Evaluation of methods for comfort assessment

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Evaluation of methods for comfort assessment

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SUMMARY

Mechanical vibration in vehicles and working-machines can cause human discomfort. Several methods (such as the standard ISO 2631) try to evaluate the discomfort from whole-body vibration by rating the severity of exposure. The main issue discussed in this report is to determine a quantitative description of (dis)comfort, especially in the case of shocks. This objective measure has to have a linear relation with the subjective estimate of the degree of discomfort. Because of the somewhat elder concepts in the common standard ISO 2631 and the lack of information about the evaluation of discomfort when shocks occur, the standard has been taken into reconsideration. Other, more recently published studies provide additional information.

In order to determine the most discomforting vibration direction(s), 12 axes of measurement are used, namely 3 translational axes on the seat surface, 3 translational axes at the backrest, 3 translational axes on the feet support and 3 additional axes on the seat surface for the assessment of rotational vibration. The presence of a backrest, a vibrating feet support or rotational vibration can highly influence the degree of discomfort. The most important directions are the 3 translational axes on the seat surface, the for-and-aft vibration at the backrest and the vertical vibration at the feet support. Comparison of vibration at different locations and in different directions is possible by using an axis multiplying factor.

For the horizontal seat vibration, the frequency weighting contour according to ISO 2631 seems to be appropriate for the assessment of the degree of discomfort. The frequency weighting for the vertical seat vibration proposed in some other studies, appears to give more acceptable results than the ISO 2631 contour. Underestimation of low-frequency shocks in the vertical direction, however, may then be possible in some cases. The performance of the experiments and subject characteristics may influence the dependency on frequency and hence the frequency weighting contour.

Some studies show that the subjective estimate of the degree of discomfort increases with duration of exposure at the beginning of the vibration. After a certain time, there is no certainty about the effect of exposure duration on the level of discomfort because of very divergent results.

The Vibration Dose Value (a cumulative measure) seems to be the best objective measure for the evaluation of discomfort in most of the cases, especially when shocks occur. One of the main reasons is that a cumulative measure takes into account the whole shock event. A cumulative measure makes it possible to compare motions of different durations. Another possibility is to use a time-mean value with a fixed integration time, which is as long as the duration of the shock event. Note that these measures are still objective and may differ from the subjective assessment, so only an indication of the severity of vibration can be given.
A single frequency weighting per direction and a single method considering the effect of duration appear to be sufficient, because the increase of the degree of discomfort with increasing shock magnitude is independent of frequency, duration and direction of motion for single shocks. For constant Vibration Dose Values, the frequency and damping ratio have effect on the degree of discomfort. The Vibration Dose Value may underestimate the effect of shock duration in some cases. In case of repeated shocks, the prediction of the degree of discomfort by the Vibration Dose Value seems to be very acceptable.
PREFACE

At the Eindhoven University of Technology investigations are going on in cooperation with DAF, MONROE and CONTI to determine an applicable control concept for a (semi-)active suspension system of a tractor semi-trailer combination. The purpose of these investigations is to improve comfort for the occupants as well as for the cargo and to diminish the weariness of the chassis when driving on bad road-surfaces, kerbstones, level crossings and other objects that cause incidental excitations.

My contribution to this investigation during my term of probation is given in this report, which deals with a quantitative description of human comfort. Different methods for the evaluation of whole-body vibration, especially in case of shocks, are evaluated. For this, I had to read a great deal of literature.

I would like to thank ir. H. Muijderman for his assistance and contribution to this report.
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1. INTRODUCTION

In vehicles and working-machines mechanical vibrations occur. Such vibrations can interfere with human activities and can cause discomfort. There may even be some risk to the health and safety of the exposed subjects. The design of a successful (semi-) active vehicle suspension system which improves the subjective comfort, depends on the adequacy of the description of comfort. The evaluation of discomfort from whole-body vibration has led to a variety of methods and standards. All these methods try to compare and evaluate data from experiments and consequently rate the severity of exposure.

The purpose of this study is to give a quantitative description of comfort, especially for incidental road excitations. One of the issues is to consider the various quantities put forward in relevant studies, with which the degree of comfort is estimated. Special attention has to be paid to the case of shocks. As no uniform description of comfort for incidental excitations can be formulated, a survey of the quantities found in the literature will be given.

The problem can be described in a more mathematical way. The purpose is to find an objective measure for the evaluation of discomfort, $\phi$, which is related with a subjective estimate of the degree of discomfort, $\psi$. When the relation between $\phi$ and $\psi$ is linear, the objective measure $\phi$ will be a good measure for the evaluation of human discomfort.

Chapter 2 deals with the differences between the assessment of discomfort in the standard ISO 2631, 'Evaluation of human exposure to whole-body vibration' and in some other studies. In section 2.1. some information is given about the standard ISO 2631. As this standard is the most common source of information about the assessment of human discomfort, it will serve as a reference in this report. In section 2.1. information is also given about methods, which determine the subjective estimate of the degree of discomfort. Section 2.2. is dedicated to the lack of sufficient data to arrive at a well-founded conclusion with respect to the degree of discomfort due to the absence of several locations and measurement directions in the standard. More recent studies provide additional information. Frequency weighting of the acceleration signals is another important matter, which also gives rise to different approaches. See section 2.3. The duration of vibration has its effect on the subjective estimate of the degree of discomfort. Therefore, section 2.4. is dedicated to this topic.

The major concern of this study is the assessment of discomfort for occasional or repeated shocks. In chapter 3, several objective measures for the evaluation of human discomfort are included. These methods analyse the weighted acceleration signals: peak-value measures, time-mean measures and dose measures. Chapter 4 describes the validation of the objective discomfort measure, considered as the most likely solution in the previous chapter, in relation with the subjective estimate of the degree of discomfort. The overall conclusion with respect to the several methods of assessing discomfort can be found in the last chapter.
2. ISO 2631 AND OTHER STUDIES

2.1. Introduction

The most common standard is the international standard ISO 2631/1, titled 'Evaluation of human exposure to whole-body vibration' of the International Organization for Standardization (ISO) [7]. ISO 2631/1 - part 1: 'General requirements' deals with the evaluation of exposure of seated or standing subjects to whole-body vibration at the work place. Other parts of the standard provide data on vibration in buildings, low-frequency vibration (0.1 to 0.63 Hz.) and vibration on board of sea-going ships.

In view of this study, part 1 of the standard is the most important one. The standard gives satisfactory results for the assessment of discomfort produced by stochastic, stationary vibration. However, this standard is based on somewhat elder concepts. Meanwhile several other studies, which throw light on relevant matters and review the ISO standard, have been published. It appears to be necessary to give additional information to come to a reasonable good objective measure which assess the severity of subjective discomfort. Special attention has to be paid to vibration containing shocks, because the standard hardly treats of this subject. In the standard one remark can be found saying that ISO 2631 only applies to vibrations with crest factors¹ up to 6.

In the course of years, several experiments with respect to subjective discomfort have been conducted in different ways. It is possible to measure vibration in a vehicle while driving on a test track (studies in the field). Laboratory experiments make use of a simulator, which consists of a vibrating table. The subject undergoing the experiment has to take a seat on that vibrating part.

In a number of laboratory studies the method of constant stimuli is employed. This means that the subject compares test motions with one reference motion and judges whether the test motion or the reference motion is more uncomfortable. In this way, determination of vibrations of equivalent severity and consequently determination of frequency weighting contours is possible.

Studies in the field and some laboratory studies use the method of magnitude estimation. A subject compares a test motion with a reference motion and assigns a number to each test motion. This number, which can be seen as the subjective estimate of the degree of discomfort, gives an indication of the severity of the test motion in relation with the reference motion and determines the subjective relative discomfort. The ratio between the number assigned to the test motion and the number of the reference motion has to correspond to the ratio between the subjective discomfort caused by the test motion and the subjective discomfort.

¹ The crest factor is the ratio of the peak value to the r.m.s. value of the frequency weighted motion.
discomfort caused by the reference motion. When driving on a test track, the first motion serves as the reference motion.

2.2. Locations and directions of vibration

2.2.1. Introduction

ISO 2631 applies to the situation in which rectilinear vibrations are transmitted to the body through the supporting surface of a standing man (i.e. the feet) or of a seated man (i.e. the buttocks). Thus, only one surface (the seat or the floor) is taken into account. No backrest is present when ISO 2631 experiments are carried out. However, according to Griffin et al. [3,6] and Griffin [10], there are at least three locations where the vibration influences the discomfort: the seat surface, the backrest and the feet support. There may also be a contribution of the vibration of some other objects, such as a steering wheel, to the degree of discomfort but this can only be included when the necessary data are available.

2.2.2. Axes of vibration

2.2.2.a. 12 axes of measurements

The vibration acceleration at each of the indicated locations has to be measured in the appropriate directions of an orthogonal co-ordinate system. This procedure leads to the assessment of 12 axes of vibration: 3 translational axes on the seat surface \( (x_s, y_s, z_s) \), 3 translational axes at the seat backrest \( (x_{sb}, y_{sb}, z_{sb}) \), 3 translational axes on the feet support \( (x_f, y_f, z_f) \) and 3 additional axes for the assessment of rotational vibration on the seat surface: \( r_x \) (i.e. roll), \( r_y \) (i.e. pitch) and \( r_z \) (i.e. yaw). See figure 2.1.

In the study conducted by Griffin [10] a table is given with a frequency weighting and a multiplying factor for every axis. This multiplying factor has to be used for weighting of the relevant axis. Multiplication of the frequency-weighted acceleration value by this factor gives an axis-weighted value. In this way, comparison of vibrations at different locations and in different directions is possible for evaluation of the degree of discomfort. In the appendix a survey of the frequency weightings and the axis multiplying factors is given (according to Griffin [10]).

It is of course unpractical to measure the acceleration in all specified axes. The locations and directions of vibration which contribute most to the degree of discomfort are generally known for the cases being investigated. For road vehicles, it appears to be suitable to consider the vibration in all translational directions on the seat surface, \( x_s, y_s \) and \( z_s \), the for-and-aft vibration at the backrest, \( x_{sb} \), and the vertical vibration on the feet support, \( z_f \).

---

2 See chapter 4 for more information about this topic
2.2.2.b. Influence of backrest

When for-and-aft vibration occurs, a backrest can have a strong effect on the subjective response to that motion and can therefore be an important source of subjective discomfort. In fact, most of the time the for-and-aft vibration at the backrest is more annoying than the vibration on the seat surface in the same direction. Measurements of vibrations in some vehicles (Griffin [10]) show that the for-and-aft vibration at the backrest can be the dominant motion. According to a study by Parsons et al. [5], the presence of a backrest may reduce sensitivity to vibration at low frequencies.

The location of vibration measurement at the backrest is at the highest point of contact between the back of the subject and the backrest of the seat. If there is no backrest, the accelerations at the backrest of the seat are of no interest.

2.2.2.c. Influence of feet support

The studies by Parsons et al. [5] and by Griffin et al. [6] report about the influence of the feet support on subjective discomfort. There are several ways of implementing a feet support to test its influence on discomfort. The support can be attached to the seat or the seat and the feet support can vibrate independently. A possibility is to combine a vibrating seat with a stationary feet support. These different experimental configurations give different results.
An experiment with a stationary feet support by Parsons et al. [5] shows that the subjects are submitted to greater (relative) displacements between their feet and their upper legs at low frequencies than at high frequencies. For, this experiment has been conducted with a sinusoidal vibration signal having a constant r.m.s. value for all used frequencies, which results in a smaller amplitude for higher frequencies. As a result of this, the sensitivity to low-frequency vibration appears to be higher than when the feet undergo the same vibration as the rest of the body (Parsons et al. [5], Griffin et al. [6] and Corbridge and Griffin [9]).

A vibrating feet support may reduce sensitivity to low-frequency vibration, which corresponds to the situation with the vibrating backrest (see [5, 6]). It turns out that the sensitivity to feet support vibration is less than the sensitivity to seat surface vibration at low frequencies. When the seat transmissibility causes the vibration between the seat and the feet support to attenuate, the feet support vibration can be uncomfortable at high frequencies. In fact, the severity of vibration of the feet support depends on the seat transmissibility.

2.2.2.d. Rotational vibration

Rotational vibration may be a significant source of subjective discomfort. The sensitivity to rotational vibration is highest at low frequencies. The distance between the centre of rotation and the subject influences the severity of vibration. Rotation about a point a certain distance away from the subject (more than 1 m.), causes translational vibration at the seat. In this case, measurement of the translational vibration in one direction indicates the severity of the rectilinear and the rotational motion in that direction. Consequently, this translational vibration may become the most important source of discomfort. Note that this does not mean that rotational vibration never influences the subjective estimate of the degree of discomfort for a great distance.

2.2.3. Conclusion with respect to the axes of vibration

Measurement of vibration in only 3 axes at the seat surface as described in the standard ISO 2631 is not sufficient to determine the degree of discomfort. The possible presence of a backrest, the way in which the feet support vibrates in relation to the seat (and consequently the transmissibility of the seat) and the possible appearance of rotational vibration influence the subjective discomfort for a great deal. Therefore, measurement of vibration in these axes is necessary. So, when a backrest is present, at least the vibration in the $x_s$ direction has to be measured in addition to the 3 translational axes on the seat surface. Measurement of the vibration in the $z_f$ direction is at least necessary in addition to the 3 translational axes on the seat surface when the feet support vibrates.

Comparison of vibrations at different locations and in different axes for the evaluation of the degree of discomfort is possible by introducing an axis multiplying factor for every axis. This multiplying factor gives an indication of the importance of the location and direction of vibration with respect to the evaluation of discomfort.
For low frequencies, experiments carried out with backrest vibration or feet support vibration only, may not give appropriate information to predict the results of experiments with combined seat, backrest and feet support vibration correctly.

2.3. Frequency weighting of vibration signals

2.3.1. Introduction

Frequency weighting of the vibration signals (i.e. acceleration values) is necessary to come to an objective measure of the degree of discomfort. The weighting function depends on the human sensitivity to vibrations of different frequencies in different directions. So, frequency weighting is based mainly on equal sensation.

ISO 2631 only defines frequency weightings for the x, y, and z axis. Parsons et al. [4, 5] and Griffin [10] define weightings for 12 directions of vibration (such as the axes on the seat surface, the axes on the feet support, the axes at the backrest and the axes for rotational vibration). See appendix I for more information.

The shapes of the frequency weighting contours are scarcely or not affected by the variation in the level of vibration acceleration according to Griffin et al. [3] and Corbridge and Griffin [9]. However, many other factors influence the shapes of the frequency weighting contours. Therefore, one single frequency weighting per axis for all cases of vibration may be insufficient. For example, different activities of the subjects may have a different sensitivity to vibration and the participation of different subjects may lead to different results. The presence of additional vibration at the backrest or on the feet support may also have its effect on the shapes of the frequency weighting contours.

2.3.2. Definitions of frequency weighting

Frequency weighting of the motion can be described in two ways. It is possible to use filter equations or the asymptotic approximations to these filter equations. In the majority of studies, the asymptotic approximations are used when describing the frequency weighting. Note that the definition by filter equations is more precise, because of the unique definition of gain and phase at each frequency. See, for example, a study by Griffin [10].

In many cases, there will be no significant difference in conclusion when using either of the formulations of frequency weighting. However, when motions are not harmonic, phase shift influences the output of the filter. Differences between the two types of filter will arise, because frequency weighting by asymptotic approximation does not include a phase response. This difference between both formulations will lead to different values and therefore may result in different conclusions in relation with (dis)comfort.
2.3.3. Influences on frequency weighting contours

The sensitivity to a vibration frequency may depend on the kind of tasks of the subjects when submitted to vibration. Some activities are sensitive to a particular frequency, while other activities are sensitive to a frequency range. The effect of vibration on vision may be different from for instance the effect on hand activities.

As stated before, subject characteristics influence human response to vibration. Corbridge and Griffin [9] show that female subjects are more sensitive to high frequency vibrations than male subjects. It appears that large subjects (male and female) are less sensitive to low frequencies and more sensitive to high frequencies than small subjects in case of vertical vibration. Large subjects are also less sensitive to most frequencies of for-and-aft vibration than small subjects. Male and most female subjects seem to have a so-called seat-to-head transmissibility which is likely to reduce with increasing subject size. Correlation has been found between increased seat-to-head transmissibility and increased subjective discomfort at both low and high frequencies of vertical vibration (Griffin et al. [3]).

Another point of interest in relation with human sensitivity is the posture of the subjects. During tests the subjects were ordered to sit in an upright position. However, when vibration with high acceleration levels occurred, subjects tried to weaken the sensation of vibration by changing their postures. This may result in different responses and consequently may lead to different frequency weighting contours.

In spite of the differences in subject characteristics between groups of men and women, the 'equal comfort' contours coming from both groups correspond to one another to a reasonable degree. It seems that knowledge about the subject characteristics (such as subject size, gender or transmissibility) is not sufficient to come to a better prediction of the subjective discomfort. See for instance the study conducted by Griffin et al. [3].

The presence or absence of vibration on the feet support and at the backrest influences particularly the low-frequency contour of the vertical direction. A vibrating feet support and a backrest may both reduce the sensitivity to vibration at low frequencies. In sections 2.2.2.b. and 2.2.2.c. more information about this topic has been given.

2.3.4. Comparison of frequency weighting contours in ISO 2631 and in other studies

The contour describing the frequency weighting for horizontal vibration in ISO 2631 [7] corresponds to a high degree to the experimentally determined contour by Griffin et al. [3, 6] and Corbridge and Griffin [9]. The differences mainly occurring at low frequencies, are relatively small, so a simplified curve of the experimentally obtained contour is equal to the contour defined in ISO 2631 [7]. See figure 2.2. This frequency weighting contour gives satisfactory results according to an experiment carried out by Wikström et al. [13].

Another experiment by Wikström et al. [13] shows that application of a weighting filter for
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the \( y \), direction with a breakpoint at 4 Hz. in stead of at 2 Hz. results in higher correlations with the subjective estimate of the degree of discomfort than weighting with the filter defined in ISO 2631. This is caused by the difference in the performance of the experiments, namely the use of a different test track and of a different vehicle. In the first experiment, a terminal tractor has been driven on a track with obstacles placed at even distances, while in the second experiment a forwarder has been driven on a track in forest terrain with obstacles at irregular distances. In general, the frequency weighting with a breakpoint at 2 Hz. gives satisfactory results.

Data from studies by Griffin et al. [3, 6] and Corbridge and Griffin [9] result in another contour for vertical vibration than that proposed by ISO 2631. Comparison of the two curves (see figure 2.3.) shows that the contour defined by ISO 2631 overestimates the contribution of low-frequency vibration and underestimates the contribution of high-frequency vibration to the degree of discomfort.

A possible explanation for the greater sensitivity to vibration of somewhat higher frequencies may be the fact that female subjects took part in the studies by Griffin et al. [3, 6] and Corbridge and Griffin [9], while the results of the ISO 2631 studies are obtained with male subjects only. According to Corbridge and Griffin [9], female subjects are more sensitive to vibrations with higher frequencies. The reduction of sensitivity to low-frequency vibration seems to be caused by the presence of a backrest or a vibrating feet support.

2.3.5. Conclusion with respect to frequency weighting

In general, the frequency weighting for the lateral seat vibration in \( x \) and \( y \) direction with a breakpoint at 2 Hz. proposed by ISO 2631, Griffin et al. [3, 6] and Corbridge and Griffin [9] appears to be more appropriate for the assessment of discomfort than the frequency weighting with a breakpoint at 4 Hz.

The weighting for the vertical seat vibration, in conformity with the comprehensive study by Griffin et al. [3, 6] and Corbridge and Griffin [9] seems to be more appropriate for the assessment of the degree of discomfort than the weighting proposed by the ISO standard. This conclusion is supported by other studies ([10, 11]).

Note that several factors, such as subject activities and characteristics (size, gender, posture or transmissibility), the presence of a backrest and a vibrating feet support, may influence the suitability of a frequency weighting contour and that for other experiments another frequency weighting contour may give better results.
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\[ \text{x and y direction} \]

\[ \text{Frequency-weighting contours for the horizontal directions (on seat surface)} \]

\[ \text{z direction} \]

\[ \text{Frequency-weighting contours for the vertical direction (on seat surface)} \]
2.4. Time-dependency of vibration

2.4.1. Introduction

According to the ISO standard the subjective estimate of the degree of discomfort increases with increasing exposure time. It appears that the vibration amplitude should be lower for longer exposure times in order to preserve a similar degree of discomfort. The dependency of discomfort on duration is a function of the vibration frequency. The shape of the time-dependency contour proposed in the standard does not depend on acceleration level, frequency and direction. In this section more information is given about the effect of duration on the subjective estimate of the degree of discomfort.

2.4.2. Different studies with different results

A laboratory study of Miwa [1] showed the effect of duration on human discomfort for short duration vibration. He concluded that the vibration duration affected the estimate of the degree of discomfort of the exposed subjects. For pulsed sinusoidal "damped" and "built-up" vibration an increase in the duration leads to an increase in sensation. However, there is a limit. Beyond a critical time, the sensation ceases to increase and remains constant. For the frequency range 2 - 60 Hz. Miwa found a critical time of 2 seconds.

According to Griffin and Whitham [2], who also conducted experiments to investigate the effect of vibration duration on discomfort for single frequencies, the degree of discomfort increases with duration. During their experiments the duration of exposure to vibration did not exceed 32 seconds. Contrary to the results of Miwa, no critical time limit seems to exist. Analysis of the measurements indicates that a strong increase in the vibration levels is necessary to produce similar discomfort as duration decreases.

Experiments conducted by Kjellberg and Wikström [8] show that the subjective estimate of the degree of discomfort increases with exposure duration. For higher frequencies the critical time lies between 3 and 4 seconds, whereas for low frequencies the critical time seems not to exist. In contradiction with the results of Miwa the subjective estimate of the degree of discomfort does not cease to increase after the critical time, it still continues to increase but at a slower rate.

2.4.3. Conclusion with respect to time-dependency

The discrepancy between the results of the experiments is possibly due to the fact that the experiments have been conducted in different ways or that different things have been examined. However, all three studies indicate that at the beginning of the vibration the

\[\text{Time-dependency contour: acceleration limit for every direction as a function of exposure time and frequency.}\]
exposure duration has its effect on comfort: the subjective estimate of the degree of discomfort increases with increasing exposure duration.

Because of the different results and the somewhat vague conclusions of the experiments, further work is recommended to investigate the effect of exposure duration on the subjective estimate of the degree of discomfort.
3. OBJECTIVE MEASURES FOR THE ASSESSMENT OF COMFORT

3.1. Introduction

The majority of the studies in the field of human exposure to whole-body vibration has been conducted to assess discomfort produced by stochastic, stationary vibration. In general these methods are not applicable to shocks and to vibration containing shocks. This chapter reviews the investigations and methods concerned with the evaluation of discomfort for vibration containing occasional or repeated shocks. The purpose is to find a mathematical definition for $\phi$, being the objective measure of the degree of comfort.

Discussed are the methods that analyse the frequency weighted acceleration signals, the peak-value measures, the time-mean measures and the dose measures. These analyses have to be made for every measurement direction.

Other methods, like the impulse measures, the acceleration response measure and the displacement response measure will not be dealt with in this report because of the lack of information.

3.2. Peak-value measures

A rather simple assessment method of evaluating the effect of shocks on subjective discomfort is the peak-value measure. It is only necessary to determine the maximum positive and maximum negative weighted acceleration value of the considered vibration. Also the sum of their absolute values is calculated. These three measures are correlated with the subjective estimate of the degree of discomfort.

According to a study by Wikström et al. [13] the peak-value measures do not have very high correlations with the subjective estimate of the degree of comfort. A high correlation has been obtained with the sum of the absolute negative and positive peak-value for only one test.

A possible explanation for the somewhat lower correlations with the subjective estimate of the degree of discomfort may be the fact that the peak-value measure does not take into account the whole shock event. Discomfort appears to have a time-dependency [2, 8] as stated in section 2.4.

3.3. Time-mean measures

3.3.1. General remarks with respect to time-mean measures

A generally used objective measure for the degree of discomfort is given by the following
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formula:

$$\phi_{rm} = \left[ \frac{1}{T} \int_{0}^{T} a^p(t) \, dt \right]^{1/p}$$  \hspace{1cm} (3.1.)

where

- \(a(t)\) = frequency weighted acceleration  \([\text{m/s}^2]\)
- \(T\) = integration time  \([\text{s}]\)

\(a(t)\) is the momentary acceleration weighted with one of the frequency weighting filters, mentioned in section 2.3. \(T\) corresponds to the shock duration, i.e. the duration of the whole shock event produced by one obstacle. This implies that motions can only be compared when they are of similar duration.

The value of the exponent \(p\) may vary because of the possible dependency on the frequency, the duration, the level and the direction of the motion. However, it is more convenient to determine one useful value for the exponent \(p\) that is applicable for all kinds of motions.

The following sections deal with the most common time-mean measures, namely the root mean square (\(p = 2\)) and the root mean quad (\(p = 4\)).

### 3.3.2. Root mean square measure

Many vibration quantifying studies use the root mean square (r.m.s.) value of the vibration signal. In ISO 2631 [7] the root mean square procedure is the favoured method. The calculation of the r.m.s. value is based on the following formula:

$$\phi_{rm2} = r.m.s. = \left[ \frac{1}{T} \int_{0}^{T} a^2(t) \, dt \right]^{1/2}$$  \hspace{1cm} (3.2.)

Experiments by Griffin [10] show a high correlation between the r.m.s. value of an oscillating signal and the subjective estimate of the degree of discomfort if the oscillating signal is sinusoidal or random with frequencies in a certain frequency range. Thus, the root mean square measure seems to provide a good means of quantifying the degree of discomfort for such signals.

However, when the vibration signal contains occasional high pulses the r.m.s. value does not agree with the subjective estimate of the degree of discomfort. Comparison of motions with different duration shows that the subjective estimate of the degree of discomfort produced by pulses is higher than the expectation based on the r.m.s. value. As a result of this, motions which contain high pulses seem to produce more discomfort than motions with the same frequency and r.m.s. value but without these pulses.

The r.m.s. value should only be determined by integration throughout the period during which
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the motion is perceptible.

In general, the r.m.s. values cannot be used as an objective measure for the degree of discomfort when the crest factors of the motion are too high. As a rule (see ISO 2631), the r.m.s. procedure is not appropriate when the crest factor is greater than 6.

Considering formula 3.1., a value for $p$ in the range 2 - 4 with a tendency to the higher values in that range appears to be the outcome of some experiments conducted by Griffin and Whitham [2] and Wikström et al. [13]. Analysis with analog and digital computers is not complicated when using an exponent of 2 or 4. Therefore, $p = 4$ seems to result in the best approximation. This results in the so-called root mean quad procedure.

### 3.3.3. Root mean quad measure

For calculation of the root mean quad measure the following formula is used:

$$
\phi_{r.m.q.} = \{ \frac{1}{T} \int_0^T a^4(t) dt \}^{1/4}
$$

(3.3.)

As a result of the use of the fourth power the contribution of the peak values is much larger. Discomfort produced by motions having high crest factors (higher than about 6) and similar duration can be predicted by the r.m.q. But when motions contain only a few peaks, the degree of discomfort according to the r.m.q. procedure will possibly be overestimated.

### 3.3.4. Time-mean measures with higher exponents

According to the study by Wikström et al. [13], it is not evident that the correlation of the time-mean measure with the subjective estimate of the degree of discomfort increases with increasing exponent $p^4$. The first experiment described in the mentioned study shows that the correlation reduces with higher exponents while a second experiment shows the opposite due to a difference of test track and vehicle (see section 2.3.4.). But when analyzing a set of shocks with similar duration (4 to 5 seconds) from the second experiment, which is comparable with a set of shocks from the first experiment, the time-mean measures with the lower exponents (i.e. 2 and 4) seem to show higher correlations with subjective estimate of the degree of discomfort. However, the differences between the correlations for $p = 2$ and for $p = 4$ were mostly not significant.

### 3.3.5. Conclusion with respect to the time-mean measures

As mentioned above the time-mean measures with $p = 2$ and $p = 4$ appear to give good

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4 In the study by Wikström et al. the calculations are carried out with the exponent $p$ increasing up to a value of 10.
correlations with the subjective estimate of the degree of discomfort. In the case of high crest factor motions there is a preference for the use of the root mean quad \( p = 4 \).

The objective measures mentioned in the previous sections are averaging measures, which are not very suitable for the evaluation of shocks or transient motions. The result of an averaging measure depends on the period over which the average is determined. It appears that a cumulative measure (or dose measure) is more appropriate for the assessment of the degree of discomfort when motions contain shocks [10, 12 and 13].

3.4. Dose measures

3.4.1. General remarks with respect to dose measures

Subjoined formula\(^5\) is used for the calculation of the dose measure:

\[
\phi_d = \left[ \int_0^T a(t) dt \right]^{1/p}
\] (3.4.)

where

- \( a(t) \) = frequency weighted acceleration \([m/s^2]\)
- \( T \) = integration time \([s]\)

The integration time is equal to the duration of the complete shock event. The dose measure is able to compare motions with different duration. It is important to note the duration of the measurement period for which the dose value has been determined. If the vibration during the measurement period is representative for a longer period, it is possible to compute the dose value belonging to that longer period.

The following sections contain more detailed information about the dose measures. Most attention is paid to the Vibration Dose Value, a dose measure with \( p = 4 \).

3.4.2. Vibration Dose Value

The Vibration Dose Value is a cumulative measure defined by:

\[
\phi_{vd} = \left[ \int_0^T a^4(t) dt \right]^{1/4}
\] (3.5.)

Calculation of \( \phi_{vd} \) by integration is necessary only when the crest factor of a motion is greater than 6. In case of motions having crest factors below 6 it is possible to make use of a more

\(^5\) In some studies extracting the root of the dose value is omitted.
convenient relation based on the r.m.s. value: the Estimated Vibration Dose Value (Griffin [10]):

\[ \phi_{\text{est}} = [(1.4 \times \text{r.m.s. value})^4 \times \text{duration}]^{1/4} \]  

(3.6.)

The Estimated Vibration Dose Value is not useful when the r.m.s. value is of a motion which consists of periods with no perceptible vibration (see section 3.3.2. about r.m.s. measure).

The Vibration Dose Value turns out to be a convenient and effective measure for the degree of discomfort if the vibration frequency is in the range 0.5 - 80 Hz (Griffin [10]). The Vibration Dose Value can be applied not only in the case of occasional and repeated shocks, but also for continuous and transient vibration.

The Vibration Dose Value has to be considered separately for each axis. An Overall Vibration Dose Value can be determined by extracting the fourth root of the sum of the fourth powers of the separate Vibration Dose Values.

3.4.3. Dose measures with higher exponents

The use of dose values having higher exponents (for example 6 to 10) has also been investigated [13]. Experiments show that an increase in the exponent from 4 to 10 will lead to a decrease in the correlation between the cumulative measure and the subjective estimate of the degree of discomfort.

3.4.4. Conclusion with respect to the dose measures

The dose measure with an exponent of 2 and the Vibration Dose Value give the highest correlations with the subjective estimate of the degree of discomfort. A comparison of these two measures shows that the degree of discomfort is better predicted by the Vibration Dose Value than by the dose value with an exponent of 2. For this, see the results of the laboratory studies by Griffin and Whitham [2], Kjellberg and Wikström [8] and Howarth and Griffin [12].

This differs from the results of experiments by Wikström et al. [13], which show no apparent difference between the dose measures with \( p = 2 \) respectively \( p = 4 \). This may be the result of the different ways in which the experiments have been performed. The experiments by Wikström et al. have been conducted on test tracks, so the subjects were able to see the irregularities on the track and could prepare themselves for the coming shocks, while the subjects in the laboratory [8, 10] could not predict the occurrence of the shocks. Because of this, the response of the subjects to shocks will differ.
3.5. Discussion and conclusion with respect to the objective measures

According to the mentioned studies [10, 12 and 13] the cumulative measure (i.e. the dose measure) gives a better indication of the degree of discomfort than the peak-value measures and the time-mean measures. This result supports the idea that a measure considering the whole shock event is more appropriate to assess the degree of discomfort than a measure dependent on the peak value or a measure that averages. The cumulative measure makes it also possible to compare motions of different durations.

When applying a time-mean value with a fixed integration time, this will give a similar result as a dose value with corresponding exponent. In this case, it is necessary to define the integration time as long as the duration of the shock event. Note that comparison of motions of different durations is not possible then. The study conducted by Wikström et al. [13] shows that the correlation between the time-mean measure and the subjective estimate of the degree of discomfort decreases with shorter integration times.

Note that the time-mean values and the dose values are objective measures of the severity of motions. Small values will indicate a sense of discomfort and annoyance, while high values will indicate a higher degree of discomfort. A high degree of discomfort gives an indication that pain or even injury may occur. But there is no exact relation between the magnitude of the values and the risk of injury. One of the reasons is that the influence of vibration on subjective discomfort is dependent on many aspects, such as activities, health, etc. These aspects can not be captured in one simple relation.

Because of the fact that the Vibration Dose Value is the "best" objective measure for the assessment of discomfort according to most of the studies, this measure will be mostly used in the following chapter.
4. SUBJECTIVE REACTION AND OBJECTIVE ASSESSMENT

4.1. Relation between subjective estimate and objective measure

Experiments have been conducted by Howarth and Griffin [12] to obtain a simple relation between the subjective estimate of the degree of discomfort, $\Psi$, and the objective measure $\Phi_{\text{d4}}$, the Vibration Dose Value. The method of magnitude estimation is employed to come to the subjective estimate of the degree of discomfort (see section 2.1.). In this case, the stimuli used by the experimenters are the responses of a single-degree-of-freedom spring-mass-damper system to a unit displacement step input. The following function has been determined which applies for all analysed frequencies, damping ratios and directions of motion:

$$\Psi = k(\Phi_{\text{d4}})^n$$  \hspace{1cm} (4.1.)

where

- $\Psi$ = subjective estimate of the degree of discomfort
- $k$ = a constant (depending on the used unit)
- $\Phi_{\text{d4}}$ = Vibration Dose Value (i.e. objective measure)

The exponent $n$ is an important variable because it determines the rate of change of increase in the subjective measure $\Psi$ with increasing objective measure $\Phi_{\text{d4}}$. If $n = 1$ for each frequency, duration and direction, the Vibration Dose Value is a good objective measure for the evaluation of human discomfort. Note that in these experiments by Howarth and Griffin, the duration of motion and damping ratio of the system are closely connected with each other.

4.2. Applicability of the Vibration Dose Value

Howarth and Griffin [12] suggest that frequency, duration and direction of vibration do not influence the value of the exponent $n$. In figure 4.1. and in figure 4.2 the regression lines (log-log co-ordinates) of some of the experiments [12] are shown. The exponent of the function remains constant at different frequencies, damping ratios and directions of motion when the amplitude of vibration is increased. For almost all conditions $n \approx 1$. Therefore, the frequency weightings used for the assessment of shocks do not depend on the vibration amplitude. As a result of this, it is possible to make use of a single frequency weighting when assessing the degree of discomfort.

If a regression line is obtained with $n$ greater than 1, the Vibration Dose Value would not be a good objective measure for the evaluation of human discomfort. Then, it would be possible to correct the regression line ($n \rightarrow 1$) if the frequency weighting is dependent on the vibration amplitude.
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Upward motion, frequency:
1 Hz. = cont., 4 Hz. = dash.
16 Hz. = dot.

Fig. 4.1. Regression of the subjective estimate of the degree of discomfort $\psi$ on the Vibration Dose Value $\Phi_d$ (upward motion, variable damping ratio $\xi$ and variable frequency)
The increase in the subjective estimate of the degree of discomfort with duration of motion does not depend on the vibration amplitude. Therefore, a single method considering the effect of duration is satisfactory.

Statistical analysis has been conducted on the results of experiments [12] to obtain information about the effect of frequency, duration (damping ratio) and direction of motion on the subjective estimate of the degree of discomfort for constant Vibration Dose Values. From this, it appears that the eigenfrequency of the spring-mass-damper has a significant effect on the subjective estimate of the degree of discomfort, \( \psi \), for constant Vibration Dose Values. See the first three graphs of figure 4.1.

At low frequencies the estimated magnitude of the degree of discomfort, \( \psi \), appears to be greater than at higher frequencies for constant Vibration Dose Values. One of the causes may be the fact that subjects sense greater displacements at low frequencies than at high frequencies. These results indicate an underestimation of the subjective sensitivity to low-frequency shocks by the applied frequency weighting for vertical vibration (proposed by Griffin et al. [3, 6] and Corbridge and Griffin [9]).

The duration of the motion also has its effect on the subjective estimate of the degree of discomfort, \( \psi \). However, according to the last three graphs of figure 4.1., the effect caused by the duration of the motion seems to be less than the effect caused by frequency. For
constant Vibration Dose Values, the subjective estimate of the degree of discomfort increases with decreasing damping ratio. Note that this is not entirely true for the frequency of 16 Hz. in the last graph of figure 4.1. The values of the subjective estimate of the degree of discomfort show that the effect of changing the damping ratio is greater at low frequencies (about 1 Hz.). The Vibration Dose Value seems to underestimate the influence of shock duration on the degree of discomfort for low frequencies, but this is not very evident.

The effect of the direction of motion on the degree of discomfort seems to be of little or no significance, as shown in figure 4.2. Analysis also indicates that the interactions between the frequency, duration and direction of motion are not significant.

### 4.3. Motions containing repeated shocks

In the previous section the Vibration Dose Value has been used for the assessment of the degree of discomfort on single shocks. The number of shocks also contributes to the degree of discomfort. In this section the relation between the subjective estimate of the degree of discomfort of motions containing repeated shocks and the Vibration Dose Values will be investigated.

The study by Howarth and Griffin [12] compared the Vibration Dose Value measure:

$$\phi_{dv} = \left[ \int_0^T a^4(t) \, dt \right]^{1/4}$$

(4.2)

with a cumulative measure, which contains a square:

$$\phi_{d2} = \left[ \int_0^T a^2(t) \, dt \right]^{1/2}$$

(4.3)

1, 2, 4, 8 or 16 shocks (occurring at regular intervals) have been added to a background motion. Laboratory experiments have been conducted in such a way that the number of shocks increases every time while the shock magnitude is adjusted to obtain the same objective degree of discomfort for all motions. Motions with a constant objective degree of discomfort are determined on the basis of $\phi_{dv}$ and on the basis of $\phi_{d2}$.

Hereafter, a scale value for the subjective relative discomfort, which is linearly correlated with the subjective estimate of the degree of discomfort, has been calculated\(^6\) for the considered motions. In figure 4.3, the subjective relative discomfort as a function of the number of shocks is shown. The motions with constant $\phi_{dv}$ are represented by the upper curve while the motions with constant $\phi_{d2}$ are represented by the lower curve.

---

\(^6\) See the study by Howarth and Griffin [12] for the extensive calculation procedure.
The upper curve shows that for a constant Vibration Dose Value the subjective estimate of the degree of discomfort first slightly decreases and next slightly increases with an increasing number of shocks. However, the subjective estimate of the degree of discomfort decreases more with increasing number of shocks for a dose value involving an exponent of 2 according to the lower curve. Conclusion: the Vibration Dose Value procedure is a more accurate method (compared with the dose value having an exponent of 2) of predicting the required adjustment of the shock magnitude to obtain a similar subjective degree of discomfort for motions with a different number of shocks.

![Graph showing relative discomfort as a function of the number of shocks]

**Fig. 4.3.** Relative subjective discomfort as a function of the number of shocks

### 4.4. Conclusion with respect to subjective reaction and objective assessment

The experiments with single shocks show that frequency, duration and direction of motion do not influence the increase of the subjective estimate of the degree of discomfort with increasing shock magnitude. Thus, a single frequency weighting per direction and a single method considering the effect of duration is sufficient to assess discomfort. For constant Vibration Dose Values, it is shown that the direction of motion does not influence the subjective estimate of the degree of discomfort. Frequency has a significant effect on the subjective estimate of the degree of discomfort for constant Vibration Dose Values. For low-frequency shocks, the applied frequency weighting underestimates sensitivity to shocks to a small extent. For constant Vibration Dose Values the subjective estimate of the degree of discomfort increases with decreasing damping ratio. The Vibration Dose Values may underestimate the effect of shock duration on the subjective estimate of the degree of discomfort.
When a number of shocks occur in a motion, the Vibration Dose Value seems to give a good prediction of subjective estimate of the degree of discomfort (compared with a dose value involving an exponent of 2). The experimenters investigated the case where a prediction of the adjustment of the shock magnitude is required to obtain a similar degree of discomfort for motions with a different number of shocks.
5. SUMMARY OF CONCLUSIONS

Reconsideration of ISO 2631 seems to be necessary to come to a suitable method for the evaluation of whole-body vibration with respect to comfort. Because of the lack of information in the standard about shocks, information about this topic is given in this report.

Because of the influence on comfort of a backrest, of the vibration of the feet support (or transmissibility of the seat) and of rotational vibration, the measurement of vibration at the seat surface in only 3 axes is certainly not sufficient. In order to get a clear picture of the directions in which the most severe vibration occurs, it is necessary to use 12 axes of measurement: 3 translational axes on the seat surface (x, y, z), 3 translational axes at the backrest (x_b, y_b, z_b), 3 translational axes on the feet support (x_f, y_f, z_f) and 3 additional axes for the assessment of rotational vibration on the seat surface (r_x, r_y, r_z). In general, the most important directions for road vehicles are the 3 axes on the seat surface, the for-and-aft vibration at the backrest and the vertical vibration at the feet support. An axis multiplying factor makes it possible to compare vibration at different locations and in different directions.

The frequency weighting contour for the lateral seat vibration (in x and y direction) proposed in ISO 2631 [4], by Griffin et al. [3, 6] and Corbridge and Griffin [9] seems to give acceptable results in most of the cases. The frequency weighting for the vertical seat vibration, proposed by Griffin et al. [3, 6] and by Corbridge and Griffin [9], appears to be more convenient for the assessment of the degree of discomfort than the weighting proposed by the ISO standard. However, the sensitivity to low-frequency shocks may be underestimated by the frequency weighting (proposed by Griffin et al.) in some cases. Subject characteristics (size, gender and transmissibility) and the way in which tests are performed (sort of apparatus, etc.) may have their influence on the fitness of a frequency weighting contour.

The effect of exposure duration on the subjective estimate of the degree of discomfort is not very apparent. Only at the beginning of the vibration the subjective sensation increases with exposure duration. Further examination shows a discrepancy between the results of several experiments which were conducted in different ways.

When shocks occur, the subjective estimate of the degree of discomfort is best predicted by the Vibration Dose Value. This measure considers the whole shock event and therefore seems to be more appropriate for the assessment of the degree of discomfort than, for instance, the peak-value measure or time-mean measure. A cumulative measure makes it also possible to compare motions of different durations. A similar result may be obtained when using a time-mean value (r.m.q. measure) with a fixed integration time as long as the shock event. The objective measures, such as the time-mean measures and the dose measures, can not give a definite answer on the safety or risk of injury. They can only give an indication.

The increase of the subjective estimate of the degree of discomfort with increasing shock...
magnitude is not influenced by the frequency, duration and direction of motion (for single shocks). For the assessment of discomfort only a single frequency weighting per direction and a single method with respect to the effect of exposure duration is needed.

Frequency and the duration of motion have a significant effect on the subjective estimate of the degree of discomfort for constant Vibration Dose Values. Underestimation of the subjective sensitivity to low-frequency shocks by the applied frequency weighting may be possible. The subjective estimate of the degree of discomfort increases with decreasing damping ratio for constant Vibration Dose Values. The Vibration Dose Values may underestimate the effect of shock duration. The Vibration Dose Value predicts the degree of discomfort in the case of repeated shocks better than a dose value with an exponent of 2.
I. REFERENCES


II. FREQUENCY WEIGHTINGS AND AXIS MULTIPLYING FACTORS

Application of frequency weightings and axis multiplying factors for the evaluation of vibration with respect to comfort according to a study by Griffin [10].

Frequency weightings for seat surface, backrest and feet support:

Location: seat surface

Fig. B.1. Frequency weightings for seat surface
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**Location: backrest**

- x axis
- - - y, z axis

![Graph](image)

**Fig. B.2.** Frequency weightings for backrest

**Location: feet support**

- x, y, z axis

![Graph](image)

**Fig. B.3.** Frequency weightings for feet support

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Axis multiplying factors:

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<th>Multiplying factor:</th>
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Table B.1. Axis multiplying factors