Vibrations in Dwellings: exposure and annoyance

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CONTENTS

EXECUTIVE SUMMARY

Subject of the desk study

This report presents the results of a desk study focused on the subjective response of people to vibrations in their homes. In accordance with international and national standards (ISO 2631-2: 1989; BS 6472: 1992; DIN 4150, Teil 2: 1992) the vibration frequencies considered have been limited to the range from 1 to 80 Hz.

Extent of vibration annoyance in the living environment

Some large scale investigations on effects from environmental factors, such as vibrations, noise, and dust, show that annoyance caused by vibrations from road traffic in the domestic environment is widespread. Based on a Netherlands and a British investigation an estimate of the percentage of people highly annoyed by road traffic induced vibrations is 6 to 8%. Vibration-induced annoyance is less in case of other traffic and industrial sources. In situations in which environmental sources emit vibrations as well as noise, noise-induced annoyance is often dominant over vibration-induced annoyance.

Specification of a vibration measure

The main objective of the study is to determine a vibration measure which can be used in the evaluation of human exposure to vibrations with respect to annoyance. In the specification of such a measure a 5 step-model is used which is based on the theory of hierarchical power summation. In these five steps the following subjects have been considered:

step 1: frequency dependency of vibrations;

step 2: magnitude to specify a single-axis vibration event;

step 3: magnitude to specify exposure to single-axis vibration events occurring during a period of time;

step 4: magnitude to specify exposure to multi-axes vibration events occurring during a period of time;

step 5: magnitude to specify a measure for the 24 hours human exposure to vibrations in dwellings.

There are only a very limited number of well-controlled fundamental laboratory studies available that could be used for the specification of a vibration measure. With respect to information from field investigations, only in one field investigation effects of *road traffic* induced vibrations have been related to vibration magnitudes. However, vibration magnitudes in that survey have been determined for window vibrations, and not for vibrations of the floor or objects (seat, bed) with which persons are in contact in their domestic environment. Thus, no information is available on relations between currently used vibration magnitudes and vibration-induced subjective effects for the most annoying vibration source considered on a national level. Information about effects from *air traffic*, inducing vibrations in dwellings through *air-borne radiated sound*, is also lacking. More research has been carried out with respect to *railway-induced* vibrations. Two social surveys and a number of laboratory studies, in which railway-induced vibrations recorded in real life situations have been used as stimuli, investigated various aspects of railway-induced vibrations.

The results of the analyses have been compared with three Standards: ISO 2631-2: 1989, BS 6472: 1989, and DIN 4150, Teil 2: 1992. These Standards specify frequency weightings and frequency-weighted vibration magnitudes, that to some extent differ from each other, although the scope and field of application of the three Standards is identical. In ISO 2631-2: 1989 three frequency-weightings have been specified: z-, x/y-, and worst case weighting, in BS 6472: 1992 two weightings identical to the ISO z-, and x/y-weighting and in DIN 4150, Teil 2: 1992 a weighting nearly identical to the ISO worst case weighting. With respect to the specification of a frequency-weighted vibration magnitude ISO 2631-2: 1989 favours the use of the acceleration r.m.s. value, BS 6472: 1992 the use of VDV and eVDV, and DIN 4150, Teil 2: 1992 the use of KB_{Fmax} and KB_{FTr}.

It is concluded in the report that the laboratory and field investigations do not provide at present a sufficient basis for the choice of a vibration measure and no unambiguous answer is possible with respect to the main objective of the present study.

Exposure-effect relations

The second objective of the desk study is to collect data about exposure-effect relations in the range of vibration magnitudes relevant for the determination of health-based exposure limits. The exposure-effect relations given in Zeichart et al. (1993) constitute at present the only available information. These relations are restricted to vibrations induced by *rail road traffic*. In Zeichart et al. (1993) exposure-effect relations are expressed with KB values as vibration magnitude measures. In the present report preliminary exposure-effect relations for railway-induced vibrations have been derived with eVDV and acceleration r.m.s. values taken as vibration measures.

Interaction between vibrations and noise

The third objective of the study is to consider a possible interaction effect of vibration and noise emitted simultaneously by the same source. The results of laboratory investigations do not exclude the existence of a small interaction effect, but substantial evidence for such an effect could not be found. In the field investigation by Zeichart et al. (1993) there are some indications of an interaction between noise and vibration at higher vibration magnitudes. The results of an estimation of a possible interaction effect in real life situations suggest that such an effect is very small, at least in situations in which vibration magnitudes are not more than about a factor 4 larger than the base curve values presented in ISO 2631-2: 1989.

Trade-off between vibrations and noise

The report also considers the trade-off between vibrations and noise in simultaneous exposures. Based on the pooled results of several laboratory studies, the relation between noise and vibration magnitudes in situations in which vibrations and noise are equally annoying has been given in an equation for event durations of about 16 s (a typical duration of a passing train).

Indicator for vibration exposures

The fourth objective of the study is to determine one or more indicators that can be used on a statistical basis in investigations (on a national scale) into the effects of environmental factors, such as vibrations, without knowledge of the actual exposure magnitudes. The limited number of relevant surveys, all from outside the Netherlands, nearly all concern vibrations induced by rail road traffic; only one (British) survey dealt with road traffic vibrations.

One indicator may be the distance of the dwellings to the vibration emitting source (railroad traffic). In the report two equations are presented from which the percentage of people observing or being annoyed by railway-induced vibrations may be estimated by first approximation. With these equations the percentage of people noticing or being annoyed is given as a function of the logarithm of the distance of the dwelling to the railway. The equations represent a maximum and minimum percentage at a given distance. At a distance of 10 m the percentage of people noticing or being annoyed by railway-induced vibrations in their homes is thus estimated to be between 48 and 95%, and at a distance of 100 m this percentage is estimated to be between 7 and 35%. Considering the very limited information, however, this result needs further verification by research, in which conditions in the Netherlands situations are taken as a basis.

For situations in the vicinity of roads with a dense traffic flow, a British survey showed that a *noise* exposure measure, the 24 hours equivalent sound level, allows a rough estimate to be made of the annoyance due to road traffic induced vibrations. However, it is doubtful whether this result is also applicable for situations other than those examined in the survey, and especially for conditions in the Netherlands that differ in many respects from those in the British survey.

1. INTRODUCTION

1.1 Objectives

By order of the Ministry of Housing, Spatial Planning and Environment a desk study has been carried out with the following objectives:

1. to determine a measure of vibration to rate vibration annoyance experienced by people in their domestic environment. Such a measure is to be determined by using the model of hierarchical power summation. Specifications are to be limited to effects from one source of vibrations acting at a specific time, thus excluding possible interaction effects from the simultaneous occurrence of more than one source of vibrations. Evaluation of human exposure will be limited to vibration exposures in buildings. In accordance with international and national standards (ISO 2631-2: 1989; BS 6472: 1992; DIN 4150, Teil 2: 1992) this limits the vibration frequencies to be considered to the range from 1 to 80 Hz;
2. to collect data about exposure-effect relations. If possible, data will have to be collected in the range of vibration magnitudes relevant for the determination of health-based exposure limits. In this respect, the effect to be considered as an endpoint is subjective response/annoyance/ disturbance;
3. to consider a possible interaction effect of vibration and noise emitted by the same source upon subjective response of people exposed simultaneously to both environmental factors. In everyday life many of the sources that emit vibrations in buildings also emit sounds, audible in those buildings. Vibration combined with noise may have an effect on the subjective response of people that is different from the effect of exposure to vibrations alone;
4. to determine one or more indicators which can be used in other projects to estimate to which extent vibration annoyance exists in the Netherlands population. Such estimates are to be based upon knowledge about the location and extent of disturbing environmental sources, such as road, railroad and air traffic and industrial sources, but without knowledge of the actual vibration magnitudes.

1.2 Outline of the report

The organization of the report is as follows. The four objectives of the desk study have been presented in the first section of this report. This section of chapter 1 presents the outline of the report.

In the first section of chapter 2 the various sensory systems involved in the perception of whole-body vibrations are listed, as well as the various effects which such vibrations may induce in people. The present desk study focuses on the subjective response (annoyance) of people to vibrations in their domestic environment. An overview is given of the various aspects involved in that subjective response. The second section of chapter 2 puts vibrations in the living environment into perspective by comparing their effects with effects from other environmental factors, such as noise.

Section 2.3 presents definitions and terms in an informal way. It also explains a step-model which will be applied to specify exposure measures for predicting vibration-induced annoyance. The step-model is based on the theory of hierarchical power summation and it specifies vibration measures by the following steps:

step 1: frequency dependency of vibrations;

step 2: magnitude to specify a single-axis vibration event;

step 3: quantification of a combination of single axis vibration events during a part of the 24 hour period;

step 4: quantification of a measure for multi-axes vibration exposure during a part of the 24 hour period;

step 5: quantification of a measure to specify the 24 hour human exposure to vibrations in dwellings.

In chapter 3 step 1 is treated. Vibrations in the domestic environment that cause annoyance often have vibration magnitudes that are only slightly above perceptions thresholds. Therefore perception thresholds are taken as a basis for weighting the contributions from the different frequencies. Section 3.2 gives information about perception thresholds for sinusoidal test signals and about equal sensation contours for this type of test signals above perception thresholds. Furthermore, vibration perception thresholds and equal sensation contours of sinusoidal vibrations will be compared with those of narrow-band vibrations. For more complex vibrations alternative frequency-weighting procedures are considered. The results are compared with the frequency-weighting procedures specified for building vibrations in ISO 2631-2: 1989, BS 6472: 1992 and DIN 4150, Teil 2: 1992. Since there are many variables involved in the quantification of a vibration measure, such as posture of the subjects and the direction of the vibrations to which the subjects are exposed, sections of the chapters 3 and 4 contain a synopsis, in which the available information has been classified.

Chapter 4 concerns step 2 to 5 of the step-model. First, the quantification of a single-axis vibration event on the basis of the instantaneous vibration magnitudes is considered. Then, measures for the quantification of a series of single-axis vibration events and for exposure to continuous single-axis vibrations during longer periods, such as hours, are taken into consideration. The combination of vibrations occurring simultaneously in different directions are a following matter of concern. To specify steps 2 to 5, information of laboratory studies and field investigations will be analyzed. For step 5, the results of field investigations are used to estimate differences in subjective response to day- and night-time vibrations. The scanty information on exposure-effect relations for vibrations in the domestic environment is presented in section 3.6. Where appropriate results are compared with the specifications given in ISO 2631-2: 1989, BS 6472: 1992 and DIN 4150, Teil 2: 1992. Also a diagram is given which gives the exponents in the hierarchical power sums applied in the specifications of these Standards.

Most environmental sources that emit vibrations do also emit noise. Therefore, people are sometimes simultaneously exposed to both vibrations and noise. Chapter 5 considers possible interactions in the effect of both stimuli on the subjective response. Chapter 5 also deals with the trade-off between noise and vibration for situations in which subjects are exposed simultaneously to these two environmental factors.

In chapter 6 data from a very limited number of field investigations are analyzed in order to establish a simple indicator for the prediction of vibration annoyance.

Chapter 7 summarises the results of the foregoing chapters with respect to the four objectives specified in section 1.1.

In chapter 8 terms, definitions and equations are presented.

At the end of the report references are given. In the Annex the results are presented of a German field investigation. This is the largest investigation dealing with annoyance from (railway-induced) vibrations.

2. ASPECTS OF VIBRATIONS IN BUILDINGS

2.1 Perception of vibrations and vibration-induced effects

The following sensory systems are involved in the perception of vibrations:

- visual;
- vestibular;
- auditory;
- somatic:
  . cutaneous (skin-related)
  . kinaesthetic (muscle-related)
  . visceral.

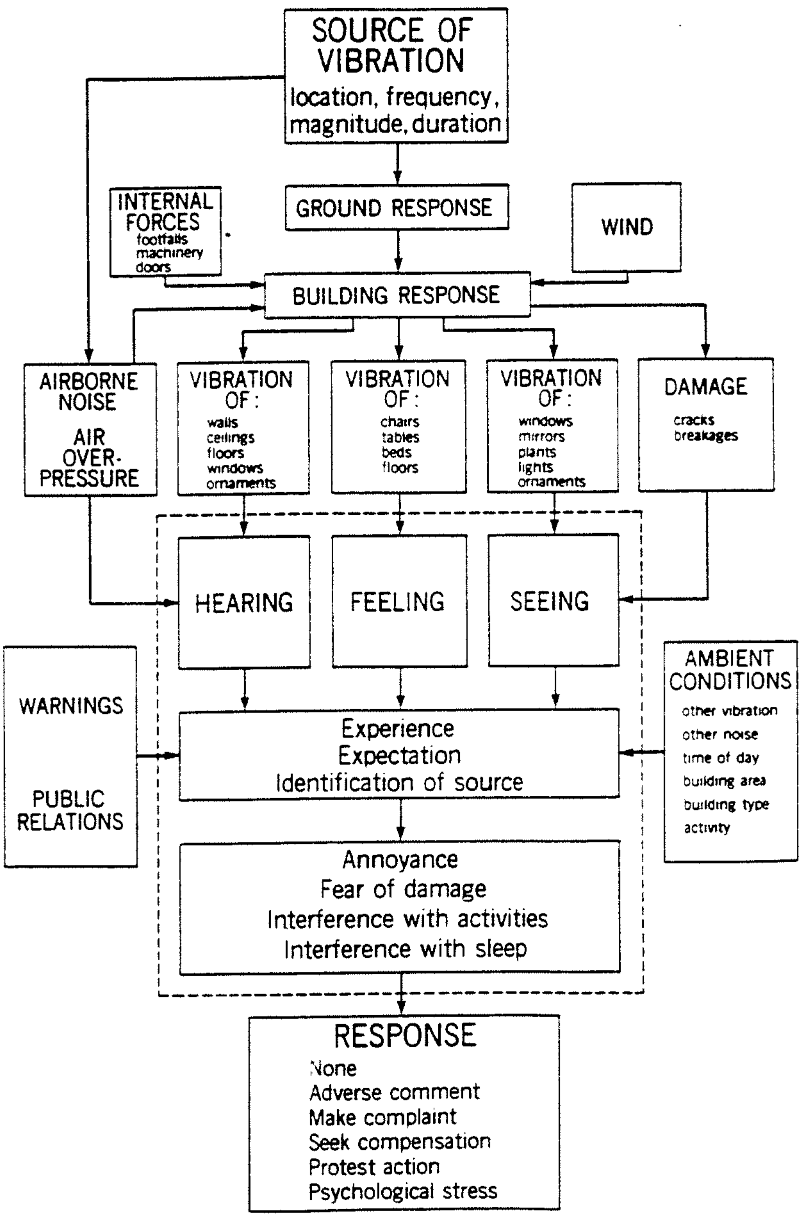
These systems themselves are complex and interrelated. Dependent upon the frequency of the vibration one system or different systems act together in the perception of vibrations. At low frequencies vision, the vestibular system, and the vestibular control of eye movements are important. In dwellings visual perception of vibration commonly occurs through shaking objects, swinging lights, and the movement of reflections in mirrors and windows. Vibration of the dwelling may also produce low frequency sound, that can be noticed. Whether sound or vibration dominates the perception, depends upon the room characteristics and the transmission loss from the vibrating surface to the contact points with the human body. At intermediate frequencies movements and forces within the body may produce a kinaesthetic sense of motion. At high and intermediate frequencies the cutaneous sensory system is considered to be of importance. Due to this complex nature of the perception of vibrations thresholds and equal sensation contours over a wide frequency range are governed by various sensory systems.

The following six effects are experienced by people as a result of whole-body vibration:

- perception;
- annoyance, adverse subjective response, degraded quality of life;
- degraded comfort, fatigue;
- degraded working efficiency;
- motion sickness;
- impaired health.

As stated in ISO 2631-2: 1989 "Experience has shown in many countries that complaints regarding building vibrations in residential situations are likely to arise from occupants of buildings when the vibration magnitudes are only slightly in excess of perception levels. In general, the satisfactory magnitudes are related to the minimum adverse comment level by the occupants and are not determined by any other factors, such as shortterm health hazard and working efficiency. Indeed, in practically all cases the magnitudes are such that there is no possibility of fatigue or other vibration-induced symptoms". Since this report is aiming at perception and annoyance from vibrations in the domestic environment on authority of ISO 2631-2 no attention will be paid in this report to other effects.

Figure 2.1 Factors affecting subjective response due to whole-body vibration in dwellings (Source: Griffin, 1990).



Not only the physiological phenomenon of the perception of vibrations is complex, also the subjective reactions of people to vibrations in their domestic environment depend on many variables. Figure 2.1 gives an overview of aspects involved and their possible interrelations. The figure has been presented by Griffin (1990).

2.2 Vibrations in the domestic environment in perspective

In this section the prevalence of annoyance due to vibrations in the domestic environment is roughly estimated and compared to the prevalence of annoyance due to other environmental factors.

A TNO-report (Jong de, Opmeer and Miedema, 1994) gives an overview of the annoyance in the Netherlands in 1993 due to environmental factors, such as noise, vibration, odour, dust/soot/smoke and illumination. The results are based on face-to-face interviews with more than 4000 inhabitants of the Netherlands population. Some results with respect to vibrations and noise are presented in table 2.1.

Table 2.1 Percentage of respondents in the Netherlands survey on environmental factors which are highly annoyed by vibrations and noise, respectively, in their domestic environment (Source: Jong de et al., 1994).

source	percentage of respondents highly annoyed by:	
	vibrations	noise
road traffic	6	25
aircraft traffic	3	12
industrial sources	1	6
railway traffic	1	2

A national survey carried out in the United Kingdom in 1972 (Sando and Batty, 1974) on the perception and annoyance from road traffic shows about the same percentage of respondents highly annoyed by vibrations from road traffic as the Netherlands survey: 8% of the respondents report to be seriously bothered by road traffic induced vibrations. The response rate of the survey was 82% (5700 out of 7200 addresses). The specific categories of disturbances covered by the investigation were noise, vibration, fumes, dust and dirt, pedestrian danger and visual intrusion.

Jeans (1983) investigated various aspects of annoyance due to heavy vehicles in four samples of populations which were known to complain about the presence of heavy vehicles in their living environment. The results, which have only a relative importance since the populations considered are a-specific, are given in table 2.2.

Table 2.2 Percentage of respondents with an opinion about several aspects of heavy vehicles in their domestic environment (Source: Jeanes, 1983).

opinion	percentage of respondents with an opinion about			
	noise	vibration	dust/dirt	fumes
biggest nuisance	40	20	16	1
next biggest nuisance	16	18	15	3
no nuisance	38	52	50	84

Three other surveys (Zeichart et al., 1993; Watts, 1984; Woodroof and Griffin, 1987) are only briefly considered here and will be further considered in chapter 4. They concern annoyance from traffic-induced vibrations. Watts (1984) seeks to specify a relation between subjective response to vibrations and road traffic and Woodroof and Griffin (1987) and Zeichart et al. (1993) examined the subjective responses to railway-induced vibrations. In all three surveys vibration measurements have been carried out.

In the investigation by Watts (1984), fifty sites were chosen in the southern part of England. Some sites were close to dual-carriageways where traffic flow was relatively constant, and other sites were close to heavily congested urban roads near junctions where the flow was intermittent. The total number of completed face-to-face questionnaires was 1625. The percentage of respondents who noticed various road traffic induced vibrations in their homes is given in table 2.3. A large percentage (62%) noticed windows and doors rattling or buzzing, and 16% noticed ornaments rattling or buzzing. From this Watts concludes that road traffic induced vibrations in situations close to the road are often noticed because objects or structures in the home emit audible noise when set into vibration. Road traffic induced vibrations were also received by tactile stimulation: 30% felt floors shake or tremble, and 14% felt the bed shake by road traffic induced vibrations.

Table 2.3 Percentage of respondents who noticed vibrations. Respondents live close to dual-carriageways and heavily congested urban roads (Source: Watts, 1984).

vibration effect	percentage noticing effect
windows or doors rattling or buzzing	62.2
floors shaking or trembling	29.5
ornaments rattling or buzzing	15.7
traffic causing the bed to shake	13.6
muffled sensation in the ears or fluttering sensation in the chest	18.9
feeling vibration in the air	30.2

Watts showed that vibration nuisance by road traffic is more closely related to noise exposure measures than to levels of window vibration. In fact, his results indicate that vibration annoyance and window vibration levels have a very low correlation.

In the survey by Woodroof and Griffin (1987) 459 respondents who lived within 100 metres of a railway line were interviewed. A total of 160 (35%) reported noticing railway-induced vibrations in their homes. However, no statistical significant relationship between vibration annoyance and vibration magnitude was found. On the basis of an additional analysis of the data of the 133 of the respondents who said, after being specifically asked, that they noticed railway-induced building vibration, the authors suspect that these subjects seldom or never thought about railway-induced building vibration. For instance, when asked about their particular dislikes of the area, 117 of the 133 made no mention of the railway; 11 respondents mentioned noise and 2 mentioned vibration from the railway spontaneously. The data showed that when environmental factors other than vibration existed, these were considered to be more annoying than vibration by the majority of those who mentioned the other factor.

The largest social survey on vibration annoyance in the domestic environment (Zeichart et al., 1993) is presented in Annex A of this report. In the survey 1026 respondents have been interviewed about their subjective response to railway-induced vibrations and noise, 765 respondents living in the neighbourhood of intercity train railroads (Fernbahn) and 261 in the neighbourhood of overground suburban rapid transit systems (S-bahn). Three quarters of the respondents living in the F-bahn areas considered railway-induced noise (much) more annoying than railway-induced vibrations, 16% of them considered them equally annoying and 8% considered the vibrations (much) more annoying that the noise produced by the railroad traffic. In the survey vibration-induced annoyance is considerable: the percentage of respondents in the F-bahn areas at least somewhat annoyed by railroad vibrations increased from 20% in the lower vibration exposed areas up to 60% in the areas highly exposed to vibrations.

In conclusion:

- annoyance caused by vibrations from road traffic in the domestic environment is widespread; based on Netherlands and British national scale investigations an estimate of the percentage of highly annoyed people is 6 to 8%. Vibration-induced annoyance is (much) less but not neglectible in case of other traffic and industrial sources;

- in situations (very) close to densely-trafficked roads and railroads the percentage of people highly annoyed by vibrations may be 20 to 60%;
- noise-induced annoyance is often dominant over vibration-induced annoyance in situations in which sources emit vibrations as well as noise. Estimates range in two to ten times as many people annoyed by noise in their living environment than annoyed by vibrations.

2.3 A model specifying annoyance and whole-body vibration

2.3.1 Definitions and variables

In chapter 8 definitions, mathematical terms, and some relevant equations are presented. This section presents terms on vibration in a more descriptive way.

Measures of vibration

Three measures with which the magnitude of an oscillatory motion can be expressed are: acceleration, velocity, and displacement. The SI-unit for quantifying acceleration magnitude is metres per second per second (commonly abbreviated to ms^{-2}), velocity is expressed in ms^{-1} and displacement in m. Preferred units for acceleration are ms^{-2} and mms^{-2}, for velocity mms^{-1}, and for displacement mm and μm.

For a sinusoidal vibration, i.e. a vibration that is a sine function of time, there are fixed relations between acceleration, velocity, and displacement. Equations specifying these relations are given in chapter 8. Vibrations caused by environmental sources usually are composed of vibrations with a range of frequencies. The frequency content of such vibrations is an aspect to be considered in addition to their magnitude. Since the human body is not equally sensitive to vibrations with the same vibration magnitude but with different frequencies, usually the contributions from different frequency ranges are weighted differently.

The magnitude of a vibration event is usually expressed in terms of frequency-weighted

. root-mean-square (r.m.s.) acceleration or velocity;
. root-mean-quad (r.m.q.) acceleration;

- peak or peak to peak velocity or acceleration;
- time-weighted maximum velocity or acceleration.

Definitions of r.m.s. and r.m.q. values of a function are given in chapter 8. The peak value is the maximum value of a function during a given time interval. The peak value is usually taken as the maximum deviation from the mean value. The peak-to-peak value is the deviation of the positive peak value from the negative peak value. The crest factor of a vibration is the ratio of the peak value to the r.m.s. value over a specified time interval. For many purposes the acceleration or velocity is frequency-weighted prior to the formation of this ratio. If the instantaneous values of a frequency-weighted vibration measure x are measured using a weighting network with a given time constant τ, the maximum value of the time-weighted signal, $x_{\tau max}$, is also used to describe the magnitude of a vibration event.

For the assessment of the magnitude of sound a logarithmic scale is in common use, in which the sound level is defined relative to the logarithm of the r.m.s. value of the sound pressure. This is partially because of the wide range of sound pressures occurring in real life (r.m.s. values varying a factor 10 000 000 from perception threshold to pain threshold) and because of the logarithmic relation between sound pressure r.m.s. values and sensation of loudness. With whole-body vibration there is a range of a factor 1000 from perception threshold to pain threshold and vibration sensation increases by first approximation in linear proportion to sensation magnitude. Therefore vibration magnitudes are usually not expressed on a logarithmic scale.

The magnitude of vibrations over longer periods of time (e.g. hours or the 24 hours during a day) is usually characterized by the frequency-weighted r.m.s. or r.m.q. value over that period of time. Cumulative measures such as the vibration dose value (VDV) or estimated vibration dose value (eVDV) are also sometimes used as a measure of vibration over longer periods. Vibration dose value is the frequency-weighted r.m.q. value of the acceleration, with a reference time taken equal to 1 s. The unit of VDV is $ms^{-1.75}$. There is an empirically determined relation between eVDV, acceleration and exposure duration. This relation is given by:

$$eVDV = 1.4\, a_t\, t^{1/4}$$

in which:

t duration of exposure;

a_t the r.m.s. acceleration value over duration t.

For vibrations with low crest factors, such as sinusoidal vibrations, eVDV is higher than VDV and for vibrations with high crest factors (over 6) eVDV may be lower than VDV. For the relation between VDV and eVDV for sinusoidal vibrations, see chapter 8.

The trade-off between duration and instantaneous acceleration in eVDV and VDV implies that a halving of the acceleration is equivalent to a 16-fold increase of exposure duration. The corresponding figure for r.m.s. averaging (and a^2t = constant) is a 4-fold increase of exposure duration per halving of acceleration.

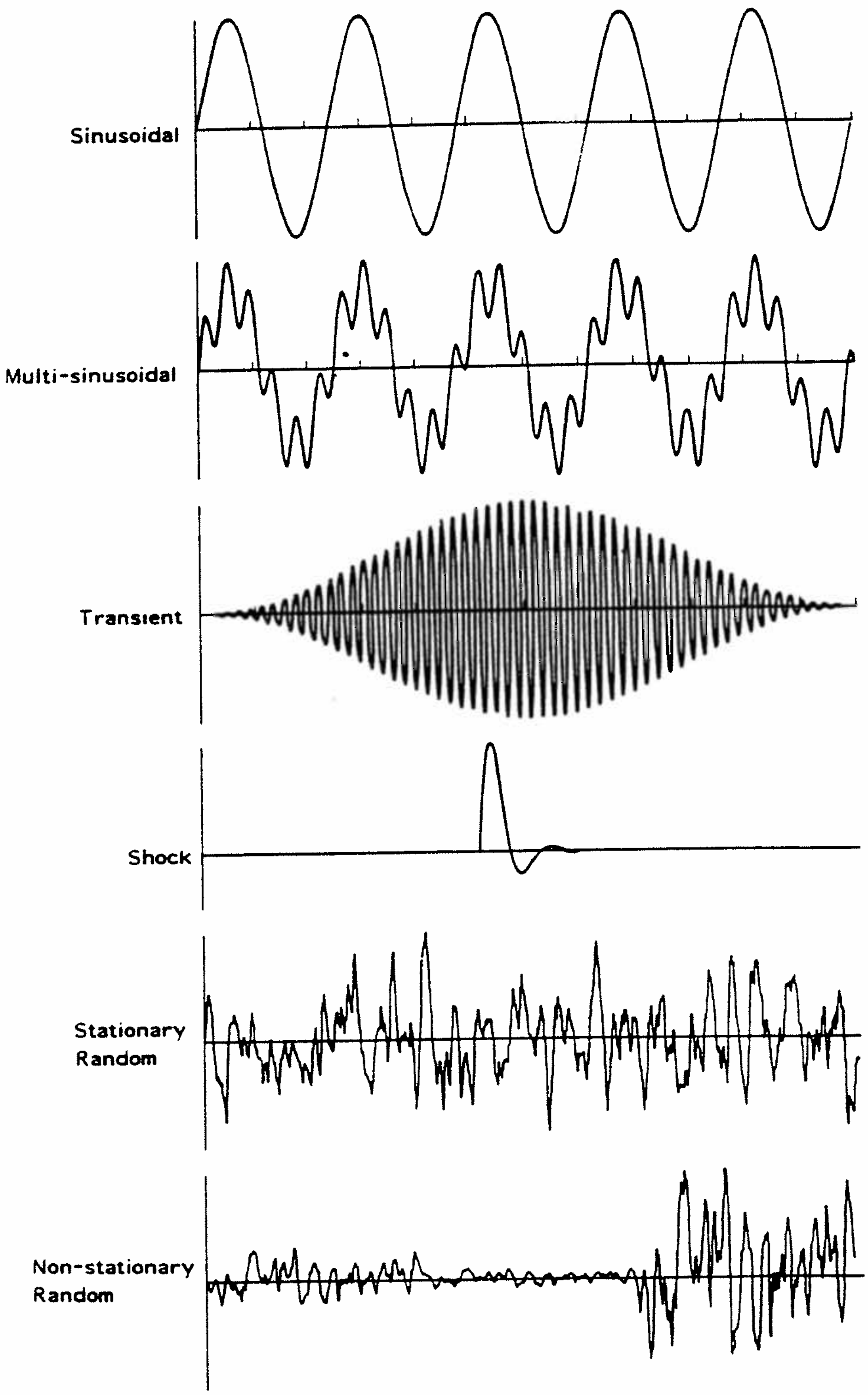
Description of vibrations

In ISO 4866: 1990 definitions are given to describe the occurrence of vibrations in the course of time. Vibrations can be described either in a deterministic way or as a random process. The deterministic processes can be divided into periodic, quasi-periodic and non- periodic processes. For a periodic vibration each of the magnitude values recurs in equal increments of time; a quasi-periodic vibration only slightly deviates from a periodic vibration. Periodic vibrations can be either sinusoidal or complex. A complex vibration can be written as the sum of sinusoidal vibrations. A continuing periodic vibration is called a steady-state vibration. A transient vibration occurs when a system changes from one steady state to another. A specific transient vibration is a shock vibration, which results from a shock excitation. Vibrations caused by rapidly repeated shocks are called impulsive vibrations.

A random vibration, i.e. a vibration whose magnitude cannot be predicted precisely for any given instant of time, is either stationary or non-stationary. It can also be either a broad-band vibration, i.e. the frequency components are distributed over a broad frequency range (e.g. one octave or greater), or a narrow-band vibration.

Various waveforms, i.e. the instantaneous acceleration as a function of time, are given in figure 2.2.

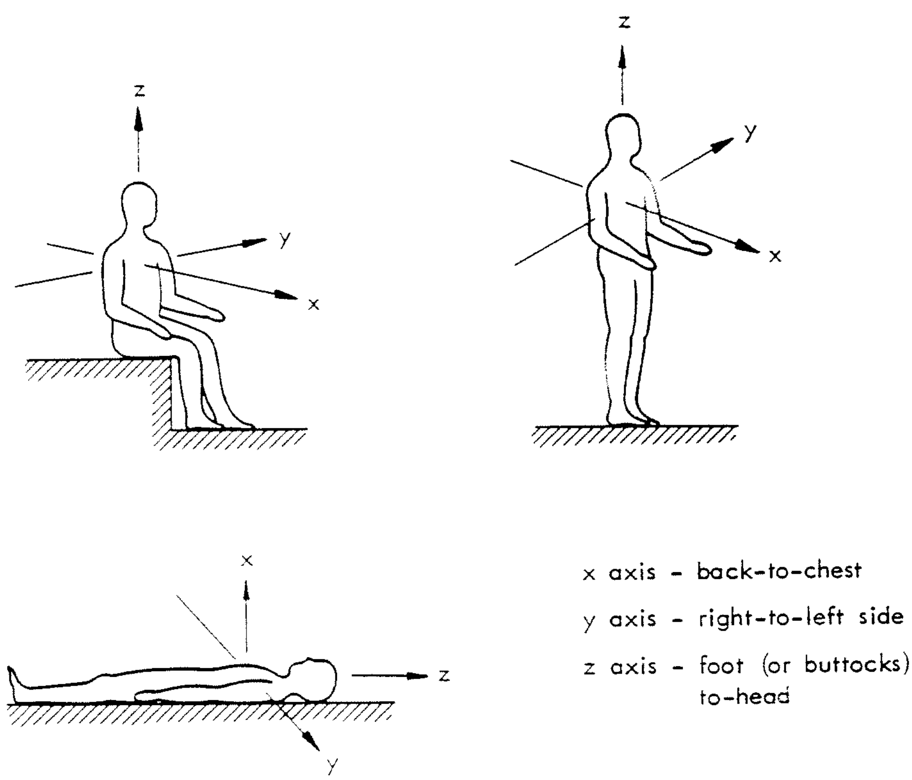
Figure 2.2 Waveforms of different types of oscillatory motion.



Vibration axes

International Standard ISO 2631-1: 1985 defines an orthogonal co-ordinate system for vibrations. The vibration axes are defined relative to the human body (see figure 2.3). The x-axis represents back-to-chest vibrations, the y-axis right to left side vibrations, and the z-axis foot or buttocks to head vibrations. Thus, for standing and sitting persons, vertical vibrations correspond to z-axis vibration, but vibrations along the z-axis represent horizontal motions for lying persons. The nomenclature specified in ISO 2631-1: 1985 will be used throughout this report.

Figure 2.3 Directions of basicentric coordinate systems for mechanical vibrations influencing humans (Source: ISO 2631-1: 1985).



Posture

Posture can have an influence on the amount of vibration transmitted to and through the body. Three main postures can be distinguished: sitting, standing and recumbent. In a recumbent position a person may lie on one side of the body, or on the front (i.e. prone), or on the back (i.e. supine) or in some variation of these positions. At the same time the full length of the body or only parts of it may be exposed to the same vibration. A bed may either allow movements to be transmitted from the floor or may provide stability. Therefore, the variations in the conditions of recumbent persons is considerable. Also in the seating position, transmission of vibrations largely depend upon dynamics of the seat as well as on the points of contact of the body with the vibrating seat. In a standing position vertical vibrations are often experienced in the same way as in a seated position. However, transmission through the body of vibrations with higher frequencies may be greatly reduced by bending the knees. Thus, small changes in the body position and in the transmission characteristics of the vibration transmitting object may have a large impact on the vibration magnitude experienced by persons.

2.3.2 Step-model

In Miedema (1993) the model of hierarchical power summation has been applied to noise measures with respect to noise annoyance. The report describes how a trade-off between more basic noise attributes (intensities per frequency band per point in time) determines the annoyance caused by noise. According to that model, a quantification of annoyance is a hierarchical power sum of quantifications of these basic attributes. This hierarchical power sum is obtained by the repeated application of the power sum rule:

$$[\Sigma_k (b_k x_k)^{a_k}]^{1/a}.$$

The hierarchical power sum rule is more general than a weighted addition. In this report this model will be applied to vibrations and vibration annoyance.

All measures considered in this report are based on vibration intensities in a specific direction as the quantification per <u>frequency-time combination</u>. Per point of time a frequency-weighted vibration intensity, I_F is determined. This quantity is defined as follows:

$$I_F = [\Sigma_j(F_jI_j)^2]^{1/2},$$

where the I_j values are the one-third octave band intensities at a certain moment, and F_j frequency weightings for a specific direction.

Two different quantifications of single axis vibration events are used. Let $I_F(t)$ denote the I_F value at point of time t in a specific direction. Then a vibration event in that direction may be quantified by the maximum of the I_F values that occur during an event with a duration T:

$$I_{Fmax} = \max_t I_F(t).$$

This maximum is the limit of a power sum of the I_F values that occur during an event.

A vibration event can also be quantified by the second power sum of the I values that occur during the event:

$$I_{FX} = 1/T\ [\Sigma_t[I_F(t)]^2]^{½}.$$

I_{FX} represents the frequency-weighted r.m.s. value in a specific direction.

Another quantification of a vibration event is by the fourth power sum of the I_F values:

$$I_{FQ} = 1/T\ [\Sigma_t[I_F\ (t)]^4]^{¼}.$$

There are several ways to quantify single-axis vibration exposure during a period of time (e.g., day, evening, night). Let $I_{Fmax}(i)$, $I_{FX}(i)$, and $I_{FQ}(i)$ denote the I_{Fmax} , the I_{FX}, and I_{FQ} value, respectively, for event i. Then single-axis vibration exposure during a period of time may be quantified by the following (power) sum of the I_{max}, I_{FX}, and I_{FQ} values, respectively, during that period:

$$I_p = \Sigma_i\ I_{Fmax}(i);$$

$$I_{FXX} = \Sigma_i\ I_{FX}(i);$$

$$I_{FQQ} = \Sigma_i\ I_{FQ}(i).$$

The quantification of a multi-axes vibration exposure during a period of time from single axis values occurs as follows. Let $I_s(d_i)$ denote the I_s value for direction d_i (the subscript s denotes P, FXX and FQQ). Then the multi-axes value I_{3s} may be quantified by:

$$I_{3s} = \Sigma_i I_{smax}(d_i);$$

$$I_{3s} = \Sigma_i I_s(d_i).$$

Vibration exposures during a 24 hours period may be quantified in various ways. Let $I_{3p}(k)$, $I_{3FXX}(k)$, and $I_{3FQQ}(k)$ symbolize the values of I_{3p}, I_{3FXX}, and I_{3FQQ} , respectively, for period k. Furthermore, let T be the length of a 24 hours period in seconds and let T_k be the length of a period k of the day in seconds. Vibration exposure during a 24 hours period may then be quantified by:

$$I = \Sigma_k w_k I_{3p}(k);$$

$$I = \Sigma_k w_k I_{3FFX}(k);$$

$$I = \Sigma_k w_k I_{3FQQ}(k).$$

in which: w_k weighting factors for different periods of the 24 hours.

Therefore, the model specifies vibrations measures by the following steps:

step 1: frequency dependency of vibrations;

step 2: magnitude to specify a single-axis vibration event;

step 3: quantification of a combination of single axis vibration events during a part of the 24 hour period;

step 4: quantification of a measure for multi-axes vibration exposure during a part of the 24 hour period;

step 5: quantification of a measure to specify the 24 hour human exposure to vibrations in dwellings.

Chapter 3 treats step 1 and chapter 4 concerns step 2 to 5. At the end of chapter 4 a diagram is given which specifies the exponents in the hierarchical power sums applied in the specifications given in ISO 2631-2: 1989, BS 6472: 1992, and DIN 4150, Teil 2: 1992.

3. FREQUENCY DEPENDENCY

3.1 Introduction

As already stated in chapter 2, disturbances due to vibrations in the domestic environment arise when the vibration magnitudes are only slightly in excess of perceptions thresholds. Therefore, perception thresholds are used to take into account the frequency dependency of the vibration sensation in a vibration measure. First in section 3.2.1 information will be given about perception thresholds for sinusoidal test signals.

If the shape of the equal sensation contours does not change with increasing vibration magnitude, a frequency weighting in the range above thresholds according to the perception thresholds may be appropriate. However, if the shapes of the equal sensation contours do change with vibration sensation magnitude, this implies that a frequency weighting dependent upon vibration magnitude may be required. Then, the rating of vibration magnitude would be much more complicated. Section 3.2.2 deals with equal sensation contours above perception thresholds.

Since the bandwidth of the signal may have an effect on the perceived magnitude of a vibration, in section 3.3 vibration perception thresholds and equal sensation contours of sinusoidal vibrations will be compared with those of narrow-band Gaussian random vibrations. The relevant publications give data only on narrow-band signals of (at least) 1/3-octave wide. The available information is presented in sections 3.3.1 and 3.3.2.

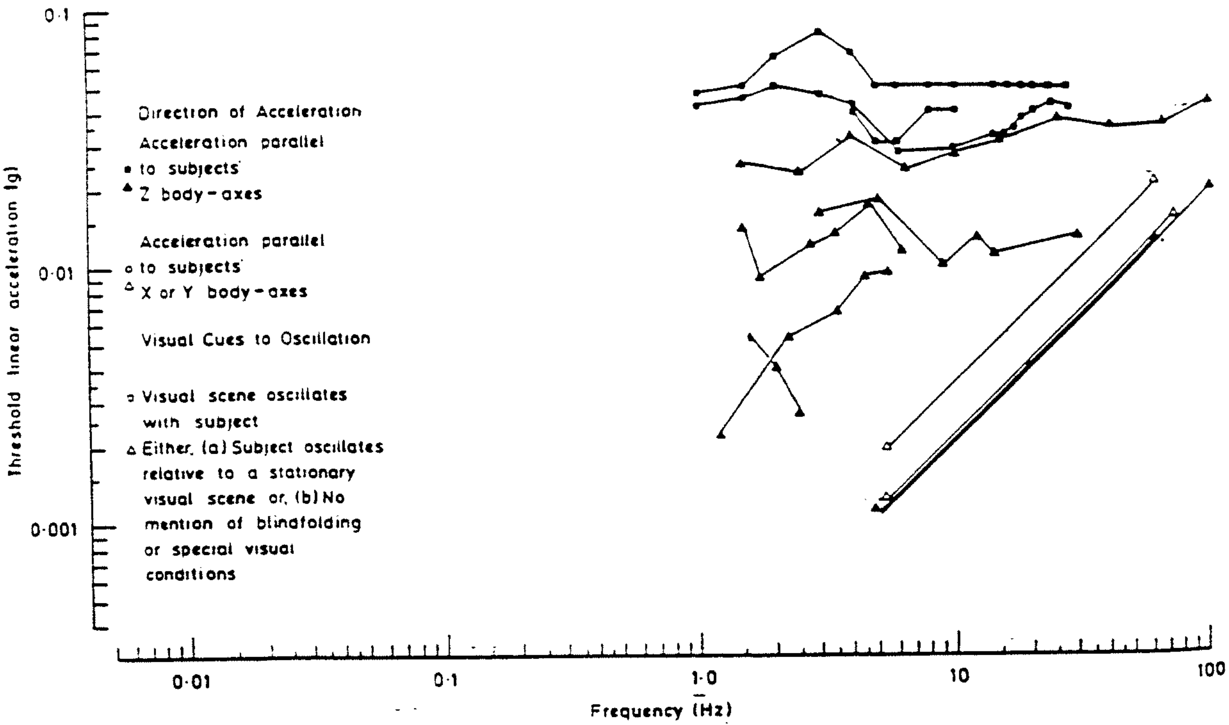
For more complex vibrations two alternative frequency-weighting procedures are considered. The first procedure consists of a frequency-weighting and then a summation of the various frequency components to determine an overall vibration magnitude. The second method takes into account that interaction effects between frequency components of a complex vibration occur which have an effect upon the perceived sensation of the magnitude of complex signals and which do not allow a simple summation of frequency components. In section 3.4 information is given about wide-band random Gaussian vibrations and vibrations consisting of two or more sinusoidal or 1/3-octave band vibrations. Section 3.5 gives the result of an investigation into the evaluation of railway-induced building vibration. In section 3.6 results are compared with the frequency-weighting procedures specified for building vibrations in ISO 2631-2: 1989, BS 6472: 1992, and DIN 4150, Teil 2: 1992.

3.2 Exposure to single-axis sinusoidal vibration

3.2.1 Perception thresholds

In 1978 Gundry compiled the available results on perception thresholds of sinusoidal vibrations. The results of his compilation for frequencies of at least 1 Hz have been reproduced in figure 3.1. The perception thresholds have been given in peak acceleration values relative to g ms^{-2}. For sinusoidal vibrations these peak acceleration values relative to g can be transformed into acceleration r.m.s. values by applying the relations given in chapter 8 (i.e. g x 10^{-3} peak corresponds to 6.9 x 10^{-3} ms^{-2} r.m.s.). The postures of the test subjects have not been specified by Gundry. Most test results relate to z-axis vibrations. Apparently, there is a wide dispersion in test results. For z-axis vibrations at 5 Hz perception thresholds vary by a factor of 50, i.e. from 0.001g to 0.05g peak.

Figure 3.1 Perception thresholds for sinusoidal vibrations, derived from investigations carried out before 1978. The ordinate shows the peak acceleration amplitude at threshold relative to 9.81 ms^{-2} (adapted from Gundry, 1978).



The upper extremes in figure 3.1 are based on studies with small numbers of subjects and most probably the curves do not represent the boundaries between feeling and not feeling but describe a degree of discomfort.

In Griffin (1990) a major attempt has been made to compile more recent studies, in which the purity and quality of the vibration stimuli (distortion, background vibration, cross-axis coupling and seating dynamics) and other relevant factors have been documented, and in which established psychophysical procedures have been applied. The figures presented by Griffin have been reproduced in this report as figure 3.2 to figure 3.6. In preparing the figures, data have been classified according to the axis of the vibrations and according to the posture of the test subjects. The results of the study by Reiher and Meister (1931) have been included in the figures by Griffin because they have influenced several vibration standards to a large extent.

Figure 3.2 Perception thresholds for z-axis (vertical) sinusoidal whole-body vibration of seated and standing persons (Source: Griffin, 1990).

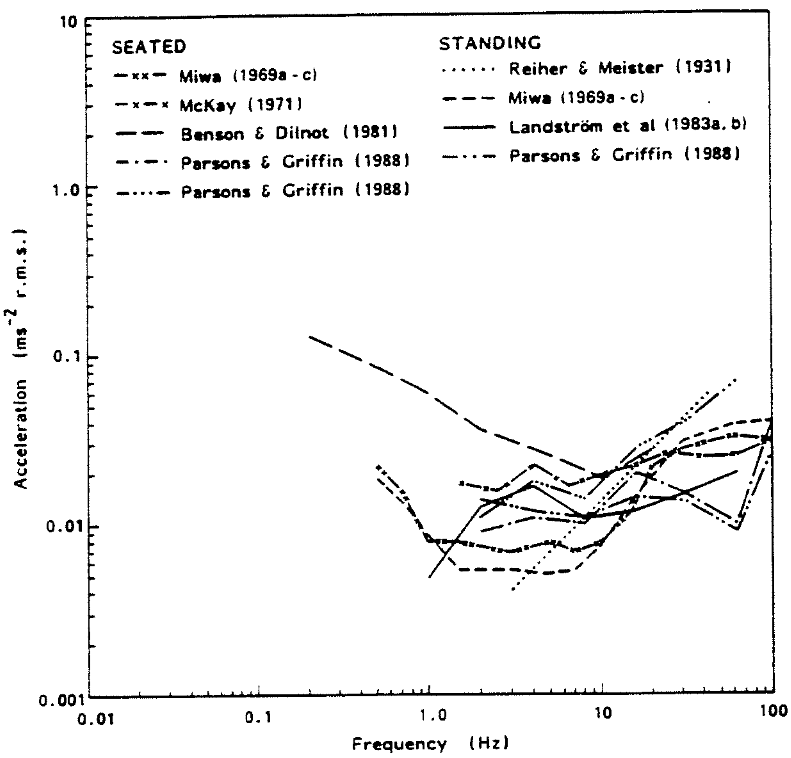


Figure 3.3 Perception thresholds for x- and y-axis (horizontal) whole-body vibration of seated persons (adapted from Griffin, 1990).

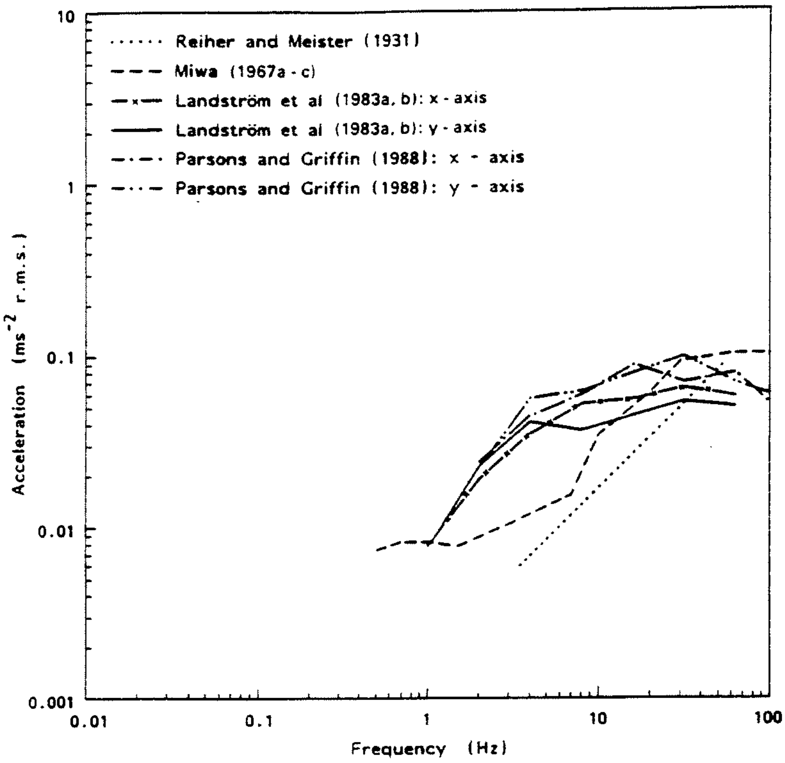


Figure 3.4 Perception thresholds for x- and y-axis (horizontal) whole-body vibration of standing persons (adapted from Griffin, 1990).

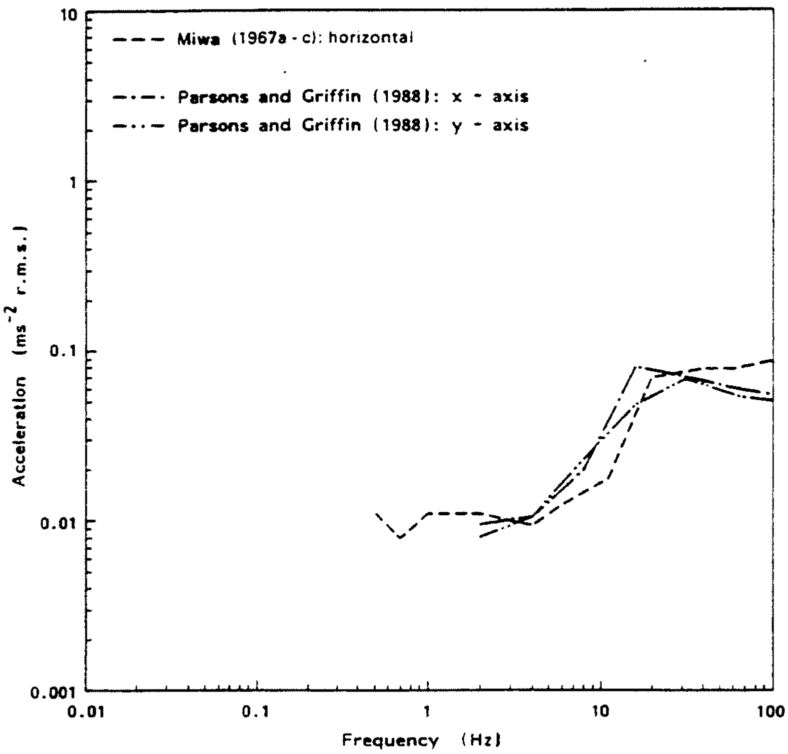


Figure 3.5 Perception thresholds for x-axis (vertical) whole-body vibration of recumbent (supine) persons (adapted from Griffin, 1990).

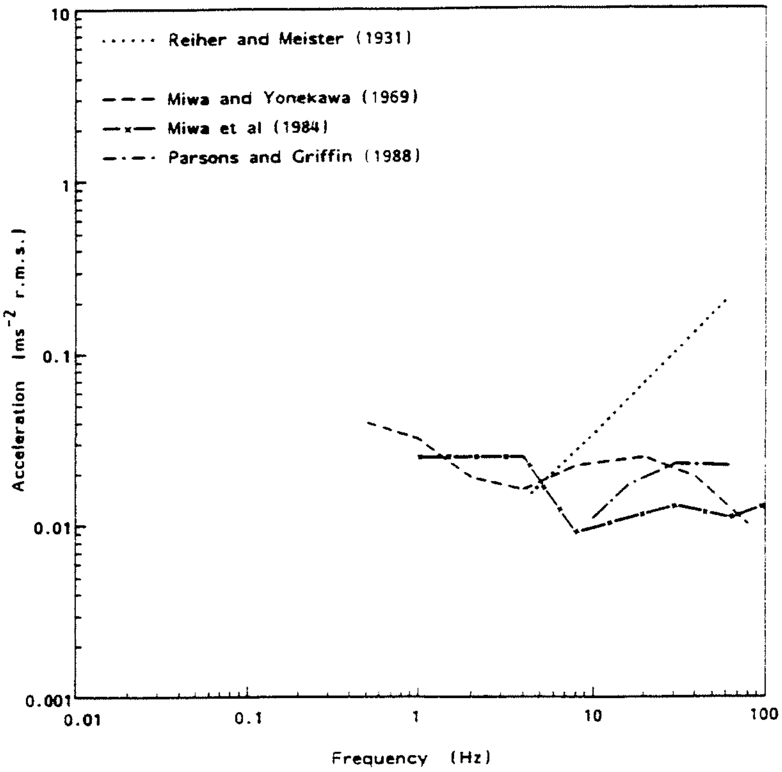


Figure 3.6 Perception thresholds for y- and z-axis (horizontal) whole-body vibration of recumbent (supine) persons (adapted from Griffin, 1990).

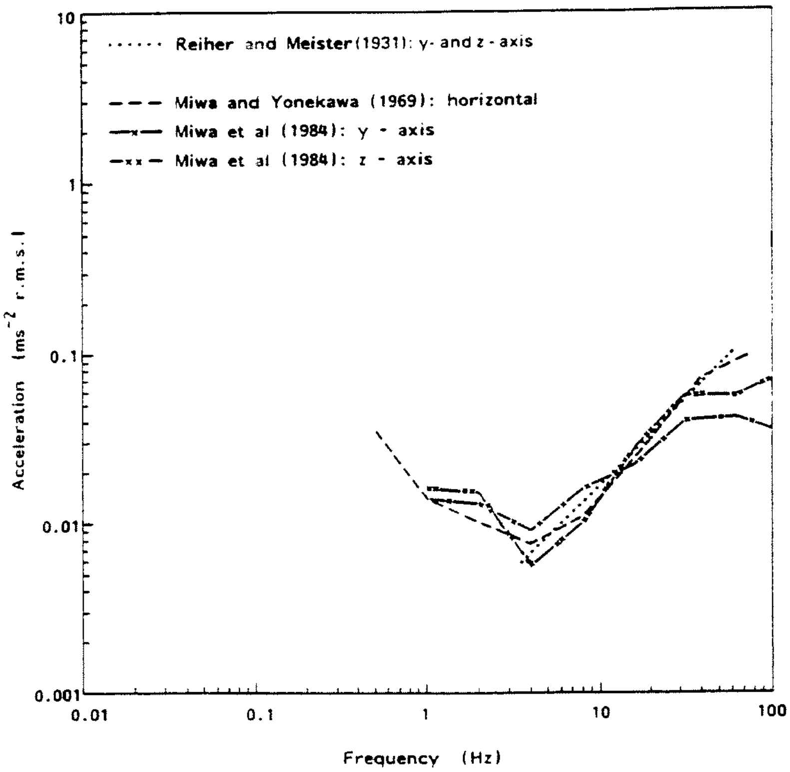


Figure 3.7 and 3.9 present two base curves from ISO 2631-2: 1989. With respect to building vibration, BS 6472: 1992 specifies two curves identical to the ISO curves. In ISO 2631-2: 1989, a third so-called 'worst case' base curve is introduced because: 'In many situations the same building area may be used by humans in both the lying and standing positions at different times of the day. If this is the case, then a combined standard using the worst case combination of both the z-axis and x- and y-axis conditions may be applied. This has to be obtained by using the z-axis response from 8 to 80 Hz and the x/y-axis response from 1 to 2 Hz. For frequencies between 2 and 8 Hz, there is an interpolation between the two curves'. This combination curve is shown in figure 3.8. The combination curve has not been included in BS 6472: 1992.

In DIN 4150-2: 1992, vibration velocity is frequency-weighted according to the following formula

$$|H_{KB}(f)| = \frac{1}{[1 + (f_o/f)^2]^{½}}$$

in which:

$\mid H_{KB}(f) \mid$	the frequency-dependent weighting of the vibration velocity;
f_o	equal to 5.6 Hz.

Therefore, using the equations given in chapter 8, vibration acceleration is frequency-weighted according to:

$$1/2\pi f \, [1 + (f_0 / f)^2]^{½}$$

The reciprocal function can be compared with the base curves presented in the figures 3.7, 3.8, and 3.8. The German weighting function has been included in figure 3.9. Apparently, the frequency weighting according to DIN 4150-2: 1992 is in close agreement with the worst case ISO base curve presented in figure 3.8. It is exactly the same weighting function as the weighting function specified in ISO 2631-2: 1989.

Figure 3.7 Building vibration z-axis base curve for acceleration (ISO 2631-2: 1989).

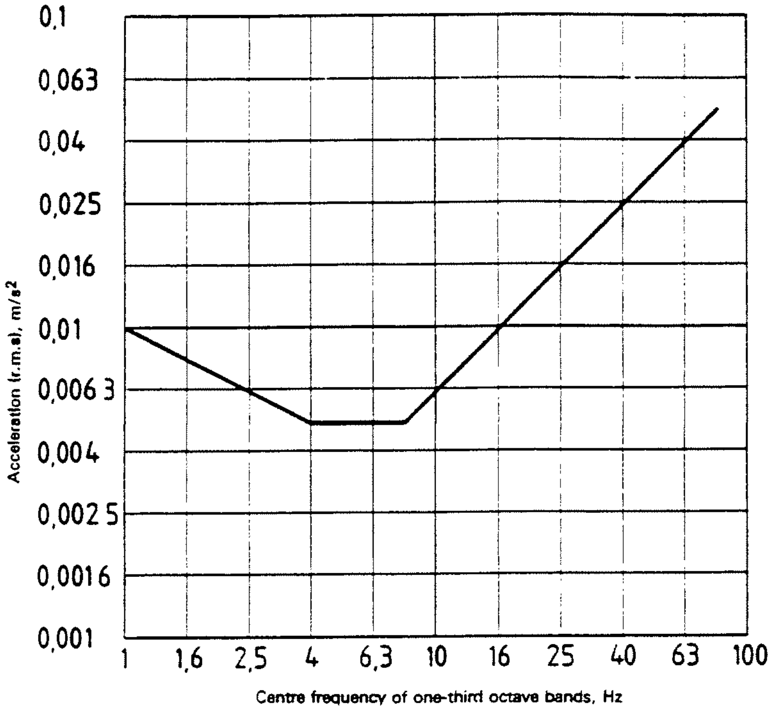


Figure 3.8 Building vibration worst case base curve for acceleration (ISO 2631-2: 1989). Interrupted curve: frequency weighting according to the frequency weighting function given in ISO 2631-2: 1989 and DIN 4150, Teil 2: 1992a.

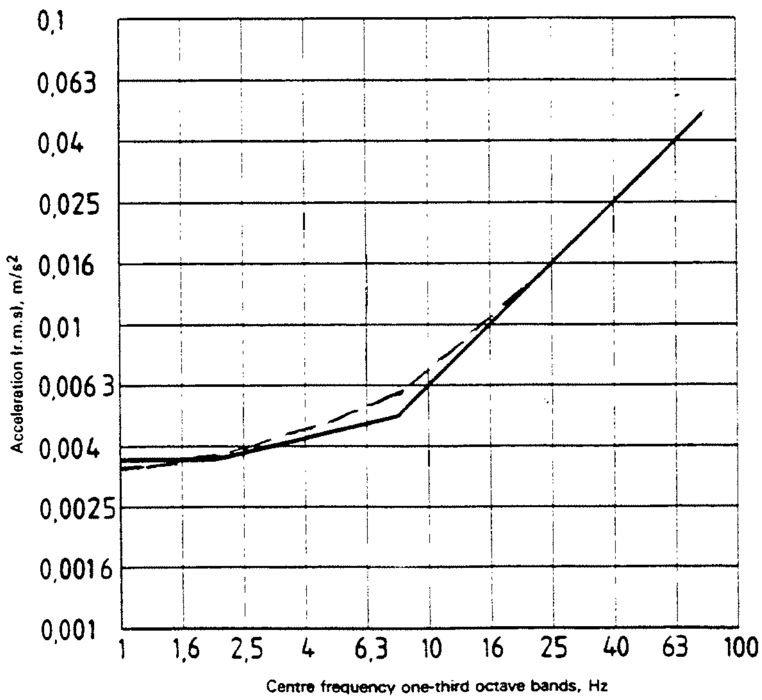
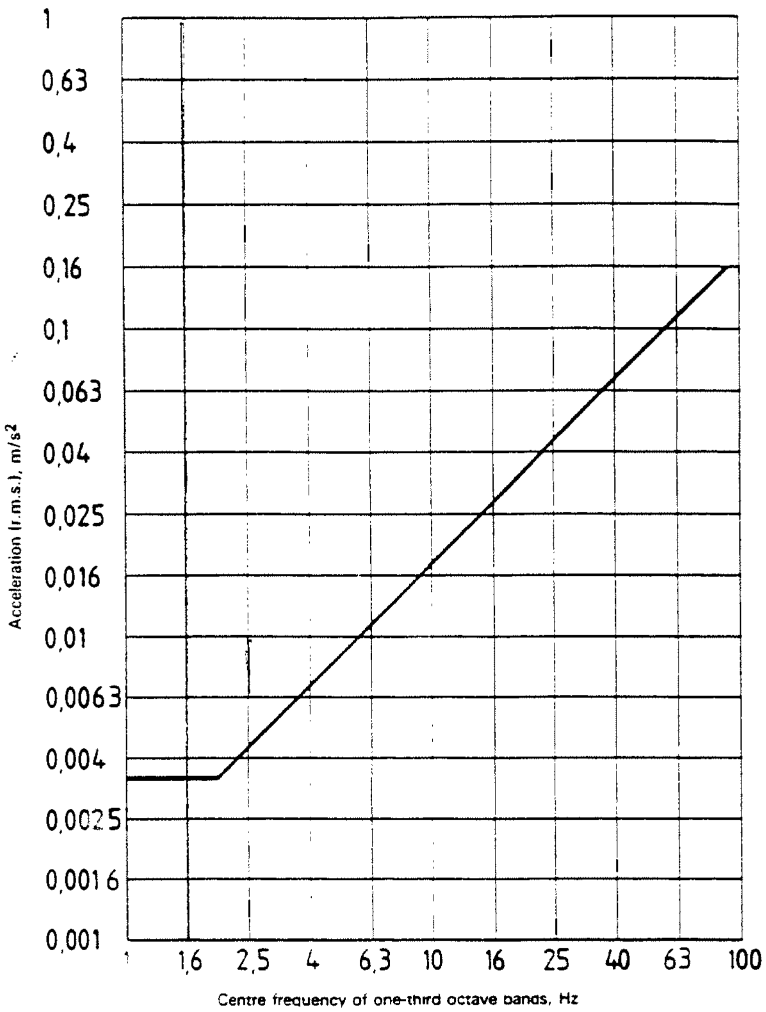


Figure 3.9 Building vibration x- and y-axis base curve for acceleration (ISO 2631-2: 1989).



3.2.2 Equal sensation contours above perception threshold

Information about investigations on the frequency dependency of equal discomfort/sensation contours is given in table 3.1. The results of the investigations presented in the last column of table 3.1 indicate that at the lower acceleration values equal sensation contours for vibrations in the z-direction for sitting or standing subjects are reasonably parallel to perception thresholds. Consequently, a dependency of the shape of the equal sensation contours on vibration magnitude in the z-direction for sitting or standing subjects is not very plausible. The data for the y-direction, although very scarce, do suggest a frequency-dependency of the shape of the equal sensation contours on vibration magnitude. No data are available for equal sensation contours for vibrations in the x-direction, nor for recumbent subjects with respect to vibrations in any direction.

Table 3.1: Data from 5 publications on the frequency-dependency of equal discomfort and equal sensation contours for sinusoidal vibrations at one axis

publication	number of test subjects	posture subjects	vibration axis	vibration range at 10 Hz* (in ms^{-2} r.m.s.)	frequency dependency
Miwa, 1967	10?	standing	z	perception threshold -1	small effect***
	10?	sitting	z	perception threshold -1	small effect***
	10?	standing	y	perception threshold -3	small effect***
	10?	sitting	y	perception threshold -3	small effect***
Jones, 1974	30	standing	z	0.5-5	no
	60	sitting	z	0.5-5	no
Oborne, 1981	24	standing	z	0.6-2.5	> 1.2 ms^{-2}: yes
Corbridge, 1986	40	sitting	z	0.5**-1.5**	no
Howarth, 1988	20	sitting	z	0.04-0.40	no
	20	sitting	y	0.004-0.40	yes

* Perception threshold is at about 0.01 ms^{-2} at 10 Hz.
** Extrapolation from accelerations at 2 Hz.
*** The difference between the acceleration at the perception threshold and the acceleration at the lowest equal sensation contour measured is at 80 Hz on average 2 times as large as at 10 Hz.

3.2.3 Synopsis

Posture of the test subjects and direction of vibration are variables which are important factors with respect to the frequency dependency of perception thresholds and equal sensation contours. However, only for a limited number of combinations of these variables research has been carried out. Synopsis 3.1 lists which combinations of posture and vibration axis have been the subject of research with respect to the determination of single-axis sinusoidal perception thresholds. Apparently, all combinations have been examined. Synopsis 3.2 presents an overview of the combinations which have been examined with respect to equal sensation contours. The synopsis shows that data are only available for sitting and standing subjects exposed to vibrations in the y- and z-direction.

Synopsis 3.1 Information* on perception thresholds for single-axis sinusoidal vibration

posture of test subjects	direction of vibration		
	x	y	z
standing	+	+	+
recumbent	+	+	+
sitting	+	+	+

* +: information present
-: information not present

Synopsis 3.2 Information* on equal sensation contours above threshold for sinusoidal single-axis vibration

posture of test subjects	direction of vibration		
	x	y	z
standing	-	+	+
recumbent	-	-	-
sitting	-	+	+

* +: information present
-: information not present

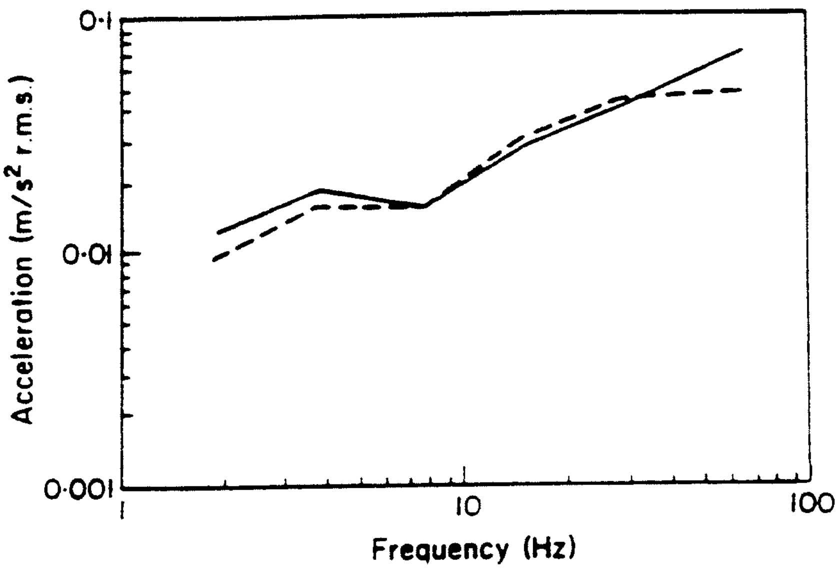
3.3 Exposure to single-axis 1/3-octave and octave band random Gaussian vibration

3.3.1 Perception thresholds

Parsons and Griffin (1988) determined the perception thresholds of eight seated test subjects, exposed to vertical (z-axis) vibration. The stimuli were sinusoidal vibrations, one-third octave bands and octave bands of random (Gaussian) vibration, and a 5 octave-band Gaussian random vibration. In figure 3.10 the perception thresholds for 1/3-octave bands of vibration and sinusoidal vibration are given. Perception thresholds are expressed in acceleration r.m.s. values. There was no statistically significant difference in the perception thresholds for sinusoidal and 1/3-octave bands of vibration. There appeared also no statistically significant difference in acceleration perception thresholds when these thresholds were evaluated in r.m.q. values. The acceleration perception thresholds for octave-band stimuli also did not differ statistically significant from the acceleration perception thresholds for sinusoidal and 1/3-octave bands when these thresholds were expressed in r.m.s. values, but they were different when they were evaluated by r.m.q. measures. Test results with respect to the 5 octave band vibration will be treated in section 3.4.

The result of the investigation indicate that the critical bandwidth of vibrations is larger than 1/3-octave band and may be about one octave band wide. Further research is needed to explore this question.

Figure 3.10 Mean vibration perception thresholds for sinusoidal (———) and one-third octave random (---) vibration (Source: Parsons and Griffin, 1988).

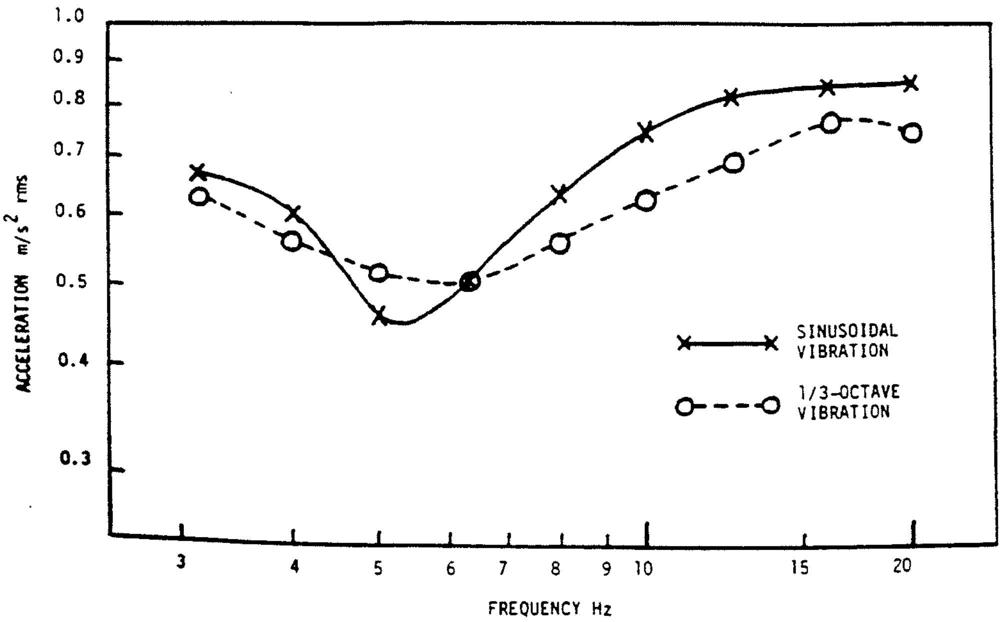


3.3.2 Equal sensation contours above perception threshold

Two publications compare equal sensation contours for sinusoidal vibrations with those for narrow bands of vibrations. Both publications give results which have been obtained for a vibration range which is well above the perception threshold.

Griffin (1976) exposed seated test subjects to vertical sinusoidal, 1/3-octave bands, octave-bands and a three-octave band random vibration. Subjects were required to adjust the level of a test vibration such that it produced a degree of discomfort equal to that of a 'standard' exposure to a 10 Hz sinusoidal vertical vibration at 0.75 ms^{-2} r.m.s.. In figure 3.11 the equal sensation contour of the 1/3-octave band random vibrations is compared with the contour for sinusoidal vibrations. To obtain a match with the 10 Hz sinusoidal 'standard' vibration the subjects adjusted the sinusoidal vibrations on average 7% higher than the random vibrations. There appeared small but statistically significant differences in equal sensation levels at the centre frequencies 10 and 12.5 Hz.

Figure 3.11 Equal sensation contours for sinusoidal and 1/3-octave band random Gaussian vibration (Source: Griffin, 1976).



Donati et al. (1983) determined equal sensation contours for seated subjects in the frequency range of 1-10 Hz using sinusoidal vibrations and random vibrations with a bandwidth of at most one octave. Their results are presented in the figures 3.12 and 3.13: on average test subjects were somewhat more sensitive to random vibrations than to sinusoidal vibrations. This is in agreement with the results of Griffin (1976). Donati et al. calculated that over all axis and all frequencies considered the ratio of the acceleration values for the random vibrations and those of sinusoidal vibrations is 1.12. In particular for z-axis vibration in the range from 2 to 3.5 Hz this ratio increased to 1.25.

Figure 3.12 Equal sensation contours for sinusoidal and random vibrations with a bandwidth of at most one octave applied to seated subjects along the y- and z-axis. Points indicate individual results (Source: Donati et al., 1983).

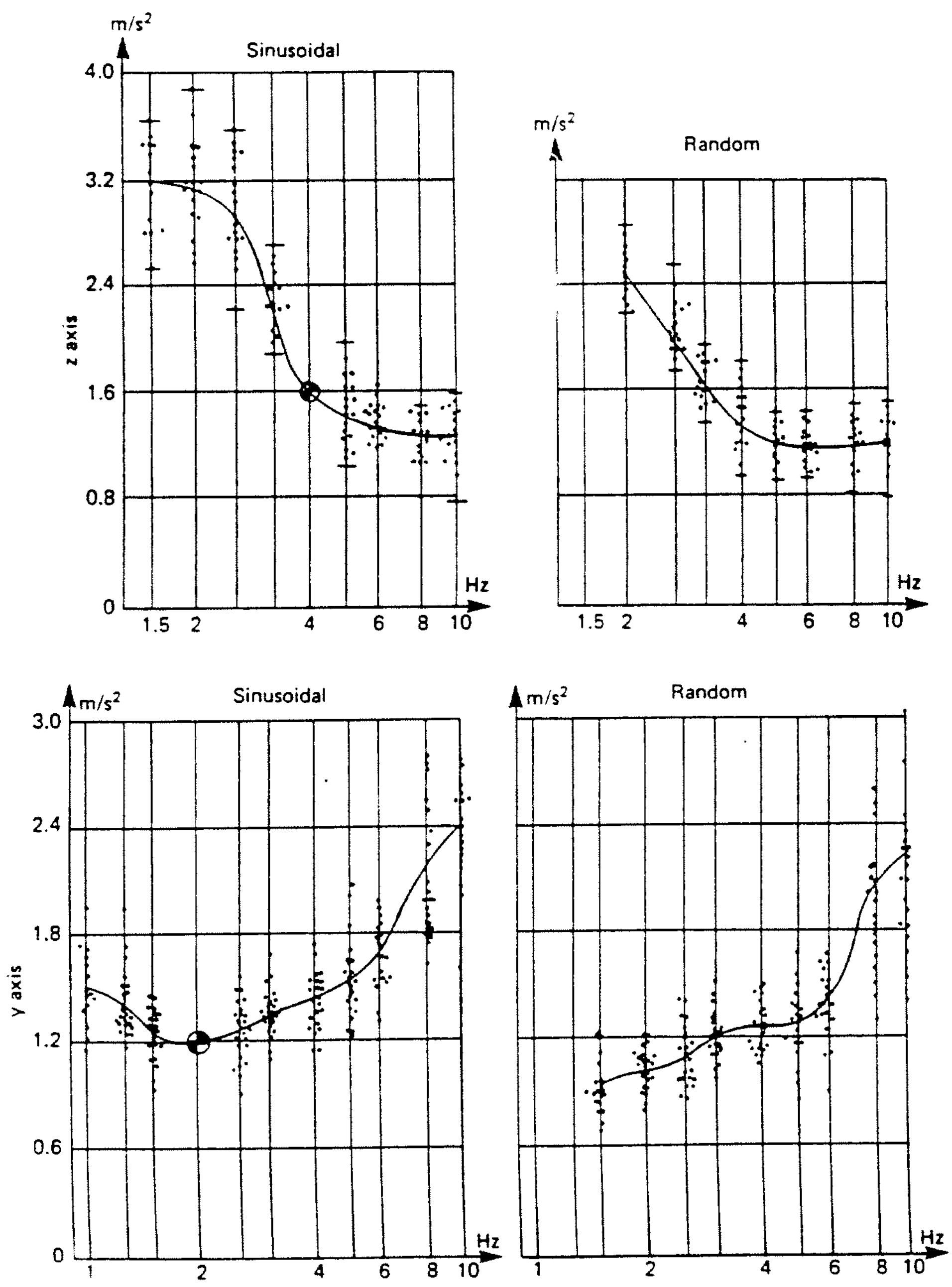
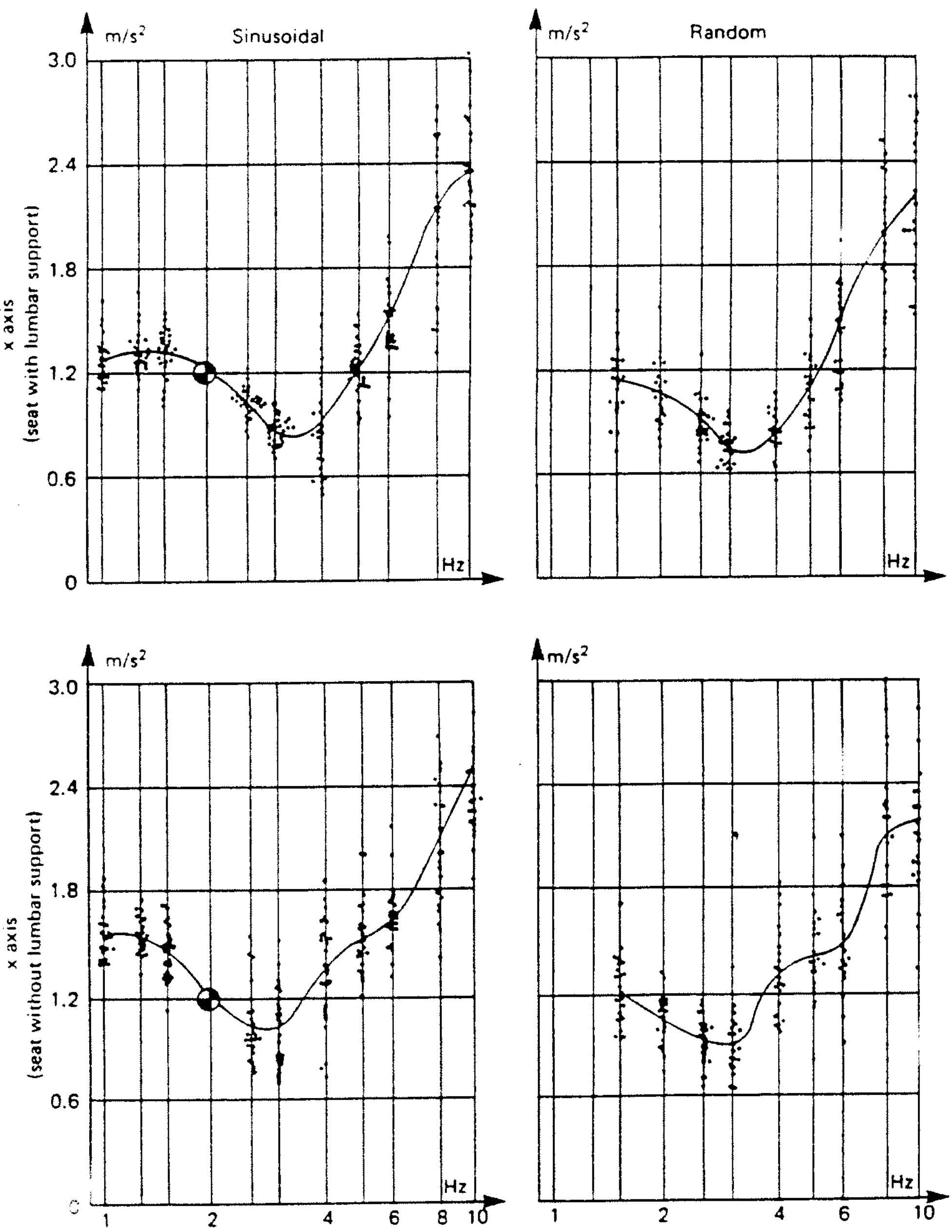


Figure 3.13 Equal sensation contours for sinusoidal and random vibrations with a bandwidth of at most one octave applied to seated subjects along the x-axis. Points indicate individual results (Source: Donati et al., 1983)



3.3.3 Synopsis

Synopsis 3.3 presents an overview of the information that is present from the literature with respect to perception thresholds for single-axis random Guassian vibrations with a bandwidth of at most one octave. Synopsis 3.4 concerns single-axis random Gaussian vibration with a bandwidth of at most one octave. Synopsis 3.3 shows that information on perception thresholds for random vibrations is very scanty: only for sitting subjects and only for the z-axis perception thresholds have been determined. Synopsis 3.4 shows that with respect to equal sensation contours for single-axis random vibrations information is available for sitting test subjects exposed to vibrations in either of the three directions.

Synopsis 3.3 Information* on perception thresholds single-axis random vibrations with a bandwidth of at most one octave

posture of test subjects	direction of vibration		
	x	y	z
standing	-	-	-
recumbent	-	-	-
sitting	-	-	+

* +: information present
-: information not present

Synopsis 3.4 Information* on equal sensation contours for single-axis random vibrations with a bandwidth of at most one octave

posture of test subjects	direction of vibration		
	x	y	z
standing	-	-	-
recumbent	-	-	-
sitting	+	+	+

* +: information present
-: information not present

3.4 Exposure to single-axis wide-band random Gaussian and multiple sinusoidal vibration

3.4.1 Model for broadband noise and vibration data

For the assessment of loudness of broadband noises Zwicker and Feldtkeller (1955) and Stevens (1956) developed models, taking into account the interaction effects of noise in adjacent frequency bands. The model developed by Zwicker is more sophisticated and takes into account more phenomena related to noise perception than Stevens's model. The physiological interpretation by Zwicker of interaction effects in terms of excitations by bands of noise of adjacent parts of the basilar membrane is not readily transferable to the physiological processes involved in the perception of vibrations. Nevertheless, a possible interaction between vibrations at different frequencies should not be excluded. Since the model proposed by Stevens for noise has been applied to vibrations in several publications it is explained below.

When a (1/3-octave or octave) band of noise is added to a complex noise, the loudness of the combination increases by only a proportion F of the loudness of the added band. According to Stevens specified F as follows:

$$F = (S_t - S_m/[(\Sigma S)-S_m]$$

in which:
S_m is the loudness (in sones) of the loudest band;
ΣS is the sum of the loudnesses of all bands;
S_t is the total perceived loudness.

For octave bands of noise F is about equal to 0.3.

This model has been applied by Miwa (1968, 1969) to determine the total "vibration greatness" of a complex vibration and Miwa concluded that an appropriate F value for vibrations might also be on average about 0.3. However, his data suggest that F may decrease to 0.1 (greater inhibition) with high levels of vibration and may increase to 1.0 as the number of octaves between the frequency components increases. When F is equal to 1.0, there is no interaction between the various frequency bands. Miwa's observations do not contradict the model of Stevens.

Fothergill and Griffin (1977b) showed that the inhibition model adapted from Stevens noise model can be made to produce reasonable predictions of the discomfort of dual frequency vertical vibrations of seated subjects. They did not confirm the increase in the value of F with frequency separation as reported by Miwa. From the first experiment with dual frequency vibrations the value of F turned out to be 0.35. For the dual frequency vibrations in the second experiment a mean value of F equal to 0.38 was found. The results of Fothergill and Griffin suggest that F decreases as the frequency separation between components increases. This is inconsistent with the findings by Miwa and also against expectation when the inhibition model would be appropriate. In the third experiment subjects have been exposed to vibrations containing four sinusoidal components. Applying the inhibition method in a specific way resulted in estimated values that did not differ significantly from observed values.

In all three experiments it was shown that the discomfort of a multiple sinusoidal vibration could also be estimated from a weighted value, obtained by first weighting each of the acceleration r.m.s. values of each of the sinusoidal vibrations separately according to their discomfort, and then determining the total vibration acceleration r.m.s. value from the weighted acceleration r.m.s. values. This last method corresponds with the use of a frequency weighting network in the measurement of an overall frequency-weighted vibration magnitude.

In another experiment described earlier (Griffin, 1976b) it was shown that discomfort due to a three-octave band vertical vibration applied to sitting test subjects could be best estimated from the vibration spectrum when it was weighted according to an equal discomfort contour for sinusoidal vibration. This finding supports the application of a frequency-weighting method.

Also the results of the experiments carried out by Shoenberger (1978) favour a weighting method to evaluate complex vibrations. Three experiments were conducted with seated subjects exposed to z-axis vibrations. Experiments were carried out using simultaneously up to four sinusoidal vibrations, and up to four 1/3-octave band random vibrations. The results of the experiments do not support the method in which the rating is determined solely by the most intense 1/3-octave band, as specified in the former ISO 2631 (1974).

3.4.2 Synopsis

The following synopsis applies both to single-axis wide-band random Gaussian vibrations and to single-axis multiple sinusoidal vibrations. It indicates that information is available only for sitting subjects exposed to z-axis vibration.

Synopsis 3.5 Information* on sensations by single-axis wide-band random vibrations and single-axis multiple sinusoidal vibrations compared to sensations by sinusoidal or 1/3-octave bands of vibrations.

posture of test subjects	direction of vibration		
	x	y	z
standing	-	-	-
recumbent	-	-	-
sitting	-	-	+

* +: information present
-: information not present

3.5 Exposure to single-axis railway-induced building vibration

Woodroof, Lewis, and Griffin (1983) present results of experiments using reproductions of railway-induced building vibration. The experiments involved eight vibration stimuli derived from recordings of vertical vibration produced by different trains at several sites and in different dwellings. The stimuli contained frequency components in the range of 8 to 60 Hz. The subjective responses of the seated test subjects were correlated with 108 alternative measures of the vibration stimuli formed from three alternative frequency weightings and several averaging times and averaging procedures. The three frequency weightings were the ISO 2631 z-axis frequency weighting, an alternative frequency weighting (flat up to 20 Hz and above 20 Hz with the same slope as in ISO 2631) and no weighting. It was concluded that the ISO 2631 z-axis frequency weighting provided the best practicable objective evaluation procedure.

A synopsis for this type of (vertical) vibrations would again show that information is only available for sitting test subjects.

3.6 Frequency weighting: conclusions and comparison with Standards

With respect to the perception of vibrations there are only a very limited number of well-controlled fundamental studies. As shown by the figures 3.2 to 3.6, there is a considerable dispersion of the published results on the perception thresholds for sinusoidal single-axis vibrations when the results are classified according to the posture of test subjects and the direction of the vibrations. The frequency dependency of the threshold curves in the higher frequency range as shown in the more recent publications is apparently much less than suggested by the publication by Reiher and Meister (1931), by the base curves given in ISO 2631-2: 1989 and BS 6472: 1992, and by the frequency-weighting defined in DIN 4150, Teil 2: 1992. The largest discrepancy between perception thresholds and the frequency-weightings specified in the three Standards concerns vertical (x-axis) vibration for recumbent persons. However, the following considerations may partly explain the discrepancies described. In the German Standard the location of the vibration measurements is on the floor of the relevant rooms. However, whether vibrations will be felt while lying on a bed or sitting on a chair depends also on the dynamic response of the bed or chair. Usually furniture attenuates vibrations at intermediate and high frequencies, and therefore it may be appropriate to apply frequency weightings to floor vibrations which have greater attenuation at the higher frequencies than the perception thresholds suggest. ISO 2631-2: 1989 and BS 6472: 1992 both specify that vibrations should be measured on a structural surface supporting the human body at the point of entry to the human subject. If measurements are made at another point an allowance should be made for the transfer function between the measurement point and the point of entry to the body. It is, however, questionable whether such regulations are indeed applied in routine testing of vibrations in the domestic environment.

In conclusion, due to a lack of well-controlled fundamental investigations there is much uncertainty about the frequency weighting of vibrations. At the same time it is questionable whether further fundamental studies will be undertaken since to a certain extent international agreement seems to exist about frequency weightings for practical purposes.

There is some evidence that subjective response to single-axis multiple frequency vibrations and to single-axis broadband random vibrations can be more or less accurately predicted by first frequency weighting the components in the complex motion and then calculating the r.m.s. level of the frequency-weighted components. This has been demonstrated to some extent for sitting subjects and vertical vibrations. The limited data suggest that inhibition between components does indeed occur. However, measures which take inhibition into account do not predict test results significantly better than a frequency-weighting does. Since for practical purposes the r.m.s. calculation procedure is less complicated and the measurement of a frequency-weighted overall vibration magnitude is much easier than procedures based upon the inhibition method, preference should be given to a frequency weighting procedure.

4. QUANTIFICATION OF A 24 HOUR HUMAN EXPOSURE TO BUILDING VIBRATIONS

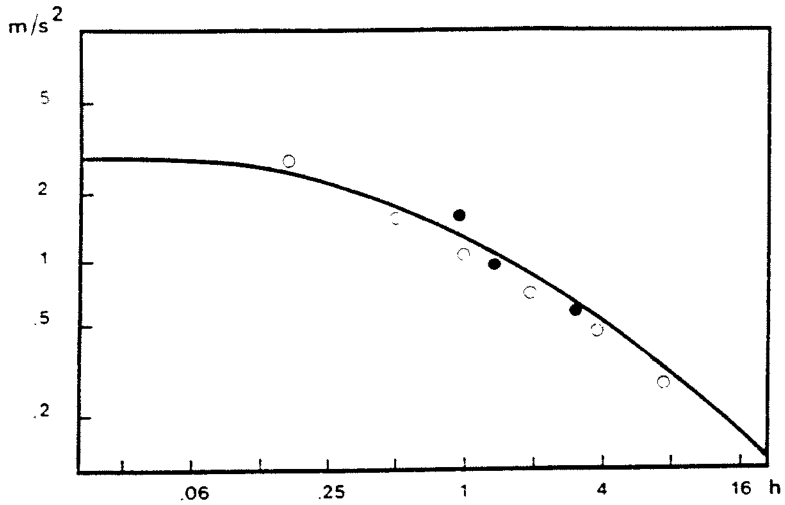
4.1 Measure for a single-axis vibration event

4.1.1 Information

A measure for a vibration event is derived from the instantaneous vibration magnitudes during the event. Usually vibration magnitude has been specified in terms of acceleration. For a simple waveform, such as the one representing sinusoidal vibration,there is a straightforward analytical transformation of one kind of vibration measure to another. For more complex vibration waveforms, the transformation from acceleration measures to velocity or displacement measures is usually not straightforward.

In Von Gierke (1975) the time dependency employed in ISO 2631 (1974) is explained. The relevant figure is reproduced here as figure 4.1. This time dependency has been criticized by many researchers (e.g. Clarke, 1979; Oborne, 1983; Howarth, 1985; Kjellberg and Wikström, 1985a; Griffin and Whitham, 1980b) who report that the subjects in the Simic investigation (see figure 4.1) were not exposed as long as suggested by the exposure durations given in the figure. Instead they were exposed to various vibrations for 5 minutes, and thereafter they had to judge how long a duration of such vibrations they would be prepared to accept. The results in Miwa's paper are also stated to be inconclusive (Clarke, 1979), since no attempt was made to provide any control data and the interpretation by Miwa of his results seems to be questionable.

Figure 4.1 Contour of equal subjective response to vibration, according to ISO 2631 (1974) and results of investigations by
. Miwa et al.
0 Simic
(Source: von Gierke, 1975; copied from Oborne, 1983).



Some experimental studies investigated for short-term vibration events the relation between discomfort or subjective response, and the instantaneous accelerations during an event (Griffin and Whitham, 1975; Clarke and Oborne, 1975; Parsons and Griffin, 1988; Kjellberg et al., 1985b; Miwa, 1968d; Griffin and Whitham, 1980a; Hiramatsu and Griffin, 1984; Kjellberg and Wikström, 1985; Woodroof, Lewis and Griffin, 1983). Details of these investigations are presented in table 4.1, and are summarized in the following text. If it was possible, the value of n in the following formula has been derived in this report from the results of these experiments:

$$a^n t = k$$

in which:

t the duration of the event in s;

a the acceleration in ms^{-2};

k a constant.

The so-called 'growth rate' is equal to 1/n. If n is equal to 2, vibration events with the same r.m.s. acceleration result in the same level of subjective response. If n is equal to 4, vibration events with the same r.m.q. acceleration give rise to the same level of subjective response. The values of n derived from the investigations are also given in the table.

Table 4.1 Investigations about effects of the duration of vibration events on subjective response to these events.

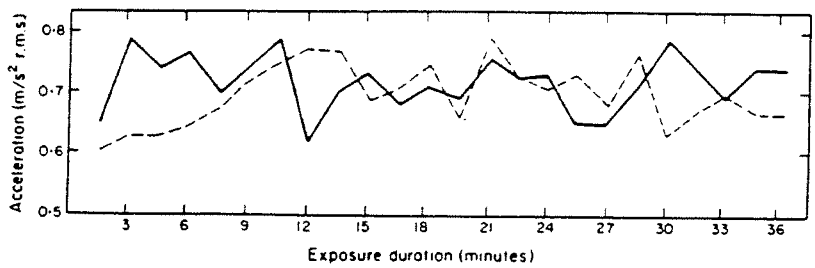
authors	duration of vibration exposure	magnitude of vibration exposure	type of stimulus	frequency of stimulus in Hertz	value of n in $a^n t$ = constant
Miwa, 1968d	0.007 - 6s	VGL: 20-50 dB*	pulses	2 ... 300 Hz	< 2s: 2.9; > 2s: 5
Griffin and Whitham, 1975	36 minutes	0.75 ms^{-2} r.m.s.	sinusoidal	4,16 Hz	-
Clarke and Oborne, 1975	25 minutes 160 minutes	0.8 ms^{-2} r.m.s. 0.3 ms^{-2} r.m.s.	hovercraft railway	8-16 Hz band	-
Griffin and Whitham, 1980a	0.025 - 32s	0.2 - 4 ms^{-2} r.m.s.	impulses	4,8,16,32 Hz	4
Woodroof et al., 1983	9 - 27s	0.018-0.084 ms^{-2} r.m.s.	railway	8-60 Hz	4
Hiramatsu and Griffin, 1984	2 - 50s	0.5 - 2.5 ms^{-2} r.m.s.	non-steady	8 Hz	1.8
Kjellberg et al., 1985b	0.25 - 64 minutes	1.4 - 1.6 ms^{-2} r.m.s.	forklift truck	3.1, 6.3 Hz	-
Kjellberg and Wikström, 1985c	0.1 - 4; 1 - 128; 0.1 - 117s	1.1, 2.3 ms^{-2} r.m.s.	sinusoidal	6.3, 31.5 Hz	4; 5.6, 7.7; 10, 7
Parsons and Griffin, 1988	0.06 - 4s	0.01 - 0.03 ms^{-2} r.m.s.	sinusoidal	16 Hz	-

VGL: vibration greatness level.

Miwa (1968d) carried out experiments with ten sitting subjects to determine the effect of vibration duration of three types of pulsed vibrations in the vertical and horizontal direction with durations varying from 0.007 to 6 seconds and with frequencies from 2 to 300 Hz. The "vibration greatness" of the pulses increased with a growth rate of 0.35 (i.e. $a^{2.9}t = k$) for pulse durations up to approximately 1 to 2 seconds, and for longer pulses with a growth rate of 0.20 (i.e. $a^5t = k$).

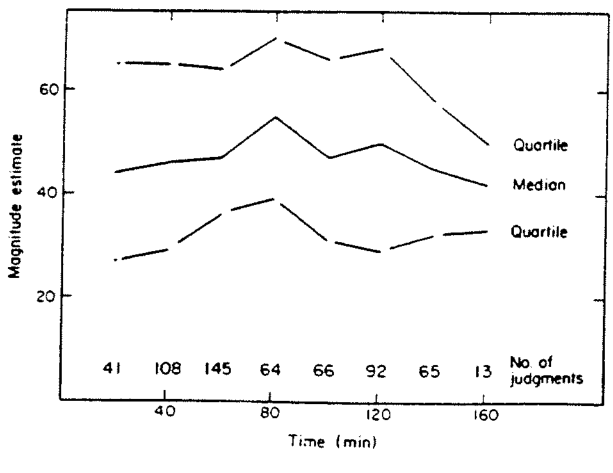
Griffin and Whitham (1976) exposed test subjects two times for 36 minutes to vibrations. Both exposures consisted of ten-second periods of 4 Hz and 16 Hz vibration alternating continuously. During one exposure the r.m.s value of the acceleration of the 4 Hz vibrations was equal to the 'standard' level of 0.75 ms^{-2} and during the other exposure the r.m.s. of the acceleration of the 16 Hz exposure was equal to this 'standard' level. Test subjects were requested to adjust the vibration level of the test vibration so that it produced an amount of discomfort similar to that from the 'standard' vibration. Figure 4.2 shows a result. Apparently there is no systematic trend as exposure time increases. Therefore, for the two frequencies considered there was no significant difference in their time dependency over the exposure period examined. Any changes in discomfort associated with the exposure was therefore similar for both the 4 Hz and the 16 Hz stimulus. The investigation does not provide information about the absolute changes in subjective response, and therefore a trade-off between acceleration and time could not be derived from the results.

Figure 4.2 Mean equivalent acceleration levels during 36-minute exposures to vertical sinusoidal whole-body vibration. ____, levels of 16 Hz equivalent to 0.75 ms^{-2} r.m.s. of 4 Hz; --------, levels of 4 Hz equivalent to 0.75 ms^{-2} r.m.s. of 16 Hz (Source: Griffin and Whitham, 1976).



Clarke (1979) presents results from Clarke and Oborne (1975) concerning passenger reactions to a variety of environmental variables, including vibrations. Passengers of hovercrafts, trains, and other means of transportation were asked to rate at any time during the journey the vibrations they had already experienced. Figure 4.3 summarizes the subjective ratings of vibrations in a long distance train (duration of the journey 160 minutes). The figure shows that there is no effect of duration on the subjective response to the vibrations. Passengers, however, were aware of the length of the duration of the exposure at the time of their subjective rating, and therefore judgements may have been influenced by that awareness and may not have been based solely on the actual already perceived vibrations.

Figure 4.3 Subjective rating (median and quartile values) by passengers of train vibrations during travel. Ratings range from 0 (complete rest) to 100 (travelling over an unmade car in an old car). Vertical acceleration about 0.3 ms^{-2} r.m.s. (Source: Clarke and Oborne, 1975).



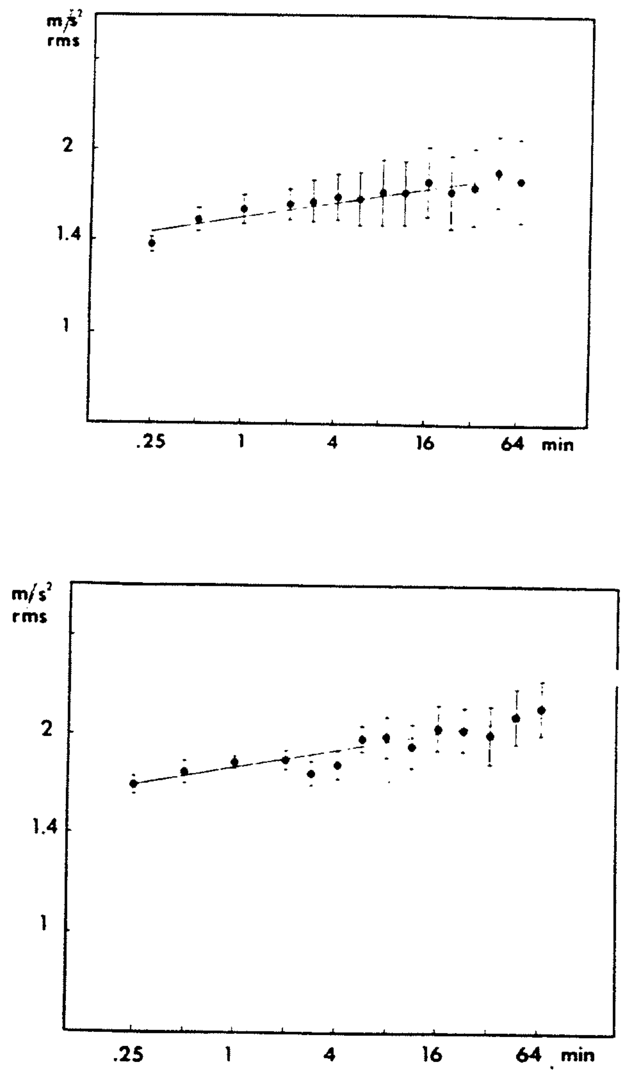
Griffin and Whitham (1980a) report on four experiments about the effects of duration of vertical impulsive vibration on discomfort of seated subjects. The first experiment investigated the variation in discomfort for vibrations with frequencies 4, 8, 16 and 32 Hz. Duration of the exposures ranged from one cycle of motion to 4s. In the second experiment subjects were exposed to 8 Hz impulsive vibrations up to 32 seconds. The third experiment involved complex motions with the same r.m.s. acceleration but with different peak levels (crest factors from 2.1 to 8.5) and the fourth experiment investigated the effect of vibration duration (1, 4, and 16 s) of a 32 Hz sinusoidal vibration. The results show that the time dependency implied by $a^2t = k$ overestimates the effect of duration on discomfort. The time dependency in these experiments is more accurately described by $a^4t = k$.

Woodroof, Lewis and Griffin (1983) investigated four alternative averaging times and nine alternative averaging procedures using eight stimuli representing the reproductions of railway-induced building vibration. They concluded that the vibration dose value provides the best practical measure for predicting annoyance.

Hiramatsu and Griffin (1984) investigated the effect on discomfort of the duration of vibrations (durations varying from 2 to 50 s) and of vibration acceleration magnitude (r.m.s. values varying from 0.5 to 2.5 ms^{-2} at 8 Hz) for vertical sinusoidal vibration applied to seated subjects. The trade-off between vibration acceleration and duration of vibration could be described by $a^{1.8}t = k$.

Kjellberg et al. (1985b) determined the development of discomfort during exposure to vibrations recorded in forklift trucks (resonance frequencies 3.1 Hz and 6.3 Hz) by using a cross-modality method. By using such a method the level of discomfort due to a vibration is rated by means of the magnitude of a noise stimulus, which causes the same level of discomfort as the vibration. Figure 4.4 shows the results. Discomfort increases as the duration of the vibration exposure increases. Unfortunately no attempt was made to provide any control data to determine whether the experimental conditions influenced the response to the noise stimuli. The data do not permit the determination of the trade-off between acceleration magnitude and time.

Figure 4.4 The development of discomfort during the exposure to the vibration recorded on forklift trucks (upper figure: resonance frequency 3.1 Hz, lower figure: resonance frequency 6.3 Hz). Mean sound settings (transformed into vibration levels) as a function of exposure time (Source: Kjellberg et al., 1985b).

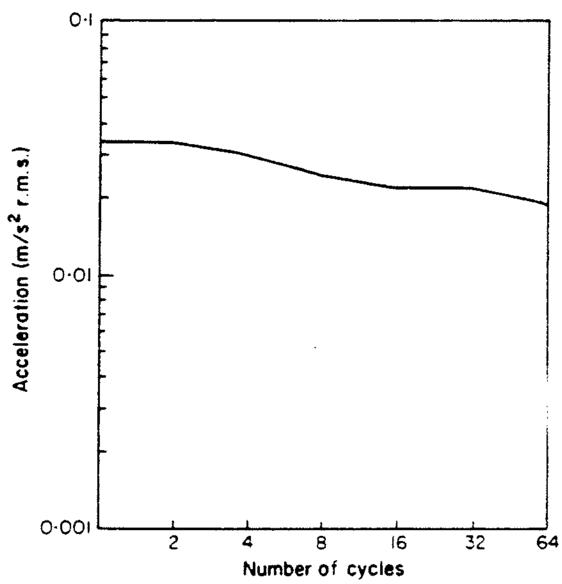


Kjellberg and Wikström (1985c) investigated the effect of duration on discomfort using a matching method. Reference vibrations with accelerations of 2.3 and 1.1 ms^{-2} r.m.s. were used, and the frequency of the test and reference vibrations was 31.5 Hz in three experiments and, in addition, 6.3 Hz vibrations were used in the third experiment. The first experiment investigated durations between 0.1 and 4 seconds. A growth rate of 0.25 was found for vibrations with an acceleration of 1.1 ms^{-2} r.m.s. (i.e. $a^4t = k$), and a growth rate of 0.21 for vibrations with an acceleration of 2.3 ms^{-2} r.m.s. (i.e. $a^{4.8}t = k$). The second experiment investigated durations between 1 and 128 seconds. The growth rates found were 0.18 and 0.13 (i.e. $a^{5.6}t = k$ and $a^{7.7}t = k$, respectively) for acceleration values of 1.1 and 2.3 ms^{-2} r.m.s., respectively, if the duration was less than 3 seconds. The third experiment, with exposures with durations from 0.19 to 117 seconds and vibration r.m.s.

values of 1.1 and 2.3 ms^{-2}, showed growth rates of 0.10 and 0.14 for durations between 0.2 and 3 seconds ($a^{10}t = k$ and $a^{7}t = k$, respectively). It is unclear why the various growth rates (from 0.10 to 0.25) do show such a large discrepancy.

Parsons and Griffin (1988) determined the perception threshold as a function of exposure duration. Subjects were exposed to a 16 Hz sinusoidal vibration which lasted 1, 2, 4, 8, 16, 32 or 64 cycles (exposure durations from 0.06 to 4s). The median perception thresholds are given as a function of the number of cycles in figure 4.5. Apparently at smaller durations higher magnitudes are required for the perception of vibrations. The figure suggests a change from an acceleration r.m.s. value of 0.03 ms^{-2} for a one cycle vibration (duration 0.06 s) to a value of 0.02 ms^{-2} for a 8 to 64 cycles vibration (durations between 0.5 and 4 s). Presumably, this decrease of the perception threshold is related to the integration time with respect to the perception of vibrations. It is not clear whether the observed decrease in perception threshold is related to the duration of the stimulus or to the number of cycles. This could be verified by using other test frequencies.

Figure 4.5 Median perception thresholds for 12 male subjects exposed to different numbers of cycles of a 16 Hz vibration. (Source: Parsons and Griffin, 1986).



4.1.2 Conclusions and comparison with Standards

The following synopsis applies to the time-weighting of single axis vibration events.

Synopsis 4.1 Information* on time-weighting of single-axis vibration events

posture of test subjects	direction of vibration		
	x	y	z
standing	-	-	-
recumbent	-	-	-
sitting	+	+	+

* +: information present
-: information not present

Conclusions with respect to a measure for the magnitude of one single-axis vibration event are:

- only a few publications allow a determination of the trade-off between acceleration magnitude and duration of a vibration event;
- in these publications the magnitudes of the vibrations ranged from those at the perception threshold up to 2.5 ms^{-2} r.m.s. This last value is far above the range in which subjective effects, such as annoyance, start to occur. These results are therefore less relevant for annoyance;
- there is a wide variation in the value of n in the formula $a^n t$ = k(constant) derived from various experiments (n ranges from 1.8 to 10);
- The data do not allow to specify whether n depends on the vibration magnitude;
- only in one experiment a value of n of less than 2 has been observed; therefore the r.m.s. value of the acceleration of a vibration event probably overestimates the importance of the duration of the event;
- for the very limited number of conditions considered, a value of n larger than 2 seems to rate the importance of the duration of a vibration event more accurate than smaller values.

The preferred method in ISO 2631-2: 1989 for assessing continuous vibrations is to determine the r.m.s. value of the weighted acceleration. The document also specifies that there are insufficient data on human response to transient (impulsive) vibrations to justify inclusion in ISO 2631-2: 1989 of a preferred method for analyzing such motions. Additional methods being researched and tested are identified in an informative Annex. This Annex includes the assessment of shocks by VDV and r.m.q. values of the weighted acceleration.

BS 6472: 1992 states that vibration should be assessed on the basis of VDV or the r.m.s. value of the frequency-weighted acceleration. VDV may be used to assess impulsive and intermittent vibration. The eVDV value may be used to estimate the total vibration dose value for vibrations with crest factors not exceeding a value indicated by 'about 6'.

DIN 4150, Teil 2: 1992 states that vibrations should be assessed by KB_{Fmax}, the maximum of the effective KB-values, with the vibration meter using time constant F. The instantaneous KB-value of a vibration is the instantaneous frequency-weighted velocity. According to the German Standard for longer vibration durations the total duration should be splitted up in 30 s periods and a vibration event is then also rated by the vibration effective KB_{Fmax} value (KB_{FTM}) (see chapter 8).

4.2 Measure for single-axis vibration exposure during a part of the 24 hour period

4.2.1 Introduction

Section 4.1 considered the determination of a measure for the vibration magnitude of a short-term single event, such as a train passage, and of a short-term continuous exposure. This section tries to specify a measure for the vibration magnitude of a series of events and of an exposure to continuous vibrations for longer periods, such as hours. Only a very few publications deal with the adverse effects of continuous or intermittent exposure to vibrations during such longer periods, namely one laboratory study (Howarth and Griffin, 1988) and several field investigations. Vibration measurements have been carried out only in three of those field investigations. Other social surveys were primarily concerned with the relation between *noise* annoyance and *noise* exposure. The subjective response to vibrations coming from the noise sources was determined but without any vibration magnitudes measured. Responses, however, have in those publications been related to other secondary physical variables, such as distance from the noise and vibration source and number of occurrences of noise and vibration events per specified period of time (day-time, 24 hours period). These publications will be discussed in chapter 6, which is related to the fourth objective of this study, specified in section 1.1.

In this section, first the laboratory study by Howarth and Griffin is outlined. Then the field investigations in which vibration magnitudes have been measured will be summarized. Conclusions and comparisons with Standards are given in section 4.2.4.

4.2.2 Laboratory study

Howarth and Griffin (1988) report two laboratory experiments on annoyance due to simulated railway-induced building vibrations. Forty eight sitting subjects have been exposed to vertical vibrations recorded in a house from a train passage with 12.5 seconds duration and an acceleration of 0.059 ms^{-2} r.m.s. In the first part of the first experiment test subjects have been exposed to 4, 8, 16, and 32 repetitions of the train passage in one hour. The second part of the first experiment consisted of the presentation of six stimuli, each presented twice. The stimuli were the same as the one used in the first part, but the acceleration magnitude has been multiplied by six different factors ranging from 0.63 to 2.0. It was found that the trade-off between vibration magnitude and number of events can be described by the following equation:

$$N\,V^{3.7} = c$$

in which:

V vibration magnitude in ms^{-2} r.m.s.;

N number of vibration events per hour.

In the second experiment test subjects have been exposed to three conditions: 4 and 32 trains per hour with two different vibration magnitudes for 4 trains per hour. Details of the exposure conditions are given in table 4.2, together with the mean annoyance rating of each of the exposures. The annoyance produced by the two repetition rates of passing trains appears to be equal when the magnitude of vibration was adjusted using V^4N= constant.

Table 4.2 Mean annoyance rating for three conditions (Source: Howarth and Griffin, 1988).

repetition rate N (per h)	magnitude of stimuli V (ms^{-2}r.m.s.)	$(V^2N)^{1/2}$ ($ms^{-1.5}$)	$(V^4/N)^{1/4}$ ($ms^{-1.75}$)	mean annoyance rating
32	0.059	0.334	0.140	2.4
4	0.099	0.198	0.140	2.2
4	0.166	0.332	0.234	3.8

The relation 'V^4N= constant' indicates the degree to which the magnitude of the vibration induced by passing trains must be reduced so as to counteract the effect of an increase of the number of passages on annoyance. Howarth and Griffin suggest that this relation is consistent with the use of a vibration dose value for vibration assessment. However, since V is the acceleration r.m.s. value, this is only correct if r.m.q. is a linear function of r.m.s.. This last assumption is correct for sinusoidal functions. For those functions the r.m.q. value of the acceleration is 1.107 times the r.m.s. value. The relationship for many other vibrations, e.g. railway-induced vibrations, however, is unknown to the present author.

4.2.3 Social surveys including vibration magnitude measurements

The largest survey on subjective response to vibrations (from railroad traffic) presently available has been carried out in Germany (Zeichart et al., 1993). Since the Zeichart report is in the German language only and since the present report also aims at non-German speaking persons, the Zeichart-report has been summarized in more detail in Annex A of the present report. Conclusions from the Zeichart report will be incorporated in this section. Two other social surveys (Watts, 1984; Woodroof and Griffin, 1987) on subjective response to vibrations will be summarized below. The survey by Watts concerns road traffic vibrations, and the investigation by Woodroof and Griffin railway-induced vibrations.

Watts (1984) described the overall annoyance due to vibration at a site by the median value of the vibration nuisance rating of the respondents at that site. The 1625 respondents, living in any of the 50 sites examined, rated their vibration nuisance on a 7 points nuisance scale (from not at all to extremely bothered). Since rattling of windows was supposed to be the main disturbance from vibrations, vibration measurements were made by attaching an accelerometer to the largest window pane located in the ground floor window facing the road. Noise measurements have been carried out outside the dwellings. Traffic flow variables determined are the total number of vehicles (excluding two-wheeled vehicles) from 06.00 to 24.00 hours, the number of medium heavy vehicles (including two axles goods vehicles weighting more than approximately 1.5 tons, buses, and coaches) and the number of heavy vehicles (including goods vehicles with three or more axles) during the same period from 0.600 to 24.00 hours.

The relation between the median vibration scores at the fifty sites and various 18-hour traffic flow measures, vibration magnitude measures and noise measures has been investigated. If a relation between subjective response and a objective measure can be represented by a linear function, then the accuracy of such a relation is expressed by the correlation coefficient between subjective response and objective measure. The highest correlation coefficients (0.57 and 0.59) between subjective response and traffic flow measures were obtained with traffic flow expressed in the logarithm of the number of vehicles and with percentage heavy vehicles. L_{Aeq} over the period from 0.6.00 to 24.00 hours is the noise exposure variable with the highest correlation coefficient with the median vibration score (correlation coefficient 0.76, if one site was for obvious reasons excluded). However, for other measures (L_{Ceq}, octave band L_{eq} values, L_{10}, L_5 and L_1 values) the correlation coefficients were nearly the same. For vibration magnitude measures the correlation coefficients were about 0.50. Thus, vibration nuisance caused by road traffic is more closely related to 18-hour noise exposure measures than to levels of window vibration or traffic flow measures.

In the report mean annoyance score was determined as a function of $L_{Aeq,06\text{-}24h}$. The report presented also a relation between mean annoyance score and percentage of people highly annoyed by vibrations. From these data the following equation has been estimated, which would be applicable for $L_{Aeq,06\text{-}24h}$ values of at least 60 dB(A):

$$(\%\text{ of people very much annoyed by vibrations}) = 1.7\ L_{Aeq,06\text{-}24h} - 102.3.$$

From this it follows that for $L_{Aeq,06\text{-}24h}$ equal to 60 dB(A) (measured outdoors), the percentage of people very much annoyed by objects rattling or perceived vibrations from road traffic is equal to 0 and for $L_{Aeq,06\text{-}24h}$ equal to 72 dB(A) 20%. Whether the equation is applicable more general than for the situations examined in the survey is a matter of debate. Many variables, apart from the noise emission of motor vehicles, have an impact on the equivalent sound level of road traffic noise, such as road surface, reflections of noise by fronts of opposite houses, transmission loss related to distance of the dwelling to the road, ground surface, height of the road above ground surface, and height of the dwelling above the road. These variables may be irrelevant with respect to building vibrations or they may have another relation with the magnitude of building vibrations than with the magnitude of the noise exposure. On the other hand, many variables that determine building vibrations, such as the structure of the ground between the dwelling and the road and the foundation of the dwelling, are irrelevant with respect to the magnitude of the noise exposure.

In the survey by Woodroof and Griffin (1987) 459 respondents who lived within 100 metres of a railway line were interviewed. The respondents were clustered in 24 sites. A total of 160 (34.9%) reported noticing railway-induced building vibration and most of these, 133, lived at one of 12 sites. Vibration was recorded at these 12 sites in 52 dwellings, each of them occupied by one of the 133 respondents who noticed vibration. The correlation between subjective response and objective vibration measures is therefore based on 52 subjects only.

Railway-induced vibration was assessed by 30 measures of vibration magnitude defined by two frequency-weightings, three integration time constants, and five different averaging procedures. The values of these measures from all the trains causing perceptible vibrations during the 24 hour period were combined in three different ways to produce 90 different objective "24 hour measures of vibration magnitude" for each axis of vibration. Analysis of the vibration data showed that horizontal vibration was not generally perceptible. Therefore it is not considered in this summary of the Woodroof and Griffin survey. Analysis of the full correlation between the subjective response and vibration magnitudes and other variables gave the results presented in table 4.3.

Table 4.3 Values of z* for the relationship between vibration annoyance rating and vibration magnitude measures of railway-induced building vibration and measures of duration and number of events (Source: Woodroof and Griffin, 1987).

measures of perceptible vibrations from trains** in 24 hours	value of z***
$[\sum_{N=O}^{N=N}[[[\int_0^T a^2(t)dt]^{1/2}]^2]]^{1/2}$	1.48
$\sum_{N=O}^{N=N}[[\frac{1}{T}\int_0^T a^2(t)dt]^{1/2}]$	1.79
$[\sum_{N=O}^{N=N}[[[\int_0^T a^4(t)dt]^{1/4}]^4]]^{1/4}$	1.04
$\sum_{N=O}^{N=N}[[\frac{1}{T}\int_0^T a^4(t)dt]^{1/4}]$	1.78
$\sum_{N=O}^{N=N}[\lvert a(t)\rvert_{max}]$	1.74
total duration of vibration	2.10
number of trains causing perceptible vibrations	2.37
number of trains passing site in 24 hours	2.68

* The z-score is related to the probability of a particular value of Kendall's tau occurring by chance and therefore represents the significance of the relationship between objective and subjective measures.

** a(t) is the frequency-weighted acceleration representative for time t
T is the duration of the event (in seconds)
N is the number of perceptible trains in 24 hours
$|a(t)|_{max}$ is the maximum value of a(t) determined with time constants of 1 s, 125 ms or 0 s.

Apparently the r.m.s. and r.m.q. value of the acceleration determined over 24 hours have about equal full correlation with subjective response to vibration (z = 1.79 and 1.78 respectively). However, a further analysis showed that the full correlation of these vibration magnitude measures with the vibration annoyance rating was significant only because of the implicit inclusion of the number of perceptible trains in these measures and because of the existence of the highly significant relationship between vibration annoyance and the number of trains. Also the relationship between total duration and vibration annoyance is largely due to the relationship of both variables with the number of trains causing perceptible vibration. In conclusion: the investigation only showed two positive significant relationships of vibration annoyance rating. The first relation is with the number of trains in 24 hours which cause vibration exceeding the criterion of perceptibility and the second relation concerns the total number of trains which passed the dwellings in 24 hours. There appeared no statistically significant relationship between vibration annoyance and any measure of the magnitude of vibration.

4.2.4 Vibration exposure during a part of the 24 hours period: conclusions

The result of the laboratory study by Howard and Griffin (1988) on railway-induced building vibrations supports the use of VDV for the evaluation of vibrations during longer periods. The study is, however, limited in scope. It only concerns exposure periods up to one hour.

In fact, the only field investigation with results which can be used for the evaluation of vibration exposures in real life situations is the investigation by Zeichart et al. (1993), summarized in Annex A of this report. The correlation between various vibration measures in the investigation was high: about 0.90 to 0.99. The correlation between the r.m.s.-value of KB_{Fmax} and VDV is 0.97 for day-time exposure and 0.93 for night-time exposure. Therefore, no significant difference was found in the correlation of these measures with subjective response. However, this conclusion only relates to railway-induced vibrations. Whether the conclusion is also correct for other environmental vibration sources cannot be deduced from the data available.

A comparison with the three Standards will be made in section 4.4.2.

4.3 Measure for multi-axes vibrations during a part of the 24 hours period

4.3.1 Information on multi-axis vibrations

The only guidance with respect to multi-axis vibration comes from a publication of Griffin and Whitham (1977). Seated subjects were exposed to various level and phase combinations of vertical (a_z) and lateral (a_y) sinusoidal (3.15 Hz) vibrations. It was concluded that for the dual-axis motions studied, the discomfort is not greatly influenced by the phase between the two components producing the resulting vibration. The results indicate that the discomfort produced by dual-axis stimuli can be rated by the root mean-square of the squared weighted accelerations in both directions.

4.3.2 Multi-axis vibration: conclusions and comparison with Standards

The following synopsis represents the information on dual axis vibrations.

Synopsis 4.2 Information* on combinations of vibrations at more than one direction. Information is present only for dual axis vibrations

posture of test subjects	direction of vibration		
	x/y	x/z	y/z
standing	-	-	-
recumbent	-	-	-
sitting	-	-	+

* +: information present
-: information not present

The observations made in only one relevant publication have a limited scope, as was also stated by the authors: the number of seated test subjects was limited to eight, the test time to each stimulus was limited to 5 seconds and the tests concerned dual axis vibration at the frequency 3.15 Hz only.

ISO 2631-2: 1989 does not make clear in which way vibrations occurring in different directions should be evaluated. It is stated that "measurements should be taken along the three axes and reference should be made to the appropriate human axis curve. Alternatively, the combined x-, y- and z-curve could be considered in relation to the worst case found". The term 'worst case' is ambiguous: 'worst case' could mean the highest value in any of the three directions when compared with the base curve in the appropriate direction. This interpretation, however is not in agreement with the specifications given in ISO 2631-1: 1985. In ISO 2631-1: 1985 the effects of multi-axis vibration with respect to comfort and performance is assessed by combining the weighted r.m.s. acceleration values in the three directions as follows:

$$a = [(1.4a_{XW})^2+(1.4a_{YW})^2 + a_{ZW}^2]^{½}$$

According to ISO 2631-1: 1985 evaluations of multi-axes vibrations with respect to comfort and performance should be made by comparing the value of 'a' with specifications given for vibrations in the z-axis.

Also the text in BS 6472: 1992 is ambiguous with respect to multi-axis vibration. The text of the Standard reads as follows: 'if the orientation of the occupants with respect to the vibration environment is constant and known, the weighting functions established for the x,y, or z directions should be used. If the orientation of the occupants is varying or unknown with respect to the detected vibration, the weighted values should normally be obtained for all axes and the highest value used'. From this it might be concluded that if the orientation of the occupants is known, the weighted values should normally be obtained for all axes and the highest value used, but this might be a wrong conclusion.

DIN 4150 Teil 2: 1992 states that the KB-values have to be measured and evaluated separately, and comparison with limits should be done by using the largest value in either of the three directions.

In conclusion, each of the three Standards on building vibration seem to suggest that in multi-axis vibration the relatively largest weighted acceleration value in either of the three directions should be used for evaluating the vibration event. This implies that a summation effect should not be taken into account with respect to vibrations in the domestic environment. As mentioned already scientific data are lacking to support or contradict such an evaluation.

4.4 Measure for vibration during 24 hours

4.4.1 Information

Publications with data with respect to subjective response to vibrations in the domestic environment as a function of the time of the day are very limited. Actually, there are only indirect indications that night-time vibrations induce higher annoyance than day-time vibrations. In Zeichart et al. (1993) for both noise and vibration various effects such as disturbance of communication, rest, and sleep and annoyance during day-time and during night-time have been determined. Some results have been reproduced in figure A2. For all effects considered exposure to noise does have a higher mean score than exposure to vibrations. However, vibrations and noise cause about the same sleep and night-time disturbance. This indicates that night-time vibrations cause higher annoyance than day-time vibrations.

The same indication has been found in the railway noise and vibration study by Fields and Walker (1982). This investigation will be summarized in chapter 6. Figure 6.2 shows the effect of night-time use of the railway. At shorter distances (within 50 m from the railroad) night-time railway traffic is a factor which contributes to the percentage of people having problems with railway-induced vibrations. This is contrary to the results of the Fields and Walker investigation with respect to noise exposure: night-time railway-induced noise did not have a larger effect on annoyance than day-time railway-induced noise of the same magnitude.

Both surveys concern railway traffic induced vibrations. Presumably such effects also occur with other environmental vibration sources. No data are available to test such a hypothesis. The available information does not allow to quantify a penalty factor for night-time exposure to vibrations.

4.4.2 Vibration exposure during 24 hours: conclusions

Information about differences in subjective response to night-, evening- and day-time vibrations in the domestic environment is very scarce. Surveys with respect to railway-induced vibrations suggest that vibrations during night-time cause higher annoyance than day-time vibrations.

4.5 Exposure-effect relations for vibrations in the domestic environment

4.5.1 Information

Only in one investigation (Zeichart et al, 1993) exposure-effect relations are given. These relations relate to railway-induced vibrations in the domestic environment.

Two types of railways have been considered: intercity trains (Fernbahn, F-trains) and overground suburban rapid transit systems (S-bahn, S-trains). A major part of the report deals with results for the F-train areas. Results for S-trains have only been given in comparison to those for F-trains. Exposure-effect relations for domestic environments with F- or S-trains are given in figure A8 of this report. In that figure the mean score on an 11-points annoyance thermometer scale is given as a function of a KB_{Fmax} value representative for all vibrations due to railway traffic. Although KB_{Fmax} values of 0.07 usually are considered to be at about the perception threshold, mean annoyance score at that value is apparently not equal to zero. The mean annoyance score is an increasing function of KB_{Fmax}. The results in figure A8 are restricted to respondents with low railway-induced noise exposures, since only these noise exposures occurred in the S-train areas. The difference between the subjective response to vibrations from S- and F-trains is preserved if also intervening factors such as the number of trains per 24 hours are taken into account. Zeichart et al. (1993) are unable to give an explanation of the discrepancy in the subjective response to F- and S-trains. It seems that exposure-effect relations determined for a specific vibration source in the living environment may not be correct for other vibration sources.

Figure A9 gives for F-trains the percentage of persons much and very much annoyed during day- and night-time as a function of the KB_{Fmax} value representative for all railway-induced vibration events occurring during 24 hours. The percentages of persons much and very much annoyed by vibrations increase with KB_{Fmax} up to a value of 0.35 and then remain constant or even decrease with increasing KB_{Fmax} value.

No data on the relation between vibrations in buildings and subjective response are available for other environmental vibration sources, such as road and air traffic, and industrial sources. There is also no information about effects from more or less continuous vibration exposures and effects from exposures consisting of vibrations with high crest factors, such as vibrations from blasts.

4.5.2 Conclusions and comparison with Standards

In 4.5.1 it was concluded that very few data are available with respect to exposure-effect relations. Such relations are necessary to determine limits for environmental vibration exposures on the basis of health effects. Due to this lack of information ISO 2631-2: 1989 takes a cautious line by specifying most of the information in an informative Annex.

According to ISO 2631-2: 1989 and also according to BS 6472:1992 vibration values obtained in the domestic environment should be specified in multiples of the values of the base curve specified in the Standards. Both Standards give in an informative Annex the state of the art of multiplication factors frequently used in connection with the base curves. The multiplication factors specify satisfactory magnitudes of building vibration to keep human response to 'acceptable' levels. Annoyance which may be caused by noise as a result of structural vibrations is not taken into consideration. For residential areas a multiplication factor of 2 to 4 is mentioned for day-time vibrations and a factor of 1.4 for night-time vibrations in the case of continuous vibrations, and according to ISO 2631:2 1989 also for intermittent and quasi-stationary vibrations caused by repetitive shocks. For transient vibration excitation with up to three occurrences per day ISO 2631:2 1989 specifies a multiplication factor of 30 to 90 during day-time and 1.4 to 20 during night-time. The Standard suggests to use a provisional relationship for cases of more than three events a day pending further research. It involves further multiplying by a number factor:

$$F_n = 1.7\ N^{-0.5}$$

in which:

N the number of vibration events during day-time or night-time (for N=3: F_n = 0.98; for N=10 F_n = 0.54; for N=30 F_n=0.31 and for N=100: F_n=0.17).

For discrete events with durations exceeding 1 s, the multiplication factors can be adjusted by further multiplying it by a duration factor:

$F_d = T^{-1.22}$ for concrete floors, with T between 1 and 20

$F_d = T^{-0.32}$ for wooden floors, with T between 1 and 60 in which:

T the duration of the event in seconds, to be estimated from the 10 percentage points of the motion time histories (for T=1: F_d=1; for T=10: F_d=0.06 for concrete floors and 0.48 for wooden floors; for T=20: F_d=0.03 for concrete floors and 0.38 for wooden floors; for T = 60: F_d=0.27 for wooden floors).

It is unclear from which information these factors have been derived.

In BS 6472: 1992 the number factor F_n and duration factor F_d are restricted to vibrations induced by blasts. The multiplication factors are equal to 60 to 90 for day-time and 20 for night-time blast-induced vibrations. In addition BS 6472: 1992 favours the use of eVDV and VDV when evaluating all other than blast-induced vibrations. The eVDV corresponding to a unity multiplying factor for day-time vibrations is approximately equal to 0.1 $ms^{-1.75}$ and for night-time vibrations approximately equal to 0.091 $ms^{-1.75}$. The eVDV's above which various degrees of adverse comment may be expected in the domestic environment are given in table 4.4.

Table 4.4 The estimated Vibration Dose Values (in $ms^{-1.75}$) above which according to BS 6472: 1992 various degrees of adverse comment may be expected in residential buildings.

location	low probability of adverse comment	adverse comment possible	adverse comment probable
residential buildings during the 16 h day	0.2 to 0.4	0.4 to 0.8	above 0.8
residential buildings during the 8 h night	0.13 to 0.26	0.26 to 0.51	above 0.51

As already specified, DIN 4150, Teil 2: 1992 uses to KB-values to evaluate vibrations in the living environment: KB_{Fmax} and KB_{FTr}. These values are compared to three A-values: A_u (u: unteren, lower value), A_o (o: oberen, upper value) and A_r (r: Ruhezeit beobachtet, longterm measure). The A-values in table 4.5 are mentioned for residential areas.

Table 4.5 A-values for the evaluation of vibrations in dwellings according to DIN 4150, Teil 2: 1992

day-time			night-time		
A_u	A_o	A_r	A_u	A_o	A_r
0.15	3	0.07	0.1	0.2	0.05

In the German Standard a flow diagram for the evaluation procedure has been given. This flow diagram has been reproduced in English in figure 4.7 of this report.

Figure 4.6 Flow diagram according to DIN 4150, Teil 2: 1992.

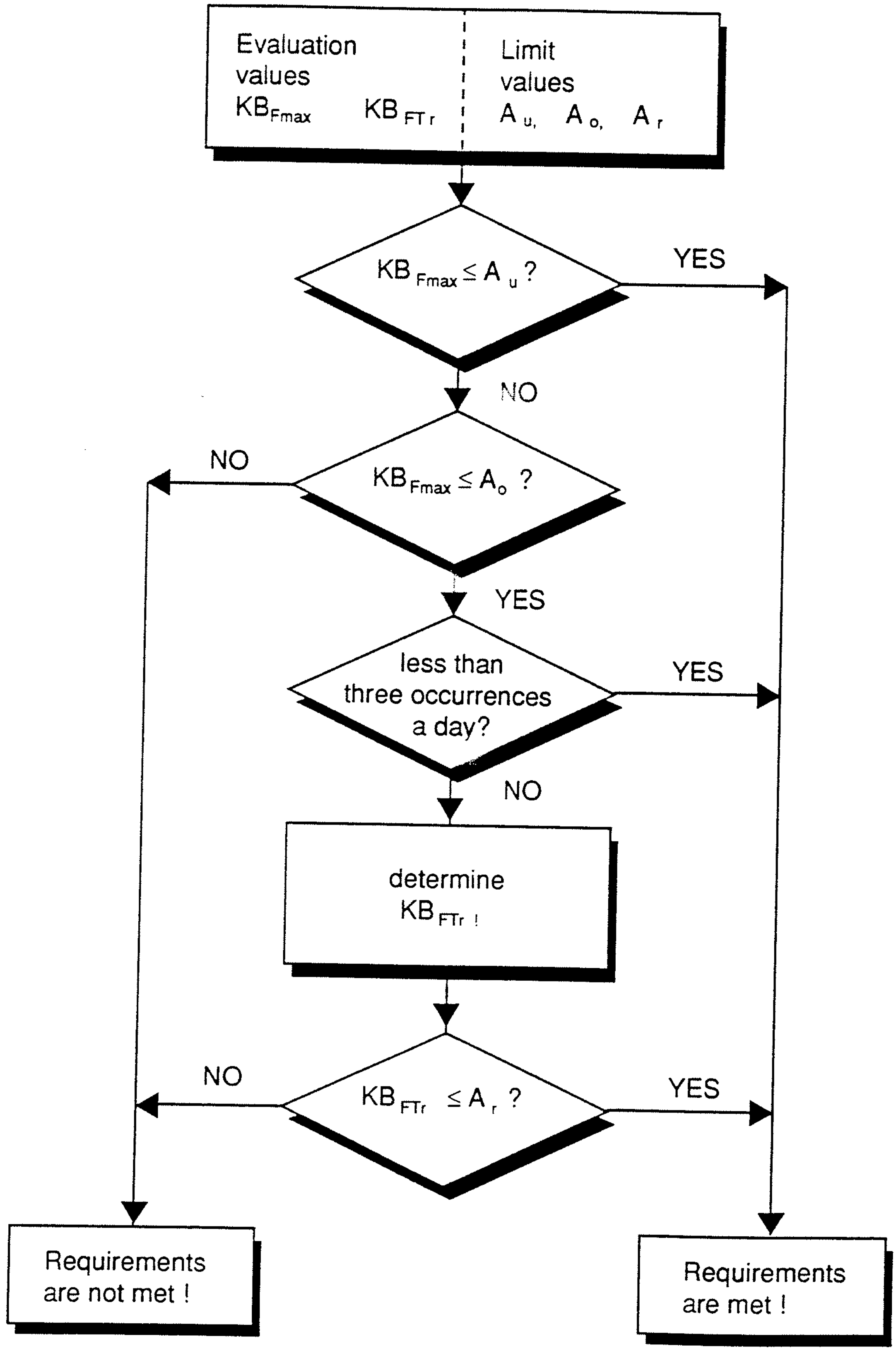
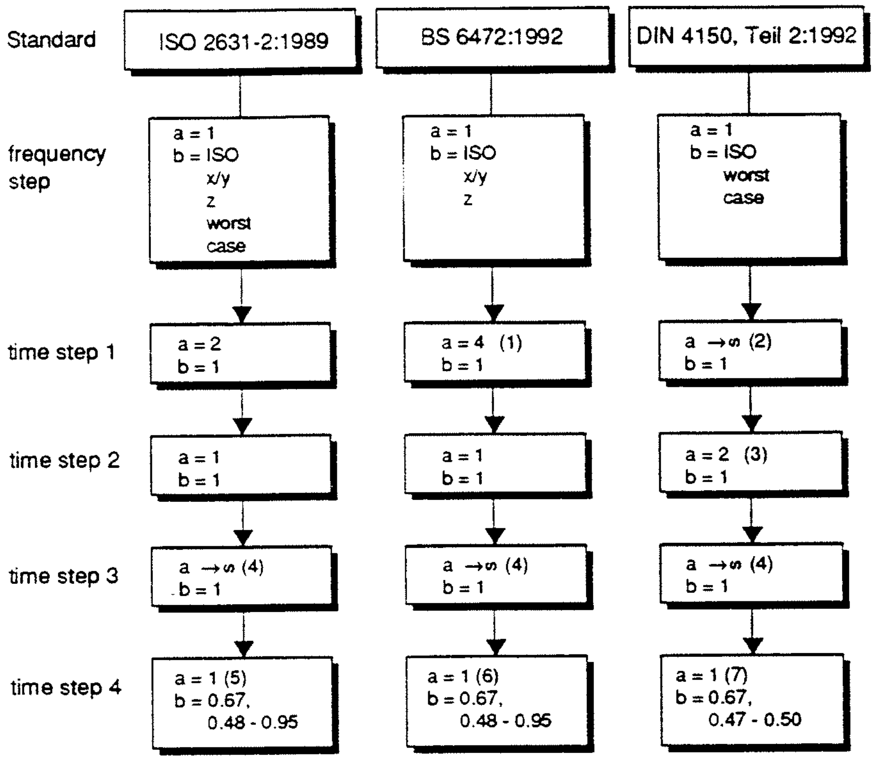


Figure 4.7 Diagram specifying the exponents in the hierarchical power sum specified in ISO 2631-2: 1989, BS 6472: 1992, and DIN 4150, Teil 2: 1992.



(1) based on eVDV

(2) based on KB_{Fmax}

(3) based on KB_{FTm}

(4) based on maximal value in any direction

(5) based on table 5 of appendix A, multiplying factor for residential areas, continuons vibration

(6) based on table 5 of appendix A, multiplying factor for residential areas, continuons vibration

(7) based on table 1, area 4, Au and Ar

5. SIMULTANEOUS EXPOSURE TO NOISE AND VIBRATION

5.1 Introduction

Most environmental sources that emit vibrations do also emit noise. In certain domestic situations, therefore, people are simultaneously exposed to both vibrations and noise. This section discusses possible interaction effects of both stimuli on the subjective response to the combined exposure.

Some research has also been devoted to the trade-off between vibration and noise in simultaneous exposures, e.g. to the question which noise and vibration exposures contribute equally to the overall annoyance of the combined exposure.

5.2 Interaction between noise and vibration in simultaneous exposures

5.2.1. Information on interaction effects

An early publication (Hempstock and Sanders, 1973) describes the difficulties in performing a study on the subjective reaction to a combined environment. They report that their subjects found it a too difficult task to equate the sensation of one combined noise and vibration exposure to another one. All their subjects reported that they found it impossible to consider the two stimuli in a combined exposure together. They were of the opinion that they based their judgement on that stimulus which appeared to be the most dominant. Therefore, Hempstock and Sanders changed their experimental design, and presented alternately a vibration and a noise stimulus.

In Howarth and Griffin (1990b) twenty four subjects assigned values to a combined exposure of railway noise and vibration. A 'standard' exposure, a combined exposure to railway noise with a SEL value of 64 dB(A) and railway vibration with a vibration dose value of 0.14 $ms^{-1.75}$, was assigned the value of 100. Subjects were asked to assign such a number to an exposure that the ratio between the number assigned and 100 corresponds to the ratio between the annoyance caused by that exposure and by the 'standard exposure'. A similar method of magnitude estimation was used in Howarth and Griffin (1991). The Howarth and Griffin (1990b) investigation consists of three experiments. The stimuli were reproductions of noise and vibrations caused by the passage of an iron-ore train and each passage had a duration of 24 s.

In the first experiment test subjects rated the vibration component of the combined exposure, in the second experiment they indicated their reactions to the noise component, and in the third experiment they gave their overall subjective reactions to the combined noise and vibration exposure. In figure 5.1 results of the first experiment are given. The median annoyance rating is given as a function of SEL, with vibration dose value as parameter. In figure 5.2 results of the second experiment have been plotted.
Figure 5.2 shows little change in the assessment of noise with increasing vibration magnitude: the lines are more or less parallel and horizontal. Figure 5.1 shows the tendency that at the lower vibration dose values the annoyance due to vibration is somewhat reduced by high noise levels. At high vibration dose values, the annoyance seems to be somewhat increased by high noise levels.

In figure 5.3 and figure 5.4 results of the third experiment are given. The (median) annoyance rating of the combined exposure are plotted as a function of vibration dose value, with SEL as parameter, and as a function of SEL with vibration dose value as parameter.

Figure 5.1 Annoyance rating as a function of SEL with vibration dose value as parameter. Annoyance rating determined for the vibration exposure component of a combined exposure to noise and vibration (Source: Howarth and Griffin, (1990b).

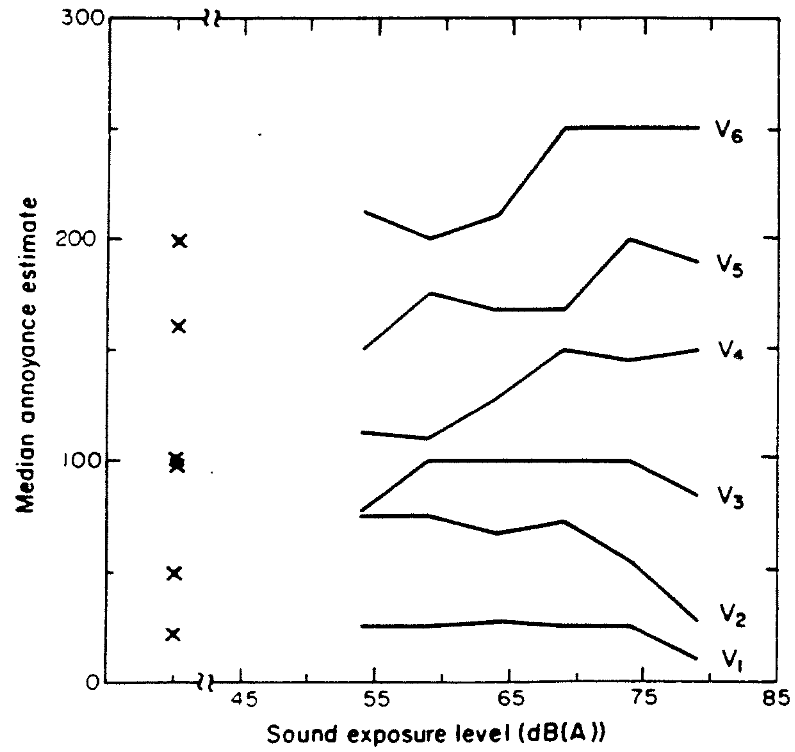


Figure 5.2 Annoyance rating as a function of vibration dose value with SEL as parameter. Annoyance rating determined for the noise exposure component of a combined exposure to noise and vibration (Source: Howarth and Griffin, (1990b).

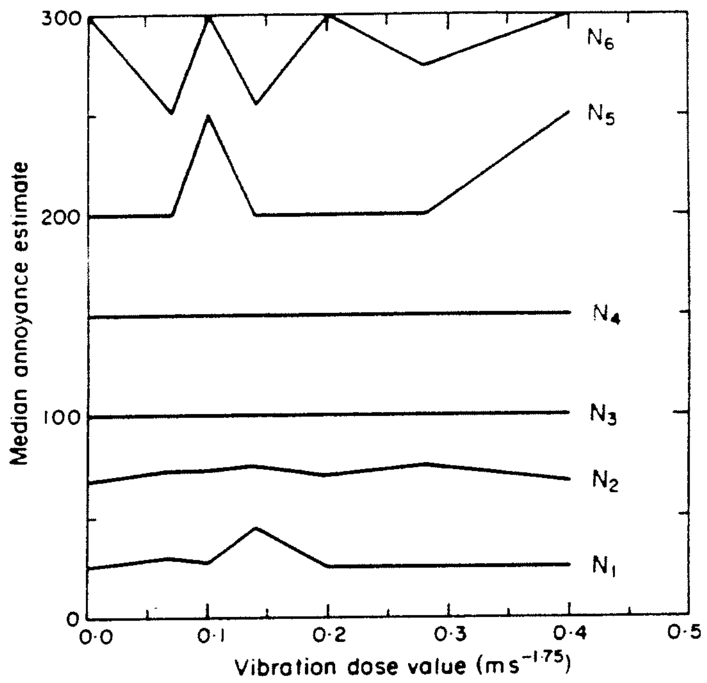


Figure 5.3 Median annoyance estimate as a function of vibration dose values with SEL as parameter. Annoyance assessed for the combined exposure to noise and vibration (Source: Howarth and Griffin, (1990b).

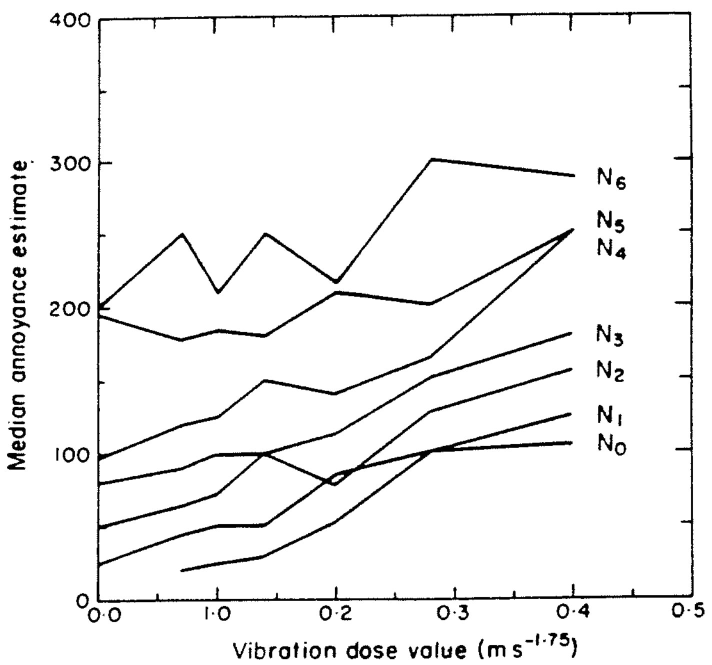
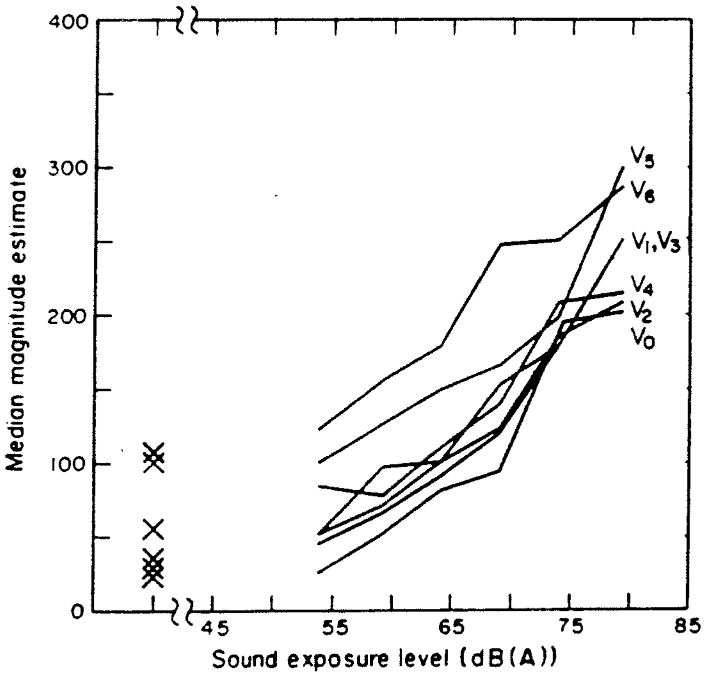


Figure 5.4 Median annoyance estimate as a function of SEL with vibration dose value as parameter. Annoyance assessed for the combined exposure to noise and vibration (Source: Howarth and Griffin, (1990b).



In Howarth and Griffin (1990b) a model was employed which relates subjective magnitude, Ψ, to the objective magnitudes of the vibration (VDV, vibration dose value) and noise exposures (SEL). First a linear regression analysis was carried out on the results from the third experiment for exposure to noise alone and to vibration alone. When subjects received noise alone, the relation between magnitude of annoyance Ψ_s and SEL turned out to be as follows:

$$\Psi_s = 0.217 \times 10^{0.039SEL}$$

The relation between magnitude of annoyance (Ψ_v) and VDV was given by:

$$\Psi_v = 245\ (VDV)^{1.04}$$

The values determined for the noise exponent (0.039) and for the vibration exponent (1.04) were employed to predict the annoyance produced by combined noise and vibration exposures. First, the assumption was made that annoyance, Ψ, of the combined exposure may be approximated by a summation of the individual effects and may be described by:

$$\Psi = a + \Psi_v + \Psi_s = a + b\,(VDV)^{1.04} + c\ 10^{0.039SEL}$$

The values of a, b and c were determined by multiple regression analysis on the two variables $10^{0.039SEL}$ and $(VDV)^{1.04}$. The resulting relation is:

$$\Psi = 15.9 + 260\,(VDV)^{1.04} + 0.167 \times 10^{0.039SEL}$$

The correlation coefficient for the grouped data is 0.97.

Then an interaction variable between the two stimuli was included in the equation for Ψ. The parameters in this equation were determined by a multiple regression analysis of Ψ on three variables: $(VDV)^{1.04}$, $10^{0.039SEL}$ and $(VDV)^{1.04} \times 10^{0.039SEL}$. The equation is:

$$\Psi = 10.8 + 290(VDV)^{1.04} + 0.178 \times 10^{0.039SEL} - 0.066\,(VDV)^{1.04} \times 10^{0.039SEL}$$

The correlation coefficient of the grouped data was again 0.97.
For the 36 combined exposures considered by Howarth and Griffin (1990b) in their third experiment, the interaction variable contributed to Ψ only up to 3.7% of Ψ (for SEL = 79 dB(A), VDV = 0.125 $ms^{-1.75}$, Ψ = 249 and the contribution of the interaction term is 9.15: 3.7%). Therefore, including an interaction variable does not substantially improve the prediction of Ψ. Since also the correlation coefficients between predicted and observed response values are equal with and without an interaction variable it might be concluded that there does not exist an interaction between noise and vibration. However, further analysis presented below will put this conclusion into perspective.

For the 36 combinations of noise and vibration considered in the third experiment the contribution of vibration to Ψ ranged from 4.5 to 29.9 and that of noise from 21.3 to 201.2 if the formula without an interaction term is applied. Table 5.1 shows that in 34 of the combined exposures the contribution of noise to Ψ was larger, and many times much larger, than the contribution of vibration. In one situation the contributions were about equal (21.25 from vibration, 21.32 from noise) whereas in only one situation the contribution of vibration was larger than that of noise (29.91 versus 21.32).

Table 5.1 Contribution of vibration and noise exposure to the subjective rating of the combined exposure. Derived from Howarth and Griffin (1990,b).
+ indicates higher contribution from vibrations
- indicates lower contribution from vibrations
= indicates equal contribution from noise and vibration (differences less than 1%)

vibration dose value in $ms^{-1.75}$						
SEL in dB(A)	0.02	0.03	0.04	0.06	0.09	0.125
54	-	-	-	-	=	+
59	-	-	-	-	-	-
64	-	-	-	-	-	-
69	-	-	-	-	-	-
74	-	-	-	-	-	-
79	-	-	-	-	-	-

Obviously, the noise exposures dominated the combined exposures and the vibration exposures contributed little to the subjective magnitudes of the combined exposures. It therefore seems unlikely that this experiment would be able to show a considerable interaction effect. If the vibration components would have been relatively larger, a conclusion about an interaction effect might have been different. Nevertheless, dependent upon the noise and vibration magnitudes in real life situations in residential areas, the result of the investigation may be relevant for these situations.

The coefficient of the interaction variable turned out to be negative. This would imply that the interaction decreases the overall subjective response to a combined exposure. However, as mentioned before, the contribution of the interaction variable was only small compared to the separate contributions of noise and vibration to the overall subjective response. Since the interaction variable is the difference between various other variables, this implies a large inaccuracy in the magnitude of the interaction variable. Presumably, a statistical test on the results of the investigation might even have shown that a 'real' positive interaction term should not be excluded.

Unfortunately in other publications no attempt has been made to determine an interaction effect between noise and vibration. However, in Howarth and Griffin (1990a) curves which give an indication of an interaction effect are presented. These curves are comparable to those in Howarth and

Figure 5.5 The assessment of combined railway noise and vibration exposure as a function of the vibration dose value with SEL as parameter (Source: Howarth and Griffin, 1990a)

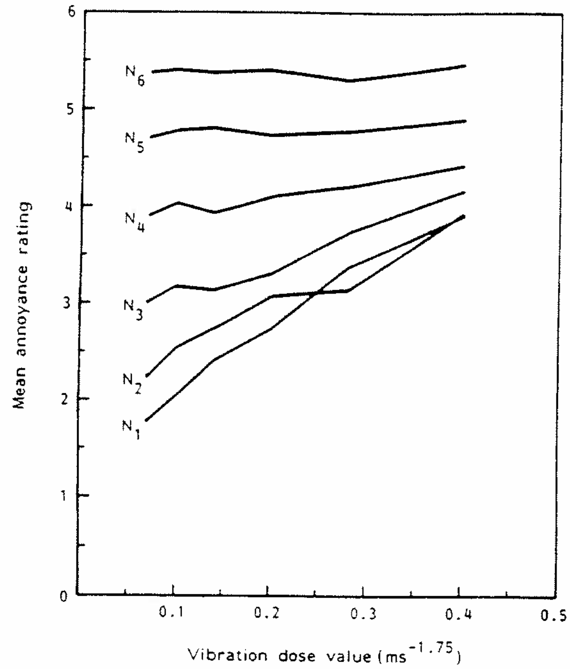
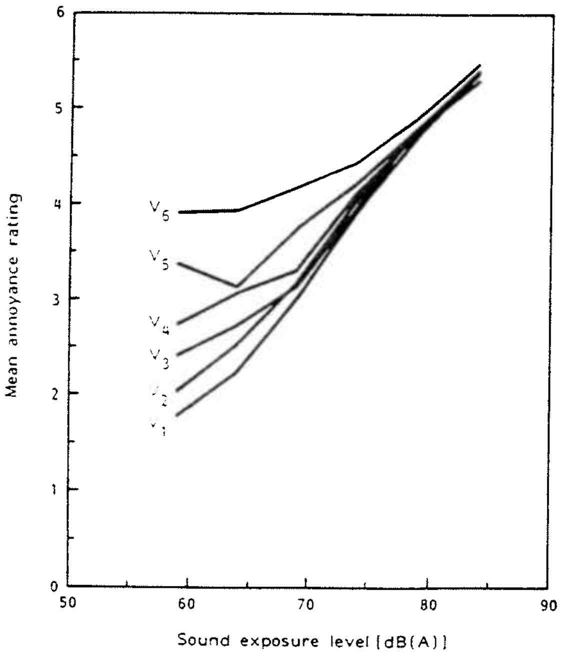


Figure 5.6 The assessment of combined noise and vibration exposure as a function of SEL with vibration dose value as parameter (Source: Howarth and Griffin, 1990a).



Griffin (1990b) which have been reproduced as figures 5.3 and 5.4. The 1990a study also concerns simultaneous exposure to railway noise and vibration. Figures from the 1990a publication have been reproduced in this report as figure 5.5 and figure 5.6. In figure 5.5 the median annoyance estimate is given as a function of the vibration dose value with SEL as parameter. In figure 5.6 the data are plotted as a function of SEL with the vibration dose value as parameter.

To get some insight in the contributions of the noise exposures and vibration exposures on the overall annoyance rating, the formula presented in Howarth and Griffin (1990b) has been applied to the exposures in the 1990a publication. Application of that formula seems to be appropriate, since both investigations concern railway noise- and vibration-induced subjective responses and vibration and noise magnitudes in both investigations are not too wide apart. In table 5.2 a comparison is made of the contributions to Ψ of noise and vibration in the 36 combined exposures.

Table 5.2 Contribution of vibration and noise exposure to subjective rating of the combined exposure, by using the equation on page 52 without the interaction component. Derived from Howarth and Griffin (1990a).
+ indicates higher contribution from vibrations
- indicates lower contribution from vibrations
= indicates contributions from noise and vibration about equal

	Vibration dose value in $ms^{-1.75}$					
SEL in dB(A)	0.07	0.10	0.14	0.20	0.28	0.40
59	-	-	=	+	+	+
64	-	-	-	-	+	+
69	-	-	-	-	-	+
74	-	-	-	-	-	-
79	-	-	-	-	-	-
84	-	-	-	-	-	-

It is obvious from figure 5.5 that at the three highest sound levels the mean annoyance rating for the combined exposure does not depend on the vibration dose value: the upper three curves are horizontal. An interaction effect seems to be absent. However, at the lowest sound levels the curves giving mean annoyance as a function of vibration dose value are not parallel. This suggest an interaction effect between noise and vibration on overall annoyance. Table 5.2 shows that at these sound levels the contribution of the higher vibrations dose values surmounts the contribution of the noise exposures.

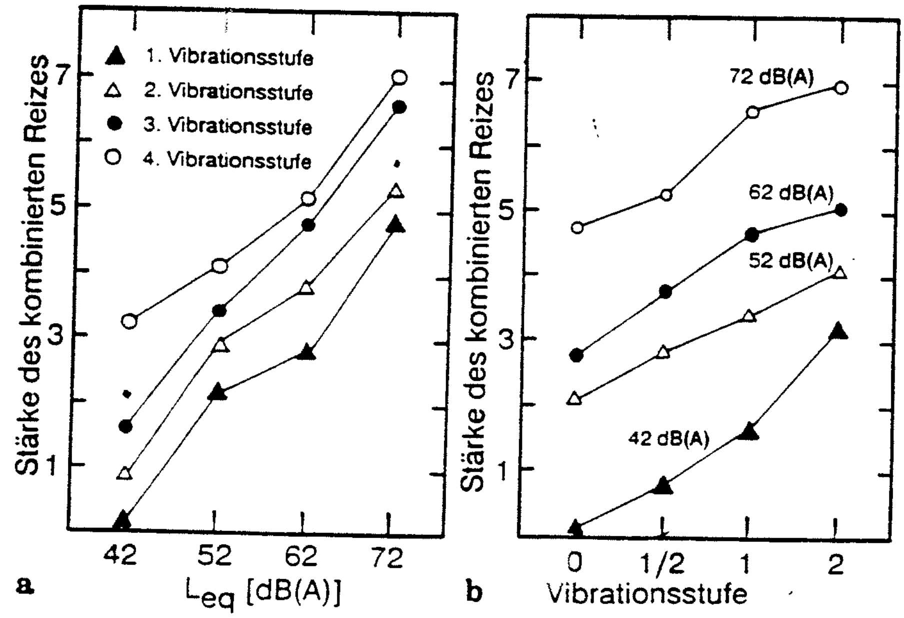
Howarth and Griffin (1991) carried out an experiment in which subjects were exposed to various combined noise and vibration signals: passages of six different trains, with for each train nine combinations of three levels of vibration and three noise levels. Based on the results of Howarth and Griffin (1990b), they assumed the overall annoyance to be equal to the sum of the individual effects of the noise and vibration stimulus without an interaction effect. Applying the formula given in the 1990b publication to the data in the 1991 study shows that in 1/3 of the combined exposures considered the contribution of *vibration* to the total annoyance was larger than that of the noise exposure, and in 2/3 of them the contribution of *noise* exposure was larger (see table 5.3). Therefore, in principle this investigation would have allowed the determination of an interaction effect in simultaneous exposures in which the vibration exposure would have contributed considerable to the overall subjective response. Unfortunately an attempt to do so has not been made.

Table 5.3 Contribution of noise exposure and of vibration exposure during simultaneous exposure to the overall annoyance. Situations concern those from Howarth and Griffin (1991) describing six passages of a train, the vibration and noise exposure each set at three levels, thus producing 9 exposures for each train.

train	contribution of vibration	contribution of noise
1	13.4	18.6
	26.9	41.8
	55.3	93.8
2	15.2	21.6
	30.4	47.4
	62.5	106.4
3	16.8	23.8
	33.6	53.3
	69.1	119.5
4	19.4	27.7
	38.7	62.1
	79.6	139.2
5	21.8	31.7
	43.7	71.0
	89.9	159.3
6	23.8	35.6
	48.8	79.8
	100.3	179.1

In Melloni and Krueger (1990) eight test subjects were simultaneously exposed to reproductions of tramway noise and vibrations. Each test signal lasted 22 s and test subjects were in a sitting position. Annoyance was rated by means of a thermometer scale relative to the annoyance caused by a standard exposure. Figure 5.7 and 5.8 present the mean annoyance rating as a function of the equivalent sound level during the exposure of 22 s (which implies that the SEL value is 13.4 dB(A) higher than the equivalent sound level) and as a function of 'vibration-class'. The 'vibration-class' is 1 if the vibration acceleration r.m.s. value is the same as in the original situation (the first floor of a large building at 5 m distance from the tramway). For 'vibration-class' 2 the vibration amplitude was 2 times that of class 1, and for vibration class 1/2 the vibration amplitude was 1/2 of that of class 1. In the situation with vibration class 0 test subjects were not exposed to vibrations. Both noise and vibration contribute to the response of the test subjects. There is no clear indication for an interaction effect in the figures.

Figure 5.7 The subjective rating of combined tramway noise and vibration exposure as a function of the equivalent sound level during the 22 s exposure with the vibration class as parameter (figure a) and as a function of vibration magnitude with equivalent sound level as parameter (figure b) (Source: Melloni and Krueger, 1990).



Paulsen and Kastka (1995) conducted four experiments to investigate the combined effects of noise and vibration on annoyance. Two signals with different time patterns were investigated, namely a passing tram and a hammermill each lasting 16 s. The noise and vibration magnitudes were equal to those established in the apartments where the stimuli were recorded. The results showed that the assessment of the combined stimuli is dominated by the noise exposure, but that it is to some extent influenced by the simultaneously occurring vibrations. The 16 test subjects rated their annoyance on a ten points scale. In the first two experiment they were required to rate vibration annoyance, in the third experiment to rate noise annoyance, and in the last experiment to rate their overall annoyance of the combined test stimuli. Results are presented in figures 5.8, 5.9, and 5.10.

Figure 5.8 Annoyance caused by vibration in a combined noise and vibration exposure rated on a ten point scale. Means and standard errors for 16 subjects for four noise levels and four vibration levels. (a) Tram; (b) hammermill (Source: Paulsen and Kastka, 1995).

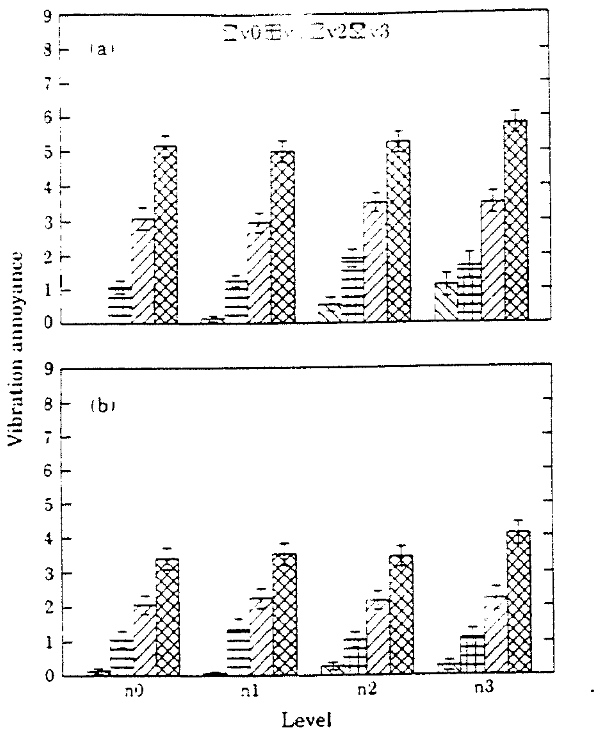


Figure 5.9 Annoyance caused by noise in a combined noise and vibration exposure rated on a ten point scale. Means and standard errors for 16 subjects for four noise levels and four vibration levels. (a) Tram; (b) hammermill (Source: Paulsen and Kastka, 1995).

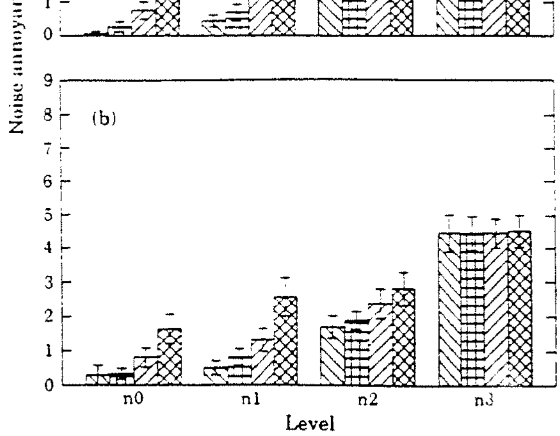
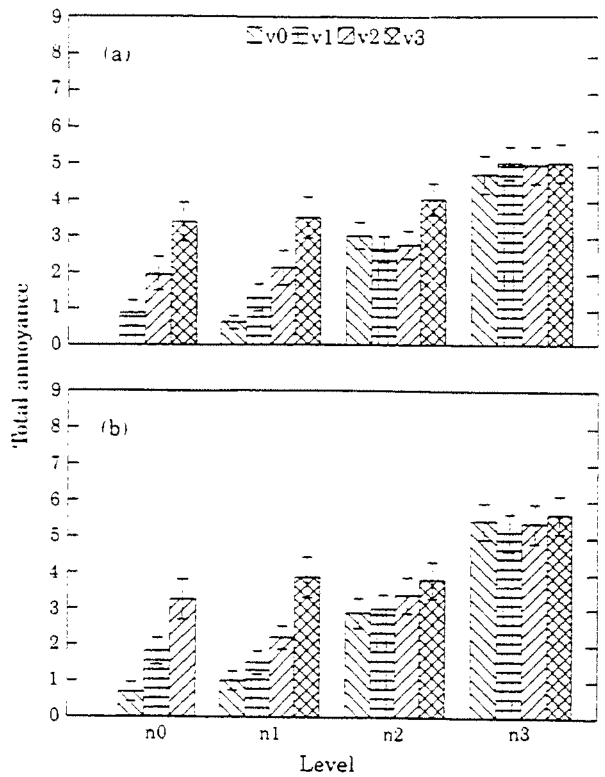


Figure 5.10 Overall annoyance caused by vibration and noise in a combined noise and vibration exposure rated on a ten point scale. Means and standard errors for 16 subjects for four noise levels and four vibration levels. (a) Tram; (b) hammermill (Source: Paulsen and Kastka, 1995).



The results in the figures 5.8, 5.9, and 5.10 show the same tendency as could be observed in the other investigations: vibration annoyance is influenced by the noise level, noise annoyance is influenced by the vibration magnitude only at the lower noise levels, whereas the overall subjective response shows the same trend as noise annoyance. The overall annoyance, however, exceeds the noise annoyance by at least one point on the ten points scale.

5.2.2 Conclusion about interaction effects

The results of laboratory investigations do not exclude the existence of a small interaction effect, but substantial evidence for such an effect could not be found. Future investigations with higher values of the vibration component in the simultaneous exposure to noise and vibration are needed to arrive at a more definite conclusion.

5.3 Trade-off between noise and vibration

5.3.1. Information about trade-off

Seven publications present data about simultaneous exposures to noise and vibration that are relevant for the determination of the noise and vibration levels that cause equal annoyance. These publications are listed in table 5.4. Some noise and vibration parameters, and formula's describing the equivalence of noise and vibration are given. The formula's have been taken from the publications themselves (Howarth and Griffin, 1990a, 1990b, 1991), or they have been calculated by the present author from the descriptions of the various noise and vibration exposures given in the publications (Hempstock and Sanders, 1973; Fleming and Griffin, 1975; Kjellberg et al., 1985; Paulsen and Kastka, 1995). The noise exposure is expressed in SEL (in dB(A)), and the vibration exposure variable is vibration dose value (in $ms^{-1.75}$). The vibration and noise exposure ranges are also specified in the table. In figure 5.11 SEL has been plotted as a function of log VDV.

Table 5.4 Data about the investigations used in the determination of the equivalence of vibration and noise in simultaneous exposures.

publication	description of noise exposure	description of vibration exposure**	duration of exposures in s	equation	range VDV (in $ms^{-1.75}$)
Fleming and Griffin, 1975	1000 Hz tone	10 Hz sinusoidal	10	SEL = 33.0 log VDV + 89.2	0.5-3.0
Howarth and Griffin, 1990a	railway	railway	24	SEL + 29.3 log VDV + 89.2	0.02-0.125
Howarth and Griffin, 1990b	railway	railway	24	SEL + 26.7 log VDV + 81.7	0.02-0.125
Howarth and Griffin, 1991	railway	railway	7-29	SEL + 32.4 log VDV + 81.6	0.055-0.4
Kjellberg et al., 1985b	broadband	forklift truck	6	SEL = 38.4 log VDV + 76.2	2.0-7.7
Hempstock and Sanders, 1973*	broadband	random	2.5	SEL = 16.9 log VDV + 75.5	0.9-6.9
Paulsen and Kastka, 1995***	tram	tram	16	SEL = 14.4 log VDV + 59.5	0.015 - 0.09
	hammermill	tram	16	SEL = 13.7 log VDV + 58.10	0.015 - 0.09

* No simultaneous, but alternate exposures

** All vibrations concern z-axis vibrations of sitting test subjects

*** Paulsen expressed the vibration magnitude in velocity in ms^{-1}, stating that these velocity values are equal to KB values. There is also some uncertainty whether the values specified by Paulsen and Kastka represent SEL values. This will be verified. Taking the relation between VDV and KB for railway-induced vibrations specified in Zeichart et al. (1993) (VDV = 0.29 KB) the equation and range is estimated to be as given in this table. Since the equations for tramway-and for hammermill-induced vibrations are about equal, they are taken together in figure 5.11.

Figure 5.11 Trade-off between noise and vibration in simultaneous exposure to both stimuli.
Results of experimental investigations by:
——— Howarth and Griffin, 1990a
——— Howarth and Griffin, 1990b
-·-·-·- Howarth and Griffin, 1991
········ Fleming and Griffin, 1975
– – – – Kjellberg et al., 1985
-·-·-·- Hempstock and Sanders, 1973
——— Paulsen and Kastka, 1995

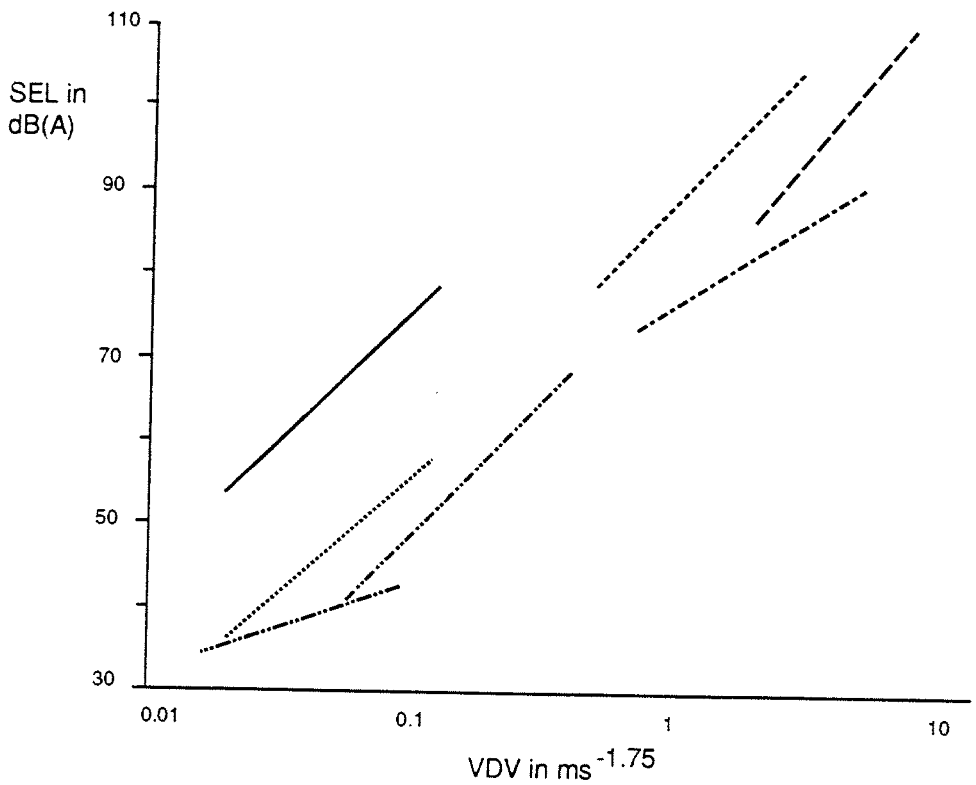
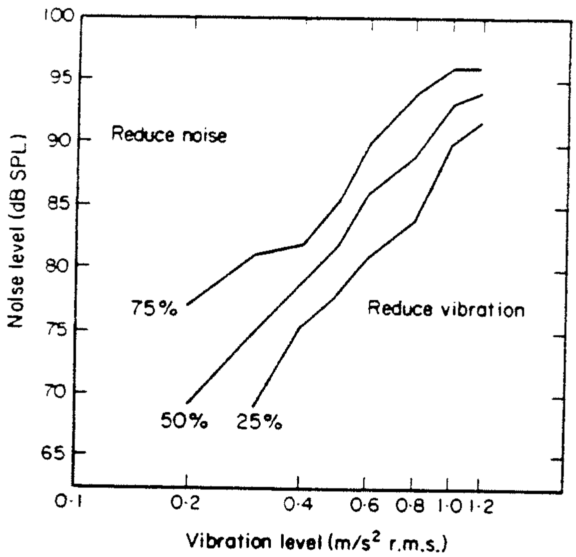


Figure 5.11 shows a difference in SEL values of 25 dB(A) or a factor 7.5 in the vibration dose values between the highest and lowest straight lines. This dispersion is not easily explained. E.g. the three investigations by Howarth and Griffin all concern railway noise and vibration. Differences between the methods by which subjective responses were established may be a partial explanation. Therefore some additional information about the methods used will be given below.

Fleming and Griffin (1975) presented noise and vibration simultaneously for a period of ten seconds, and subjects (20) were asked to indicate whether they would prefer that the noise or the vibration should be reduced, if they were to be presented with the combination again. A result is presented in figure 5.12, which shows the percentage of subjects who favour the reduction of either noise or vibration. In this figure the 50% curve has been interpreted as representing noise and vibration levels which are subjectively equivalent.

Figure 5.12 Percentage of test subjects who indicated a preference for a reduction of the noise or the vibration after a combined exposure to noise and vibration (Source: Fleming and Griffin, 1975).



The same method as in Fleming and Griffin (1975) has been applied in Howarth and Griffin (1990a) (see also Howarth, 1985, which presents results of the same experiment as reported in 1990a). Kjellberg et al. (1985) used the method of cross-modality testing, in which subjective response to vibration exposures and combined exposures were rated by the noise exposure resulting in the same annoyance. As mentioned earlier Hempstock and Sanders (1973) alternated exposure to vibrations and noise and the other three researchers performed magnitude estimation tests.

As is shown in figure 5.11, a relatively high tolerance with respect to noise is found in the two investigations in which test subjects were forced to indicate what stimulus they would prefer to be reduced. It is, however, not readily explained why such a method would give this relatively high tolerance.

Another reason for the discrepancy between the various straight lines in figure 5.11 might be inadequate measures of the noise and/or vibration magnitude. However, most data in the publications do not allow noise and vibration magnitudes to be expressed in other measures.

5.3.2 Conclusions about trade-off between noise and vibrations

The following equation of the trade-off between noise and vibration gives the best description of the pooled results presented in section 5.3.1:

$$SEL = 26.7 \log VDV + 83.3$$

From this equation it follows that if SEL = 30 dB(A) then VDV = 0.01 $ms^{-1.75}$ and if SEL = 110 dB(A) then VDV = 10 $ms^{-1.75}$. This equation is restricted to events lasting about 16 s (median value taken form table 5.4). For an event of 16 s duration, a SEL value of 30 dB(A) corresponds to an equivalent sound level during that time of 18 dB(A), and VDV of 0.01 $ms^{-1.75}$ corresponds to an acceleration r.m.s. value of 7 x 10^{-3} ms^{-2}. Both values are just above the respective perception thresholds. At the lower noise and vibration magnitudes, the trade-off between SEL and VDV is apparently according to expectations. A SEL value of 110 dB(A) (equivalent sound level over 16 s equal to 98 dB(A)) corresponds to a VDV of 10 $ms^{-1.75}$ (acceleration r.m.s. value approximately equal to 7 ms^{-2}). Both exposures would be considered as highly undesirable.

Whether the same equation holds for event durations other than those considered is unknown.

5.4 Conclusion

As mentioned in section 5.2, in the publication of Howarth and Griffin (1990b) an equation has been given in which overall subjective response to a combined exposure to vibrations and noise is taken equal to the sum of the separate subjective responses and an interaction term. This equation, which has been derived from conditions which are similar to those specified in section 5.3, allows the estimation of the relative magnitude of an interaction term in situations in which the noise and vibration contributions to overall subjective response are equal. In the situation in which SEL = 30 dB(A) and VDV = 0.01 $ms^{-1.75}$, the interaction term is less than 1% of the magnitude of the overall subjective response. For the situation in which SEL = 83 dB(A) and VDV = 1 $ms^{-1.75}$, the interaction term is about 15% of the magnitude of the overall subjective response.

Zeichart et al. (1993) considers a possible interaction between vibration and noise exposure in their analysis of the results of their field investigation. A statistical analysis resulted in a chance of 0.07

of such an interaction, which means that the hypothesis that such an interaction does exist should be rejected. However, as Zeichart et al. states, an analysis in which the nightly disturbance was not taken into account, showed a statistical significant interaction effect (p= 0.03). Various figures in the report from Zeichart et al. show that some of their results could be partially explained by a negative interaction between noise and vibration at higher exposure magnitudes.

To obtain some insight in the possible magnitude of an interaction effect in the results obtained by Zeichart et al. the model presented by Howarth and Griffin (1990b) is applied to the data in the report of Zeichart et al.. The actual combinations of SEL and VDV values are unknown. Therefore SEL is estimated from VDV by applying the relation between SEL and VDV at the equivalence curve. This results in a higher estimate of an interaction term than presumably would exist in the real situation, since in the real situation SEL, measured indoors would be less than follows from the equivalence equation. For the four vibration magnitude classes considered in the investigation by Zeichart et al. the interaction term would be 4%, 5.5%, 9%, and 15% with increasing vibration magnitude. Since the actual figures may be below these values it is not surprising that the investigation does not show a clear interaction effect at the lower vibration magnitudes. However, since the actual SEL values are unknown, and since it is uncertain whether the model presented by Howarth and Griffin can be used for real life situations, these results should be interpreted with care.