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INTERCITY BUS USERS VIBRATION COMFORT ANALYSIS THROUGH AN OSCILLATORY MODEL WITH SEVEN DOF USING ADAMS/VIEW SOFTWARE

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An analysis of the vibration comfort of the users of an intercity bus IK-302 is carried out. Evaluation of the vibrations effect is made through criteria of comfort for means of public transport, defined in the international standard ISO 2631. The plane longitudinal model of the bus, with seven degrees of freedom (DOF) is created in the module ADAMS/View. Comfort is considered with the places of driver and passengers, in the middle part of the bus as well as on the rear overhang. Vertical seats accelerations of users were analyzed for two actual excitations: asphalt-concrete in bad condition and the same in good condition. The results of the simulation show that the vibrations mostly endanger the comfort of passengers in the rear end of the bus, and driver's comfort is not threatened.

Key words: bus comfort, ISO 2631, road roughness, simulation, ADAMS/View

INTRODUCTION

During driving the drivers and passengers in the vehicle are exposed to vibration from ground excitation. Vibration raise a sense of discomfort, reduces working ability, and in the long term action can endanger the health [02, 03]. Particularly risky groups are the drivers of construction machinery, agricultural machines, heavy trucks and buses [08].

Researches [08, 12, 13] have shown that the bus drivers can be exposed to high intensity vibration. The most frequent diseases of drivers due to long-term exposure to high levels of vibration are related to the musculo-skeletal disorders (pain in the lower back, neck, shoulders and knees), psychological disorders (tiredness, tension, mental fatigue), disorders of sleep and others [17, 01].

In order to minimize the negative impact of vibrations and protect the health at work, the European Union adopted in June 2002. the Directive 2002/44/EC. In this Directive the whole human body allowable levels of vibration exposure at work are defined, and in accordance, clearly highlighted the obligations of working organization for taking the appropriate safety measures [11].

A timely response, in order to prevent the disease of the bus driver as well as of the passengers, requires continuous monitoring of the vibration levels that they are exposed. That means frequent measuring of the intensity of vibrations to which the vehicle users are exposed in actual circumstances of bus service. Except by the measurements, it is possible to make an analysis by simulation through the oscillatory models of vehicles. Simulations get in importance in cases when the measurements, due to of various restrictions, are rarely carried out.

In this paper the oscillatory comfort of the users is analyzed using a plane oscillatory model of the intercity bus IK-302 with seven DOF. Oscillatory comfort of bus driver and passengers is evaluated after the procedure and criteria prescribed by the Standard ISO 2631 [07]. Oscillatory model of the bus is made in the module ADAMS/View of the software pack ADAMS (Version MD ADAMS M3). The oscillatory model is excited by two signals registered on actual road surface: asphalt-concrete in bad condition and the same in good condition.

BUS OSCILLATORY MODEL

The analysis is carried out using an oscillatory model of the intercity bus IK-302 with seven DOF, made using the module ADAMS/View of

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the ADAMS software pack - Figure 1. Figure 2. shows a schematic representation of the oscillatory model. The independent motions of concentrated masses of the mechanical oscillatory system are: vertical motions of driver's body, of the bodies of the passenger in the middle of the bus (passenger1) and the passenger on the bus rear overhang (passenger 2), of the bus Center of gravity (CG), of the CG of front and rear axle as well as the angular motion of bus suspended mass around the y-axis.

The oscillatory mod of the bus IK-302 is made in ADAMS/View module with eight stiff bodies with freedom limited by means of appropriate connections. The driver, the passenger1 and the passenger2 are defined as three stiff bodies connected to the bus body through three translational joints. The translational joints allow translational motion of stiff bodies only in vertical direction. The bus body is also defined as a stiff body connected to GROUND by two joints - Inline Primitive Joint and Parallel Axes Primitive Joint. The combination of

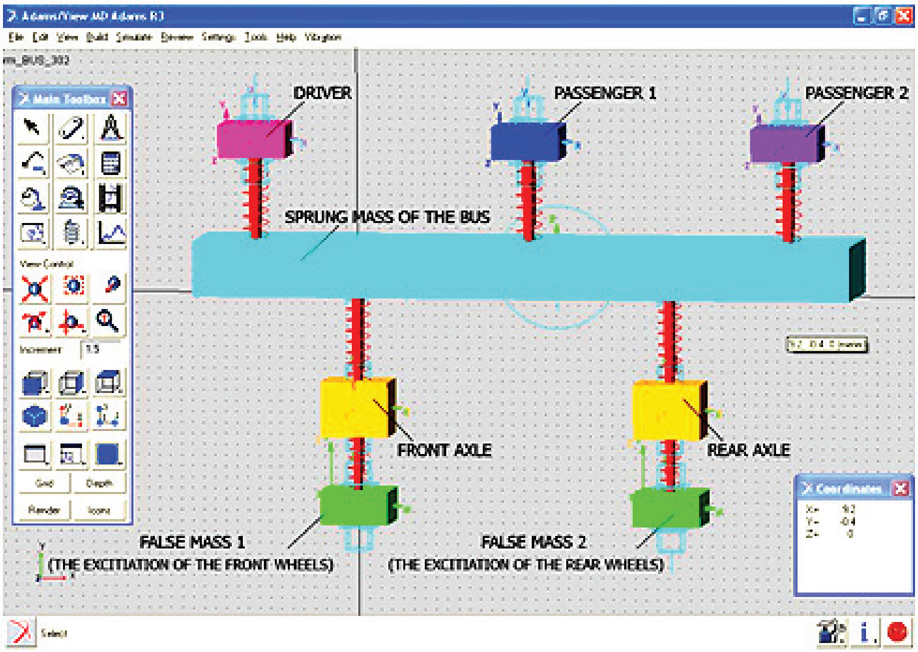

Figure 1. Plane oscillatory model of the bus in ADAMS/View

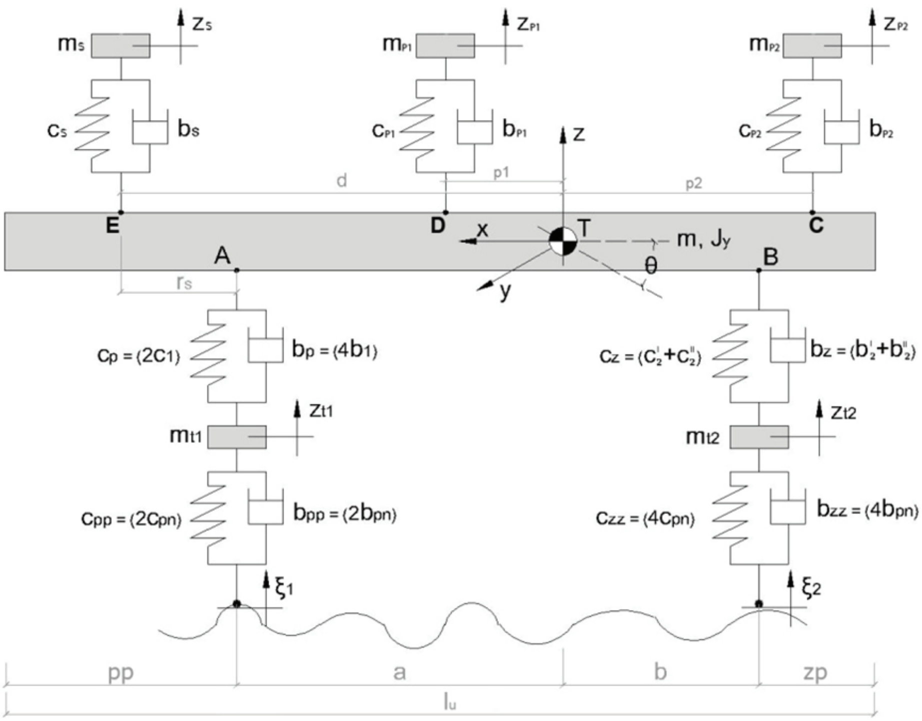

Figure 2. Schematic representation of the plane oscillatory model of the bus

these allows translational motion of the bus body in vertical direction and angular motion around transversal CG axis. Front and rear axles are defined as two stiff bodies joined to GROUND by translational joints that also allow translational motion of the axles only in vertical direction.

To realize the motion in the point of contact between the tire and pavement, two virtual stiff bodies are introduced, connected to the GROUND by translational joints. The actual road roughness is introduced to these joints by means of CUBSPL function.

Suspension system of the bus, driver's seat, passengers' seats and tires are defined as SPRING-DAMPER elements with appropriate stiffness and damping (Table 3).

Table 1. Geometry parameters of the bus

Geometry parameter	Value [m]
l - distance between axles	5.65
a - distance from the front axle to CG of the loaded bus	3.55
b - distance from the rear axle to CG of the loaded bus	2.10
p_p – front overhang of the bus	2.82
z_p – rear overhang of the bus	3.392
l_u - total length of the bus	11.862
r_s - distance from the driver's seat to the front axle	1.30
d - distance from the driver's seat to bus CG	4.85
p_1 - distance from the passenger 1 seat to bus CG	0.5
p_2 - distance from the passenger 2 seat to bus CG	4.2

Table 2. Masses parameters of the bus

Masses parameter	Value
m_v - mass of the driver and the seat	100 [kg]
m_{p1} - mass of the passenger 1 and the seat	90 [kg]
m_{p2} - mass of the passenger 2 and the seat	90 [kg]
m - suspended mass of the loaded bus	15400 [kg]
m_{t1} - mass of the front axle	746 [kg]
m_{t2} - mass of the rear axle	1355 [kg]
J_y - inertia moment of the suspended mass related to transversal axis	150000 [kgm2]

The meanings of labels in Figure 2. are given in tables (1-3). Tables also show all values of parameters used in simulation, taken from available sources [09].

Table 3. Oscillatory parameters of the bus

Oscillatory parameter	Value
c_s - driver's seat spring stiffness	25000 [N/m]
b_s - driver's seat damping	1000 [Ns/m]
c_{p1}, c_{p2} - passengers' seat spring stiffness	40000 [N/m]
b_{p1}, b_{p2} - passengers' seat damping	220 [Ns/m]
c_1 - one front axle pneumatic suspension element stiffness	175000 [N/m]
c_p - equivalent stiffness of front axle pneumatic suspension elements	350000 [N/m]
b_1 - one front axle shock absorber damping	15000 [Ns/m]
b_p - front axle shock absorbers equivalent damping	60000 [Ns/m]
c_2 - one rear axle pneumatic suspension element stiffness	20000 [N/m]

Oscillatory parameter	Value
c_z - equivalent stiffness of rear axle pneumatic suspension elements	816350 [N/m]
b_2 - damping of one rear axle hock absorber	22500 [Ns/m]
b_z - equivalent damping of rear axle shock absorbers	91839 [Ns/m]
c_{pn} - front and rear tire stiffness (pertire)	1000000 [N/m]
c_{pp} - equivalent front axle tires stiffness	2000000 [N/m]
c_{zz} - equivalent rear axle tires stiffness	4000000 [N/m]
b_{pn} - front and rear tire damping (pertire)	150 [Ns/m]
b_{pp} - equivalent front axle tires damp ing	300 [Ns/m]
b_{zz} - equivalent rear axle tires damping	600 [Ns/m]

The equivalent stiffness of air springs and equivalent damping of dampers on rear axle are calculated by using expressions 1 and 2 from [15]. Figure 3. shows the eigenvalues for oscillatory parameters and mass parameters of the bus. All real parts of eigenvalues are negative, so the equilibrium position of the oscillatory system is stable.

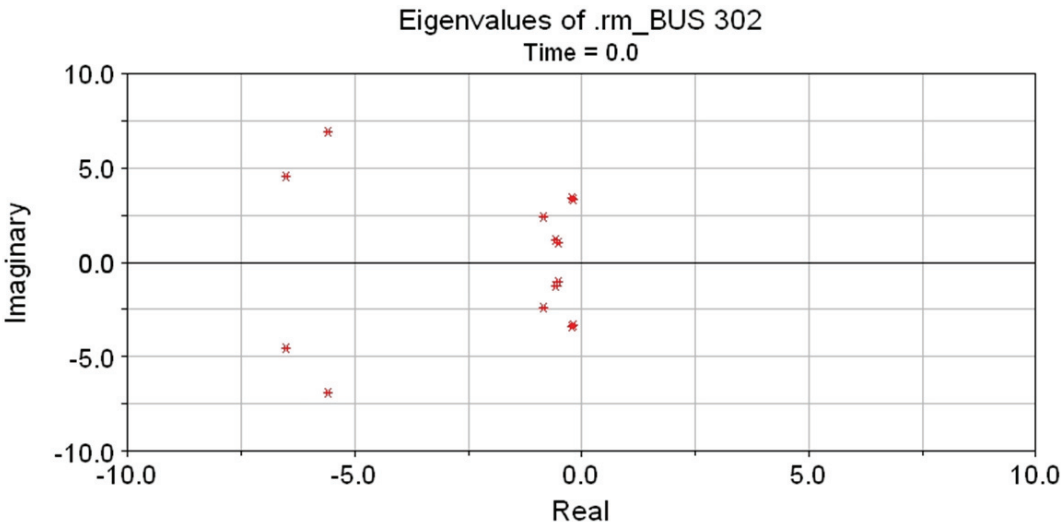

Figure 3. Eigenvalues for the defined oscillatory model

Table 4. Modes of oscillation of the oscillatory system

Mode number	Undamped natural frequency	Damping ratio	Real	Imaginary
1	1.134706E+000	0.457225E+000	-5.188163E-001	+/- 1.009152E+000
2	1.345294E+000	0.428959E+000	-5.770759E-001	+/- 1.215237E+000
3	2.561561E+000	0.328449E+000	-8.413420E-001	+/- 2.419451E+000
4	3.363872E+000	0.058918E+000	-1.981937E-001	+/- 3.358028E+000
5	3.392065E+000	0.061392E+000	-2.082473E-001	+/- 3.385667E+000
6	7.951542E+000	0.819930E+000	-6.519709E+000	+/-4.551968E+000
7	8.886907E+000	0.629679E+000	-5.595898E+000	+/-6.903842E+000

A pair of imaginary numbers corresponds to each real part of eigenvalues. It follows that the motion of the system around the equilibrium position has an oscillatory character.

Table 4. presents the oscillatory modes of the oscillatory system. Natural oscillation frequencies of the system correspond to typical frequencies of the bus oscillation [04].

BUS EXCITATION

The paper analyses the oscillatory comfort of the bus users which is the consequence of the reactions of the vehicle model to excitation by two signals recorded on actual pavements - asphalt-concrete in bad condition and asphalt-concrete in good condition (Figures 4(a) and 4(b)). Road roughness is taken from [06], and it is recorded by means of measurement vehicle K. J. Law Engineers on the road sections of the length of 161 m, with vehicle speeds of 72 km/h and 80 km/h. Longitudinal road roughness is random function that contains different wave lengths and different roughness amplitudes. Not all roughness wave lengths have the same level of outcome to the oscillatory behavior of the vehicle. For example, the roughnesses with very short wave length (up to 1 m) produce major effect to the interior noise in the vehicle. On the opposite, the roughnesses with long wave length indicate the longitudinal road profile character and have no significant effect to oscillatory motion of the vehicle. For the analysis of the vehicle oscillatory behavior, the range of excitation frequencies between 1 Hz and 30 Hz is the most important [16]. The connection between roughness wave length, vehicle velocity and road frequency is represented by expression:

$$\lambda = \frac{V}{f}$$

where:

λ - is road roughness wave length (m);
V - is vehicle velocity (m/s) and
f - is road roughness frequency (Hz).

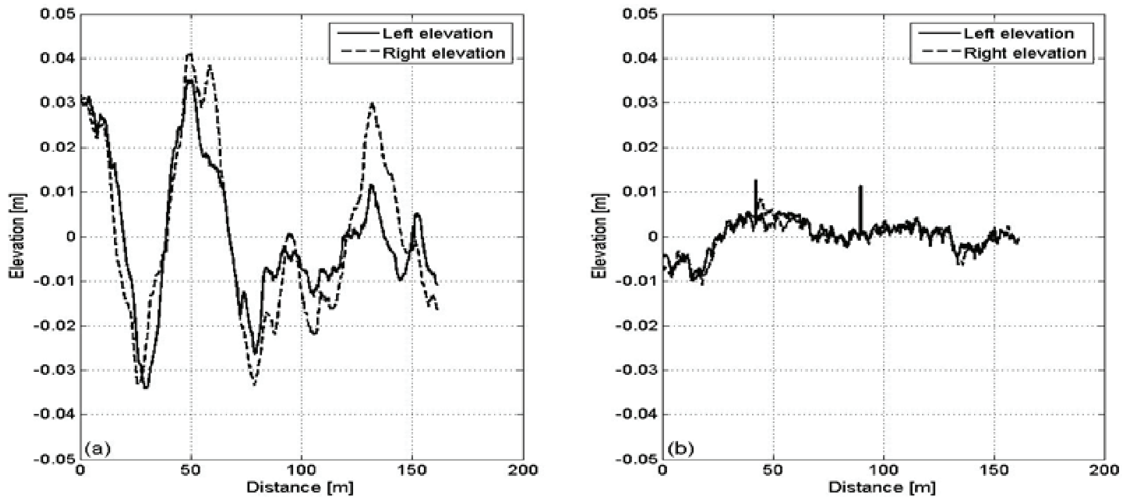

Figure 4. Road roughness recorded on (a) asphalt-concrete in bad condition (b) asphalt-concrete in good condition

The ranges of roughness wave lengths from 20.00 m to 0.67 m and 22.22 to 0.74 m correspond to the frequency range for vehicle velocities of 72 km/h and 80 km/h, respectively. That's why the recorded signals were filtered using Moving average filter in the software pack ProVal 2.73 [05]. The Figures 5(a) and 5(b) show filtered and averaged signals of road roughness on the left and right wheel as function of time.

ANALYSIS OF THE RESULTS

Gear Stiff (GSTIFF) integrator with formulation I3 is used for numerical integration. GSTIFF integrator uses backwards differentiation formula and Newton-Raphson algorithm for numerical integration of differential equations [10]. The time sequence of 7 s is chosen. The acceleration signals of vehicle users are sampled at each 0,001 s. Simulation is carried out in a way that the oscillatory model is first brought in the equilibrium, using the command "Find static equilibrium", and only after that the dynamic simulation is completed.

Vertical accelerations of bus users for two types

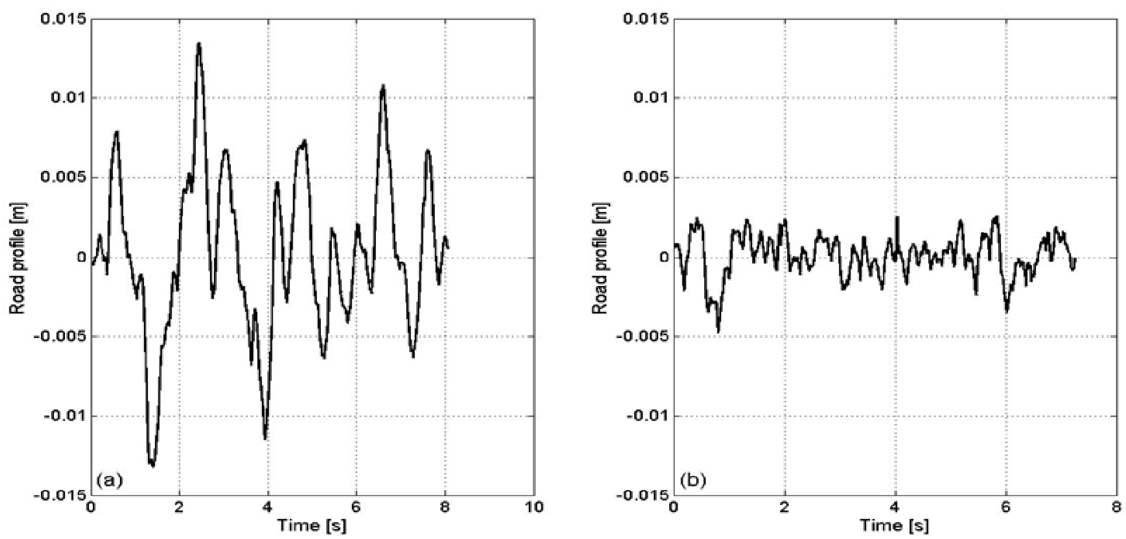

Figure 5. Filtered and averaged road roughness of (a) asphalt-concrete in bad condition (b) asphalt-concrete in good condition

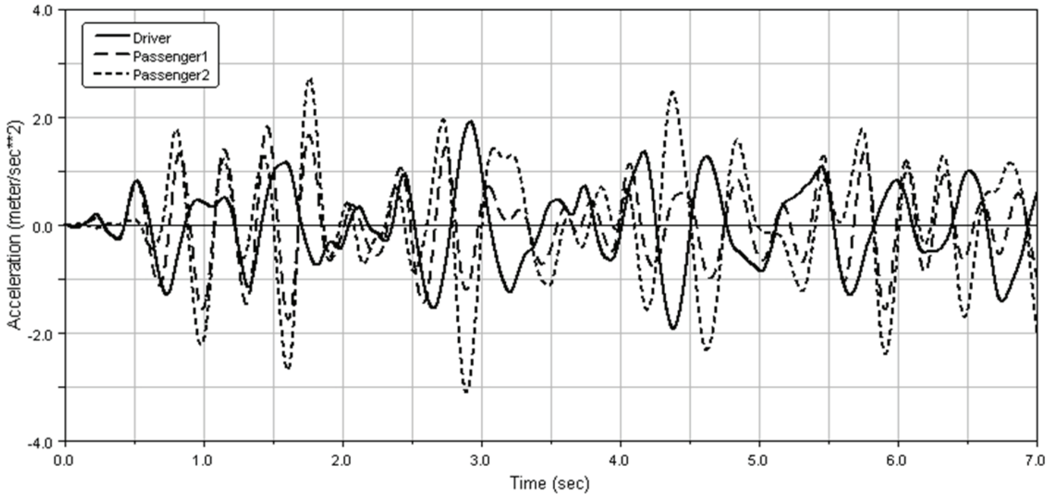

Figure 6. Vertical acceleration of the bus user body for the excitation from asphalt-concrete in bad condition and bus speed 72 km/h

Table 5. Statistical parameters for vertical user's body acceleration, for the excitation from asphalt-concrete in bad condition and bus speed 72 km/h

User's body acceleration	Maximum value	Minimum value	Mean value	RMS value
Driver [m/s^2]	1.9195	-1.9247	-0.0163	0.746
Passenger 1 [m/s^2]	1.8221	-1.7446	0.0004	0.7137
Passenger 2 [m/s^2]	2.7324	-3.0992	0.0112	1.0681

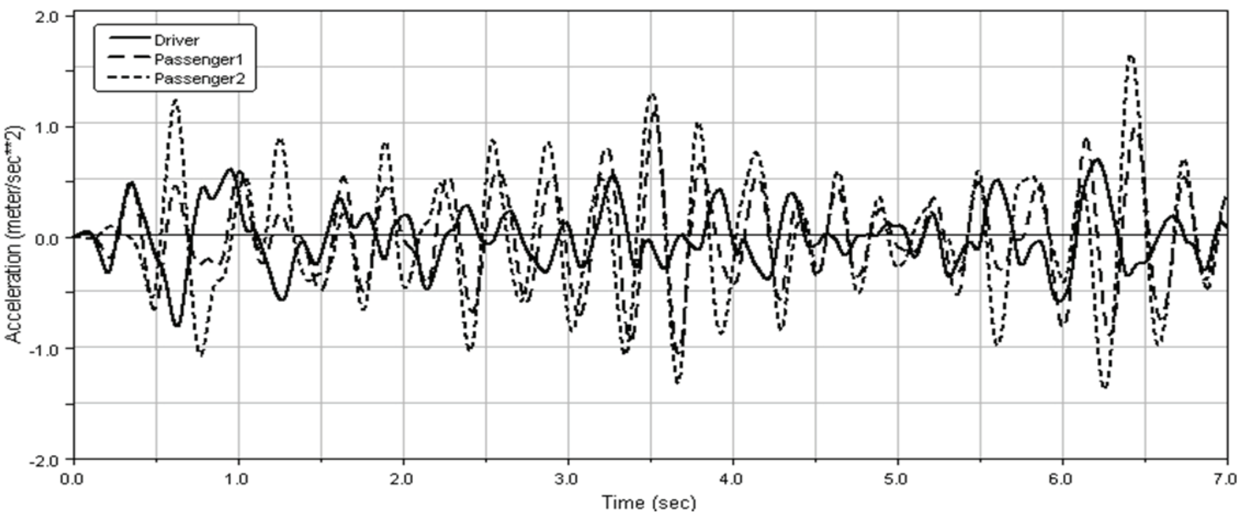

Figure 7. Bus user vertical acceleration for the excitation from asphalt-concrete in good condition and bus speed 80 km/h

Table 6. Statistical parameters for vertical user's body acceleration, for the excitation from asphalt-concrete in good condition and bus speed 80 km/h

User's body acceleration	Maximum value	Minimum value	Mean value	RMS value
Driver [m/s^2]	0.7041	-0.8065	-0.0006	0.2665
Passenger 1 [m/s^2]	1.1207	-1.0524	0.0001	0.4097
Passenger 2 [m/s^2]	1.6516	-1.374	0.0015	0.5448

of excitation are shown in figures 6. and 7. In the tables 5 and 6 the important statistical parameters of the users' accelerations are given, by means of "plot-tracking" command in ADAMS/PostProcessor.

Vertical accelerations of users have greater values when the bus is excited from asphalt-concrete in bad condition than when excited from asphalt-concrete in good condition. The maximum value of vertical acceleration, for both excitations, abides the passenger in the rear of the bus (passenger 2). The peak value of the acceleration of the passenger 2 on the worse pavement is about -3.0 m/s^2, and on the better one is 1.65 m/s2. Peak values of the acceleration for driver and passenger in the middle of the bus (passenger1) on the worse pavement are almost the same (table 5). On the good pavement the peak vertical accelerations of driver and passenger 1 are about -0.8 m/s^2 and 1.12 m/s^2 respectively.

The evaluation of the effect of vibrations to the bus user comfort is made through procedures prescribed by the International Standard ISO 2613-1 (1997) [11]. This standard prescribes the total root mean square value of weighted acceleration as the basic value for the evaluation of effect of vibrations to the comfort, expression 1.

$$a_v = ((k_x \cdot \ddot{x}_{rms,w})^2 + (k_y \cdot \ddot{y}_{rms,w})^2 + (k_z \cdot \ddot{z}_{rms,w})^2)^{1/2} \quad (1)$$

where:

a_v - is total root mean square value of weighted acceleration on the seats of bus users [m/s^2];

$\ddot{x}_{rms,w}, \ddot{y}_{rms,w}, \ddot{z}_{rms,w}$ - are root mean square values of weighted acceleration for x, y, z axis [m/s^2];

k_x, k_y, k_z - are multiplying factors for acceleration RMS for x, y, z axis;

Values of multiplying factors kx, ky, kz for acceleration RMS, for the assessment of the vibrations effect to the comfort, are equal to 1.

This comfort analysis is carried out regarding the calculated root mean square value of weighted vertical accelerations on the driver's and passengers' seats, expression 2.

$$\ddot{z}_{rms,w} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \ddot{z}_{w_i}^2} \quad (2)$$

where:

$\ddot{z}_{rms,w}$- is root mean square value of weighted vertical acceleration on the users' seats [m/s^2];

$\ddot{z}_{w_i}$- is the i-th sample of weighted vertical acceleration on the users' seats [m/s^2];

N - is the number of samples of the signal of weighted vertical acceleration on the users' seats;

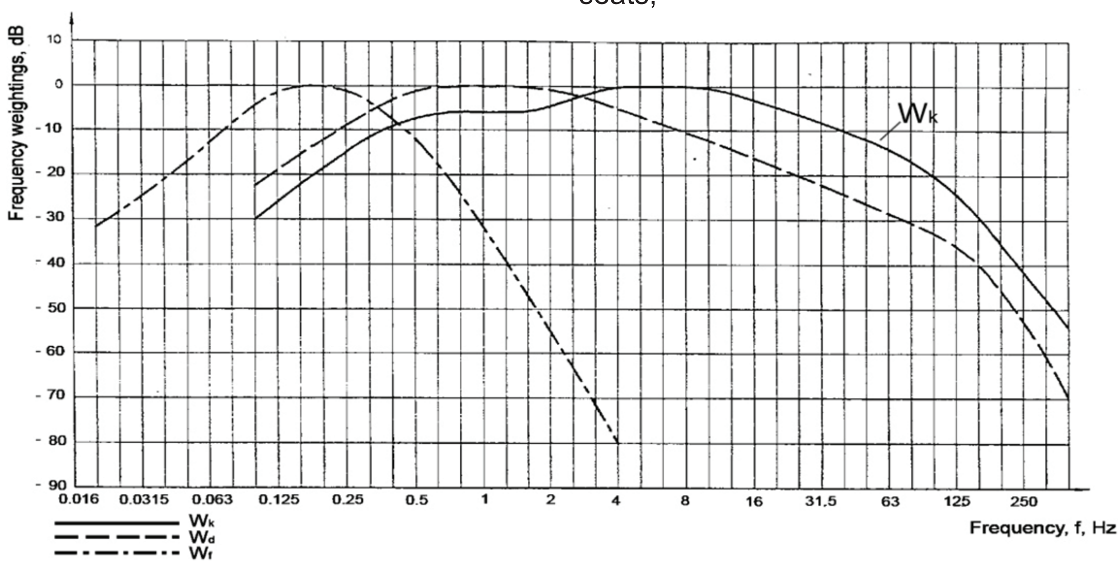

Figure 8. Filters for weighting the acceleration on users' seats

Number of samples of the signals of vertical acceleration N is equal to 7001. A specific program is made in software pack Matlab® for the weighting of vertical acceleration of bus users.

Within this program, according to Standard ISO 2631-1, the filter Wk is defined to weight vertical acceleration of users on their seats (Fig. 8).

Figure 8. shows also the filter Wd for weighting horizontal accelerations on the users' seats (accelerations for x- and y- axis). Filters Wk and Wd are used for evaluation of effect of vibrations to comfort, work ability and health of users [11]. The same figure shows also filter Wf for weighting vertical accelerations on seats for low frequencies excitation, i.e. for evaluation of the

effect of vibrations to appearance of motion sickness with users. The weighting filters describe the sensitivity of human body to vibrations of different frequencies. For example, human body is the most sensitive to vertical accelerations in frequency range of 4 to 8 Hz, and out of this range the sensitivity decrease, both with frequencies lower than 4 Hz and higher than 8 Hz. That is why the modulus of the transfer function of the filter Wk for frequencies 4 to 8 Hz is equal to 1, i.e. 0 dB.

The comfort evaluation is made by comparing of the root mean square values of weighted vertical acceleration of bus users obtained by simulation (table 7), with limit comfort criteria for means of public transport (table 8), according the Standard ISO 2631-1 (1997).

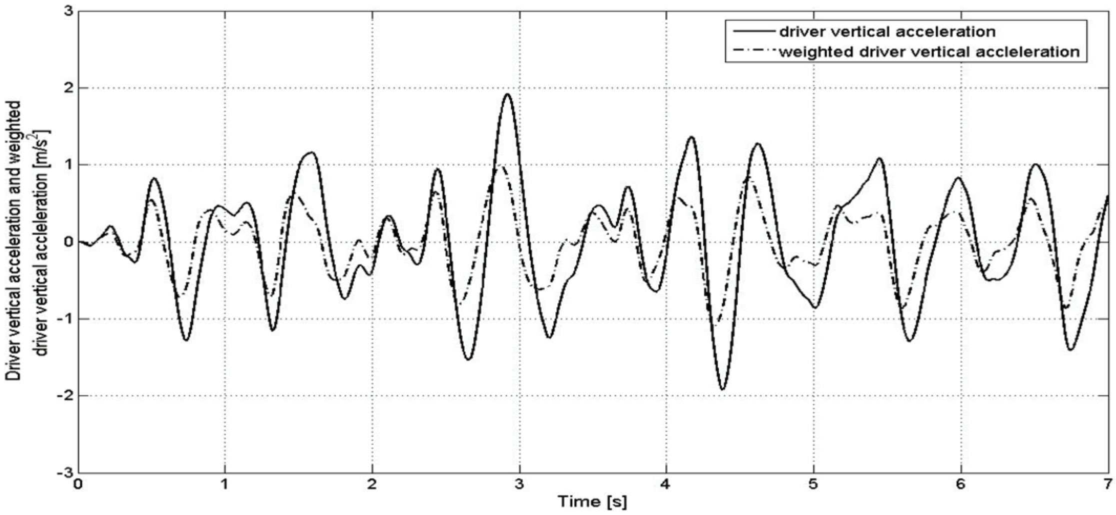

Figure 9. Vertical acceleration and weighted vertical acceleration on bus driver's seat for the excitation from asphalt-concrete in bad condition and bus speed of 72 km/h

Table 7. Root mean square values of weighted vertical acceleration of bus users

Type and state of pavement	Bus speed [km/h]	Root mean square values of weighted vertical acceleration [m/s²]		
		driver	passenger 1	passenger 2
Asphalt-concrete (bad)	72	0.4099	0.5737	0.7190
Asphalt-concrete (good)	80	0.1732	0.3453	0.4337

Table 8. Comfort criteria for the means of public transport

Vibration intensity	Comfort experience
< 0.315 [m/s2]	not uncomfortable
0.315 - 0.63 [m/s2]	a little uncomfortable
0.5 - 1.0 [m/s2]	fairly uncomfortable
0.8 - 1.6 [m/s2]	uncomfortable
1.25 - 2.5 [m/s2]	very uncomfortable
> 2.0 [m/s2]	extremely uncomfortable

As an example, figure 9. shows the vertical acceleration and weighted vertical acceleration on driver's seat, for asphalt-concrete in bad condition excitation and vehicle speed of 72 km/h.

For the excitation from asphalt-concrete in bad condition, root mean square value of weighted acceleration of driver and passenger1 is greater than 0.315 m/s², so that vibrations, after the evaluation criteria, have the effect on their comfort designated as "a little uncomfortable". Root mean square value of weighted acceleration of passenger2 is 0.719 m/s², and the comfort designation is “fairly uncomfortable”.

For the excitation from asphalt-concrete in good condition, root mean square value of weighted acceleration of driver is 0.1732 m/s^2. After the standard, the vibrations do not have effect to his comfort. For the same excitation, the vibrations influence the comfort of both passengers, after the criterion of ISO 2631, are designated with notion “a little uncomfortable”.

Root mean square values of weighted vertical acceleration of users, from table 7., are represented also graphically, in Figure 10.

The graph shows that, for both excitements, the passenger 2 exposed to higher RMS values of weighted acceleration compared with the driver and passenger1. In opposite to the passenger 2, the lowest RMS value of weighted acceleration, and accordingly the highest comfort, is on the driver’s seat.

The effective values of weighted vertical acceleration of the driver, obtained by simulation for the excitation from asphalt-concrete in good condition, are comparable with effective acceleration values measured in earlier researches [09].

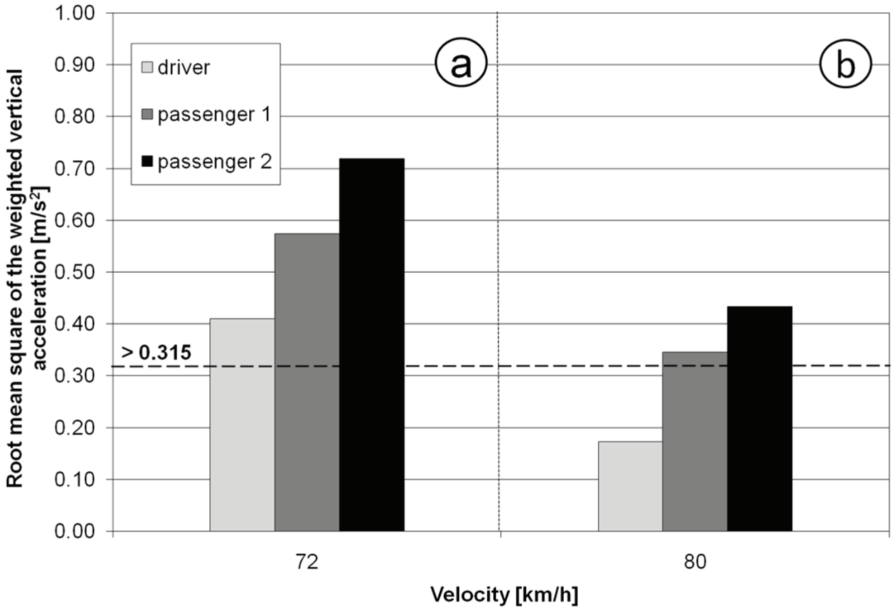

Figure 10. Root mean square values of weighted vertical acceleration of users for the excitement from (a) asphalt-concrete in bad condition and (b) asphalt-concrete in good condition

CONCLUSION

The bus driver and passengers are exposed to negative effect of vibrations excited from road roughness and filtered through the bus to their bodies. The research presented shows that bus drivers are exposed to vibrations that intensities may exceed the allowed values prescribed. Understanding of the intensity of vibrations that bus drivers and passengers are exposed is important for proper acting to reduce negative effect of vibrations to their comfort, and which is even more important, to their health.

The paper analyzed the effect of vibrations to the comfort of intercity bus IK-302 users, applying an oscillatory model with seven DOF and two actual excitations: asphalt-concrete in bad condition and asphalt-concrete in good condition. The velocities of test vehicle during recording were almost the same. Actual excitement on asphalt-concrete in bad condition was recorded at 72 km/h, and on asphalt-concrete in good condition at 80 km/h.

The analysis shows that the vibration effect to the users comfort for a certain velocity and pavement depends on pavement state. The users comfort decrease on pavements with low quality. Vibrations affect mostly the comfort of passengers in rear end of the bus, and at least the bus driver comfort.

The results of simulation show that the passenger on the rear overhang of the bus abides highest values of vertical acceleration on asphalt-concrete in bad condition pavement. Root mean square value of weighted vertical acceleration of this passenger is 0.719 m/s2. For the excitement from asphalt-concrete in good condition, root mean square value of weighted vertical acceleration is more favorable and amounts 0.4337 m/s2. For the same excitement, root mean square value of weighted vertical acceleration of the driver, calculated by simulation, is 0.1732 m/s2, which means that the vibrations due to this pavement do not affect the driver's comfort.

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