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VEHICLE RIDE COMFORT ASSESSMENT METHODS

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ABSTRACT - Vibration of motor vehicles can produce wide variety of different sensations in different parts of the driver's human body. A large range of expressions as well comfort, discomfort, intensity, etc. can be used to obtain information on subject preferences. It is of primary importance to distinguish between the sensation of discomfort and the interference with driving activities. Context of judgments should be made clear so that subjects whether they should judge the motion as they are experienced or as they might be experienced in different place or alter a different length of time.

It seems preferable to ask subjects to judge the sensations they actually experience, to phrase the question so as to emphasize the subjective sensations and to a void words that may relate solely to activity disturbance or physical magnitude of the stimulus. There are many different methods of relating judgments along a psychological dimension to the physical characteristics of stimulus. Scaling methods may be used to determine the extent to which discomfort changes when physical magnitude of stimulus is altered.

These are other methods are also used to determine the subjective response to changes in vibration frequency and axis.

INTRODUCTION

The importance of improving vehicles dynamic properties is constantly growing in vehicle development. Various areas like ride comfort, active safety and driver environment are dependent on enhanced dynamic behavior. An essential tool in this process is the ability to quantify and upgrade these properties.

The complex connection between ratings expressed by test drivers and explicit design parameters makes improvement work difficult. Since test drivers change their acceptance level over time, lack of repeatability in subjective testing is a problem. A long time goal is therefore to develop objective measures for driving impressions.

COMMON RIDE EVALUATION METHODS

Many different strategies on how objective methods can be evaluated together with subjective ratings are established. Subjective ratings can be collected in several different ways and various rating scales may lead to a very wide spread of ratings. Many problems are connected to evaluations where humans are used as measuring instruments. Humans' sensitivity and calibration values are relatively unknown and vary between individuals and over time. One additional difficulty is the ability to judge one thing at a time without being influenced by other properties.

The most important factor of objective evaluation methods is that they correlate well with how most test drivers perceive the vehicle. Objective measures therefore consist of two important building blocks: subjective information from test drivers and measured vehicle properties. Correctly performed rating tests are essential when building meaningful models that generate objective evaluations.

Subjective Ratings

Today the most common method to evaluate vehicle ride and handling qualities is by subjective rating tests. When subjective rating tests are performed it is important that the methods are carefully constructed. Different rating form designs can result in more or less useful results. In order to either check or construct an objective measure, data from subjective evaluations are needed.

When subjective rating tests are utilized in vehicle development as decision material for changes affecting dynamic properties, there are a number of issues that must be considered:
-*Many issues not directly coupled to the ride or handling influence the test drivers, such as, tiredness and mood.*
-*Preconceived opinions among test drivers.*
- *Changes in test drivers' acceptance levels over time.*
-*Differences between individuals in vocabulary used for rating.*
-*Property changes smaller than driver perception.*
Even if these types of problems always exist in subjective ratings, a good rating scale may decrease their effect.

Design of Rating Scales

A common way to collect subjective ratings is through a number of statements that are given relative a predefined scale. This scale could either have a description of what the scale values correspond to or be anchored to a reference vehicle.
A rating test that separates driver's assessment of a dynamic property from the opinion of whether it is an improvement or not, is formed in (15). The idea is that the scale should not inflict opinion values to objective questions nor demand objective answers to opinion questions, since this will confuse test drivers. It is often possible to get more exact and repeatable answers if a reference vehicle is used. The choice of reference is of great importance, since it influences how accurate ratings test drivers are able to give.

Interpretation of Ratings

Since test-drivers have different opinions, sensitivity ability and interpretation of questions, the rating data is preferably processed and changing of dynamic properties will reveal these differences.
Correlation analysis, performed in (15), between each test driver's answer to each question and performed parameter change made it possible to determine if the answer is systematically dependent on parameter changes or not. Random answers could possibly appear due to a number of issues.

Objective Measures

Efforts have been made to create objective ride comfort measures (1,2,12,15). Ride quality is commonly estimated through measurements with accelerometers positioned to measure driver exposed vibrations.

Humans will cope with vibrations from certain frequencies better than others, which make frequency spectra interesting to study. Results from (2) show that it is hard to distinguish the small differences that test drivers perceive.

The main advantages with objective evaluations are:

-*Objectivity.*

-*Repeatability.*

-*Problem identification: Characterization of driving impression problems.*

-*Market positioning: Objective comparison between competitors.*

-*Scalability: Driving impression scales for comparison.*

When an objective measure is developed the following points should be taken into consideration.

Demands on objective measures:

- *Agreement with subjective ratings.*
- *Reproducibility i.e. the measurements should not depend on the actual driver.*

Desirable qualities of objective measures:

- *No need for a special test track.*

-*No complex testing procedures with demands like constant velocity.*

-*Indication of which alterations that will lead to improvement.*

The most important factor of objective evaluation methods is that they should correlate well with how most test drivers perceive the vehicle. All objective methods that use some evaluation formula based on subjective data are dependent on correctly performed rating tests. A weak link from subjective ratings to objective measures could be the regarding subjective rating scales must be thoroughly considered. Large differences in vehicle configurations will probably lead to a distinct connection between subjective and objective evaluations. Tests performed on actual vehicles instead of driving simulators tend to have weaker connections. This may be due to the fact that it is easier to accomplish large and evident property differences in driving simulators. Property differences in vehicle development are however often small and require sensitive measures. In many cases subjective evaluations have to be used to conclude which vehicle that is the most comfortable, since available measures are not sensitive enough.

Most ride comfort measures in this literature survey have problems with the link between objective measures and subjective ratings. In many cases problems with subjective rating evaluations occur and in other cases the objective measures are based on parameters that do not reflect the driving impressions. Due to the lack of accurate and reliable objective measures, ride comfort is today mostly subjectively evaluated with test drivers.

Efforts to measure discomfort by using ISO weighting curves together with PSDs have been quite successful (7). As long as big differences in the RMS values can be shown and the accelerations are quite stationary, the subjective ratings seem to correlate well with the objective measures. However, as ride comfort in heavy vehicles is constantly improving, there is a growing need for more sensitive objective methods to evaluate ride. One additional problem is that transients seem to have a large effect on the ride quality and the averaging in these kinds of measures, decreases the sensitivity to transients, (16).

BIODYNAMIC RESPONSES OF HUMAN BODY

Biodynamic responses of human body in different position have been widely measured under whole-body vibration. The measures are most often expressed in terms of force motion relations at the driving-point, mechanical impedance, apparent mass and absorbed power, and flow of vibration through the body, such as seat-to-head and body segments vibration transmissibility. The measured biodynamic responses have been used to identify mechanical-equivalent properties of the exposed human body and critical frequency ranges associated with resonances of different body segments (14) to understand the potential injury mechanisms and for deriving frequency-weightings for exposure assessments, and to help developing and validating continuum and discrete distributed-parameter models. These biodynamic models can be further used to help quantify and understand the distributed joint forces, tissue stresses, and strains that may be directly related to the vibration-induced injury and disorder mechanisms, to help design better seats and anti-vibration systems, and to construct anthropodynamic manikins for assessing vibration isolation performance of suspension seats, as an attractive alternative to the use of human subjects in the standardized seat assessment method.

The effectiveness of biodynamic models and the manikins strongly relies on representative biodynamic responses of the body. The need to identify the range of biodynamic response of the human body to vibration was identified over 2 decades ago. The ISO-5982 and ISO-7962 standards have proposed driving-point mechanical impedance (DPMI) and seat-to-head transmissibility (STHT) magnitude and phase characteristics of the human body based on the averaging of various data sets reported by different investigators. The synthesis included datasets generated under vastly different conditions, such as standing and sitting postures with feet supported and hanging. These standards did not differentiate between the two postures, which are known to yield considerably different biodynamic responses (14)14,16). The proposed values were thus found to deviate considerably from the datasets reported under conditions considered applicable in many exposure situations, such as vehicle driving.

The applicability of biodynamic mechanical-equivalent models and anthropodynamic manikins seem to have met limited success thus far. While some of the studies on seats with biodynamic models and manikins have shown good agreements with the data acquired from the seat-human system under particular conditions and body mass, others have identified substantial limitations of the current models and manikin designs. Only limited efforts have been made to assess the performance of models and manikins under ranges of representative conditions.
The study concluded that the manikins provided an overestimate of isolation effectiveness of seats, when compared to those with human subjects, while the SEAT values of the low natural frequency (<2Hz) seats coupled with manikins were comparable with those of the seats loaded with equivalent rigid mass. Considerable differences between the results predicted from vertical human-seat models and laboratory-measured data have also been shown. These differences in part may be attributed to: (i) limited applicability of biodynamic model and thus the manikin in the vicinity of the experimental conditions associated with the target response used for identifying the model, namely, the body mass, sitting posture, magnitude of vibration; (ii) assumption of linear response of the seated body; (iii) lack of consideration of contributions of the body coupling with elastic seats, since the measurements have been invariably performed with rigid seats, although a recent study has reported the driving-point responses of body seated on a soft seat.

The initial efforts made in defining the idealized ranges need to be enhanced for broadening their applicability for standing subjects, different vibration directions, and sitting with back support. Considerable exposure to vertical vibration of subjects in many situations have been documented, (1,5,6,12-14). A large number of work vehicles transmit significant magnitudes of fore-aft and lateral vibration, which are either comparable or exceed those in the vertical direction. A few recent studies have explored means of controlling horizontal vibration by considering biodynamic models of the body, since exposure to large magnitudes of horizontal vibration could cause greater shear forces in the lumbar spine. Moreover, the biodynamic responses of the seated body are greatly influenced by the back support condition. The vertical biodynamic responses of the body seated against vertical and inclined back supports have been reported in a few studies, which could be applied to define the ranges under back supported sitting conditions, (2,3).

In (14) the ranges of biodynamic responses under different postures and vibration directions are defined on the basis of syntheses of available data. In particular, the reported data are synthesized to define ranges of (1) apparent mass and seat-to-head vibration transmissibility of seated human body exposed to vertical vibration with and without a back support; (2) apparent mass characteristics of seated body exposed to fore-aft and lateral vibration; and (3) apparent mass characteristics of standing human body exposed to vertical whole-body vibration. The experimental conditions associated with the reported data sets are carefully examined and selection criteria are defined so as to select datasets considered applicable under conditions considered representative of the work situations.

A synthesis of the reviewed data was performed and limits encompassing the mean values of the selected data were constructed to define the ranges of fore-aft, lateral and vertical apparent mass, and vertical seat-to-head transmissibility responses of the body seated with feet supported and exposed to vibration excitation levels from 0.5 to 1.0 m/s^2 rms and from 1.0 to 1.75 m/s^2 rms, respectively. The limits of apparent mass responses of standing body exposed to vertical vibration are also proposed on the basis of the synthesis of the available data. The proposed AM ranges are considered applicable for body seated with and without a back support, and exposed to vibration up to 1 m/s^2 rms. Owing to considerable effects of the back support on the biodynamic responses, particularly under fore-aft and vertical vibration, different ranges of AM responses are defined for both back unsupported and back supported conditions. The identified ranges for the vertical AM and STHT responses differ considerably from the standardized ranges in both the primary resonance frequency and the magnitudes in most of the frequency range. The considerably lower primary frequency of the standardized ranges is most likely caused by consideration of data attained under high excitation magnitudes, up to 5 m/s^2 rms, (2-4,13)
Random excitations are more used in biodynamics analysis of human body transfer functions than sine excitations. Mean magnitude values are more used than median values, (14).

The conclusion that subjects were `more sensitive' to random vibration than to sinusoidal vibration came in contradiction with earlier conceptions that the discomfort caused by a vibration could be predicted from the rms: value. This shows the need for an alternative measure of magnitude which would be suitable for consistently evaluating various types of motion stimuli, including sinusoidal, random, or transient vibration. It is reasonable to assume that subjects or passengers exposed to vibration for 1 minute would feel more uncomfortable than if they were exposed to the same magnitude of vibration for only a few seconds. This suggests that the discomfort caused by vibration does not only depend on the magnitude, but also on the duration of exposure, (3,15).

To conclude, it seems that for long durations of exposures (5 to 30 minutes), the frequency weightings depend on the duration, but for exposures of 30 seconds or less, the effect of duration on frequency weightings is less clear, (16).

The average response to vibration is similar for males and females. The responses of women showed much more variability than the responses of males. This suggests that using male subjects would provide similar average results as female subjects, but may induce less variability in the data.

INVESTIGATIONS OF MULTI-AXIAL VIBRATION

Several studies were designed to investigate the discomfort experienced by seated people exposed to dual-axis vibration, (1,4,6,11,16). Griffin and Whitham (6) investigated the discomfort caused by simultaneous vertical and lateral 3.15-Hz sinusoidal vibration. The method of magnitude production was used, where subjects were asked to adjust the magnitude of a dual-axis test motion until it caused discomfort similar to that of a single-axis (vertical or lateral) reference motion. The discomfort caused by the stimuli was measured by their \`vertical equivalent acceleration' or \`lateral equivalent acceleration', i.e. the magnitude of single-axis vibration (respectively, vertical or lateral) that causes an equivalent discomfort.

The objective was to compare methods for predicting the equivalent magnitude of a dual-axis motion, from the equivalent magnitudes of the single-axis components. Several summation methods were compared, based on the models used for the evaluation of multi-frequency motions. In (3) a similar method based on magnitude production to compare the equivalent magnitude of dual-axis (x+z) vibration with the equivalent magnitudes of its components was used. One of the components of the dual-axis motion was in the same direction as the reference, and it was observed that this seemed to bias the responses as subjects gave more importance to that component. Reference motion, vertical, was in the orthogonal direction, so that no component of the test motion was in the same direction as the reference. The authors only concluded that a summation was occurring, as the equivalent magnitude of the dual-axis motions was greater than the equivalent magnitudes of its components. This suggested the need for a summation method. Partial results are given in Figure 1.

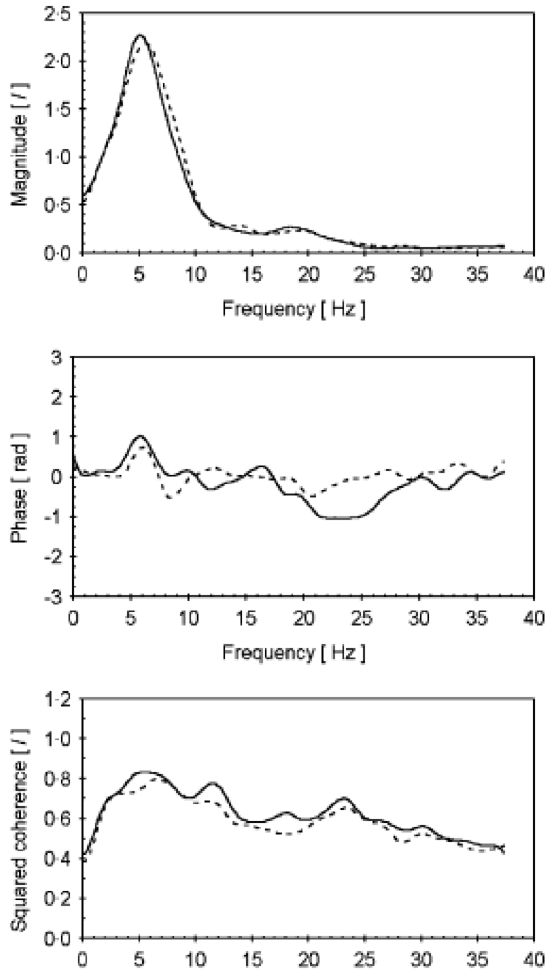

Figure 1 The influence of seat-backrest angle on averaged STHT in the fore and aft direction under two directional random vibrations.———backward inclined sitting position, -------- upright sitting position.

A very low correlation was found between the predicted Vibration Total Value (VTV) and the reported discomfort of multi-axis motions. It was concluded that the method recommended in the standards for multi-axis vibration is not adequate and needs revising. The experimental design did not allow to determine whether the discrepancies between predictions and measurements were due to wrong axis weightings, k, or to the root-sum-of-square summation method not being appropriate, (16).

In (6) determined a method for predicting the discomfort of dual-axis vibration (x + z) was designed to establish a relation between the subjective magnitude (i.e., the discomfort) of the dual-axis motion and the subjective magnitude of its components. The difference between subjective magnitude (discomfort) and equivalent magnitude (acceleration) lies in Stevens' power law (1,16) which predicts that the subjective magnitude depends on the physical magnitude according to a power law. If the exponent in this power law is different from 1.0, the subjective and equivalent magnitudes are not linearly related.
The optimal exponent was found to be around 2, with no significant difference as the vibration frequency varied from 2.5 Hz to 10 Hz. The linear sum method was found to overestimate, and the `worst component' to underestimate, dual-axis discomfort.

It appears that vibration is an important cause of discomfort for passengers in public transport, as it affects the passengers' opinion about the travel experience and their future choice of a transport mode. It is therefore important for transport operators to take vibration discomfort into account.

Current International and national standards include methods for predicting vibration discomfort, but it seems they are not always satisfactory, and their applicability to standing people is uncertain. Indeed, they were based on knowledge of vibration discomfort of seated people. Since it has been shown that, in particular, the frequency-dependence of vibration discomfort depends on the posture (seated or standing), methods advocated in the standards may not be appropriate for standing people.
Equivalent comfort contours showing the effect of the frequency of vibration on the vibration discomfort of standing people have been constructed in several studies, generally with vertical vibration and at frequencies greater than about 3 Hz. The effect of the frequency of horizontal vibration and the lower-frequencies of vertical vibration is less well known.
The effect of other characteristics of vibration on the discomfort of seated people have been investigated, in particular the effect of magnitude, duration, body supports, and direction; but their effect on the discomfort of standing people is unknown, and may be different, in particular because different mechanisms are involved when seated people and standing people are exposed to vibration. In particular, postural stability is expected to be an important cause of discomfort for standing people, but not for seated people.

PREDICTION OF DISCOMFORT

Discomfort cannot be predicted by simple physical parameters such as acceleration, and can not always be predicted from the biodynamic response of the body. So, because of the subjective nature of discomfort, investigation must be conducted with subjective methods, where subjects describe the sensations they experience when they are exposed to vibration stimuli. A variety of methods can be used for this purpose.

So, this literature review has identified areas where further research is required. For predicting the discomfort caused by vertical vibration, it is necessary to understand the relations between the characteristics of vibration and the discomfort experienced by standing people.

In particular, subjective experiments are needed to determine the effect of frequency on the discomfort of standing people exposed to horizontal and low-frequency (<3 Hz) vertical vibration, and the magnitude-dependence of this frequency effect. Additionally, the effects of postural supports and of the direction, waveform and duration of vibration on discomfort of standing people are unknown and may not be extrapolated from knowledge of the discomfort of seated people. Therefore, these factors need to be investigated in experimental studies. Experimental studies should be designed so that they bring answers to these questions, but also provide a better understanding of the mechanisms of vibration discomfort of standing people, so that the result can be interpreted in appropriate ways.

The rate of growth of sensation, the shapes of equivalent comfort contours and the causes of discomfort are similar for fore-and-aft and lateral vibration. For both axes, the frequency weightings correspond to constant velocity at lower frequencies (where loss of balance is a cause of discomfort) and constant acceleration at higher frequencies (where loss of balance is not a cause of discomfort), with a transition at about 3.15 Hz. This is not consistent with the weighting advocated in current standards that was based on studies with seated subjects.

The equivalent comfort contours for vertical vibration are consistent with the weighting advocated in standards except at frequencies less than 1.6 Hz. Subjects were particularly sensitive to vibration at frequencies in the range 4 to 16 Hz, with greatest sensitivity to low magnitude acceleration around 6.3 Hz, possibly due to a resonance of the body. Comparisons with the weightings advocated in the standards suggest that the responses of standing and seated people are similar when exposed to vertical vibration, except at lower frequencies where vibration was probably perceived through the vestibular system. The responses of standing and seated people were different when exposed to horizontal vibration,(5), (16). Partial results are given in Figure 2.

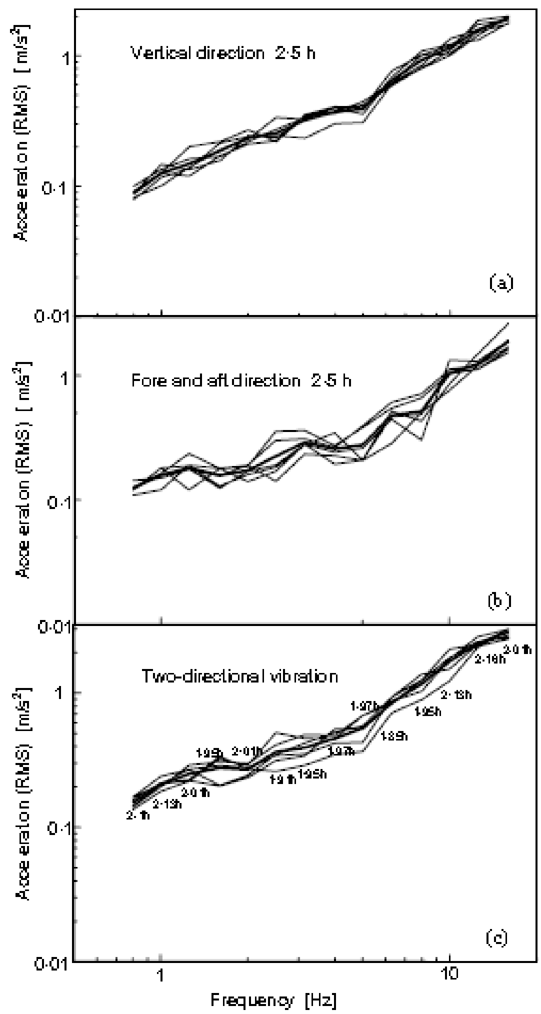

Figure 2 Partial and averaged equivalent comfort curves in the vertical direction under (a) vertical, (b) fore and aft and (c) two-directional narrowband random vibration for 2.5 h of exposure.

For all three axes of excitation, different mechanisms are responsible for discomfort caused by low frequency and high frequency vibration (i.e. less than or greater than 3 or 4 Hz). From the experimental results, frequency weightings that can be used for evaluating vibration so as to predict the discomfort of standing people exposed to fore-and-aft, lateral, or vertical vibration have been constructed.

CONCLUSION

Based on literature survey and performed experimental research following conclusions can be established:

The analysis of the results allowed the construction of a model showing the mechanisms of ride comfort assessment that can be used to estimate the discomfort experienced by sitting human exposed to simultaneous fore-and-aft and vertical vibration.

When exposed to low-frequency vibration, human experienced more discomfort in low frequency region.
In following research investigation of lateral vibration in combination with vertical should be performed in order to define new method.

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