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Methodology for wheelchair design based on simulation analyses

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Abstract: The article presents the results of research on the development of a new design of a wheelchair capable of moving up and down stairs. In the first stage, a simulation model of the wheelchair was prepared in order to verify the possibility of climbing stairs by own design concept. Then, the simulation model was analysed in terms of dynamic influences affecting the person using such a wheelchair. The article describes the method of building this simulation model and presents the results of these analyses. In the next stage of works, a laboratory prototype of a new wheelchair design was built and experimental tests were carried out to verify the phenomena analysed in the simulations. The study was also carried out for a tracked wheelchair available in the commercial offer. The presented research work allowed for the synthesis of the construction parameters of the wheelchair as well as the parameters of sensors and control systems.

Keywords: Wheelchair, climbing stairs, dynamics of movement, sensors

1. Introduction

Conducting simulation experiments on vehicle models at the conceptual stage allows for the analysis of, for example, the ability to overcome obstacles and a preliminary assessment of the impact of vibrations on people moving this vehicle. The authors of the article made an attempt to early verify their own concept of a wheelchair design with a unique design solution for the climbing mechanism. The first results of these works were published in Polish in articles [2], [6], [7], [12]. They focus mainly on the problem of climbing stairs. These works showed the correctness of the design assumptions. In the next stage of work, an attempt was made to assess the dynamic phenomena affecting a person on a wheelchair, and this issue is the subject of this article. In publications of other research teams, you can come across articles presenting tests of wheelchairs with the use of tools and experiences with the problems of motor vehicle traffic [18], [23]. By limiting the area of research to publications on simulation models of wheelchairs overcoming obstacles, one can find works from research centers around the world related to this subject. Authors from the USA in [5] systematize the problem of research on new designs of wheelchairs with special capabilities. Apart from determining the current state of affairs, they propose new directions of research. An example of computer analysis with the use of simulation tools and optimization of construction parameters, ending with tests on a real model, is the Campus study of the University of Castilla-La Mancha, Ciudad Real, Spain [15], [9], [14]. This is an example of a comprehensive approach to solving a scientific problem in the study of a new means of transport. The works present the next stages of analytical considerations for static and dynamic models. The influence of various parameters of the control system and its influence on the wheelchair user was also analysed. A similar methodology of problem analysis was also adopted by the Italian center. The concept of wheelchair overcoming obstacles presented in [19] is significantly different, but the scope and tools for analysing the problem are very similar. In the papers [11], [22] the authors from Japan presented other design solutions for wheelchair overcoming obstacles, with an emphasis on analytical considerations and experimental research. A unique design for climb-

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ing stairs powered by the muscles of the hands was also on show. The authors from Taiwan in [13] presented a mechanically complex structure, in which they limited the problem of the analysis of overcoming obstacles to the conditions of static stability. A similar approach was also presented in work [4].

All the works presented above distinguished the research object. Each research center proposed its own concepts of structures and conducted research works for them. Despite working on different designs, researchers carried out their projects to a similar extent, using similar analysis methods and simulation tools. In none of these works analyses of the influence of vibrations on a person using a wheelchair have been presented.

The aim of the simulation tests presented in the article was to analyse the model's properties, taking into account its dynamic characteristics in terms of the assessment of driving comfort and the required sensor characteristics. The subject of the simulation was the task of climbing stairs and the analysis of driving comfort. These works were carried out for the simulation model of our own design and for the TGR "Explorer" wheelchair, which is in the commercial offer.

2. Simulations Studies Of Model Dynamics

In building the model for the simulation analysis of the obstacle crossing dynamics, the following simplifications were made. The wheelchair model is defined in 3 dimensions and has a symmetrical structure with respect to its vertical XY plane. The position of the model will be defined relative to an inertial OXYZ system, associated with the ground and located as in [10].

The structure of the model consists of single-body, three-dimensional rigid elements with mass parameters (Figure 1). The human model is represented by a rigid lump with defined mass parameters, hereafter referred to as a dummy. The frame and seat model of the wheelchair represents a single element reflecting also the mass parameters of the other components connected to the frame such as: batteries, actuators, front wheels, electronic module, gears, etc. The leveling arm (with skid) is connected at one end via a rotating kinematic pair to the frame of the wheelchair. The other end of this arm will rest on the ground. The walking arm (windmill) is connected, in the middle of its length, by a rotating kinematic pair to the frame of the wheelchair. The ends of the windmill arms will alternately rest on the ground. The rear wheels in their axis are connected to the frame through a rotary kinematic pair. There is no friction in the rotational pairs shown above.

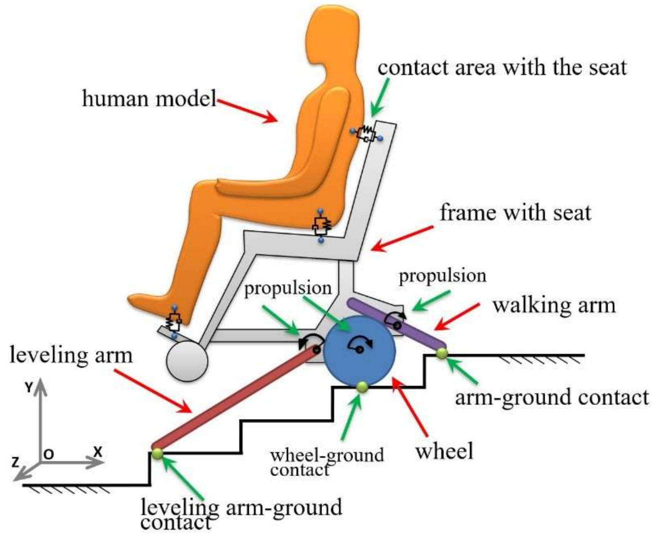

Figure 1. Model diagram for dynamic studies during obstacle crossing

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When negotiating an obstacle such as stairs, the front wheels do not contact the ground. Therefore, they were not modeled as a separate member and the mass parameters were included in the frame.

2.1. Model of contact of wheels, leveling arm and walking arm with the ground

Contact phenomena in dynamic runs determine, among other things, the stability of motion, the intensity of material wear of the wheel-substrate system, the ability to change the direction of motion, etc. [1]. In this chapter, these phenomena will have a significant impact on the simulation results of overcoming an obstacle. A look at the issues of modeling contact phenomena was made under the assumption that the wheelchair is modeled as a discrete mechanical system. This limits the applicability range of such a model to relatively low frequencies. In this study, the range of 0.44 - 89.09 Hz was analyzed.

A simplified model of the ground was adopted - it is rigid and consists of flat elements reflecting the floor and obstacle surfaces. During normal obstacle crossing, impact, friction and sliding occur. All these phenomena must be reflected in the modeled system in order to correctly represent the real course. The contact model presented below will be used to describe this phenomenon between the ground and:

- the rear wheels (right and left),
- the walking arms (left and right windmill arms),
- the levelling arm with skid.

To describe the normal forces occurring in the ground contact zone, the equation (1) from [8].was used:

$$F(y,\dot{y}) = \begin{cases} k(R-y)^{e} - c\dot{y} & dla \quad y \le R \\ 0 & dla \quad y > R \end{cases} \tag{1}$$

where:

y – distance between wheel axle and ground surface,
$\dot{y}$ – instantaneous rate of change of the distance between the wheel axis and the ground,
R – radius of the wheel,
k – coefficient of elasticity,
e – exponent of the power of elasticity,
c – damping factor.

The normal force is powerfully proportional to the amount of deformation and proportional to the velocity of that deformation. In this analysis, deformation is understood as the deflection of an element during contact with the ground. The nature of the course of the elastic component of the normal force depends on the value of the power exponent and for the value of e=1 its increase is proportional to the strain, for e<1 its course reflects the so-called soft elasticity, and for e>1 is hard elasticity [8].

The course of the damping component depends on the value of the strain d with the value of which the course of change of the damping ratio c in the transition period is shaped (0). Outside the transition period, before the element comes into contact, the component of normal damping is zero, while the value of damping for deformations larger than d maintains a constant maximum value.

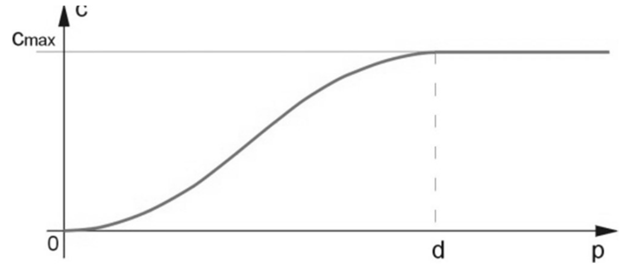

Figure 2. Dependence of damping c on deformation (deflection) p where p=R-y [8]

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In the presented model, the characteristic curve of a variable friction coefficient is used to reflect the friction phenomena [8]. The characteristic curve takes into account both the static and dynamic friction coefficient.

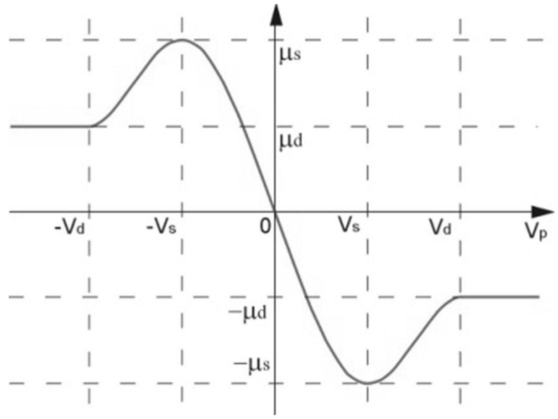

Figure 3. Dependence of friction factor on sliding speed Vp [8]

where:
μs – coefficient of static friction,
μd – dynamic friction coefficient,
Vs – threshold speed module for μs,
Vd – threshold speed module for μd,
Vp – Slip velocity at the point of contact.

The Adams program has an indicated contact model and this was used in the analysis conducted [8]. The contact model will be used to describe the phenomena in the simulation model of the wheelchair, for which nominal parameters were taken and compiled in table 1.

Table 1. Contact model parameters

Name of parameter	Designation	Substrate contact parameters for the component:			Unit
		Rear wheels	Walking arm (windmill)	Levelling arm	
Static friction coefficient	μ_s	0,7	0,7	0,05	-
Coefficient of dynamic friction	μ_d	0,6	0,6	0,01	-
Radial stiffness	k	4,0 e7	1,0 e8	2,0 e8	N/m
Damping constant	c	6,0 e3	1,0 e3	1,0 e3	Ns/m
Deformation value for which the damping reaches its maximum value c_{max}	d	2	0,5	0,1	mm
Power exponent of the dependence of elastic force on deformation	e	2	2	2	-

The above parameters were subjected to variational analyses in which simulation results were compared for their different values. They are described in more detail in the paper [6].

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2.2. Human Body Simulation Model

When building a simulation model of the human body, it was simplified to a rigid solid. In addition, we followed the guidelines contained in "ISO 7176-11 Wheelchairs: Test dummies" [17]. The indicated works contain a description of the geometry of the dummy's members and their masses, but do not provide information about the location of the center of gravity and moments of inertia. This information is necessary for the correct construction of the simulation model of the human body.

CATIA V5R20 software was used to build a multi-member solid model of the manikin representing the human body and to give the members a uniformly distributed mass, corresponding to the human body, especially the Ergonomics Design & Analysis module. This tool has a built-in library of anthropometric parameters with the possibility of their modification. The model generated by this tool can be used for ergonomic analyses concerning the determination of spatial structure of a workstation.

The parts of this manikin such as thighs, shins or arms do not have independent mass parameters. The whole manikin has an assigned mass and position of the center of gravity, but no information about moments of inertia. Additional geometric models corresponding to the indicated members were built to determine them. The guidelines are taken from the standard [17]. It indicates the mass values of the dummies used in the study and how the dummy was placed on the wheelchair. Three components of the model construction and their respective masses were distinguished: body, thighs, shins. Three variants of the model were selected with masses: 50kg, 75kg and 100kg a The selected variants correspond to: 5th percentile for women (48kg), 50th percentile for men (76kg) and 95th percentile for men (98kg) according to [17]. These values are within the tolerances given by the standard.

A dummy model with mass parameters consistent with the presented variants was introduced in the form of a single mechanism member, which was given ties to the wheelchair model.

Standard [17] provides general guidelines for the placement of manikins on the wheelchair for testing. The dummy should be as close as possible to the seat back, equidistant from each side of the seat. The back edge of the legs is to coincide with the back edge of the footrest. Following these guidelines, each model was placed on the seat of the wheelchair according to the arrangement indicated on the Figure 4.

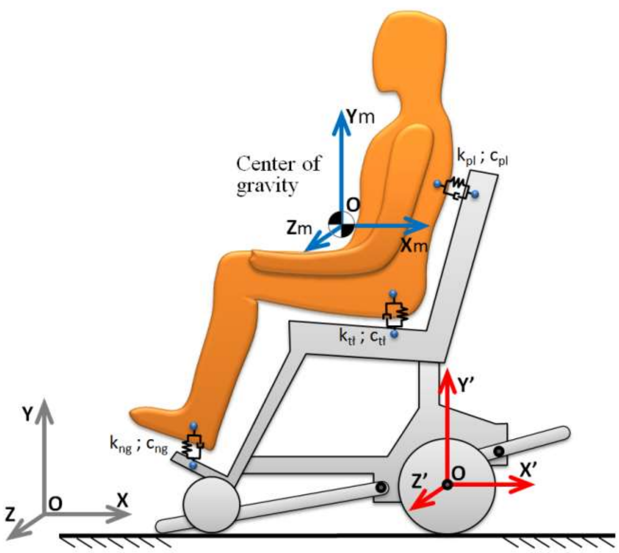

Figure 4. Local coordinate system for the definition of the dummy model located on the seat

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Due to the complexity of such activities and the fact that in this analysis the main goal was to identify the problem of overcoming the obstacle, the indicated models were not more detailed. The use of a single-body model also prevents the possible evaluation of vibration propagation to different parts of the body.

2.3 Simulation studies

The aim of the conducted simulation studies on the task of climbing a man-carriage system on stairs was to analyze dynamic phenomena. Based on it, an attempt was made to evaluate the application area of the proposed concept of the means of transport.

The simulation model was built in MD. Adams. Following the assumptions made for the model, five members were constructed, linked by appropriate ties.

The GSTIF-SI2 method developed by C. W. Gear was used to integrate the equations of motion. It uses the Backward Differentiation Formula (backward differentiation method). It is a variable order, variable step integration method and is dedicated to solving stiff systems of differential equations [8].

2.4. Determination of vibration accelerations of model elements

One of the important features of the tested simulation model is the possibility to determine the vibration acceleration experienced by its elements. As the most significant, from the point of view of human impacts, the area of torso contact with the seat of the wheelchair was assumed [3]. On Figure 5 the course of changes of vibration acceleration in X, Y, Z directions that act on the dummy model is presented.

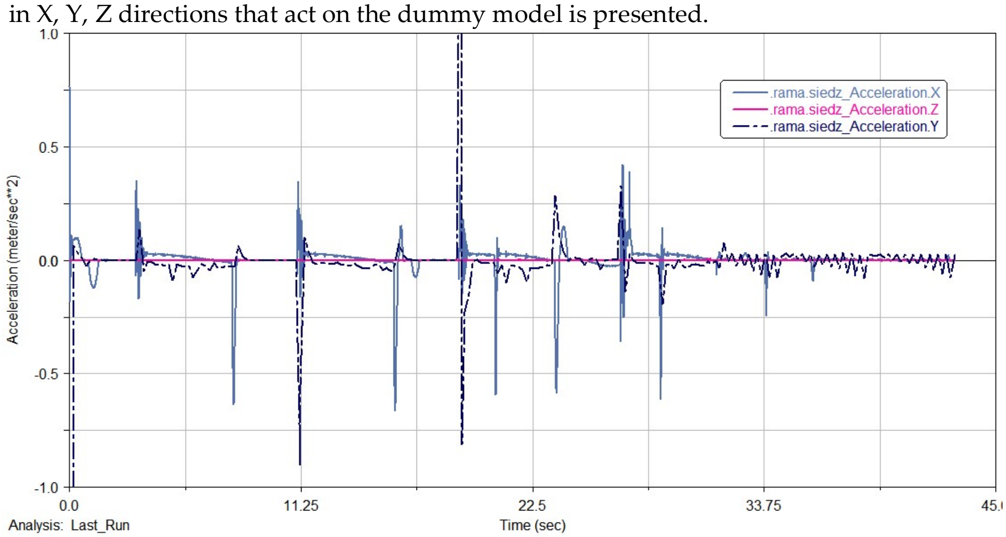

Figure 5. Changes in vibration acceleration in X, Y, Z directions affecting the manikin model

The presented characteristics allow to assess the type and parameters of the used shock-absorbing elements between the seat and the frame of the stroller. The characteristics show the peak values of accelerations in the X and Z directions every few seconds. They reached the value of about 1 m/s^2. Due to a number of simplifications used in the simulation model, it can be assumed that the phenomena on the prototype will have more varied values. This simulation model does not take into account the dynamic effects of electric driving motors. The observed frequency of peaks results directly from the sequence of changes in the type of cooperation with the ground: changes between the rolling of the wheels and the work of the walking arm.

The obtained results of acceleration were exported to the DASYlab program in order to analyze the vibrations acting on the human model when climbing stairs, which will allow to assess the comfort in accordance with [10].

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2.5. Analysis of vibrations affecting humans during stair climbing

Analyses conducted at this stage of design concept development evaluate the impact of driving conditions on the wheelchair rider. This is the use of simulation to virtually test the prototype. The analysis of vibrations affecting the human being during the ascent of the stairs made it possible to perform a comfort assessment in accordance with [10]. This standard concerns the measurement of steady and transient vibrations considered in 3 aspects: harmfulness, annoyance and comfort. It considers the following parameters of vibration effects: the value of vibration accelerations (acceleration equivalent or corrected value), the period of vibration effects, the frequency in third or octave bands and the direction of effects. Accelerations are analyzed in Cartesian coordinate system XYZ, the origin of which determines the place of vibration penetration into the body. The Y direction is determined by the spine. In this study, only the driving comfort evaluation method was used. The analysis was limited to one measurement point, located on the seat in the place of vibration transmission to the manikin's torso.

The method consists in recording stationary acceleration time courses in three directions at the assumed measurement point. The record must contain data from a representative measurement period, but its length is not strictly defined. Then the evaluation of the nature of the resultant vibrations should be carried out based on formula (2) for the peak factor [10].

$$k = \frac{a_{wpeak}}{a_{wRMS}} \tag{2}$$

where:

a_{wpeak} – weighted peak value of the vibration acceleration in m/s^2

$a_{w\,RMS}$ – effective weighted value of the vibration acceleration in m/s^2

Depending on the result obtained, different values of weighting factors are used. When it is between 1 and 9, basic coefficients are used. When it is 9 or more, additional coefficients are used. The signal for each axis is then divided into frequency thirds bands. The waveform of each band is multiplied by the corresponding weighting factor given in the standard. The rms value for each band is calculated. The rms values of the bands for the three directions are then vector summed, and the result is the basis for comparison with the threshold values.

The next step was to calculate the value of the peak factor. Its value was 1.34, so the basic values of the weighting factors were used in the next step. A tool was built to calculate the frequency-weighted RMS values.

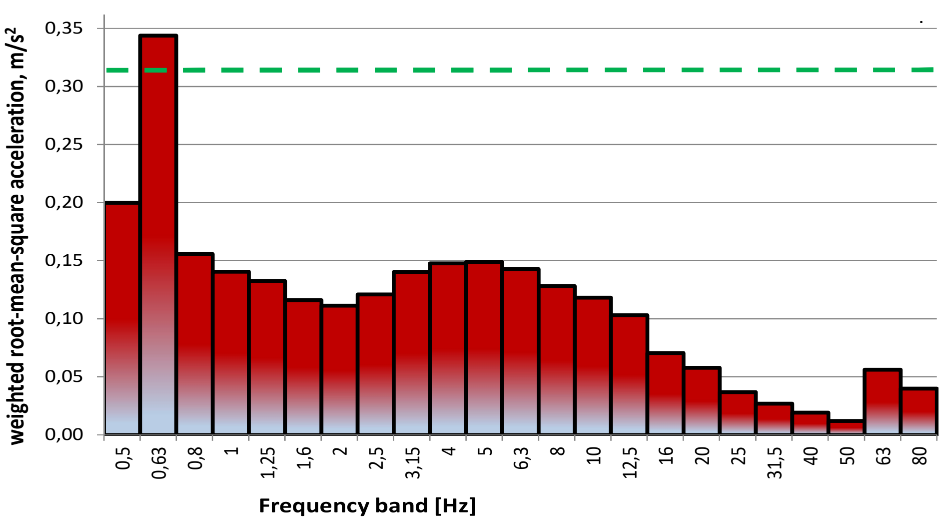

Figure 6. Effective values of vibration accelerations recorded at the measurement point

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According to the guidelines of the standard, the measurement point corresponding to the point of vibration penetration into the human body was determined. The point is related to the seat part of the wheelchair and is located at the base of the manikin's torso. In the signal analyses, the phenomena occurring in the 1st second were omitted as they are related to the model stabilization in the initial phase of the simulation. The RMS-weighted values of the accelerations in the thirds bands are shown in [10].

The calculated resultant rms values of the frequency-weighted accelerations were related to the comparative threshold values (Figure 6). Accelerations in the 0.63 Hz band assume the largest values and, in relation to the comparative threshold values, are on the borderline of the ranges of comfortable and slightly uncomfortable conditions. The results for the other bands are within the comfort limit.

The results of these analyses allow us to conclude that the wheelchair stair climbing method proposed in this paper does not have any negative effects in terms of comfort. Simplifications applied at this stage of the simulation, and consisting in considering the members of the model as rigid solids, may have increased the maximum values of vibration acceleration.

3. Experimental research on the prototype of the wheelchair of own design

The remainder of this paper presents a comfort evaluation conducted for a prototype of the presented wheelchair. This design was developed by the author of this paper, and is part of a patent application [2]. In laboratory tests an attempt was made to evaluate the comfort of a person moving on a prototype wheelchair called "WEKTOR". The results of this analysis were compared with the results obtained for the “EXPLORER” tracked wheelchair. This is a wheelchair produced by the Italian company TGR. This vehicle has two drive systems. To move on flat terrain, it uses a three-wheel system, of which two rear wheels are driven and the front wheel is responsible for giving the direction of travel. On the other hand, it moves on stairs using tracks with independent drive for each of them, which allows to overcome any type of stairs.

Triaxial accelerometers connected to the recording system were used to record the vibrations. The triaxial sensor was placed in the center area of the seat, at a location assumed to be the resultant seat-passenger response. The location of this accelerometer along with the directions of operation are shown on Figure 7.

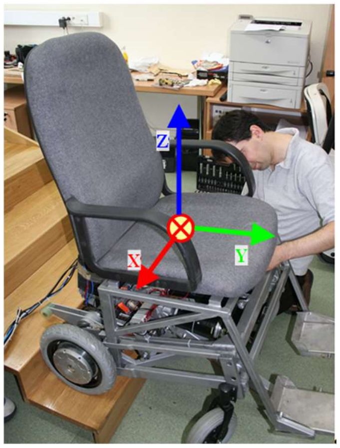

Figure 7. Location and directions of the triaxial acceleration sensor

Due to the nature of the motion, signals recorded in the Y and Z directions were used for further analysis, where the highest values of vibration energy were observed in the Z direction. After placing the sensor in the selected measurement point (Figure 7.) The wheelchairs were subjected to a load of 75 kg. The distribution of weights in an approximate way allowed to replace the human model.

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The ascent and descent stages were recorded separately for each wheelchair. The tested wheelchairs have different methods of climbing stairs and the time of this task depends on many factors. For the purposes of this work, the research was based on the assumption that the scope of the task understood as the work to be done, i.e. the ability to overcome 4 stairs, is more important than the analysis time. The measurement signal was recorded from the moment when the wheelchairs switched to the stair driving mode until the moment when they entered the final part of the stairs and switched to the mode of driving on horizontal surfaces.

Below on the Figure 8. the vibration time courses for the wheelchairs while ascending the stairs are presented. The Explorer wheelchair took 42 sec to climb these stairs, while the Wektor wheelchair took 54 sec. Comparison of the vibration acceleration time courses showed differences in the maximum values for both wheelchairs.

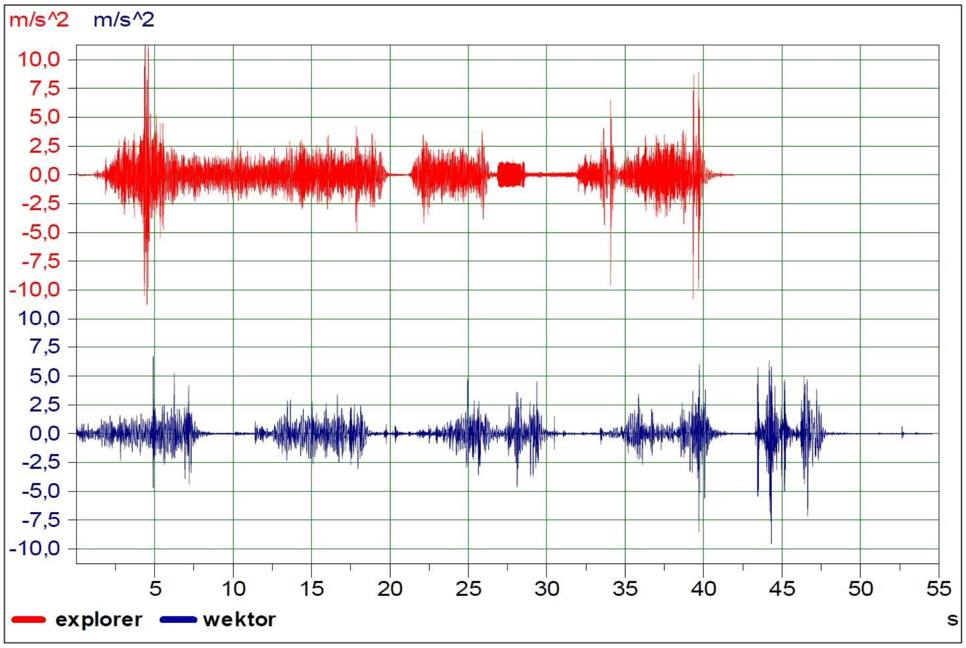

Figure 8. Vibration time courses for wheelchairs during stair ascent

When assessing the time courses for accelerations in general, we notice a difference in the peaks of these accelerations. It is influenced by different design solutions of both wheelchairs. The characteristics of the "Explorer" wheelchair reach significantly higher values because the structure of its frame does not have vibration damping elements. This trolley has a caterpillar with teeth that introduce additional vibrations when driving up stairs. The observation of the results for the "Wektor" wheelchair shows significantly lower impact values compared to the "Explorer" wheelchair. It should also be noted that an attempt to compare the results with the simulation model presented earlier will be more reliable when we use the [10] method.

The analysis of vibrations affecting humans during ascent of the stairs made it possible to assess comfort in accordance with ISO 2631-1:1997 - Mechanical Vibration and Shock - Evaluation of Human Exposure to Whole-Body Vibration- General Requirements [10]. The algorithm described earlier was used to analyze the results. These results are illustrated in the graph Figure 9.

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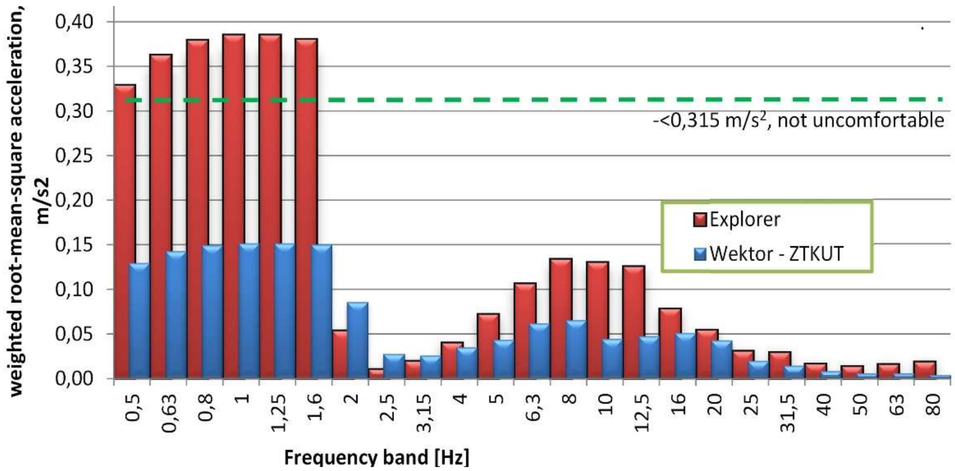

Figure 9. Plot of weighted RMS vibration acceleration values for Explorer and Vector wheelchair

The graph presents the RMS weighted vibration acceleration values for the Explorer and Wektor wheelchair. Comparison of the calculated values with the threshold comparison values of accelerations showed that the author's concept achieves results in the comfortable range, while the Explorer wheelchair in the low frequency range achieves values in the slightly uncomfortable range. The presented results indicate the correctness of the assumptions of the stair climbing method used in the design of the Wektor wheelchair. This proprietary design outperforms the commercial and well-known Explorer wheelchair design.

4. Summary and conclusions

The paper deals with issues related to the analysis of the dynamics model of a wheelchair overcoming obstacles. Simulation and experimental studies of vibration effects on a person moving on this wheelchair are presented. The obtained results made it possible to verify the simulation studies in terms of driving comfort assessment. The use of simulation techniques allows to shorten the development time of the project and reduce the costs associated with prototyping. Another important issue of the simulation studies was the validation of the model, which allowed to assess the consistency of the simulated processes with those occurring in reality. The results of simulation were compared with the results of tests on the prototype, obtaining qualitative consistency in the evaluation of driving comfort.

The formulated conclusions related to the construction of the wheelchair concern mainly the assessment of the driving comfort. The performed tests and the evaluation of their results showed that the simulation model of the construction provides sufficient comfort during driving in the conditions that may occur during real operation. It should be emphasized that the applied simplification of the wheelchair frame segment, as a perfectly rigid body, as well as the way of modeling the dummy, may affect the change of values of accelerations transmitted to the dummy.

5. Patents

The original design solutions for the wheelchair presented in this article were the basis for the development of the patent application. Patent no: PL-219658 was obtained, date of granting the right: 29-10-2014 [2].

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