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RESEARCH ARTICLE

ANALYSIS OF VERTICAL VIBRATIONS TRANSMITTED TO CHILDREN WHEN RIDING IN SAFETY SEATS IN A CAR

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ABSTRACT

So far, the problem of harmful impact of vibrations on children when riding in safety seats in a car has not been sufficiently tackled. In the field of design of child safety seats, most effort was made to ensure safety during a collision because this is the main function of such seats. On the other hand, children significantly differ from adults in respect of their anatomy and physiology. The issue of the influence of vibrations on adult people's bodies has been relatively well described, which is reflected in numerous normative acts having been adopted. For children, however, the studies on these issues are still at an early stage and there are no normative acts of this kind. The child should be treated in a special way, differently from the adult. The paper covers experimental tests related to the impact of vertical vibrations on the body of a child riding in a car in a safety seat. Results of road tests carried out for various road surface types as well as results of rig tests have been analysed and comparisons have been made in the frequency domain.

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INTRODUCTION

There are many fields of human activity where the human may be exposed to harmful impacts when performing his or her tasks. The environment continuously changes under the influence of new technologies and varying economic, social, and demographic conditions. This also applies to transport, including motor transport. In the latter case, the driver and passengers not only must remain in a position that cannot be changed for a prolonged time but they are also exposed to noise and mechanical vibrations felt by them as most oppressive. Among the vibrations caused by technical means of transport, those occurring in motor transport impose the greatest hazard (Nader, 2001). Although the ride comfort improves, the amount of time spent by people, children inclusive, travelling by cars grows at the same time (http://www.polloco.pl/pdf/biala_ksiega_pl.pdf). 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. In this case, it is important that medical aspects should be taken into consideration (Giacomin, 2000; Rangel *et al*., 2008; Starr *et al*., 2001). The validation tests of child safety seats are chiefly focused on the evaluation of protection from harmful collision effects (UN-ECE Regulation No. 44). Examples of the research work of this kind have been described in (Pedder *et al*., 1994; Paine *et al*., 2003; Fildes, 2003). They do not cover the impact of vibrations (occurring during "normal" ride in a car) on the child's body, while the vibrations both cause discomfort and have a harmful impact on human health. The issue of the influence of vibrations on adult people's bodies has been relatively well described, which is reflected in numerous normative acts having been adopted (ISO 2631:1974. Guide for the evaluation of human exposure to whole-body vibration; ISO 2631-1:1997. Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements; BS 6841:1987. Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock; ISO 5982:2001. Mechanical vibration and Shock – Range of idealized values to characterize seated-body biodynamic response under vertical vibration; ISO 7962:1987. Mechanical vibration and Shock – Mechanical transmissibility of the human body in the "z" direction; PN-EN 30326-1:2000. Drgania mechaniczne. Laboratoryjna metoda oceny drgań siedziska w pojeździe. 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; 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

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shocks). For children, however, the studies on these issues are still at an early stage and there are no normative acts of this kind. Why should children be treated in a special way? The proportions between specific parts of the child's body change with their age and body mass (until the adolescence). In particular, the torso and limb lengths and the chest circumference grow faster than the head circumference does (see Fig. 1 (Janicki *et al*., 1989; Gomułka *et al*., 2001)). A comparison of body proportions of the newborn baby and the adult has been given in Table 1. The data presented show that the child should be treated in a special way, differently from the adult. Simultaneously, the authors of (Bell *et al*., 1994) have suggested, based on experimental tests carried out, that the resonance frequencies of specific body parts of the child differ from those of the adult.

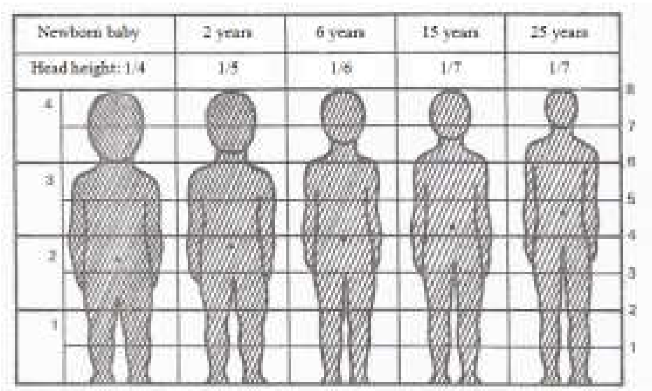

Fig. 1. Changes in human body proportions with body growth (Janicki *et al*., 1989)

Table 1. Comparison of body proportions of the newborn baby and the adult (Janicki *et al*., 1989)

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

The investigation of the harmful impact of vibrations and the evaluation of ride comfort with respect to small children whose anthropological characteristics differ from those of adults is undertaken by very few research centres. Two important examples may be given here: one of them is a team of researchers at the Institute of Sound and Vibration Research, University of Southampton, England, headed by J. Griffin (their studies include e.g. (Paddan and Griffin, 1993; Paddan and Griffin, 1996; Corbridge *et al*., 1987; Paddan and Griffin, 2002; Griffin, 2007), and the other one is a team headed by J. Giacomin at the BrunelUniversity (whose works include e.g. (Giacomin and Bracco, 1995; Giacomin, 2000; Giacomin, 2005; Giacomin and Hacambwa, 2000; Giacomin, 2004; Giacomin, and Gallo, 2000; Giacomin, 2007). Their publications have been dedicated to e.g. ride comfort issues (Corbridge *et al*., 1987; Griffin, 2007; Giacomin and Hacambwa, 2000), modifications of car seat characteristics aimed at ride comfort improvements, or transmission of vibrations to the human body (Paddan and Griffin, 1993; Paddan and Griffin, 1996; Giacomin, 2000; Paddan and Griffin, 2002). We may state, however, that the evaluation of the impact of vibrations generated during car movement on small children whose anthropological characteristics differ from those of the adults is still an open question (Murphy, 1998). Based on a piece of research work done at PIMOT (Automotive Industry Institute) and described in (Wicher *et al*., 2009), a need to carry out experimental tests on the impact of vertical vibrations on the body of a child riding in a safety seat in a car has been shown in (Więckowski and Wicher, 2010). The difference in the ride comfort felt by the child and the adult has been highlighted there, with showing that the ride comfort of the child is no better than that of the adult. Differences in the impact of vibrations on the child depending on the type of the safety seat used have also been pointed out. The lack of research work on this issue has been emphasised as well.

Experimental road tests

The road tests carried out included measurements intended to define the impact of vibrations on an adult and to compare it with the impact of such vibrations on children transported in safety seats. A HYBRID II test dummy with a mass of 75 kg was placed on the car backseat, on its left side, and fastened to the seat with a conventional three-point seat belt. On the right side of the backseat, a child safety seat was installed and a dummy representing a child (hereinafter referred to as a CHILD dummy) and having a mass of 15 kg was fixed in it. Why were dummies used for the tests? It would be ideal if the measurements could be carried out on living individuals, i.e. an adult and a child in this case. In practice, however, this would be very difficult, if not impossible at all. While the participation of an adult in tests of some kinds could be thought of, it is difficult to imagine that a child aged about 3 years (with a body mass of 15 kg) could be subjected to such experiments. The research on the impact of vibrations on a child's body is now at the initial stage and these questions in relation to children fixed in safety seats only begin to be noticed. Therefore, experimental tests must be based on what is available. A solution is offered by dummies (Bonnet *et al*., 2011). At PIMOT, dummies are used at many different tests. No wonder then, that an idea emerged to employ them for this purpose as well. Previously, this idea was tried at tests described in (Wicher *et al*., 2009). Moreover, a stress should be put here again on the unavailability of test results regarding the impact of vibrations on the body of a child riding in a safety seat in a car. Therefore, any research work that might result in a progress in this field, i.e. in the obtaining of any definite test results, information, or data, would automatically become helpful in exploring the impact of vibrations on a living child's body. This is a sufficient reason for the use of dummies for such tests. Six different child seats presented in Fig. 2 were used for the measurements (there are seven seats shown in the photo because two of them are specimens representing one seat type). The safety seats were selected on a random basis from among the seat types available in the market and represented different levels of technological advancement.

Fig. 2. General view of the child safety seats used for tests

The CHILD dummy was fixed in each safety seat at the successive series of measurements. At first, the dummy was placed in four conventional child seats and fastened with a three-point seat belt (Fig. 3). These seats were named, for simplification, as “STANDARD” 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 (Fig. 4) and denoted by F5X and F6X.

Fig. 3. One of the FS seats with the CHILD dummy, installed in the test car

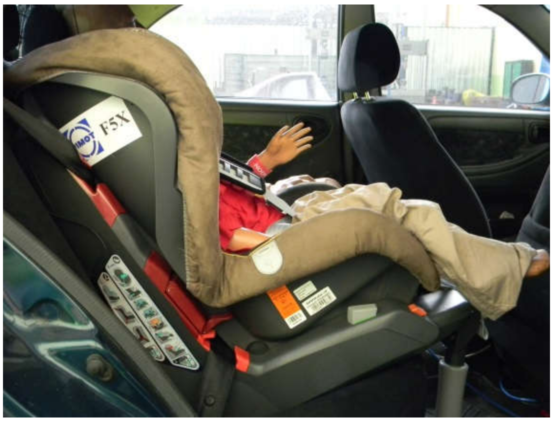

Fig. 4. One of the FX seats with the CHILD dummy, installed in the test car

Measuring circuit

During the tests, the measurement signals were recorded by means of a measuring circuit specially built for this purpose and schematically presented in Fig. 5.

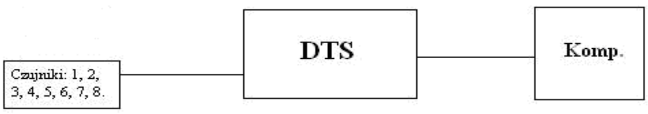

Fig. 5. Schematic diagram of the measuring circuit (DTS = Digital Technology System)

The measurements were carried out with the use of uniaxial piezoresistive accelerometers Brüel&Kjaer, type 4574, installed as specified below:

- Accelerometer No. 1: on the vehicle floor;
- Accelerometer No. 2: in the head of the HYBRID II dummy;
- Accelerometer No. 3: in the torso of the HYBRID II dummy;
- Accelerometer No. 4: at the pelvis of the HYBRID II dummy;
- Accelerometer No. 5: on the backseat cushion under the HYBRID II dummy;
- Accelerometer No. 6: in the head of the CHILD dummy;
- Accelerometer No. 7: at the pelvis of the CHILD dummy;
- 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 measuring sensor locations, with coordinate values, have been presented in schematic diagrams in Figs. 6a and 6b. All the sensors were positioned to measure vertical accelerations, i.e. accelerations in the direction where the highest vibration amplitudes occur during vehicle ride.

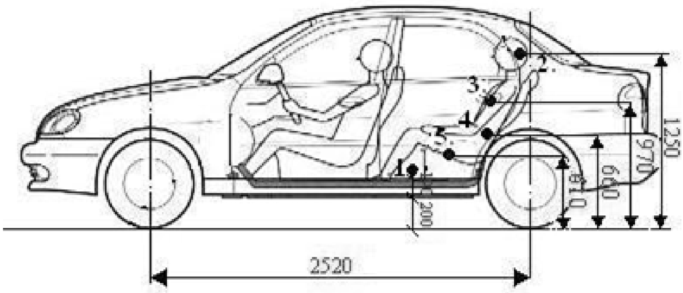

Fig. 6a. Accelerometer locations, viewed when facing the HYBRID II dummy side

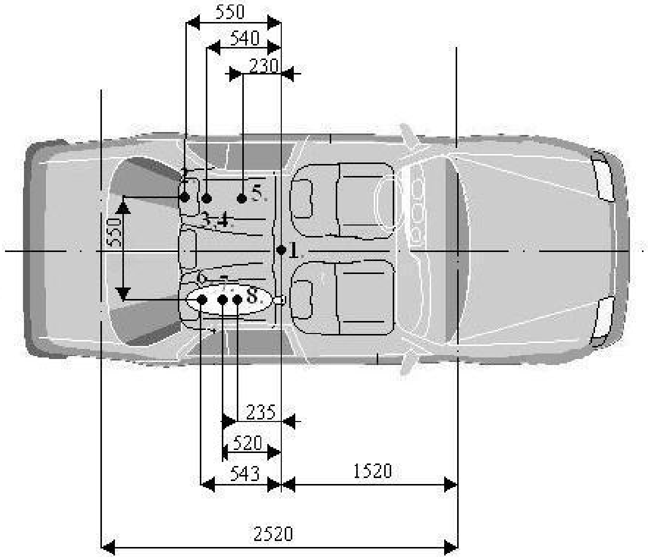

Fig. 6b. Accelerometer locations, viewed from the top

The measurements were carried out on test road sections with three road surface types: “even” asphalt (Fig. 7), drive speed 60 km/h; “rough” road with significant unevenness (Fig. 8), drive speed 60 km/h; and the crossing of a “hump” (Fig. 9), drive speed 40 km/h.

The following symbols have been adopted in the description of the test results:

A– “Even” asphalt;
B– Accelerometer placed at dummy’s pelvis;
Br– “Rough” road with significant unevenness;
D– CHILD dummy;

FS– STANDARD safety seat;
FX– Safety seat with the ISOFIX fixing system;
G– Accelerometer placed in dummy's head;
Gb– Crossing of a "hump";
H2– HYBRID II dummy;
K– Accelerometer placed on the seat cushion, between the cushion and the dummy;
Kf– Accelerometer placed under the CHILD dummy's seat;
P– Accelerometer placed on the vehicle floor;
T– Accelerometer placed in dummy's chest (torso).

Examples of symbol combinations:

FSDGBr–STANDARD child safety seat (FS), CHILD dummy (D), accelerometer in dummy's head (G), rough road with significant unevenness (Br); FXH2BGb–ISOFIX child safety seat (FX), HYBRID II dummy (H2), accelerometer at dummy's pelvis (B), crossing of a "hump" (Gb).

Fig. 7. Test road section with "even" surface (asphalt)

Fig. 8. Test road section with "rough" surface

Fig. 9. Test road section with a "hump"

Analysis in the frequency domain

According to the research work previously carried out at PIMOT (34), where comparisons were made between curves representing the power spectral density (PSD) of the vertical accelerations recorded by the accelerometers situated at the pelvis and in the chest of the H2 dummy's (H2B and H2T, respectively), the said PSD curves recorded for the two accelerometers did not differ from each other in both quantitative and qualitative terms. This means that the recording of PSD curves by only one accelerometer, e.g. that placed at the pelvis (H2B), would be sufficient. At the work covered in this paper, the author compared PSD values of the signals recorded by accelerometers installed in the HYBRID II and CHILD dummies (H2 and D, respectively), i.e. H2B, H2G, DT, and DG. The signals were also compared with the one recorded by the accelerometer placed on the vehicle floor (P). An analysis was carried out where the corresponding PSD values were directly compared with each other. Why was power spectral density chosen for the analysis? As regards children, almost no information is available about how vibrations are felt by them. Due to lower body mass, the frequency at which vibrations are most strongly felt by a child may be expected to be considerably higher than that observed in the case of an adult. 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) (2). This shows that the PSD may be taken as an appropriate indicator, suitable for making comparisons between signals recorded for the H2 and D dummies.

Figs. 10 through 15 provide examples of the PSD values determined for a STANDARD seat (FS). The following can be seen in the graphs presented:

- For H2B and DT, the highest PSD values were recorded in frequency ranges of about 5÷8 Hz and 7.5÷8 Hz, respectively;
- For H2G and DG, the highest PSD values were recorded in frequency ranges of 5÷5.5 Hz and 6÷8 Hz, respectively.

Figs. 16 through 21, in turn, provide examples of the PSD values determined for an FX seat. The following can be seen in the graphs presented:

- For H2B and DT, the highest PSD values were recorded in frequency ranges of 5÷8 Hz and 8.5÷9.5 Hz, respectively;
- For H2G and DG, the highest PSD values were recorded in frequency ranges of 5÷5.5 Hz and 8÷10.5 Hz, respectively.

In result of comparisons made between the power spectral density (PSD) values determined for particular signals recorded during test drives on various road surfaces, the following findings may be formulated as regards the impact of vibrations on children.

1) Test drive on a road section with "even" surface (asphalt):
The PSD values of the DT and DG signals were similar in qualitative terms to those recorded by the H2B and H2G accelerometers, respectively, and the highest PSD values of these signals occurred at frequencies ranging from 0.5 to 2 Hz.

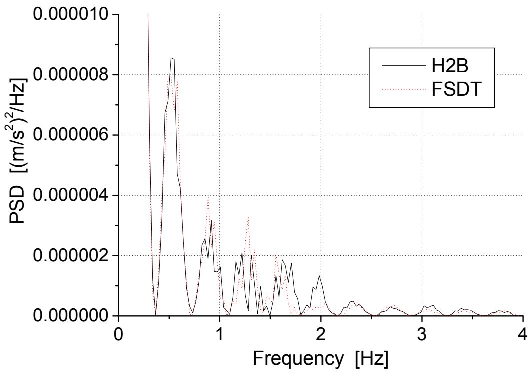

Fig. 10. FSA H2B compared with DT

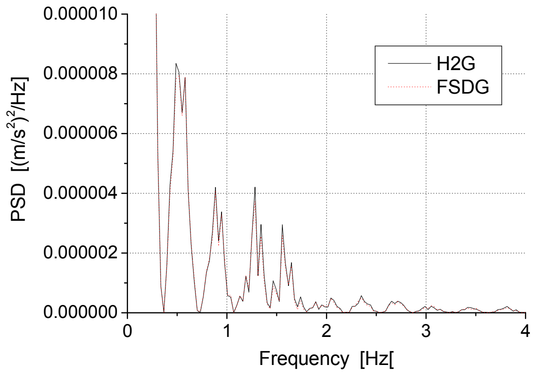

Fig. 11. FSA H2G compared with DG

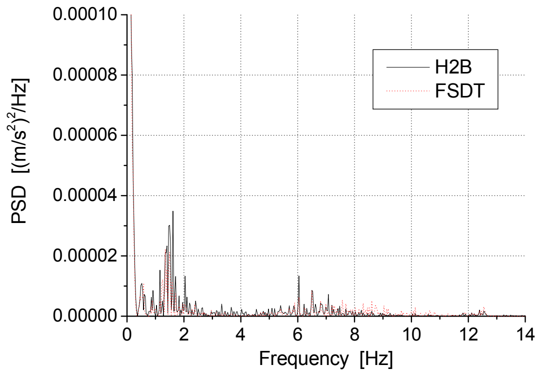

Fig. 12. FSBr H2B compared with DT

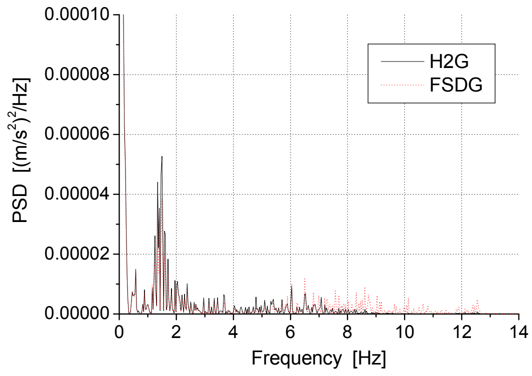

Fig. 13. FSBr H2G compared with DG

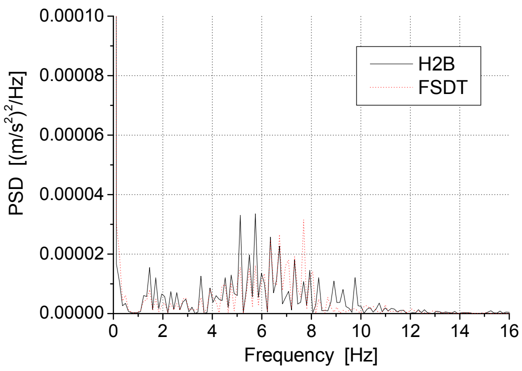

Fig. 14. FSGb H2B compared with DT

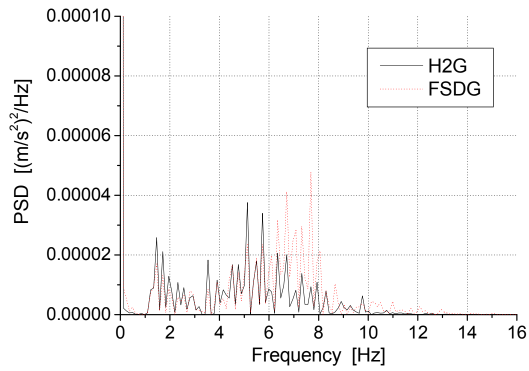

Fig. 15. FSGb H2G compared with DG

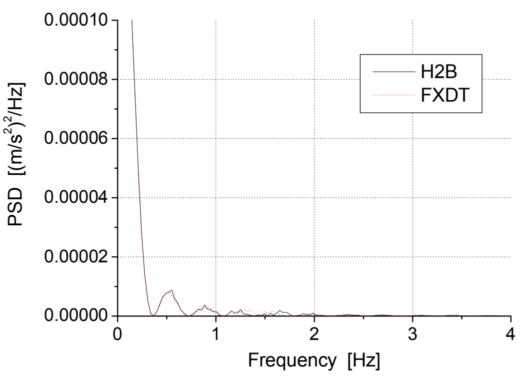

Fig. 16. FXA H2B compared with DT

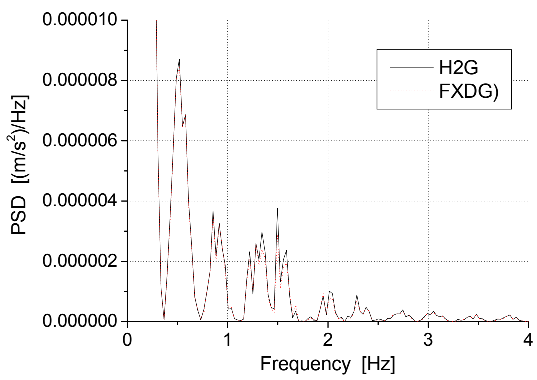

Fig. 17. FXSA H2G compared with DG

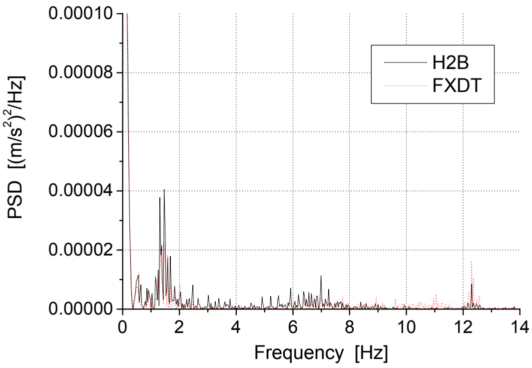

Fig. 18. FXBr H2B compared with DT

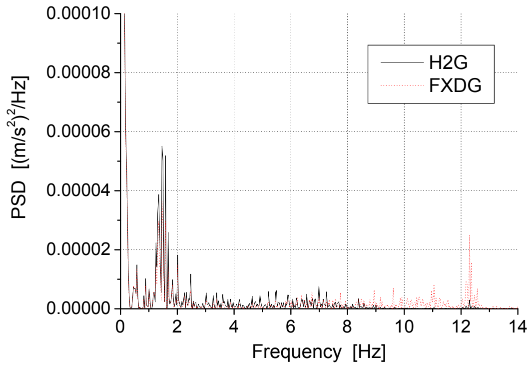

Fig. 19. FXBr H2G compared with DG

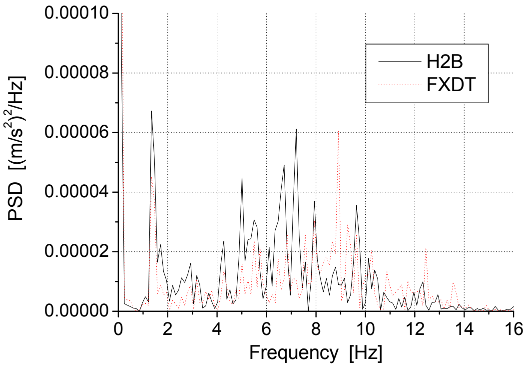

Fig. 20. FXGb H2B compared with DT

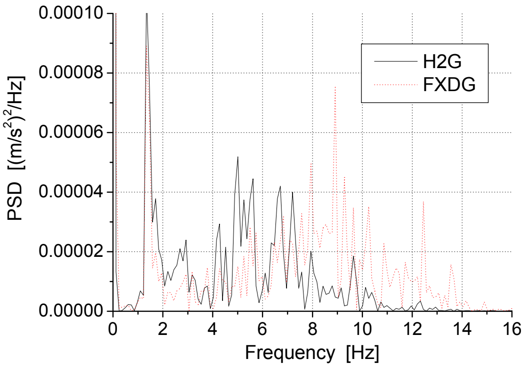

Fig. 21. FXGb H2G compared with DG

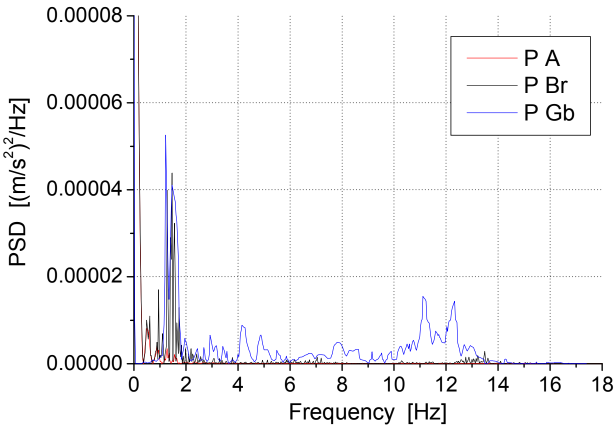

Fig. 22. Comparison of the power spectral density of the signals recorded on the vehicle floor for three road surface types

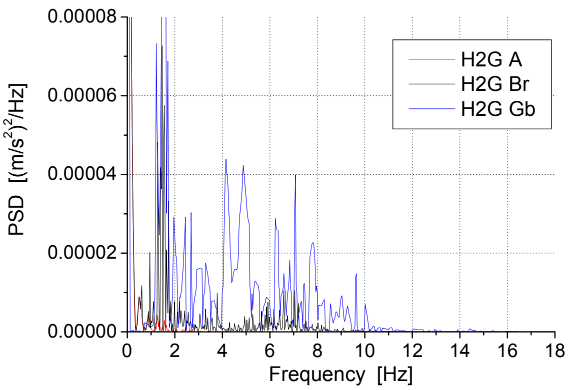

Fig. 23. Comparison of the power spectral density of the signals recorded by the H2G accelerometer for three road surface types

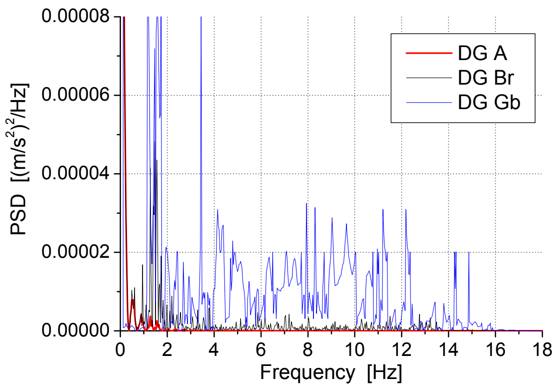

Fig. 24. Comparison of the power spectral density of the signals recorded by the DG accelerometer for three road surface types

2) Test drive on a road section with "rough" surface:
For the FS seats, the PSD values of the signals recorded for the H2 and D dummies were similar to each other in qualitative and quantitative terms and reached their highest values at frequencies ranging from 1.5 to 1.8 Hz. For the H2B and H2G signals, the PSD values faded away at frequencies exceeding 9 Hz; for the DT and DG signals, the fading away of the PSD value was observed at frequencies higher than 13 Hz. For the ISOFIX seats, the PSD values of the signals recorded for the H2 and D dummies were similar to each other in qualitative and quantitative terms within a frequency range of up to 8 Hz. The PSD values of the DT and DG signals faded away at frequencies exceeding 13 Hz.
3) Crossing of a "hump":
For the FS seats, the PSD values of the DG and DT signals exceeded those recorded for the H2 dummy at frequencies higher than 6 Hz. For the ISOFIX seats, this was observed for frequencies of above 8 Hz.
4) Comparison between the impacts of vibrations on the D and H2 dummies:
For the test drives on the road section with asphalt surface, the ride comfort assessed for the D dummy was in general close to that of the H2 dummy, whether the FS or FX seat was used. On the "rough" road surface and with the FX seat being used, the PSD values measured for the D dummy exceeded those of the H2 dummy in a frequency range of 9÷14 Hz. A similar observation was made for the FS seat, but this took place in a frequency range of 9÷13 Hz. When the "hump" was crossed, it was observed in a frequency range of up to 6 Hz that the PSD values for the D dummy were lower than those determined for the H2 dummy. For the FS seat, the PSD values for the D dummy exceeded those for the H2 dummy at frequencies of above 6 Hz. For the FX seat, the phenomenon that the PSD values for the D dummy exceeded those for the H2 dummy was recorded at frequencies of above 8 Hz.
5) Comparison between the FS and FX seats:
It is interesting that the highest PSD values for individual safety seats occurred at different frequency values in a frequency range from 0.5 to 13 Hz. This means that a considerable frequency shift took place not only between specific seats but also (which is perhaps much more important) between the D and H2 dummies. An exception was the frequency of about 0.5 Hz for the asphalt road and about 1.5÷1.8 Hz for the "rough" road and the crossing of a "hump," at which maximum PSD values were recorded for all the safety seats used for tests. Simultaneously, an increase in the PSD values was observed in a frequency range of 7÷10.5 Hz for all the safety seats when the test car was driven on the "rough" road and when it crossed the "hump."
6) The worse the road surface (i.e. the higher road input magnitude) is, the more clearly the differences in natural frequencies of the adult and the child can be seen.
7) For the frequency range of 4÷5 Hz, the highest PSD values were recorded for the H2 dummy.
In general, a statement may be made that the FS and FX seats used for tests differed from each other in the natural frequencies determined from the DT and DG signals recorded during test drives on the road sections with different surface types. A "shift" between these frequencies and those determined for the H2 dummy was also found to occur. An exception was observed for low frequencies of 0.5 and 1.5 Hz, where the PSD values were found to be close to each other in qualitative and quantitative terms. This was below the level of maximum susceptibility of the human body to vibrations, i.e. below the frequency range of 4÷8 Hz; hence, this fact should be considered favourable. For the D dummy, the resonance frequencies come within the range of 3÷16 Hz, and this should be considered an adverse effect.

Examples of comparison of the power spectral density (PSD) of vertical accelerations measured for various road surfaces (A, Br, and Gb) and for the STANDARD seats have been presented in Figs. 22, 23, and 24. The lowest PSD values for the three road surface types were recorded for the accelerometer placed on the vehicle floor. For the Br and Gb road surface types, it can be clearly seen that the PSD values measured by the H2G and DG accelerometers fade away at frequencies above 10 and 14 Hz, respectively, which is consistent with the findings described previously. This shows that the range of vibration frequencies determined for the CHILD dummy (D) differs from that of the dummy representing an adult (H2). For the D dummy, the frequency range is wider than that observed in the H2 case. Similar findings can be formulated for the comparison of the power spectral density (PSD) of vertical accelerations measured for the three road surface types (A, Br, and Gb) in the case of the ISOFIX seats.

Comparison between the STANDARD and ISOFIX safety seats

A comparison between the PSD values of the vertical acceleration signals recorded for the FS and FX seats has been presented in Figs. 25 through 30. For the test drives on the asphalt road (Figs. 25 and 26), the signals recorded by both the DT and DG accelerometers for the FS and FX seats were close to each other, in qualitative and quantitative terms, for frequencies of up to 1.2 Hz, but differences were observed in a frequency range from 1.2 to 1.7 Hz. In particular, the PSD values measured for the FS seat at frequencies of 1.3÷1.4 Hz exceeded those of the FX seat by about 60%. Conversely, the PSD values for the FX seat rose above those of the FS seat at frequencies of about 1.6÷1.7 Hz. For the "rough" road (Figs. 27 and 28), the signals recorded by both the DT and DG accelerometers for the FS and FX seats were close to each other, in qualitative and quantitative terms, for frequencies of 0.5÷4 Hz. Differences were observed at frequencies of 5÷12.5 Hz. In this frequency range, the PSD values for the FX seat exceeded those for the FS seat. The maximum PSD values were recorded at a frequency of about 1.5 Hz. For the crossing of the "hump" (Figs. 29 and 30), the signals recorded by both the DT and DG accelerometers for the FS and FX seats were close to each other, in qualitative and quantitative terms, for frequencies of up to 2 Hz. In the frequency range from 2 to 4.5 Hz, the highest PSD values occurred for the FS seat, while for frequencies of 5÷10.5 Hz, the highest PSD values occurred for the FX seat. At a frequency of about 1.5 Hz, qualitative and quantitative similarity between the FS and FX seats was observed. Based on comparisons of the PSD values of specific signals recorded at test drives on various road surfaces with the FS and FX seats being used for tests, the following findings may be formulated as regards the impact of vibrations on children.

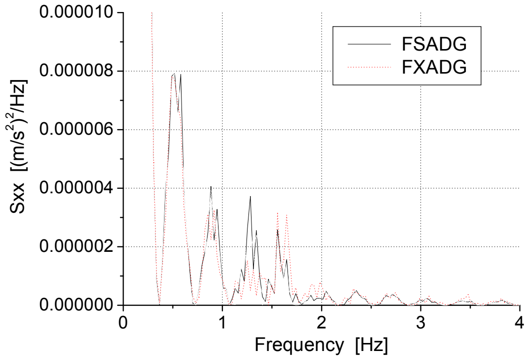

Fig. 25. The FS and FX seats, A, DG

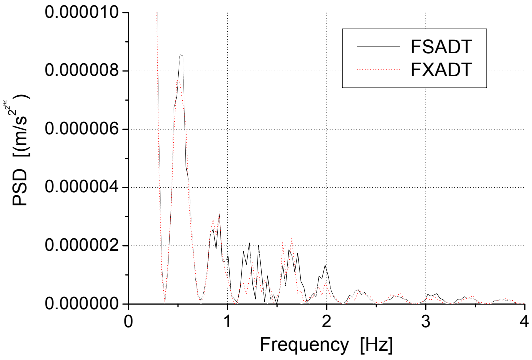

Fig. 26. The FS and FX seats, A, DT

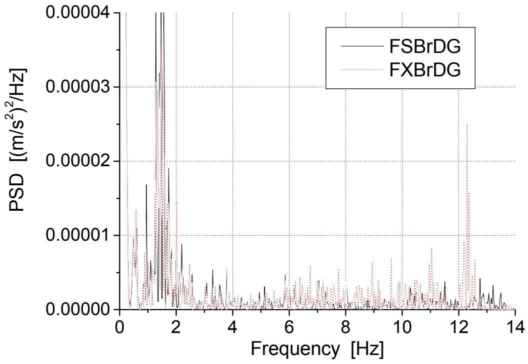

Fig. 27. The FS and FX seats, Br, DG.

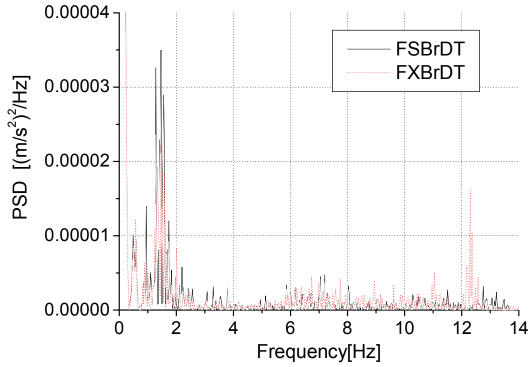

Fig. 28. The FS and FX seats, Br, DT

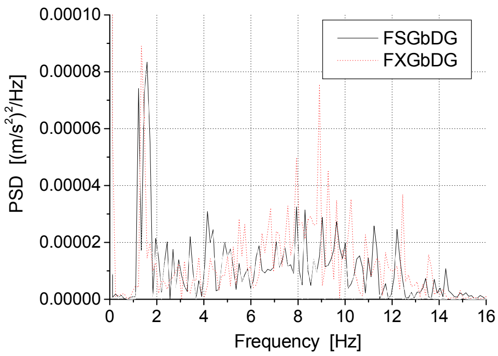

Fig. 29. The FS and FX seats, Gb, DG.

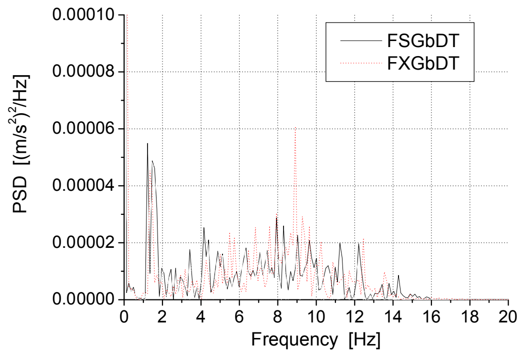

Fig. 30. The FS and FX seats, Gb, DT

a) **b)**

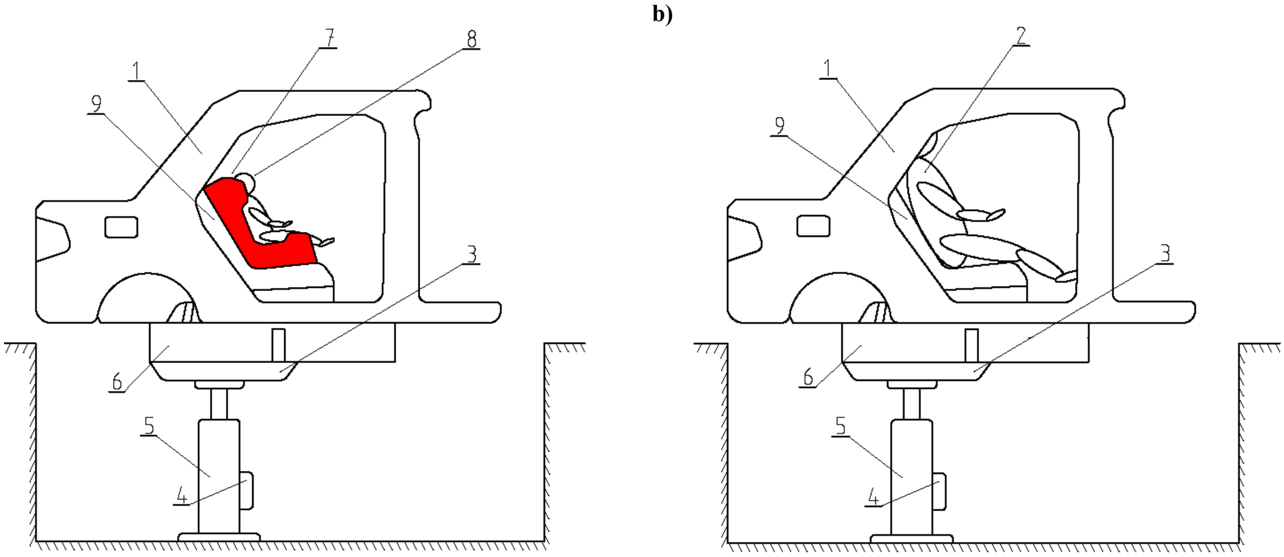

Fig. 31. Schematic diagram of the test stand.
a) View of the CHILD dummy fixed in a safety seat; b) View of the HYBRID II dummy seated in the car: 1 – car body; 2 – dummy representing an adult; 3 – measurement base plate; 4 – electro-hydraulic servovalve of the actuator; 5 – hydraulic actuator; 6 – car body fixture; 7 – safety seat; 8 – dummy representing a child; 9 – car backseat

1)The CHILD (D) as against the HYBRID II (H2) dummies:

During test drives on the asphalt road, the ride comfort evaluated for the D and H2 dummies was generally on the same level. For the D dummy fixed in the FX seat, the PSD values observed in a frequency range of 9÷14 Hz were higher than those recorded for the H2 dummy, which means that the ride comfort of the child was inferior (in this frequency range) to that of the adult. A similar situation was observed in the case of the FS seat being used. During test drives on the "rough" road, the worsening of child's ride comfort (D) compared with that of an adult (H2) was observed in a frequency range of 9÷13 Hz (for both the FS and FX seats). At the crossing of the "hump," the child's ride comfort (D) became worse than that of an adult (H2) for frequencies higher than 7 Hz (for both the FS and FX seats).

2)Comparison between the FS and FX seats:

It is interesting that the highest PSD values for individual safety seats occurred at different frequency values in a frequency range from 0.5 to 13 Hz. This means that considerable frequency shift took place not only between specific seats but also (which is perhaps much more important) between the D and H2 dummies. Simultaneously, an increase in the PSD values was observed in a frequency range of 6÷8 Hz for all the seats during the test drives on the "rough" road surface and at the crossing of the "hump."

3)The worse the road surface (i.e. the higher road input magnitude) is, the more clearly the differences in natural frequencies of the adult and the child can be seen.

In general, a statement may be made that the FS and FX seats used for tests differed from each other in the natural frequencies determined from the DT and DG signals recorded during test drives on the road sections with different surface types. A "shift" between these frequencies and those determined for the H2 dummy was also found to occur. An exception was observed for low frequencies of 0.5 and 1.5 Hz, where the PSD values were found to be close to each other in qualitative and quantitative terms. This was below the level of maximum susceptibility of the human body to vibrations, i.e. below the frequency range of 4÷8 Hz; hence, this fact should be considered favourable. As stated previously, almost no information is available about how vibrations, including vertical vibrations generated during car movement, are felt by children. Due to lower body mass, the frequency at which vibrations are most strongly felt by a child may be expected to be considerably higher than that observed in the case of an adult. As described above, the child's body exhibits the highest capability to absorb vibrations in a frequency range of 3÷16 Hz. However, an increase in the acceleration values was observed in this frequency range for both the FS and FX seats. The shift of resonance frequencies between the D and H2 dummies also results in the fact that for the child, the resonance frequencies come within the range of 3÷16 Hz, and this should be considered an adverse effect.

Recapitulation of the road tests

Based on results of the analysis in the frequency domain of the test drives with individual safety seats on roads with various surface types, the following findings regarding the impact of vibrations on a child riding in a car may be formulated.

1) The FS and FX seats differed from each other in the natural frequencies determined from the DT and DG signals recorded during test drives on the road sections with different surface types. In other words, these frequencies were "shifted" from those determined for the H2 dummy. This resulted in a fact that, in the case of a child, the resonance frequencies came within the range of 3÷16 Hz, i.e. the range where the child's body exhibits the highest capability to absorb vibrations. An exception was observed for low frequencies of 0.5 and 1.5 Hz, where the PSD values recorded were found to be close to each other in qualitative and quantitative terms.
2) The analysis in the frequency domain has unequivocally shown that the absorption of vibrations by the child's body at frequencies of above 9 Hz definitely exceeds that occurring in the case of an adult.
3) Based on the analysis in the frequency domain, it may be judged impossible to indicate the specific seat type (FS or FX) for which the impact of vibrations on a child would be weaker (and thus, the child's ride comfort would be better). It cannot be claimed, either, that the placing of a child in a safety seat would cause the impact of vibrations on the child to be less harmful than it is in the case of an adult; an opposite effect should rather be expected.

The road test results have confirmed the need for tests of this kind to be continued on a special simulation test stand as well.

Rig tests

Description of the test stand

A concept was developed and then a test stand was built at PIMOT to investigate the impact of vertical vibrations on a child fixed in a safety seat and on an adult when riding in a car (Fig. 31). As it was at the road tests, dummies representing an adult (H2) and a child (D) were used for this purpose.

The complete rear part of a car body (1) was fastened through a car body fixture (6) to a measurement base plate (3) connected with a hydraulic actuator (5), which was controlled by means of an electro-hydraulic servovalve (4). The car body was provided with a backseat (9), on which a dummy representing a child (8) and fixed in a safety seat (7) as well as a dummy representing an adult (2) could be placed (Fig. 31, a and b, respectively). The test stand built as described above had the following major good points:

– The safety seats and the test dummies could be placed in the car body identically as it was done at the road tests.
– The measuring sensors (accelerometers) could be installed in locations identical to those adopted at the road tests.
– The complete rear part of the car body could be taken from a car of the same make and model as that used at the road tests.

Thus, the peculiarities of the system subjected to the road tests could be reproduced, i.e. the initial conditions of the rig tests could be identical to those that took place in the real car during the road tests and the rig tests could be repeated in the same conditions. Thanks to this, the rig test results were equivalent and comparable to the results of the road tests. As it was at the road tests, a HYBRID II test dummy (H2) with a mass of 75 kg was placed on the car backseat, on its left side, and fastened to the seat with a conventional three-point seat belt. On the right side of the backseat, a child safety seat was installed and a CHILD dummy (D) having a mass of 15 kg was fixed in it. Seven child safety seats were used again for the tests. The CHILD dummy was fixed in each safety seat at the successive series of measurements. Examples of the mounting of the STANDARD and ISOFIX seats with a CHILD dummy and of the H2 dummy seated in the car have been shown in Figs. 32 and 33, respectively. During the rig tests, the measurement signals were recorded by means of a measuring circuit similar to that used at the road tests (see Fig. 5). The tests were carried out with sine waveforms being used as test inputs and with specific waveform frequencies having been selected from the signals recorded at the road tests. Spectra of the road test signals were analysed and then the appropriate frequency bands were chosen on these grounds. The frequency range of interest was determined as 0.5÷9 Hz. For detailed analysis, frequencies of 0.5, 0.9, 1.3, 1.5, 4.2, 5, 7, and 8 Hz were deliberately selected as those at which the highest power spectral density (PSD) values were recorded, globally and locally, during the road tests (for both the H2 and D dummies).

Analysis in the frequency domain

As it was done at the road tests, the PSD values of the signals recorded by the accelerometers installed in the HYBRID II and CHILD dummies, i.e. H2B, H2G, DT, and DG, were compared as appropriate. The signals were also compared with the one recorded by the accelerometer placed on the vehicle floor (P). The corresponding PSD values were directly compared with each other (as it was done at the road tests). As mentioned above, sine waveforms were used as test inputs. For individual safety seats, the curves representing the PSD values recorded for frequencies of 0.5, 0.9, 1.3, and 1.5 Hz were similar to each other, in qualitative terms (10). Therefore, only the signals recorded for the frequency of 1.3 Hz were selected for the evaluation of individual seats. For the frequency range from 2 to 10 Hz, the curves recorded for the frequencies of 5, 7, and 8 Hz were taken for the analysis. For the frequency of 1.3 Hz, the PSD curves recorded for the FS and FX seats were similar to each other, in quantitative terms (Figs. 34 through 37). For the frequency of 5 Hz, the highest PSD values were recorded for the H2 dummy (Figs. 38 through 41). For the frequencies of 7 and 8 Hz, the highest PSD values were recorded for the D dummy (Figs. 42 through 49). These test results are consistent with the results of road tests. A comparison between the power spectral density (PSD) values determined for different safety seats at various input frequencies has been shown in Figs. 50, 51, and 52.

a) b)

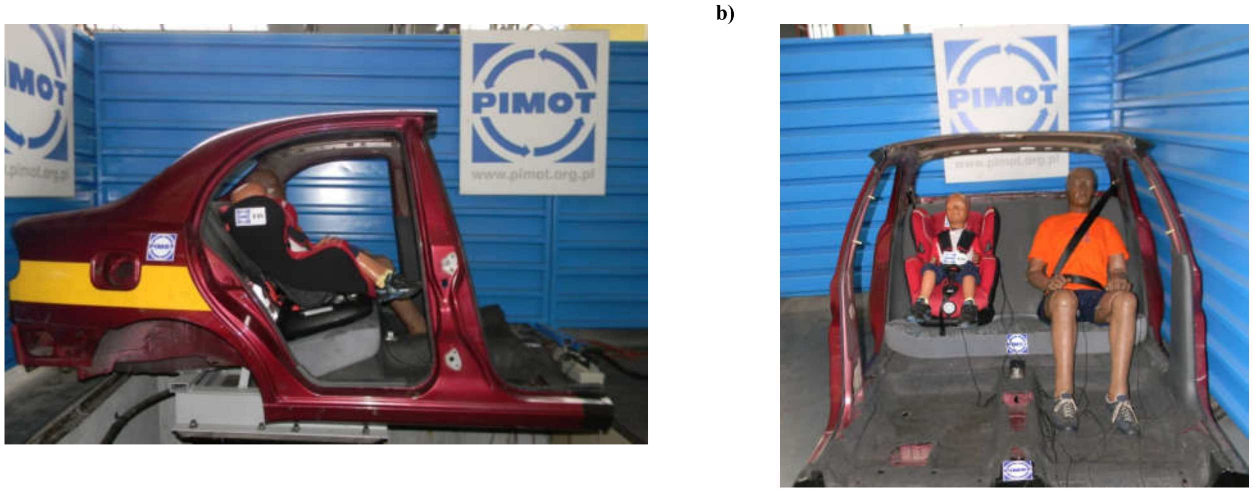

Fig. 32. Example of the mounting of a STANDARD safety seat with the CHILD dummy and of the H2 dummy seated in the car installed on the test stand

a) b)

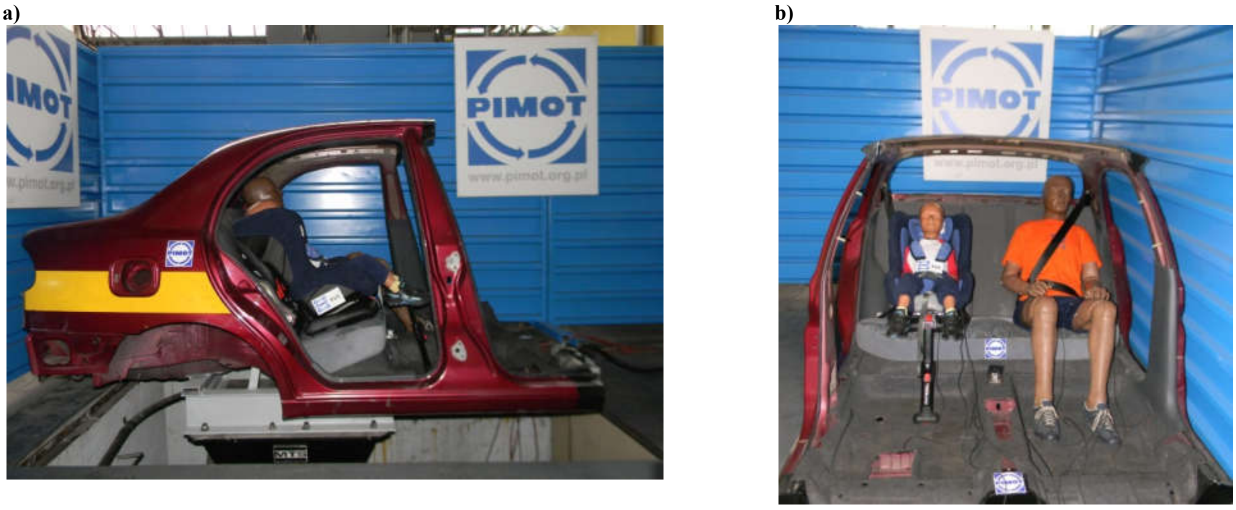

Fig. 33. Example of the mounting of a ISOFIX safety seat with the CHILD dummy and of the H2 dummy seated in the car installed on the test stand

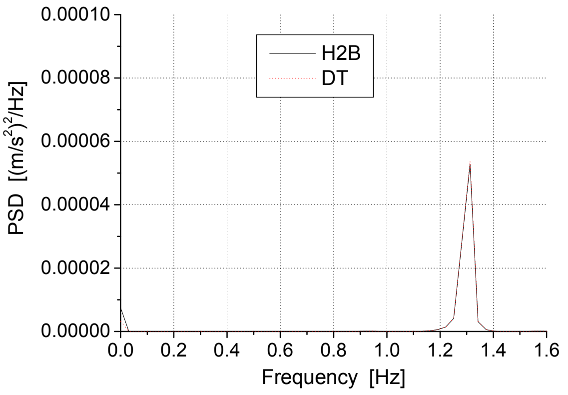

Fig. 34. The FS seat, DT against H2B

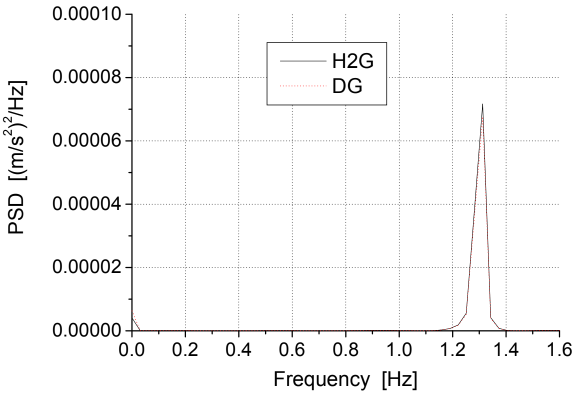

Fig. 35. The FS seat, DG against H2G

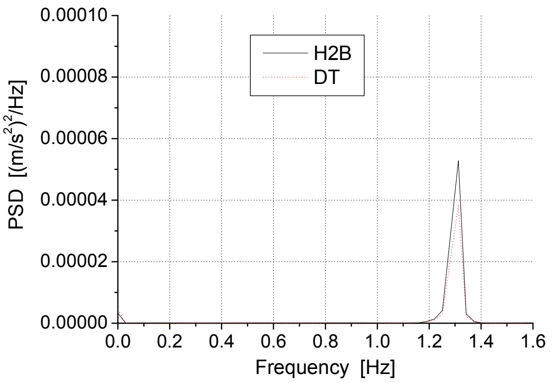

Fig. 36. The FX seat, DT against H2B

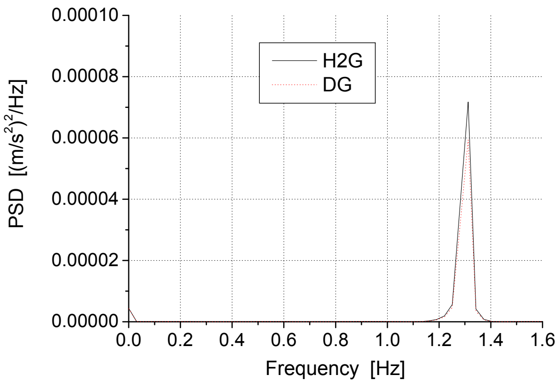

Fig. 37. The FX seat, DG against H2G

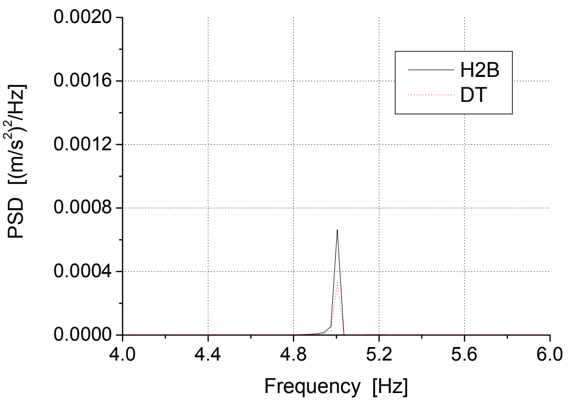

Fig. 38. The FS seat, DT against H2B

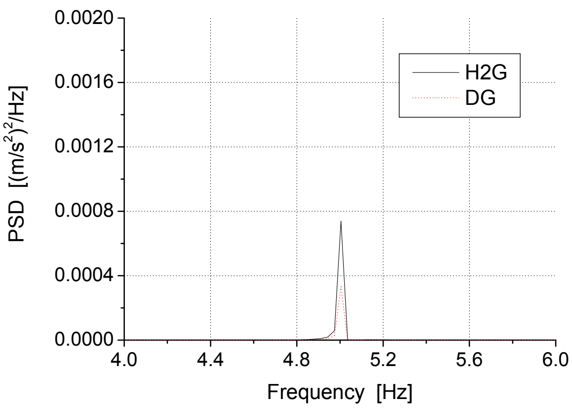

Fig. 39. The FS seat, DG against H2G

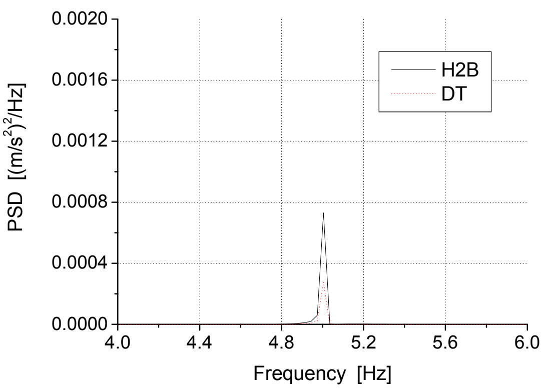

Fig. 40. The FX seat, DT against H2B

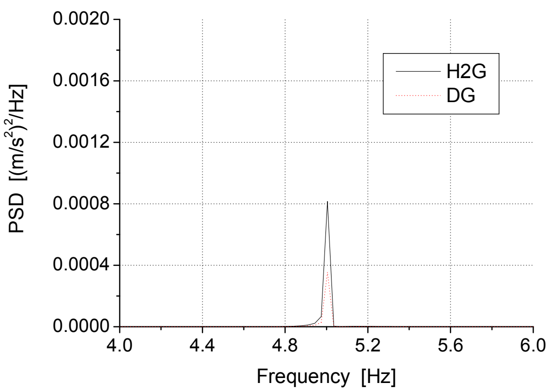

Fig. 41. The FX seat, DG against H2G

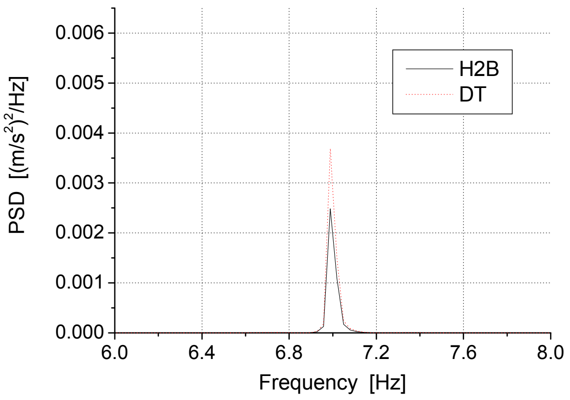

Fig. 42. The FS seat, DT against H2B

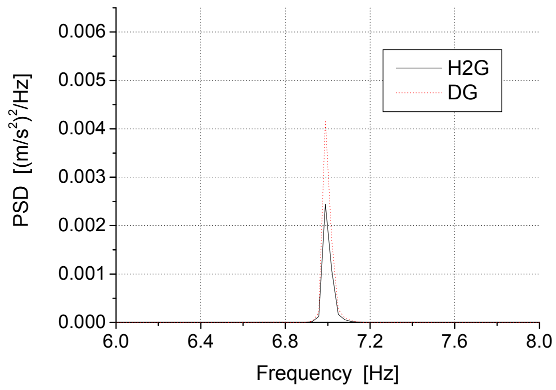

Fig. 43. The FS seat, DG against H2G

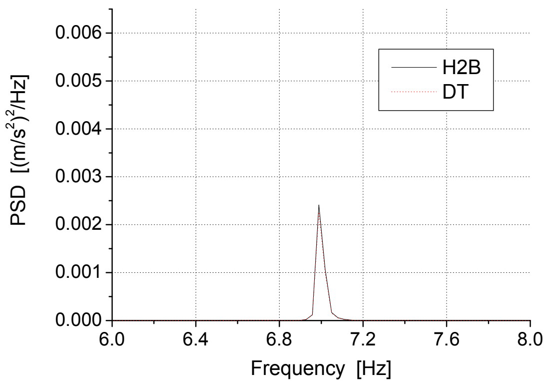

Fig. 44. The FX seat, DT against H2B

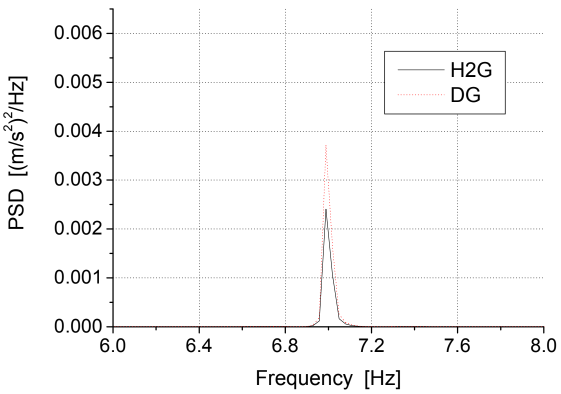

Fig. 45. The FX seat, DG against H2G

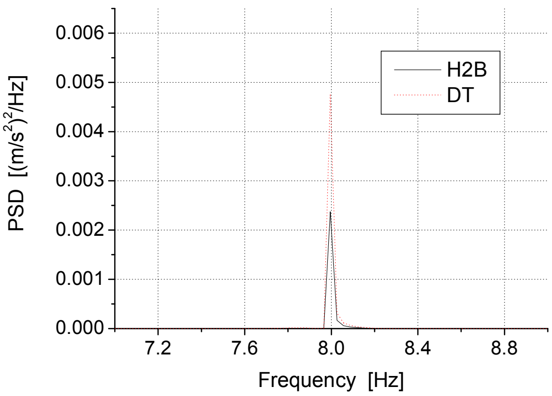

Fig. 46. The FS seat, DT against H2B

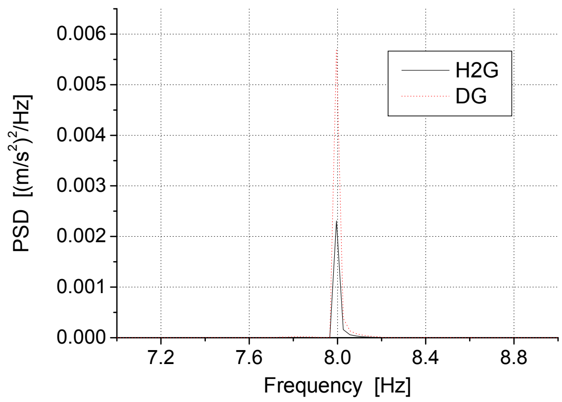

Fig. 47. The FS seat, DG against H2G

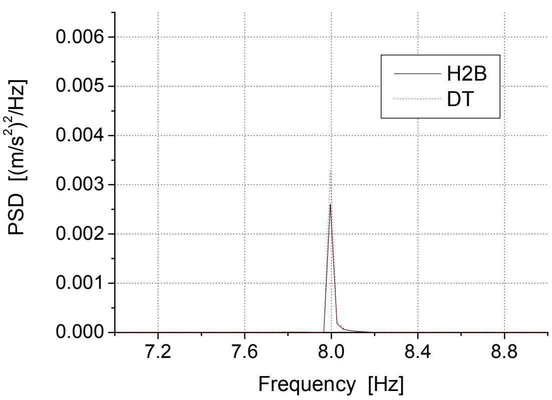

Fig. 48. The FX seat, DT against H2B

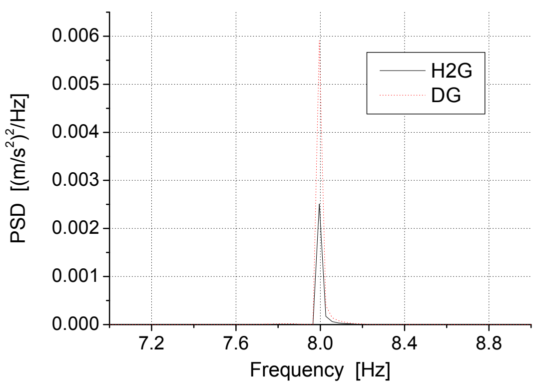

Fig. 49. The FX seat, DG against H2G

A comparison of the PSD values determined at various frequencies for the D dummy fixed in the FS seat with those recorded for the P and H2 accelerometer locations has been graphically presented in Fig. 50. According to the graph, the PSD values determined for the D dummy not only became significantly higher (more than doubled) than those for the H2 dummy at frequencies exceeding 6 Hz, but also the PSD curves plotted for the P, D, and H2 signals reached their maxima at different frequencies. It should be noted at the same time that for the P and D signals, the frequencies at which the PSD values reached their maxima did not significantly differ from each other.

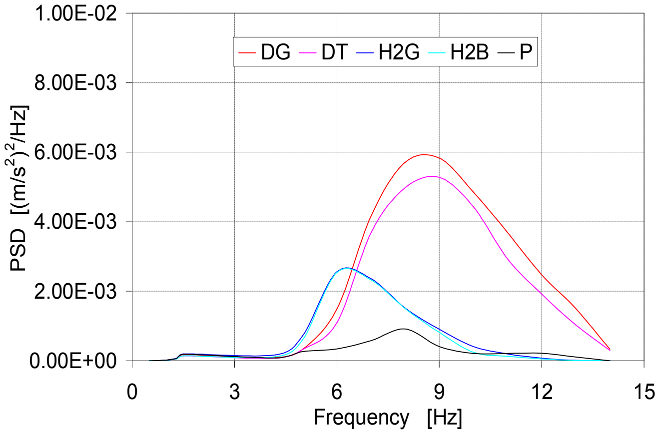

Fig. 50. Comparison of the PSD values at various frequencies; the FS seat

A comparison of the PSD values determined at various frequencies for the D dummy fixed in the FX seat with those recorded for the P and H2 accelerometer locations has been graphically presented in Fig. 51. Here again, the PSD values determined for the D dummy not only became significantly higher (more than doubled) than those for the H2 dummy at frequencies exceeding 6 Hz, but also the PSD curves plotted for the P, D, and H2 signals can be seen to have reached their maxima at different frequencies. As it was observed in the preceding graph, the difference between the frequencies at which the PSD values of the P and D signals reached their maxima was again quite small.

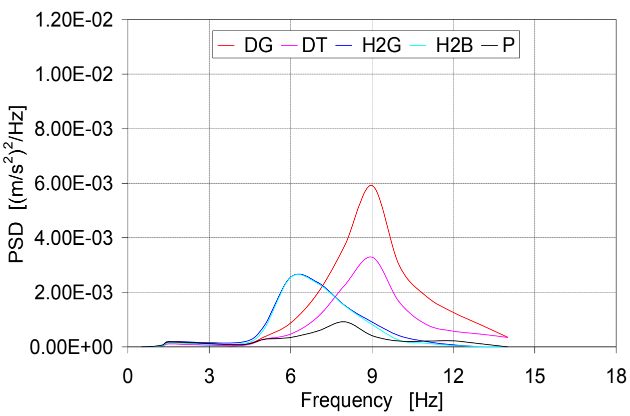

Fig. 51. Comparison of the PSD values at various frequencies; the FX seat

In the case of one of the STANDARD seats (denoted here by FS'), a situation occurred as shown in Fig. 52. Unlike the curves displayed in Figs. 50 and 51, this graph indicates that the PSD values for the H2 and D dummies were rather close to each other. On the other hand, a qualitative similarity could be seen: the PSD curves for the P, D, and H2 signals reached their maxima at different frequencies and the frequencies at which the PSD values for the P and D signals reached their maxima did not significantly differ from each other.

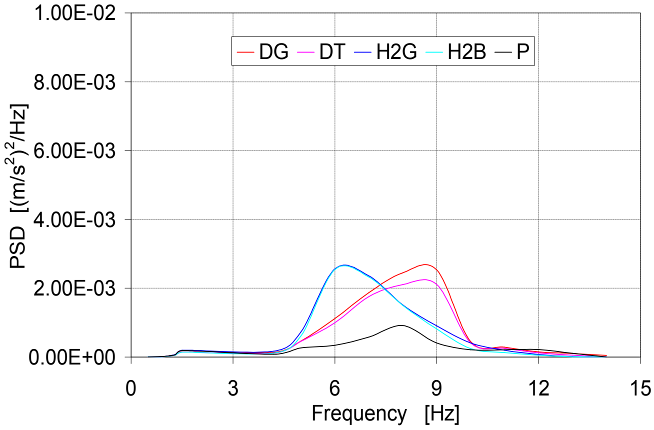

Fig. 52. Comparison of the PSD values at various frequencies; the FS' seat

Comparison between the STANDARD and ISOFIX safety seats

A comparison between the graphs of Figs. 50 and 51 reveals a difference in the areas under the DG curves for the FS and FX seats. For the FX seat, we can see a distinct "sharp" maximum, with the area under the curve being significantly smaller than that for the FS seat. Simultaneously, the maximum PSD value for the DG signal was about twice as high as that for the DT signal in the case of the FX seat. A comparison of the power spectral density (PSD) values for the FS and FX seats has been presented in Figs. 53 through 56. For the frequency of 1.3 Hz, quantitative differences were recorded: the highest PSD values were observed for the FS seats. For the DT signals, differences between ten and twenty percent were recorded between the PSD values for the FS and FX seats, with the former exceeding the latter. For the DG signals, these percentage differences dropped to a single-figure level. For the frequency of 7 Hz, these differences were even bigger. For the DT and DG signals, the ratio of the PSD value for the FS seat to that for the FX one was more than two and about two, respectively. The results of the tests carried out with the FS and FX safety seats, presented here as examples, would suggest that the FX seats may be expected to offer lower PSD values than the FS seats would do. However, taking into account the PSD graph shown in Fig. 52, we cannot formulate such unequivocal conclusions. In consideration of the values presented in Figs. 53 through 56 for the FS' seat, it is impossible to indicate unambiguously which of the seat types (FS or FX) is "better."

Recapitulation of the road tests

Within the analysis in the frequency domain, appropriate comparisons were made between the power spectral density (PSD) values of the signals recorded by the accelerometers installed in the HYBRID II and CHILD dummies (H2 and D, respectively), i.e. H2B, H2G, DT, and DG, and on the vehicle floor (P). The corresponding PSD values were directly compared with each other, with the general objective being to make comparisons between the H2 and D data (as it was in the case of the road tests).

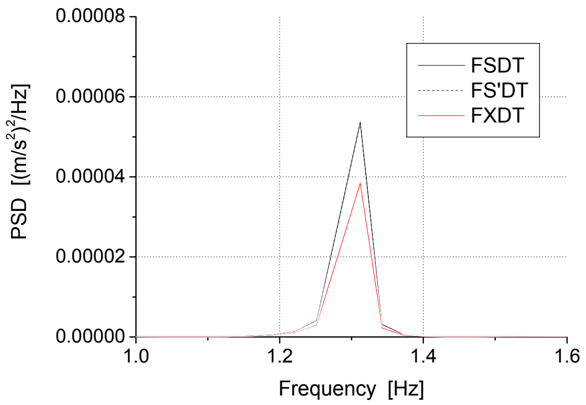

Fig. 53. Comparison of the PSD values at a frequency of 1.3 Hz; the DT signal

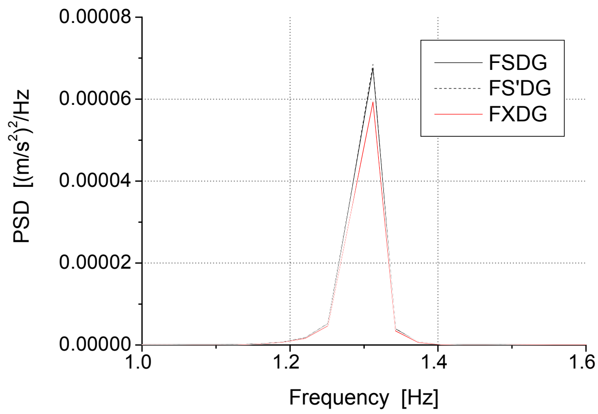

Fig. 54. Comparison of the PSD values at a frequency of 1.3 Hz; the DG signal

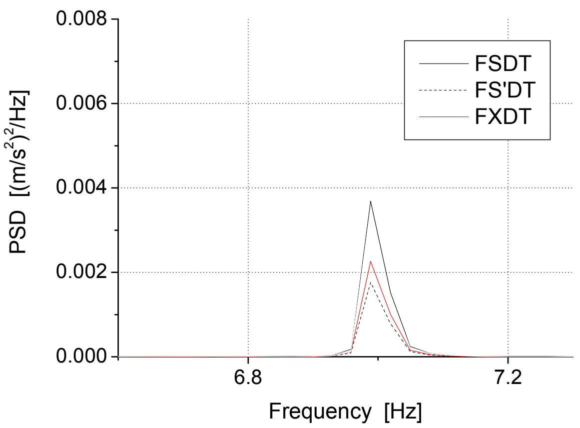

Fig. 55. Comparison of the PSD values at a frequency of 7 Hz; the DT signal

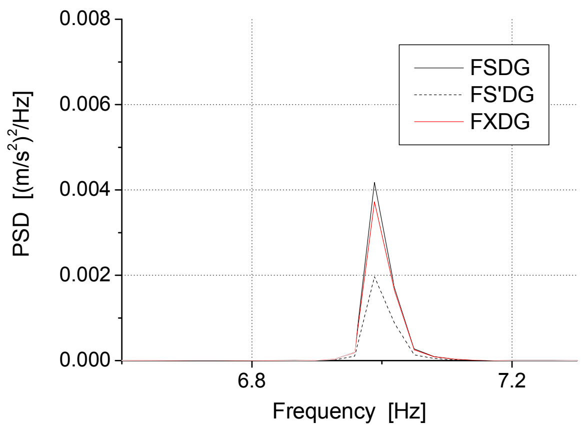

Fig. 56. Comparison of the PSD values at a frequency of 7 Hz; the DG signal

In result of the comparisons made within the analysis in the frequency domain, the following findings may be formulated:

1. The higher input frequency values are, the more clearly the differences in natural frequencies of the adult and the child can be seen.
2. The highest power spectral density values for the H2 dummy were recorded for a frequency of abut 6 Hz.
3. For frequencies of over 6 Hz (up to 15 Hz), the power spectral density values recorded were higher for the D dummy (even three times as high), as against those for the H2 dummy. When compared with the signal recorded on the vehicle floor (P), the PSD values of the D signal may be even five times as high as those of the former; is should be emphasised at the same time that the maximum PSD values of the P and D signals occur at a similar frequency value.
4. When comparing the STANDARD and ISOFIX safety seats, it may be stated that for different seat models, differences occur in the ranges of frequency of the vibrations transmitted to the child. This means that the classifying of a seat as being of the STANDARD or ISOFIX type does not define without ambiguity the seat properties as regards the impact of vertical vibrations on the child transported in the specific seat. The frequency ranges within which the properties of specific safety seats may be considered favourable vary as well.

Recapitulation

In this paper, some problems related to the impact of vertical vibrations on a child riding in a car in a safety seat have been discussed and the study results have been compared with the impact of such vibrations on an adult. Experimental road and rig tests were carried out with HYBRID II (H2) and CHILD (D) dummies as well as child safety seats of the STANDARD (FS) and ISOFIX (FX) types being used. For the rig tests, a test stand specially built for this purpose was used. An attempt was made to evaluate the correlation between the road tests and the rig tests. Issues related to the dangers caused by mechanical vibrations (vertical in this case) in motor transport facilities have been presented. The work on the impact of vibrations on the human being was undertaken with paying special attention to children. The lack of research work on this issue has been emphasised. An analysis in the frequency domain has been carried out, based on author's experimental research. The exploration of the problem, or rather of the variety of problems, related to the impact of vertical vibrations on a child riding in a car in a safety seat is important inasmuch as it is directly connected with children's health, that is to say children's safety, and it helps to improve child's ride comfort.
This paper has not exhausted the subject concerning the complex issue of the impact of vibrations on a child riding in a car in a safety seat; it should rather be said to begin or to justify the undertaking of research in this field.

The experimental road and rig tests carried out have made it possible to formulate the following general findings:

1) The STANDARD and ISOFIX safety seats used for tests differed from each other in the natural frequencies determined from the DT and DG signals recorded during test drives on the road sections with different surface types. In other words, these frequencies were "shifted" from those determined for the H2 dummy. An exception was observed for low frequencies of 0.5 and 1.5 Hz, where the PSD values were found to be close to each other in qualitative and quantitative terms. This was below the level of maximum susceptibility of the human body to vibrations, i.e. below the frequency range of 4÷8 Hz; hence, this fact should be considered favourable.
2) As regards children, almost no information is available about how vibrations, including vertical vibrations generated during car movement, are felt by them. The child's body exhibits the highest capability to absorb vibrations in a frequency range of 3÷16 Hz. However, an increase in the acceleration values was observed in this frequency range for all the safety seats. The shift of natural frequencies between the D and H2 dummies also results in the fact that for the child, the resonance frequencies come within the range of 3÷16 Hz, and this should be considered a very adverse effect.
3) The analysis in the frequency domain has shown that the ride comfort of the child became inferior to that of the adult at frequencies exceeding 6 Hz.
4) Based on the analysis in the frequency domain, it may be judged impossible to indicate the specific seat type (FS or FX) for which the impact of vibrations on a child would be less severe. It cannot be claimed, either, that the ride comfort of the child in a safety seat would be better than that of the adult; an opposite effect should rather be expected. For different seat models, differences occur in the ranges of frequency of the vibrations transmitted to the child. It may be stated that for the signals recorded at child's head and torso, the PSD values of the former were higher.

The work described herein indicates and justifies the need to continue interdisciplinary experimental research and theoretical studies on the subjects under consideration, within technical and medical sciences.

The experiments as well as simulation tests should be continued, with their scope being widened and special attention being paid to the absorption of vibrations by the complex child's body structure. In the future research work, the following major objectives should be pursued:

- To identify the biggest possible number of problems related to the transmission of vibrations to the child's body fixed in a safety seat;
- To eliminate faulty solutions and incorrect concepts in the field of the construction of child safety seats and seat fastening systems;
- To indicate possible directions towards the improving of ride comfort.

The continuation of the tests on a larger number of the STANDARD and ISOFIX seats would make it possible to confirm and develop the conclusions of the research work having been carried out; on the other hand, such tests might provide a basis for the preparation of a procedure that would enable the assessment of the quality of child safety seats from the point of view of the harmful impact of vibrations on children transported by car, which is essential for the health safety of such children. In consequence, the work of this kind might provide grounds for the elimination of the worst solutions from the market.

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