Julius GRIŠKEVIČIUS

MOTION STABILITY ANALYSIS OF THE NONLINEAR DYNAMIC SYSTEM “MAN – WHEELCHAIR – VEHICLE” UNDER ACTION OF IMPULSIVE LOADS

Summary of Doctoral Dissertation
Technological Sciences, Mechanical Engineering (09T)

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Vilnius LEIDYKLA TECHNIKA 2005

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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Doctoral dissertation was prepared at Vilnius Gediminas Technical University in 2001 – 2005

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Julius GRIŠKEVIČIUS

IMPULSINIŲ APKROVŲ VEIKIAMOS NETIESINĖS DINAMINĖS SISTEMOS „NEĮGALUS ŽMOGUS – VEŽIMĖLIS – TRANSPORTO PRIEMONĖ“ JUDESIO STABILUMO TYRIMAS

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GENERAL CHARACTERISTIC OF THE DISSERTATION

Topicality of the problem – Nowadays disabled persons are actively integrated into social life. Different compensatory equipment allows them to work and travel independently. The wheelchair is one of such means; it provides mobility function for physically impaired persons. Not every disabled person has possibilities to travel by his own car and sometimes there is no necessity to use the car in the city, where the intensity of traffic is high. It is more convenient to use public transport facilities, for example bus or trolleybus. Wheelchair-bound passengers' transportation safety is one of the most important problems facing transit providers and engineers. Improperly or totally unsecured wheelchair can lose the stability and tip over during the emergency driving situations and result in passenger falling and becoming injured. Standard 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 and do not function properly. Hence there is a need for additional, simplified wheelchair restraint system that is safe, comfortable, and easy-to-use and allows independent usage for wheelchair-bound passengers.

Aim and tasks of the work – the main object of the scientific research work is complex dynamic system "Man – Wheelchair – Vehicle", which is under action of environmental factors (road roughness, motion oscillations of vehicle). The main tasks of the work are:

- to form and research non-linear model of dynamic system "Man – Wheelchair – Vehicle" and to define system's stability limits, to provide means for safe travel;
- to determine main characteristics of the external action and analyze its influence on to considered dynamic system;
- to build engineering computation methodology for estimation of the rational parameters to fasten the wheelchair to the vehicle.

Scientific novelty

- Nonlinear model of dynamic system "Man – Wheelchair – Vehicle" proposed enables to analyze motion stability and to determine critical limits of system's stability;
- Investigated spectral density and its intensity of vehicle's external action on the wheelchair during different driving regimes, like steady motion and emergency braking situations, on road with different pavement;
- Analyzed influence of wheelchair fastening characteristics on to wheelchair stability during the motion of vehicle;

- Build simple computation methodology, which enables to select rational parameters of wheelchair fastening to the vehicle depending on disabled person stature and weight.

<u>Methodology of research</u> – analytical, experimental and statistical methods were used in scientific research work to achieve set tasks. LaGrange energy method was used to build two mass 12 degrees of freedom non-linear mathematical model of disabled person in a wheelchair was developed. Equations of motion were solved using numerical Runge-Kutta method, which algorithm was built in MATLAB environment. Experimental measurements of accelerations in three directions during the different driving regimes of public transport in Vilnius and Kaunas (two passenger buses Mercedes and Solaris Urbino) on different road state (dry, wet and snowy pavement) were performed using tri-axial accelerometers and portable "Bruel&Kjaer" equipment. The center of gravity of disabled person in a wheelchair was calculated using anthropometric data tables. Stiffness characteristics of wheelchair tyres were measured using loads and deformation indicators. The results of measurements data were processed using correlation analysis.

<u>Practical value</u>

- Nonlinear model of dynamic system "Man – Wheelchair – Vehicle" was proposed, which enables to analyze the stability of the wheelchair during the steady motion and emergency driving conditions of the vehicle, revealing non-stable motion velocities and dangerous acceleration values; to analyze spectral density of external action and its relation with the natural frequencies of wheelchair-seated disabled person; to diminish negative effects by selecting rational parameters of wheelchair and wheelchair fastening.
- Created simple computation methodology enables to select rational parameters for wheelchair fastening to the vehicle.

<u>Defended propositions</u>

- Presented nonlinear model of dynamic system "Man – Wheelchair – Vehicle" allows to determine the stability limits of the wheelchair and dangerous acceleration values which occur during the motion of the vehicle, and to estimate external action's influence onto dynamic system.
- Given engineering computation methodology allows to select rational wheelchair fastening to the vehicle parameters.

<u>The scope of the scientific work.</u> The scientific work consists of the general characteristic of the dissertation, 4 chapters, conclusions, list of literature, and addenda. The total scope of the dissertation is 94 pages, 62 pictures, 13 tables.

STRUCTURE OF THE WORK

The first chapter gives a review of scientific research works on transportation safety of wheelchair-seated passengers. Analysis of the system “Man – Vehicle – Environment” was performed describing relations between people and vehicles they operate, traffic and environmental conditions. Evolution and comparison of different mathematical models “Man – Vehicle”, which describe and analyze accidental situations was presented. Various wheelchair fastening systems used in transport mean nowadays were reviewed. The main tasks of the scientific work were formulated at the end of the chapter.

The second chapter presents the development of non-linear model of dynamic “Man – Wheelchair – Vehicle” system. The case when disabled person sits in his wheelchair during short-trip through the city using public transport was considered. The most common manual rear-wheel-driven wheelchair was chosen and two mass 12 degrees of freedom simplified dynamical model of dynamic system “Man – Wheelchair – Vehicle” (MWV) shown in Figure 1 was developed. The wheelchair is connected to the vehicle through elastic constraints in one point “F” with coordinates h_t and L_t. The disabled person is bound by elastic constraints only to the wheelchair.

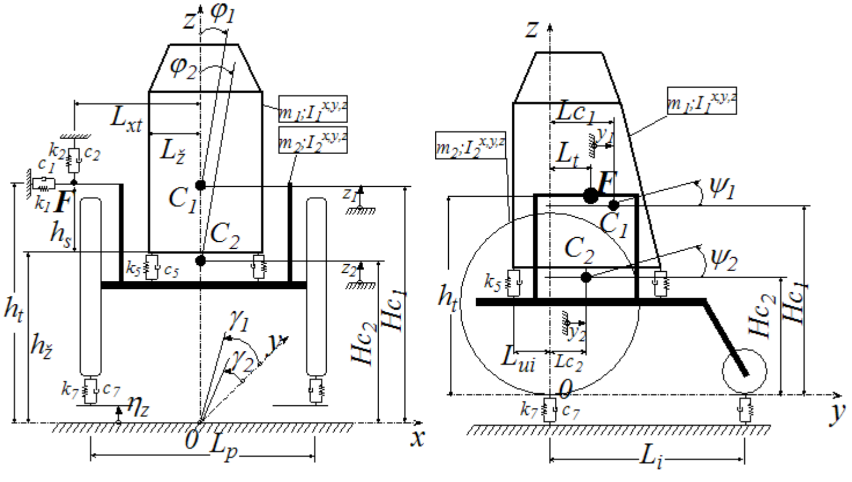

Fig 1. The dynamical model of the wheelchair-seated disabled person

Particular system’s behavior cases were summarized and three possible situations were determined: the steady motion regime when the loads are small, the partial and complete abruption cases when as a result of loads increase the wheelchair tyres loose the contact with the vehicle’s ground. Vertical displacement z_2 of the wheelchair in *Oz* direction and the angle of angular displacement φ_2 about the *Oy* axis are the basic parameters for the evaluation of dynamic system MWV stability in considered case. These parameters are bundled with the value of static deformation between the wheelchair tyres and the vehicle’s ground z_{st} by the following expressions which describe previously mentioned three behavior cases of dynamic MWV system:

$$\begin{cases} 1.\ z_2 + \frac{L_p}{2}\varphi_2 \le z_{st} \text{ and } z_2 - \frac{L_p}{2}\varphi_2 \le z_{st}, \\ 2.\ z_2 \pm \frac{L_p}{2}\varphi_2 > z_{st} \text{ and } z_2 \mp \frac{L_p}{2}\varphi_2 \le z_{st}, \\ 3.\ z_2 + \frac{L_p}{2}\varphi_2 > z_{st} \text{ and } z_2 - \frac{L_p}{2}\varphi_2 > z_{st}, \end{cases} \tag{1}$$

where L_p is the distance between the wheels of the wheelchair.

The equations of system’s motion were obtained using LaGrange energy method. When the transport mean is driving under the steady regime of motion (case 1 in expression (1)), forces of kinematic or other excitation sources are moderate. Thus, vibrations in the dynamic system MWV will be small and the system of equations can be simplified assuming *sin* (φ, γ, ψ) ≈ φ, γ, ψ and *cos* (φ, γ, ψ) ≈ 1, but the increase of oscillations will make them significant. Consequently, system of 2$^{\text{nd}}$ order non-linear differential equations describes the motion of the dynamic MWV system. It consists of two subsystems: first subsystem (2) describes the linear displacements in vertical, horizontal and forward directions and, taking into account simplifications made, the rotational motion of the system about the *0x*, *0y*, *0z* axis is described by the second subsystem (3) of non-linear differential equations:

$$\begin{cases} m_1\ddot{x}_1 + c_4\dot{x}_1 - c_4\dot{x}_2 + k_4x_1 - k_4x_2 = 0, \\ m_1\ddot{y}_1 + c_6\dot{y}_1 - c_6\dot{y}_2 + k_6y_1 - k_6y_2 = 0, \\ m_1\ddot{z}_1 + c_5\dot{z}_1 - c_5\dot{z}_2 + k_5z_1 - k_5z_2 = 0, \\ m_2\ddot{x}_2 + \left(c_1 + c_4 + 4c_8\right)\dot{x}_2 - c_4\dot{x}_1 + \left(k_1 + k_4 + 4k_8\right)x_2 - k_4x_1 = F_1\left(t\right), \\ m_2\ddot{y}_2 + \left(c_3 + c_6 + 4c_9\right)\dot{y}_2 - c_6\dot{y}_1 + \left(k_3 + k_6 + 4k_9\right)y_2 - k_6y_1 = F_2\left(t\right), \\ m_2\ddot{z}_2 + \left(c_2 + c_5 + 8c_7\right)\dot{z}_2 - c_5\dot{z}_1 + 2c_7L_i\dot{\gamma}_2 + \left(k_2 + k_5 + 8k_7\right)z_2 - k_5z_1 + 2k_7L_i\gamma_2 = F_3\left(t\right), \end{cases} \tag{2}$$

$$\left\{\begin{aligned}
&\left(I_1^y - m_1 h_{\check{z}} \dot{\varphi}_2 \left(H_{C1} - h_{\check{z}}\right)\left(1 + \varphi_1 \varphi_2\right)\right)\ddot{\varphi}_1 - m_1 \dot{\varphi}_1 \dot{\varphi}_2 h_{\check{z}} \left(H_{C1} - h_{\check{z}}\right)\left(\varphi_2 - \varphi_1\right) + \\
&+\left(c_4 h_{\check{z}}^2 + c_5 L_{\check{z}}^2\right)\dot{\varphi}_1 - \left(c_4 h_{\check{z}}^2 + c_5 L_{\check{z}}^2\right)\dot{\varphi}_2 + \left(k_4 h_{\check{z}}^2 + k_5 L_{\check{z}}^2\right)\varphi_1 - \left(k_4 h_{\check{z}}^2 + k_5 h_{\check{z}}^2\right)\varphi_2 = \\
&= Q_1 \left(H_{C1} - h_{\check{z}}\right)\varphi_1, \\
&\left(I_1^x - m_1 h_{\check{z}} \dot{\gamma}_2 \left(H_{C1} - h_{\check{z}}\right)\left(1 + \gamma_1 \gamma_2\right)\right)\ddot{\gamma}_1 - m_1 \dot{\gamma}_1 \dot{\gamma}_2 h_{\check{z}} \left(H_{C1} - h_{\check{z}}\right)\left(\gamma_2 - \gamma_1\right) + \\
&+\left(c_5 \left(L_u^2 + L_{ui}^2\right) + c_6 h_{\check{z}}^2\right)\dot{\gamma}_1 - \left(c_5 \left(L_u^2 + L_{ui}^2\right) + c_6 h_{\check{z}}^2\right)\dot{\gamma}_2 + \left(k_5 \left(L_u^2 + L_{ui}^2\right) + k_6 h_{\check{z}}^2\right)\gamma_1 - \\
&-\left(k_5 \left(L_u^2 + L_{ui}^2\right) + k_6 h_{\check{z}}^2\right)\gamma_2 = -Q_1 L_{C1} \gamma_1, \\
&I_1^z \ddot{\psi}_1 + \left(c_4 \left(L_u^2 + L_{ui}^2\right) + c_6 L_{\check{z}}^2\right)\dot{\psi}_1 - \left(c_4 \left(L_u^2 + L_{ui}^2\right) + c_6 L_{\check{z}}^2\right)\dot{\psi}_2 + \\
&+\left(k_4 \left(L_u^2 + L_{ui}^2\right) + k_6 L_{\check{z}}^2\right)\psi_1 - \left(k_4 \left(L_u^2 + L_{ui}^2\right) + k_6 L_{\check{z}}^2\right)\psi_2 = 0, \\
&\left(I_2^y + m_1 h_{\check{z}}^2 - m_1 h_{\check{z}} \dot{\varphi}_1 \left(H_{C1} - h_{\check{z}}\right)\left(1 + \varphi_1 \varphi_2\right)\right)\ddot{\varphi}_2 - m_1 \dot{\varphi}_1 \dot{\varphi}_2 h_{\check{z}} \left(H_{C1} - h_{\check{z}}\right)\left(\varphi_1 - \varphi_2\right) + \\
&+\left(c_1 h_t^2 + c_2 L_{xt}^2 + c_4 h_{\check{z}}^2 + c_5 L_{\check{z}}^2 + \tfrac{1}{2} c_7 L_p^2\right)\dot{\varphi}_2 - \left(c_4 h_{\check{z}}^2 + c_5 L_{\check{z}}^2\right)\dot{\varphi}_1 + \\
&+\left(k_1 h_t^2 + k_2 L_{xt}^2 + k_4 h_{\check{z}}^2 + k_5 L_{\check{z}}^2 + \tfrac{1}{2} k_7 L_p^2\right)\varphi_2 - \left(k_4 h_{\check{z}}^2 + k_5 L_{\check{z}}^2\right)\varphi_1 = \\
&= \left(Q_1 h_{\check{z}} + Q_2 H_{C2}\right)\varphi_2 + F_1(t) h_t + F_3(t) L_p, \\
&\left(I_2^x + m_1 h_{\check{z}}^2 - m_1 h_{\check{z}} \dot{\gamma}_1 \left(H_{C1} - h_{\check{z}}\right)\left(1 + \gamma_1 \gamma_2\right)\right)\ddot{\gamma}_2 - m_1 \dot{\gamma}_1 \dot{\gamma}_2 h_{\check{z}} \left(H_{C1} - h_{\check{z}}\right)\left(\gamma_1 - \gamma_2\right) + \\
&+\left(c_2 L_t^2 + c_3 h_t^2 + c_5 \left(L_{ui}^2 + L_u^2\right) + c_6 h_{\check{z}}^2 + 4 c_7 L_i^2\right)\dot{\gamma}_2 - \left(c_5 \left(L_{ui}^2 + L_u^2\right) + c_6 h_{\check{z}}^2\right)\dot{\gamma}_1 + \\
&+\left(k_2 L_t^2 + k_3 h_t^2 + k_5 \left(L_{ui}^2 + L_u^2\right) + k_6 h_{\check{z}}^2 + 4 k_7 L_i^2\right)\gamma_2 - \left(k_5 \left(L_{ui}^2 + L_u^2\right) + k_6 h_{\check{z}}^2\right)\gamma_1 = \\
&= F_2(t)\left(h_t + L_t \gamma_2\right) - \left(Q_1 + Q_2\right) L_{C2}, \\
&I_2^z \ddot{\psi}_2 + \left(c_1 L_t^2 + c_3 L_{xt}^2 + c_4 \left(L_{ui}^2 + L_u^2\right) + c_6 L_{\check{z}}^2 + \tfrac{1}{2} c_8 L_i^2 + \tfrac{1}{4} c_9 L_p^2\right)\dot{\psi}_2 - \\
&-\left(c_4 \left(L_{ui}^2 + L_u^2\right) + c_6 L_{\check{z}}^2\right)\dot{\psi}_1 - \left(k_4 \left(L_{ui}^2 + L_u^2\right) + k_6 L_{\check{z}}^2\right)\psi_1 + \\
&+\left(k_1 L_t^2 + k_3 L_{xt}^2 + k_4 \left(L_{ui}^2 + L_u^2\right) + k_6 L_{\check{z}}^2 + \tfrac{1}{2} k_8 L_i^2 + \tfrac{1}{4} k_9 L_p^2\right)\psi_2 = F_1(t) L_t + F_2(t) L_t \psi_2,
\end{aligned}\right. \tag{3}$$

where F_1, F_2 and F_3 are forces of external excitation, Q_1 and Q_2 are weight of the man and the wheelchair respectively, and $I_1^{x,y,z}$ and $I_2^{x,y,z}$ are moments of inertia of the man and the wheelchair respectively about *Ox*, *Oy* and *Oz* axis.

When one of the conditions 2 or 3 in expression (1) are satisfied, 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, a set of elastic constraints intermit and the motion of the dynamic "Man – Wheelchair – Vehicle" system is described by additional systems of non-linear differential equations.

The third chapter presents the methodology of experimental measurements of vehicle motion characteristics and statistical processing of obtained data. Dynamical loads, which occur during the motion of vehicle, are caused by acceleration, which was recorded using tri-axial accelerometer and portable „Bruel&Kjaer" PULSE Type 3560C equipment. Figure 2 shows diagrammatically setup of experimental measurements.

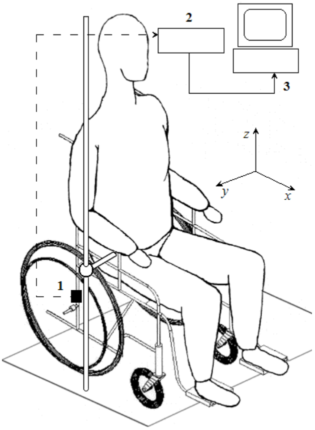

Fig 2. Setup of experimental measurements:
1 – accelerometer; 2 – portable data acquisition system;
3 – PC with analysis software

Measurements were performed in two passenger buses Mercedes Benz O-305 and Solaris Urbino; the latter was low-floored, with rearward-facing compartment equipped with restraint belt for wheelchair-seated passengers. During daily routes of the public transport in city specific and frequently repetitive motion regimes were noted. They were: the start of moving and stopping in bus-stops, in traffic jams, high radius turnings, different maneuvers and so on. Accelerations, which affect the disabled person in the wheelchair during different bus driving regimes, were recorded and graphs of acceleration pulses, which depict the magnitude of dynamical loads, are shown in Figure 3.

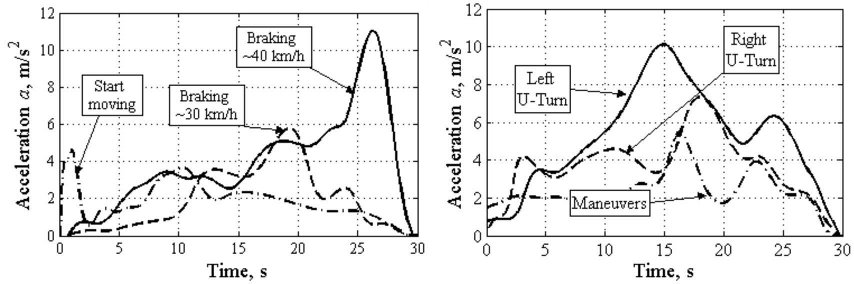

Fig 3. Acceleration pulses during different driving regimes

Excessive motion of the wheelchair, which was not restricted by restraint belt installed in public vehicle, was noted during the experimental measurements. In order to prevent such dangerous motions, wheelchair-seated passenger must keep a tight hold additionally on stanchion, for example, which can be a hard task for physically weaker disabled persons and people with different degrees of limbs dysfunction.

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 working engine and similar sources. The spectral analysis of the “Man – Wheelchair” subsystem was performed in order 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. Figure 4 shows comparison of spectral densities during the emergency braking of vehicle.

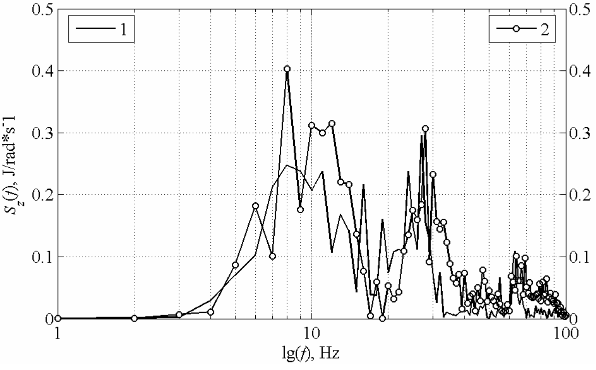

Fig 4. Power spectral densities during emergency braking:
1 – wheelchair, 2 – vehicle

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 system “Man – Wheelchair – Vehicle” can decrease, especially in vertical and lateral directions.

The fourth chapter presents analysis of wheelchair characteristics, determination of rational parameters of wheelchair fastening to the vehicle and their influence on to MWV stability. Above mentioned quantity z_{st}, that is the value of static deformation between the wheelchair and the vehicle’s ground, is determined mainly by stiffness characteristics of the wheelchair tyres and it is non-linear dependent on the pressure in tyres:

$$z_{st} = z_0 - \Delta, \tag{4}$$

where Δ is measured tyre deformation and z_0 is height of undeformed tyre.

Figure 5 shows relations of the stiffness and static deformation of the wheelchair tyres on load and pressure magnitudes depending on the applied load and pressure in wheelchair tyres.

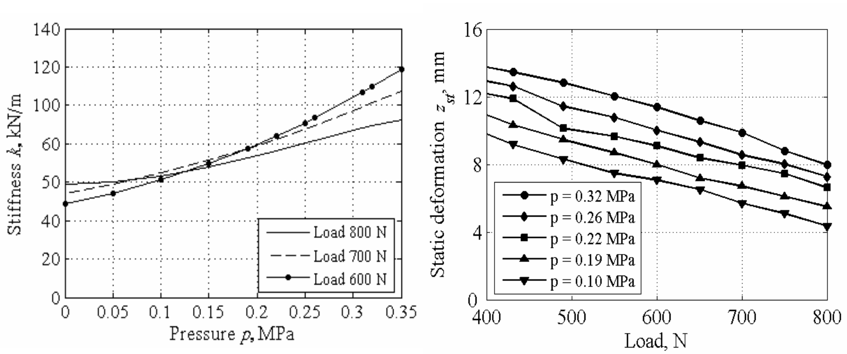

Fig 5. Stiffness k and static deformation z_{st} of the wheelchair tyres

Fastening height has significant influence on the oscillations amplitudes of dynamic MWV system. Wheelchair fastening height to the vehicle can be expressed as the ratio S_t of the fastening height h_t and the center of gravity of the system:

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

where H_{CG} is the height of the system’s center of gravity.

In order to improve safety of the travel, the wheelchair can be fixed to the vehicle through the stanchion by simplified wheelchair restraint system. Possible fastening device with adjustable height h_t and folding clamping-like fixation head F can be mounted into a wheelchair frame as shown in Figure 6. Thus, even if the vehicle is not equipped with usual wheelchair restraint systems the disabled person can fasten his wheelchair to the vehicle interior parts like stanchions or holders. The diameter of fastening stick should be chosen according the weight of disabled person – I. $10 \leq m \leq 30$ kg, $d = 25$ mm; II. $30 \leq m \leq 60$ kg, $d = 28$ mm; III. $60 \leq m \leq 120$ kg, $d = 32$ mm.

When fastening height ratio S_t equals or is more than 1.0, the amplitudes of displacements are smaller, thus the wheelchair fastening at the same height as the system's gravity center or slightly above, seems to be more efficient for improving stability. To be able fix the wheelchair in proper height, the disabled person could use simple calculation technique by following expression (6):

$$h_t = \left(h_{\check{z}} \cdot H\right) - a, \tag{6}$$

where $h_{\check{z}}$ is the height of the wheelchair's seat above the ground, H is the stature of disabled person and a is corrective coefficient that varies from 0.05 for shorter people and to 0.20 for higher.

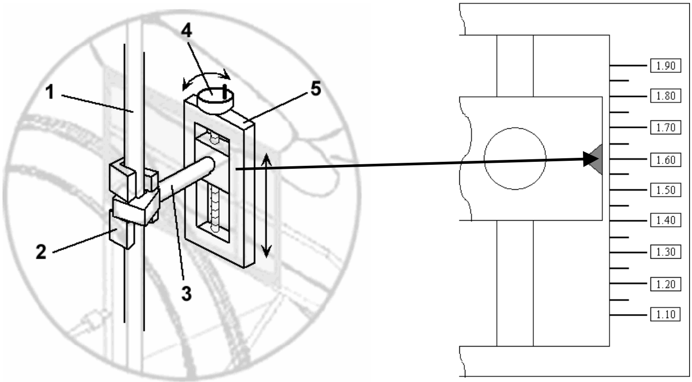

Fig 6. Simplified wheelchair restraint system: 1 – stanchion, 2 – clamping-like fixation head, 3 – fastening beam, 4 – fastening height adjuster, 5 – housing and selection of fastening height

The nature of external excitation forces is kinematic and they can be modeled in the form of half-sine function, which corresponds to the acceleration pulse measured close to the peak values in different vehicle's driving regimes:

$$a(t)=\begin{cases} A\,sin(\omega t), 0 < t < T_{imp} = \dfrac{\pi}{\omega}, \\ 0, t < 0 \,\&\, t > T_{imp}, \end{cases} \tag{7}$$

where A is the peak value of acceleration and T_{imp} is the duration of impulse.

The fourth-order Runge-Kutta method was chosen as a numerical method to solve systems (2) and (3) of non-linear second order differential equations. Series of calculations were performed to evaluate the response of the system and to determine how different parameters, like fastening height and stiffness, influence the stability of the dynamic system "Man – Wheelchair – Vehicle". Part of the results is presented in Figure 7.

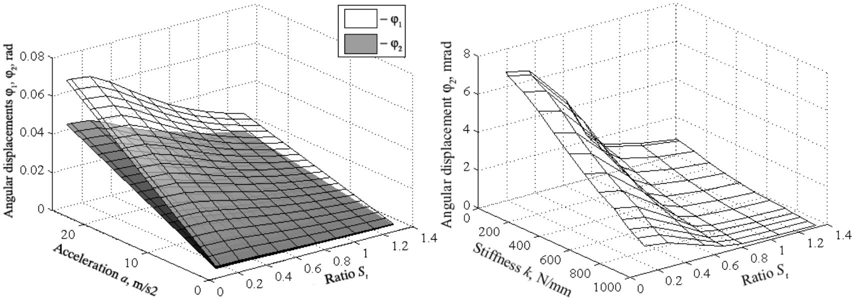

Fig 7. Relations between angular displacements and fastening height and stiffness, indexes 1 and 2 correspond to the man and the wheelchair respectively

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 system's dynamical behavior cases described by conditions 2 or 3 in (1) are satisfied with lower pressure values for smaller accelerations. 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_t values of the fastening height and the height of center of gravity.

When the stiffness of the fastening is low, the displacements of the dynamic MWV system are large, especially rotational displacements φ_1 and φ_2 about the *Oy* axis grows and stability decreases. Furthermore, if the wheelchair would be fastened rigidly to the vehicle (the stiffness approaches ∞) loads that are close to excitation loads on the wheelchair-bound passenger would act, thus the ride comfort and stability of the dynamic MWV system would decrease. Figure 8 shows relation of displacements to fastening stiffness and height.

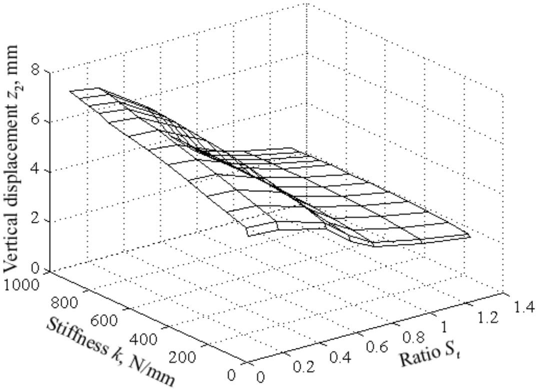

Fig 8. Influence of fastening stiffness on the displacements

Three cases of dynamical behavior of the non-linear system, which also describe safety of the wheelchair-seated disabled person (Figure 9) were explained.

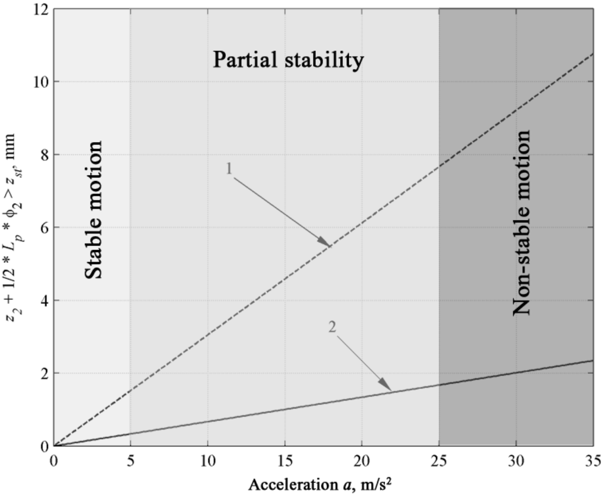

Fig 9. Wheelchair stability: 1 – wheelchair is not fastened,
2 – wheelchair is fastened to the vehicle

During steady motion, when vehicle rides steady rectilinearly, acting accelerations do not exceed 5 m/s^2 and the wheels of wheelchair are in full contact with the ground of vehicle. When system moves uneven and acting accelerations are in range $5 < a < 20$ m/s^2 (during turnings, braking and similar), condition of partial stability is satisfied, therefore the tyres of wheelchair could partly loose the contact and the wheelchair could start to tumble. When system moves uneven and accelerations exceed 25 m/s^2, ride velocity is larger than >50 km/h, the tyres of wheelchair can abrupt from the vehicle's ground completely and stability of the wheelchair-bound disabled passenger is determined only by parameters of fastening stiffness. Fastening of wheelchair to the vehicle can reduce oscillations up to 4.5 times, and in such way increase stability and travel safety.

CONCLUSIONS

1. Presented nonlinear model of complex dynamic system "Man – Wheelchair – Vehicle" enables to perform numerical calculations, to analyze external action impact on system, and to analyze influence of wheelchair fastening manner on system stability.
2. Three cases of dynamical behavior of non-linear system which also describe safety of the wheelchair-seated disabled person were ascertained:
   - steady motion condition, when vehicle rides steady rectilinearly, acting accelerations do not exceed 5 m/s^2 and the wheels of wheelchair are in full contact with the ground of vehicle;
   - when system moves uneven and acting accelerations are in range $5 < a < 20$ m/s^2 (during turnings, braking and similar), condition of partial stability is satisfied, therefore the tyres of wheelchair could partly loose the contact and the wheelchair could start to tumble;
   - when system moves uneven and accelerations exceed 25 m/s^2, ride velocity is larger than >50 km/h, the tyres of wheelchair can abrupt from the vehicle's ground completely and stability of the wheelchair-bound disabled passenger is determined only by parameters of fastening stiffness.
3. The factors of external action and their influence onto stability of wheelchair-bound disabled person were researched experimentally and following features were determined:
   - when vehicle moves with speed of 30 – 40 km/h, accelerations varied in range from 9 m/s^2 to 14 m/s^2 depending on the braking regime and different maneuvers, the condition of partial stability was satisfied. Therefore, in order to improve safe travel it is not recommended to increase velocity of the public transport when transporting wheelchair-seated disabled persons;

- the state of pavement influences the stopping distance and braking accelerations are varying in range from 5 to 12 m/s^2. Facing conditionally with safer status of dynamic system, other risks associated with longer stopping distance, for example, collision with the obstacles and similar arise.

4. Spectral analysis of the frequencies was performed and following findings were obtained:

- three main groups of frequencies are distinguished in spectral density independently of motion regime, they are: 0 – 80 Hz, 300 – 500 Hz and 750 – 950 Hz. First of them is the lowest frequency and the highest intensity, and it is caused by road roughness and changes in velocities of vehicle motion. It is close to natural frequencies of disabled person in a wheelchair;
- second and third groups of frequencies are related with oscillations of transport mean, with low intensity and their influence on stability and oscillations of wheelchair-bound passenger is insignificant;
- 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.

5. Numerical analysis has showed that wheelchair fastening parameters have significant influence on the stability of dynamic “Man – Wheelchair – Vehicle” system:

- the oscillations of wheelchair-seated disabled persons can be diminished 2.1 times by selecting proper height of wheelchair fastening, and system stability can be improved;
- wheelchair fastening at height as of system gravity center or 1.1–1.2 times higher ensures the best stability conditions;
- oscillations can be diminished 1.2 times by changing pressure values in tyres from 0.10 to 0.32 MPa. Especially, effect of oscillation reduction is noted when transport mean is riding with steady velocity, therefore in order to increase ride comfort it is advisable to diminish tyre pressure during long-distance travels;
- it is recommended to select fastening stiffness in range $1000 < k < 3000$ kN/m, because when fastening stiffness is very low ($k < 500$ kN/m), considered system transit very fast to non-stable state.

- selecting proper wheelchair fastening to the vehicle may decrease dangerous displacements in the system more than 4.5 times, of the same time increasing stability and travel safety.

6. Simple engineering computational technique provided enables to select rational parameters for wheelchair fastening adjusted to each disabled person individually depending on the person's stature and weight and improve travel safety.

<u>Published works on the topic of the dissertation</u>

In the acknowledged editions

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3. Mariūnas, M.; Griškevičius, J. The analysis of the impacts influence on the dynamic "Man – Wheelchair – Vehicle" system. *Acta of Bioengineering and Biomechanics*, Vol 6, Sup 1, Wrocław, Poland, 2004, p. 100–104, ISBN 83-7085-809-0.
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8. Mariūnas, M.; Griškevičius, J. Neįgalaus žmogaus pasyvios saugos įvertinimas naudojant kompiuterinį modeliavimą. In: Proceedings of the VI Conference of Lithuanian Young Scientists “Lithuania without science – Lithuania without future”, held in Vilnius on 15-16 April, 2003, Mechanics (6-osios Lietuvos jaunųjų mokslininkų konferencijos „Lietuva be mokslo – Lietuva be ateities“, įvykusios Vilniuje 2003 m. balandžio 15–16 d., medžiaga. Mechanika, medžiagų inžinerija, pramonės inžinerija ir vadyba.) Vilnius: Technika, 2003, p. 15–20 (In Lithuanian), ISBN 9986-05-658-6.
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IMPULSINIŲ APKROVŲ VEIKIAMOS NETIESINĖS DINAMINĖS SISTEMOS „NEĮGALUS ŽMOGUS – VEŽIMĖLIS – TRANSPORTO PRIEMONĖ“ JUDESIO STABILUMO TYRIMAS

Darbo aktualumas. Neįgalūs žmonės aktyviai integruojami į visuomeninį gyvenimą ir įvairių pagalbinių, kompensacinių priemonių dėka jie gali nepriklausomai dirbti bei keliauti. Viena iš tokių kompensacinių priemonių yra vežimėlis, leidžiantis neįgaliesiems likti mobiliais, nepriklausomai judėti bei dirbti. Be specialiai adaptuotų transporto priemonių, neįgaliesiems turi būti suteikta galimybė naudotis ir įprastinėmis visuomeninio transporto paslaugomis, ypatingai miestuose viešuoju transportu. Nors autobusų ir troleibusų parkai yra pastoviai atnaujinami naujesnėmis, labiau neįgaliesiems ir senyvo amžiaus žmonėms pritaikytomis transporto priemonėmis, vis dar skaičius senų, nepatogių transporto priemonių išlieka didelis, kurių pakeitimas reikalauja nemažų investicijų. Keleivių, tarp jų ir neįgalių žmonių vežimėliuose, saugumo užtikrinimas kelionės metu yra vienas iš svarbiausių uždavinių transporto paslaugų tiekėjams bei inžinieriams. Siekiant užtikrinti efektyvią keleivių su negalia vežimėliuose apsaugą kelionės metu, reikalingos papildomos tvirtinimo priemonės, užtikrinančios vežimėlio ir neįgaliojo stabilumą transporto priemonėje. Nepritvirtintas arba neteisingai pritvirtintas vežimėlis gali netekti stabilumo ir tapti pavojingas tiek jame sėdinčiam neįgaliajam, tiek kitiems eismo dalyviams: gali apvirsti ir prispausti neįgalųjį, laisvai judėdamas transporto priemonėje gali sužaloti kitus keleivius. Nelaimingo įvykio metu būtina užtikrinti, kad vežimėlis išliktų stabilus. Todėl yra būtina ištirti dinaminį stabilumą ir numatyti priemones neįgalaus žmogaus vežimėlyje saugumui padidinti.

Darbo tikslas ir uždaviniai. Tyrimo objektas yra kompleksinė dinaminė sistema „Neįgalus žmogus – vežimėlis – transporto priemonė“, veikiama išorinės aplinkos veiksnių (kelio nelygumai, transporto priemonės judėjimo virpesiai ir kt.). Pagrindiniai uždaviniai yra:

- sudaryti nagrinėjamos netiesinį sistemos „Neįgalus žmogus – Vežimėlis – Transporto priemonė“ dinaminį modelį bei jį ištirti, nustatyti stabilumo ribas bei priemones saugiam judesiui užtikrinti.
- nustatyti išorinio poveikio pagrindines charakteristikas bei ištirti jų įtaką nagrinėjamai dinaminei sistemai.
- sudaryti inžinerinę skaičiavimo metodiką racionaliems vežimėlio tvirtinimo prie transporto priemonės parametrams parinkti.

Mokslinis naujumas

- Sudarytas sistemos „Neįgalus žmogus – vežimėlis – transporto priemonė“ netiesinis dinaminis modelis leidžia tirti judesio stabilumą, nustatyti sistemos kritines stabilumo ribas.
- Ištirtas transporto priemonės į vežimėlį poveikio spektrinis tankis ir jo intensyvumas transporto priemonei judant tiesiu keliu, staigiuose posūkiuose ir staigiai stabdant keliuose su skirtinga dangos būkle.
- Ištirta tvirtinimo būdo ir jo parametrų įtaka vežimėlio stabilumui transporto priemonei judant skirtingais greičiais bei ekstremaliais atvejais.
- Sudaryta inžinerinio skaičiavimo metodika, leidžianti priklausomai nuo neįgaliojo ūgio ir svorio paskaičiuoti racionalius vežimėlio tvirtinimo prie transporto priemonės parametrus.

Tyrimų metodika apima analitinius, eksperimentinius ir statistinius metodus, kurie buvo naudojami pasiekti užsibrėžtiems tikslams. 12 laisvės laipsnių netiesinis neįgalaus žmogaus vežimėlyje matematinis modelis buvo sudaromos Lagranžo energetiniu metodu bei skaitmeninis Rungės ir Kuto metodas panaudotas dinaminių lygčių sprendimui, kurio algoritmas buvo suprogramuotas MATLAB programinio paketo pagalba. Pagreičio trejomis kryptimis matavimams važiuojančiame viešajame transporte atlikti buvo panaudota portatyvinė „Bruel&Kjaer“ pagreičių matavimo aparatūra su triašiais pagreičiomačiais. Matavimai buvo atliekami Vilniuje ir Kaune dviejuose Mercedes bei Solaris Urbino keleiviniuose autobusuose, šiems judant įvairiais režimais ant skirtingos kelio dangos būklės (sausos, šlapios, padengtos sniegu asfaltinės kelio dangos). Neįgalaus žmogaus vežimėlyje svorio centro koordinatės apskaičiuotos naudojantis antropometrinių duomenų lentelėmis. Vežimėlio padangų standuminės charakteristikoms matuoti buvo panaudoti svoriai bei deformacijos indikatoriai. Eksperimentinio tyrimo rezultatų apdorojimui buvo panaudota koreliacinė analizė.

Praktinė vertė

- Sudarytas dinaminės sistemos „Neįgalus žmogus – vežimėlis – transporto priemonė“ modelis leidžia tirti vežimėlio stabilumą transporto priemonei judant normaliu režimu ir ekstremaliais atvejais; išaiškinti nestabilius judesio greičius bei pavojingus pagreičių dydžius; nustatyti išorinio poveikio spektrinį tankį ir jo santykį su vežimėlio savaisiais dažniais, įvertinti galimybę sumažinti išorinį poveikį parenkant vežimėlio bei tvirtinimo parametrus.
- Sudaryta inžinerinio skaičiavimo metodika leidžia parinkti racionalius vežimėlio tvirtinimo prie transporto priemonės parametrus.

Ginamieji teiginiai

- Sudarytas dinaminės sistemos „Neįglus žmogus – vežimėlis – transporto priemonė“ netiesinis matematinis modelis leidžia nustatyti vežimėlio stabilumo ribas bei transporto priemonės judėjimo metu kylančius pavojingus pagreičių dydžius, bei leidžia įvertinti transporto priemonės perduodamo išorinio poveikio įtaką.
- Pateikta inžinerinė skaičiavimo metodika leidžia parinkti vežimėlio tvirtinimo prie transporto priemonės racionalius parametrus.

Darbo apimtis. Darbą sudaro bendra darbo charakteristika, 4 skyriai, išvados, literatūros sąrašas ir priedai. Bendra disertacijos apimtis – 94 puslapiai, 62 paveikslai, 13 lentelių.

Išvados

1. Sudarytas kompleksinės dinaminės sistemos „Neįgalus žmogus – vežimėlis – transporto priemonė“ netiesinis matematinis modelis leido atlikti skaičiavimus, nagrinėti išorės poveikį sistemai, tirti vežimėlio tvirtinimo būdo įtaką stabilumui.
2. Išaiškintos trys netiesinės sistemos dinaminės elgsenos būsenos, kurios nusako ir neįgalaus žmogaus vežimėlyje judesio saugą:
    - tolygaus judesio būsena, kai transporto priemonė juda tiesiai ir tolygiai, vežimėlis su transporto priemone kontaktuoja visais keturiais ratais, o veikiantys pagreičiai neviršija 5 m/s^2;
    - kai pagreičių dydis yra $5 < a < 20$ m/s^2 (posūkiuose, stabdant ir pan.), tuomet sistema juda netolygiu judesiu ir vežimėlis pereina į nepilno stabilumo būseną, t.y. pusiau praranda kontaktą su transporto priemonės grindimis, gali pradėti vartytis;
    - kai pagreičiai viršija 25 m/s^2 , o judėjimo greitis – >50 km/h, sistema juda netolygiu judesiu ir vežimėlio ratai gali pilnai atitrūkti nuo transporto priemonės grindų. Tuomet vežimėlio stabilumas nusakomas tik tvirtinimo prie transporto priemonės parametrų standumu.
3. Eksperimentiniu būdu ištirti išorinio poveikio veiksniai bei jų įtaka neįgalaus žmogaus vežimėlyje stabilumui transporto priemonės judėjimo metu ir nustatyta, kad:
    - judant transporto priemonei 30–40 km/h greičiu, priklausomai nuo stabdymo režimo bei įvairių judėjimo manevrų, pagreičiai kito intervale 9 – 14 m/s^2, kuriems veikiant nagrinėjamos sistemos stabilumas bus nusakomas nepilno stabilumo sąlygomis. Todėl, norint užtikrinti kelionės

saugą, didinti transporto priemonės judesio greitį transportuojant neįgalius žmones vežimėliuose nerekomenduotina;

- nuo kelio dangos būsenos priklauso stabdymo kelio ilgis, o pagreičiai stabdymo metu kinta intervale nuo 5 iki 12 m/s^2. Susiduriame su sąlyginai saugesne dinaminės sistemos būsena, tačiau atsiranda pavojai, kurie gali būti sąlygoti ilgesnio stabdymo kelio, pvz. transporto priemonei susiduriant su kliūtimis ir pan.

4. Atlikta dažnių spektrinė analizė parodė, kad:
   - nepriklausomai nuo judėjimo režimo, spektriniame tankyje išskiriamos trys pagrindinės dažnių grupės: 0–80 Hz, 300–500 Hz ir 750–950 Hz. Pirmoji iš jų, sąlygojama kelio dangos nelygumais ir transporto priemonės judesio greičio pokyčiais, yra žemo dažnio bei didžiausio intensyvumo, be to artima neįgalaus žmogaus vežimėlyje saviesiems dažniams;
   - antroji ir trečioji dažnių grupės sąlygojamos transporto priemonės virpesiais, jų dažnis yra aukštas ir mažas intensyvumas bei mažai įtakoja neįgalaus žmogaus vežimėlyje virpesius bei stabilumą;
   - sutampantys transporto priemonės ir neįgalaus žmogaus vežimėlyje dažniai yra intervale nuo 1 iki 15 Hz. Ypatingai išryškėję vertikalia kryptimi 5 Hz, 7 Hz ir 13 Hz transporto priemonei stabdant; šonine horizontalia kryptimi 4 – 5 Hz ir 8 Hz transporto priemonei manevruojant. Viešojo transportavimo atveju sutampančių dažnių įtaka yra nedidelė, kadangi kelionė mieste su dažnais sustojimais trunka neilgai, tačiau ilgų kelionių metu gali būti diskomforto priežastimi.
5. Skaitmeninė analizė parodė, kad dinaminės sistemos „Neįgalus žmogus – vežimėlis“ stabilumui didelę įtaką turi vežimėlio tvirtinimo prie transporto priemonės parametrai:
   - tinkamai parinkus vežimėlio tvirtinimo aukštį, neįgalaus žmogaus vežimėlyje virpesius galima sumažinti 2,1 karto, tuo pačiu padidinant sistemos stabilumą;
   - nustatyta, kad geriausiom vežimėlio stabilumo sąlygom pasiekti yra būtina vežimėlį tvirtinti ties sistemos svorio centru arba 1,1-1,2 karto aukščiau;
   - varijuojant slėgio dydžiu vežimėlio padangose nuo 0,10 iki 0,32 MPa, virpesius galima sumažinti iki 1,2 karto. Ypatingai virpesių mažinimo efektas pastebimas transporto priemonei judant tolygiu greičiu, todėl ilgesnių kelionių metu komforto padidinimui tikslinga sumažinti oro slėgį padangose;
   - nustatyta, kad kai vežimėlio tvirtinimo standumas labai mažas, t.y. $k < 500$ kN/m, tai nagrinėjama sistema labai greitai pereina į nestabilią

būseną. Rekomenduotina parinkti vežimėlio tvirtinimo standumą $1000 < k < 3000$ kN/m ribose;

- nustatyta, kad papildomas vežimėlio tvirtinimas prie transporto priemonės gali sumažinti sistemos poslinkius iki 4,5 karto.

6. Sudaryta paprasta inžinerinė skaičiavimo metodika racionaliems vežimėlio tvirtinimo parametrams parinkti leidžia neįgaliajam individualiai ir nesunkiai pritaikyti tvirtinimo įtaisą bei užtikrinti kelionės saugumą.

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MOTION STABILITY ANALYSIS OF THE NONLINEAR DYNAMIC SYSTEM "MAN – WHEELCHAIR – VEHICLE" UNDER ACTION OF IMPULSIVE LOADS
Summary of doctoral dissertation
Technological Sciences, Mechanical Engineering (09T)

Julius Griškevičius
IMPULSINIŲ APKROVŲ VEIKIAMOS NETIESINĖS DINAMINĖS SISTEMOS „NEĮGALUS ŽMOGUS – VEŽIMĖLIS – TRANSPORTO PRIEMONĖ“ JUDESIO STABILUMO TYRIMAS
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