THE RESEARCH ON THE INFLUENCE OF THE EXTERNAL EXCITATION CHARACTERISTICS ON THE DYNAMIC "MAN – WHEELCHAIR – VEHICLE" SYSTEM

Mečislovas Mariūnas[1], Julius Griškevičius[2]

Vilnius Gediminas Technical University,
Faculty of Mechanics, Department of Biomechanics
J.Basanavičiaus Str. 28a, LT-03224, Vilnius, Lithuania
Ph: (+370)-5-2744748. Fax: (+370)-5-2745043.
[1] E-mail: biome@me.vtu.lt,
[2] E-mail: julius@kanda.lt

INTRODUCTION

Safe transportation of the wheelchair-seated passengers nowadays is one of the most important problems facing transit providers and engineers. In a public transport disabled individuals often sit in their wheelchairs, therefore there must be certain means for securing the wheelchairs. Wheelchair is not typically designed to function as motor vehicle seat and it must be tested to withstand high loads that may occur during different traffic accidents [1, 2]. Because of the high traffic intensity, complex structure of the street system, non-uniform quality of the pavement, particularity of the public transport route the motion in the city is the most changeable, non-steady regime [3, 4]. During such motion high accelerations and forces act on the passengers, and therefore it is essential to determine magnitude of the dynamical loads and their influence on the wheelchair-seated passengers' safety during the travel. Despite the fact that the transportation safety of wheelchair-users and wheelchair crashworthiness problems has been solved partly by implementing the standards (ISO, ANSI/RESNA, FMVSS) for different wheelchair tie-down occupant restraint systems, some problems still exist [5, 6]. For example, wheelchair tie-down occupant restraint systems are not installed in all public transport and are often difficult to reach, uncomfortable to wear, and time-consuming to use [7]. Improperly or totally unsecured wheelchair can lose the stability and may become dangerous during an accident or emergency braking, especially the heavier electrical wheelchair. Furthermore, in the event of rollover the passenger should not be allowed to fall out of his wheelchair. However, if this should occur, the wheelchair itself should not be allowed to tumble on the passenger or through the bus during an accident. Most injuries to wheelchair users riding the city transport seem to result not from the traffic accident but more from sudden braking and turning that bus drivers do during daily routs in the city streets [8, 9]. Often disabled person travels seated in his wheelchair during the long-distance travel outside the city. When the wheelchair is rigidly fixed on the vehicle floor, vibration caused by different sources (road roughness, engine vibration) is directly transmitted to the body and therefore passenger may feel discomfort [10]. Therefore it is essential to determine whether the resonant frequencies of the vehicle cover the frequency range from 1 to 15 Hz, wherein human body mostly feels the discomfort. Most wheelchair restraint devices are designed primarily to prevent the wheelchair and the wheelchair occupant from moving excessively in a transportation situation and [11, 12].

Thus the main objectives of present paper are to determine characteristics of the external excitation during the motion of the vehicle and their influence on to dynamic "Man – Wheelchair – Vehicle" system, and to provide certain means to reduce negative effects on the safety and safe transportation of wheelchair-seated disabled persons.

MATERIAL AND RESEARCH METHODS

Since the wheelchair-seated passenger is in the moving vehicle, it is essential to determine external excitation forces that occur during the vehicle's motion. In turn the motion of the vehicle can be divided into the steady and non-steady motion regimes. During the steady motion transport mean is riding at a constant velocity, without sharp maneuvers, therefore forces of the kinematic or other sources of excitation are small. Non-steady regime of the motion is more dangerous, because sharply varying speed and/or path increases the loads like accelerations which in turn cause the reduction of the stability and therefore safety of the wheelchair-seated disabled person. Furthermore, because of high traffic intensity, complex structure of the street system, non-uniform road surface, and traffic jams, unexpected accidental situations, and particularity of the public transport daily routes in the city are exactly the non-steady regime of the motion. Consequently, analyzing the daily routes of the public transport can be distinguished specific and frequently repetitive motion regimes. They are: start moving and stopping in bus-stops, in traffic jams, high radius turnings, different maneuvers and so on. Thus, series of experimental measurements in most widely usable public transportation means (busses, trolleys) were performed. Accelerations in three directions, which affect the disabled person in the wheelchair during before mentioned vehicles driving regimes, were recorded using "Bruel&Kjaer" portable PULSE Type 3560C 4/2-ch. Input/Output module Type 3109. Tri-axial accelerometer was mounted on the plate and attached to the floor of vehicle, in special space for the disabled passengers with the wheelchairs. Usually it is located in the middle of the low-floor passenger bus or trolley. The setup of the experimental measurements in moving vehicle is shown schematically in Figure 1.

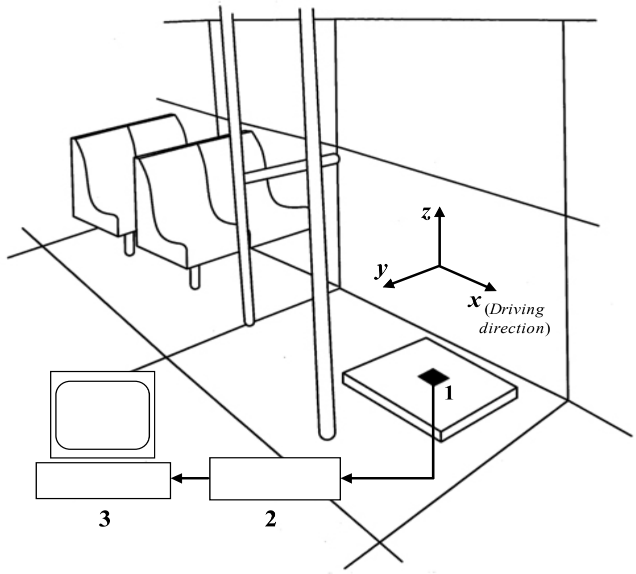

Fig.1. *Setup of the experimental measurements*
1 – Accelerometer; 2 – Portable data acquisition system; 3 – PC with analysis software

Shapes of the measured acceleration pulses during most common motion regimes of the public transport are shown in Figure 2 on the left. Peak values of the acceleration produce significant large forces acting on the wheelchair-bound disabled person and the stability of the dynamic "Man – Wheelchair – Vehicle" system reduces. Large accelerations that occur during traffic accidents are very dangerous and can cause severe or fatal injuries of passengers. Form and duration of the acceleration pulse determines the severity of the dynamical loads during the motion of the vehicle.

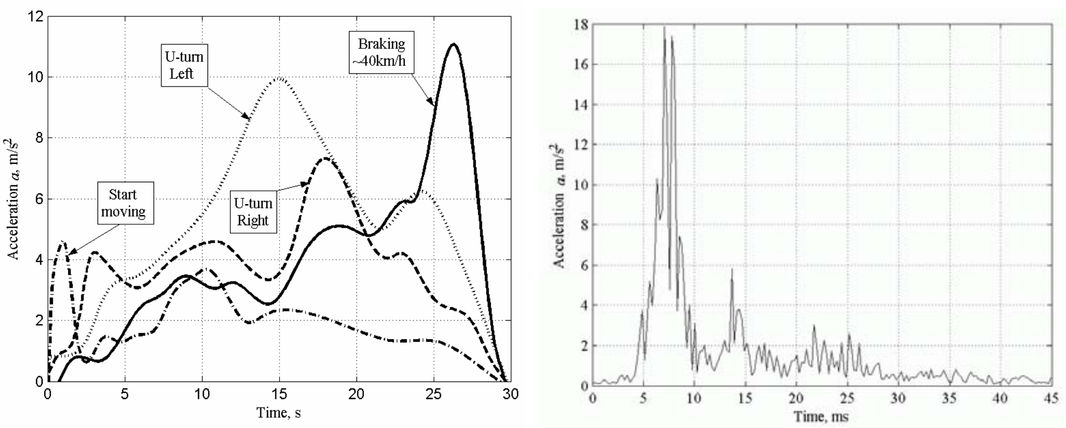

Fig.2. *Measured acceleration pulses during different motion regimes (on the left) and acceleration pulse during tug-like motion of the vehicle (on the right)*

The motion regimes of the public transport and ranges of the measured acceleration values in terms of gs are listed in Table 1.

Table 1. Acceleration values

Nr.	Motion regime	Acceleration values, g's	
		min	max
1.	Start moving	0.508	0.653
2.	Braking (from ~30–40 to 0 km/h)	0.570	1.394
3.	U-turn (~20–30 km/h with ~20m radius turn)	0.639	1.156
4.	Different maneuvers	0.594	0.724
5.	Route cycle through the city streets	0.356	0.869
6.	Unexpected tug-like motion	–	1.825

The speed in the city is limited up to 50-60 km/h and often it is lesser (average speed is about 30-40 km/h) because of the traffic intensity and street structure. Therefore severe collisions are very rare and disabled person travels in so called "low-g" environment, where acceleration loads are up to 2 g's in comparison with the accelerations up to 30 g's when the car crashes into a wall at speed ~54km/h for example. Particular cases in driving regimes that occur occasionally but nevertheless are significant should be marked. It is the regime when the bus or other mean of transportation suddenly changes its state of motion. For example, it can be an emergency braking or tug-like motion of the vehicle. The nature of acting forces during such motion is impulsive, with high amplitudes and short duration. Figure 2 on the right shows acceleration pulse of the tug-like motion.

Together with the measurements of accelerations during the most common driving regimes also the vehicle's accelerations during the usual route in the city streets were recorded. Figure 3 shows the accelerations during the 5 minutes long driving cycle.

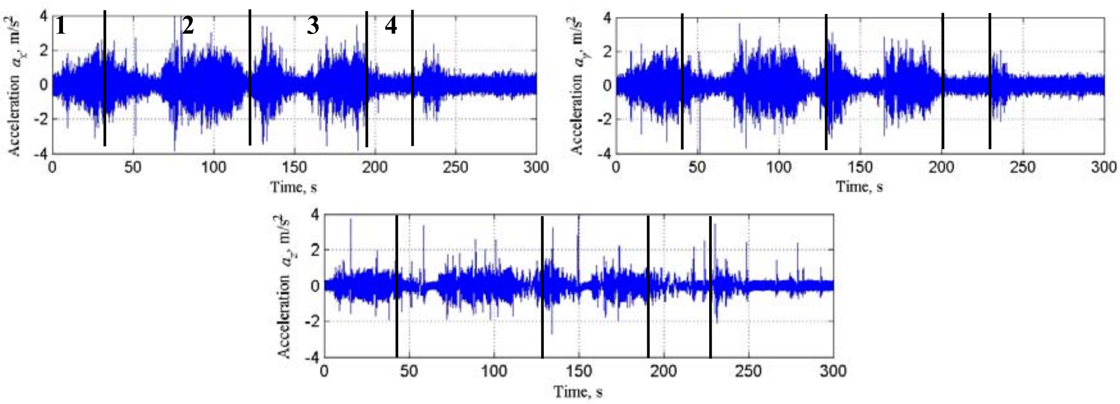

***Fig.3.** Measured accelerations in three directions during the route in the city*

Four intervals can be distinguished from the obtained acceleration data for the separate analysis. First interval lasts from 0 to 60 seconds (Fig.3. No.1), the bus starts moving from one bus stop to the next and stops there. Acceleration a_x coincides to the bus driving direction, a_y to the lateral movements in horizontal direction and a_z to the vertical. Second interval lasts from 70 to 150 seconds (Fig.3. No.2) and the bus moves again from one bus-stop to the next. Third interval lasts form 160 to 220 seconds (Fig.3. No.3), and the bus starts from a bus stop and stops in a traffic jam. Fourth interval (Fig.3. No.4) depicts the jerk of the bus in a traffic jam. Acceleration data was recorded and represented in time domain. Common practice is to present data in frequency domain, because the frequency spectrum gives more detailed information about the signal sources that cannot be obtained from the time signal and for this study especially important are the frequencies in lowest range. For this reason spectral analysis of the acceleration data using discrete fast Fourier transformation and Matlab software was performed.

Figure 4 shows the estimated power spectral densities (PSD) of the measured acceleration data during before mentioned cycle intervals.

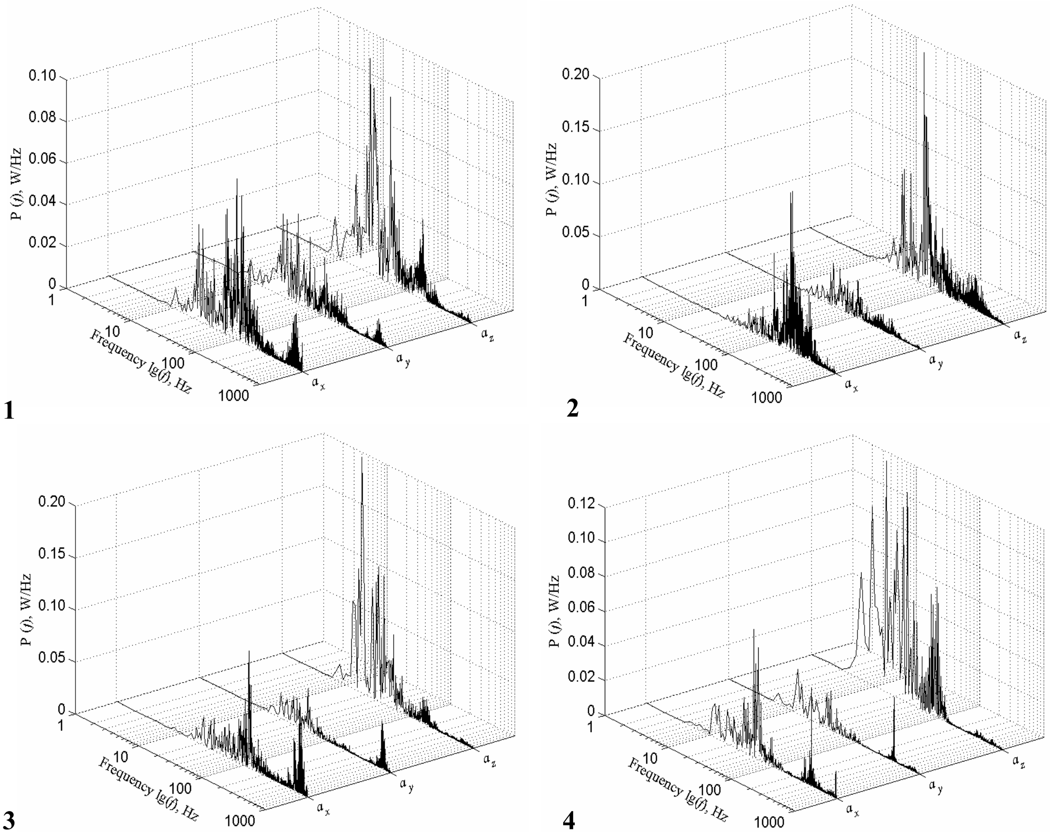

Fig.4. *Power spectral density graphs of the measured acceleration*

The spectral analysis of the frequencies spectrum of the system's accelerations showed 3 dominant groups in it: 0–80 Hz; 300–500 Hz and 750–950 Hz. However, amplitudes of vibrations, matching the second and the third groups are very small and can be assigned to the structure of vehicle body, working engine and similar sources. To depict clearly the range of lowest frequencies logarithmic scale was chosen, because the effect of the lower frequencies to the disabled person in a wheelchair is very significant. On purpose to determine whether the frequencies of the external excitation in the lowest range from 0 to 80 Hz cover the natural frequencies of the wheelchair-seated disabled person, the spectral analysis of the "Man – Wheelchair" subsystem was performed. The wheelchair was chosen a manual rear-wheel-driven wheelchair, which is the most common (Fig. 5, on the left). Furthermore, the stiffness characteristics of the wheelchair were measured experimentally and the relationship between the stiffness and the pressure in the wheelchair tyres for different loading situations is shown in Figure 5 on the right.

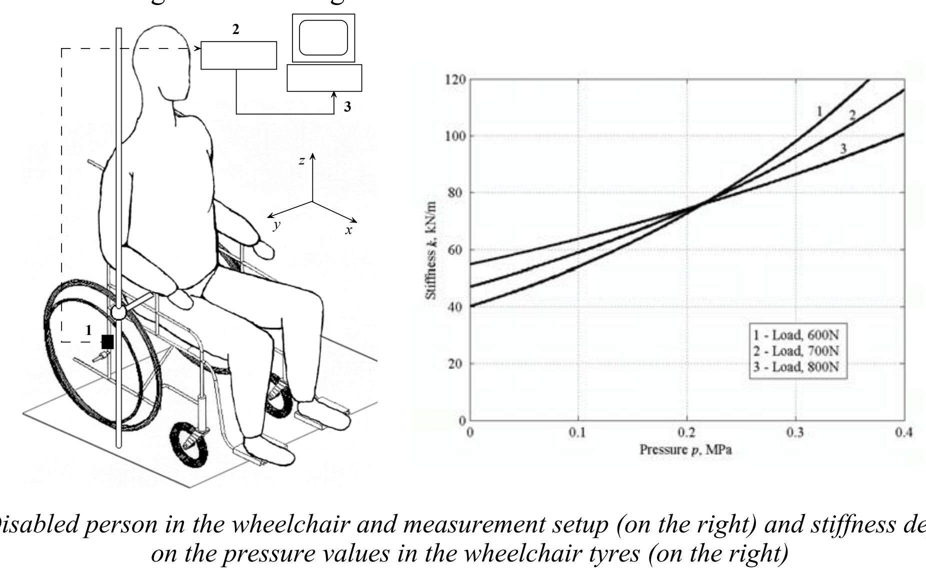

Fig.5. *Disabled person in the wheelchair and measurement setup (on the right) and stiffness dependence on the pressure values in the wheelchair tyres (on the right)*
1 – Accelerometer; 2 – Portable data acquisition system; 3 – PC with analysis software

In Figure 6 are shown the power spectral densities graphs of the wheelchair-seated disabled person in three directions x (Fig.6, 1), y (Fig.6, 2) and z (Fig.6, 3) in comparison with the frequency spectrum of the vehicle during the emergency braking from the velocity 40 km/h to full stop of the bus.

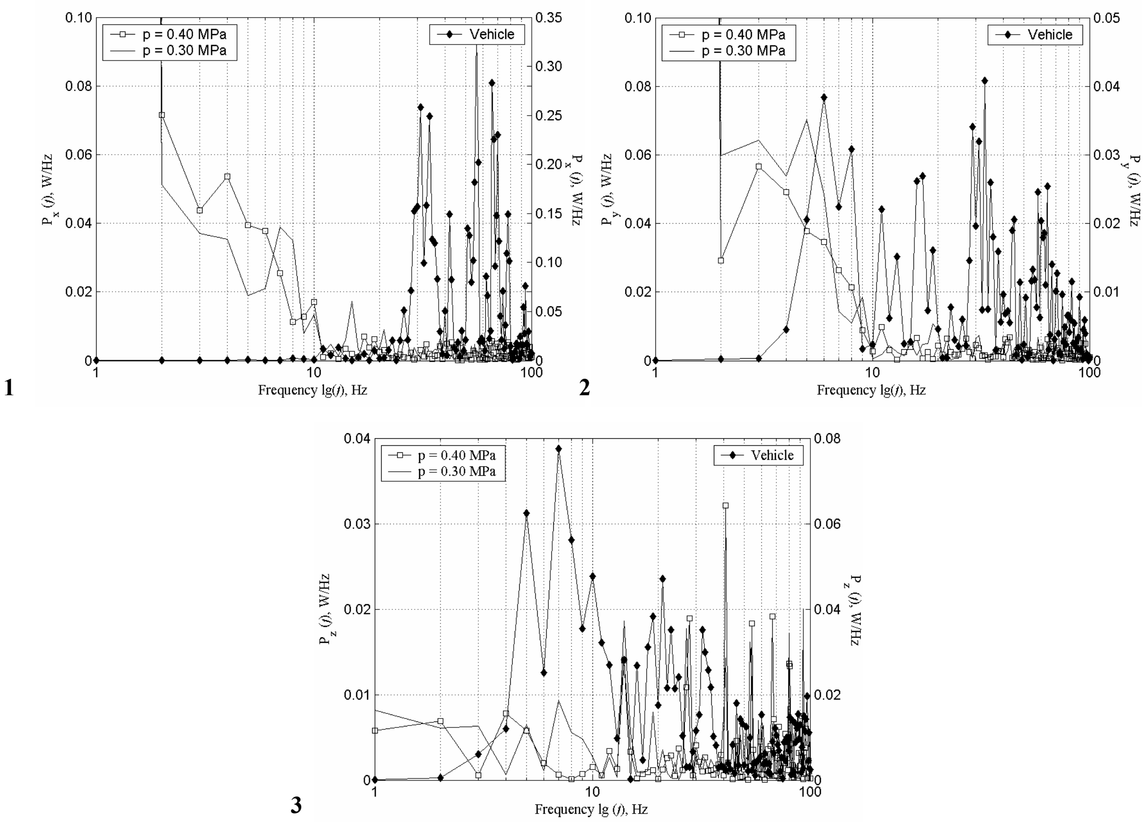

Fig.6. *Power spectral densities of the wheelchair-seated disabled person in comparison with the vehicle's during an emergency braking*

Analyzing the frequency spectrums of the vehicle during the full cycle motion in the city (Figs. 3 and 4) and during an emergency braking situation (Fig.6) it can be marked that the lowest range of well-defined frequencies is in vertical and lateral directions. It can be marked coincident resonant frequencies peaks of the vehicle and the wheelchair – seated disabled person in the range from 1 to 15 Hz. In vertical direction resonant frequencies are at 5 Hz, 7 Hz and 13 Hz; in lateral (y) direction at 4 – 5 Hz and 8 Hz. And the more sudden the vehicle changes its state of motion (for example, emergency braking, tug-like motion and similar), the more emphasizes the lowest frequencies with higher amplitudes. Therefore the stability of the dynamic "Man – Wheelchair – Vehicle" (MWV) system can decrease especially in vertical and lateral directions. Thus it can be distinguished three possible cases of the dynamic MWV system behavior; they are the steady motion, partial and complete abruption cases (Fig. 7. 1, 2 and 3).

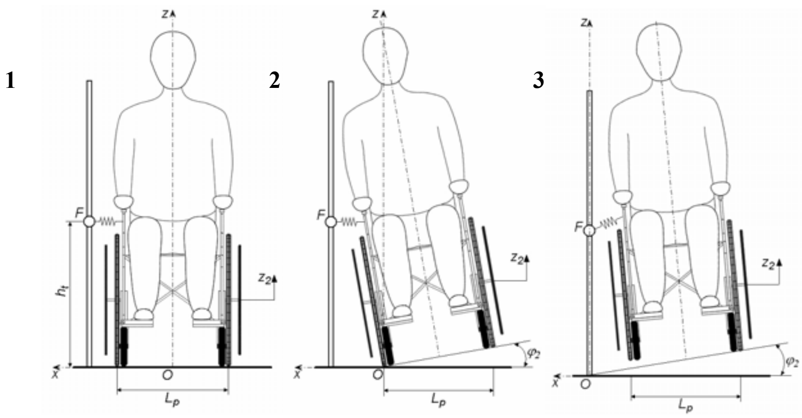

Fig.7. *Possible cases of the dynamic "Man – Wheelchair – Vehicle" system's behavior*

The research was made on the system consisting of two bodies (the man and the wheelchair) with concentrated masses m_1 and m_2 respectively (Fig. 8). The dynamic MWV system is connected to the vehicle through elastic constraints in one point (Fig. 8, point “F”) with coordinate’s h_t and L_t. The disabled person is bound by elastic constraints only to the wheelchair.

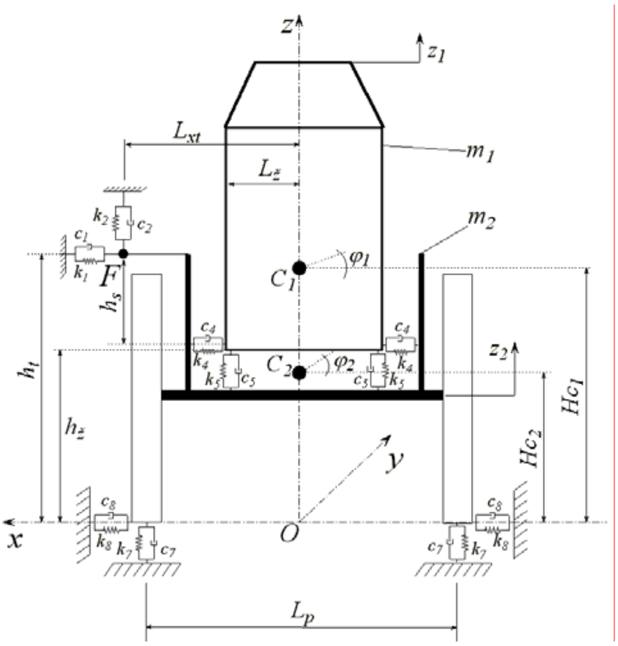

Fig.8. *The simplified model of the wheelchair-seated disabled person*

The man in a wheelchair and the wheelchair each has 6 degrees of freedom; therefore using the LaGrange’s energy method the system of 12-second order non-linear differential equations that describes the steady motion of the system was obtained. The equation of motion is shown using generalized coordinates:

$$[M]\{\ddot{q}\}+[C]\{\dot{q}\}+[K]\{q\}=\{Q\}, \qquad (1)$$

where M is the mass matrix, C is the dissipative matrix, K is the stiffness matrix, Q is the column vector of the generalized external forces and $\{q\}$, $\{\dot{q}\}$, $\{\ddot{q}\}$ are the column vectors of the generalized translational and rotational displacements, linear and angular velocities and accelerations respectively.

The wheelchair’s vertical displacement z_2 in vertical Oz direction and the angle of rotation φ_2 around the Oy axis are the primary parameters that determine the stability of the dynamic MWV system. System’s stability is described by the relationships of the static deformation between the wheelchair tyres and vehicle’s ground and dynamic MWV system’s behavior under different loading situations. The value of static deformation z_{st} (Fig. 9) is determined basically by the experimentally measured stiffness characteristics of the wheelchair’s tyres and it is non-linearly dependent on the pressure in the tyres.

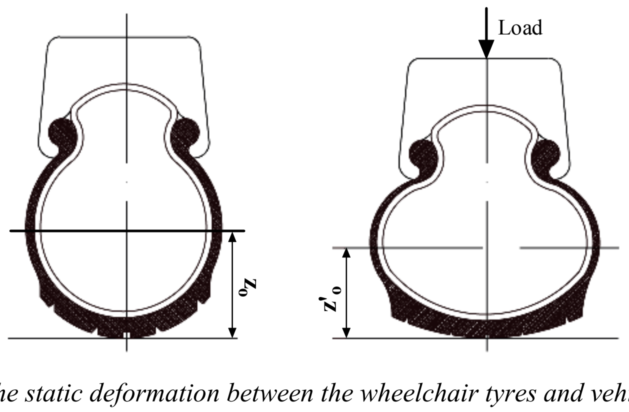

Fig.9. *Value of the static deformation between the wheelchair tyres and vehicle’s ground*

Thus, during the steady motion regime of the MWV system the stability is defined by following inequalities:

$$\begin{cases} z_2 \le z_{st}, \\ z_2 + \dfrac{L_p}{2}\varphi_2 \le z_{st} \text{ and } z_2 - \dfrac{L_p}{2}\varphi_2 \le z_{st}, \end{cases} \tag{2}$$

where L_p is the width between the wheelchair's wheels, z_2 is the vertical displacement and z_{st} ($z_{st} = z_o - z'_o$) is the static deformation between the wheelchair's tyres and vehicle's ground.

When the vehicle is moving under extreme conditions, for example sudden braking or sharp turning, higher accelerations act on the disabled person in the wheelchair and following inequalities for the dynamic system's behavior cases (Fig. 7, 2 and 3) exists respectively:

$$\begin{cases} z_2 > z_{st}, \\ z_2 + \dfrac{L_p}{2}\varphi_2 > z_{st} \text{ and } z_2 - \dfrac{L_p}{2}\varphi_2 \le z_{st}, \end{cases} \tag{3}$$

$$\begin{cases} z_2 > z_{st}, \\ z_2 + \dfrac{L_p}{2}\varphi_2 > z_{st} \text{ and } z_2 - \dfrac{L_p}{2}\varphi_2 > z_{st}. \end{cases} \tag{4}$$

When the conditions (3) or (4) are fulfilled, the tyres of the wheelchair lose the contact with the vehicle's ground and the wheelchair is restrained only at one fastening point. Thus, the frame of reference changes, sets of elastic constraints intermit and the motion of the dynamic MWV system is described by other systems of equations. When the condition (2) in the considered system's motion is fulfilled again, an impact occurs between the wheelchair's wheels and the vehicle's ground. Very large accelerations that exceed the stability limit of the MWV system can cause more complex gross motion of the system. Therefore, the analysis of the dynamical system's motion is performed using the numerical methods.

Another significant parameter can be expressed as the ratio S of the fastening height h_t and the center of gravity of the system:

$$S = \frac{h_t}{H_{CG}}, \tag{5}$$

where h_t is the fastening height and H_{CG} is vertical coordinate of the system's center of gravity.

The fourth-order Runge-Kutta method with fixed time step was chosen as a numerical method to solve system (1) of non-linear differential equations. Series of calculations were performed to determine the response of the system and to establish how fastening height influence on the overall stability of the dynamic "Man – Wheelchair – Vehicle" system. Gradually increasing the acceleration pulse magnitude and ratio S, the obtained dependencies are shown in Fig. 10. For a man with the weight m_1 = 80 kg (load 800 N) sitting in the wheelchair, the magnitude of static deformation value z_{st} equals to ~8 mm. Thus, when a vertical displacement z_2 of the wheelchair exceeds z_{st}, the motion of the system must be described by another system of equations.

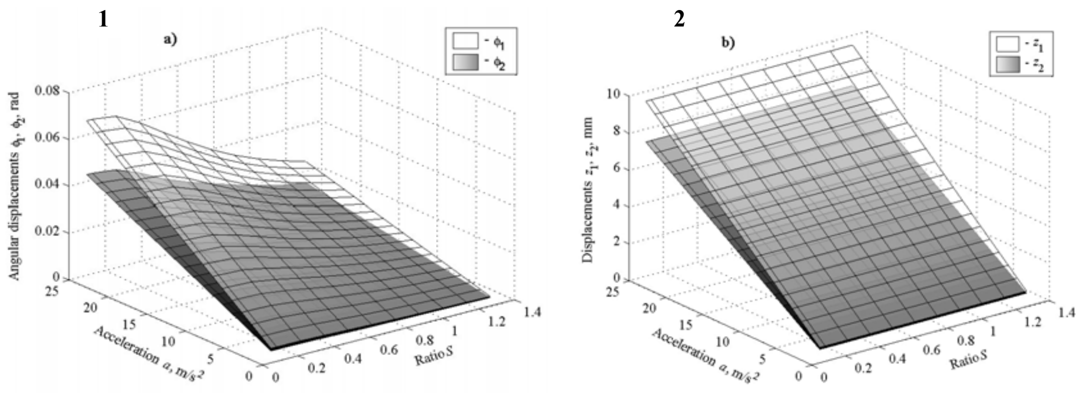

Fig.10. *Angular (1) and vertical (2) displacements, tyre pressure p_{max} = 0.32 mpa*

When the pressure in the wheelchair tyres is low, large accelerations increase the amplitudes of vertical displacements of the MWV system 1.2 times, and vice versa, vertical displacements are smaller when the tyre is stiffer. Thus, the stability condition (2) is satisfied with lower pressure values for smaller accelerations. Fig. 10, 2 shows gradually growth of vertical displacements independent of the wheelchairs' fastening height. Analyzing the angular displacements about the *Oy* axis it can be seen, that amplitudes of the rotations are growing during the increase of the accelerations. However, depending on the fastening height, largest values will be at lower ratio *S* values of the fastening height and the height of center of gravity. It was also determined that when the accelerations exceed 25 m/s^2, motion of the system cannot be described by the system (1) of equations because the frame of reference has changed and the amplitudes of oscillations increased. Taking in to account measured accelerations during daily routes of the public transport, it can be seen that the peak of values is up to 18 m/s^2 and therefore the motion of the dynamic "Man – Wheelchair – Vehicle" system lies within the stable region.

CONCLUSIONS

The main findings of the present research of the external excitation influence on the dynamic "Man – Wheelchair – Vehicle" system are listed below.

1. Measurements showed that the largest accelerations in terms of g's were up to 1.4 g's during the emergency braking from the velocity 40 km/h to full stop; during the full left-right-turns up to 1.2 g's and other regimes from 0.4 to 0.9 g's. During an unexpected jerk of the vehicle largest acceleration up to 2 g's was measured. Therefore the disabled person travels in so called "low-g" environment and in spite of the loads are small in comparison with high loads (up to 30 g's) during severe car crashes there must be certain means to safely secure the wheelchair.
2. The spectral analysis of the spectrum of the "Man – Wheelchair – Vehicle" system's accelerations showed 3 dominant groups in it: 0-80 Hz, 300-500 Hz, and 750-950 Hz. However, amplitudes of vibrations, matching the second and the third groups are very small and depend mainly on the vehicle's body structure, engine action. More significant is the lowest range of the frequencies, because the natural frequencies of the disabled person in a wheelchair are very low and lie in range of 1-15 Hz. Thus the frequencies of the vehicle and wheelchair-seated disabled person were superposed and coincident resonant frequency peaks of the vehicle and wheelchair – seated disabled person in the range from 1 to 15 Hz were noted: in vertical direction at 5 Hz, 7 Hz and 13 Hz; in lateral direction at 4 – 5 Hz and 8 Hz. The superposition effect of the resonant frequencies in considered public transportation case is minor, because the trip through the city usually is of small duration, with often stops; however during the long-distance trips mentioned phenomena may be the cause of the ride discomfort.
3. Numerical analysis showed that the condition of the wheelchair tyres to lose contact with the vehicle's ground fulfilled when the acceleration exceeds 25 m/s^2. The frame of reference is changed and therefore another system of equations for the analysis of MWV system's stability is required.
4. Observed, that the fastening height of the wheelchair to the vehicle is also very important. Decreasing the fastening height 3 times, rotation amplitudes about an *Oy* axis increased 2.1 times thus resulting in the decrease of the dynamic system stability. The fastening device of the wheelchair to the transport mean must have an ability to change the mentioned dimensions and must be adjusted to each disabled person individually, that is safe, comfortable and allows independent usage.
5. Pressure magnitude in the wheelchair tyres has the significant influence on amplitudes of oscillations in the MWV system. When the pressure in the wheelchair tyres is diminished 3 times, the amplitudes of oscillations increase 1.2 times at the same parameters of the dynamic system. Last-mentioned phenomena indicates that despite lowered stiffness is more effective in the reduction of the ground vibrations, during braking and turning increased acceleration forces act directly on the MWV system resulting in the increase of the angular displacements especially.

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