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A CONCEPT OF MODIFICATION AND SIMULATION STUDIES OF A MECHATRONIC STAIR TRANSPORTER FOR THE DISABLED

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Abstract: A numerical model of existing stair climber with its passenger was built and its operation was analysed through simulations. A modification of the stair climber has been developed on a basis of the simulation studies. The modification depends on equipping the device with additional controllable mechanism the function of which is to change the position of the passenger's centre of gravity. Comparative simulation studies were carried out for the standard version and the modified version of the stair transporter in a system for the dynamic.

Keywords: Computational Model, Stair Transporter, Operator Relief System

1. INTRODUCTION

The problem of the locomotion of persons with impaired mobility on a flat terrain has been quite effectively solved through various wheelchairs. One of the major difficulties for those people is to overcome architectonic barriers, mainly stairs (Laffont et al., 2008). This problem is being solved chiefly through approach ramps or special lifts. Such solutions enable locomotion impaired persons to independently overcome stairs. They are psychologically important since the disabled person can get to another level in a building without asking other people for help. Unfortunately, there are still many places, e.g. the aircraft boarding ramp or very narrow stairs, in which the use of such devices is impossible or costly. In such situations the solution is the use of stair transporters, commonly called stair climbers.

Depending on the way they overcome stairs the devices are divided into driving (usually tracked) devices (Yu et al., 2013) and walking devices (in which a proper mechanism enables the translocation of their particular members at a momentary absence of contact of the members with the base).

From the point of view of kinematics, a device which is to overcome obstacles (e.g. stairs) must have a proper mechanism (Bałchanowski et al., 2012; Bałchanowski et al., 2010) whose geometric features enable overcoming obstacles of particular type and size. Moreover, the stability of the device during obstacle overcoming must be ensured. The R&D work on stair transporters has resulted in various technical solutions.

This paper presents an analysis of the motion of the AAT S-Max Aviation stair climber for transporting disabled persons up and down the stairs. First a numerical model of the actual device was created in a system for the dynamic analysis of multilink systems and then simulations were run. The results of the simulation studies were used to develop a modification of the device in order to facilitate the work of the operator.

2. STRUCTURE OF STANDARD WALKING STAIR TRANSPORTER

Designed stair climbers are different in design depending on their purpose (Gonzalez et al., 2009; Shriwaskar et al., 2013;Fang et al, 2011; Trochimczuk et al., 2014). The S-Max Aviation stair climber made by AAT is an example of a device which uses walking to climb stairs. It was designed to service persons with impaired mobility at airports. The device can be operated exclusively by a trained operator. The stair climber consists of a frame on which a seat and adjustable operator handle are mounted and a driving-walking mechanism supplied from a battery. The device is shown and described in Fig. 1.

Fig. 1. S-max Aviation walking stair climber made by ATT (http://www.aatgb.com/)

Stair climbing is effected by means of the lifting foot which by moving downwards lifts the device with the passenger. During this time the wheels move to the next stair. The device ascends the stairs with its back to the latter. When the device descends

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the stairs the passenger faces the direction in which it moves. Driving on a flat terrain is effected solely by the operator's muscles. The operator operates the device via a proper control panel. The drive unit is a 275 W motor supplied with 24 V direct current, with a maximum lifting capacity of 160 kg. The other basic specifications of the device are as follows.

- Overall dimensions: height 1.1-1.5 m, width 0.38 m, length with footrest 1 m;
- Mass parameters: total weight 36 kg, lifting mechanism 17 kg, the seat with the backrest 11 kg, handle 3 kg, battery set 3 kg,
- Stairs overcoming speed: 8-23 stairs per minute;
- Maximum stair height: 25 cm.

The S-Max Aviation stair climber is operated by a single operator and enables the transport of a disabled person up and down the stairs. It is a wheeled-walking device in which walking up/down the stairs is effected by a proper electrically powered walking mechanism. The main difficulty which the operator has to cope with is to keep the whole device (with its passenger) in equilibrium. Unfortunately, this requires considerable effort and skill. Somewhat oversimplifying it, the operator must bear the person sitting in the device which is supported only in one point. In addition, at a certain moment the point of support changes quite abruptly: first the whole device rests on the foot situated on the lower stair and then the whole weight is carried by the wheel resting on the higher stair. In order to keep the transported person in the stability field the operator must use considerable force.

3. CREATION OF MECHATRONIC MODEL OF STAIR TRANSPORTER

In order to define the characteristics of walking transporter mechanism a numerical model of the existing device for transporting disabled persons up/down the stairs had to be built and several simulations had to be run. The kinematic scheme of S-max Aviation walking transporter which was the basis for the model is shown (in scale) in Fig. 2.

The numerical model was built on the basis of the technical documentation and measurements performed by the authors. The interactions of the foot and the wheels with the base were modelled as contact forces (Bałchanowski, 2012). The transported person's mass was assumed to amount to 90 kg.

The aim of this part of the simulation studies was to determine the kinematic and dynamic parameters of the device during overcoming the stairs. At this stage of the studies the focus was on the changes in the position of the device and passenger's centre of gravity. View of the device and its walking sequence is shown in Fig. 3.

Moving up the stairs takes place with passenger rear-facing. Pressing the "UP" button on the control panel will start the process of entering implemented in two stages. It begins with foot moving downward (Fig. 3a). After touching base, foot takes load from the wheels (Fig. 3b), which together with the entire chassis are raising. Simultaneously wheels axis is moving circularly relative to chassis in the direction of the next stair. Afterwards, wheels touch the surface of the next stair (Fig. 3c). At this point, wheels abruptly takes the load, which was previously on the foot (Fig. 3d), and the step of retracting the foot to the chassis begins. In the presented procedure it is evident, that to maintain the device in balance it is necessary to put in work by the operator, who is omitted in Fig. 3. To overcome the following stair process is repeated with the same sequence.

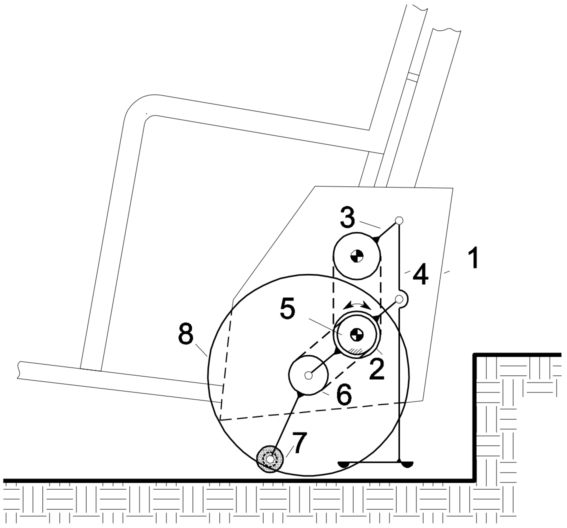

Fig. 2. Kinematic scheme of standard version of stair climber: 1 – frame, 2 – driving chain wheel, 3 – parallelogram chain wheel, 4 – foot (parallelogram connecting link), 5 – stationary chain wheel, 6 – satellite chain wheel, 7 – braking wheel, 8 – driving-walking wheel

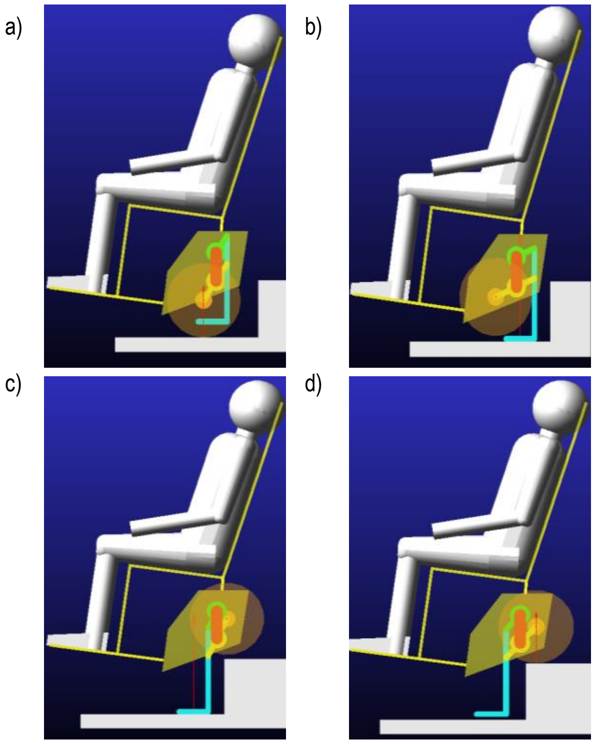

Fig. 3. Stairs walking procedure shown on example of one stair upcoming

Carried out simulations allowed to define quantitative assessment of the operator's applied force during transporter operation and indicate the necessity of modification toward its reduction.

Having in mind operator work facilitation the authors undertook to equip the device with an additional kinematic system whose purpose is to change the position of the centre of gravity of the passenger. The essence of good design of such system is to appropriately develop structure and geometry so as to acquire horizontal movement of seat with passenger in the range sufficient for necessary centre of gravity of man-device system position change relative to actual fulcrum.

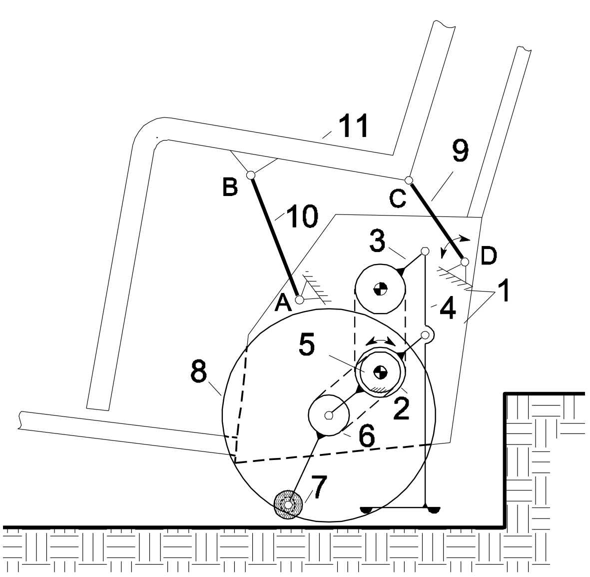

Fig. 4. Kinematic scheme of stair climber with mechanism changing passenger's gravity centre position: 1 – frame, 2 – driving chain wheel, 3 – parallelogram chain wheel, 4 – foot (parallelogram connecting link), 5 – stationary chain wheel, 6 – satellite chain wheel, 7 – braking wheel, 8 – driving-walking wheels 9 – control mechanism crank, 10 – control mechanism rocker, 11 – seat

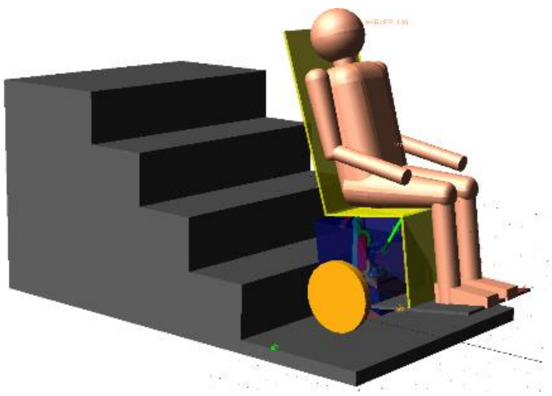

Fig. 5. Model of stair transporter

The authors decided to use four-bar linkage mechanism, whose main advantage is to occur only rotational joint. Geometric synthesis of four-bar linkage was performed using extreme position of seat relative to frame. Next condition was the change of seat angle from horizontal position within ten degrees. The parallelogram mechanism obviously fulfils above assumptions. Unfortunately usage of this mechanism was impossible because of the construction restriction. It was only used as the base for geometric synthesis of four-bar linkage. It consisted of searching AB length and the position of joint B on part 11 (seat) for different position of joint A on frame. Therefore, the synthesis process was brought to a classic task of defining dimensions of the basic four-bar linkage with three coupler position synthesis with alternate attachment points (Miller S., 1987) and additional design criteria. The procedure for dimensions design of the basic four-bar linkage is a separate issue and is not the subject of this work.

Kinematic diagram of the stair transporter mechanism equipped with the changing passenger mass centre position is shown in Fig. 4. The results of the first part of the simulation studies provided the basis for development of control algorithm whose function is to position the centre of gravity of the transported person as close as possible to the point of support of the system.

To sum up, the task of the additional mechanism equipped with a control system is to change the position of the seat so as to make it easier for the operator to keep the passenger in the stability field. The model together with the disabled person in the seat is shown in Fig. 5.

4. MECHATRONIC CONTROL SYSTEM OF STAIR TRANSPORTER

The aim of the next stage in the research was to develop a model and carry out numerical analyses of the device equipped with the mechanism automatically adjusting the position of the centre of gravity. The obtained results were the base for developing a proper mechanical control algorithm (Bałchanowski, 2012; Morales et al., 2010). Fig. 6 shows the procedure of overcoming stairs by the stair transporter. The function of the control system is to properly position the centre of gravity of the passenger relative to one of the two points of support. The location of the point of support depends on the current device configuration (it can be the contact between the base and the driving wheel or the foot).

The purpose of passenger centre of gravity control is to minimize the handle moment needed to achieve balance and thus to reduce the force needed to hold the stair climber by the operator. The moment should have the same sense during the whole work cycle so that the vehicle's handle does not pull the operator down the stairs. Thanks to this requirement the danger that the operator will be pulled towards the base of the stairs, which may result in the fall of and serious injury to both the operator and the transported person, is minimized.

Control is effected through the adjustment, according to relationship (1) of the driving torque in the rotational joint connecting the device casing with crank 9 of the four-bar linkage (Fig. 4) supporting the seat. Control task, which is to consist in keeping the transported person's centre of gravity in the permissible range of positions relative to the support point, is effected by means of two PD controllers. The set value for the first controller is the position of the seat relative to the foot while the position of the seat relative to the driving wheel is the set value for the second controller. Application of two regulators allows to set control parameters independently for control with the foot or wheels as an active fulcrum. A scheme of the control algorithm is shown in Fig. 7. For each regulator, the set value has been matched independently to achieve the control aim described above. At a given instant only one controller is active. The choice of a controller depends on the current point of support – the device can stand on its foot or driving wheel. The base function of PD regulator is to minimize the control error $e(t)$.

$$M = k_P^i \cdot e(t) + k_D^i \cdot \frac{\mathrm{d}e(t)}{\mathrm{d}t} \tag{1}$$

where: $M -$ the crank torque, $e(t) = q_{set}^i - q -$ control error, $\frac{de(t)}{dt} = \frac{d(q_{set}^i - q)}{dt} = \frac{dq_{set}^i}{dt} - \frac{dq}{dt}$, $q_{set}^i -$ the set position for the i-th controller, $q -$ the actual value of passenger's centre of gravity relative to chassis, $\frac{dq_{set}^i}{dt} -$ derivative of set value for i-th controller, $\frac{dq}{dt} -$ derivative of actual value, $i = \begin{cases} 1 \; for & F_n > 0 \\ 2 & F_n \leq 0 \end{cases}$, where: $F_N -$ the pressure force measured in the foot base, $\mathrm{i} = 1$ for the controller connected with the leg, $i = 2$ for the controller connected with the driving wheel.

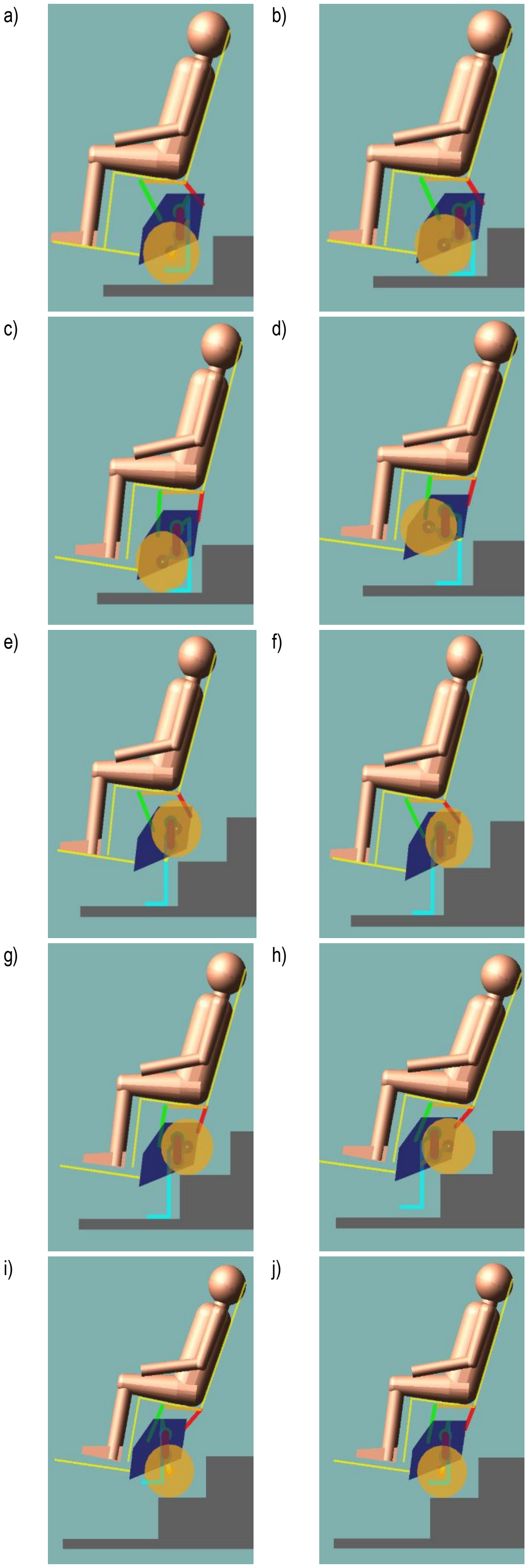

Fig. 6. Procedure of overcoming stairs, illustrated for single stair

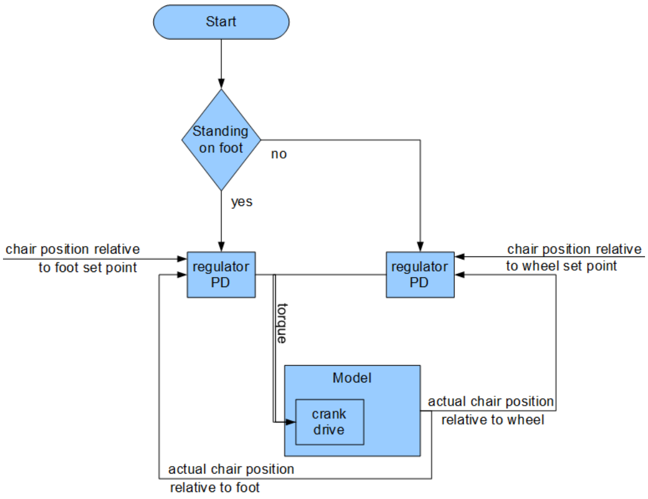

Fig. 7. Block diagram of control

In the climbing process repeating cycles can be distinguished. Each cycle consists of four phases. During first phase weight of device with passenger lay on driving wheels. In control algorithm, PD regulator, whose set value is determined by position of seat relative to driving wheels, is active. The crank torque is computed, according to equation (1), for keeping passenger in the appropriate position relative to chassis of the mechanism. Value of the control signal depends on value of the error signal e(t). The greater the error, the greater the control signal is, according to the value of proportional part parameter. Additionally, derivative part of the regulator is used. It is assumed to correct control signal in situation when the error signal is changing quickly. When error signal is increasing, value that is product of error derivative and derivative part parameter, is added to control signal. As a result, the regulator's output signal is increased as a reaction to increasing error. In case of decreasing error the reaction of regulator is similar. The derivative part of regulator decreases value of control signal. According to that, the over-regulation is eliminated in control algorithm. This over-regulation would cause yaw of seat, which would be very unpleasant for the passenger. After initiation of gait sequence in stair climber, driving wheel changes position relative to chassis. Seat also changes position according to maintain its and passenger centre of gravity above the wheel and base fulcrum. In certain moment the foot of mechanism touches the base and second fulcrum is created. This is the second phase of cycle, in which weight of device and passenger lay on both driving wheel and foot. At this moment controller changes active regulator to that which present value is measured relative to foot. Seat is moving, so that centre of gravity is above the foot. Driving wheel is moving of the base.

The third phase begins, in which the weight lay only on foot. Working of algorithm is similar to phase one but control error is substrate of seat position and position of foot and base fulcrum. Next, mechanism comes into fourth phase, in which weight lay on foot and driving wheel simultaneously. Algorithm works similarly to phase two. Controller changes active regulator to that, which set value is relative to position of driving wheel. Seat is moving so that its and passenger's mass centre is above driving wheel and base fulcrum. Next, algorithm comes into phase one and the cycle is looped.

5. RESULTS OF SIMULATION STUDIES

The numerical model of the stair transporter equipped with the mechanism for changing the position of the passenger's centre of gravity, and with a control system was used to study the dynamics of the whole device together with its passenger for one full work cycle. In the model the force put in by the operator was replaced with constraints keeping the device in a specified orientation. The moment of force which needs to be applied to the handle in order to keep the position of balance was treated equally with the moment applied to the stair climber body by the operator.

In the simulations a single cycle time of 6.5 s was assumed. In the first 0.5 s the position of balance would be reached. Fig. 6 shows the graphs of changes in the moments which need to be applied to the device body in order to keep it balanced for the standard device and the one equipped with a controllable mechanism aiding the operator work. It appears from Fig. 6 that during most of the working period the balancing moment value in the model with control is lower. The peaks visible in Fig. 8 are caused by changes in the point of support, which are practically stepwise. The demand for moment in the control mechanism is shown in Fig. 9, but its maximum value in the control system was limited to 100 Nm. The pattern of changes in torque in the main drive (Fig. 10) is practically the same for the two models.

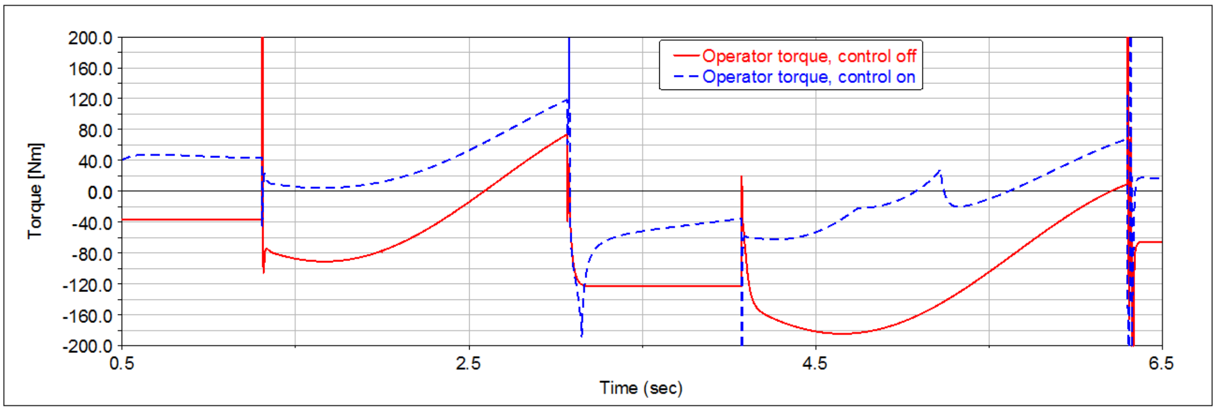

Fig. 8. Changes in moment applied to device body

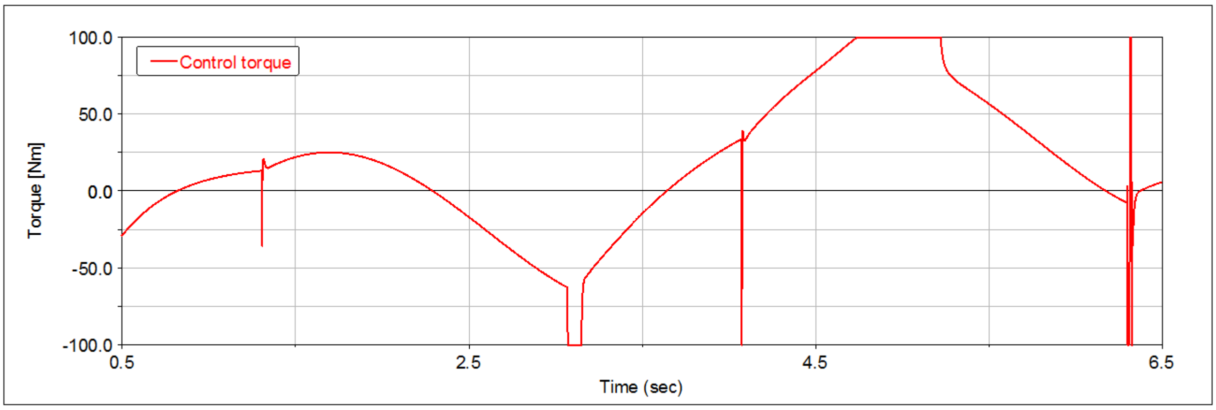

Fig. 9. Changes in torque in controlling drive

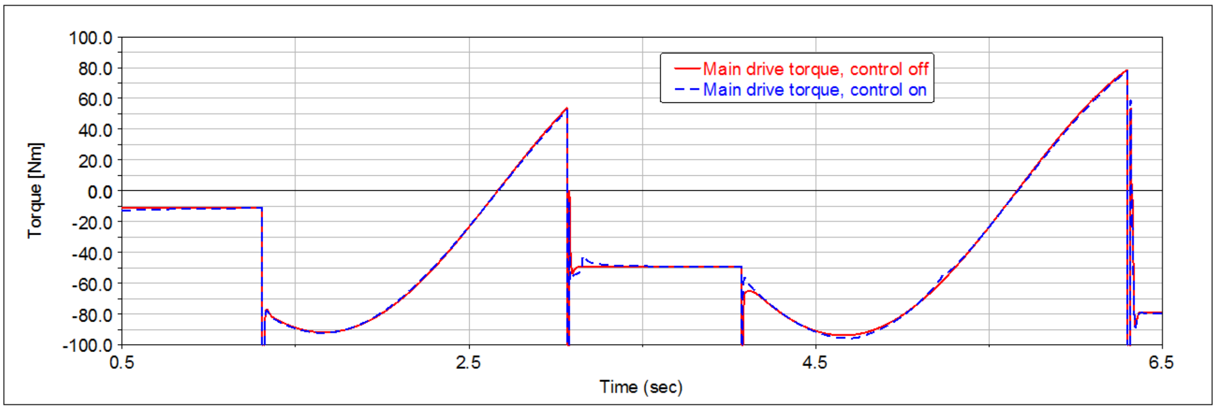

Fig. 10. Changes in torque in main drive

6. CONCLUSION

The results of the simulation studies have shown, that the design of the easing mechanism added to standard stair climber, is correct. Control is effected through adjusting the torque of the four-bar linkage crank.

Two PD controllers are used for this purpose. One of the controllers is input with the set position of the seat relative to the foot, whereas the other is input with the set position of the driving-walking wheel (only one controller operates at a time). The selection of the active controller depends on the point of support (the driving-walking wheel/the foot).

The proposed equipment of the stair climber with the additional mechanism changing the position of the passenger's centre of gravity significantly aids the work of the operator. Thanks to this solution the operator's effort is considerably reduced. The results of the kinematics and dynamics simulation studies show that a battery powered electric drive can be used for the mechanism. The operation of the device equipped with a sensor and control system can significantly improve the operator's work comfort.

A drawback of the solution is that a change in the position of the passenger's centre of gravity requires an additional time for the change of the mechanism configuration.

The simulation studies were carried out for a constant transporter orientation. In reality the operator changes this orientation continuously, seeking an orientation which requires the least effort. In further research the effect of the decisions made by the operator should be included in the model.

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