AN ATTEMPT TO ESTIMATE NATURAL FREQUENCIES OF PARTS OF THE CHILD'S BODY

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Summary

Recently, particular attention has been increasingly often paid by researchers to the children that are transported in safety seats as such children should be treated with no less care than "normal" passengers would, especially in the case of long-distance travels. The issue of the influence of vibrations on adult's bodies has been relatively well described, which is reflected in numerous normative acts [S1 to S13]. For children, however, the studies on these issues are still at an early stage.

We may state, therefore, that the evaluation of ride comfort with respect to small children whose anthropological characteristics differ from those of adults is still an open question [1].

In this paper, the issue of natural frequencies of parts of the human body has been raised and attention has been drawn to the lack of data about natural frequencies of parts of the child's body. A method has been proposed that would make it possible to estimate the frequencies of free vibration of organs and parts of the child's body, based on data collected from adults. A computational method to estimate the natural frequencies of parts of the body has been presented. Results of experimental road tests carried out with the use of dummies representing an adult (HYBRID II) and a child, made at PIMOT, have been included.

Keywords: child, automotive vehicle, vertical vibrations, natural frequencies of parts of the body.

1. Introduction

The biggest dangers to human health are caused by resonance vibrations of internal organs because these organs have the greatest possibility to move. The human body is most susceptible to vibrations along its longitudinal axis (vertical vibrations). Damage to the internal organs takes place when the damping of vibrations (by other organs, tissues, peritoneal fluid, air, or gases present in the organs) is too weak for the resonance vibrations of the internal organs to be sufficiently damped down. In the case of a sitting body, the vibrations, especially those of the highest frequencies, are dampened to the highest degree

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by the buttocks. The vibrations are further dampened when they are transmitted through the vertebral column, which has relatively high vibration damping characteristics (it is surrounded by ligamentous and chondral elements). At this stage, low-frequency vibrations cause alternating compression and tension of the vertebral column and propagation of vibration wave along the human body. If the vibration amplitude is adequately damped down during the vibration wave propagation process then only a small part of the vibration may reach the head. For the vertebral column, the type of the sitting position is important [2]. The body position may have a significant impact on the magnitude of the transmission of vibrations in sitting persons and it determines the degree of the harmful effects. In the range close to the body resonances, a change in the body position or in the tension of muscles may help to reduce the impact of vibrations. The effects of a change in the body position increase with rising frequencies, which may result in considerable changes in the transmission of vibrations along the vertebral column up to the head. A change in the body position that results in a change in the body contact with the vibrating surface, such as the seat backrest, may also have an impact on the vibration effects [3]. The sitting man's vulnerability to vibration with a frequency of 5 Hz is 10 times as high as that observed at 100 Hz [4]. Simultaneously, the research works carried out by M. J. Griffin, N. J. Mansfield, A. J. Messenger, and G. S. Paddan [5, 6, 7, and 8] have shown that the test results are significantly affected by the type of the sitting position adopted, i.e. deviation of the torso under tests from the perpendicular. The highest values of the tension and pressure in the intervertebral disc occur when the torso is situated vertically; they decline with increasing angle at which the torso is tilted back.

For the standing position, the effects of vertical vibrations are often similar to those observed for the sitting body; however, the impact of frequencies exceeding 3 Hz may be significantly reduced when the knees are bent [3].

Natural frequencies of selected organs and parts of the adult human body, determined experimentally and causing the feeling of severe discomfort, have been presented in Table 1 [9].

Table 1. Examples of natural frequencies of organs and parts of the adult human body, determined experimentally [9]

Part of the body	Frequency [Hz]	Observed pathological signs possible to occur
Head Head with neck Shoulders and head Jaw Eyeballs	4÷5; 17÷25 20÷30 20÷30 6÷8 60÷90; 40÷90	Pains, vertigo, disequilibrium, feeling of pressure in the larynx, nausea, forced rotational movements of the head, dysarthria, general state of psychophysical tiredness
Organs in the abdominal cavity: Liver Stomach Urinary bladder Kidneys	4,5÷10 3÷4 2÷3 10÷18 6÷8	Feeling of vibration of internal organs, pains, nausea, feeling of fullness, urge to urinate and to pass a stool, weakness and tiredness

Thorax	5÷7 4÷11	Respiratory disorders, feeling of being squeezed, shallow breath, burning pains in the chest
Organs in the thorax: Lungs Heart Trachea, bronchi	5÷9 4÷11 4÷6 12÷16	Respiratory disorders, breathlessness, quickening of breath, feeling of anxiety, quickening of pulse, variations in blood pressure, quickened heart beating, speech disorders, general ill-being
Upper part of the torso: Shoulders and head	4÷5 20÷30	Joint and muscular pains, pains in the cervical spine, increased muscle tone, feeling of tiredness
Lower part of the torso: Pelvis Vertebral column Sacral spine Lumbar spine	4÷6 5÷9 10÷12 8÷12 8÷12	Joint and muscular pains, pains in the sacral spine and lumbar spine, increased muscle tone, feeling of tiredness
Lower limbs: Hips Calves Feet	5 5 20 -	Joint pains, increased muscle tone, numb sensation and formication in muscles
Upper limbs: Arm Forearm Hand	4÷5 16÷30 4÷6 20÷30	Joint pains, increased muscle tone, muscular pains, involuntary muscular contractions causing additional hand movements, difficult carrying out of tasks

2. Natural frequencies of parts of the child's body

A comparison of body proportions of the newborn baby and the adult has been presented in Table 2. The head length to body length ratio changes with age: for children aged 2, 6, and 15 years, this ratio is 1/5, 1/6, and 1/7, respectively [10].

Specific parts of the skeleton system grow with different rates. The modulus of elasticity (E) changes with age, too, i.e. it increases in people aged, roughly, up to 25 years (Fig. 1). Simultaneously, the amount of energy absorbed at impact declines with age, from 30 kJ/m^2 for children aged 2 years to 8 kH/m^2 for people 90 years old. The tensile strength changes with age as well, according to a formula $\sigma_r = 134 - 0.61T$ (where T = age in years) [11].

Table 2. Comparison of body proportions of the newborn baby and the adult [10]

Part of the body	Children (in relation to the overall body length)	Adults (in relation to the overall body length)
Head	1/4	1/8
Torso	2/4	3/8
Lower limbs	1/4	4/8

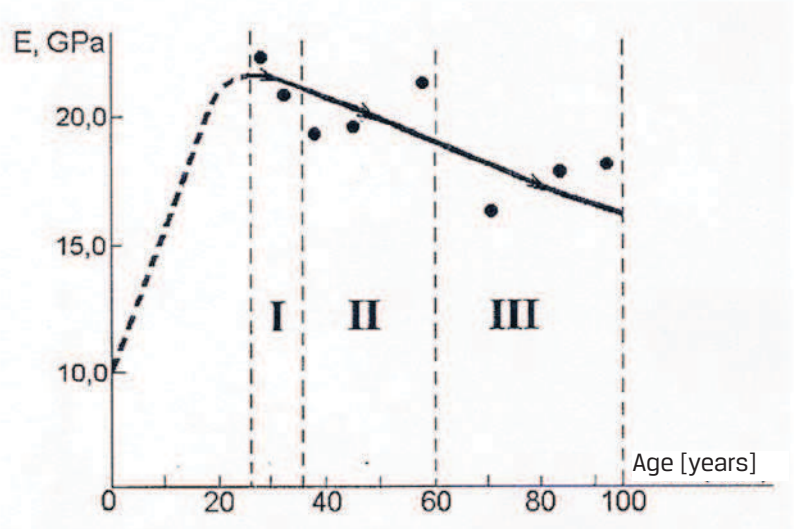

Fig. 1. Modulus of elasticity (E) of bones of the human body vs. age [11].

As it can be seen from the above, the differences between the organisms of a child (at specific development stages) and an adult are so significant that the child and the adult should be treated differently. Therefore, a question should be considered how to determine the natural frequencies of organs and parts of the child's body in order to obtain data similar to those described in Table 1 for the adult. A method that may make it possible to estimate the values of such frequencies is presented below.

The estimation was based on the natural frequencies of organs and parts of the adult's body determined experimentally, see Table 1.

According to the theory of the strength of materials, the longitudinal and bending stiffness of a beam depends on the modulus of longitudinal elasticity (Young's modulus, E) [12].

For tension, the specific stiffness k_{jR} is defined by the product (1):

$$k_{jR} = E \cdot A \tag{1}$$

where: A – the cross-sectional area.

For bending, the specific stiffness k_{jZ} is defined by the product (2):

$$k_{jZ} = E \cdot J \tag{2}$$

where: J – the area moment of inertia of the beam cross-section.

The natural frequency ω_0 as defined by (3) depends on mass (m), modulus of longitudinal elasticity (E) (through stiffness (k)), and damping coefficient (c).

$$\omega_0 = \sqrt{\frac{k}{m} - (c/2m)} \tag{3}$$

The damping coefficient (c) is unknown; therefore, equation (3) may be simplified to the following form (4):

$$\omega_0 = \sqrt{\frac{k}{m}} \tag{4}$$

According to Fig. 1, the Young's modulus value (E) of human bone tissue changes with age [9].

In consequence of the fact that a dummy representing a child with a mass of 15 kg (i.e. aged about 3 years) was used for the tests, we may assume, based on Fig. 1, that the E value of the child was in this case about a half of that of the adult, whose mass may be assumed as 75 kg (the mass of the HYBRID II dummy used for the tests was about 75 kg). The natural frequency of the adult may be described by equation (5):

$$\omega_{0adult} = \sqrt{\frac{k_{adult}}{m_{adult}}} \tag{5}$$

where: k_{adult} depends on E of the adult.

Similarly, the natural frequency of the child may be described by equation (6):

$$\omega_{0child} = \sqrt{\frac{k_{child}}{m_{child}}} \tag{6}$$

where: k_{child} depends on E of the child.

Taking into account the assumptions made that the mass of a child (dummy with a mass of 15 kg) is 1/5 of that of an adult (dummy with a mass of 75 kg) and that the E modulus of a child is 1/2 of that of an adult, we may deduce that the ratio of the natural frequency of the child's body to that of the adult's body may be estimated from formula (7). Of course, this is only applicable to the skeletal system, because the curve shown in Fig. 1 represents the E modulus determined for bones.

$$\omega_{0child}/\omega_{0adult} = \sqrt{\frac{\frac{1}{2}}{\frac{1}{5}}} = \sqrt{2.5} \tag{7}$$

According to (7), the natural frequency of parts (skeletal system) of the child's body may be expected to exceed that of the body (skeletal system) of an adult with a ratio of $\sqrt{2,5}$. Based on this, natural frequencies of the skeletal system of parts of the child's body may be estimated. Table 1 offers a set of resonance frequencies of selected parts of the adult's body, determined experimentally [9]. In turn, some resonance frequencies of selected parts of the child's skeletal system, estimated as described above, have been given in Table 3.

Table 3. Examples of natural frequencies of parts of the child's body, estimated from natural frequencies of the corresponding parts of the adult's body

Part of the body	Frequency*)[Hz]
Head	6÷8; 27÷40
Head with neck	32÷47
Shoulders and head	32÷47
Jaw	9÷13
Thorax	8÷11 6÷17
Pelvis	8÷14
Vertebral column	16÷19
Sacral spine	13÷19
Lumbar spine	13÷19
Lower limbs:	8
Hips	8
Calves	32
Feet	-
Upper limbs:	6÷8
Arm	25÷47
Forearm	6÷9
Hand	32÷47

*) Rounded off to integers in Hz

3. Experimental tests

As stated before, the questions related to the impact of vibrations on the organisms of adult humans have been extensively explored. In consideration of unavailability of adequate data about children, the values of natural frequencies were estimated from data determined for adults. To verify the estimates obtained, a decision was taken to carry out experimental tests. Due to the absence of experimental data collected from living individuals, indirect tests with the use of dummies representing an adult (HYBRID II, H2) and a child (CHILD, D) had to be carried out.

At PIMOT (Automotive Industry Institute), vertical vibrations were measured during test drives of a passenger car, with the use of the dummies mentioned above. The HYBRID II test dummy (H2) with a mass of 75 kg was placed on the back seat on the left side and fastened with a conventional three-point seat belt. On the right side of the back seat, a child safety seat was installed and a child dummy (D) with a mass of 15 kg was seated in it. Six different child seats were used for the measurements.

The CHILD dummy was seated in each safety seat at the successive series of measurements. At first, the dummy was seated in four conventional child seats and fastened with a three-point seat belt. These seats were named, for simplification, as "STANDARD" (FS) and denoted by F1S, F2S, F3S, and F4S. Then, the CHILD dummy was seated in two other child seats provided with a modern fixing system ISOFIX. In general, these seats were given a symbol of FX and individually denoted by F5X and F6X.

All the child safety seats used for tests (both STANDARD and ISOFIX) were designed for children with a body mass ranging from 9 to 18 kg or from 9 to 25 kg. They were selected for tests on a random basis; they represented different levels of technological advancement; all of them, however, met the validation requirements of UN-ECE Regulation No. 59 [S14]. The CHILD dummy was fixed in the seats in compliance with the instructions for use attached to the seats.

3.1. Preparations for measurements

During the tests, the measurement signals were recorded by means of a measuring circuit specially built for this purpose, where uniaxial piezoresistive accelerometers Brüel&Kjaer, type 4574, were installed as specified below:

- Accelerometer No. 1: on the vehicle floor (P)
- Accelerometer No. 2: in the head of the HYBRID II dummy (H2G);
- Accelerometer No. 3: in the torso of the HYBRID II dummy (H2T);
- Accelerometer No. 4: at the pelvis of the HYBRID II dummy (H2B);
- Accelerometer No. 5: on the seat cushion under the HYBRID II dummy;
- Accelerometer No. 6: in the head of the CHILD dummy (DG);
- Accelerometer No. 7: at the pelvis of the CHILD dummy (DT);
- Accelerometer No. 8: under the CHILD dummy's seat.

The measurement signals were recorded with the use of a digital recorder TDAS DTS Pro Lab, at a sampling frequency of 500 Hz. The measurement circuit was supplied with power from a 12 V storage battery, with the use of a converter Micro Control 12 V 600 W.

The measuring sensor locations, with coordinate values, have been presented in schematic diagrams in Figs. 2 and 3. All the sensors were positioned to measure vertical accelerations, i.e. accelerations in the directions where the highest vibration amplitudes occur during vehicle ride.

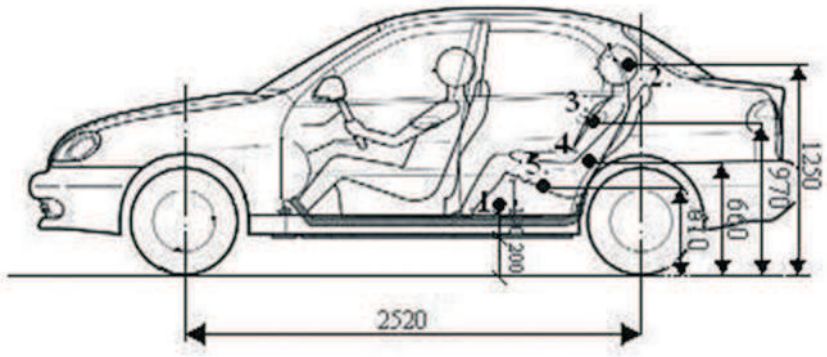

Fig. 2. Accelerometer locations, viewed when facing the HYBRID II dummy side.

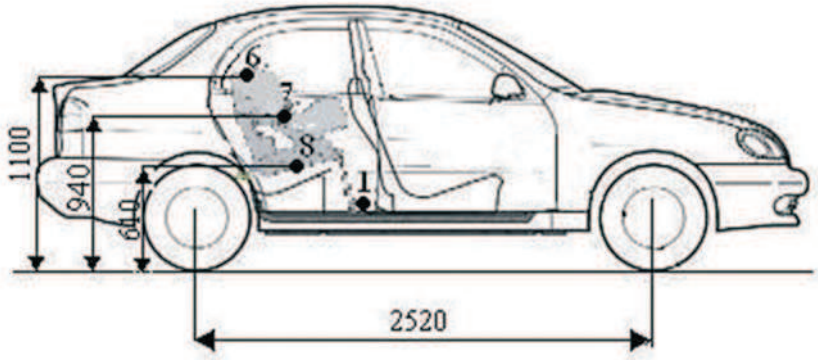

Fig. 3. Accelerometer locations, viewed when facing the CHILD dummy side.

3.2. Road tests

The measurements were carried out on a sunny day, on test road sections with dry surface, for three road surface types:

- "Even" asphalt (A, Fig. 4), drive speed 60 km/h, measured drive time 30 s;
- "Rough" road with significant unevenness (Br, Fig. 5), drive speed 60 km/h, measured drive time 30 s;
- The crossing of a "hump" (Gb, Fig. 6), drive speed 40 km/h, measured drive time 5 s.

Fig. 4. Test road section with "even" pavement (asphalt, A).

Fig. 5. Test drive on a "rough" road (Br).

Fig. 6. The crossing of a "hump" (Gb).

Below are given examples of the test results recorded for a STANDARD seat (Figs. 7 through 12) and an ISOFIX seat (Figs. 13 through 18).

Figs. 7 through 12 provide examples that make it possible to compare the power spectrum density of the signals recorded for the head and pelvis of dummies H2 and D during tests carried out on the three road types with a STANDARD seat (FS).

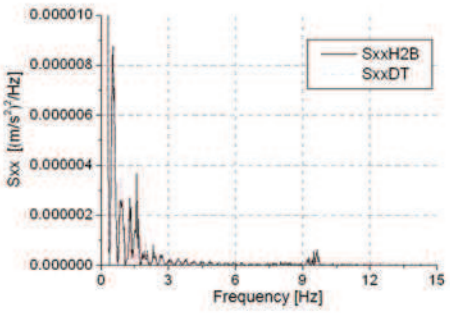

Fig. 7. Safety seat FS, test drive on a road with asphalt surface, comparison between H2B and DT.

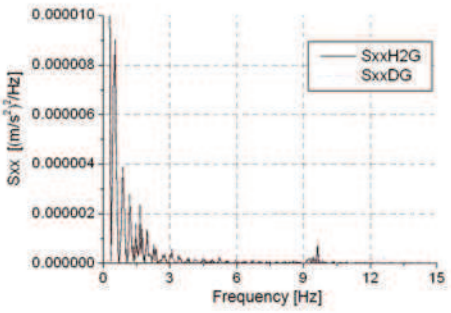

Fig. 8. Safety seat FS, test drive on a road with asphalt surface, comparison between H2G and DG.

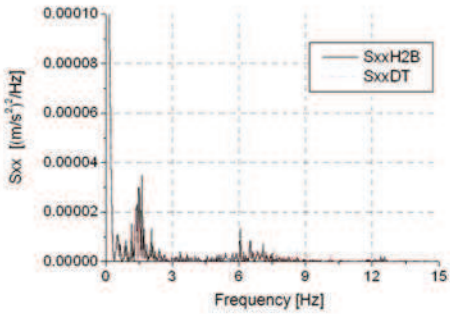

Fig. 9. Safety seat FS, test drive on a road with "rough" surface, comparison between H2B and DT.

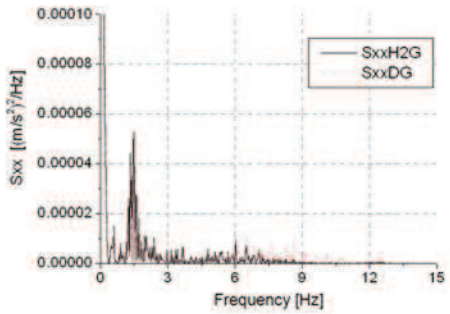

Fig. 10. Safety seat FS, test drive on a road with "rough" surface, comparison between H2G and DG.

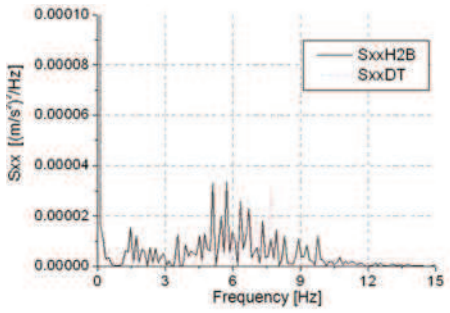

Fig. 11. Safety seat FS, the crossing of a "hump," comparison between H2B and DT.

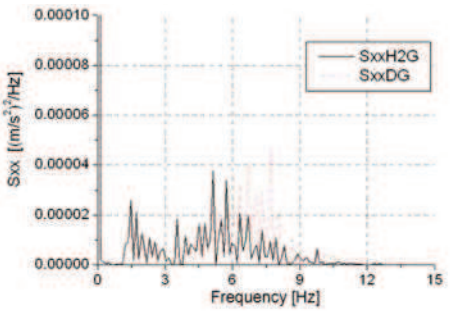

Fig. 12. Safety seat FS, the crossing of a "hump," comparison between H2G and DG.

Figs. 13 through 18, in turn, provide examples that make it possible to compare the power spectrum density of the signals recorded for the head and pelvis of dummies H2 and D during tests carried out on the three road types with an ISOFIX seat (FX).

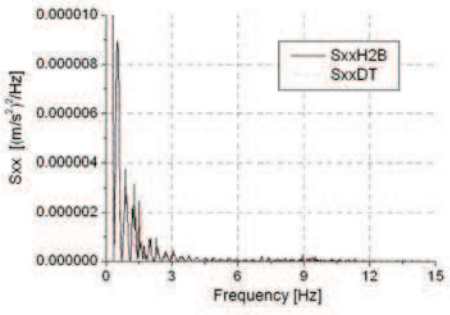

Fig. 13. Safety seat FX, test drive on a road with asphalt surface, comparison between H2B and DT.

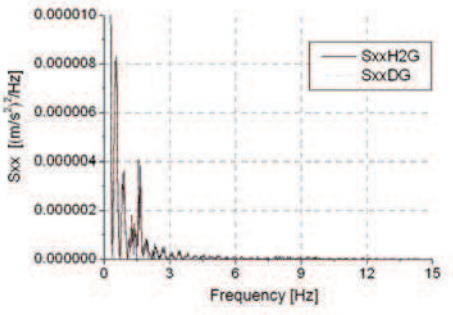

Fig. 14. Safety seat FX, test drive on a road with asphalt surface, comparison between H2G and DG.

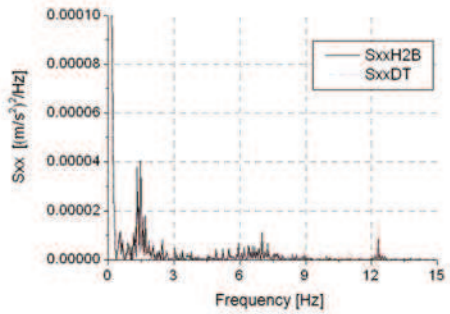

Fig. 15. Safety seat FX, test drive on a road with "rough" surface, comparison between H2B and DT.

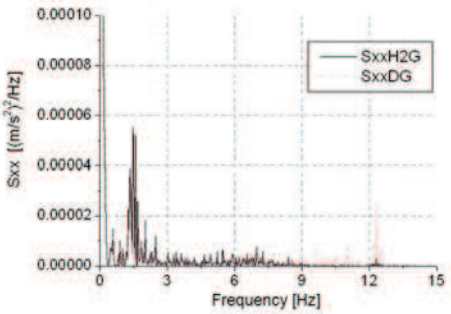

Fig. 16. Safety seat FX, test drive on a road with "rough" surface, comparison between H2G and DG.

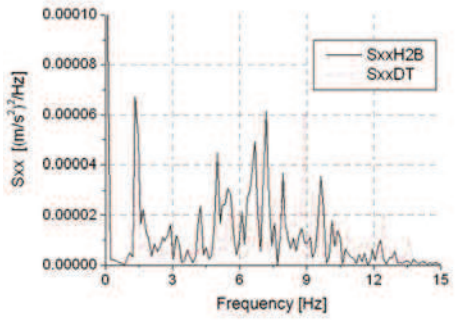

Fig. 17. Safety seat FX, the crossing of a "hump," comparison between H2B and DT.

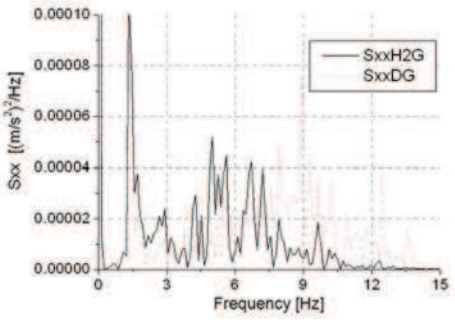

Fig. 18. Safety seat FX, the crossing of a "hump," comparison between H2G and DG.

For the test drives on a road with "even" surface (A) (Figs. 7, 8, 13, and 14), no differences were found to occur between the corresponding resonance frequencies of the H2 and D dummies (the signals recorded were similar to each other, in qualitative terms). It should be remembered, however, that the human body subjected to vibrations with frequencies of below 2 Hz begins to behave as a homogenous substance and this is the case when the test drive is carried out on an asphalt road. This applies to both the FS and FX safety seats.

At the test drives on a road with "rough" surface (Br) (Figs. 9, 10, 15, and 16), qualitative similarity between the signals recorded was also observed. Noteworthy is the fact that for H2B and H2G, the S_{xx} values fade away at frequencies above 8.5 Hz while for DT and DG, this threshold is 13 Hz. The ratio between these two frequency thresholds corresponds to the value of $\sqrt{2,5}$ (7). This applies to both the FS and FX safety seats.

At the crossing of a "hump" (Gb) (Figs. 11, 12, 17, and 18), both qualitative and quantitative differences between the signals recorded were noticed: considerable shift of natural frequencies is clearly visible between the values obtained for the H2 and D dummies. When comparing the test results recorded for the H2 and D dummies, the following findings could be formulated:

- The highest S_{xx} values were recorded at frequencies of the order of 1÷1.5 Hz, which confirms the statement that the human body subjected to vibrations with frequencies of below 2 Hz begins to behave as a homogenous substance.
- For the FS safety seats, the highest S_{xx} values measured by the DT and DG sensors occurred at frequencies of about 7.5 Hz and 7.5÷8 Hz, respectively. The H2B and H2G accelerometers recorded the highest S_{xx} values within a frequency range of 5÷5.5 Hz. The ratio between these frequencies is again close to the value of $\sqrt{2,5}$ (7).
- For the FX safety seats, the highest S_{xx} values measured by the DT and DG sensors occurred at a frequency of 9 Hz. For the H2B and H2G accelerometers, this frequency range is 5÷5.5 Hz. The ratio between these frequencies is again close to the value of $\sqrt{2,5}$ (7).

4. Recapitulation

The human body is a complex system and the adult and the child differ from each other not only in their mass and height but also in the proportions of their organs and parts of the body, i.e. in the size and mass (and hence, the moments of inertia) of specific body parts. Even this in itself shows how complex and intricate the human body is, from the engineer's point of view. This complexity translates into the variety of natural frequencies of individual organs and parts of the body, where the frequencies cannot be defined by single specific figures (see Table 1). Consistently, specific numerical values of the natural frequencies cannot be determined for the child's body, either.

We may state that the use of child seats of the FS and FX types for test drives on roads with different surfaces made it possible to reveal the "shift" of the natural frequencies of body parts between the D and H2 dummies. An exceptional situation takes place at low frequencies of 0.5 and 1.5 Hz, where qualitative and quantitative similarity between the corresponding S_{xx} values was recorded during the tests under consideration. This happens below the level of maximum susceptibility of the human body to vibrations, i.e. below the frequency range of 4÷8 Hz, and this should be considered a favourable phenomenon. Additionally, it should be stressed here that the human body subjected to vibrations with frequencies below 2 Hz begins to behave as a homogenous substance.

As regards children, very little information is available about how vibrations are felt by them. The child's body exhibits the highest capability to absorb vibrations in a frequency range of 3÷16 Hz (around 7.4 Hz, in average terms) [13]. In this frequency range, an increase in the acceleration values was observed for all the child seats. The shift between the D and H2 resonance frequencies also results in the fact that those measured for the child come within the range of 3÷16 Hz.

A method has been proposed here that would make it possible to estimate the resonance frequencies of organs and parts of the child's body. For this purpose, the dependence of the modulus of elasticity (E) of human bones on the age has been used. In the situation of general unavailability of data about the natural frequencies of parts of the child's body, it seems reasonable to employ such methods (where the H2 and D dummies would be used at the tests) that would help to acquire information of this kind. The method of estimating natural frequencies of organs and parts of the child's body as presented here is consistent with this line in the research work on this subject.

In general, the following statements may be formulated:

1. The higher input (the worse road surface) is, the more clearly visible are the differences in natural frequencies of parts of the body of an adult and a child.

2. At low vibration frequencies (of the order of 1÷1.5 Hz), the differences do not occur because the human body behaves in such conditions as a homogenous substance.

3. At vibration frequencies ranging from 2 to 10 Hz, the differences in natural frequencies of parts of the body of a child and an adult produce a ratio of the former to the latter close to $\sqrt{2,5}$ as determined from formula (7).

4. The method proposed may be used for the estimation of natural frequencies of organs and parts of the child's body.
5. The method proposed makes it possible to estimate the natural frequencies for children of various body mass values.
6. Apart from experimental road tests, there is a need for tests to be carried out on a special test stand.

References

[1] GIACOMIN J.: *Some observations regarding the vibrational environment in child safety seats*. Applied Ergonomics, No 31, 2000, pp. 207-215.

[2] KITAZAKI S., GRIFFIN M. J. *Resonance behavior of the seated human body and effects of posture*, Journal of Biomechanics 31 (1998), pp: 143-149.

[3] GRIFFIN M.J., *Handbook of human vibration*, Academic Press, London, 1990, ISBN, 0-12-303040-4.

[4] MANSFIELD N.J., *Human response to vibration*, CRC Press, London, 2005.

[5] MESSENGER A.J., GRIFFIN M.J.: *Effects of anthropometrical and postural variables on the transmission of whole-body vertical vibration from seat-to head.* The Institute of Sound and Vibration Research. Technical Raport No 172, University of Southampton, England 1989.

[6] MANSFIELD N.J., GRIFFIN M.J.: *Effects of posture and vibration magnitude on apparent mass and pelvis rotation during exposure to whole-body vertical vibration.* Journal of Sound and Vibration, No 253(1), 2002 Institute of Sound and Vibration Research, University of Southampton, England, pp. 93-107.

[7] PADDAN G.S., GRIFFIN M.J.: *Transmission of mechanical vibration trough the human body to the head.* Southampton Institute of Sound and Vibration Research, University of Southampton, England, Technical Raport , No 260, 1996.

[8] PADDAN G.S., GRIFFIN M.J.: *The transmission of translational seat vibration to the head –I: Vertical seat vibration*. Journal of Biomechanics, No 21, 1988, pp. 199-206.

[9] ZABOROWSKI T., ŻUKOWSKI P., *Podstawy zagrożeń hałasem i wibracją zdrowia człowieka.* IBEN, Gorzów Wlkp. 1995.

[10] JANICKI K. i inni, *Domowy poradnik medyczny,* Państwowy Zakład Wydawnictw Lekarskich, Wydanie II, Warszawa 1989.

[11] NAŁĘCZ M. I inni., *Biocybernetyka i inżynieria biomedyczna 2000*. Akademicka Oficyna Wydawnicza EXIT. Warszawa 2004.

[12] DEN HARTOG J. P., *Drgania mechaniczne*. PWN 1971 Warszawa.

[13] GIACOMIN J. *Absorbed power of small children,* Clinical Biomechanics 20 (2005), pp. 372–380.

Normative acts

[S1] BS 6841; 1987 Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock.

[S2] ISO 2631 1974 Guide for the evaluation of human exposure to whole-body vibration.

[S3] ISO 2631-1: 1997 Mechanical vibration and shock. Evaluation of human exposure to whole –body vibration. Part 1: General requirements.

[S4] ISO 2631-4: 2001 Mechanical vibration and shock. Evaluation of human exposure to whole –body vibration. Part 4: Guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed-guideway transport system.

[S5] ISO 2631-5: 2004 Mechanical vibration and shock. Evaluation of human exposure to whole –body vibration. Part 5: Method for evaluation of vibration containing multiple shock.

[S6] ISO 5982: 2001 Mechanical vibration and Shock – Range of idealized values to characterize seated-body biodynamic response under vertical vibration.

[S7] ISO 7962:1987 Mechanical vibration and Shock – Mechanical transmissibility of the human body in the direction.

[S8] Polska Norma PN-ISO 5805 grudzień 2002. Drgania i wstrząsy mechaniczne. Ekspozycja człowieka. Terminologia.

[S9] PN-EN 30326-1 2000 Drgania mechaniczne. Laboratoryjna metoda oceny drgań siedziska w pojeździe. Wymagania podstawowe.

[S10] PN-N-01352: 1991 Drgania. Zasady wykonywania pomiarów na stanowiskach pracy.

[S11] PN-N-01353: 1991 Drgania. Dopuszczalne wartości przyspieszenia drgań na organizm człowieka przez kończyny górne i metody oceny narażenia.

[S12] PN-N-01354: 1991 Drgania. Dopuszczalne wartości przyspieszenia drgań o ogólnym oddziaływaniu na organizm człowieka i metody oceny narażenia.

[S13] PN-S-04100: 1991 Drgania. Metody badań i oceny drgań mechanicznych na stanowiskach pracy w pojazdach.

[S14] Regulation No. 44, Uniform provisions concerning the approval of restraining devices for child occupants of power-driven vehicles ("child restraint system").