Simulation Study on Stiffness of Suspension Seat in the Aspect of the Vibration Assessment Affecting a Vehicle Driver

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This paper presents an original approach to the problem of the optimal stiffness evaluation in a suspension of driver seat for the best reduction of human vibration (whole-body vibration). The basic idea is to take into consideration the individual personal features (biomechanical parameters) of a human being in the process of vibrations assessment. In this article the author presents a complete system to the influence analysis of suspension stiffness on driver vibrations. It consists of the following subsystems: biomechanical model of human representing a specific driver, model of seat with suspension and adjustable spring, model of vehicle, subsystem of road excitation and module for signals processing. The actual research has focused on numerical simulations in the environment Matlab-Simulink-SimMechanics.

Keywords: suspension stiffness, seat, vehicle driver, vibrations.

In the era of intensive development of the transport problem of safety has become a priority item and a huge challenge for researchers and designers. Safety in transport is associated most often with solutions which help prevent accidents or minimize their effects. However, safety in case of people working professionally means also minimizing all those factors which can adversely affect the psychomotor state of the driver during the ride (e.g. lowering the concentration or increasing the time of the reaction), as well as their subsequent health. Large-scale population studies conducted in different regions of the world have shown a convincing relationship between driver health and whole-body vibration (WBV) [1, 2, 3]. They confirm the adverse affects of vehicle vibrations on the human while driving. The risk of disorders is elevated in a broad range of driving occupations, including truck drivers, bus drivers, helicopter pilots, subway operators and other vehicle drivers. Vibrations with the specific parameters can cause resonance of human body structures and organs. For example, vibrations between 2.5 and 5.5 Hz generate strong resonance in the vertebra of the neck and lumbar region. These situations can cause chronic musculoskeletal stress or even permanent damage to the effected region. The Risk increases with vibration duration, dose and intensity.

Directive 2002/44/EC of the European Parliament and of the Council [4] lays down minimum requirements for the protection of workers from risks to their health and safety arising from exposure to mechanical vibration (including whole-body vibration -WBV). Employers should make adjustments in the light of technical progress and scientific knowledge regarding risks related to exposure to vibration, with a view to improving the safety and health protection of workers. In the case of transport, WBV controls may include the use of suspended seats, suspended cabs, maintenance of vehicle suspension systems, proper tire inflation. Seats with armrests, lumbar support, an adjustable seat back, and an adjustable seat pan are also useful.

The level of exposure to vibration can be more effectively reduced by application of the appropriate suspension of driver seat. The use of a suspension seat is a common way to isolate the vehicle operator from the adverse effects of vibration exposure. Thus, many researchers perform computer and laboratory studies on passive, active and semi-active seat suspension designs[13, 15, 16]. Passive seat suspension design includes selecting an appropriate natural frequency and optimization of damping according to a set stiffness. The consequence is a trade-off between isolation of vibration peak amplitudes at resonance and isolation of higher frequency vibrations. Semi-active systems change the suspension response using variety technologies to adjust suspension damper characteristics in real time. Active systems dissipate energy from the suspension system by forcing extension or retraction in response to measured and anticipated motion. In these suspensions, the dampers are replaced with hydraulic cylinders that are pressurized by a hydraulic pump.

The difficulty to predict human vibration is due to the non-linear behaviour of various parts of the person/seat system [5, 6]. For the human body, non linear behaviour has several causes including the geometry of person/seat contact, postural position, dimensions, ages..., and many biomechanical parameters [17]. Therefore, for the best performance of driver seat suspension the relationships between vibration accelerations of human body parts and parameters of suspension (including stiffness) should be found. Described examinations are a continuation of earlier works of the author [e.g. 7, 8].

1. THE CONSTRUCTION OF THE SYSTEM FOR STUDY OF SUSPENSIONS STIFFNESS IN THE ASPECT OF VIBRATIONS ASSESSMENT AFFECTING A VEHICLE DRIVER

In order to achieve the purposes of the research the author developed a complex model of a human-seat-vehicle system. The structure of this system is presented in Figure 1. It consists of five inter-related subsystems:

1. biomechanical model of human
2. seat with suspension model
3. vehicle subsystem
4. subsystem of road excitation
5. system of measurement.

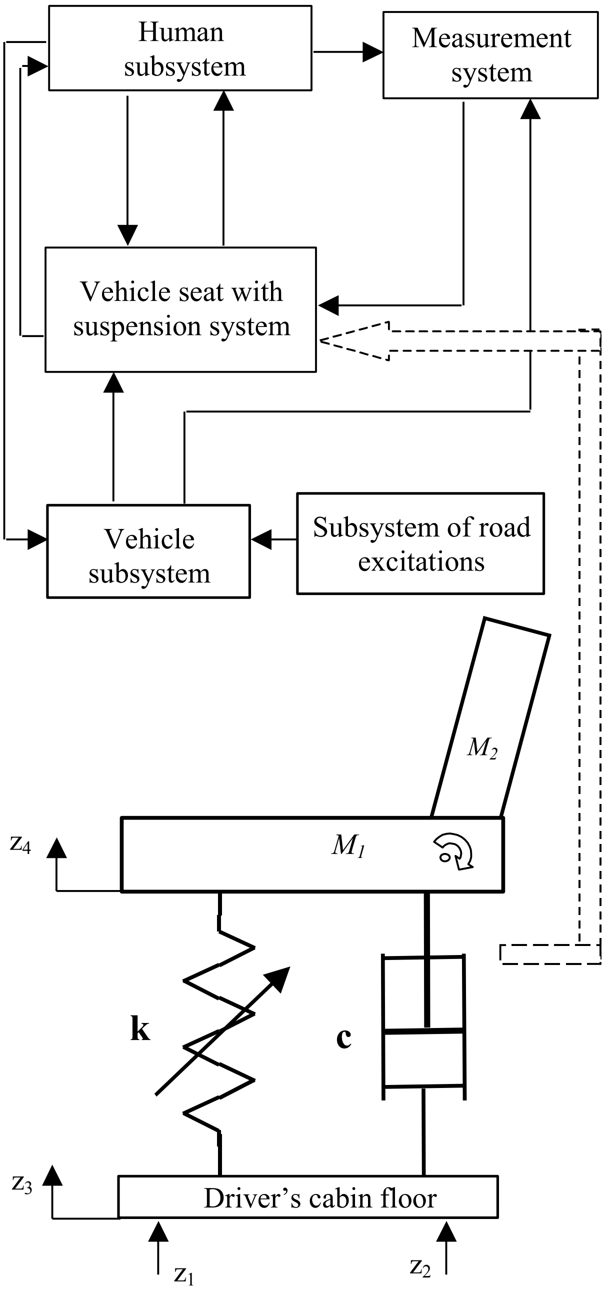

Figure 1. A complex human-seat-vehicle system analysed in the paper.

The dynamic response of the whole human body to vibrations can be modelled using a variety of approaches. Modelling research of the seat (vehicle) dynamics and computer simulations have most often been conducted by using one- degree-of-freedom model of a human disregarding his anatomy [9, 10]. Author proposed nonlinear model of human to the dynamic analysis of vertical (z) and horizontal (x) vibration, as well as of angular displacements (α) in sagittal plane (fig. 2). In this models the human anatomy and biomechanicals parameters are taken into account such as:

- stiffness and damping of intervertebral discs
- stiffness and damping of spinal muscles and ligaments
- stiffness and damping of body muscles
- elements masses and moments of inertia.

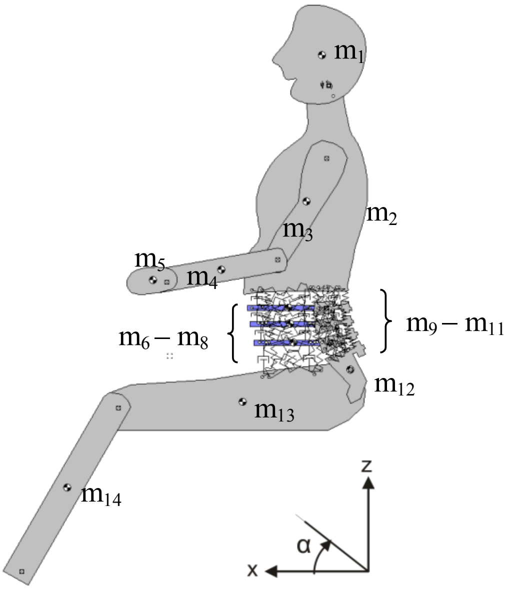

Figure 2. A model of a driver.

The most common effect of WBV is lower back pain. Chronic WBV exposures may irritate spinal tissues. The resultant inflammation can contribute to degeneration of the intervertebral discs that can lead to functional impairment or structural changes such as nerve entrapment. Numerous back disorders are involved, including lumbago, sciatica, general back pain, and intervertebral disc herniation and degeneration. Considering most frequent diseases of drivers occurring due to the influence of vibrations (such as "low back pain ") the low spine has been taken into account in this model. The geometry of the spine has been determined in accordance with the Cobb's method [18].

Table 1. Layout of the human body mass for model

Structure of human body	Mass [kg]
Head	$m_1=5.27$
Neck – upper torso	$m_2=25.05$
Upper arms	$m_3=4.76$
Lower arms	$m_4=2.89$
Hands	$m_5=1.02$
Abdominal segment 3	$m_6=2.38$
Abdominal segment 4	$m_7=2.54$
Abdominal segment 5	$m_8=2.62$
Lumbar vertebra L3	$m_9=0.12$
Lumbar vertebra L4	$m_{10}=0.13$
Lumbar vertebra L5	$m_{11}=0.14$
Sacral spine	$m_{12}=0.3$
Pelvis and thigh	$m_{13}=28.09$
Shins and foots	$m_{14}=9.69$
Total mass	$M=85$

Table 2. Layout of moments of inertia for model

Structure of human body	Moment of inertia[kgm^2]
Head	$I_1=0.022$
Neck – upper torso	$I_2=0.362$
Upper arms	$I_3=0.031$
Lower arms	$I_4=0.016$
Hands	$I_5=8.470e-004$
Abdominal segment 3	$I_6=0.005$
Abdominal segment 4	$I_7=0.005$
Abdominal segment 5	$I_8=0.005$
Lumbar vertebra L3	$I_9=5.883e-005$
Lumbar vertebra L4	$I_{10}=6.304e-005$
Lumbar vertebra L5	$I_{11}=7.223e-005$
Sacral spine	$I_{12}=3.428e-004$
Pelvis and thigh	$I_{13}=0.584$
Shins and foots	$I_{14}=0.138$

In order to obtain the real human mass layout, the whole body was divided into the following segments (fig 2): head (m_1), neck with upper torso (m_2), upper arms (m_3), lower arms (m_4), hands (m_5), three abdominal segments (m_6, m_7,..., m_8), pelvis and thighs (m_{13}), shins and feet (m_{14}). Abdominal segments are connected to the centers of corresponding vertebral bodies.The layout of the body mass is very important and has a high influence on the work and the dynamics of the spine (and consequently on the vibration of each of these structures). The layout of the human body mass and moments of inertia in a model representing a specific driver has been shown in tables 1 and 2.

Table 3. Stiffness of spine discs in driver model

Spring joint of mass elements	Stifness of spine disc [N/m]
Upper torso - vertebra L3	k_1=86520
Upper torso - vertebra L3	k_2=86520
vertebra L3 - vertebra L4	k_3=92000
vertebra L3 - vertebra L4	k_4=92000
vertebra L4 - vertebra L5	k_5=70000
vertebra L4 - vertebra L5	k_6=70000
vertebra L5 - sacral vertebra	k_7=55760
vertebra L5 - sacral vertebra	k_8=55760

Table 4. Damping of spine discs in driver model

Damping joint of mass elements	Damping of spine disc [Ns/m]
Upper torso - vertebra L3	c_1=217
Upper torso - vertebra L3	c_2=217
vertebra L3 - vertebra L4	c_3=102
vertebra L3 - vertebra L4	c_4=102
vertebra L4 - vertebra L5	c_5=111
vertebra L4 - vertebra L5	c_6=111
vertebra L5 - sacral vertebra	c_7=126
vertebra L5 - sacral vertebra	c_8=126

Soft tissues such as muscles, ligaments and intervertebral discs were modelled by means of spring-damper elements (rheological models of non - activated tissue without nervous system). The identification of biomechanical parameters of human tissue (in vivo, in vitro methods and other) is a complicated problem. These studies are strictly connected with an interference into the human body . Processes happening in tissues are non-linear and variable in time and the wide range of biomechanical parameters is connected with many factors (the variety of the human population, age, the state of health, etc.). Attempts in this respect were undertaken by many researchers [e.g. 19, 20]. The range of values found in literature has been taken into account for model representing driver with individual personal features. The parameters of soft tissue for model representing specified driver has been shown in tables 3, 4, 5 ,6, 7, 8 (see table 3 -stiffness of intervertebral discs, /k_1, k_2, ..., k_8/; table 4 - damping of intervertebral discs, /c_1, c_2, ..., c_8/, table 5 -stiffness of spinal muscles and ligaments / k_9, k_{10}, ..., k_{16}; /, table 6 - damping of spinal muscles and ligaments /c_9, c_{10}, ..., c_{16}/, table 7 -stiffness of body muscles / k_{17}, k_{18}, ..., k_{27}; /, table 8 - damping of body muscles /c_{17}, c_{18}, ..., c_{27}/).

Table 5. Stiffness of spine ligaments and muscles in driver model

Spring joint of mass elements	Stifness of spine ligaments and muscles [N/m]
Upper torso - vertebra L3	k_9=106120
Upper torso - abdominal seg. 3	k_{10}=72540
Vertebra L3 - vertebra L4	k_{11}=40800
Abdominal segments 3 - 4	k_{12}=33000
Vertebra L4 - vertebra L5	k_{13}=35200
Abdominal segments 4 - 5	k_{14}=24000
Vertebra L5 - sacral vertebra	k_{15}=35200
Abdominal segment 5 - pelvis	k_{16}=33000

Table 6. Damping of spine ligaments and muscles in driver model

Damping joint of mass elements	Damping of spine ligaments and muscles [Ns/m]
Upper torso - vertebra L3	$c_9=70$
Upper torso - abdominal seg. 3	$c_{10}=90$
Vertebra L3 - vertebra L4	$c_{11}=98$
Abdominal segments 3 - 4	$c_{12}=64$
Vertebra L4 - vertebra L5	$c_{13}=90$
Abdominal segments 4 - 5	$c_{14}=95$
Vertebra L5 - sacral vertebra	$c_{15}=93$
Abdominal segment 5 - pelvis	$c_{16}=72$

Table 7. Stiffness of abdomen muscles in driver model

Spring joint of mass elements	Stifness of abdominal muscles [N/m]
Upper torso - abdominal seg. 3	$k_{17}=54600$
Upper torso - abdominal seg. 3	$k_{18}=89940$
Upper torso - abdominal seg. 3	$k_{19}=89940$
Abdominal segments 3 - 4	$k_{20}=38400$
Abdominal segments 3 - 4	$k_{21}=42000$
Abdominal segments 3 - 4	$k_{22}=42000$
Abdominal segments 4 - 5	$k_{23}=22800$
Abdominal segments 4 - 5	$k_{24}=67966$
Abdominal segments 4 - 5	$k_{25}=67966$
Abdominal segment 5 - pelvis	$k_{26}=28800$
Abdominal segment 5 - pelvis	$k_{27}=58000$

Table 8. Damping of abdomen muscles in driver model

Damping joint of mass elements	Damping of abdominal muscles [Ns/m]
Upper torso - abdominal seg. 3	$c_{17}=234$
Upper torso - abdominal seg. 3	$c_{18}=275$
Upper torso - abdominal seg. 3	$c_{19}=275$
Abdominal segments 3 - 4	$c_{20}=152$
Abdominal segments 3 - 4	$c_{21}=154$
Abdominal segments 3 - 4	$c_{22}=154$
Abdominal segments 4 - 5	$c_{23}=105$
Abdominal segments 4 - 5	$c_{24}=150$
Abdominal segments 4 - 5	$c_{25}=150$
Abdominal segment 5 - pelvis	$c_{26}=120$
Abdominal segment 5 - pelvis	$c_{27}=240$

In the model of seat suspension the adjustable spring (k) and constant damping (c) have been taken into account (fig. 1). Elastic properties of the cushion (M_1) and backrest (M_2) are also modelled as a spring and a dashpot. The subsystem human has been connected with seat and vehicle by integrated model: seat–human body interface and vehicle–body interface. Motions of drive's cabin floor (z_3) and seat (z_4) were generated with use the subsystem of road excitation (z_1 and z_2 inputs – see fig. 1). The human body motion and the excitation forces are restricted to the vertical (Z) and horizontal (X) direction. In the construction of the measurement system the requirements of international standards ISO [11, 12] have been taken into account.

2. COMPUTER SIMULATIONS AND RESULTS

Numerical simulations were conducted in the environment Matlab-Simulink-SimMechanics. The computer analysis aimed at assessing the vibrations of modelled human body parts for different stiffness of seat suspension. The human model used in this study represents the driver with specific personal features and total mass 85 kg (the values of biomechanical parameters shown in the table 1, 2, 3, 4, 5, 6 ,7 and 8). Construction of human body model allowed to perform the simulations and obtain the vibration exposure characteristics for the specified driver (for the specified human body structures). The range of spring stiffness coefficients were determined with taking into account available construction of suspension seats. Computer simulations were performed for constant optimal value of damping c= 980Ns/m [13]. and for the following values of stiffness coefficients(k): k_1=7000 N/m, k_2=8000 N/m, k_3=9000 N/m, k_4=10000 N/m, k_5=11000 N/m, k_6=12000 N/m, k_7=13000 N/m, k_8=14000 N/m, k_9=15000 N/m, k_{10}=16000 N/m, k_{11}=17000 N/m, k_{12}=18000 N/m, k_{13}=19000 N/m, k_{14}=20000 N/m, k_{15}=21000 N/m, k_{16}=22000 N/m, k_{17}=23000 N/m, k_{18}=24000 N/m.

Evaluation of the effects of vibration on the health, according to ISO 2631 (1997), was determined using vibration accelerations for translational motion (x and z – directions) of all modelled structures of human body, seat and vehicle. RMS weighted acceleration in accordance with ISO standard (ISO 2631) should be calculated for each translational direction as follows:

$$\mathrm{RMS}=\sqrt{\frac{1}{T}\int_0^T a_w^2(t)\,dt}\ , \qquad (1)$$

where $a_w(t)$ is the weighted acceleration as a function of time and T is the duration of measurement.

A couple of weighting curves (filters) are specified by ISO 2631 (1997) depending on the orientation of the person and the direction of vibration. For a seated person the Wk filter is used to weigh the frequency contribution for vertical vibrations and the Wd filter is used to weigh the frequency contribution for lateral vibrations.

Real road acceleration inputs were considered in the range of natural frequencies of the human body. In the first stage of this study one random excitation was chosen for z_1 and z_2 inputs. It is described trough power spectral density of acceleration (PSD) illustrated on figure 3(a).

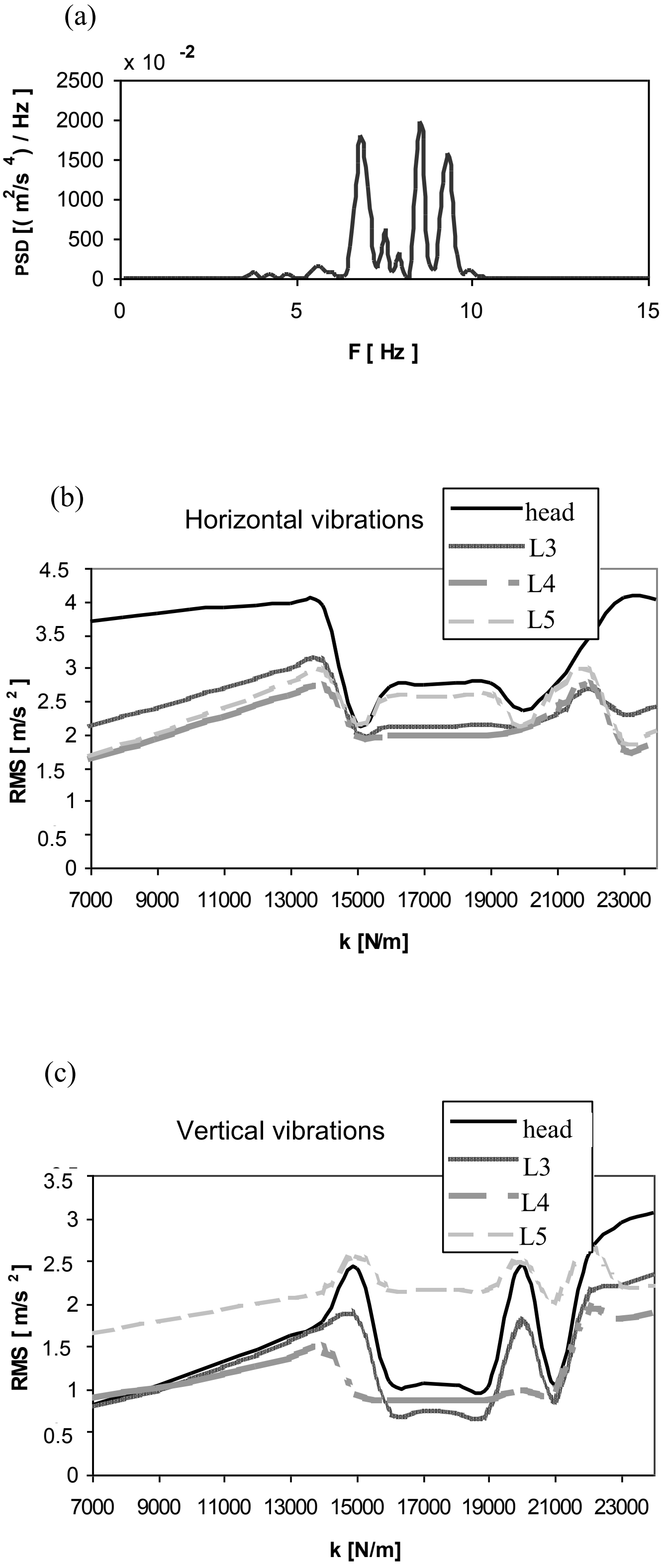

Figure 3. RMS accelerations of body structures of human model as function of suspension stiffness – vibrations comparison for selected body segments and two directions: (a) excitations (PSD of acceleration), (b) horizontal vibration – x-directions, (c) vertical vibration – z-directions

The examplary results for horizontal and vertical vibration of the selected segments of driver model in the stiffness function have been shown in the figure 3(b) and 3(c). Individual characteristics represent RMS weighted accelerations of head, lumbar vertebrae L3, L4, L5. On the basis of achieved results the following conclusions were put forward:

- For all analysed directions (X and Z) it can observe a strong nonlinear relationship between vibration accelerations of modelled human body parts and stiffness of suspension.
- For individual segments of the human model several values of stiffness can be pointed out, where the level of accelerations is very high (it can be associated with the resonance of the specific anatomical structures). For example, in the x-direction there are two main resonance peaks in the case of head vibrations (Fig. 3(b)), this is k_8=14000 N/m and k_{17}=23000 N/m, whereas in the z-direction three strong amplifications of haed accelerations are visible (Fig. 3(c)): at k_9=15000 N/m (first peak), k_{14}=20000 (second peak), k_{18}=24000 N/m (third peak).
- The results show that several effective stiffnesses of seat suspension can be determined for driver with specific biomechanical parameters. For example (of the same as above), the horizontal vibrations of head (Fig. 3(b)), are reduced to minimum at k_9=15000 N/m and k_{14}=20000 N/m (two optimal values of stiffness)), whereas in case of vertical vibrations four minimum values are visible(Fig. 3(c)): at k_l=7000 N/m, k_{10}=16000 N/m, k_{13}=19000 N/m and k_{15}=21000 N/m.
- In the z-direction (Fig. 3(c)), the larger spring stiffness leads to a differently shaped response of the human body model than in x-direction (Fig. 3(b)). The difference between horizontal and vertical vibration makes difficult to find common optimal stiffness for specific driver.
- The results suggest that the set-up of optimal stiffness is necessary to minimize the acceleration of head and other parts of the body such as the vertbrae of spine for driver with specific biomechanical parameters.

3. CONCLUSION

In this paper the complex model of a human-seat-vehicle system for dynamic analyses of vertical and horizontal vibration has been presented. New model of a person representing a driver with specified biomechanical parameters and new strategies for computer study of seat suspension have been proposed. This approach can be used to determine optimal passive mechanical parameters of a vehicle seat suspension system taking into account biomechanical parameters of human. In this work, a driver model is used in an optimization problem to determine an optimum set of stiffness to achieve the best performance of the seat suspension system.

The results obtained for the different suspension stiffness show the complexity of the problem associated with a proper parameters selection in the aspect of the vibration reduction which affect on human health. On the basis of achieved results it can be found, that changing of suspension stiffness have a large and nonlinear effect on the accelerations level of individual body structures making it difficult to assess vibrations. It can determine several ranges of stiffness in examined case, where the level of exposure to vibration can be more effectively reduced by application of the appropriate suspension of driver seat.

In this study, the human body motions are restricted to the vertical (Z) and horizontal (X) directions because the studies prove, that vertical and horizontal vibrations most affect the spine and other human body parts [14]. The differences between horizontal an vertical vibration of the same body parts suggest necessity of the compromise at optimal stiffness determination. For all analysed directions strong accelerations amplifications of modelled body parts were observed. Such a accelerations transmitted to the vertebraes of the spine body, upper body and head can be the most important factors affecting drivers' fatigue, health, ride comfort and safety in transport.

The suspension choice (harder or softer) is made conditional also on the class of the road. So, for further research of the suspension stiffness it is necessary to take into account not only variety of biomechanical parameters of drivers, but also a wide range of road and rail excitations.

Majority of the semi-active solutions (for example the systems with magneto-rheological fluid dampers) is designed to adjust the damping in real time [15]. There are much less the solutions with variable stiffness. The major drawback for this type of system is that it is complicated, costly, and needs a power supply. However, the presented results suggest that the application of variable stiffness to the design optimization of an seat suspension system give a large potential of the adaptation to different biomechanical parameters of drivers and ride conditions. Therefore, to optimize a human vibration suppression the suspension variable stiffness should be also taken into account.

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