown in Figure 7.10 which illustrates the noise waveform at 1000 rpm, full-load, resulting from

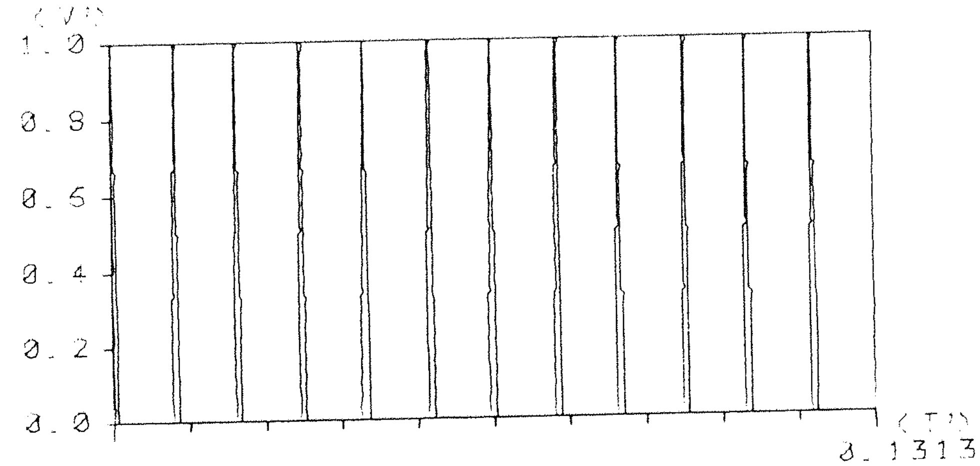



Figure 7.9 Series of delta functions equally spaced

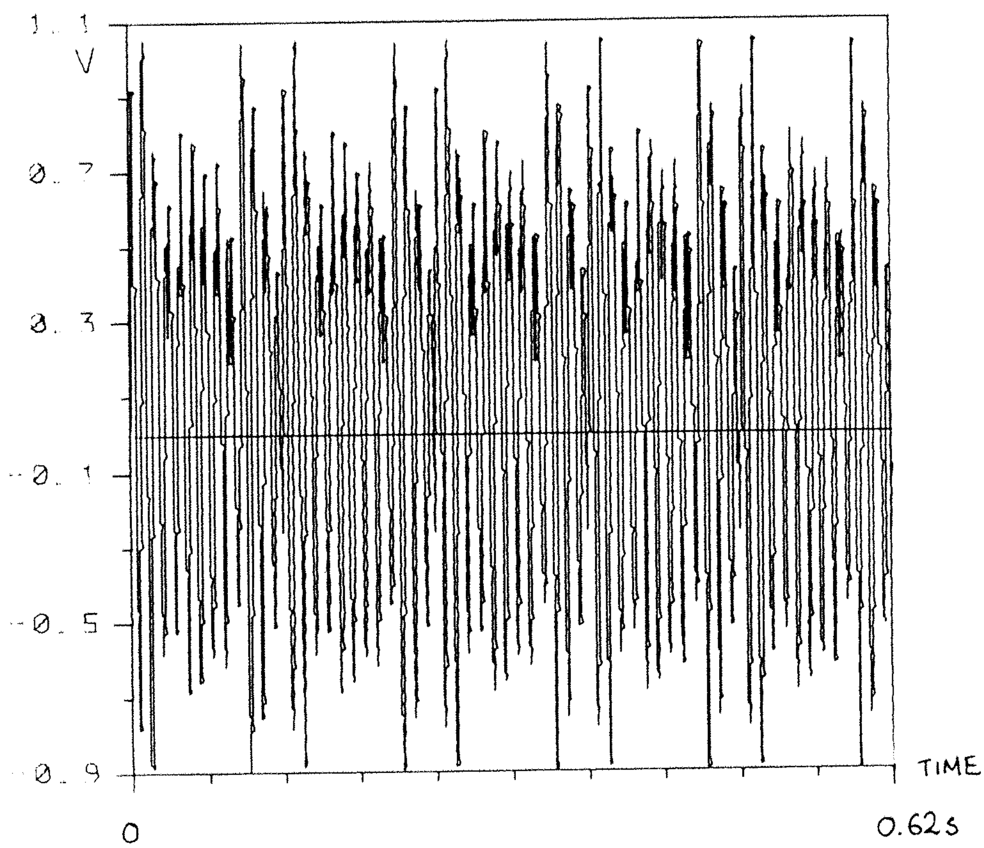



Figure 7.10 Simulated waveform at 1000 rpm full-load, resulting from the equally spaced pulses

equally spaced exhaust pulses. The depth of modulation is shown to be reduced by approximately 10 dB. Although both noise waveforms of Figures 7.7 and 7.10 have the same frequency spectra, they sound different. The waveform which resulted from the equally spaced exhaust pulses sounds smoother and tends to hide the "pulsing" character of the highly modulated waveform of Figure 7.7.

This result will be investigated further in a subjective experiment to determine whether a significant reduction in annoyance results from reducing the depth of modulation in the noise waveform.

## 7.6 Theory to Describe the Modulation Envelope

During the operation of the engine, every cycle can be described by the sum of the twelve exhaust pulses. This can be written as follows

$$\sum_{n=0}^{k-1} e^{-\sigma(t-t_n)} \sin \omega(t - t_n) = m(t) \sin(\omega t + \phi)$$

$k = 1, \ldots, 12.$

Expanding the sines we have

$$\sum_{n=0}^{k-1} e^{-\sigma(t-t_n)}(\sin \omega t \cos \omega t_n - \cos \omega t \sin \omega t_n)$$

$$= m(t)(\sin \omega t \cos \phi + \cos \omega t \sin \phi).$$

Equating sides we get

$$\sum_{n=0}^{k-1} e^{-\sigma(t-t_n)} \cos \omega t_n = m(t) \cos \phi$$

$$- \sum_{n=0}^{k-1} e^{-\sigma(t-t_n)} \sin \omega t_n = m(t) \sin \phi$$

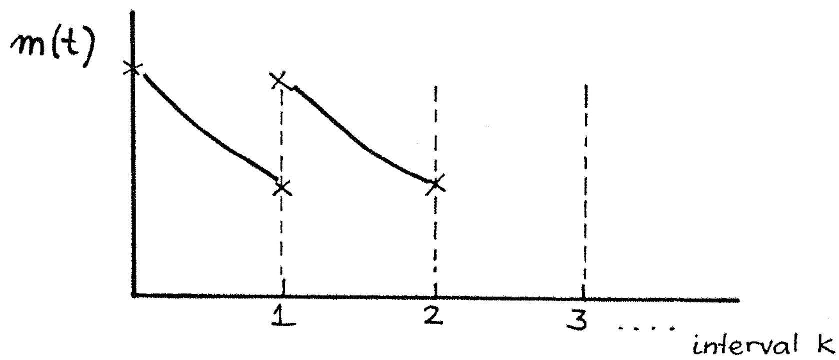
Squaring, we have

$$m^2(t) = \left( \sum_{n=0}^{k-1} e^{-\sigma(t-t_n)} \cos \omega t_n\right)^2 + \left( \sum_{n=0}^{k-1} e^{-\sigma(t-t_n} \sin \omega t_n\right)^2$$

and

$$m(t) = e^{-\sigma t}[(\sum_{n=0}^{k-1} e^{\sigma t_n} \cos \omega t_n)^2 + (\sum_{n=0}^{k-1} e^{\sigma t_n} \sin \omega t_n)^2]^{1/2}$$

The function m(t) looks as shown below




in each interval

$$m(t) = e^{-\sigma t}.c_k \tag{4}$$

$c_k$ is the constant in the interval which is given by

$$c_k = [(\sum_{n=0}^{k-1} e^{\sigma t_n} \cos \omega t_n)^2 + (\sum_{n=0}^{k-1} e^{\sigma t_n} \sin \omega t_n)^2]^{1/2}$$

Numerically one can calculate the value for c for $k = 1, \ldots, 12$. Assuming that the maximum m(t) for each interval occurs at the start, m(t) can be calculated at the start of each interval and the largest value is the maximum.

Similarly, the minimum of m(t) can be calculated by assuming that the minimum will be at the end of the interval.

### 7.7 Conclusions

With the existing exhaust manifold, the exhaust pulses from each cylinder are each delayed by a different amount, while travelling in the manifold and silencing pipework. The amount of delay controls the overlap of consecutive pulses, and in turn the amount of overlap determines the final shape of the resulting noise waveform.

It was found that the existing arrangement of the exhaust manifold, for the particular engine considered, produces a highly amplitude-modulated waveform of "pulsing" character. However, by arranging a series of equally spaced exhaust pulses, thus removing the effect of the manifold, it was possible to produce a new noise waveform with lower depth of modulation which had a "smoother" character.

# 8. SUBJECTIVE EVALUATION OF MODELLED WAVEFORMS

## 8.1 Introduction

An experiment was designed to investigate responses to modelled exhaust amplitude modulated noise waveforms of a typical diesel locomotive.

The factors examined in the experiment were:

1. depth of modulation
2. frequency of modulation (i.e., speed of the engine).

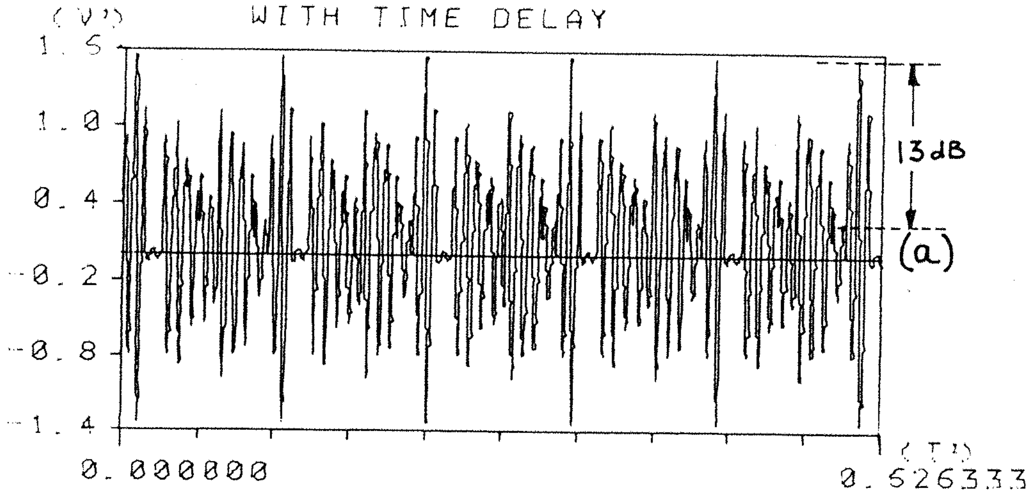
## 8.2 Modelled Waveforms

The basic aim of the experiment was to investigate whether variation in the modulation depth can be detected. Two different types of waveform were used, shown in Figures 8.1a and 8.1b. The waveform of Figure 8.1a is similar to the real situation where a time delay is introduced to the exhaust pulses from the manifold, as discussed in Chapter 7, thus creating a maximum to minimum ratio of about 13 dB. The waveform shown in Figure 8.1b was produced by equally spaced exhaust pulses and has a maximum to minimum ratio of about 5 dB. The two waveforms were converted to analogue form in order to be used in the experiment.

## 8.3 The Experiment

A laboratory experiment was designed to investigate the effect of the modulation depth and frequency of modulation on the subjective response. The following conditions were tested:

1. Two different depths of modulation, i.e., modulation 1 (M1) corresponding to high modulation depth and modulation 2 (M2) corresponding to low modulation depth. These are shown in Figures 8.1a and 8.1b.



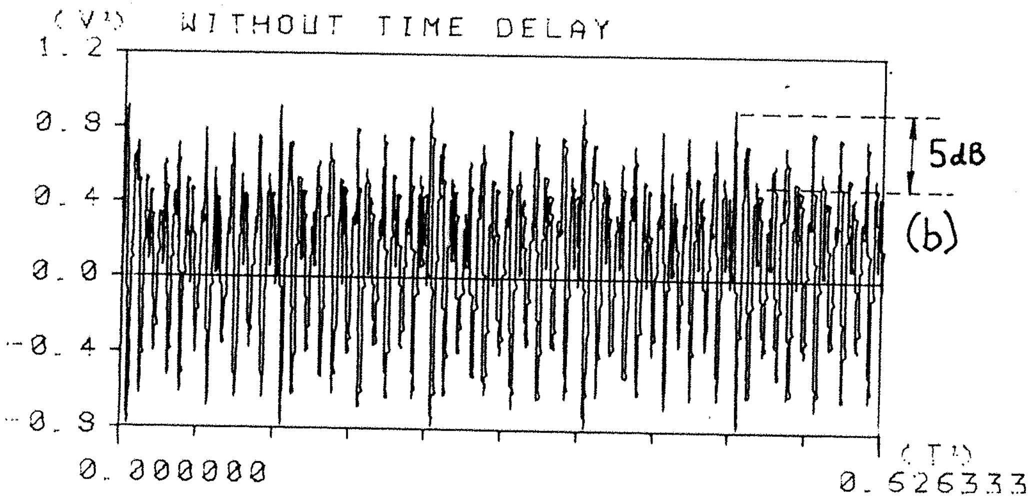




**Figure 8.1** **Modelled noise waveforms used in the experiment.**

2. Two frequencies of modulation, F1, F2, equivalent to two engine speeds, i.e., "HIGH", which corresponded to 2000 rpm and "LOW", which corresponded to 1000 rpm.

3. Each of the above conditions was presented at four levels (65, 70, 75 and 80 dB(A)).

Thus, the experiment consisted of 16 different treatments ($2 \times 2 \times 4 = 16$). To present the treatments a balanced Latin square design was used, as in previous experiments, to eliminate any order effect. Sixteen subjects were used and judged the relative annoyance of the sixteen different treatments. Each noise treatment was recorded on a single spool of tape and lasted for 20 seconds. There was an interval of about half a minute between treatments. During this time the subject was asked to judge how much annoyance resulted from the treatment by allocating a number on a 0 to 9 scale. The single session lasted approximately 20 minutes.

The subjects listened to the noises through a pair of high quality headphones. These were calibrated using KEMAR [8.1]. The frequency response is as good as expected of high-quality headphones and is shown in Figure 8.2.

The four different levels obtained inside the ear canal are shown below.

| | A weighted (dB) | Linear (dB) |
|---|---|---|
| L1 | 80 | 95 |
| L2 | 75 | 90 |
| L3 | 70 | 85 |
| L4 | 65 | 80 |

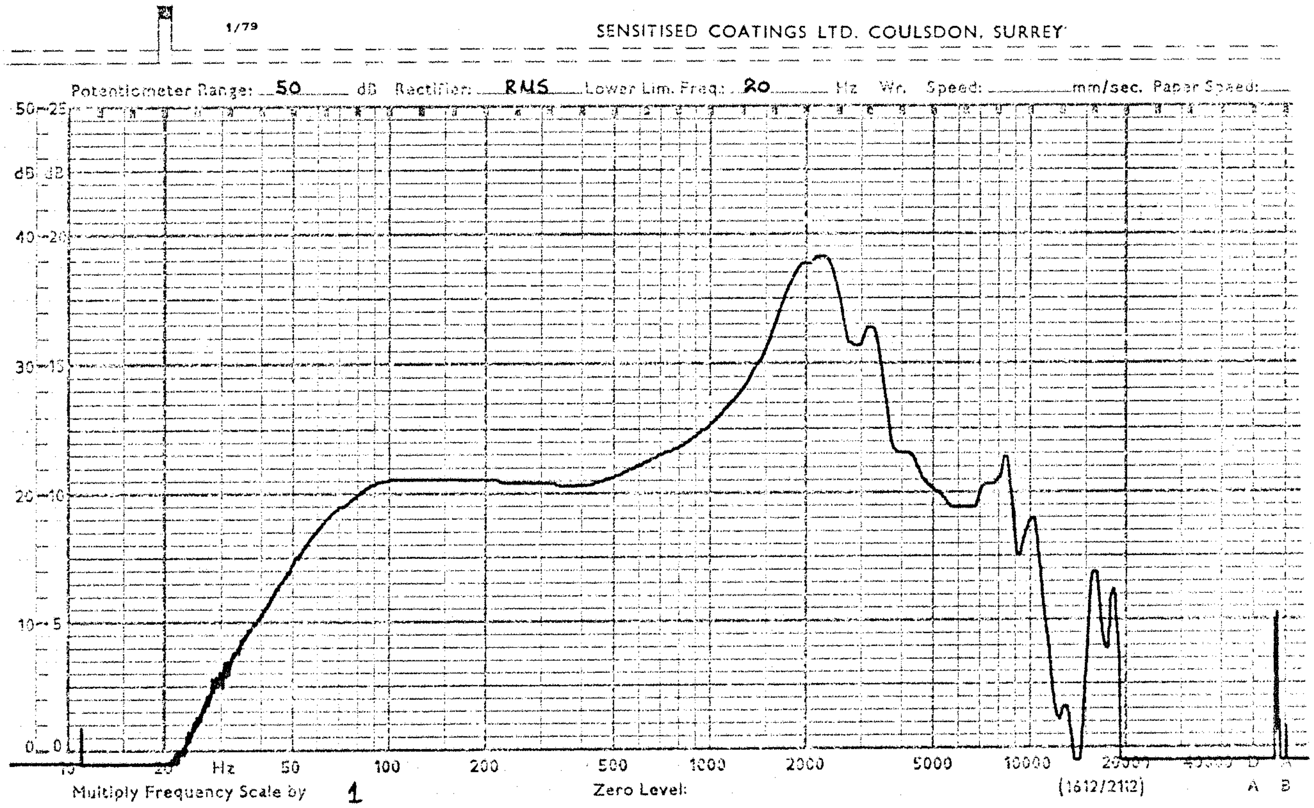



**Figure 8.2** **Frequency response of headphones used in the experiment (measured using KEMAR).**

## 8.4 Results and Analysis

The mean response score for each treatment was calculated and plotted (see Figures 8.3-8.6). The graphs show subjective annoyance rating against noise level in dB(A) for the different modulation depths and frequency of modulation (i.e., engine speed).

The results were analysed by using analysis of variance. Details of the analysis of variance are shown in Table 8.1. The variance ratio tests revealed that differences in subjects, noise levels and frequency were significant at the 1% level. Also, the interaction of modulation depth and frequency was found to be significant. The differences in the order of presentation and the modulation were not found to be significant at both 1% and 5% levels.

The important interactions were plotted and are shown in Figure 8.7. Subjective response scores were plotted against noise levels (see Figure 8.8). It can be observed that one point on the subjective scale corresponds to approximately 5 dB difference in noise level, and that the relation is linear.

## 8.5 Discussion

At noise levels above 70 dB(A) and engine speeds of 1000 rpm, the noise waveform with the high depth of modulation was subjectively more annoying than the noise waveform with the low modulation depth. At the faster engine speed of 2000 rpm, there was no significant difference in subjective response between the two different depths of modulation.

Perhaps the most important implication results from the significance of the interaction of frequency of modulation (engine speed) with modulation depth. As can be seen from Figure 8.7, at a modulation frequency of approximately 8 Hz (1000 rpm) the high modulation depth of 13 dB was subjectively more annoying than the low modulation depth of 5 dB. The subjective difference was found to be approximately 5 dB. Thus the noise from the diesel engine can be subjectively quieter by 5 dB if the depth of modulation in the noise waveform is reduced from 13 dB to

Table 8.1 Analysis of variance.

| Source of variation | DF | SS | SS% | MS | VR |
|---|---|---|---|---|---|
| Subject | 15 | 408.734 | 33.15 | 27.249 | 20.209 |
| Order | 15 | 22.109 | 1.79 | 1.474 | 1.093 |
| Mod. | 1 | 2.250 | 0.18 | 2.250 | 1.669 |
| Freq. | 1 | 21.391 | 1.73 | 21.391 | 15.864 |
| Noise | 3 | 472.328 | 38.30 | 157.443 | 116.766 |
| Mod. freq. | 1 | 10.563 | 0.86 | 10.563 | 7.834 |
| Mod. noise | 3 | 5.781 | 0.47 | 1.927 | 1.429 |
| Freq. noise | 3 | 3.141 | 0.25 | 1.047 | 0.776 |
| Mod. freq. noise | 3 | 3.656 | 0.30 | 1.219 | 0.904 |
| Residual | 210 | 283.156 | 22.96 | 1.348 | |
| TOTAL | 225 | 802.266 | 65.06 | 3.566 | |
| GRAND TOTAL | 255 | 1233.109 | 100.00 | | |

GRAND MEAN 5.164

TOTAL NUMBER OF OBSERVATIONS 256

<u>Table 8.2</u> Table of means.

| Mod | 1 | 2 |
|---|---|---|
| | 5.258 | 5.070 |

| Freq. | 1 | 2 |
|---|---|---|
| | 5.453 | 4.875 |

| Noise | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| | 6.891 | 5.969 | 4.422 | 3.375 |

| Freq. | 1 | 2 |
|---|---|---|
| Mod. | | |
| 1 | 5.750 | 4.766 |
| 2 | 5.156 | 4.984 |

| Noise | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Mod. | | | | |
| 1 | 7.188 | 6.125 | 4.313 | 3.406 |
| 2 | 6.594 | 5.813 | 4.531 | 3.344 |

| Noise | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Freq. | | | | |
| 1 | 7.281 | 6.375 | 4.625 | 3.531 |
| 2 | 6.500 | 5.563 | 4.219 | 3.219 |

| Freq. | 1 | | | | 2 | | | |
|---|---|---|---|---|---|---|---|---|
| Noise | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Mod. | | | | | | | | |
| 1 | 7.875 | 6.813 | 4.750 | 3.563 | 6.500 | 5.438 | 3.875 | 3.250 |

STANDARD ERROR OF DIFFERENCES OF MEANS

| | Mod | Freq. | Noise | Mod. Freq. | Mod. Noise | Freq. Noise | Mod. Freq. Noise |
|---|---|---|---|---|---|---|---|
| REP: | 128 | 128 | 64 | 64 | 32 | 32 | 16 |
| SED: | 0.1451 | 0.1451 | 0.2053 | 0.2053 | 0.2903 | 0.2903 | 0.4106 |

5 dB. A similar reduction in the subjective response can be achieved by increasing the modulation frequency from 8 Hz to 16 Hz.

Therefore from these findings two courses of action could be taken in order to make diesel locomotives quieter subjectively:

(a) reduce the depth of amplitude modulation by a special manifold design as described in Chapter 7, or

(b) (this could apply to new engines) design engines which could operate at speeds faster than 1000 rpm at full load. This will result in modulation frequency greater than 10 Hz and thus will not be detected by the human ear, as discussed in Chapter 6.

According to the results of the experiment in this chapter both (a) and (b) will reduce the annoyance of diesel locomotives by approximately 5 dB.

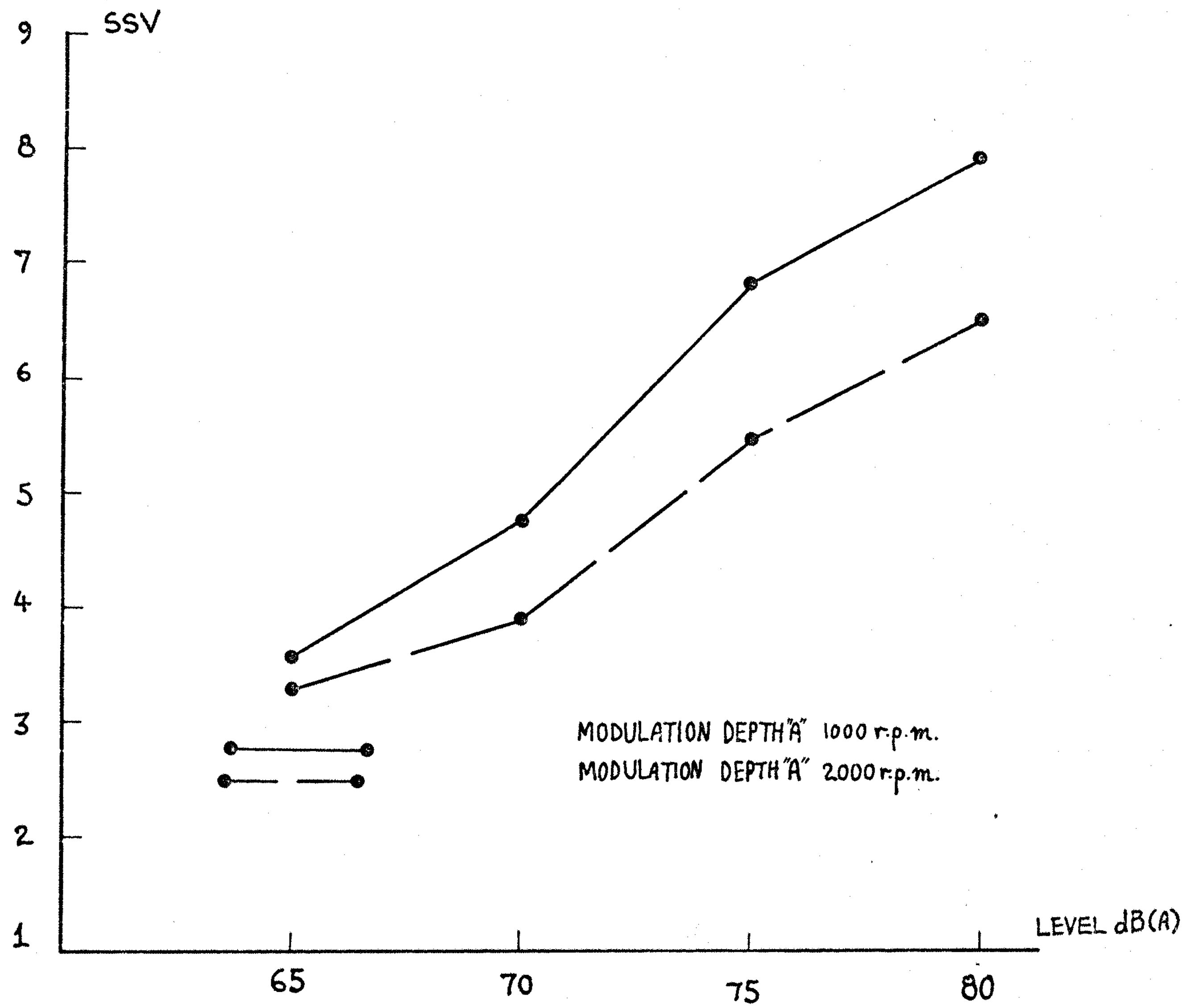



Figure 8.3 Relationship between subjective response and noise level.

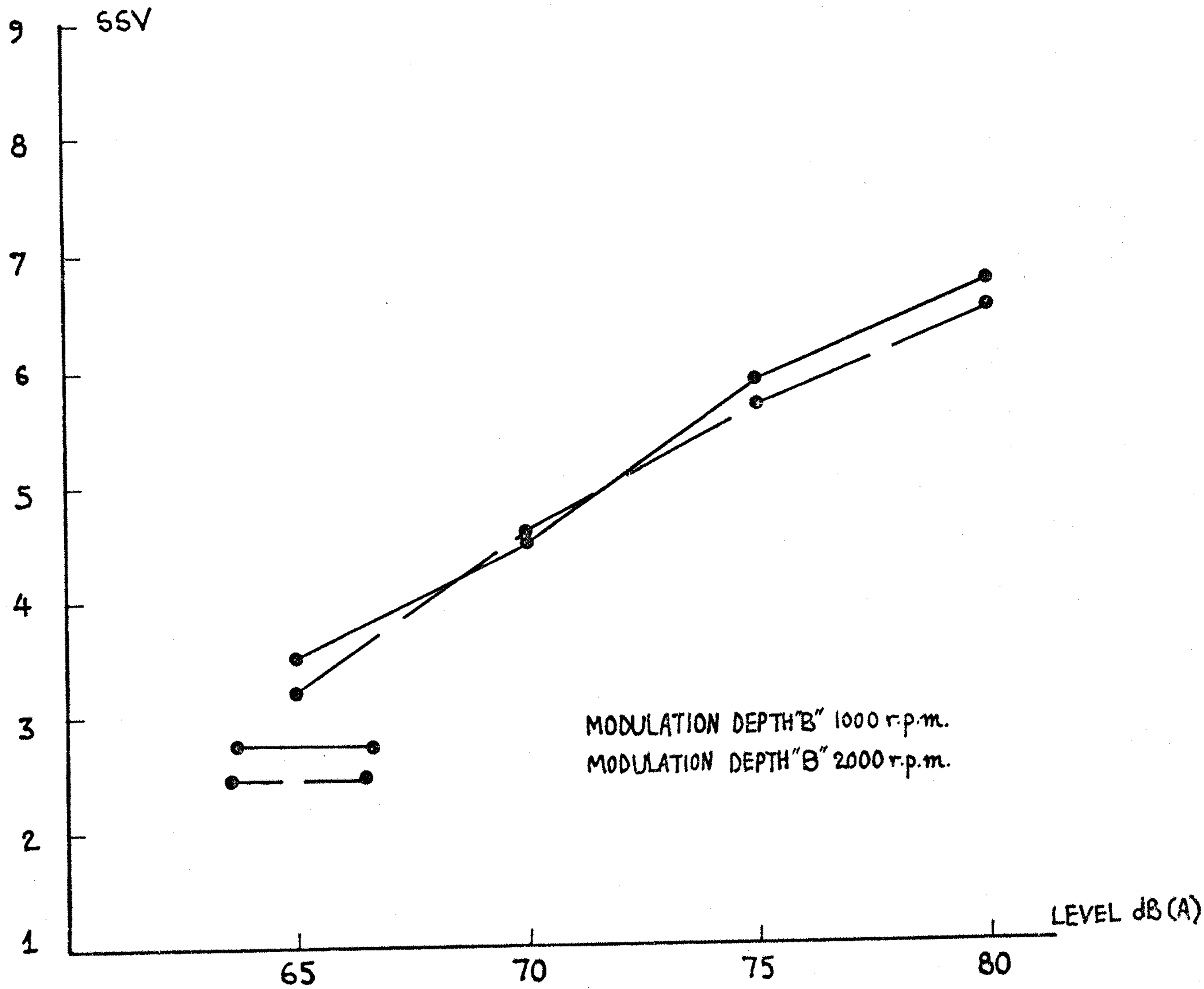



Figure 8.4 Relationship between subjective response and noise level.

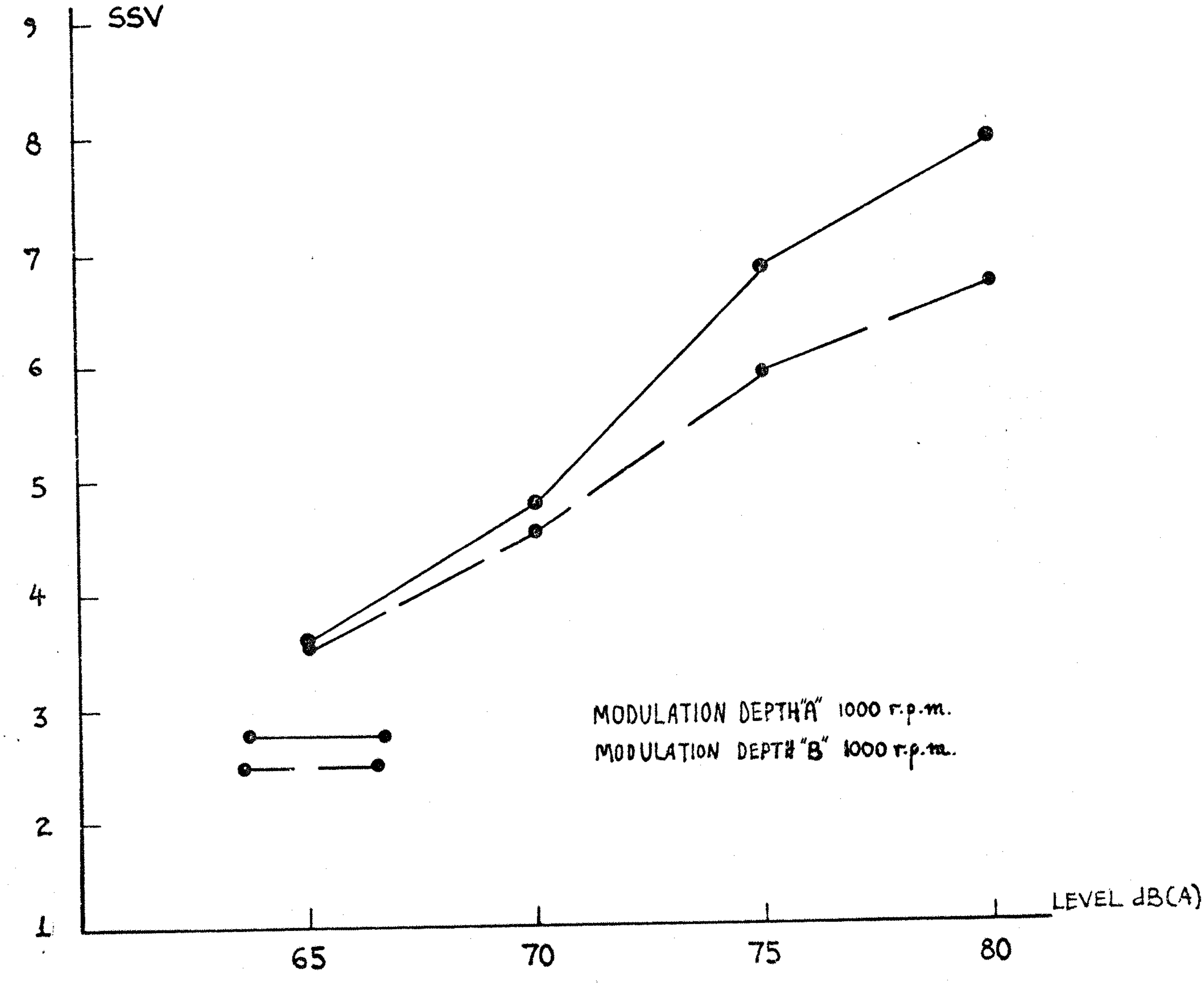



**Figure 8.5** Relationship between subjective response and noise level.

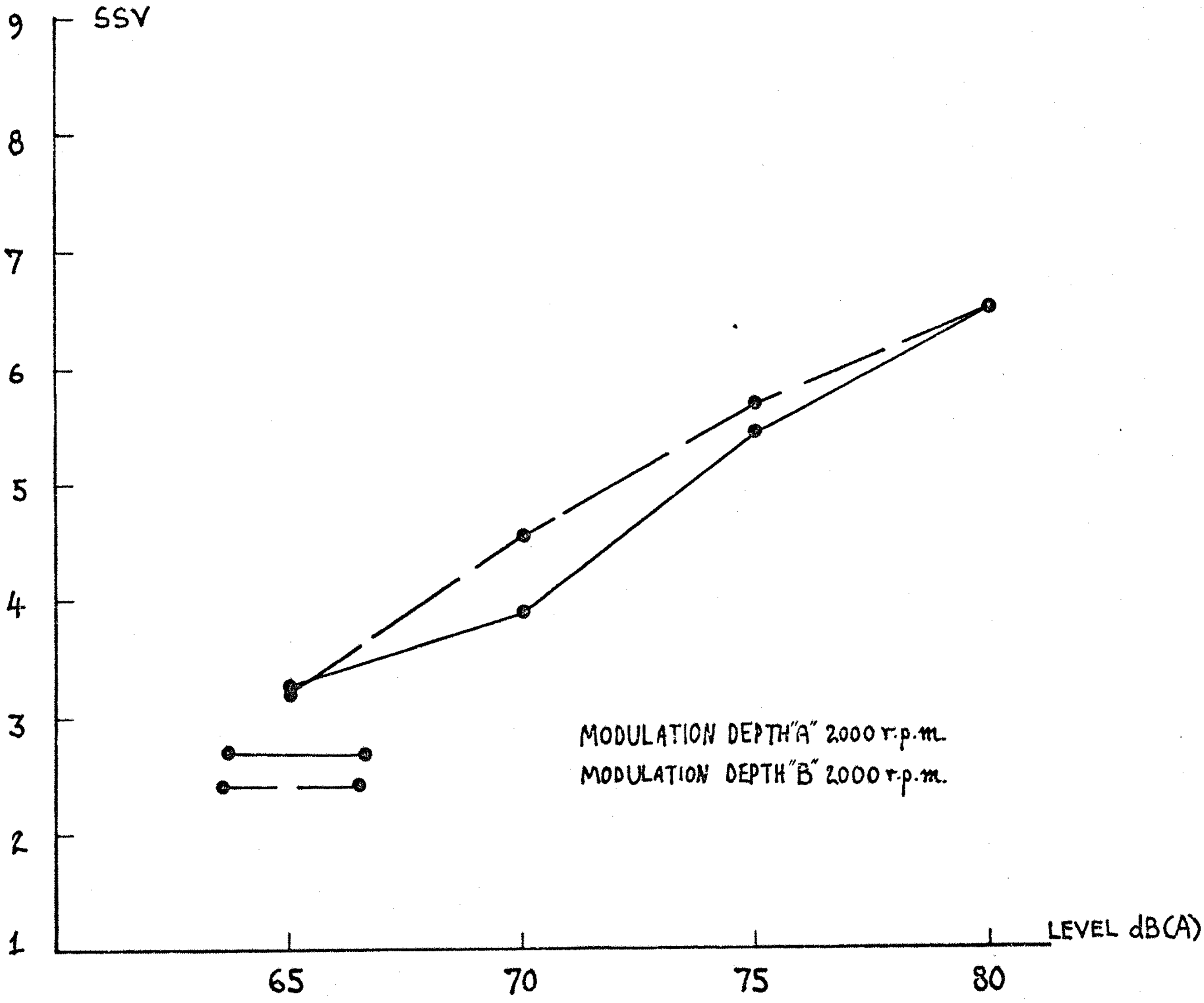



Figure 8.6 Relationship between subjective response and noise level.

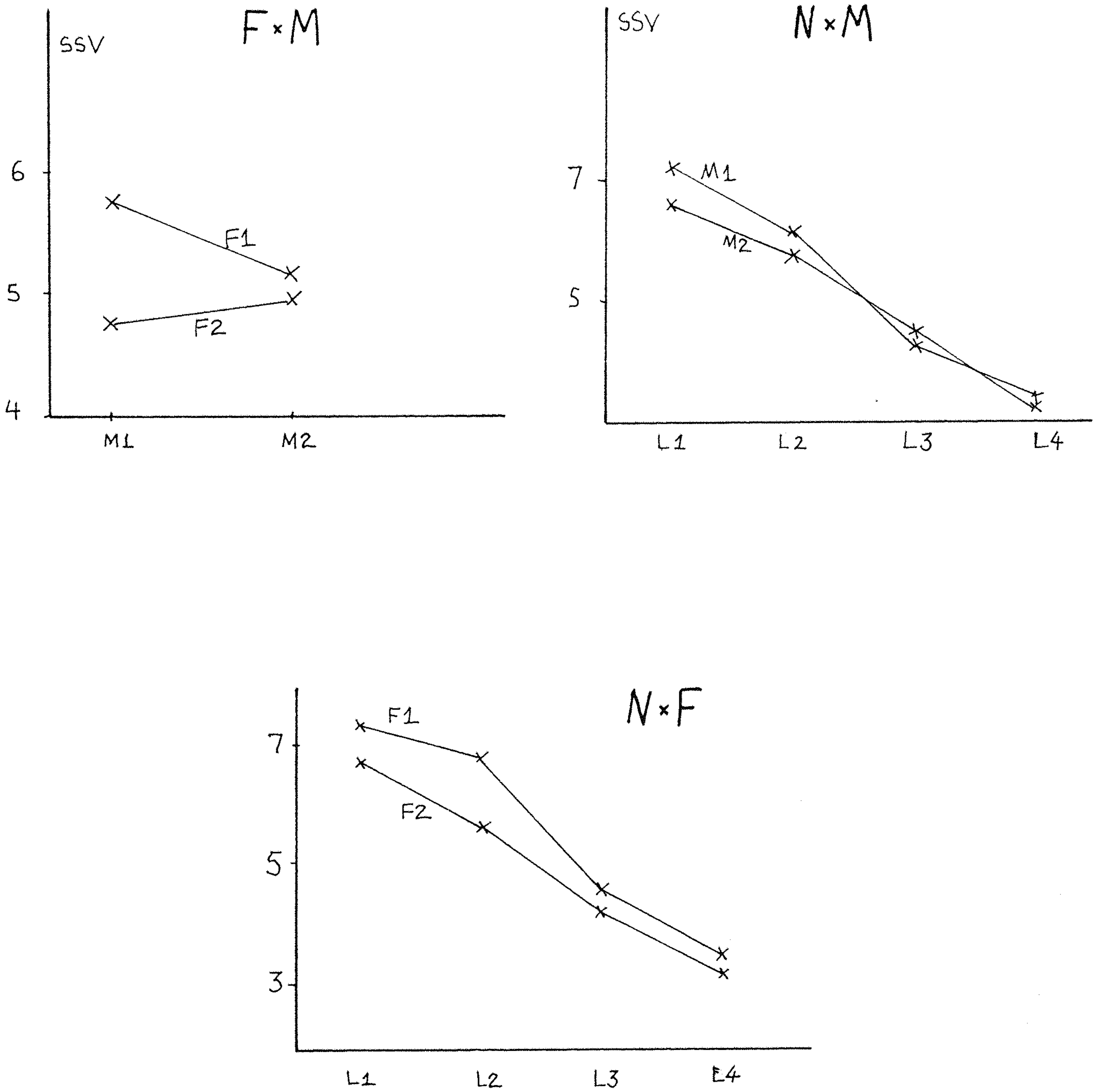



**Figure 8.7 Interactions**

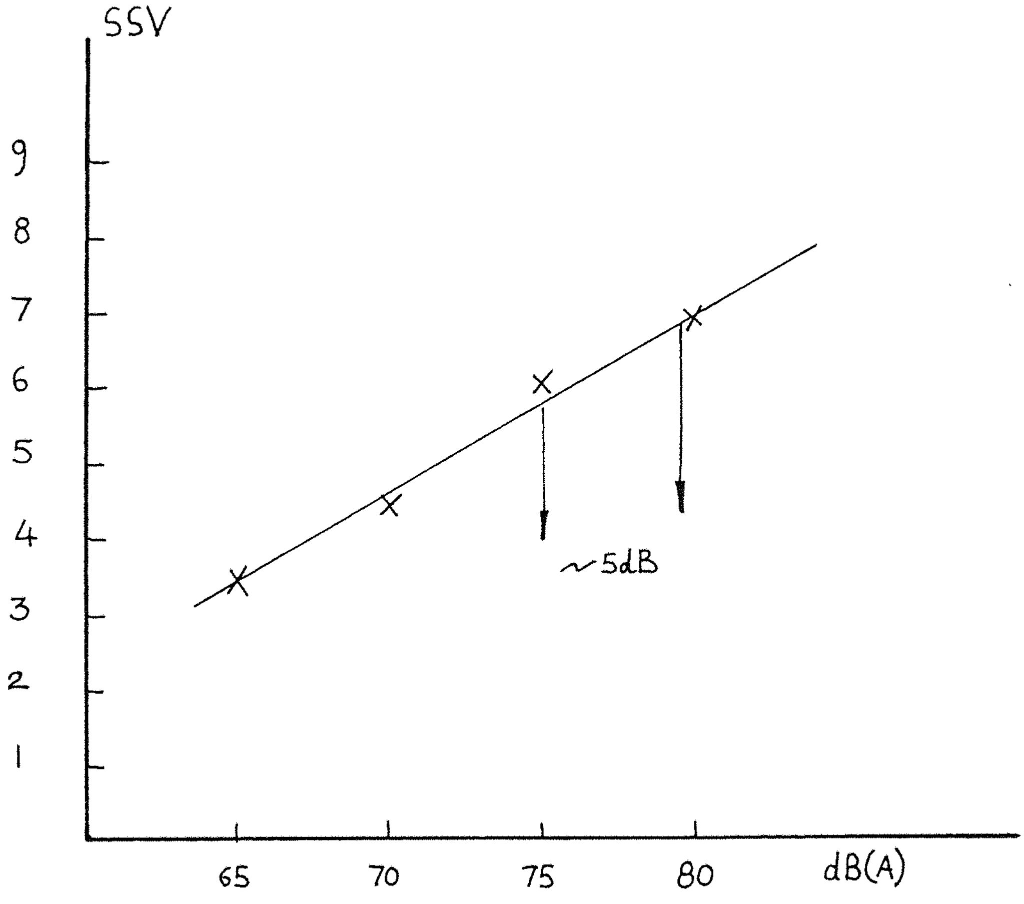



Figure 8.8 Subjective response against noise level.

# 9. CONCLUSIONS

One conclusion of this work concerning the reactions to different traction type confirmed that the noise from diesel trains is more annoying than noise from overhead and third-rail electric trains. However, when the low frequency noise below 250 Hz was omitted there was no consistent significant difference between all three types.

Although the diesel was more annoying than the third-rail electric, both types display a remarkable similarity as far as the one-third octave spectra is concerned. It was believed that the most likely reason for the different response is due to the low frequency characteristics in the diesel locomotive exhaust noise. From listening to the noise of the two types of train, it was clear that there was a special characteristic in the noise of the diesel which discriminated it from the third-rail electric train. This could be described as "pulsing" or "thumping" and it could be the sound to which people responded.

Examination of the noise waveform of a number of diesel trains identified the presence of a low frequency modulation component of around 6-8 Hz. This modulation is the source of the characteristic "pulsing" sound associated with diesel locomotives. When this characteristic was reduced in level, the diesel train was judged to be subjectively equivalent to an electric train (see Chapter 4).

Using signal analysis theory, the envelope of the modulation was calculated. In an attempt to explain the mechanism which generates the amplitude modulation in the noise waveform, a model of the exhaust noise was made. This takes into account the firing order of the engine, the time delay introduced by the exhaust manifold to each exhaust pulse and the shape of the exhaust gas pressure.

Using the model it was found that the existing arrangement of the exhaust manifold, for the particular engine considered, produced a highly amplitude modulated waveform of "pulsing" character. The "pulsing" was shown to be related to the depth of the modulation, which was created by the uneven spacing of the exhaust pulses. However, by arranging a series of equally spaced exhaust pulses, it was possible to produce a new noise waveform with lower depth of modulation, which had a much "smoother" character. In practice this can be achieved by using an exhaust manifold which will provide equal travelling distance for the exhaust pulses from each cylinder.

Finally, in Chapter 8, an experiment was designed to investigate the subjective response to modelled exhaust amplitude modulated exhaust noise waveforms of a typical diesel locomotive. Both depth and frequency of modulation were examined. It was found that the noise waveforms with the lower depth of modulation were less annoying than noise waveforms with higher depth of modulation at the same engine speed. Thus by reducing the depth of modulation in the noise waveforms of the diesel engine from 13 dB to 5 dB makes the diesel engine subjectively quieter by 5 dB overall. This could be achieved by using the exhaust manifold discussed in Chapter 7.

These studies provide for a better understanding of the way in which diesel engine noise is perceived. In particular it highlights the subjectively significant components in the noise. It is hoped that these findings will provide a more effective solution in the area of exhaust manifold and silencer design.

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## APPENDIX 1

## LIST OF EQUIPMENT USED FOR RECORDING TRAIN PASS-BYS IN ORDER TO BE USED FOR SUBJECTIVE TESTS IN THE LABORATORY

1. Tape recorder, Nagra IV-S.
2. dBX noise reduction system.
3. Pair of CALREC condenser microphones with omnidirectional directivity pattern.
4. Pair of Senheizer condenser microphones with cardioic directivity pattern.
5. A pair of headphones for monitoring purposes.
6. Two tripods.
7. Windshields.
8. Microphone cable.

Placing of the microphones depended upon the type used. The CALREC microphones were mounted on the tripods, the spacing distance was approximately equal to the spacing distance of the loudspeakers in the listening room.

The Senheizer microphones were arranged in a crossed pair configuration.

The height from the ground for both configurations was approximately 1.5 metres.

Recordings of train pass-bys were made with both types of microphones. Then a selection of best recordings was made in order to be used for the subjective tests.

### List of equipment used for recording train pass-bys for analysis purposes

1. B & K integrating sound level meter, type 2218
2. 1/2" B & K microphone
3. B & K FM tape recorder, type 7003
4. Calibrator
5. Windshield

During the recordings a record was kept of information for each pass-by according to the following table.

| Type of train (including class of locomotive) | Number of coaches | Direction | $L_{eq}$ during the pass-by in dB(A) | Peak level reached during the pass-by in dB(A) | Distance from the tracks |
|---|---|---|---|---|---|

# APPENDIX 2

## ISVR SIMULATED DOMESTIC LIVING ROOM

The simulated living room allowed experimental subjects to make annoyance judgements of tape recorded sessions of noise in a similar way to that if they were in their own homes. A stereo set of loudspeakers was provided and also a low frequency unit was especially constructed in order to be able to produce the high levels of low frequency noise associated with diesel and third-rail electric trains. The loudspeakers were concealed in order to make the simulation as unobstructive as possible. For the stereo pair Bowers and Wilkins type DM-2 3-way monitor loudspeaker units were used.

The internal dimensions of the room were 3.7 × 3.8 × 2.3 m. A plan is shown in Figure A1. A control room adjacent to the simulated living room contained all the tape reproducing equipment and noise monitoring equipment. Revox and Nagra tape recorders were used. The frequency response to pink noise reproduced using the playback equipment into the room at the subject's head position, via the Bowers and Wilkins loudspeakers and the low frequency unit was within ± 5 dB from 25 Hz to 12 kHz, as one can see in Figure A2. In all cases, tapes were recorded in half-track stereo at 15 ips. 7½ ips would normally be adequate, but the higher speed was used to accommodate the higher dynamic range which was provided by using the dBX noise reduction system, and also achieve better high frequency response. The diagram in Figure A3 shows the layout of the equipment used for the reproduction of the noises. The background noise level in the listening room with the ventilation system switched on was about 35 dB(A). This effectively sets the limit to the lowest level of noise that is audible in the room.

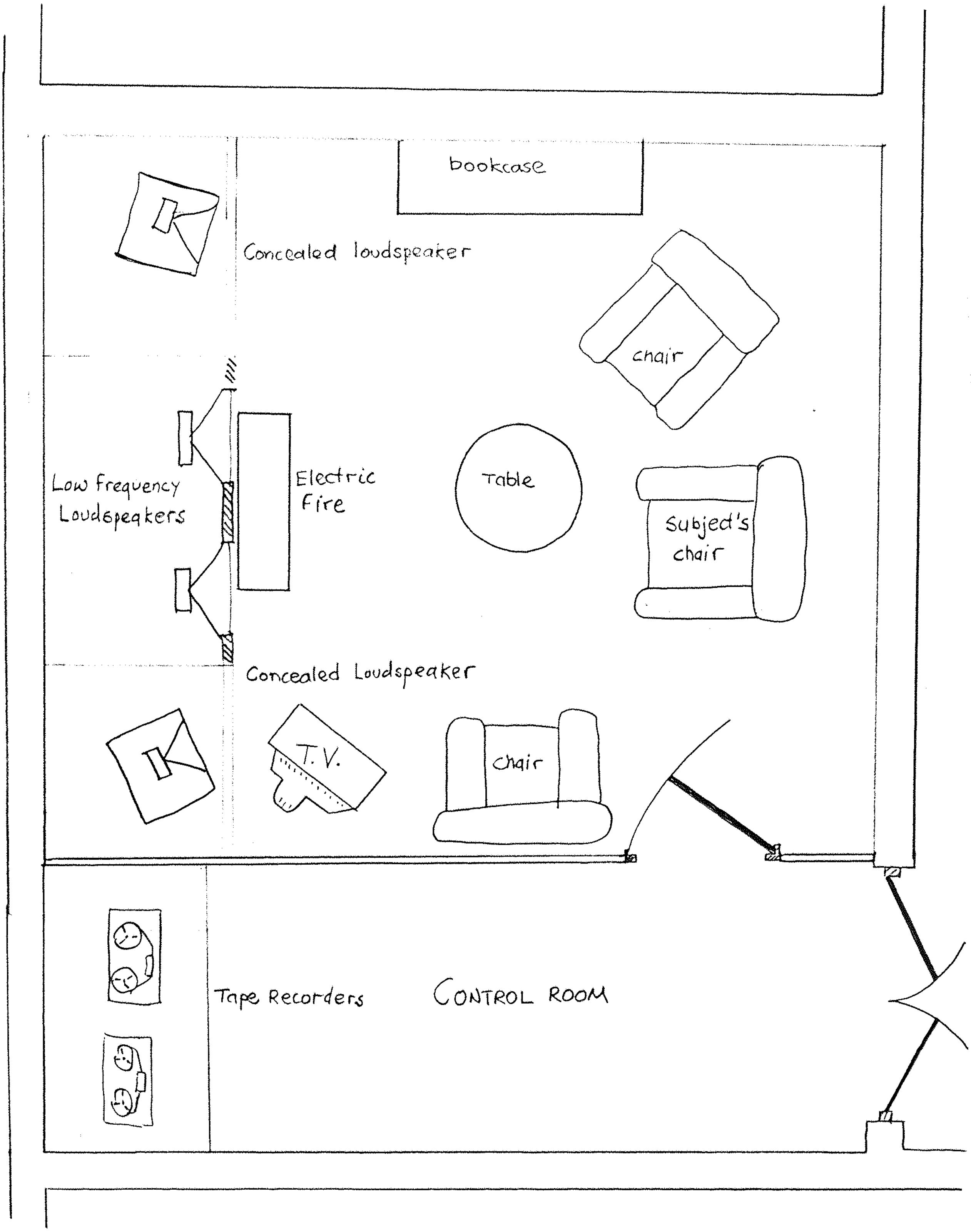


**Figure A1. Simulated domestic living room**

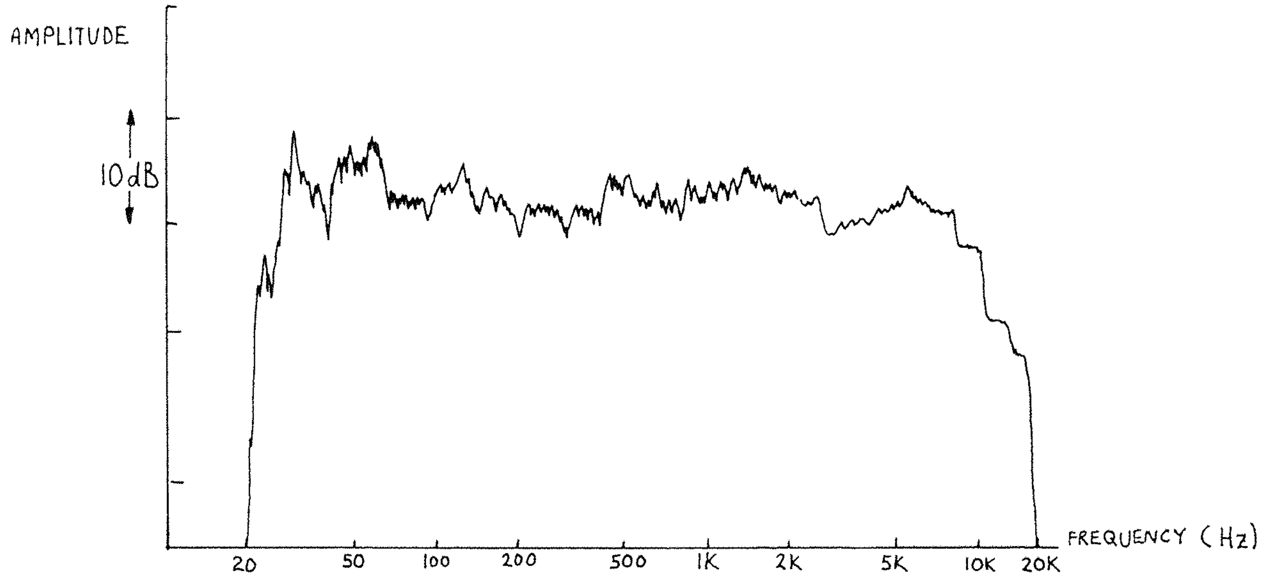


Figure A2. Frequency response of the reproduction system at the subject's head position with the low frequency unit.

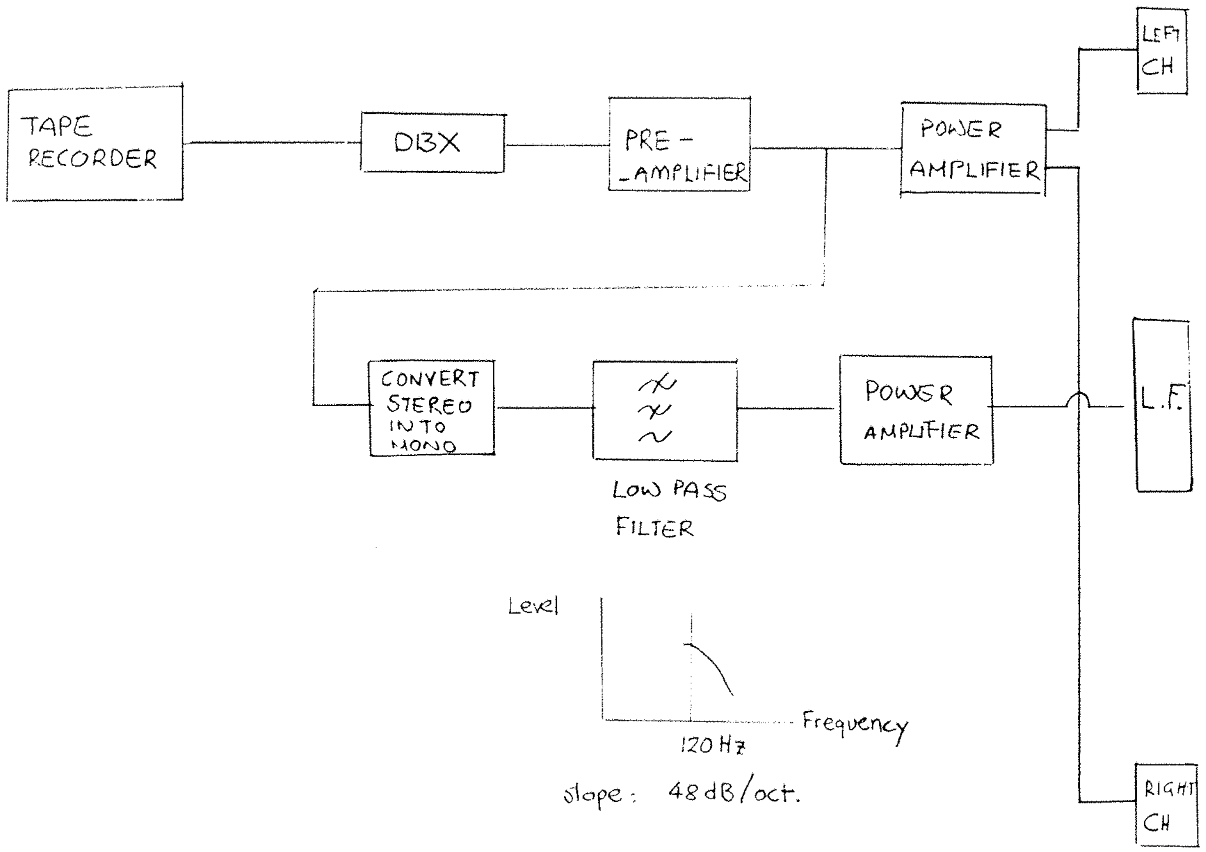


Figure A3. The layout of the equipment used for reproducing the noises.

## APPENDIX 3

## LABORATORY STUDY I (DATA)

The variables included in the experimental design were:

(a) type of train: diesel (D), third-rail (TR), overhead (OV)

(b) frequency content: linear, 250 Hz high-pass (NLF)

(c) noise level: four noise levels were used, namely: 62, 68, 75 and 80 peak dB(A) corresponding to distances of 200, 100, 50 and 20 metres from the track.

## INSTRUCTIONS

We would like you to help us study the annoyance caused by train noise.

We will play you a variety of noises which you might hear if you were living near a railway line. After each noise we would like you to circle the number on the response sheet which most closely corresponds with your annoyance.

For example, if you would find the noise highly annoying or distracting, circle a high number such as 8 or 9. If the noise is hardly annoying and you could easily ignore it circle a low number such as 1 or 2. We are interested only in your opinion - there are no "right" or "wrong" answers.

Please wait till each noise has finished before you circle the appropriate number.

If you would like to comment on some or all of the noises, please do so in the space provided.

Before we start, I will play you some examples of the types of sounds you will hear. Do not score these sounds. I will tell you when the experiment begins.

Thank you for your help. If you have any questions either now or during the experiment please ask me.

RESPONSE SHEET

Name ............................ Date ..................... am/pm Subject No......

Tape No. ....

NOT AT ALL ANNOYING 0 1 2 3 4 5 6 7 8 9 EXTREMELY ANNOYING

Any comments?

| | $D_{20}$ | $D_{50}$ | $D_{100}$ | $D_{200}$ | $D_{20}$ NLF | $D_{50}$ NLF | $D_{100}$ NLF | $D_{200}$ NLF | $TR_{20}$ | $TR_{50}$ | $TR_{100}$ | $TR_{200}$ | $TR_{20}$ NLF | $TR_{50}$ NLF | $TR_{100}$ NLF | $TR_{200}$ NLF | $OV_{20}$ | $OV_{50}$ | | $OV_{100}$ | $OV_{200}$ | $OV_{20}$ NLF | $OV_{50}$ NLF | $OV_{100}$ NLF | $OV_{20}$ N[illegible] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | | 19 | 20 | 21 | 22 | 23 | 24 |
| . no. | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 6 | 8 | 4 | 6 | 8 | 8 | 5 | 4 | 9 | 7 | 5 | 4 | 9 | 7 | 4 | 3 | 8 | 9 | | 6 | 3 | 7 | 6 | 4 | 2 |
| 2 | 8 | 7 | 5 | 5 | 6 | 5 | 3 | 4 | 8 | 7 | 5 | 3 | 6 | 6 | 3 | 3 | 7 | 6 | | 4 | 3 | 7 | 5 | 3 | 3 |
| 3 | 6 | 7 | 4 | 5 | 7 | 4 | 3 | 3 | 8 | 5 | 3 | 3 | 6 | 4 | 3 | 4 | 7 | 2 | | 2 | 2 | 6 | 6 | 4 | 3 |
| 4 | 8 | 5 | 4 | 4 | 5 | 4 | 3 | 2 | 6 | 4 | 4 | 3 | 5 | 4 | 4 | 2 | 5 | 4 | | 3 | 2 | 5 | 4 | 2 | 1 |
| 5 | 8 | 8 | 6 | 3 | 4 | 4 | 4 | 5 | 7 | 4 | 3 | 2 | 8 | 6 | 4 | 2 | 7 | 7 | | 3 | 3 | 5 | 6 | 3 | 2 |
| 6 | 7 | 7 | 8 | 3 | 5 | 6 | 3 | 2 | 8 | 4 | 2 | 3 | 7 | 7 | 5 | 4 | 8 | 7 | | 5 | 5 | 8 | 5 | 4 | 2 |
| 7 | 9 | 9 | 8 | 7 | 8 | 8 | 7 | 6 | 8 | 8 | 7 | 6 | 8 | 7 | 7 | 6 | 8 | 7 | | 7 | 6 | 8 | 7 | 6 | 5 |
| 8 | 9 | 9 | 8 | 5 | 8 | 8 | 5 | 6 | 9 | 6 | 6 | 4 | 8 | 7 | 4 | 4 | 8 | 8 | | 7 | 5 | 8 | 7 | 6 | 4 |
| 9 | 9 | 9 | 8 | 6 | 9 | 9 | 5 | 4 | 8 | 7 | 5 | 5 | 9 | 6 | 5 | 6 | 9 | 8 | | 8 | 7 | 9 | 7 | 7 | 4 |
| 0 | 9 | 5 | 4 | 4 | 6 | 5 | 4 | 4 | 7 | 7 | 5 | 4 | 6 | 3 | 2 | 2 | 6 | 5 | | 3 | 2 | 5 | 3 | 3 | 1 |
| 1 | 9 | 9 | 8 | 6 | 9 | 9 | 8 | 4 | 9 | 9 | 7 | 5 | 9 | 9 | 5 | 5 | 9 | 8 | | 8 | 7 | 9 | 7 | 7 | 5 |
| 2 | 9 | 8 | 6 | 4 | 7 | 7 | 6 | 4 | 9 | 7 | 6 | 5 | 8 | 7 | 4 | 3 | 8 | 7 | | 4 | 3 | 6 | 5 | 3 | 2 |
| 3 | 8 | 8 | 5 | 4 | 5 | 6 | 3 | 2 | 8 | 7 | 6 | 4 | 7 | 6 | 3 | 3 | 7 | 6 | | 3 | 2 | 5 | 5 | 3 | 2 |
| 4 | 9 | 9 | 5 | 3 | 9 | 9 | 5 | 4 | 9 | 7 | 5 | 1 | 4 | 4 | 0 | 0 | 7 | 6 | | 2 | 0 | 8 | 7 | 4 | 0 |
| 5 | 9 | 8 | 7 | 3 | 5 | 7 | 3 | 5 | 9 | 7 | 4 | 2 | 6 | 7 | 3 | 4 | 6 | 4 | | 4 | 2 | 6 | 5 | 4 | 2 |
| 6 | 6 | 4 | 5 | 5 | 5 | 6 | 4 | 4 | 8 | 4 | 3 | 3 | 6 | 5 | 3 | 3 | 4 | 5 | | 3 | 3 | 5 | 6 | 4 | 2 |
| 7 | 9 | 8 | 7 | 5 | 7 | 7 | 5 | 3 | 9 | 8 | 8 | 3 | 8 | 8 | 6 | 3 | 6 | 6 | | 5 | 5 | 7 | 6 | 3 | 3 |
| 8 | 9 | 8 | 8 | 7 | 8 | 8 | 5 | 5 | 9 | 8 | 8 | 6 | 8 | 8 | 7 | 6 | 8 | 7 | | 7 | 6 | 7 | 7 | 7 | 4 |
| 9 | 9 | 8 | 8 | 7 | 9 | 8 | 5 | 6 | 9 | 9 | 4 | 4 | 9 | 9 | 6 | 6 | 9 | 9 | | 9 | 7 | 9 | 7 | 7 | 5 |
| 0 | 9 | 9 | 4 | 1 | 8 | 6 | 3 | 1 | 9 | 5 | 1 | 0 | 6 | 3 | 3 | 1 | 8 | 6 | | 5 | 3 | 6 | 5 | 3 | 1 |
| 1 | 7 | 7 | 5 | 4 | 7 | 6 | 4 | 1 | 6 | 5 | 4 | 4 | 7 | 6 | 4 | 4 | 5 | 6 | | 3 | 4 | 5 | 4 | 4 | 3 |
| 2 | 8 | 7 | 5 | 3 | 7 | 5 | 1 | 2 | 8 | 7 | 5 | 2 | 7 | 2 | 2 | 1 | 4 | 5 | | 5 | 4 | 7 | 5 | 4 | 3 |
| 3 | 9 | 8 | 7 | 5 | 8 | 8 | 5 | 3 | 9 | 5 | 5 | 4 | 6 | 3 | 3 | 3 | 8 | 7 | | 4 | 3 | 7 | 6 | 5 | 4 |
| 4 | 8 | 7 | 7 | 7 | 7 | 7 | 4 | 3 | 8 | 8 | 5 | 3 | 7 | 5 | 4 | 3 | 8 | 6 | | 3 | 4 | 5 | 4 | 3 | 3 |
| | 197 | 182 | 146 | 112 | 167 | 160 | 103 | 87 | 197 | 155 | 116 | 83 | 170 | 139 | 94 | 81 | 170 | 150 | | 113 | 91 | 160 | 135 | 103 | 66 |
| 2 | 1643 | 1422 | 946 | 580 | 1215 | 1126 | 493 | 365 | 1637 | 1059 | 630 | 335 | 1246 | 893 | 428 | 335 | 1254 | 994 | | 627 | 425 | 1112 | 791 | 497 | 224 |
| | 8.21 | 7.58 | 6.08 | 4.67 | 6.96 | 6.7 | 4.29 | 3.63 | 8.21 | 6.46 | 4.83 | 3.49 | 7.08 | 5.79 | 3.92 | 3.38 | 7.08 | 6.25 | | 4.71 | 3.79 | 6.67 | 5.63 | 4.29 | 2.7 |
| mple) | | | | | | | | | | | | | | | | | | | | | | | | | |
| S | 1.06 | 1.35 | 1.58 | 1.58 | 1.52 | 1.61 | 1.49 | 1.47 | 0.93 | 1.59 | 1.74 | 1.44 | 1.35 | 1.96 | 1.61 | 1.64 | 1.47 | 1.57 | | 2,03 | 1.86 | 1.4 | 1.17 | 1.54 | 1.4 |
| SE | 0.217 | 0.275 | 0.324 | 0.322 | 0.31 | 0.327 | 0.3 | 0.3 | 0.19 | 0.32 | 0.35 | 0.29 | 0.275 | 0.4 | 0.33 | 0.334 | 0.30 | 0.32 | | 0.41 | 0.38 | 0.29 | 0.24 | 0.32 | 0.2 |

## APPENDIX 4

## LABORATORY STUDY II

In the second laboratory study the following conditions were investigated:

1. Two types of noise (real, synthesized).
2. Two types of train (diesel, third-rail electric).
3. Three frequency contents (linear and using a high-pass filter with cut-off frequencies at 160 Hz and 50 Hz with rate of attenuation 24 dB/octave).
4. Four noise levels (75, 70, 65, 60 peak dB(A)).

The subjective response scores are shown in the following table.

| 44 | 36 | 46 | 1 | 43 | 32 | [illegible] | [illegible] | [illegible] | 47 | 19 | 45 | 20 | 40 | 4 | 31 | [illegible] | [illegible] | 25 | 10 | 12 | 37 | 18 | 29 | 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CLASS A (REAL) | | | | | | | | | | | | | | | | | | | | CLASS A (REAL) | | | | |
| DIESEL | | | | | | | | | | | | THIRD-RAIL | | | | | | | | | | | | |
| LINEAR | | | | 50 Hz CUT-OFF | | | | 160 Hz CUT-OFF | | | | LINEAR | | | | 50 Hz CUT-OFF | | | | 160 Hz CUT-OFF | | | | |
| 75 | 70 | 65 | 60 | 75 | 70 | 65 | 60 | 75 | 70 | 65 | 60 | 75 | 70 | 65 | 60 | 75 | 70 | 65 | 60 | 75 | 70 | 65 | 60 | 75 |
| D75R0 | D70R0 | D65R0 | D60R0 | D75R50 | D70R50 | D75R50 | D60R50 | D75R160 | D70R160 | D65R160 | D60R1 | TR75R0 | TR70R0 | TR65R0 | TR60R0 | TR75R50 | TR70R50 | TR65R50 | TR60R50 | TR75R160 | TR70R160 | TR65R160 | TR60R160 | D75S( |
| 9 | 8 | 5 | 3 | 9 | 7 | 6 | 5 | 6 | 5 | 2 | 2 | 6 | 4 | 2 | 2 | 4 | 3 | 2 | 1 | 4 | 1 | 3 | 2 | 9 |
| 9 | 8 | 4 | 3 | 7 | 9 | 4 | 4 | 4 | 4 | 2 | 2 | 3 | 6 | 2 | 6 | 6 | 6 | 4 | 1 | 5 | 3 | 1 | 1 | 8 |
| 9 | 8 | 7 | 6 | 9 | 8 | 6 | 6 | 7 | 7 | 3 | 1 | 6 | 6 | 5 | 5 | 4 | 5 | 2 | 2 | 6 | 2 | 4 | 4 | 9 |
| 6 | 6 | 5 | 4 | 5 | 5 | 4 | 3 | 6 | 3 | 3 | 2 | 5 | 5 | 3 | 4 | 6 | 4 | 2 | 1 | 5 | 3 | 3 | 2 | 6 |
| 9 | 8 | 7 | 6 | 9 | 9 | 7 | 6 | 7 | 6 | 4 | 5 | 6 | 6 | 5 | 7 | 5 | 5 | 7 | 3 | 6 | 4 | 4 | 6 | 8 |
| 7 | 6 | 6 | 4 | 8 | 5 | 3 | 3 | 6 | 3 | 3 | 2 | 4 | 6 | 2 | 3 | 5 | 3 | 3 | 1 | 4 | 3 | 2 | 3 | 7 |
| 8 | 6 | 7 | 5 | 7 | 8 | 6 | 5 | 7 | 6 | 4 | 3 | 6 | 5 | 4 | 3 | 5 | 5 | 5 | 3 | 6 | 4 | 4 | 3 | 7 |
| 8 | 7 | 6 | 3 | 7 | 8 | 5 | 5 | 8 | 6 | 4 | 3 | 7 | 4 | 2 | 3 | 7 | 4 | 4 | 2 | 8 | 4 | 4 | 3 | 9 |
| 9 | 7 | 7 | 3 | 9 | 7 | 6 | 4 | 8 | 6 | 4 | 3 | 6 | 4 | 5 | 5 | 6 | 4 | 7 | 2 | 7 | 5 | 3 | 2 | 8 |
| 8 | 4 | 6 | 2 | 8 | 8 | 4 | 3 | 4 | 6 | 4 | 3 | 5 | 3 | 4 | 1 | 6 | 5 | 5 | 2 | 4 | 4 | 4 | 2 | 5 |
| 6 | 4 | 3 | 3 | 4 | 7 | 4 | 3 | 7 | 5 | 2 | 2 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 3 | 7 | 4 | 3 | 2 | 5 |
| 9 | 9 | 5 | 2 | 8 | 7 | 4 | 2 | 3 | 7 | 3 | 3 | 7 | 3 | 3 | 3 | 8 | 5 | 4 | 1 | 3 | 2 | 3 | 0 | 7 |
| 8 | 7 | 7 | 4 | 7 | 7 | 6 | 3 | 6 | 6 | 4 | 3 | 6 | 4 | 6 | 3 | 6 | 6 | 6 | 1 | 5 | 3 | 4 | 3 | 6 |
| 8 | 7 | 5 | 4 | 7 | 6 | 5 | 3 | 3 | 5 | 2 | 2 | 5 | 4 | 3 | 3 | 4 | 3 | 3 | 1 | 2 | 1 | 4 | 3 | 6 |
| 9 | 8 | 7 | 4 | 7 | 9 | 6 | 5 | 9 | 6 | 6 | 3 | 6 | 3 | 3 | 4 | 8 | 4 | 4 | 4 | 7 | 4 | 5 | 2 | 9 |
| 9 | 8 | 8 | 7 | 9 | 7 | 7 | 6 | 7 | 9 | 5 | 6 | 8 | 8 | 7 | 5 | 6 | 6 | 7 | 4 | 7 | 4 | 7 | 6 | 8 |
| 9 | 7 | 6 | 3 | 7 | 6 | 4 | 2 | 5 | 4 | 2 | 2 | 5 | 4 | 4 | 3 | 4 | 3 | 3 | 3 | 4 | 3 | 2 | 2 | 6 |
| 7 | 5 | 5 | 2 | 7 | 4 | 4 | 2 | 6 | 5 | 2 | 1 | 5 | 4 | 5 | 4 | 4 | 4 | 3 | 1 | 5 | 1 | 1 | 1 | 5 |
| 9 | 8 | 5 | 2 | 7 | 7 | 7 | 5 | 6 | 5 | 4 | 2 | 6 | 2 | 5 | 3 | 6 | 5 | 2 | 2 | 4 | 4 | 3 | 1 | 8 |
| 8 | 6 | 6 | 4 | 9 | 7 | 5 | 6 | 8 | 6 | 3 | 2 | 5 | 4 | 6 | 5 | 6 | 4 | 3 | 2 | 7 | 4 | 2 | 2 | 9 |
| 4 | 1 | 3 | 1 | 4 | 0 | 1 | 1 | 4 | 3 | 1 | 0 | 3 | 2 | 1 | 0 | 2 | 2 | 1 | 0 | 2 | 1 | 0 | 0 | 3 |
| 8 | 7 | 6 | 3 | 7 | 6 | 5 | 4 | 7 | 5 | 2 | 2 | 6 | 4 | 4 | 3 | 4 | 4 | 4 | 2 | 6 | 4 | 4 | 2 | 5 |
| 7 | 8 | 6 | 5 | 6 | 7 | 6 | 7 | 8 | 6 | 6 | 5 | 7 | 7 | 6 | 6 | 7 | 6 | 6 | 6 | 7 | 7 | 5 | 5 | 8 |
| 7 | 8 | 6 | 7 | 7 | 8 | 7 | 7 | 6 | 5 | 3 | 3 | 6 | 5 | 6 | 4 | 6 | 7 | 6 | 6 | 4 | 3 | 2 | 2 | 9 |
| 190 | 161 | 138 | 90 | 174 | 163 | 122 | 100 | 148 | 129 | 78 | 62 | 133 | 107 | 97 | 88 | 129 | 107 | 97 | 54 | 125 | 78 | 77 | 59 | 170 |
| 1542 | 1153 | 830 | 396 | 1310 | 1178 | 670 | 482 | 974 | 737 | 292 | 200 | 771 | 527 | 451 | 380 | 741 | 511 | 463 | 176 | 715 | 300 | 299 | 201 | 1270 |
| 7.92 | 6.71 | 5.75 | 3.75 | 7.25 | 6.75 | 5.08 | 4.17 | 6.17 | 5.38 | 3.25 | 2.58 | 5.54 | 4.46 | 4.04 | 3.67 | 5.38 | 4.46 | 4.04 | 2.25 | 5.2 | 3.25 | 3.21 | 2.45 | 7.1 |
| 1.28 | 1.78 | 1.26 | 1.59 | 1.45 | 1.92 | 1.47 | 1.69 | 1.63 | 1.38 | 1.29 | 1.32 | 1.22 | 1.47 | 1.60 | 1.58 | 1.44 | 1.22 | 1.76 | 1.54 | 1.66 | 1.42 | 1.50 | 1.56 | 1.69 |
| 0.262 | 0.363 | 0.257 | 0.325 | 0.296 | 0.391 | 0.30 | 0.34 | 0.33 | 0.28 | 0.26 | 0.27 | 0.25 | 0.30 | 0.33 | 0.32 | 0.29 | 0.25 | 0.36 | 0.31 | 0.34 | 0.29 | 0.31 | 0.32 | 0.35 |
| ±0.51 | ±0.71 | ±0.50 | ±0.64 | ±0.58 | ±0.77 | ±0.59 | ±0.67 | ±0.65 | ±0.55 | ±0.51 | ±0.53 | ±0.49 | ±0.59 | ±0.65 | ±0.63 | ±0.57 | ±0.49 | ±0.71 | ±0.61 | ±0.67 | ±0.57 | ±0.61 | ±0.63 | ±0.69 |

| 14 | 23 | 21 | 24 | 9 | 39 | 6 | 33 | 8 | 13 | 5 | 15 | 26 | 38 | 3 | 34 | 30 | 17 | 22 | 11 | 48 | 35 | 28 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CLASS B (SYNTHESIZED) | | | | | | | | | | | | | | CLASS B (SYNTHESIZED) | | | | | | | | |
| THIRD RAIL | | | | | | | | | | | | | | DIESEL | | | | | | | | |
| LINEAR | | | | 50 Hz CUT-OFF | | | | 160 Hz CUT-OFF | | | LINEAR | | | 50 Hz CUT-OFF | | | | 160 CUT-OFF | | | | |
| 70 | 65 | 60 | 75 | 70 | 65 | 60 | 75 | 70 | 65 | 60 | 70 | 65 | 60 | 75 | 70 | 65 | 60 | 75 | 70 | 65 | 60 | 75 |
| R70SO | TR65SO | TR60SO | TR75S50 | TR70S50 | TR65S50 | TR60S50 | TR75S160 | TR70S160 | TR65S160 | TR60S160 | D70SO | D65SO | D60SO | D75S50 | D70S50 | D65S50 | D60S50 | D75S160 | D70S160 | D65S160 | D60S160 | TR75 |
| 8 | 5 | 5 | 8 | 8 | 4 | 3 | 5 | 6 | 4 | 3 | 7 | 6 | 6 | 8 | 7 | 6 | 2 | 7 | 5 | 5 | 2 | 9 |
| 8 | 5 | 7 | 8 | 7 | 4 | 1 | 5 | 3 | 1 | 3 | 9 | 5 | 1 | 7 | 9 | 3 | 3 | 8 | 3 | 2 | 2 | 9 |
| 8 | 6 | 4 | 8 | 8 | 5 | 3 | 6 | 4 | 4 | 4 | 8 | 7 | 7 | 9 | 7 | 6 | 1 | 8 | 7 | 5 | 2 | 9 |
| 4 | 4 | 4 | 7 | 5 | 5 | 4 | 7 | 3' | 3 | 2 | 7 | 4 | 4 | 7 | 3 | 3 | 2 | 4 | 4 | 3 | 2 | 7 |
| 7 | 6 | 6 | 7 | 7 | 5 | 5 | 7 | 6 | 6 | 6 | 7 | 6 | 6 | 7 | 7 | 6 | 6 | 7 | 6 | 6 | 4 | 8 |
| 6 | 4 | 3 | 7 | 5 | 4 | 4 | 5 | 3 | 4 | 3 | 5 | 6 | 5 | 7 | 6 | 5 | 4 | 5 | 4 | 3 | 3 | 7 |
| 7 | 5 | 4 | 7 | 3 | 5 | 5 | 4 | 4 | 4 | 4 | 5 | 5 | 2 | 7 | 6 | 5 | 3 | 6 | 5 | 4 | 2 | 8 |
| 8 | 7 | 7 | 9 | 8 | 8 | 7 | 9 | 6 | 7 | 5 | 9 | 8 | 7 | 9 | 8 | 7 | 7 | 8 | 7 | 6 | 6 | 9 |
| 6 | 5 | 5 | 8 | 7 | 4 | 5 | 8 | 5 | 4 | 2 | 7 | 5 | 4 | 6 | 6 | 5 | 4 | 8 | 7 | 4 | 5 | 6 |
| 3 | 2 | 4 | 7 | 4 | 4 | 3 | 6 | 5 | 4 | 2 | 3 | 3 | 3 | 7 | 6 | 4 | 3 | 7 | 4 | 4 | 3 | 4 |
| 4 | 2 | 5 | 5 | 5 | 5 | 3 | 6 | 3 | 3 | 3 | 3 | 4 | 3 | 4 | 5 | 3 | 4 | 3 | 5 | 2 | 3 | 6 |
| 6 | 2 | 3 | 9 | 7 | 5 | 5 | 7 | 4 | 3 | 2 | 6 | 4 | 4 | 6 | 7 | 3 | 2 | 8 | 5 | 2 | 1 | 7 |
| 6 | 4 | 3 | 7 | 6 | 6 | 5 | 7 | 5 | 5 | 5 | 5 | 5 | 5 | 7 | 7 | 5 | 4 | 6 | 5 | 5 | 3 | 8 |
| 6 | 3 | 5 | 6 | 5 | 4 | 3 | 6 | 4 | 4 | 3 | 5 | 2 | 4 | 7 | 5 | 5 | 3 | 3 | 2 | 2 | 1 | 8 |
| 5 | 6 | 5 | 9 | 7 | 6 | 5 | 7 | 4 | 4 | 2 | 8 | 8 | 3 | 9 | 8 | 3 | 2 | 4 | 4 | 3 | 2 | 9 |
| 8 | 8 | 5 | 6 | 8 | 6 | 4 | 8 | 8 | 8 | 7 | 8 | 5 | 7 | 8 | 9 | 7 | 5 | 9 | 6 | 7 | 6 | 9 |
| 5 | 4 | 3 | 6 | 6 | 6 | 2 | 6 | 5 | 4 | 3 | 5 | 3 | 3 | 5 | 4 | 3 | 3 | 6 | 6 | 3 | 3 | 6 |
| 4 | 2 | 3 | 5 | 2 | 2 | 3 | 6 | 1 | 3 | 1 | 3 | 3 | 1 | 3 | 6 | 2 | 2 | 7 | 3 | 3 | 1 | 6 |
| 4 | 3 | 5 | 8 | 5 | 6 | 3 | 6 | 4 | 5 | 2 | 7 | 5 | 4 | 8 | 4 | 5 | 3 | 5 | 3 | 5 | 2 | 8 |
| 6 | 6 | 3 | 6 | 5 | 3 | 3 | 6 | 5 | 3 | 3 | 8 | 5 | 2 | 6 | 5 | 3 | 2 | 8 | 5 | 4 | 2 | 9 |
| 1 | 3 | 1 | 3 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 5 | 0 | 0 | 3 | 2 | 0 | 0 | 4 | 1 | 1 | 0 | 3 |
| 7 | 5 | 5 | 7 | 7 | 5 | 5 | 6 | 6 | 6 | 4 | 5 | 4 | 4 | 7 | 6 | 5 | 4 | 6 | 5 | 4 | 4 | 7 |
| 7 | 7 | 6 | 8 | 8 | 7 | 6 | 4 | 3 | 3 | 3 | 6 | 6 | 4 | 8 | 7 | 6 | 7 | 4 | 4 | 3 | 3 | 9 |
| | | | | | | | | | | | 8 | 7 | 7 | | | | | | | | | |
| 138 | 108 | 105 | 168 | 139 | 114 | 89 | 144 | 101 | 95 | 75 | | | | 161 | 147 | 104 | 79 | 145 | 110 | 90 | 64 | 1 |
| 872 | 554 | 505 | 1222 | 891 | 594 | 389 | 922 | 485 | 443 | 289 | 149 | 116 | 96 | 1143 | 969 | 516 | 327 | 953 | 558 | 388 | 222 | 13 |
| 5.75 | 4.5 | 4.38 | 7.0 | 5.79 | 4.75 | 3.71 | 6.0 | 4.21 | 3.96 | 3.13 | 1001 | 640 | 476 | 6.71 | 6.13 | 4.33 | 3.29 | 6.04 | 4.58 | 3.75 | 2.67 | 7. |
| | | | | | | | | | | | 6.20 | 4.8 | 4.0 | | | | | | | | | |
| 1.85 | 1.72 | 1.41 | 1.41 | 1.93 | 1.51 | 1.60 | 1.59 | 1.61 | 1.71 | 1.54 | | | | 1.65 | 1.73 | 1.69 | 1.71 | 1.83 | 1.53 | 1.48 | 1.49 | 1.6 |
| 0.38 | 0.35 | 0.29 | 0.29 | 0.39 | 0.31 | 0.33 | 0.32 | 0.33 | 0.35 | 0.31 | 1.82 | 1.86 | 2.0 | 0.34 | 0.35 | 0.34 | 0.35 | 0.37 | 0.31 | 0.30 | 0.30 | 0.3 |
| ±0.74 | ±0.69 | ±0.57 | ±0.57 | ±0.76 | ±0.61 | ±0.65 | ±0.63 | ±0.65 | ±0.69 | ±0.61 | 0.37 | 0.38 | 0.41 | ±0.67 | ±0.69 | ±0.67 | ±0.69 | ±0.73 | ±0.61 | ±0.59 | ±0.59 | ±0.6 |
| | | | | | | | | | | | ±0.73 | ±0.74 | ±0.80 | | | | | | | | | |

# APPENDIX 5

## LABORATORY STUDY III

This experiment was designed to investigate the effect on the subject of varying the noise level of the diesel locomotive. The noise from the diesel locomotive was presented at four conditions at each train noise level. The first three conditions were attenuated from the typical noise level measured on a real train by:

(a) 0 dB, representing the typical measured level for the real train,
(b) 5 dB below level (a),
(c) 10 dB below level (a),

whilst in the fourth

(d) the synthesized noise was not present.

The train noises were presented at four levels: 75, 70, 65 and 60 dB(A).

| ATTENUATION: | 0 dB | | | | -5 dB | | | | -10 dB | | | | -∞ dB | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | L1 | L2 | L3 | L4 | L1 | L2 | L3 | L4 | L1 | L2 | L3 | L4 | L1 | L2 | L3 | L4 |
| | 12 | 10 | 9 | 13 | 4 | 14 | 15 | 8 | 1 | 5 | 7 | 11 | 2 | 6 | 16 | 3 |
| Subjects | | | | | | | | | | | | | | | | |
| 1 | 7 | 6 | 5 | 4 | 7 | 6 | 4 | 4 | 4 | 5 | 3 | 2 | 3 | 6 | 3 | 2 |
| 2 | 7 | 6 | 5 | 2 | 7 | 5 | 4 | 2 | 6 | 5 | 3 | 3 | 4 | 6 | 3 | 3 |
| 3 | 6 | 6 | 4 | 2 | 5 | 3 | 2 | 3 | 3 | 3 | 1 | 1 | 3 | 5 | 3 | 2 |
| 4 | 7 | 6 | 5 | 4 | 4 | 5 | 6 | 4 | 6 | 4 | 4 | 3 | 5 | 5 | 3 | 3 |
| 5 | 7 | 6 | 4 | 5 | 4 | 6 | 5 | 3 | 6 | 3 | 2 | 3 | 5 | 2 | 4 | 2 |
| 6 | 7 | 6 | 5 | 6 | 6 | 6 | 3 | 3 | 7 | 4 | 3 | 2 | 6 | 3 | 3 | 3 |
| 7 | 6 | 6 | 3 | 4 | 7 | 6 | 3 | 3 | 5 | 4 | 2 | 3 | 4 | 4 | 5 | 2 |
| 8 | 9 | 8 | 5 | 3 | 8 | 6 | 3 | 1 | 7 | 6 | 2 | 1 | 7 | 7 | 3 | 1 |
| 9 | 8 | 6 | 3 | 5 | 8 | 6 | 6 | 2 | 7 | 7 | 4 | 1 | 7 | 7 | 4 | 1 |
| 10 | 3 | 3 | 3 | 3 | 5 | 4 | 4 | 2 | 6 | 4 | 3 | 2 | 5 | 4 | 3 | 2 |
| 11 | 8 | 8 | 7 | 7 | 9 | 7 | 7 | 7 | 9 | 7 | 6 | 3 | 8 | 7 | 6 | 6 |
| 12 | 7 | 7 | 6 | 3 | 8 | 6 | 4 | 3 | 8 | 6 | 2 | 1 | 6 | 6 | 5 | 3 |
| 13 | 9 | 9 | 8 | 6 | 9 | 7 | 5 | 6 | 8 | 8 | 5 | 3 | 8 | 8 | 4 | 3 |
| 14 | 9 | 8 | 9 | 5 | 9 | 7 | 6 | 6 | 8 | 8 | 7 | 4 | 8 | 8 | 6 | 6 |
| 15 | 6 | 6 | 6 | 2 | 6 | 3 | 2 | 4 | 3 | 5 | 3 | 3 | 4 | 6 | 2 | 2 |
| 16 | 7 | 6 | 4 | 2 | 6 | 4 | 3 | 2 | 5 | 4 | 2 | 1 | 4 | 3 | 2 | 1 |
| $\bar{x}$ | 7.063 | 6.438 | 5.125 | 3.938 | 6.75 | 5.436 | 4.188 | 3.438 | 6.125 | 5.188 | 3.25 | 2.25 | 5.438 | 5.438 | 3.688 | 2.625 |
| $\Sigma x$ | 113 | 103 | 82 | 63 | 108 | 87 | 67 | 55 | 98 | 83 | 52 | 36 | 87 | 87 | 59 | 42 |
| $\Sigma x^2$ | 831 | 691 | 466 | 287 | 772 | 499 | 315 | 231 | 648 | 471 | 208 | 96 | 519 | 523 | 241 | 144 |
| s | 1.435 | 1.321 | 1.691 | 1.56 | 1.639 | 1.273 | 1.467 | 1.619 | 1.726 | 1.59 | 1.561 | 1. | 1.694 | 1.767 | 1.210 | 1.452 |

APPENDIX 6

ENGINE SPECIFICATIONS FOR CLASS 47 DIESEL LOCOMOTIVE

## 1. GENERAL DESCRIPTION

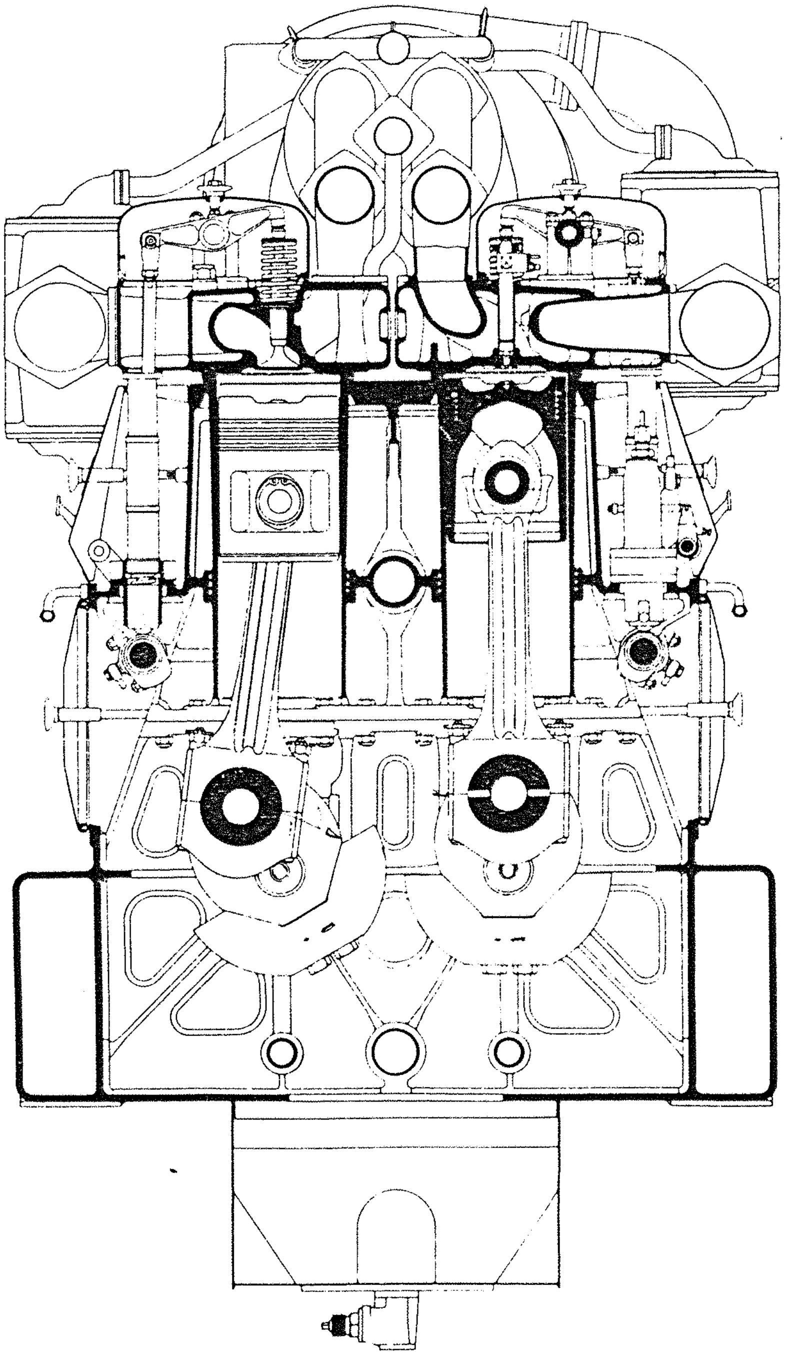

FIG. 7. CROSS SECTION OF TYPICAL 12LDA28 ENGINE

# DESCRIPTION OF DIESEL ENGINE AND ACCESSORIES

## 1. GENERAL DATA

The Sulzer diesel engine is of the four-stroke, pressure-charged vertical type and has direct injection. It is directly coupled to a generator group which consists of a main and auxiliary generator, with additionally on locomotives 1500-19 a train heating generator.

The principal data for the engine is as follows:—

| | |
|---|---|
| Engine type .. .. .. .. .. .. .. | 12LDA28-C |
| Continuous rating .. .. .. .. .. .. | 2,750 b.h.p. |
| at speed of (crankshaft) .. .. .. .. .. | 800 r.p.m. |
| Idling speed (crankshaft) .. .. .. .. .. | 325 r.p.m. |
| Generator speed .. .. .. .. .. .. | 1·44 times crankshaft speed |
| Number of cylinders .. .. .. .. .. .. | 12 |
| Bore .. .. .. .. .. .. .. .. | 280 mm. |
| Stroke .. .. .. .. .. .. .. .. | 360 mm. |
| Firing order 'A' Bank (bank 2) | 1 ╲ ╱ 5 ╲ ╱ 3 ╲ ╱ 6 ╲ ╱ 2 ╲ ╱ 4 ╲ |
| 'B' Bank (bank 1) | 6 2 4 1 5 3 |
| Dry weight with generator .. .. .. .. .. | 30 tons approx. depending on type of generator |
| Fuel injection pressure .. .. .. .. .. .. | 3,550 p.s.i. |
| Fuel pressure at busrail—engine idling .. .. .. | 30 p.s.i. approx. |
| —full load .. .. .. .. | 15 p.s.i. approx. |
| Lubricating oil pressure at bearings .. .. .. .. | 20-50 p.s.i. approx. |
| Main lubricating oil safety valve opens at .. .. .. | 60 p.s.i. |
| Heat exchanger lubricating oil by-pass valve opens at .. | 20 p.s.i. |
| Fine filter lubricating oil by-pass valve opens at .. .. | 20 p.s.i. |
| Coolant pressures .. .. .. .. .. .. | see section 15 |