Human Body Under Two-Directional Random Vibration

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ABSTRACT

Human body behaviour under the influence of two-directional random vibrations is of great importance for optimal motor vehicle design. Efforts are being made in order to discover as much information about the influence of vibration on human body as possible. References show that the most attention has been paid to vertical vibration, although intensive research has been performed lately on the other sorts of excitation. This paper shows the results of the investigation of behaviour of human body, in seated position, under the influence of random two-directional (fore and aft and vertical vibration). The investigation is performed using an electro-hydraulic simulator, on a group of 18 healthy male participants. Subjects are asked to adjust level of fore and aft excitation in order to give the same sensation as vertical excitation. Experiments are performed in order to give results which might improve human body modeling in driving conditions. Excitation amplitudes (0, 55, 1, 75 and 2, 25 m/s^2 R.M.S.) and seat backrest conditions (with (K) and without inclination (S)) were varied. Data results were analysed, and partial coherent and transfer functions analysis has been performed and results are given in detail. Human body transmissibility characteristics, under two directional random excitations, depend on its spatial position. Two directional random excitations affect human body transfer functions, which points out the fact that it behaves like a non-linear dynamic system. This should be taken into consideration in synthesis of biodynamic vibration models of human body.

Key words: human, two-directional vibrations, partial coherence function, transfer function

1. INTRODUCTION

Humans, especially, passengers and drivers are exposed to whole body vibration. Generally, vibration occurs simultaneously in all six axes. Variables such as the vehicle type, vehicle speed, road surface and type of maneuver can vary the magnitude and frequency content of vibration in each of six directions. Some vehicles, such as tractors, trucks and tanks often show a grater magnitude of vibration in fore and aft direction than in vertical direction, Dupuis and Zerlett [1], Griffin [2], Corbridge and Griffin [3], and Linden [4]. Experimental research and data analysis conducted by Lukic et al: [5], in passenger vehicles showed that the highest loading of passengers is in vertical and the lowest vibration loading is in lateral direction as well as reported by Griffin [2], Holmlund et all. [6] and Simic [7].

Describing the response of the seated human body exposed to vibration can be performed by seat-to-head transfer function (STHT). It represents a frequency dependent relation between acceleration of the head and acceleration at the seat-to-buttock interface. Beside STHT, apparent mass and mechanical impedances can be used in order to predict seated human body behaviour under two-directional vibration. Numbers of papers, which treat human body behaviour under two-directional vibration, with respect to STHT, are, not significant. In this paper an attempt to investigate seated human body behaviour under broadband random two directional vibration with respect to subjective assessments will be presented.

Experiments are performed in order to give results to improve human body modeling in driving conditions. Excitation amplitudes (0,55, 1,75 and 2,25 m/s^2 R.M.S.) and seat backrest conditions (with and without inclination) were varied. A group of 18 healthy male subjects was exposed to broadband random two directional vibrations. After that, subjects were asked to adjust a level of fore and aft excitation in order to have the same sensation for both excitations. The level of vertical excitation was determined and the magnitude of for and aft excitation was adjusted with respect to subjective assessment. Initial levels of excitations were the same as given in Lukic [8] and Demic at all. [9]. After matching levels of excitations in fore and aft direction were 0,727; 1,874 and 2,695 m/s^2 R.M.S. with S seatbackrest position and 0,643; 1,801 and 2,487 m/s^2 R.M.S. with K seatbackrest position, with respect to 0,55; 1,75 and 2,25 m/s^2 R.M.S. of vertical excitation.

2. EXPERIMENTAL METHOD

An electro-hydraulic motion simulator was used in the subjective experiment. The simulator was designed to provide a test bandwidth from 0,3-30 Hz, but with very small (negligible) power for the frequencies over 20 [Hz], with a total loading mass of 200 kg and to obtain vertical and horizontal random excitations simultaneously. The investigators had to define frequency bandwidth and magnitude of excitation.

In the experiment, data from accelerometers HBM B 12/200 mounted on the seat (S), head (H), platform (P) and steering wheel (W), in fore and aft (X) and vertical (Z) directions (Figure 1), were recorded by use of amplifier HBM DMC9012A and BEAM 3.1 acquisition data software and stored afterwards in a data file.

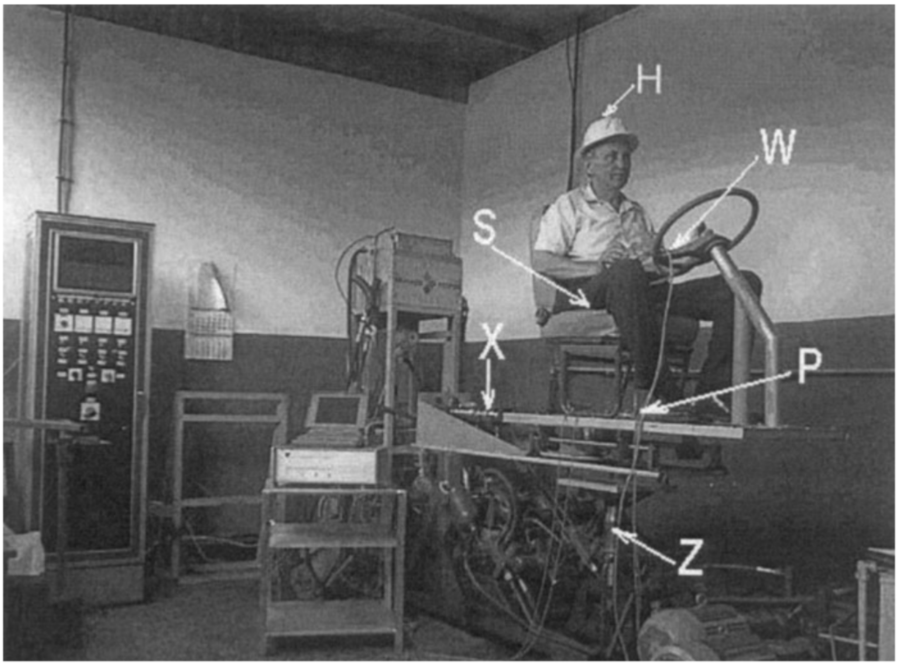

Figure 1. Measurement equipment

The test duration depends on the lower and upper limiting frequencies, signal character, data treatment, relative error, etc. There are known relations defining necessary test duration for FFT in Bendat et all [10,11,12]. The existing recommendations in literature are not ultimate, for instance ISO 2631/1 [13] recommends that in case of FFT application by use of a filter and third-octave analysis of the stationary signal, for frequencies above 0,5 [Hz], the test duration should be over approximately 227 [s] (error lower than 3 [dB], reliability 90 [%]). In case this recommendation is not fulfilled, the same standard requires a detailed description of data treatment procedure.

Having in mind that the aim of this paper was to confirm some facts relating to human vibration under the influence of two-directional random vibration, it was found acceptable to perform the FFT with a constant frequency increment, instead of third-octave analysis. The analyses performed in Linden [4] have shown that the acceptable signal duration, for vehicle ride comfort investigation is 1 to 2 [min] for the case of a linear scale of frequency. Having that in mind, and recommendations from ISO 2631/1 [13] the signal duration was 343,6 [sec].

This signal duration, with a sampling frequency of 171,8 [Hz] provided the following, Bendat et al., [10,11,12]:

- Reliability of the FFT above 0,0029 [Hz], estimated to be acceptable for the lower simulator excitation frequency of 0,3 [Hz].
- With 512 averaging of spectra used in the FFT, the random estimation errors of the following values were: for auto spectrum – 0,0454[-], for cross spectrum – 0,057 [-] and for coherence function – 0,032 [-], which were found acceptable, according to Bendat [10,11,12].

Based on these facts, it was found acceptable to apply the value of signal duration for the analyses performed in the paper.

A group of 18 trained, healthy male occupants (aged 39,1±11,8 years, 180±4 [cm] tall and 79,4+15,4 [kg] mass) were exposed to simultaneously vertical and fore and aft broadband random vibration. Bearing in mind the confidence frequency domain of the simulator, the results of frequencies lower than 0,5 [Hz] and above 18,5 [Hz] were neglected in the analysis. The final frequency domain will be defined after analysis of the dynamic system head helmet.

As is known, see Bendat [10,11,12], in frequency analyses for frequencies above Nyquist frequency, there are magnitudes that can be copied to the area below Nyquist frequency, which could lead to wrong conclusions. In order to eliminate this effect, it is common to apply anti-aliasing filters, Bendat [10,11,12], preventing the occurrence of these errors. In this investigation, anti-aliasing filters were not used, because the spectral analyses have shown that above frequencies of, approximately, 20 [Hz] there are negligibly small amplitudes.

The influence of seat characteristics was investigated in many papers [1,2,4,7] . In experiment, subjects were sitting on a soft seat, in a driving condition, with hands on the steering wheel. The seat characteristics and the transfer function of platform-seat system were obtained with the seat loaded with a sandbag of total mass of 40 [kg], Lukic [8]. The seat was excited by two-directional random vibration in both vertical and fore and aft directions. In the fore and aft direction there is a resonant frequency at approximately 22 [Hz]. Analyses have been performed in the domain up to 18,5 [Hz], because the measured resonant frequency had no influence on the results. The final frequency domain will be defined after analysis of the head helmet system.

Since the seat was subjected to the influence of the human body under random vibration, it was decided to perform investigations on the seat commonly used in local car manufacture. The seat cushion design was based on polyurethane combined with springs.

The seat backrest angle (position K inclined 14 [°] with respect to the vertical axis, and position S in a vertical position without inclination) and excitation magnitude (0,55 m/s^2 R.M.S., 1,75, m/s^2 R.M.S. and 2,25, m/s^2 R.M.S.) were varied, Lukic [8], Demic et al. [9], Lukic et al. [14]. Symbols $K_{1,75}$ and $S_{2,25}$ represent positions of the seatback rest angle (K or S) and the number in the subscript shows the amplitude of initial excitation.

In order to determine the STHT function, acceleration was measured at the seat-buttock interface and on the head. Accelerometers were mounted on the plastic helmet also.

Head vibration was registered by use of the plastic helmet, so it was necessary to analyse the errors induced by the relative motion between the head and the helmet. They are analysed by use the of the helmet-to-head transfer function, shown in figure 2. It is obvious that the major errors take place at, approximately around the 19 [Hz] resonance frequencies, because in that point the transfer function magnitude is the highest and this should be taken into consideration while analysing the data in the frequency domain. To be more specific, amplitudes close to the frequency of 15 [Hz] will not be taken into consideration for the analyses.

3. TEST RESULTS ANALYSIS

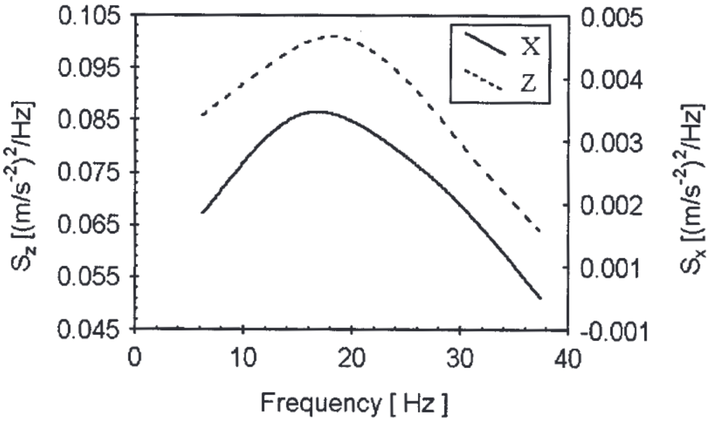

Figure 2. Head helmet system characteristics

The preliminary analyses of the time history series have shown that they belong to a group of stationary random processes. It is known that the identification of parameters of random processes can be done in time, amplitude and frequency domains, which is thoroughly described in Bendat [10,11,12].

It should be pointed out that the data treatment in the time domain is often based on the calculation of various types of mean values. The frequency domain analysis relies on auto-spectra, cross-spectra transfer function and coherence calculations, etc. Bendat [10,11,12].

Experimental results obtained for simultaneously vertical and fore and aft random vibration are briefly analysed and given in Lukic [8], Demic et al. [9], and here will be analysed by partial coherent and transfer function analysis especially in the resonant frequencies domain. This method of data analysis has been seldom used the in literature for human body vibration analyses in the past and it gave very useful results in research of two-axis random excitation of the human body. Bearing that in mind, this method has been used in this paper.

Two specific pieces of software were developed to enable the analyses of the recorded data, according to the procedures defined in Bendat [10,11,12]:

- ANALSIGDEM (Demic, [15]), is software that enables the analysis of random stationary signals by calculation of mean, minimal and maximal values, standard signal deviation, probability, probability density, joint probability density, auto-correlation and cross-correlation functions, correlation coefficients, auto-spectra and cross-spectra. The number of input data ***N*** is in ***2exp(k)*** form, where ***k*** is integer. In our analyses, the maximal value of ***N*** was 16384 points.
- DEMPARCOH (Demic, [16]), is software that enables the identification of dynamic system characteristics with multi input – output option (up to 10 channels), by calculating ordinary, partial coherence and transfer functions. Since the establishment of ensembles by use of data overlapping method is

necessary for data averaging Bendat [10,11,12], the number of input data in this software was defined with ***2N*** (***N*** is ***2exp(k)***, where ***k*** is an integer). In our investigation, N was 8192 points.

Because of the existence of intrasubjective and intersubjective variability of occupant's response (Griffin [2], Lukić [8], Demic et al. [9]), and in order to improve the test credibility, all the analyses were done for the averaged occupants responses in the frequency domain.

By use of the software "ANALSIGDEM" R.M.S. values were calculated. Acceleration signals were standardised with respect to mean value. Characteristic parameters of calculated values related to the occupant's time history ensemble are given in Table I.

Table I.

R.M.S values

Backrest angle	Value	0,55 [m/s^2] R.M.S.	1,75 [m/s^2] R.M.S.	2,25 [m/s^2] R.M.S.
K	1	0,188	0,588	0,782
	2	0,119	0,318	0,775
	3	0,251	0,376	0,600
	4	0,174	0,551	0,955
	5	1,947	3,369	5,257
	6	0,534	1,721	2,301
	7	0,643	1,801	2,487
	8	1,276	5,203	7,061
S	1	0,576	1,683	1,951
	2	0,289	0,808	3,790
	3	0,499	1,138	2,115
	4	0,264	0,892	3,738
	5	3,387	4,141	6,359
	6	0,549	1,750	2,284
	7	0,727	1,874	2,695
	8	1,522	6,310	8,141

Legend:
1- fore and aft seat acceleration, $\ddot{x}_s$
2- vertical head acceleration, $\ddot{z}_h$
3- fore and aft head acceleration, $\ddot{x}_h$
4- vertical seat acceleration, $\ddot{z}_s$
5- fore and aft steering wheel acceleration, $\ddot{x}_w$
6- vertical platform acceleration, $\ddot{z}_p$
7- fore and aft platform acceleration, $\ddot{x}_p$
8- vertical steering wheel acceleration, $\ddot{z}_w$

The analysis of the data from Table I leads to the following conclusions:

- The lowest value of R.M. S. is recorded for vertical head vibration;
- The highest R.M.S. value is for vertical steering wheel vibration;
- The highest R.M.S. value of all accelerations is for excitation of 2,25 [m/s^2] R.M.S.;
- For the same magnitude of excitation all R.M.S. values are lower in the K seat backrest position than in the S position;
- R.M.S. value of head acceleration is higher in fore and aft direction than in vertical position, because of matching equal sensation level with respect to vertical excitation;

After matching equal sensation of fore and aft and vertical vibration RMS acceleration values in fore and aft direction were 0,727; 1,874 and 2,695 m/s^2 RMS with S seatbackrest position and 0,643; 1,801 and 2,487 m/s^2 RMS with K seatbackrest position, which were used with amplitude of 0,55; 1,75 and 2,25 m/s^2 RMS in vertical direction respectively. RMS acceleration values of all measured data are given in Table I.

Analysis of vibration transmitted through the human body showed that theory known from cybernetics (multi input/multi output systems) Bendat [10,11,12]. can be used. Head vibrations are output signals, all other recorded signals should be treated as input signals (steering wheel, seat, vehicle floor). It means that human body can be treated as a system with six input and two output signals Bendat [10,11,12]. Generally, output signals depend on input signal. There is an assumption in cybernetics theory that input signals are decoupled between themselves, but it is not always the case, in real systems. Then special theory of signal decoupling should be applied.

In Figure 3, scheme of the recorded input and output vibratory signals on the human, subject is given. The system considered with six inputs and two output signals (given in Figure 3a) can be decoupled on two subsystems with six inputs and one output, Figures 3b and 3 c.

The problem shown in Fig. 3a belongs to the group of problems called ‘Multiple Input/Multiple Output Systems’, and it may as well be regarded as a ‘Multiple Input/Single Output System Bendat [10,11,12], as it is presented in Figs 3a, 3b and 3c. It is obvious that each particular output variable may be observed as a function of input variables, which may be correlated.

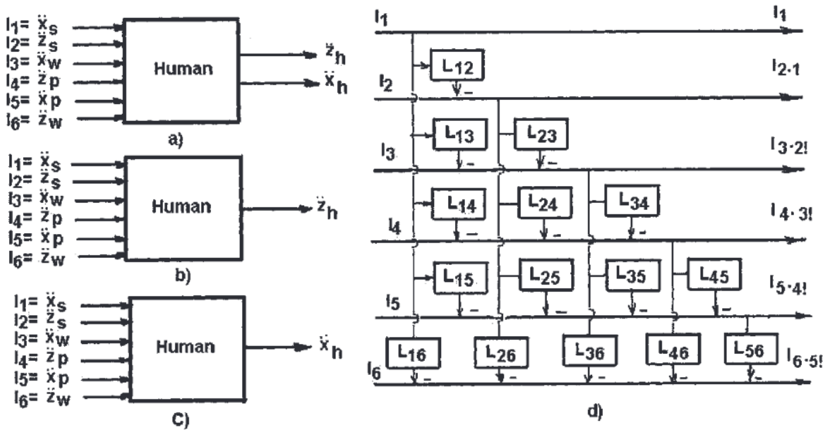

Figure 3. Fourier transformation relationships for multiple input/multiple output model

Assuming that input variables are correlated, the problem of exclusion of mutual components from the input variables is schematically presented in Fig. 3d, where variables L_{12}, L_{13}, L_{14}, L_{24}, L_{34}, L_{34}, L_{15}, L_{25}, L_{35}, L_{45}, L_{16}, L_{26}, L_{36}, L_{46} and L_{56} stand for complex values of the transfer functions between the corresponding input variables or their parts Bendat [10,11,12].

In the case of the existence of correlation between particular input variables, and based on Fig. 3d, the expressions for independent (decoupled) input variables can be written:

$$\begin{aligned}
&I_{1!} = I_1\\
&I_{2.1!} = I_1 - L_{1,2} \cdot I_1\\
&I_{3.2!} = I_3 - L_{1,3} \cdot I_1 - L_{2,3} \cdot I_{2.1!}\\
&I_{4.3!} = I_4 - L_{1,4} \cdot I_1 - L_{2,4} \cdot I_{2.1} - L_{3,4} \cdot I_{3.2!}\\
&I_{5.4!} = I_5 - L_{15}I_1 \cdot L_{25}I_{2.1} - L_{35}I_{3.2!} - L_{45}I_{4.3!}\\
&I_{6.5!} = I_6 - L_{16}I_1 \cdot L_{26}I_{2.1} - L_{36}I_{3.2!} - L_{46}I_{4.3!} - L_{56}I_{5.4!}
\end{aligned} \tag{1}$$

Transfer functions between input signals, if they exist, are defined according to Bendat [10,11,12]:

$$\begin{aligned}
&L_{12}=\frac{I_2}{I_1};L_{13}=\frac{I_3}{I_1};L_{14}=\frac{I_4}{I_1};L_{15}=\frac{I_5}{I_1};L_{16}=\frac{I_6}{I_1};\\
&L_{23}=\frac{I_{3.1}}{I_{2.1}};L_{24}=\frac{I_{4.1}}{I_{2.1}};L_{25}=\frac{I_{5.1}}{I_{2.1}};L_{35}=\frac{I_{5.2!}}{I_{3.2!}};L_{45}=\frac{I_{5.3!}}{I_{4.3!}};\\
&L_{26}=\frac{I_{6.1}}{I_{2.1}};L_{36}=\frac{I_{6.2!}}{I_{3.2!}};L_{46}=\frac{I_{6.3!}}{I_{4.3!}};L_{56}=\frac{I_{6.4!}}{I_{5.4!}};
\end{aligned} \tag{2}$$

The partial coherence function, based on (1) and (2), can be defined according to (Bendat, 1998, Bendat, Piersol, 1980, Bendat, Piersol, 2000):

$$\gamma^2_{iy*(i-1)!}=\frac{\left|S_{iy*(i-1)!}\right|^2}{S_{ii*(i-1)!}S_{yy*(i-1)!}}\ , \tag{3}$$

where:

– $S_{iy*(i-1)!}$ is the conditioned cross spectral density function between the decoupled input signals, and the output signal,

– $S_{ii*(i-1)!}$ is the conditional auto spectral density function of the input signals and

– $S_{yy*(i-1)!}$ is the conditional auto spectral density function of the output signals $\ddot{x}_h$ and $\ddot{z}_h$, Figure 3.

Based on the expressions (1) and Figures 3b and 3c, the transfer function relations can be written based on the decoupled input signals:

$$\begin{aligned}
&H_1=\frac{Y}{I_1};\ H_{2.1}=\frac{Y}{I_{2.1}};\ H_{3.2!}=\frac{Y}{I_{3.2!}};\\
&H_{4.3!}=\frac{Y}{I_{4.3!}};\ H_{5.4!}=\frac{Y}{I_{5.4!}};\ H_{6.5!}=\frac{Y}{I_{6.5!}};
\end{aligned} \tag{4}$$

where Y represents vertical in the first case and in the second case represents fore and aft accelerations of a head.

All the variables from expressions (1), (2) and (4) represent Fourier Transforms in complex form, while values defined by relation (3) are real numbers. The expression enables calculation of partial coherence and transfer functions, with necessary averaging of time and frequency realisations. Since the procedures of the calculation is thoroughly described in Bendat [10,11,12], it will not be repeated here. The method is realised by use of DEMPARCOH software (Demic [16]). The application of the software enabled the calculation of the partial coherence and transfer function between the observed output functions and the calculated independent excitations acting the human. Instead of complex modules of transfer functions determined by expression (4).

Based on the previously given statements two specific cases can be noticed:

a) Input signals (fore and aft vibration of seat, vertical vibration of seat, fore and aft vibration of steering wheel, vertical vibration of floor, fore and aft vibration of floor and vertical vibration of steering wheel) with vertical vibration of a head as output signal and

b) Input signals (fore and aft vibration of seat, vertical vibration of seat, fore and aft vibration of steering wheel, vertical vibration of floor, fore and aft vibration of floor and vertical vibration of steering wheel) with fore and aft vibration of a head as output.

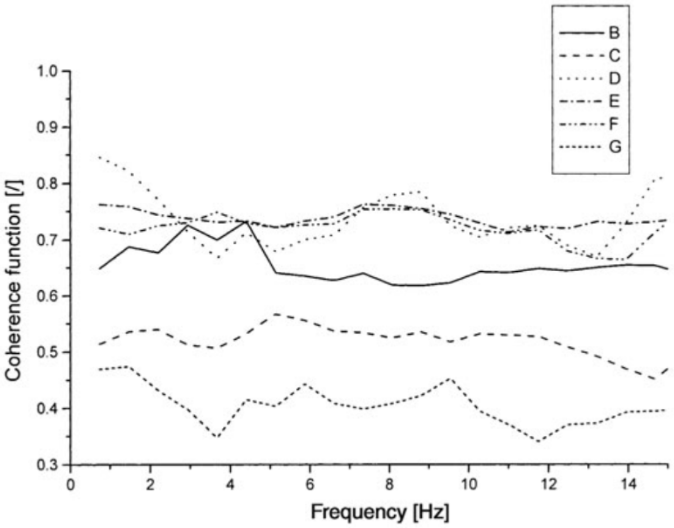

Figure 4. Partial coherence functions (vertical direction – 1, 75 m/s^2 R.M.S. K position)

B: Partial coherence functions: vertical head vibration – fore and aft seat vibration,

C: Partial coherence functions: vertical head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed,

D: Partial coherence functions: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed, E: Partial coherence functions: vertical head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed,

F: Partial coherence functions: vertical head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed,

G: Partial coherence functions: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

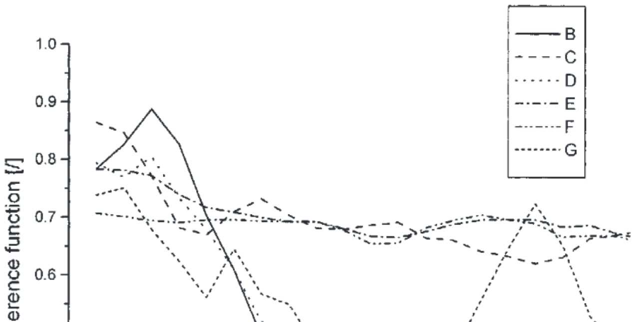

Figure 5. Partial coherence functions (fore and aft direction- 1, 75 m/s2 R.M.S. K position)

B: Partial coherence functions: fore and aft head vibration – fore and aft seat vibration

C: Partial coherence functions: vertical head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed,

D: Partial coherence functions: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed,

E: Partial coherence functions: vertical head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed,

F: Partial coherence functions: vertical head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed,

G: Partial coherence functions: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

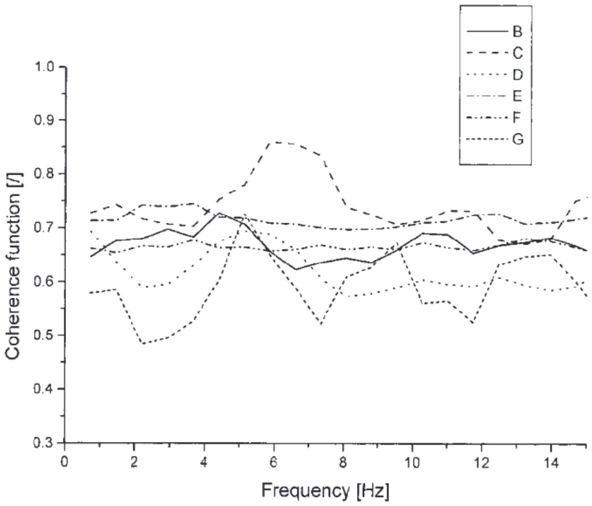

Figure 6. Partial coherence functions (vertical direction – 2, 25 m/s^2 R.M.S. K position)

B: Partial coherence functions: vertical head vibration – fore and aft seat vibration,

C: Partial coherence functions: vertical head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed,

D: Partial coherence functions: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed,

E: Partial coherence functions: vertical head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed,

F: Partial coherence functions: vertical head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed,

G: Partial coherence functions: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

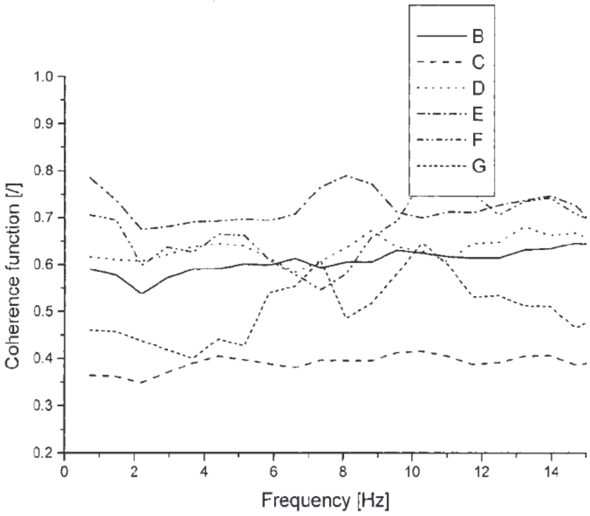

Figure 7. Partial coherence functions (vertical direction – 0, 55 m/s^2 R.M.S., S position)

B: Partial coherence functions: vertical head vibration – fore and aft seat vibration,

C: Partial coherence functions: vertical head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed,

D: Partial coherence functions: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed,

E: Partial coherence functions: vertical head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed,

F: Partial coherence functions: vertical head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed,

G: Partial coherence functions: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

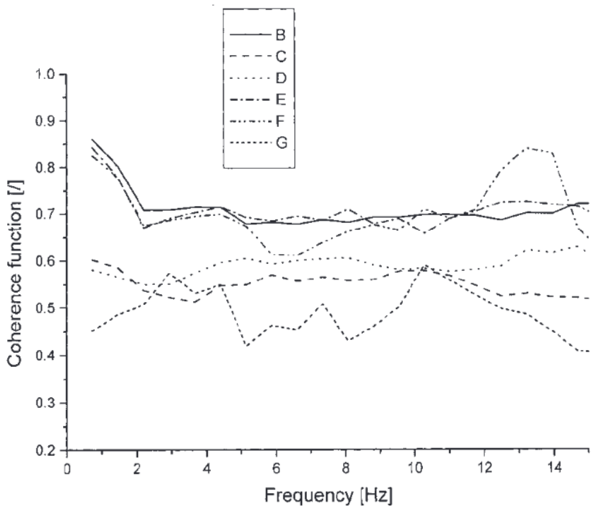

Figure 8. Partial coherence functions (fore and aft direction – 0, 55 m/s^2 R.M.S., S position)

B: Partial coherence functions: fore and aft head vibration – fore and aft seat vibration

C: Partial coherence functions: fore and aft head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed

D: Partial coherence functions: fore and aft head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed

E: Partial coherence functions: vertical head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed F: Partial coherence functions: fore and aft head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed

G: Partial coherence functions: fore and aft head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

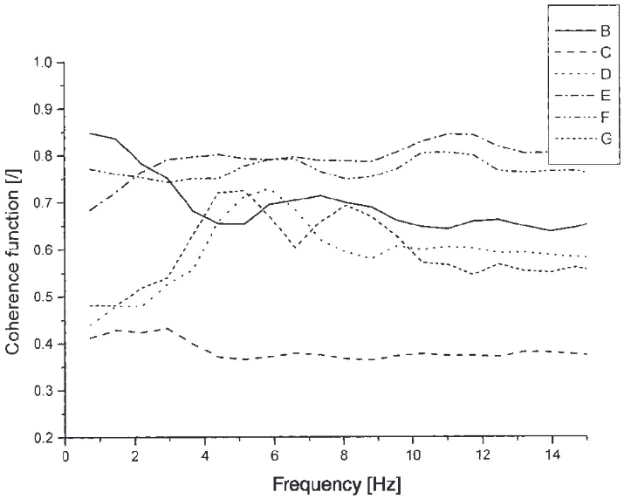

Figure 9. Partial coherence functions (fore and aft direction – 1,75 m/s^2 R.M.S., S position)

B: Partial coherence functions: fore and aft head vibration- fore and aft seat vibration

C: Partial coherence functions: fore and aft head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed

D: Partial coherence functions: fore and aft head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed

E: Partial coherence functions: vertical head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed

F: Partial coherence functions: fore and aft head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed

G: Partial coherence functions: fore and aft head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

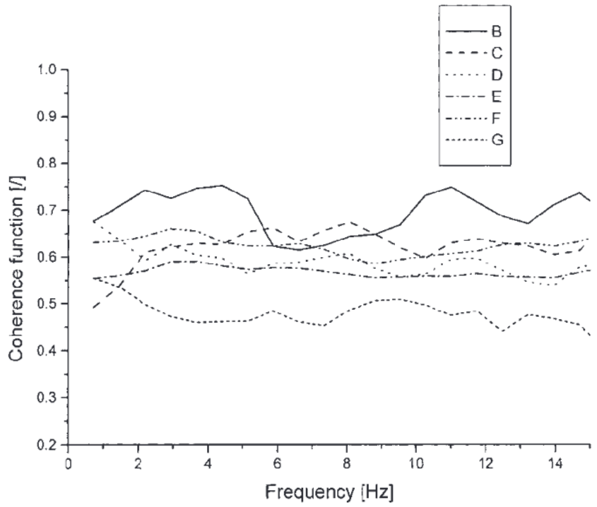

Figure 10. Partial coherence functions (vertical direction – 2,25 m/s^2 R.M.S., S position)

B: Partial coherence functions: vertical head vibration – fore and aft seat vibration,

C: Partial coherence functions: vertical head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed,

D: Partial coherence functions: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed,

E: Partial coherence functions: vertical head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed,

F: Partial coherence functions: vertical head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed,

G: Partial coherence functions: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

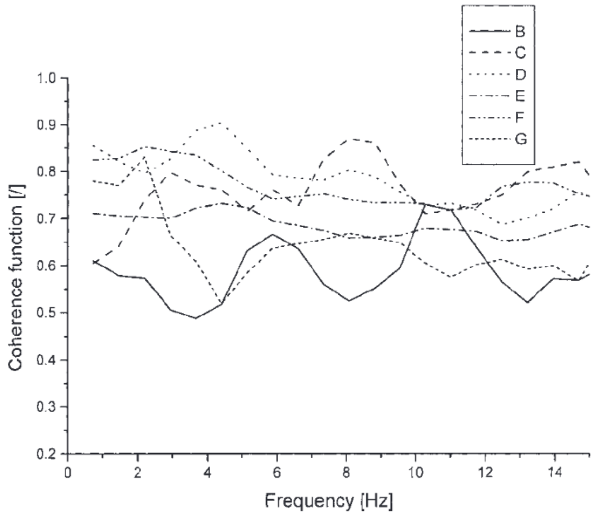

Figure 11. Partial coherence functions (fore and aft direction – 2, 25 m/s^2 R.M.S., S position)

B: Partial coherence functions: fore and aft head vibration – fore and aft seat vibration

C: Partial coherence functions: fore and aft head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed

D: Partial coherence functions: fore and aft head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed

E: Partial coherence functions: vertical head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed

F: Partial coherence functions: fore and aft head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed

G: Partial coherence functions: fore and aft head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

Partial coherence functions were determined by software (Demic, [15,16]) and the procedure given in Bendat [10,11,12] and are given in figures 4-11.

Analysis showed that partial coherence functions are intersubjectively changeable (Lukic [8]). In this paper analysis of averaged data for the whole group of subjects will be performed and for illustration, part of the results will be presented here.

Data analysis partially given in figures 4-6 (seatbackrest position K) showed that the partial coherence function depends on frequency, input data and excitation magnitude. Values of the partial coherence function are approximately in the region 0,3 – 0,9 and it can be concluded that the human body behaves as a non-linear dynamics system.

Data analysis partially given in figures 7-11 showed that partial coherence functions depend on frequency, input data and excitation magnitude. Values of excitation magnitude are in region 0, 35 – 0,9. This showed that the human body behaves as a non-linear dynamics system.

Data analysis partially given in figures 4-11 showed that the partial coherence functions depend on seatbackrest angle.

Comparing data, partially, given in figures 4 and 6 with data given in figures 7 and 10, as well as data given in figures 5 with data given in figures 8, 9 and 11 one can conclude that partial coherence functions depend on analysed output data (vertical or fore and aft head vibration).

Partial coherence functions provide analysis of the relation between output and decoupled inputs, Bendat [10-12], and they cannot be used for direct determination of system resonances. It is necessary to determine the partial transfer function, with decoupled inputs, which can be used to give a qualitative assessment of vibration transmission through the human body, especially with respect to human body resonances. Transfer functions showed intersubject variability. Here we present on analysis performed for averaged data for the whole group of subjects in the frequency domain up to 15 Hz.

From analysis of the data partially given in figures 12 – 16 it can be concluded that transfer functions depend on frequency and seatbackrest angle. The highest magnitudes of transfer functions are for input data (x_s, z_s i x_w) under K position for both output values.

Analysis of data partially given in figures 12 – 16 showed that the transfer functions depend on frequency. The highest magnitudes of transfer functions are for input values x_s, z_s and x_w and for both output values (acceleration of the head).

Based on analysis of data, partially, given in figures 12-13 and 14-16, it can be concluded that seatbackrest angle has an influence on the character and magnitude of transfer functions and it can not be neglected in human body modeling process.

Based on previously given statements it was found acceptable to perform an analysis of transfer functions resonances, especially in resonance regions, which are given in Table II.The parameters of resonances given in Table II depend on the magnitude of excitation and seatbackrest angle. There are two or three resonances, which depend on excitation magnitude and seatbackrest angle. Previously given statements confirmed that human body showed non-linear dynamic characteristics. The parameters of the resonances depend on type of output data (vertical or fore and aft vibration), which must be taken into consideration in human body modeling process.

Data given in figures 12-16 showed that excitations of floor and seat in both directions are dominant.

Transfer functions (C, D and G, figures 12 -16) can be neglected with respect to magnitude values.

Table II.
Parameters of transfer functions

Vertical direction (a)

	B		C		D		E		F		G	
	fr [Hz]	MM [-]	fr[HZ]	MM [-]	fr [Hz]	MM [-]	fr [Hz]	MM [-]	fr [Hz]	MM [-]	fr [Hz]	MM [-]
$K_{0,55}$	13,21	1,87	/	/	/	/	6,60/13,95	2,55/1,30	/	/	/	/
$S_{0,55}$	4,40/8,81	1,50/1,69	/	/	/	/	3,67/8,81	2,35/1,23	/	/	/	/
$K_{1,75}$	2,20/4,40	2,33/1,59	/	/	/	/	2,20/9,54	3,47/2,06	5,84/9,54	1,52/2,71	/	/
$S_{1,75}$	2,20/7,34/14,68	1,57/1,43/1,71	/	/	/	/	1,46/6,60/13,21	2,58/1,64/1,72	8,07/11,74	2,10/2,51	/	/
$K_{2,25}$	6,60/11,74	1,84/1,11	/	/	/	/	5,14	1,78	/	/	/	/
$S_{2,25}$	2,20/6,60/14,68	1,57/1,44/1,71	/	/	/	/	1,46/6,60/12,48	2,58/1,64/1.91	8,07/12,48	2,10/2,55	/	/

Fore and aft direction (b)

	B		C		D		E		F		G	
	fr [HZ]	MM [-]	f [Hz]	MM[-]	r [Hz]	MM [-]	fr [Hz]	MM [-]	fr [Hz]	MM[-]	fr [Hz]	MM [-}
$K_{0,55}$	13,95	6,57	/	/	/	/	14,68	4,66	10,28	1,65	/	/
$S_{0,55}$	5,14/7,34	7,14/5,75	/	/	/	/	5,14/11,74	10,28/4,89	10,28	1,52	/	/
$K_{1,75}$	2,93	16,74	/	/	/	/	1,46	26,40	4,40/8,81	10,28/10,32	/	
$S_{1,75}$	8,07/14,68	8,08/4,71	/	/	/	/	8,07	9,68	8,07	12,54	/	/
$K_{2,25}$	6,60	7,68	/	/	/	/	11,74	2,68	12,48	1,17	/	/
$S_{2,25}$	1,46/9,54	10,55/6,36	/	/	/	/	10,28/14,68	2,87/1,78	1,46	14,57		

*fr-resonant frequency, MM – maximal magnitude of the transfer function

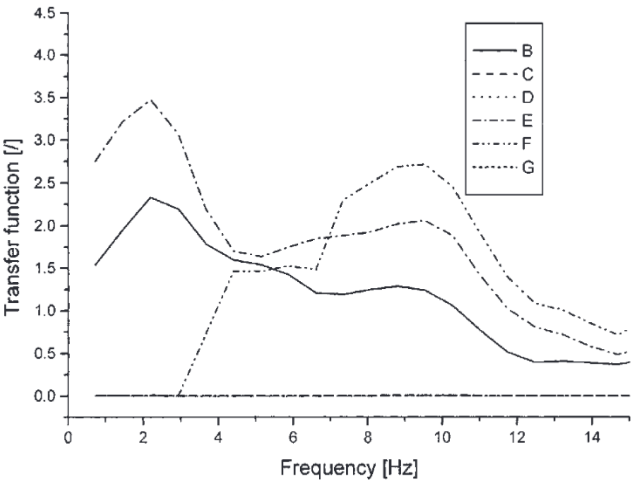

Figure 12. Transfer functions (vertical direction – 1, 75 m/s^2 R.M.S., K position)

B: Transfer function: vertical head vibration – fore and aft seat vibration

C: Transfer function: vertical head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed

D: Transfer function: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed

E: Transfer function: vertical head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed

F: Transfer function: vertical head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed

G: Transfer function: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

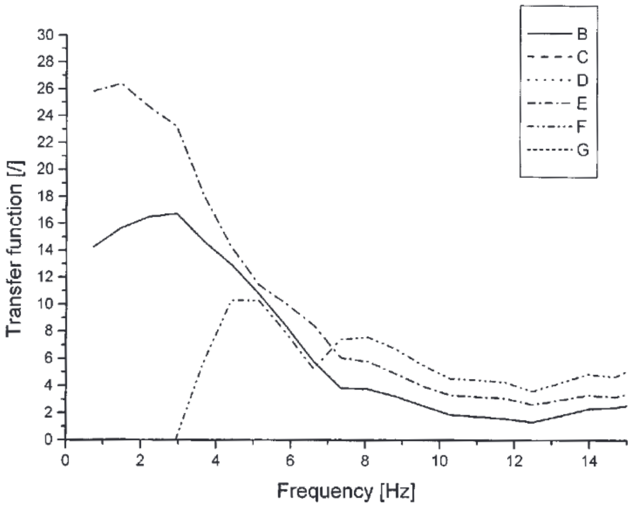

Figure 13. Transfer functions (fore and aft direction – 1, 75 m/s^2 R.M.S., K position)

B: Transfer functions: fore and aft head vibration – fore and aft seat vibration

C: Transfer functions: fore and aft head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed

D: Transfer functions: fore and aft head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed

E: Transfer functions: fore and aft head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed

F: Transfer functions: fore and aft head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed

G: Transfer functions: fore and aft head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

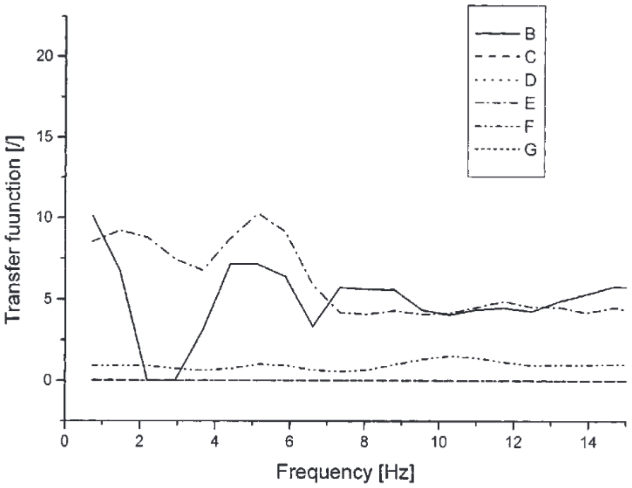

Figure 14. Transfer functions (fore and aft direction – 0, 55 m/s^2 R.M.S., S position)

B: Transfer functions: fore and aft head vibration – fore and aft seat vibration

C: Transfer functions: fore and aft head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed

D: Transfer functions: fore and aft head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed

E: Transfer functions: fore and aft head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed

F: Transfer functions: fore and aft head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed

G: Transfer functions: fore and aft head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

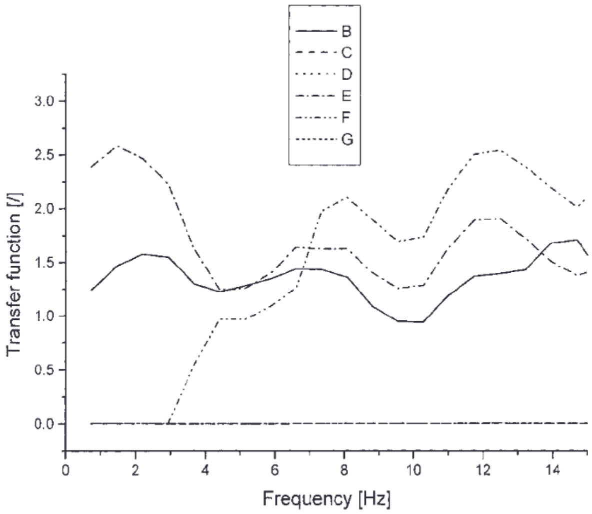

Figure 15. Transfer functions (vertical direction – 2,25 m/s^2 R.M.S., S position)

B: Transfer function: vertical head vibration – fore and aft seat vibration

C: Transfer function: vertical head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed

D: Transfer function: vertical head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed

E: Transfer function: vertical head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed

F: Transfer function: vertical head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed

G: Transfer function: vertical head vibration – vertical steering wheel, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

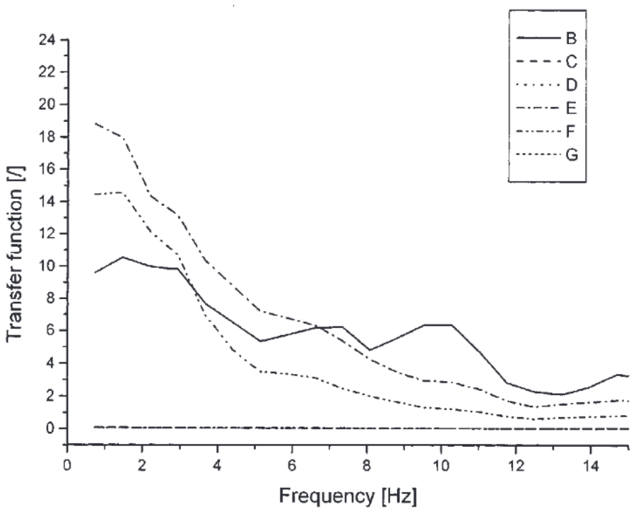

Figure 16. Transfer functions (fore and aft direction – 2, 25 m/s^2 R.M.S., S position)

B: Transfer functions: fore and aft head vibration – fore and aft seat vibration

C: Transfer functions: fore and aft head vibration – vertical seat vibration, where linear effect of fore and aft seat vibration is removed

D: Transfer functions: fore and aft head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration are removed

E: Transfer functions: fore and aft head vibration – vertical floor vibration, where linear effects of fore and aft and vertical seat vibration and fore and aft steering wheel vibration are removed

F: Transfer functions: fore and aft head vibration – fore and aft floor vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and vertical floor vibration are removed

G: Transfer functions: fore and aft head vibration – vertical steering wheel vibration, where linear effects of fore and aft and vertical seat vibration, fore and aft steering wheel vibration and fore and aft and vertical floor vibration are removed

CONCLUSIONS

On the basis of the investigations performed the following can be concluded:

- Subjective assessment of equal sensation on fore and aft and vertical vibration caused broadband random excitation with different magnitude both in vertical and fore and aft direction.
- Human body transmissibility characteristics, under two directional random excitation, depend on its spatial position. This should be taken into consideration in the synthesis of biodynamic vibration models of human body.
- R.M.S. random vibration excitation, under two directional random excitation, affects the human body transfer functions, which points out the fact that it behaves like a non-linear dynamic system.
- Seat backrest position, under two directional random excitation, affects the parameters of resonance.
- Excitation amplitude affects transfer functions, partial coherence functions and the parameters of human body resonance points, which points out the fact that the human body behaves like a non-linear system under the influence of fore and aft random vibration excitation. It caused two or three resonances.
- On the basis of transfer functions of the human body under the influence of two-directional random excitation, it can be stated that the parameters of the resonance points depend on the position of the seat backrest and the R.M.S. excitation, what is characteristic for nonlinear dynamic systems.
- The results obtained could be used for the synthesis of biodynamic vibration models of the seated human body under the influence two directional random vibrations.

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