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SOME ASPECTS OF THE INVESTIGATION OF RANDOM VIBRATION INFLUENCE ON RIDE COMFORT

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Contemporary vehicles must satisfy high ride comfort criteria. This paper attempts to develop criteria for ride comfort improvement. The highest loading levels have been found to be in the vertical direction and the lowest in lateral direction in passenger cars and trucks. These results have formed the basis for further laboratory and field investigations. An investigation of the human body behaviour under random vibrations is reported in this paper. The research included two phases; biodynamic research and ride comfort investigation. A group of 30 subjects was tested. The influence of broadband random vibrations on the human body was examined through the seat-to-head transmissibility function (STHT). Initially, vertical and fore and aft vibrations were considered. Multi-directional vibration was also investigated. In the biodynamic research, subjects were exposed to 0·55, 1·75 and 2·25 m/s^2 r.m.s. vibration levels in the 0·5–40 Hz frequency domain. The influence of sitting position on human body behaviour under two axial vibrations was also examined. Data analysis showed that the human body behaviour under two-directional random vibrations could not be approximated by superposition of one-directional random vibrations. Non-linearity of the seated human body in the vertical and fore and aft directions was observed. Seat–backrest angle also influenced STHT. In the second phase of experimental research, a new method for the assessment of the influence of narrowband random vibration on the human body was formulated and tested. It included determination of equivalent comfort curves in the vertical and fore and aft directions under one- and two-directional narrowband random vibrations. Equivalent comfort curves for durations of 2·5, 4 and 8 h were determined.

1. INTRODUCTION

A large number of people are exposed to whole-body vibration (WBV) in their occupational life, specially the drivers and passengers of various vehicles, such as trucks, cars, trains and buses. The main categories of human responses to WBV are perception, degraded comfort, and interference with activities, impaired health and occurrence of motion sickness. Based on information presented in references [1, 2], it can be concluded that human response to WBV is a complex phenomenon. During exposure to WBV many different psychological, psychophysical and physical factors, such as individual susceptibility, body characteristics and posture together with the frequency, direction, magnitude and duration of vibration are relevant in development of unwanted effects. The effect of many factors, such as

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non-linearities, sex, race, complex behaviour of human body etc., have led to the development of analytical and experimental research methods [1]. The state of the art in this research area will be reviewed in the following section.

2. LITERATURE REVIEW

Understanding of vibration transmission to and through the human body can provide an important input to our understanding of human response to WBV. The biodynamic human response to WBV can be characterized using four biodynamic response functions. The driving point mechanical impedance (DPMI), apparent mass (APMS) and transfer mechanical impedance (TMI) are biodynamic functions often used to describe "to the body" biodynamic functions. The seat-to-head transmissibility function (STHT) describes the vibration transmitted through the body [1–3]. The TMI function is a complex relation between force and velocity at different points, although it is not the best solution if the human body is exposed to multi-input excitation; the DPMI is more suitable [4]. More authors have used DPMI rather than STHT to characterize human body behaviour. For example, Boilean *et al.* [5] reported that 14 papers considered DPMI, seven of which considered random vibration and another seven considered sinusoidal vertical vibrations. Only five articles considered APMS (including magnitude and phase) nine of which considered DPMI. Data sets from eight previously published papers considered STHT (magnitude and phase), whilst only one studied random vibrations. The others concerned sinusoidal excitation. Few papers considered multi-directional vibration [6, 7].

Relationships between different measures of "to the body" biodynamic response functions and relationships between "to" and "through" the body biodynamic functions are investigated based on both experimental data and analysis of some of the reported seated body models. Analysis based on APMS and STHT showed excellent agreement with primary resonant frequencies derived from eigenvalue analysis of the model [3].

The literature reviewed [1, 3, 4, 8] has shown that most papers considered linear one-dimensional models with a few masses. If the lumped parameter model used elasto-damping elements, they were linear irrespective of the non-linear biodynamic response function. The number of degrees of freedom ranged from one to five [2, 4, 6]. Most papers considered only one-dimensional linear models with excitation in the vertical direction. Models of the apparent mass of the seated human body exposed to horizontal vibration were developed in reference [6], which show that the human body seems to respond as a three-mass system.

Demić [9] used a non-linear human model for parameter identification with DPMI.

The number of papers considering STHT is small in comparison with the number of papers considering DPMI. In this paper, the investigation of human body response to broadband random vibration was performed using STHT and these investigations were focused on multi-directional excitation.

Experimental methods that consider human body behaviour under random vibration can be both objective and subjective. Objective methods consider and evaluate change in blood pressure, fluid levels in the human body, etc. [10], which are medical methods [11].

Subjective methods are based on subjective assessments of human exposed to vibration, [10, 12, 13]. For this purpose, equal comfort curves are usually in use.

The influence of harmonic vibration on humans was investigated in many studies. The time dependencies given in ISO 2631-1(1985) [14], are based on research performed under harmonic vibration. In the experiments performed by Simić [10, 12, 13], subjects had to adjust the level of input vibration in order to be able to endure 10 min, 1 or 2 h under defined levels of excitation.

In reference [1], subjects were exposed to harmonic vibration and they had to evaluate discomfort in five points of defined semantic scale, in every 30 min. In the second part of the experiment, basic vibration was stopped on every 15 min and subjects had to adjust the level equal to the previous accumulated reaction.

A small number of papers considered the influence of random vibration on human comfort. Griffin [1] compared discomfort caused by sinusoidal and random vibrations in one-third octave bands. Sinusoidal and random vibrations stimulate similar discomfort at the same frequency. Random vibration was less discomfortable.

Corbridge and Griffin [15] used the method of floating standards and the method of constant sensations to obtain equal comfort curves in the frequency range 0·5–5 Hz. Excitations were sinusoidal and random in the fore and aft and vertical directions. According to reference [15] human body mass was more sensitive to random than to sinusoidal vibration in the vertical and fore and aft directions.

Shoenberger's [16] investigations showed similar results to those presented in reference [15].

Demić in references [19–23] investigated the influence of quasi-random vibration and repeated shocks on human body, by analysis of the walking process.

The influence of complex sinusoidal vibration in the vertical and fore and aft directions on human body in sitting position was investigated in reference [12]. A subjective method of "equal perception level" was used. It proved that, in the frequency range from 0·6–3 Hz, fore and aft accelerations were dominant. In frequencies from 3 to 7 Hz subjects were most sensitive to vertical vibration and, in the region above 7 Hz, the dominant vibration loading was caused by angular vibration.

Shoenberger [16] showed that phase angle had no influence on vibration evaluation under complex vibration in the frequency range 3–8 Hz.

Fairley and Griffin [22] performed two experiments combining fore and aft and vertical vibrations in the frequency range from 2 to 10 Hz. They concluded that the root sum of squares (RSS) method is better than "the worst component" method.

The greatest number of papers [10, 11, 14, 15–18, 21–26] considered only the influence of vertical vibration on human comfort. A few papers considered the influence of fore and aft vibration on human ride comfort. Also, many papers considered sinusoidal excitations but only a few of them considered the influence of random, quasi random vibration or repeated shocks on human body [19].

Apart from a few attempts to evaluate the influence of complex vibration on the human body [7, 8, 11], papers considering the influence of multi-directional vibration (vertical and fore and aft, vertical and rotational, etc.) are rare [7, 12, 19–21, 27].

3. EXPERIMENTAL METHOD

An electrohydraulic motion simulator was used in the subjective experiment. The simulator was designed to provide the test bandwidth from 0·5 to 40 Hz with a total loading weight of 200 kg and to simultaneously obtain vertical and horizontal random excitation. The investigators had to define the frequency bandwidth and the magnitude of excitation.

Thirty subjects, 43·9 ± 9·7 years old, 180·1 ± 6·6 cm tall, a weight of 85·9 ± 14·1 kg, and in good health, were tested. They were exposed to both narrowband and broadband random excitation.

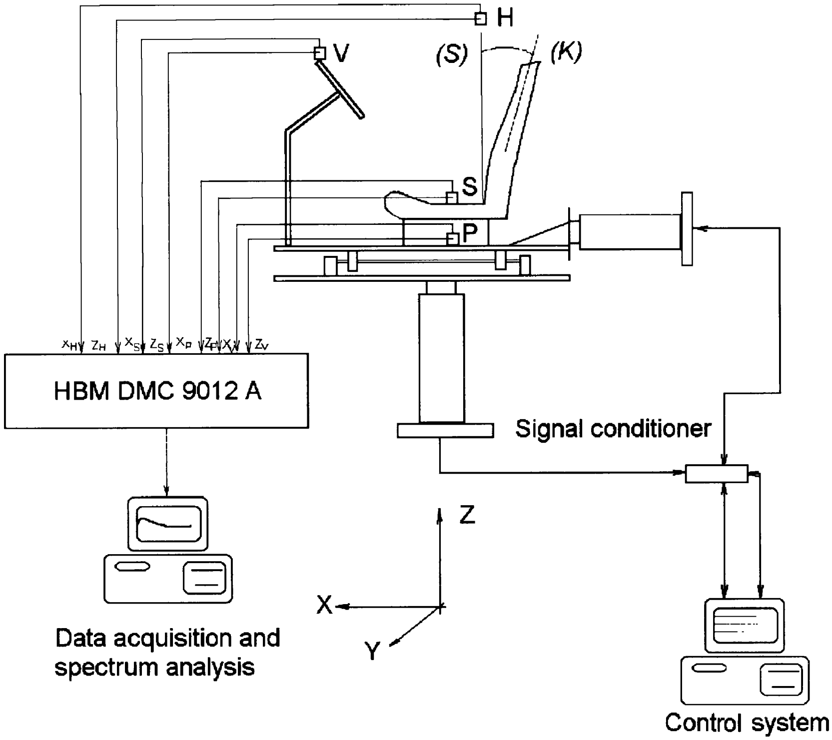

Figure 1. Measuring points.

The first laboratory experiment was carried out to determine STHT (a complex ratio between complex head acceleration and complex seat acceleration, including magnitude of response function, phase function and coherency, and in the sitting position under broadband random vibration in (1) only the vertical direction, (2) only in the fore and aft direction and (3) in both directions simultaneously. Spectral analysis was performed in the broadband frequency domain and in the second experiment one-third octave band frequency analysis was performed. The STHT functions were calculated using the cross-spectral density [28] at a frequency resolution of 0·037 Hz. Test conditions (magnitude of excitation and seat backrest angle) were varied.

In the first experiment, data from accelerometers HBM B12/200 mounted on the seat (S), head (H), platform (P) and steering wheel (W) (Figure 1) were recorded via an amplifier HBM DMC 9012A and BEAM 3.1 acquisition data software and stored in a data file. Each recording lasted 27·3 s and the number of data points was 2048. Spectral analysis was performed in the frequency domain of 0·037–37·5 Hz.

In the second experiment accelerations were measured on the seat–buttock interface. One-third octave band frequency analysis was performed. Experimental equipment enabled spectral analysis in the frequency domain of 0·63–16 Hz. The equal comfort curves in the vertical and fore and aft directions were determined under only vertical, only fore and aft, and fore and aft and vertical narrowband random excitation.

3.1 INFLUENCE OF RANDOM VIBRATION ON BIODYNAMIC HUMAN BEHAVIOUR

In the laboratory experiment, subjects were exposed to broadband random excitation in only vertical, only fore and aft and in both directions simultaneously. Subjects were sitting

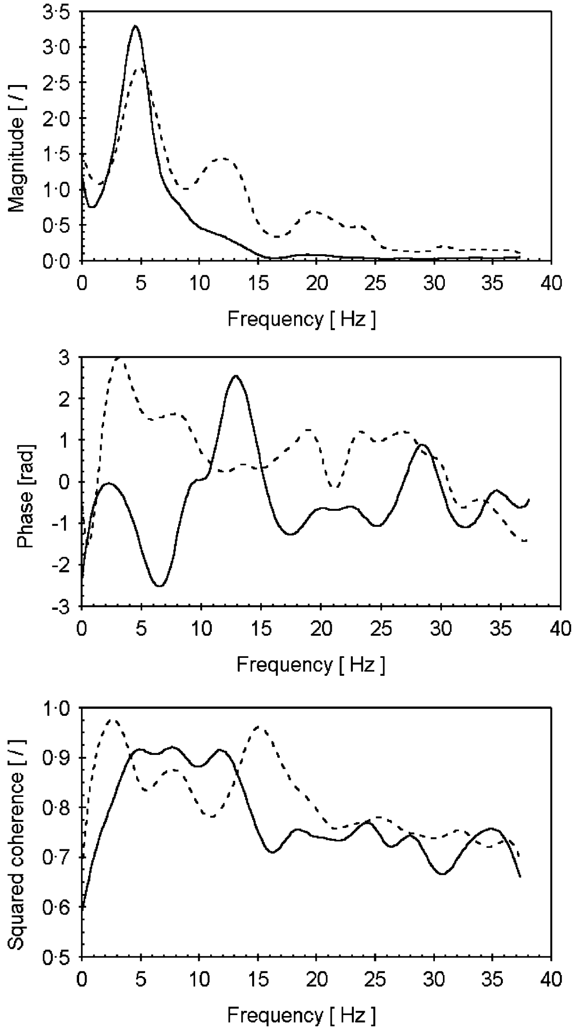

Figure 2. Transfer function of platform–seat system loaded with a sandbag of 40 kg weight under two-directional random excitation. ‐ ‐ ‐ ‐, *X*; ——, *Z*.

on a soft seat. The seat characteristic, the transfer function of platform–seat system, was obtained with the seat loaded with a sandbag of total mass of 40 kg [29]. The seat was excited by one-directional random vibration in the vertical and fore and aft directions and by two-directional random vibrations. The seat characteristics (at the seat–buttock interface) under two-directional broadband random excitation are given in Figure 2. Prime resonance in the fore and aft and vertical directions are near to 5 Hz. In the fore and aft direction there are three resonant frequencies (approximately 5, 12 and 20 Hz).

Subjects tested were sitting in a driving position with their hands on the steering wheel. Seat backrest angle was varied: position of backrest (K) with inclination angle of 14° with respect to vertical axis and position (S) with inclination angle of 0° (Figure 1). The excitation magnitude was also varied (0·55, 1·75 and 2·25 m/s^2 r.m.s.). The frequency range of excitation was 0·5–40 Hz. Thirty trained subjects participated in the experiment with one-directional excitation and seven trained subjects were involved in the experiment with two-directional excitation.

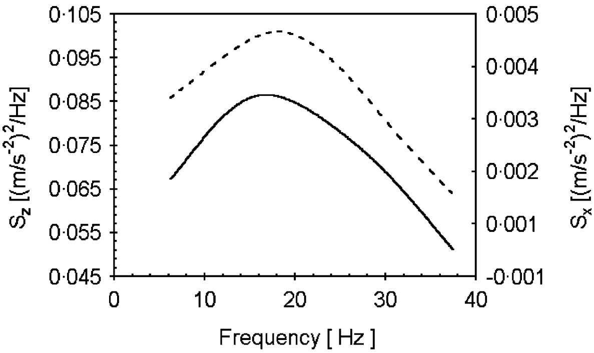

Figure 3. The characteristics of head–helmet system. ——, *X*; ----, *Z*.

In order to determine STHT function, accelerations were measured at the seat–buttock interface and on the head. Transducers were mounted on a plastic helmet. The characteristics of head–helmet system are given in Figure 3. In the figure, the resonance of the head–helmet system is 16 Hz. The determined resonance frequency was important for further data analysis. Experimental results will be analyzed in detail, especially in the frequency range of head–helmet resonance.

STHT functions in the fore and aft direction for seven subjects exposed to two-directional broadband excitation are given in Figure 4. This number of subjects was not correct for statistical analysis but it was adopted because results showed little scatter. The largest scatter of results occurred at the resonant frequencies. According to Figure 4, STHT functions had two or three resonant frequencies depending on characteristics of the subjects. The first resonant frequency (near to 5 Hz) corresponds to the whole body resonance [1, 2]. The second resonance (near to 14 Hz) corresponds to upper body resonance [1, 2], and if the third exists it corresponds to foot resonance (20 Hz) [12].

Figure 5 displays functions in the vertical direction for seven subjects exposed to two directional broadband excitation. STHT functions have two or three resonancies depending on the subject's characteristics. The first resonance (near to 5 Hz) corresponds to the whole body resonance [1, 2] and the second resonance (near to 14 Hz) corresponds to upper body resonance [1, 2], and if the third exists, it corresponds to foot resonance (20 Hz) [1, 2]. The spread of the results was caused by intersubject variability [1].

The influence of excitation magnitude on averaged STHT function for two-directional broadband random excitation are shown in Figures 6 and 7. Figure 6 shows the STHT function in the fore and aft direction increases in magnitude with respect to the increase of the excitation magnitude in frequency range below 8 Hz. A decrease in magnitude was observed in the frequency range of 8–18 Hz with respect to excitation level. At resonant frequencies the increase in excitation level caused the increase in STHT magnitude. The phase of STHT was also changed.

Figure 7 shows that the increase in excitation magnitude caused the increase in STHT magnitude in vertical direction in the low-frequency region, below the first resonance. At the second resonance, the differences between STHT magnitudes were the greatest. The increase of excitation level caused the decrease of STHT magnitude at the second resonant frequency.

From Figures 6 and 7 we can conclude that averaging of STHT curves caused the loss of the third resonant frequency. The change of excitation level caused changes of STHT magnitude, phase and coherency. It can be concluded that the platform–seat–human

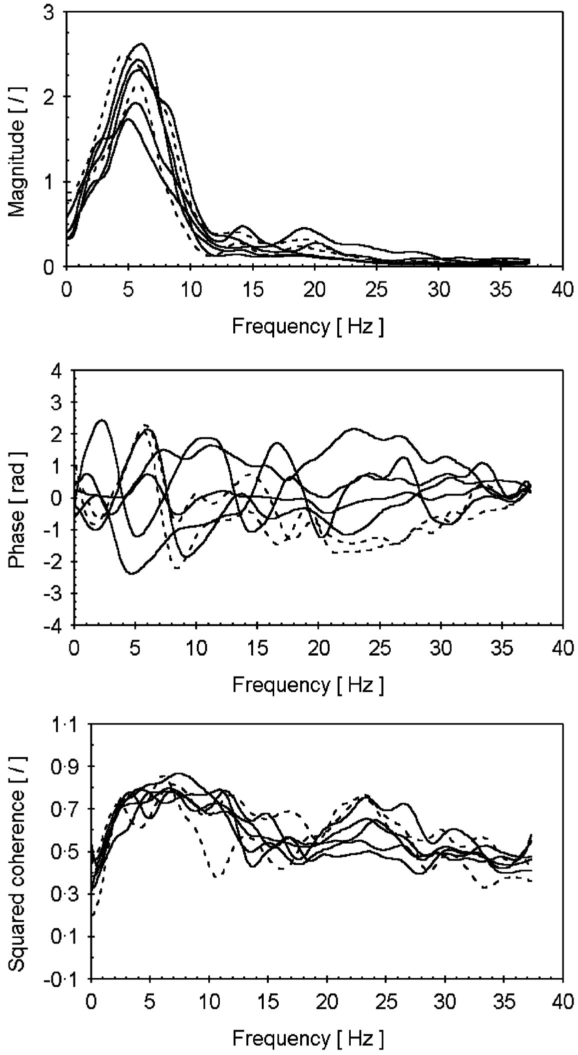

Figure 4. STHT in the fore and aft direction under two-directional random vibration for seven subjects.

system is non-linear in the vertical and fore and aft directions. The linear system has $\pi/2$ rad phase at resonant frequency [1, 2, 30]. In this case, it is obvious that the system is non-linear with respect to the previous statement. The increase in excitation level caused the change in position of resonant frequencies; they became lower.

The influence of the subject's sitting position on human response was investigated by changing the seat–backrest angle. Results obtained are shown in Figure 8 (for fore and aft direction) and in Figure 9 (for vertical direction). According to Figure 8, the increase in seat-backrest angle caused the change in the resonant frequencies.

Similar conclusions can be drawn from Figure 9. The increase of seat–backrest angle caused the increase in STHT magnitude, phase and coherency. In this case of vertical direction excitation, the changes in seat–backrest angle were minor with respect to STHT magnitude at the first resonance but considerable at the second resonance. STHT phase and coherency are related to the increase with respect to increase in seat–backrest angle.

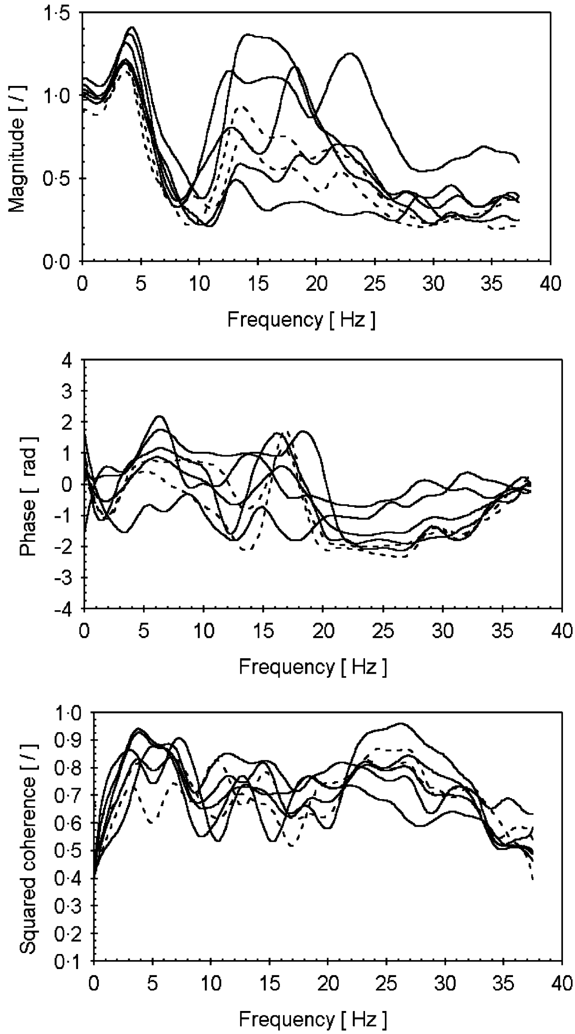

Figure 5. STHT in the vertical direction under two-directional random vibration for seven subjects.

According to Figures 4–9, it is clear that head–helmet resonance did not appear in experimental results and that the results are reliable.

Biodynamic human behaviour can be described by biodynamic functions other than STHT (APMS, DPMI). Similar observations can be seen in published papers, that have considered DPMI. For example, in reference [31], DPMI has two resonances in the vertical directions, which are different for males and females. Resonant ranges [1–3, 22] correspond to resonant ranges obtained and described in the experiment. Normalized DPMI in the fore and aft direction has one resonant peak. Excitation was one-directional, and sinusoidal [32]. Results were compared for one-directional excitation. Results of the apparent mass investigation published in reference [1] showed good agreement with the results presented in this paper with respect to resonant frequencies. Human body behaviour under multi-directional random excitations described by STHT was compared with results in reference [8].

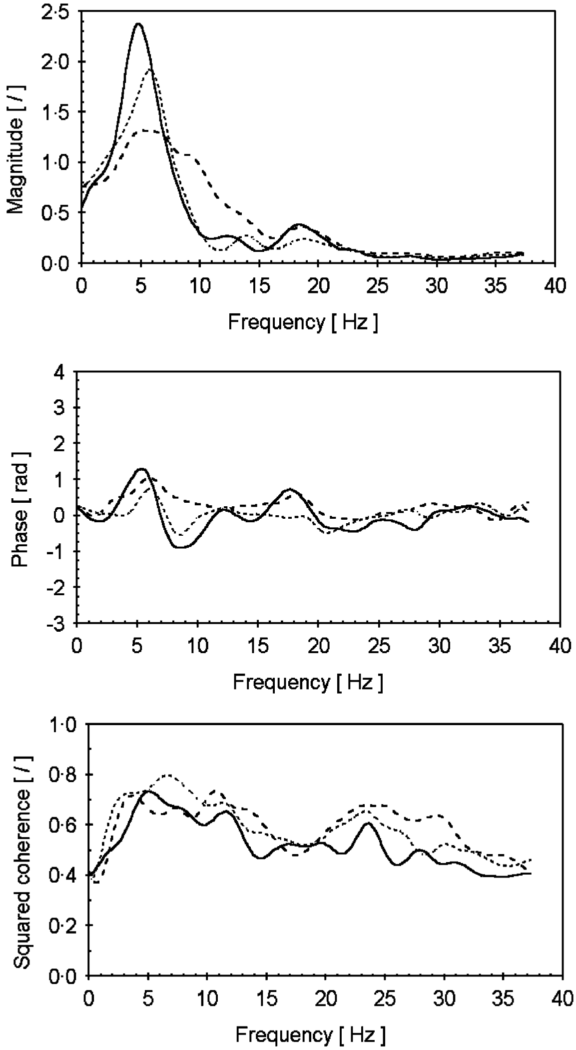

Figure 6. The influence of excitation magnitude on averaged STHT in the fore and aft direction under two-directional random vibrations. -----, 0·55 m/s^2 r.m.s.; – – – – –, 1·75 m/s^2 r.m.s.; ——, 2·25 m/s^2 r.m.s.

Experiments were conducted in order to use obtained results for development of an appropriate biodynamic human model, which can be used in the evaluation and improvement of the vehicle ride comfort.

In reference [4], a model of the human body in a sitting position was recommended for STHT consideration. This model was unnecessarily complex. A model was developed in reference [6] based on experimental research on STHT and DPMI functions. Simulation results coincided less with STHT than with DPMI. Different models were developed and identified based on experimental results of DPMI and APMS in references [1–2, 6–8]. All models were single axis models which can be used for one-directional excitation. Experimental results showed that the sitting position and the excitation level influenced subjective behaviour according to the STHT function. Also, the exploitation regimes cannot be simulated in a proper way with single axis models.

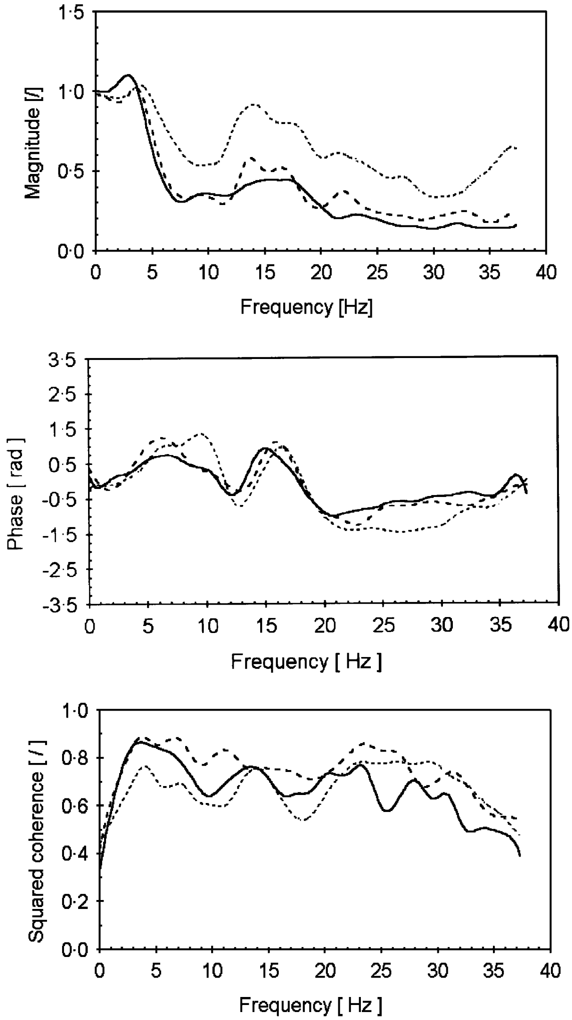

Figure 7. The influence of excitation magnitude on averaged STHT in the vertical direction under two-directional random vibrations. -----, 0·55 m/s^2 r.m.s.; – – – – –, 1·75 m/s^2 r.m.s.; ——, 2·25 m/s^2 r.m.s.

The relationship between excitation directions (one-directional and two-directional), was considered by using the model shown in Figure 10. The excitation used was broadband random, in the frequency domain of 0·5–40 Hz, with excitation magnitude of 0·55, 1·75 and 2·25 m/s^2 r.m.s. the model given in Figure 10 was developed to perform a coherent analysis of obtained results. According to Figure 10, input head acceleration signals were:

- $X_1 = X_{gz}$—for head fore and aft direction under vertical vibration,
- $X_2 = Z_{gz}$—for head vertical direction under vertical vibration,
- $X_3 = X_{gx}$—for head fore and aft direction under fore and aft vibration and
- $X_4 = Z_{gx}$—for head vertical direction under fore and aft vibration.

Output head acceleration signals were:

- $Y_1 = X_{gp}$—for head fore and aft direction under multi-directional vibration and
- $Y_2 = Z_{gp}$—for head vertical direction under multi-directional vibration.

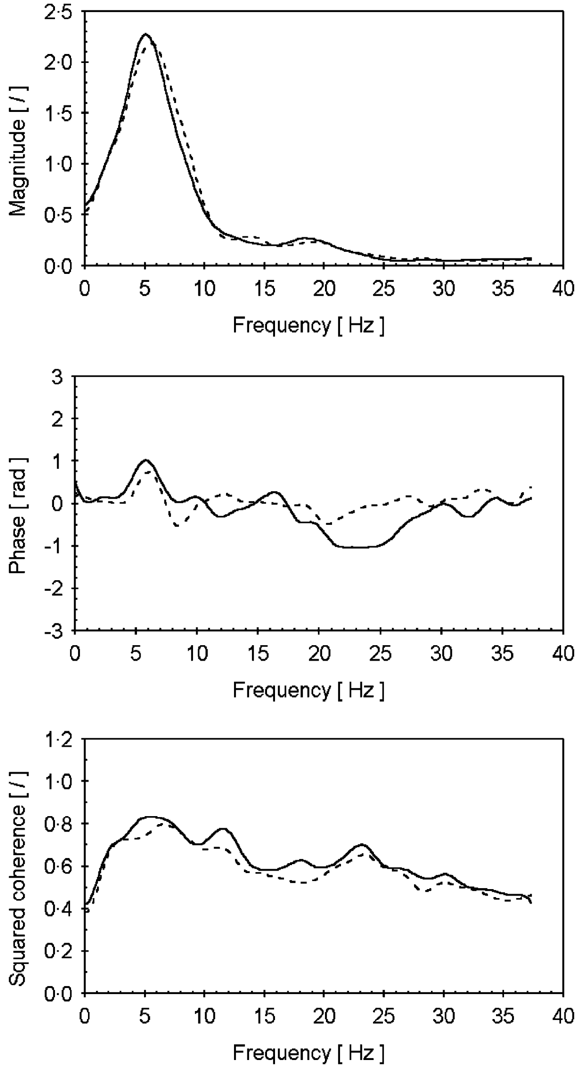

Figure 8. The influence of seat–backrest angle on averaged STHT in the fore and aft direction under two-directional random vibrations. ——, K; ----, S.

Input signals X_i $(i = 1, 2, \ldots, 4)$ were mutually correlated, but not totally (Table 1). Correlation between output signals also existed, but not with the total signal. Correlation between head accelerations in both directions under two-directional excitations and signals obtained under one-directional excitations exists and cannot be neglected. A conditional spectral analysis was performed according to references [28, 33]. Partial coherence functions between input signals X_i $(i = 1, \ldots, 4)$ and output signals, Y_i $(i = 1, 2)$ were determined according to reference [28] and one given in Figure 11. The highest level of partial coherence function is achieved between output signals Y_1 and Y_2, caused by the physical relationship. Both signals were recorded at the same measuring point. Peaks of coherence are at the resonant frequencies. The lowest level of partial coherence function is between signals X_2 and Y_2, which corresponds to the vertical direction with vertical excitation and vertical direction with multi-directional random vibration. A multiple

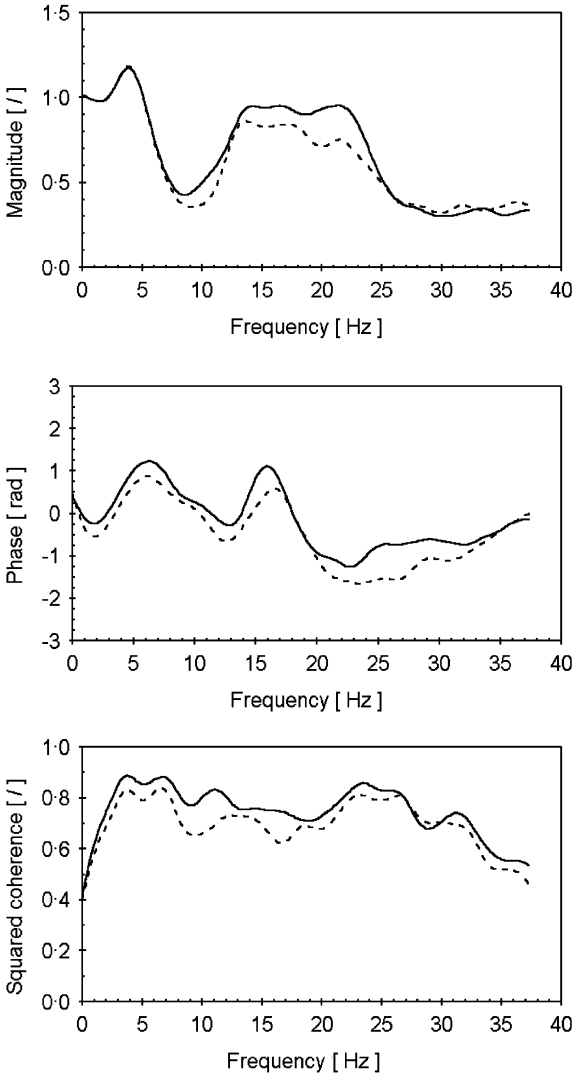

Figure 9. The influence of seat backrest angle on averaged STHT in the vertical direction under two-directional random vibrations. ——, K; - - - -, S.

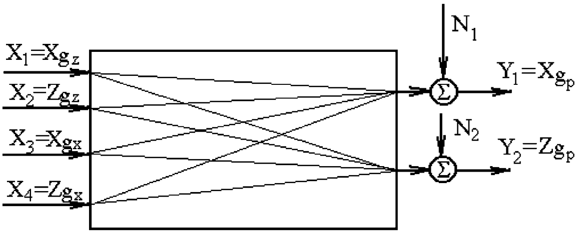

Figure 10. Model of experiment.

coherence function between output signals Y_1 and Y_2 with linear effects of input signals X_i removed, is given in Figure 12. According to the high level of partial coherence function when the linear effects of inputs X_i were removed, it can be concluded that human

TABLE 1

Correlation coefficients and statistical significance of measured accelerations ($p = 0{\cdot}005\%$, *Kendal Tau*)

	X_1	X_2	X_3	X_4	Y_1	Y_2
X_1	1	0·000	0·86772	0·0871	0·0028	0·0006
X_2	– 0·50326	1	0·0005	0·5288	0·0545	0·0012
X_3	0·00213	– 0·09578	1	0·0000	0·0288	0·0005
X_4	– 0·02184	– 0·008056	– 0·27680	1	0·0000	0·000
Y_1	– 0·03861	0·05455	0·02812	– 0·10775	1	0·000
Y_2	– 0·66708	0·04244	0·07526	– 0·11304	0·361914	1

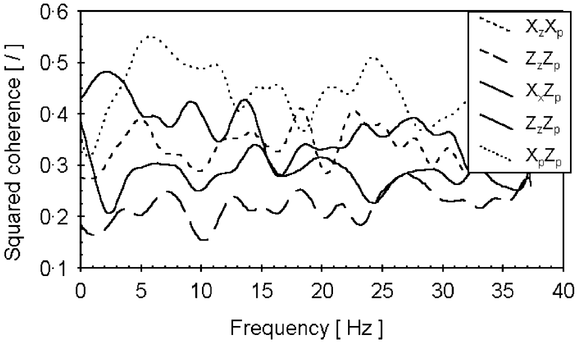

Figure 11. Partial coherence.

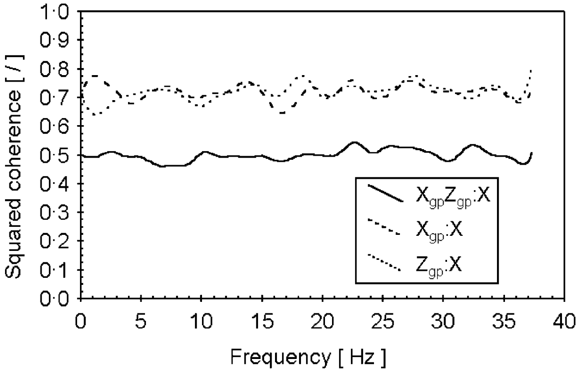

Figure 12. Multiple coherence.

behaviour under multi-directional broadband excitation cannot be simulated by simple superposition of behaviour under one-directional vibration.

3.2. THE INFLUENCE OF RANDOM VIBRATION ON RIDE COMFORT

Laboratory experiments have been performed based on the results of experimental research of dominant vibration loading in vehicles, published in reference [34]. The

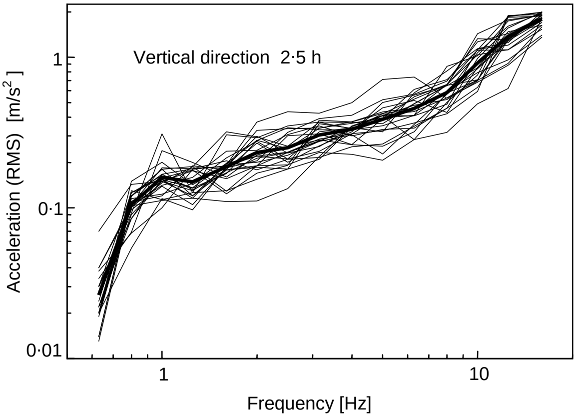

Figure 13. Partial and averaged equivalent comfort curves in the vertical direction for 2·5 h of exposure under vertical narrowband random vibration.

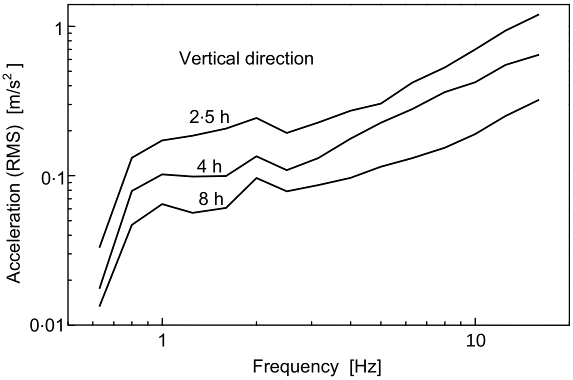

Figure 14. Averaged equivalent comfort curves in the vertical direction for 2·5, 4 and 8 h of exposure under vertical narrowband random vibration.

research on the influence of random vibration on human comfort was conducted on the simulation described previously. Trained subjects were exposed to vertical, fore and aft and multi-directional (vertical and fore and aft) narrowband random vibrations.

The investigation was conducted in order to provide equal comfort curves. A subjective assessment method was devised. Time histories of acceleration signals were analyzed and r.m.s. values were determined for each one-third octave band central frequency. The data obtained for each one-third octave band were used to determine partial and averaged equal comfort curves. Each subject was exposed to random vibration in one-third octave frequency bands. The method included subjective assessment of "comfortable ride" by adjusting the level of the exciting signal. In the literature reviewed, a unique recommendation for time exposure to the excitation was not found (for example, 10 and 41 s in reference [15] and 60 s in reference [25]). The exposure time to random excitation in the experiment was 75 s. Subjects had to estimate the vibration level equal to the subjective sensation of "feeling comfortable" for 2·5, 4 and 8 h of exposure. They were exposed to one-directional narrowband random vibration initially. The partial and averaged equivalent comfort curves in the vertical direction for exposure of 2·5 h, are given in Figure 13.

Averaged equal comfort curves in the vertical direction under vertical random vibrations for 2·5, 4 and 8 h are given in Figure 14.

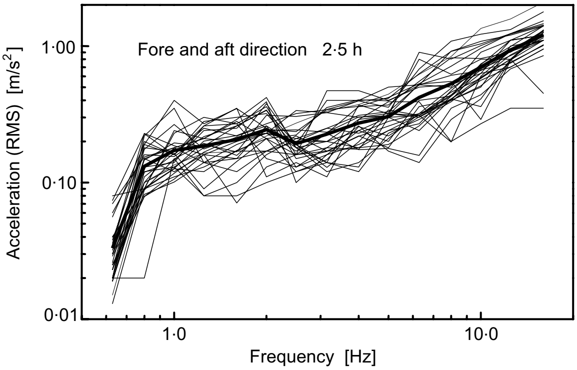

Figure 15. Partial and averaged equivalent comfort curves in the fore and aft direction for 2·5 h of exposure under fore and aft narrowband random vibration.

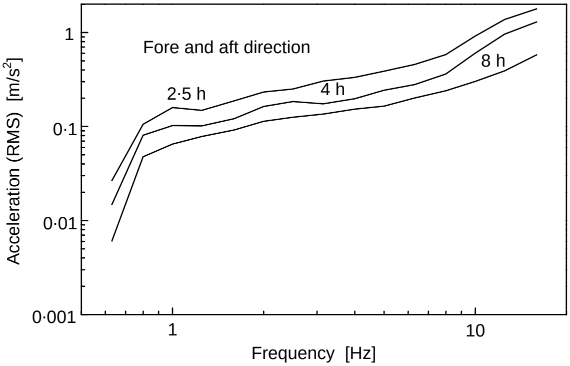

Figure 16. Averaged equivalent comfort curves in the fore and aft direction for 2·5, 4 and 8 h of exposure under fore and aft narrowband random vibration.

According to Figures 13 and 14 it is obvious that subjects are very sensitive to low-frequency random vibration (below 1 Hz). Psychological aspects (as in references [17–21]) based upon the walking process can explain this phenomenon.

The partial curves shown in Figure 13 show that subjects are less sensitive to narrowband random vibration in the frequency region 1·25–5 Hz. At frequencies above 5 Hz they are the least sensitive to vertical random vibration (Figure 14).

In the same way, subjects were exposed to narrowband random vibration in fore and aft direction. Partial and averaged equal comfort curves in the fore and aft direction for 2·5 h time exposure are shown in Figure 15.

Averaged comfort curves in the fore and aft direction under fore and aft random vibrations for 2·5, 4 and 8 h are given in Figure 16.

By analysis of the data given Figures 15 and 16, it can be concluded that humans are very sensitive to random vibration in fore and aft direction below 0·8 Hz. This can be explained psychologically [10, 17–21]. Humans are less sensitive to fore and aft random vibration in the frequency range from 1 to 5 Hz where the prime resonant frequency is located. The lowest human sensitivity to fore and aft random vibration is detected in the frequency range above 5 Hz.

Six previously trained subjects were exposed for 75 s to multi-directional narrowband random vibration. The subjects were then asked to adjust the level of one-directional

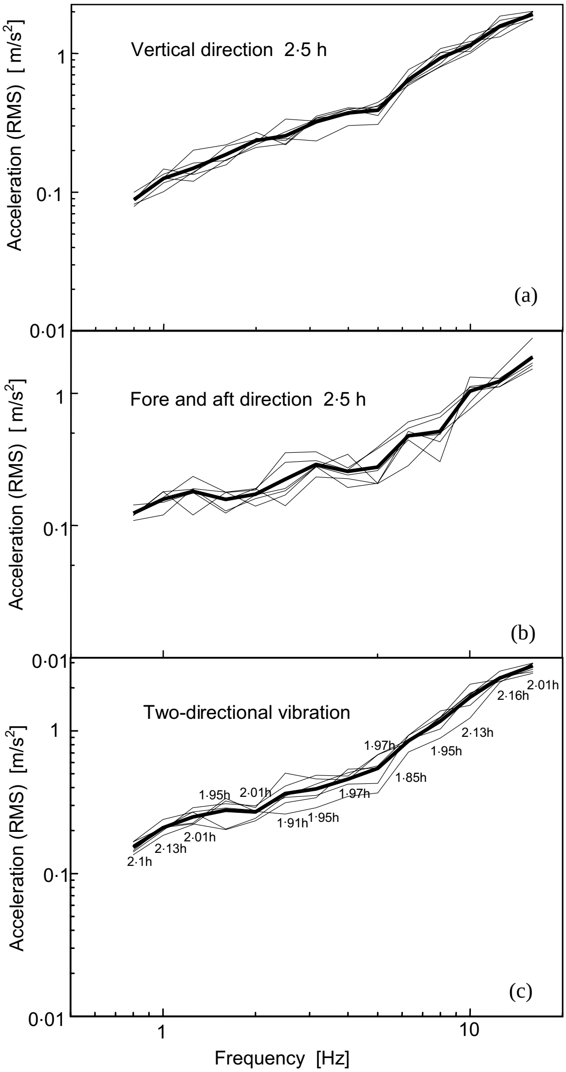

Figure 17. Partial and averaged equivalent comfort curves in the vertical direction under (a) vertical, (b) fore and aft and (c) two-directional narrowband random vibration for 2·5 h of exposure.

vibration so that it is equal to “feeling comfortable” for the duration of 2·5 h of exposure. It was performed for vertical and fore and aft directions (Figures 17 (a, b)).

The subjects initially adjusted the level of vertical excitation at a central frequency of one-third octave band to a defined exposure time and, after that, the level of fore and aft vibration for equal time exposure (for example 2·5 h). Both “recorded and adjusted” signals are used to form complex input motion. Subjects had to assess the expected exposure time for two-directional motions. Figure 17 shows partial and averaged equal comfort curves for (a) one-directional vertical vibrations, (b) one-directional fore and aft vibrations and (c) for assessed exposure time of 2·5 h under two-directional narrowband vibrations, for six subjects. Based on Figure 17, it can be concluded that assessed exposure times for two-directional vibrations are approximately 20% less than assessed exposure times for one-directional vibrations. Subjects could sustain 2 h exposure to complex two-directional

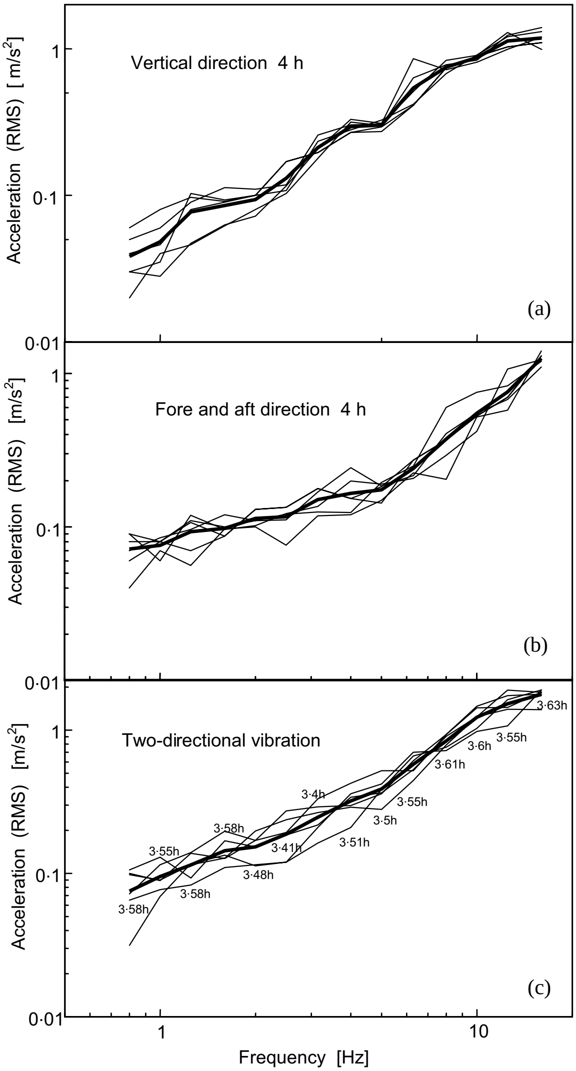

Figure 18. Partial and averaged equivalent comfort curves in the fore and aft direction under (a) vertical, (b) fore and aft and (c) two-directional narrowband random vibration for 4 h of exposure.

random vibrations compared to 2·5 h exposure to one-directional fore and aft and vertical vibration.

Similar conclusions were obtained based on analysis of results shown in Figure 18. Averaged equivalent comfort curves for one-directional vibration in the vertical direction (a), and in the fore and aft direction (b) for an exposure time of 4 h. Also, averaged equivalent comfort curves for 4 h exposure to two-directional random vibrations are shown in Figure 18(c). It is obvious that assessed exposure time to random two-directional vibration, which corresponds to 3·5 h of exposure is 15% less than exposure times to one-directional vibration.

It can be seen from Figures 13–16 that intersubject variability exists. It means that averaged values present a compromise in order to define equal comfort curves.

In order to validate the research method, the results obtained were compared to results of other authors. In Figures 19 and 20, equivalent comfort curves for one-directional random

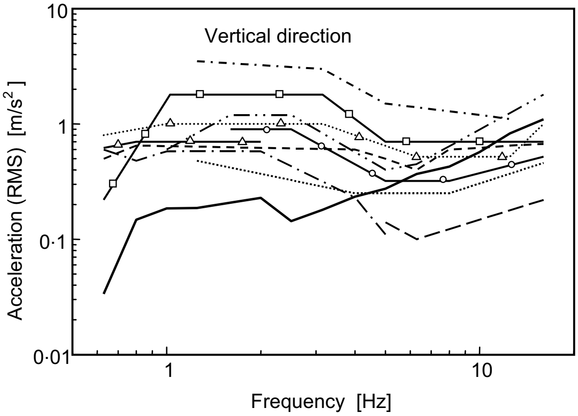

Figure 19. Comparison of experimentally obtained equal comfort curves in the vertical direction with equal comfort curves in the vertical direction obtained by different authors. ——, Authors; —□—, Simić [10]; ·······, ISO 2631-1 (1985) [12]; – – –, Howarth and Griffin [1]; - - - -, Leatherwood [18]; —○—, Goldman [1]; –··–··–, Dupuis *et al.* [1]; -·-·-·-, Donati *et al.* [1]; –·–·–·–, Corbridge and Griffin [15]; ····△····, Demić [19]; —△—, Oborne and Boarer [1].

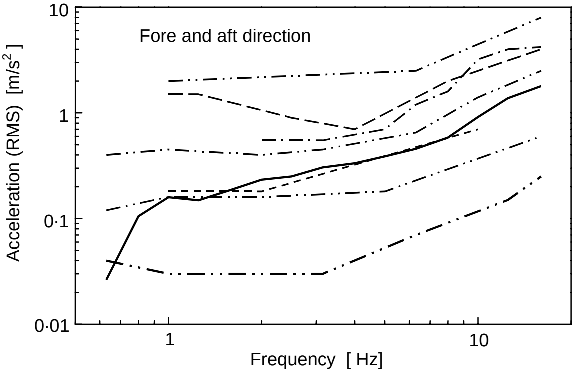

Figure 20. Comparison of experimentally obtained equal comfort curves in the fore and aft direction with equal comfort curves in the fore and left direction obtained by different authors. ——, Authors; –··–··–, Miwa [1]; –·–·–·–·, Griffin *et al.* [1]; – – –, Donati *et al.* [1]; - - - -, ISO 2631-1 (1985) [12].

vibrations in the vertical and fore and aft directions were compared to equivalent comfort curves in the vertical and fore and aft direction under sinusoidal vibrations given in ISO 2631-1 (1985) [12] and by other authors. International standard ISO 2631-1 (1997) [35] does not define equal comfort curves, so experimental results were not compared to this standard.

The characters of curves are different and this can be explained by experimental condition differences. Results obtained are for random vibration, like the results of Donnati [1, 23], Demić [17–21] (based on the walking process) and Leatherwood [24] (obtained for a standing position). The results of other authors were obtained for harmonic vibration.

The small number of subjects exposed only for 2·5 and 4 h of multi-component random vibration did not make it possible to define with confidence equal comfort curves similar to the ones for one-directional vibration.

It should be emphasized that literature previewed did not consider multi-directional random vibration, except references [7, 12, 19–21]. Based on the earlier conclusions, the results obtained for multi-directional vibration will not be compared with results of other authors.

4. CONCLUSIONS

The highest ride loads occur in the vertical and fore and aft directions, so they are adequate for the assessment of vehicle ride comfort. Seat-to-head transmissibility can be used to describe human behaviour under broadband random vibration. In the vertical direction, the STHT curve of human body has two resonant frequencies. The first peak frequency corresponds to whole body resonance (near to 5 Hz) and the second one corresponds to the upper body resonance (near to 14 Hz). In some results, depending on body characteristics, there is a third resonant frequency which represents the foot resonance. For fore and aft random vibration, STHT has only one peak resonance, which corresponds to whole body resonance. For multi-directional vibration, the STHT function has two resonance frequencies in the fore and aft direction, which is another reason why human behaviour under multi-directional vibration cannot be simulated by simple superposition of the human behaviour under one-directional excitation.

A platform–seat–human system is non-linear in the vertical and fore and aft directions. An increase in the seat backrest angle induces the increase in loading in both the vertical and fore and aft directions.

Based on analysis and the fact that, in diagrams of averaged STHT only two resonances appeared, the biodynamic human model can be defined as a two or three masses non-linear model. Such a model could be convenient for assessing human ride comfort in vehicles. Parameter identification and determination of the human biodynamic model will be the main topic of further investigations.

Humans are very sensitive to vertical random vibration at frequencies below 1 Hz, which can be explained by physiological factors. The human being is least sensitive at frequencies above 5 Hz.

Humans are very sensitive to fore and aft random vibration at frequencies below 1 Hz, which can also be explained by physiological factors. They are least sensitive under fore and aft random vibration at frequencies above 5 Hz.

Humans are more sensitive to random multi-directional vibration than to one-directional random vibration (in the fore and aft and vertical direction). Equivalent comfort curves for multi-directional random vibrations are 15–20% lower than for one-directional vibrations.

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