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NON-LINEAR CHARACTERISTICS OF TRANSMISSIBILITY IN THE DYNAMIC RESPONSES OF STANDING SUBJECTS EXPOSED TO VERTICAL WHOLE-BODY VIBRATION

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Abstract
In this paper we studied the action of vibrations with low amplitude and high frequency on the human body, especially on the bone system, because this type of vibration is quite common for some work equipment and the effect on the workers is obvious: predisposition to bones fractures, osteoporosis, etc. For the study of vertical vibrations through the body were used oscillations at amplitudes of 1, 1.5 and 4 mm and at frequencies between 5÷35Hz. Whole-body vibration measurement was carried out with a NetdB multiple acquisition system using Piezotronics 356A16 PCB triaxial accelerators. Data was processed using dBFA Suite – Purchase and post-processing data acquisition software. The transmissibility of vibrations to the body was determined as a ratio of the mean square root of the acceleration signal received by the accelerometers (a_{rms}) to the mean square root of the signal acceleration given by the vibrant platform for three regions of the body: the knee, the lumbar region and the forehead. It was found that most a_{rms} peaks were obtained for 5÷10Hz frequencies, but there were also other frequencies for which the maximum was reached, which proves that there are more maximum accelerations specific to the position than those imposed by the vibrant platform. On the other hand, it was also found that the acceleration of transmitted vibration highly decreases compared to the acceleration given by the vibrating platform. There are important differences between the transmissibility of different people, in regard to BMI: it was found that for overweight people, transmissibility is lower than that of the normal ones.

Keywords: vibrations, amplitude, frequency, acceleration, transmissibility

1. INTRODUCTION

Vibrations act on the human body through the contact surfaces between the human and the vibrant system. The vibrational field can act on the whole body (WBV) (if the person stands or is seated) or on a part of the body, for example on the hands (HAV) [1- 3].

Vibrations transmitted to the whole body or just to a part of the body lead to disturbances in the health status of people subjected to the vibrational field [4, 5] (fatigue and sleepiness, emotional states of fear or anxiety, headache , diminished attention, decreased visual acuity, changes in tactile sensitivity, respiratory function, blood pressure, nausea, etc.) (Fig.1).

All these negative effects of vibrations on the human body lead to a decrease in the work capacity of the personnel, implicitly reducing its performance [7] work accidents may also occur (Table 1).

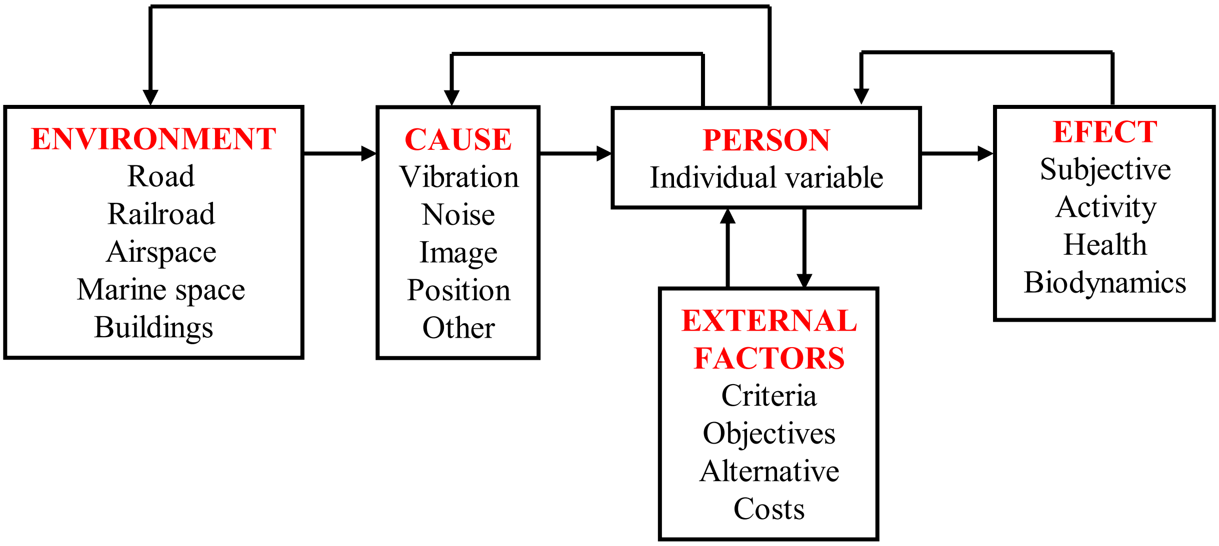


Fig. 1. The model of the relationship between the vibration environment and its effects [6]

Table 1. Variables associated with vibration discomfort

Extrinsic variables		**Intrinsic variables**	
Vibration variables	Vibration size and its combinations	Variable between subjects	Body posture
	Vibration frequency and its combinations		Body position
	Vibration direction and its combinations		Body orientation (lying, sitting, standing)
	Vibration position and combinations	Intrinsic variables of the subject	Body size and weight
	Vibration duration and its combinations		Age, sex, physical condition
Other variables	Other types of stress (noise, temperature, etc.)		Experience, personality, attitude
	Seat type		The dynamic response of the body

The relationship between the vibrations transmitted to the human body and back pain was not yet been fully understood. In this regard, Mansfield and Griffin (2000) [8] analysed „twelve subjects who were exposed to vibrations of six magnitudes, 0.25÷2.5 m/s^2 rms. The vertical vibration was in the frequency range of 0.2÷20 Hz". It was found that „twelve subjects were exposed to six magnitudes, 0.25–2.5 m s^{-2} rms, of vertical random vibration in the frequency range 0.2–20 Hz".

Kiiski et al (2008) [9] subjected four people to vibrations of different amplitudes (from 0.05 to 3 mm) and frequencies (from 10 to 90 Hz). They mounted accelerometers on different places on the body and analysed the transmission of vibrations to the body.

Ya Huang and Griffin (2009) studied on 12 subjects the resonance frequencies and the transmissibility of vertical vibrations for different frequencies (0.25÷20 Hz) and accelerations (0.0313, 0.0625, 0.125, 0.25, 0.5, 0.75 and 1.0 m/s^2 rms) for different body positions. A nonlinearity associated with soft tissue response was found [10]. Similar results were also obtained by Harazin in 1998 and Yang et al in 2012 [11, 12].

To deepen the study of human body movement subjected to vibrations, Yoshimura, Nakai and Tamaoki [13] created in 2005 a model with 10 DOFs and studied the vertebrae displacement.

2. MATERIALS AND METHODS

The one who studied in detail the way human body reacts to vibration was Dieckmann in 1958 [14]. Thus, a vibration stress coefficient k was defined, and it considers the simultaneous influence of frequency and amplitude. Based on physiological and physical studies, Dieckmann also considered the subjects' perception of and obtained for the stress coefficient k the following equations:

$$\text{Vertical vibrations}\ \left|\begin{array}{ll} k = X\nu^2 & 0.5\le\nu\le 5 \\ k = 5X\nu & 5\le\nu\le 40 \\ k = 200X & 40\le\nu\le 100 \end{array}\right. \qquad \text{Horizontal vibrations}\ \left|\begin{array}{ll} k = 2X\nu^2 & 0.2\le\nu\le 2 \\ k = 4X\nu & 2\le\nu\le 25 \\ k = 100X & 25\le\nu\le 100 \end{array}\right.$$

where X is the displacement peak (mm) and ν the frequency.

The threshold of vibration perception corresponds to k=0,1 and at the other end, the permissible limit for 1 min is given by k=100. These values are also presented in DIN 4024: 2001. Figures 2 and 3 show amplitude and acceleration variations of vertical and horizontal vibrations in relation to frequency and stress coefficient k [15].

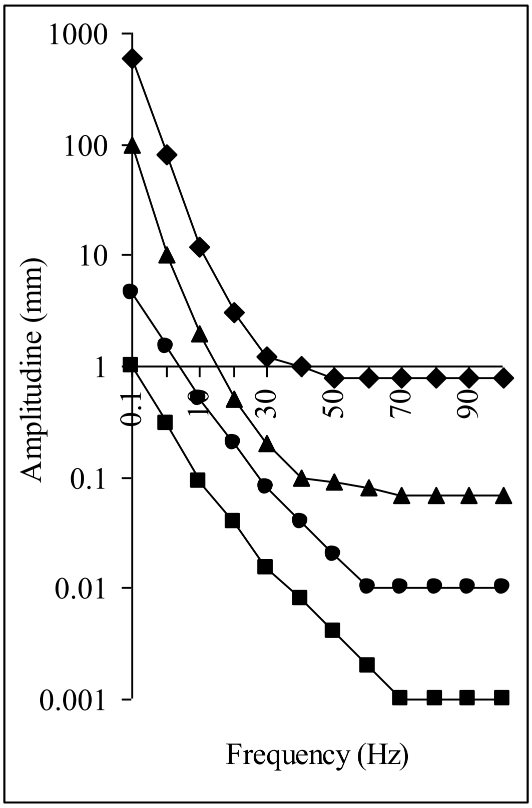


Fig. 2. Amplitude variation with frequency depending on vibration stress coefficient k (♦)-k=100; (▲)-k=10; (●)-k=1; (■)-k=0.1

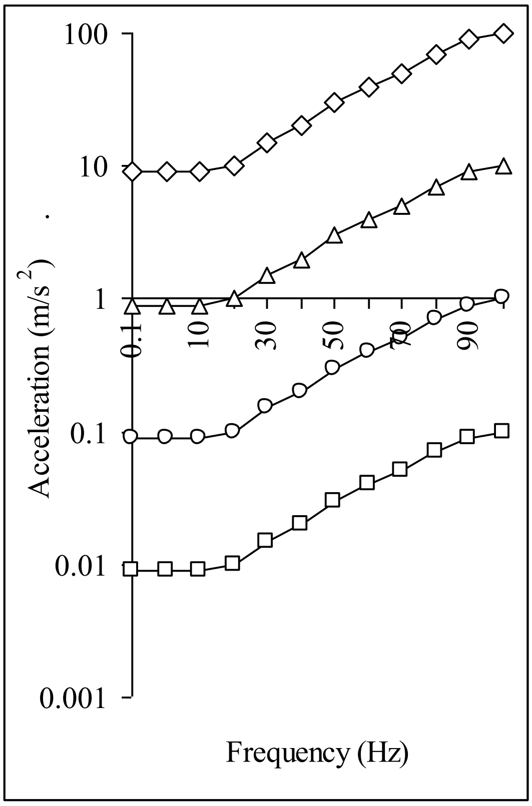


Fig. 3. Acceleration variation with frequency depending on vibration stress coefficient k (◊)-k=100; (Δ)-k=10; (o)-k=1; (□)-k=0.1

The coefficient k can be found depending on the effective acceleration r.m.s, the effective speed r.m.s. and the effective displacement r.m.s.. The values of the constants α, β and γ are given directly in the formulas, and ν_0=10Hz [15]:

$$k = a_{ef}\frac{\alpha}{\sqrt{1+\left(\frac{\nu}{\nu_0}\right)^2}} = a_{ef}\frac{18}{\sqrt{1+\left(\frac{\nu}{10}\right)^2}} = a_{ef}\frac{180}{\sqrt{100+\nu^2}} \quad (1)$$

$$k = v_{ef}\frac{\beta\cdot\nu}{\sqrt{1+\left(\frac{\nu}{\nu_0}\right)^2}} = v_{ef}\frac{0{,}112\cdot\nu}{\sqrt{1+\left(\frac{\nu}{10}\right)^2}} = v_{ef}\frac{1{,}12\cdot\nu}{\sqrt{100+\nu^2}} \quad (2)$$

$$k = x_{ef}\frac{\gamma\cdot\nu^2}{\sqrt{1+\left(\frac{\nu}{\nu_0}\right)^2}} = x_{ef}\frac{0{,}71\cdot\nu^2}{\sqrt{1+\left(\frac{\nu}{10}\right)^2}} = x_{ef}\frac{7{,}1\cdot\nu^2}{\sqrt{100+\nu^2}} \quad (3)$$

The k coefficient was also determined by the acceleration peak A (mm/s^2), the velocity peak V (mm/s) and the displacement peak X (mm). The constant values are directly given in equations, and ν_0=10Hz [6, 14].

$$k = A\frac{12{,}5}{\sqrt{1+\left(\frac{\nu}{10}\right)^2}} = A\frac{125}{\sqrt{100+\nu^2}} \quad (4)$$

$$k = V\frac{0{,}08\cdot\nu}{\sqrt{1+\left(\frac{\nu}{10}\right)^2}} = V\frac{0{,}8\cdot\nu}{\sqrt{100+\nu^2}} \quad (5)$$

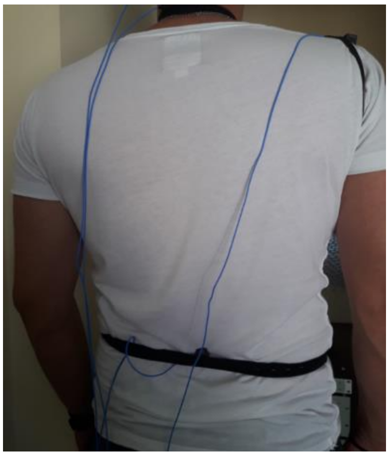
$$k = X\frac{0{,}5\cdot\nu^2}{\sqrt{1+\left(\frac{\nu}{10}\right)^2}} = X\frac{5\cdot\nu^2}{\sqrt{100+\nu^2}} \quad (6)$$

According to Griffin [6], in Table 2 are shown the values of k for which vibrations are tolerable. These tolerances are valid for discontinuous vibrations:

Table 2. Values of k for which vibrations are tolerable

k		**Tolerance**
0.1	......	Initial threshold
0.25	......	You can live with small breaks, or even without breaks
0.63	......	You can live with breaks
1,6	......	You can work without breaks
4	......	You can work with small breaks
10	......	You can work with long breaks
25	......	You can travel for long periods
63	......	You can travel for short periods

To verify how vibrations are transmitted through the human body and how the body mass index influences this, the following experiment was made: 10 subjects (males) were placed on the vibrant system (Fig. 4); men were approximately the same age (22-25 years) and in good health; none of them constantly practice sports and have sedentary jobs; 5 of these men are normal and 5 are pre-obese (Fig. 5).



accelerometer on lumbar

accelerometer on knee

accelerometer on forehead

Fig. 4. Normal subject on vibrant system

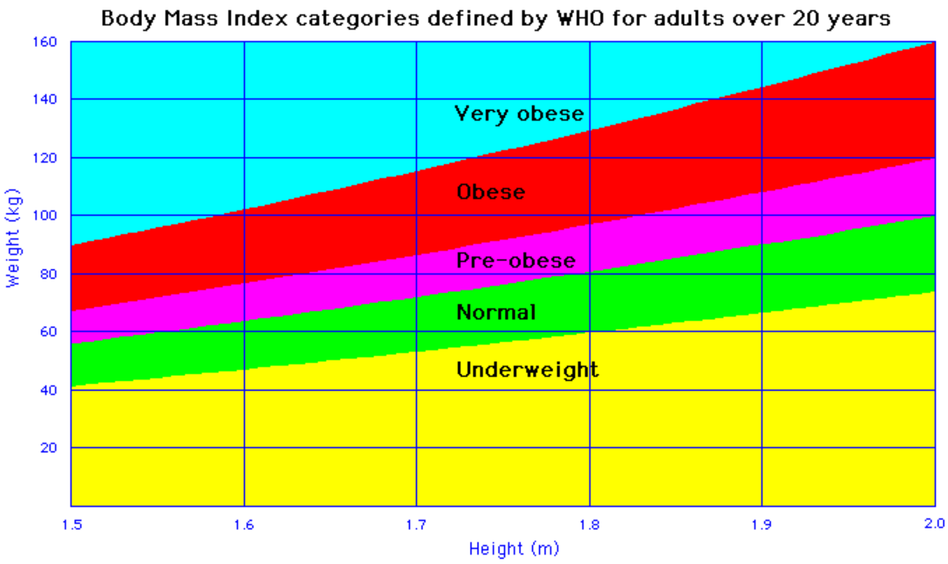


Fig. 5. Body mass index (http://links.zero.eu.org/health/bmi/)

The vibrant system was set to vibrate at frequencies between 5÷35 Hz (dangerous frequencies for the human body) and amplitudes A = 1; 1.5 and 4 mm. The irradiation time was in all cases 5 min. Accelerometers were mounted on the knee, in the lumbar region and on the forehead (Fig. 4). Transmissibility was calculated as the ratio between the acceleration measured with the accelerometer (a_{meas}) and the acceleration of the vibrating system ($a_{v.s.}$).

$$T = \frac{a_{meas}}{a_{v.s.}} \tag{7}$$

3. RESULTS AND DISCUSSION

Tables 3 and 4 present the measurement results and the calculations made with http://www.hse.gov.uk/vibration/wbv/calculator.htm of the specific physical quantities in the case of vibration transmission from the oscillating vibration system with an acceleration of 4m/s^2, in frequency band 5-35Hz. Normal subjects (Table 3) and pre-obese subjects (Table 4) are subjected to vibration for 5 minutes and accelerometers are placed on the forehead.

Table 3. The measurement results and calculations of the specific physical quantities of vibrations in the case of normal subjects

Vibration magnitude r.m.s. m/s^2	**Exposure duration** min	**Partial VDV** m/s$^{1.75}$	**Partial exposure A(8)** m/s^2	**Time to reach EAV (VDV option) 9.1 m/s$^{1.75}$** hours	**Time to reach EAV (A(8) option) 0.5 m/s^2** hours	**Time to reach ELV (A(8) option only) 1.15 m/s^2** hours
3.125	5	18.2078	0.32	0.0051994	0.2048	1.08
3.159	5	18.4059	0.32	0.0049791	0.20042	1.06
3.242	5	18.8895	0.33	0.0044885	0.19028	1.01
3.164	5	18.4351	0.32	0.0049477	0.19978	1.06
3.244	5	18.9	0.33	0.0044774	0.19	1.01

Table 4. The measurement results and calculations of the specific physical quantities of vibrations in the case of pre-obese subjects

Vibration magnitude r.m.s. m/s^2	**Exposure duration** min	**Partial VDV** m/s$^{1.75}$	**Partial exposure A(8)** m/s^2	**Time to reach EAV (VDV option) 9.1 m/s$^{1.75}$** hours	**Time to reach EAV (A(8) option) 0.5 m/s^2** hours	**Time to reach ELV (A(8) option only) 1.15 m/s^2** hours
2.845	5	16.5764	0.29	0.0075687	0.2471	1.31
2.796	5	16.2909	0.29	0.0081134	0.25583	1.35
2.879	5	16.7745	0.29	0.0072175	0.24129	1.28
2.992	5	17.4329	0.31	0.0061873	0.22341	1.18
2.744	5	16	0.28	0.0087461	0.266	1.41

It is found that for normal subjects, the average for Time to reach EAV (A(8) option) = 0.197056 h and for Time to reach ELV (A(8) option only) = 1.044h, while for pre-obese subjects, these averages are higher: 0.246726h, respectively 1.306h.

In figures 6 and 7 are shown total VDV calculation and total exposure A(8) calculation, where it can be seen that for normal subjects, total VDV calculation is 11.66% higher than for pre-obese subjects. The same result is also obtained for the total exposure A(8) calculation that is higher in normal subjects with 11.73% as against pre-obese subjects.

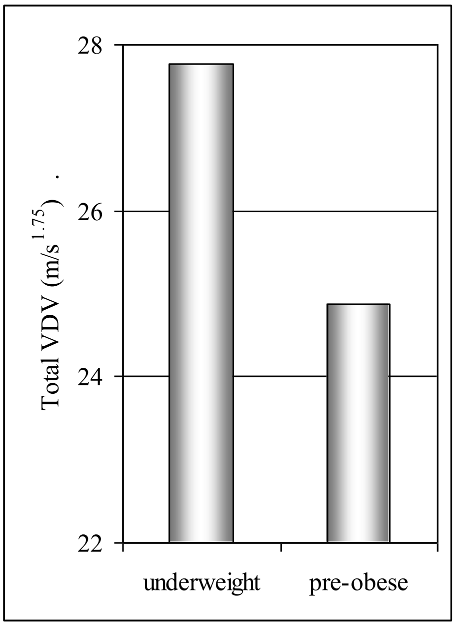


Fig. 6. Total VDV

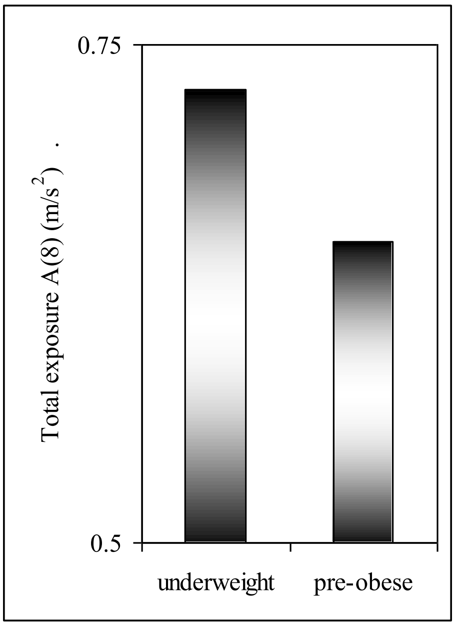


Fig. 7. Total exposure A(8)

Regarding transmissibility, it was calculated with Eq (7) for the three analysed situations: with accelerometers on the knee, on the lumbar region and on the forehead. Graphic representations of these are shown in Figures 8, 9 and 10.

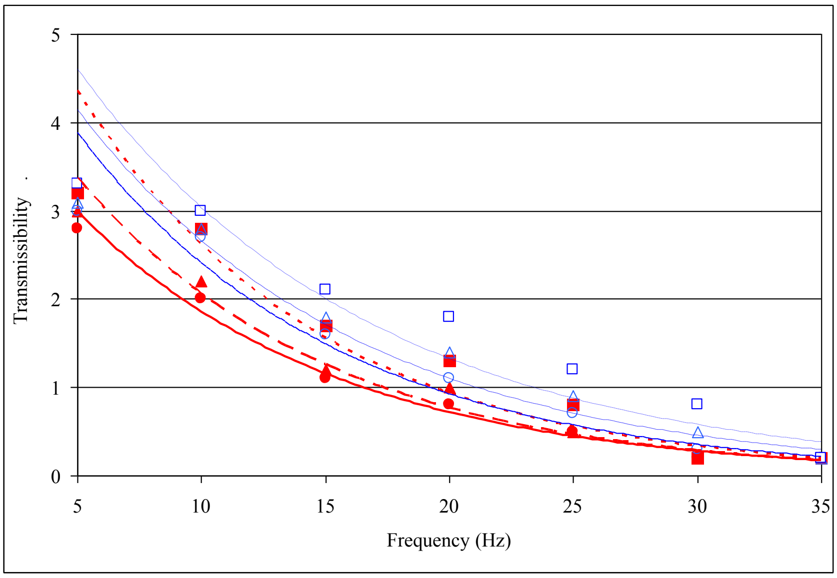


Fig. 8. Transmissibility variation on the frequency band 5÷35Hz for the 3 amplitudes A = 1mm, 1.5mm and 4mm, on the knee

For average BMI = 26.12 (pre-obese subjects)

A = 1mm ● ———	$T = 4.8092 \cdot e^{-0.0951 \cdot v}$	$R^2 = 0.9745$
A = 1.5mm ▲ – – –	$T = 5.5154 \cdot e^{-0.0985 \cdot v}$	$R^2 = 0.9658$
A = 4mm ■	$T = 5.7469 \cdot e^{-0.1005 \cdot v}$	$R^2 = 0.9356$

For average BMI = 18.27 (normal subjects)

A = 1mm o ———	$T = 6.2538 \cdot e^{-0.0953 \cdot v}$	$R^2 = 0.9706$
A = 1.5mm Δ – – –	$T = 6.4408 \cdot e^{-0.0883 \cdot v}$	$R^2 = 0.9384$
A = 4mm □	$T = 6.9639 \cdot e^{-0.083 \cdot v}$	$R^2 = 0.8531$

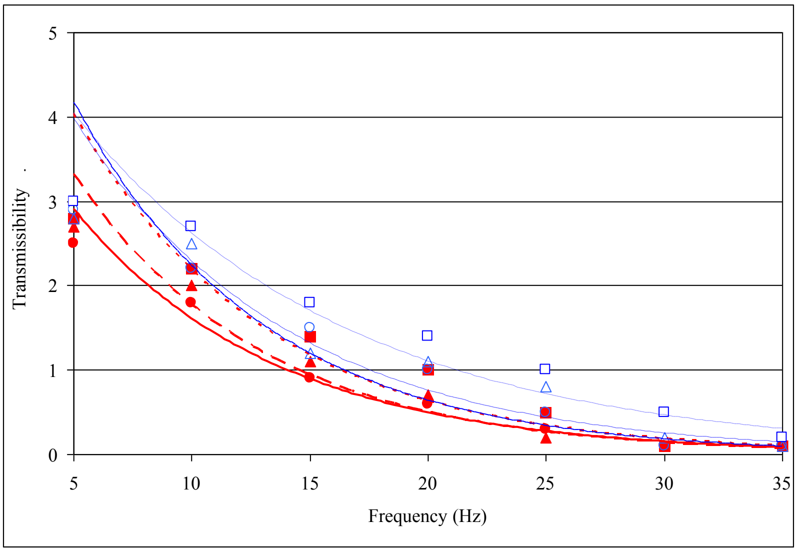


Fig. 9. Transmissibility variation on the frequency band 5÷35Hz for the 3 amplitudes A = 1mm, 1.5mm and 4mm, on the lumbar region

For average BMI = 26.12 (pre-obese subjects)			For average BMI = 18.27 (normal subjects)		
A = 1mm ● ▬▬▬	$T = 5.2554 \cdot e^{-0.1181 \cdot v}$	$R^2 = 0.9716$	A = 1mm o ───	$T = 7.76 \cdot e^{-0.1242 \cdot v}$	$R^2 = 0.9236$
A = 1.5mm ▲ ▬ ▬ ▬	$T = 6.2198 \cdot e^{-0.1256 \cdot v}$	$R^2 = 0.9585$	A = 1.5mm Δ – – –	$T = 6.921 \cdot e^{-0.1104 \cdot v}$	$R^2 = 0.911$
A = 4mm ■ · · · ·	$T = 4.8159 \cdot e^{-0.1188 \cdot v}$	$R^2 = 0.9166$	A = 4mm □	$T = 6.2235 \cdot e^{-0.0863 \cdot v}$	$R^2 = 0.9231$

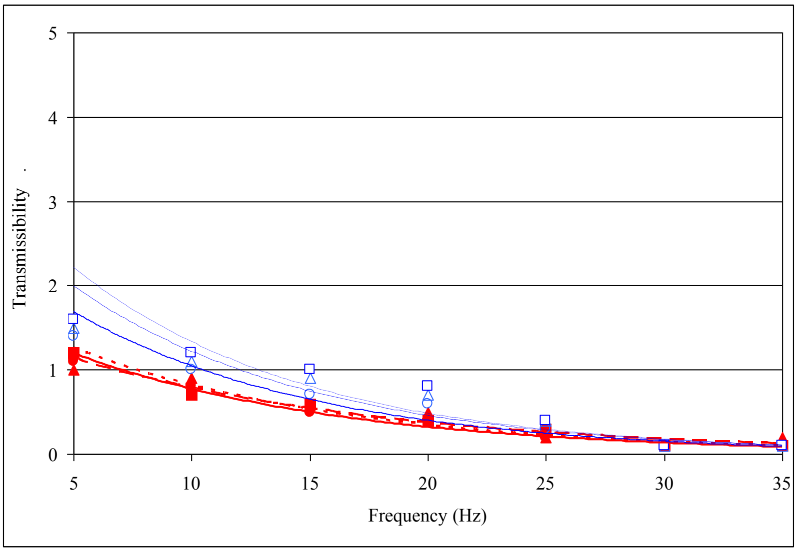


Fig. 10. Transmissibility variation on the frequency band 5÷35Hz for the 3 amplitudes A = 1mm, 1.5mm and 4mm, on the forehead

For average BMI = 26.12 (pre-obese subjects)			For average BMI = 18.27 (normal subjects)		
A = 1mm ● ▬▬▬	$T = 1.8528 \cdot e^{-0.0876 \cdot v}$	$R^2 = 0.9704$	A = 1mm o ───	$T = 2.7297 \cdot e^{-0.0955 \cdot v}$	$R^2 = 0.9371$
A = 1.5mm ▲ ▬ ▬ ▬	$T = 1.6465 \cdot e^{-0.0737 \cdot v}$	$R^2 = 0.8327$	A = 1.5mm Δ – – –	$T = 3.2489 \cdot e^{-0.0981 \cdot v}$	$R^2 = 0.9025$

A = 4mm $T = 1.9373 \cdot e^{-0.086 \cdot v}$ $R^2 = 0.9466$ | A = 4mm $T = 3.6754 \cdot e^{-0.1015 \cdot v}$ $R^2 = 0.8959$

From these graphics it is clear that for pre-obese people transmissibility is lower than for the normal people. Also, it is found that transmissibility exponentially decreases with the frequency increase of the vibrant system.

i) In the first case (measurements made at knee level), the term in front of the exponential has close values, ranging from 4.8÷5.7 for pre-obese subjects, respectively between 6.2÷6.9 for normal subjects.

ii) In the second case (measurements made at the lumbar region), the term in front of the exponential also has close values, ranging from 4.8÷6.2 for pre-obese subjects, respectively between 6.2÷7.7 for normal subjects.

iii) In the third case (measurements made on the forehead) the term in front of the exponential has close values, ranging from 1.6÷1.9 for pre-obese subjects, respectively 2.7÷3.6 for normal subjects.

The clearest delimitation between the transmissibility values for pre-obese and normal subjects is seen in the measurements made with the accelerometer mounted on the forehead.

As for the exponential powers, these are within a very narrow range: 0.07÷0.12 (both extremes are encountered in pre-obese subjects) (Fig. 11).

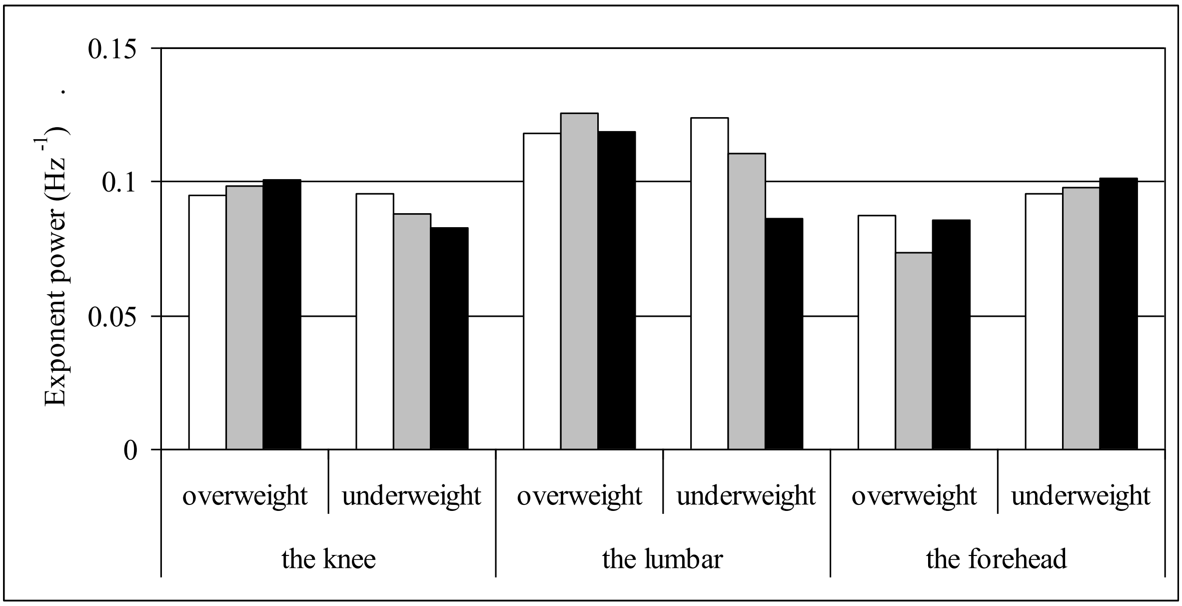


Fig. 11. Variation of exponential powers on the position of the accelerometers, vibration amplitude and BMI (□) – A = 1mm; (■) – A = 1.5mm; (■) – A = 4mm

4. CONCLUSIONS

From those presented in this paper, it can be seen that - for the studied cases - the dependence of vibrations transmissibility on frequency is strictly exponential decreasing. It is also seen that waves transmissibility is strongly dependent on BMI; for overweight people, transmissibility is lower than for normal people. In addition, transmissibility is also dependent on the magnitude of the waves. In other words, the transmissibility of elastic waves depends on the wave parameters, but also on the individual characteristics of each individual.

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References

1. Picu, L., Rusu, E.V.C., Whole body vibrations of a pushtow boat crew on the Danube, Mechanical Testing and Diagnosis, ISSN 2247-9635, 2017 (VII), Volume 1, pp 28-35.
2. Picu, M., Picu, L., Particular aspects regarding the effects of whole body vibration exposure, International Conference on Engineering Vibration, Sofia (ICoEV 2017), Bulgaria, 4-7 September 2017, MATEC Web Conf., 148 (2018) 09005, DOI: https://doi.org/10.1051/matecconf/201814809005.
3. Picu, L., Biodynamics of the Human Body under Hand-Arm Vibration: Development of a Biomechanical Model, The 11th European Congress and Exposition on Noise Control Engineering, (Euronoise 2018), Hersonissos, Crete, 27-31 May 2018, Conference Proceedings, pp 2663-2668.
4. Palmer, K.T., Coggon, D.N., Bendall, H.E., Pannett, B., Griffin, M., Haward, B., Whole-body Vibration: Occupational Exposures and their Health Effects in Great Britain. HSE Contract Research Report 233/1999, London: HMSO.
5. Picu, L., Rusu, E.V.C., Multiple physical stress exposures of sailors on several ships – A longitudinal study, Annals of Dunarea de Jos University, Fascicle II-Mathematics, Physics, Theoretical Mechanics, ISSN 2067-2071, Year X(XLI) 2018, No. 1, pp 84-93.
6. Griffin, M.J., Handbook of Human Vibration, San Diego CA: Academic Press Inc, 1990.
7. Picu, L., Picu, M., Rusu, E.V.C., Evaluation of Human Exposure to Whole-Body Vibration - Verification Method of Stevens's Power Law, The 18th International Multidisciplinary Scientific GeoConference (SGEM 2018), Albena, Bulgaria, 30 June - 9 July 2018, Conference Proceedings Vol. 18, Issue: 5.2, pp 413-420, DOI: 10.5593/sgem2018/5.2/S20.055.
8. Mansfield, N.J., Griffin, M.J., Non-linearities in apparent mass and transmissibility during exposure to whole-body vertical vibration, Journal of Biomechanics, Volume 33, Issue 8, August 2000, pp 933-941.
9. Kiiski, J., Heinonen, A., Järvinen, T.L., Kannus, Pe., Sievänen, H., Transmission of Vertical Whole Body Vibration to the Human Body, Journal of Bone and Mineral Research, Vol. 23, Nr. 8, 2008.
10. Huang, Y., Griffin, M.J., Nonlinearity in apparent mass and transmissibility of the supine human body during vertical whole-body vibration, Journal of Sound and Vibration, Volume 324, Issues 1–2, 10 July 2009, pp 429-452.
11. Harazin, B., Grzesik, J., The Transmission of Vertical Whole-Body Vibration to the Body Segments of Standing Subjects, Journal of Sound and Vibration, Volume 215, Issue 4, 27 August 1998, pp 775-787.
12. Yang, L., Gong, H., Zhang, M., Transmissibility of Whole Body Vibration Stimuli Through Human Body in Different Standing Postures, Journal of Mechanics in Medicine and Biology, Vol. 12, No. 03, 2012.
13. Yoshimura, T., Nakai, K., Tamaoki, G., Multi-body Dynamics Modelling of Seated Human Body under Exposure to Whole-Body Vibration, Industrial Health, 43, 2005.
14. Dieckmann, D., A study of the influence of vibration on man, *Ergonomics*, Vol. 1, Issue 4, 1958, 347-355, 1958.
15. Bratu, P., Izolarea și amortizarea vibrațiilor la utilaje de construcții, Ed. INCERC, București, 1982.