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UTILIZING OF A WEIGHT-FIBRE-PULLEY-DRIVE MECHANICAL SYSTEM FOR THE INVESTIGATION OF A FIBRE BEHAVIOUR

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Abstract: *Experimental measurements focused on the investigation of a fibre behaviour are performed on an assembled weigh-fibre-pulley-drive mechanical system. The fibre is driven with one drive and it is led over a pulley. On its other end there is a prism-shaped steel weight, which moves in a prismatic linkage on an inclined plane. The position of the weight can be symmetric or asymmetric with respect to the vertical plane of drive-pulley symmetry. It is possible to add an extra mass to the weight. Drive exciting signals can be of a rectangular, a trapezoidal and a quasi-sinusoidal shape and there is a possibility of variation of a signal rate. Dynamic responses of the weight and the fibre are measured. The same system is numerically investigated by means of multibody models. The coincidence of results of experimental measurements and the simulations results is evaluated. The simulations aim is to create a phenomenological model of a fibre, which will be utilizable in fibre modelling in the case of more complicated mechanical or mechatronic systems.*

Keywords: Fibre, Mechanical system, Dynamic response, Phenomenological model.

1. Introduction

The replacement of the chosen rigid elements of manipulators or mechanisms by fibres or cables (Chan, 2005) is advantageous due to the achievement of a lower moving inertia, which can lead to a higher machine speed, and lower production costs. Drawbacks of using the flexible elements like that can be associated with the fact that cables should be only in tension (e.g. Valášek & Karásek, 2009; Gosselin & Grenier, 2011) in the course of a motion.

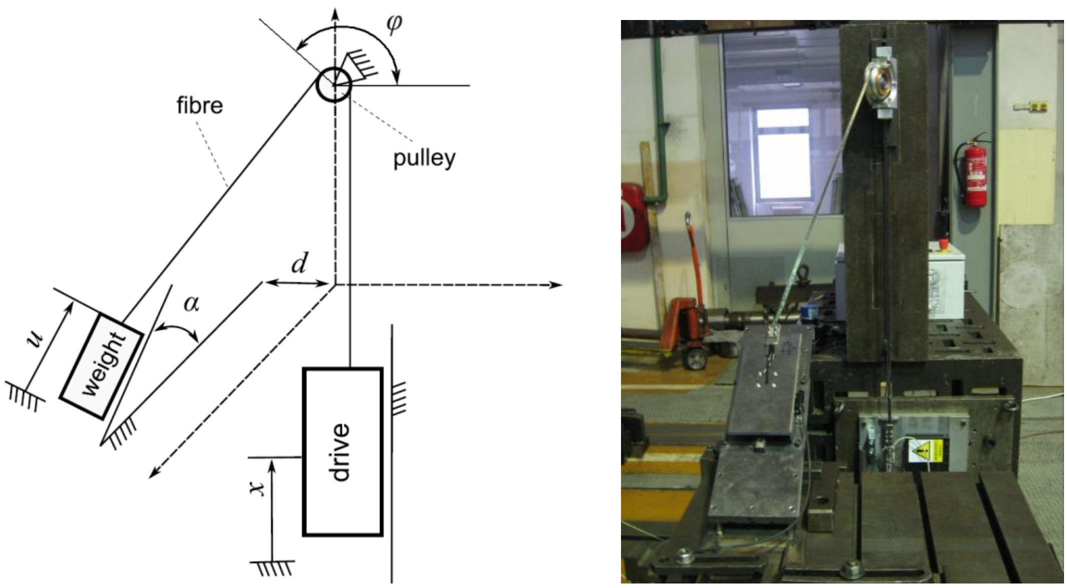

Fig. 1: Scheme and a real weight-fibre-pulley-drive mechanical system (asymmetric position of the weight).

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Experimental measurements focused on the investigation of the fibre behaviour were performed on an assembled weigh-fibre-pulley-drive system (Polach et al., 2013c; Polach et al., 2013d; Polach et al., 2013e; Polach et al., 2014). The fibre is driven with one drive, it is led over a pulley and on its other end there is a prism-shaped steel weight, which moves on an inclined plane. The position of the weight can be symmetric or asymmetric with respect to the plane of a drive-pulley symmetry (see Fig. 1). It is possible to add an extra mass to the weight. The same system is numerically investigated using multibody models created in the **alaska** simulation tool (Maißer et al., 1998). The influence of the model parameters on the coincidence of the results of experimental measurements and the simulations results is evaluated. The simulation aim is to create a phenomenological model of a fibre, which will be utilizable in fibre modelling in the case of more complicated mechanical or mechatronic systems.

The first pieces of knowledge concerning the phenomenological model of a simple fibre-mass system (the system consists of a moving weight coupled with a frame by a fibre) creation are given in Polach et al. (2013a) and Polach et al. (2013b). The paper summarizes investigating the weight-fibre-pulley-drive system given in Polach et al. (2013c), Polach et al. (2013d), Polach et al. (2013e) and Polach et al. (2014), where all combinations of the position of the weight with respect to the plane of the drive-pulley symmetry (symmetric or asymmetric) and of the mass of the weight (without or with added mass) were presented.

2. Experimental Stand

Originally it was supposed that for the experimental measurement focused on determining the properties of the fibre an inverted pendulum driven by two fibres attached to a frame would be used. Its properties were investigated very thoroughly applying calculation models (see e.g. Polach et al., 2012a). But strength calculation results drew attention to a high loading of fibres which were to be used in experimental measurements (carbon or wattled steel wire) and to the possibility of their breaking (see Polach et al., 2012b).

Due to those reasons a different mechanical system was chosen for the experimental measurements (its geometrical arrangement was changed several times on the basis of various pieces of knowledge). Experimental measurements focused on the investigation of the fibre behaviour are performed on an assembled weigh-fibre-pulley-drive mechanical system (see Fig. 1). A carbon fibre with a silicone coating (see e.g. Polach et al., 2012b) is driven with one drive and it is led over a pulley. The fibre length is 1.82 meters (fibre weight is 4.95 grams), the pulley diameter is 80 millimetres. The weight position can be symmetric (Polach et al., 2013c; Polach et al., 2013e) or asymmetric (Polach et al., 2013d; Polach et al., 2014) with respect to the vertical plane of drive-pulley symmetry. Distance of the weight from the vertical plane of drive-pulley symmetry is d = 280 mm in the case of the asymmetric weight position (see Fig. 1). At the drive the fibre is fixed on a force gauge. On the other end of the fibre there is a prism-shaped steel weight (weight 3.096 kilograms), which moves in a prismatic linkage on an inclined plane. It is possible to add an extra mass (of the weight 5.035 kilograms) to the weight (Polach et al., 2013e; Polach et al., 2014). The angle of inclination of the inclined plane can be changed (in the case of the symmetric weight position the angle is α = 30 degrees and the pulley-fibre angle is φ = 150 degrees, in the case of the asymmetric weight position the angle is α = 30.6 degrees and the pulley-fibre angle is φ = 146 degrees). Drive exciting signals can be of a rectangular, a trapezoidal and a quasi-sinusoidal shape and there is a possibility of variation of a signal rate (Michalík & Janík, 2012). The amplitudes of the drive displacements are up to 90 millimetres. Time histories of the weight position u (in direction of the inclined plane; measured by means of a dial gauge), of the drive position x (in vertical direction) and of the force acting in the fibre (measured on a force gauge at drive) were recorded using sample rate of 2 kHz.

3. Possibilities of the Fibre Modelling

The fibre (cable, wire etc.) modelling (Hajžman & Polach, 2011) should be based on considering the fibre flexibility and suitable approaches can be based on the flexible multibody dynamics (see e.g. see e.g. Shabana, 1997; Gerstmayr et al., 2012). Flexible multibody dynamics is a rapidly growing branch of computational mechanics and many industrial applications can be solved using newly proposed flexible multibody dynamics approaches. Studied problems are characterized by a general large motion of interconnected rigid and flexible bodies with the possible presence of various nonlinear forces and torques. There are many approaches to the modelling of flexible bodies in the framework of multibody systems (Hajžman & Polach, 2008). Comprehensive reviews of these approaches can be found in Shabana (1997) or in Wasfy & Noor (2003). Further development together with other multibody dynamics trends was introduced in Schiehlen (2007). Details of multibody formalisms and means of the creation of equations of motion can be found e.g. in Stejskal & Valášek (1996) or Awrejcewicz (2012).

The simplest way how to incorporate fibres in equations of motion of a mechanism is the force representation of a fibre (e.g. Diao & Ma, 2009). It is assumed that the mass of fibres is low to such an extent comparing to the other moving parts that the inertia of fibres is negligible with respect to the other parts. The fibre is represented by the force dependent on the fibre deformation and its stiffness and damping properties. This way of the fibre modelling is probably the most frequently used one in the cable-driven robot dynamics and control (e.g. Zi et al., 2008; Heyden & Woernle, 2006). The fibre-mass system fulfils all requirements for modelling the fibre using the force representation of the fibre. A more precise approach is based on the representation of the fibre by means of a point-mass model (e.g. Kamman & Huston, 2001). It has the advantage of a lumped point-mass model. The point masses can be connected by forces or constraints.

The massless fibre model is considered in this phase of investigation of the weight-fibre-pulley-drive system. The fibre model is considered to be phenomenological and it is modelled by the forces which comprise e.g. influences of fibre transversal vibration, "jumping" from pulley etc. The multibody models of the weight-fibre-pulley-drive system in the case of considering the symmetric and asymmetric position of the weight with respect to the plane of drive-pulley symmetry slightly differ (Polach et al., 2013c; Polach et al., 2013d). In the case of symmetric position the number of degrees of freedom in kinematic joints is 5. The weight (with added mass), the pulley and the drive are considered to be rigid bodies. A planar joint between the weight and the base (prismatic linkage), a revolute joint between the pulley and the base and a prismatic joint between the drive and the base (the movement of the drive is kinematically prescribed) are considered. In the case of asymmetric position the number of degrees of freedom in kinematic joints is 6. In the multibody model rigid body "cradle of pulley" and a revolute joint between the pulley and the cradle of pulley are added. The revolute joint between the pulley and the base is replaced by a revolute joint between the cradle of pulley and the base. Behaviour of this nonlinear system is investigated using the **alaska** simulation tool (Maißer et al., 1998).

4. Simulation and Experimental Results

As it has already been stated the simulations aim was to create a phenomenological model of a fibre. When looking for compliance of the results of experimental measurement with the results of simulation influences of the following system parameters are considered: the fibre stiffness, the fibre damping coefficient and the friction force acting between the weight and the prismatic linkage in which the weight moves.

Investigation of the (carbon) fibre properties eliminating the influence of the drive and of the pulley was an intermediate stage before the measurement on the stand (Polach et al., 2013a; Polach et al., 2013b). A phenomenological model dependent on the fibre stiffness, on the fibre damping coefficient and on the friction force acting between the weight and the prismatic linkage was the result of this investigation. When looking for the fibre model (Polach et al., 2013b) that would ensure the similarity of time histories of the weight displacement and time histories of the dynamic force acting in a fibre as high as possible a fibre stiffness and a fibre damping coefficient were considered to be constant in this phase of the fibre behaviour research. The friction force course (in dependence on the weight velocity) was considered nonlinear (basis for the determination of the friction force course was especially Půst et al., 2011 and Awrejcewicz & Olejnik, 2005). The phenomenological model of the fibre was determined, but only in dependence on the definite simulated test situation. The phenomenological model is not general, it is not suitable for the simulations of "quicker" tested situations (see Polach et al., 2013c; Polach et al., 2013d; Polach et al., 2013e; Polach et al., 2014) but general influences of individual parameters on the system behaviour, which are usable for all systems containing fibre-mass subsystem(s), were assessed.

"Starting" values at the phenomenological model creating are, identically with Polach et al. (2013a), fibre stiffness measured on a tensile testing machine ($94 \cdot 10^3$ N/m; see Polach et al., 2012b) and the fibre damping coefficient derived on the basis of experience (46.9 N·s/m). The "starting" friction force between the weight and the prismatic linkage is considered to be zero (Polach et al., 2013c).

Final values were calculated on the basis of the final values determined in Polach et al. (2013c) (stiffness = $34 \cdot 10^3$ N/m, damping coefficient = 27.5 N·s/m) (see Polach et al., 2013c; Polach et al., 2013d; Polach et al., 2013e; Polach et al., 2014). The friction force course determined at investigating the weight-fibre mechanical system (Polach et al., 2013a) with the angle of inclination of the inclined plane 30 degrees (see Fig. 2) was applied in the model of the weight-fibre-pulley-drive mechanical system (Polach et al., 2013c; Polach et al., 2013d; Polach et al., 2013e; Polach et al., 2014).

Results of experimental measurements and simulations of 6 selected tested situations are presented (altogether 43 situations were tested). Three tested situations at a "quicker" drive motion and three situations at a "slower" drive motion are presented in this paper (see time histories of drive motion in Fig. 3a, Fig. 4a, Fig. 5b and Fig. 7b). Frequencies of drive motion (i.e. frequencies of input signal) higher than 1 Hz are designated as "quicker" drive motions, frequencies of drive motion lower than 1 Hz are designated as "slower" drive motions.

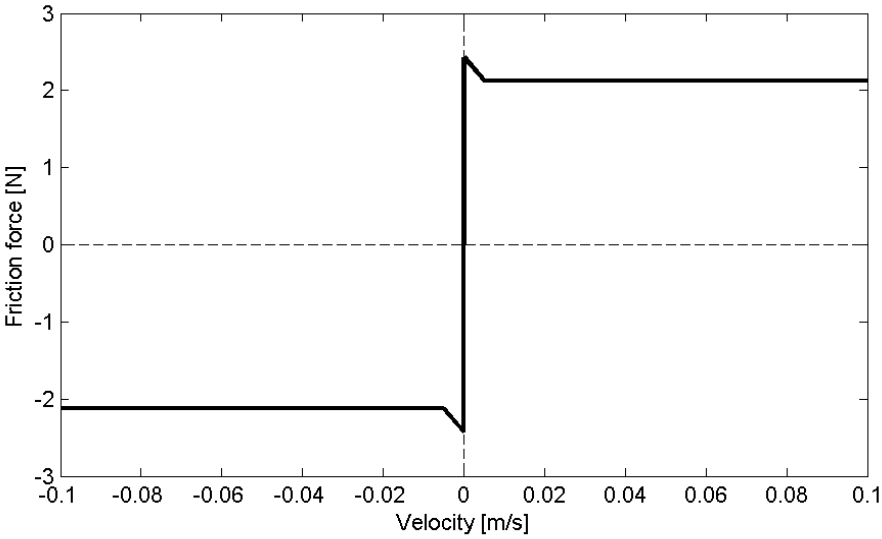


Fig. 2: Friction force acting between the weight and the prismatic linkage.

The influence of the fibre stiffness, the fibre damping coefficient and the friction force acting between the weight and the prismatic linkage on time histories of the weight displacement and also on time histories of the dynamic force acting in the fibre was evaluated partly visually and partly on the basis of the value of the correlation coefficient between the records of the experimental measurements and the simulation results. Application of the approach based on the calculation of the statistical quantities that enables to express directly the relation between two time series has appeared to be suitable for comparing two time series in various cases – e.g. Polach & Hajžman (2008), Polach et al. (2012c).

Correlation coefficient $R(\boldsymbol{p})$ (Rektorys et al., 1994) defined for two discrete time series $x^{(1)}$ (the time history recorded at experimental measurement) and $x^{(2)}(\boldsymbol{p})$ (the time history determined at simulation with the multibody model; function of investigated parameters $\boldsymbol{p}$) was calculated:

$$R(\boldsymbol{p}) = \frac{\sum_{i=1}^{n} \left(x_i^{(1)} - \mu_1\right) \cdot \left[x_i^{(2)}(\boldsymbol{p}) - \mu_2(\boldsymbol{p})\right]}{\sqrt{\sum_{i=1}^{n} \left(x_i^{(1)} - \mu_1\right)^2 \cdot \sum_{i=1}^{n} \left[x_i^{(2)}(\boldsymbol{p}) - \mu_2(\boldsymbol{p})\right]^2}} \;, \tag{1}$$

where μ_1 and $\mu_2(\boldsymbol{p})$ are mean values of the appropriate time series. The maximum value of the correlation coefficient is one. The more the compared time series are similar to each other the more the correlation coefficient tends to one. The advantage of the correlation coefficient is that it quantifies very well the similarity of two time series by scalar value, which is obtained using a simple calculation.

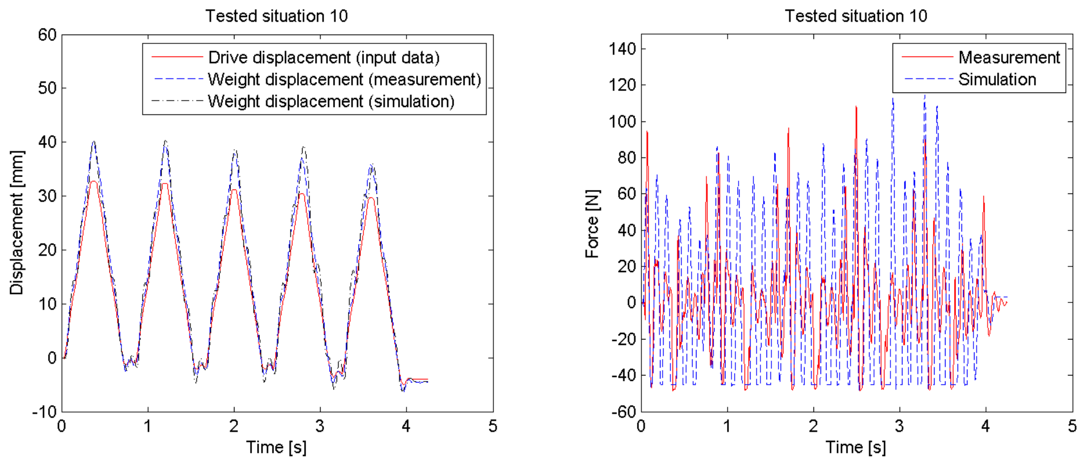
The problem is possible to put as the problem of the minimization of the objective function in the form

$$\psi(\boldsymbol{p}) = \left(1 - R(\boldsymbol{p})\right)^2 . \tag{2}$$

In case of the computer simulations in the **alaska 2.3** simulation tool, the whole process of the optimization was limited by the impossibility of executing the analysis from the statement line and evaluating the results of numerical simulations without the necessary human intervention. The whole process could not be automated. "Manual" change in the parameters on the basis of the chosen optimization method was the only solution. Comparing to automated optimization process it is not possible to perform so many iteration cycles in a short time. But the advantage is that during the evaluation it is possible to respect criteria that do not have to be strictly mathematically formulated (the coefficient of correlation given by relation (1) enables to imagine coincidence of (time) series, but it is not "universal").

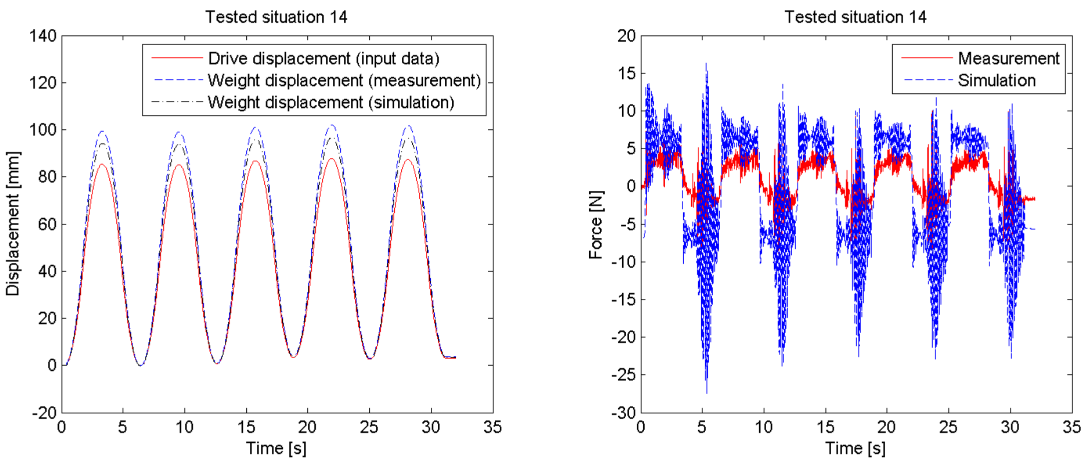
The monitored quantities at the experimental measurements and the computer simulations are presented in Figs 3 to 10. The values of correlation coefficient $R(\boldsymbol{p})$ were generally "better" for the values of parameters of the mechanical fibre-mass system model taken from Polach et al. (2013c) than for the "starting" values of parameters in all the investigated cases (see Polach et al., 2013c; Polach et al., 2013d; Polach et al., 2014).

General pieces of knowledge from investigating the weight-fibre-pulley-drive system, independently of the combination of the position of the weight with respect to the plane of the drive-pulley symmetry (symmetric or asymmetric) and of the mass of the weight (without or with added mass), are similar (see Polach et al., 2013c; Polach et al., 2013d; Polach et al., 2013e; Polach et al., 2014).



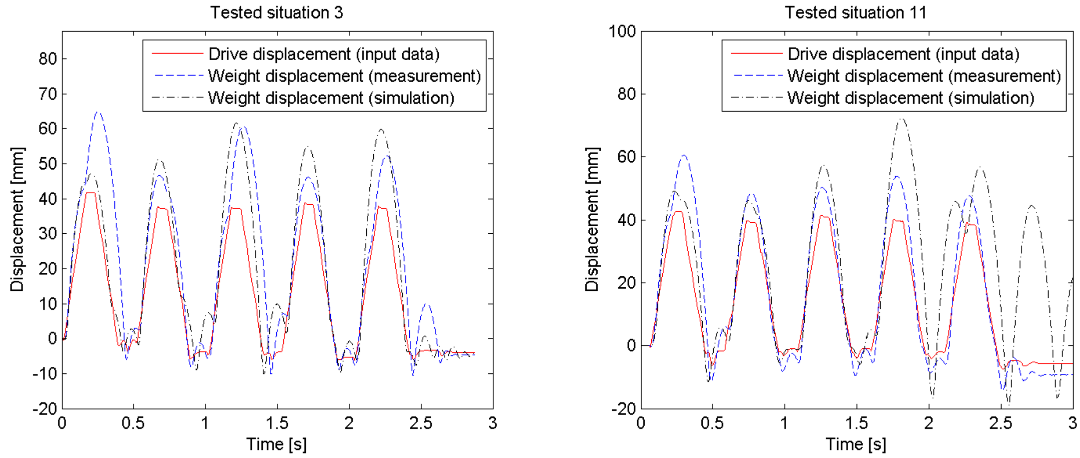
a) *b)*

Fig. 3: Time histories at a "quicker" tested situation (asymmetric position of the weight, the weight with added mass), a) weight displacement, b) dynamic force acting in a fibre. (taken from Polach et al., 2014).



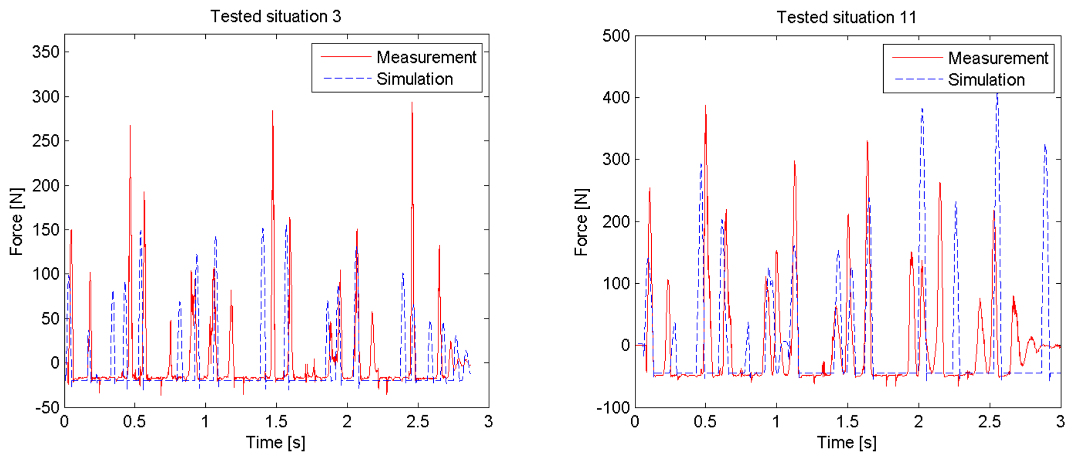
a) *b)*

Fig. 4: Time histories at a "slower" tested situation (asymmetric position of the weight, the weight with added mass), a) weight displacement, b) dynamic force acting in a fibre. (taken from Polach et al., 2014).



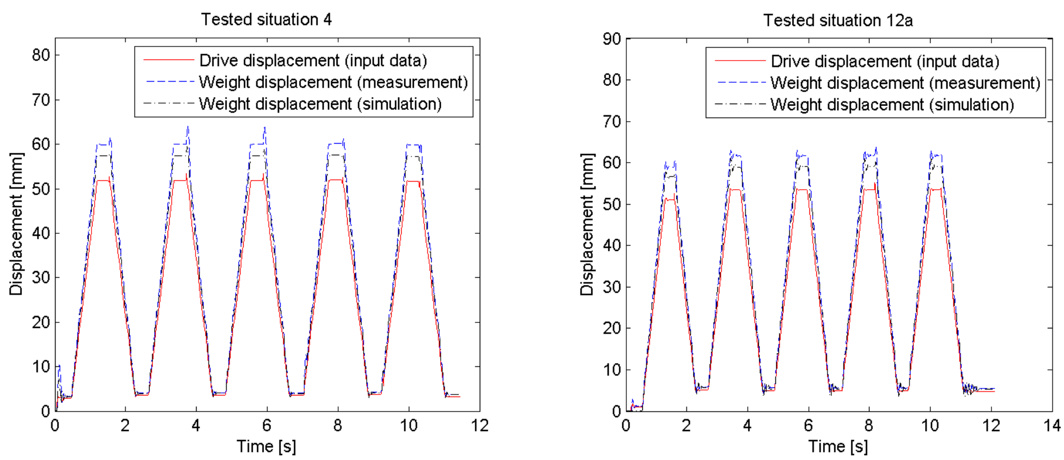
a) *b)*

Fig. 5: Time histories of the weight displacement at "quicker" tested situations (asymmetric position of the weight), influence of the mass of the weight, a) situation 3 (weight without added mass – taken from Polach et al., 2013d), b) situation 11 (weight with added mass – taken from Polach et al., 2014).



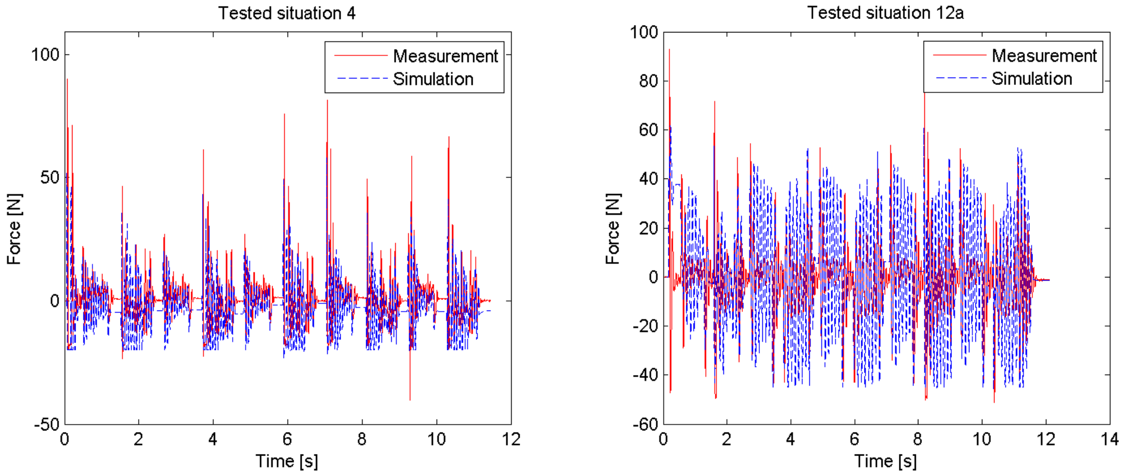
a) *b)*

Fig. 6: Time histories of the dynamic force acting in a fibre at "quicker" tested situations (asymmetric position of the weight), influence of the mass of the weight, a) situation 3 (weight without added mass – taken from Polach et al., 2013d), b) situation 11 (weight with added mass – taken from Polach et al., 2014).



a) *b)*

Fig. 7: Time histories of the weight displacement at "slower" tested situations (asymmetric the position of the weight), influence of the mass of the weight, a) situation 4 (weight without added mass – taken from Polach et al., 2013d), b) situation 12a (weight with added mass – taken from Polach et al., 2014).



a) *b)*

Fig. 8: Time histories of the dynamic force acting in a fibre at "slower" tested situations (asymmetric position of the weight), influence of the mass of the weight, a) situation 4 (weight without added mass – taken from Polach et al., 2013d), b) situation 12a (weight with added mass – taken from Polach et al., 2014).

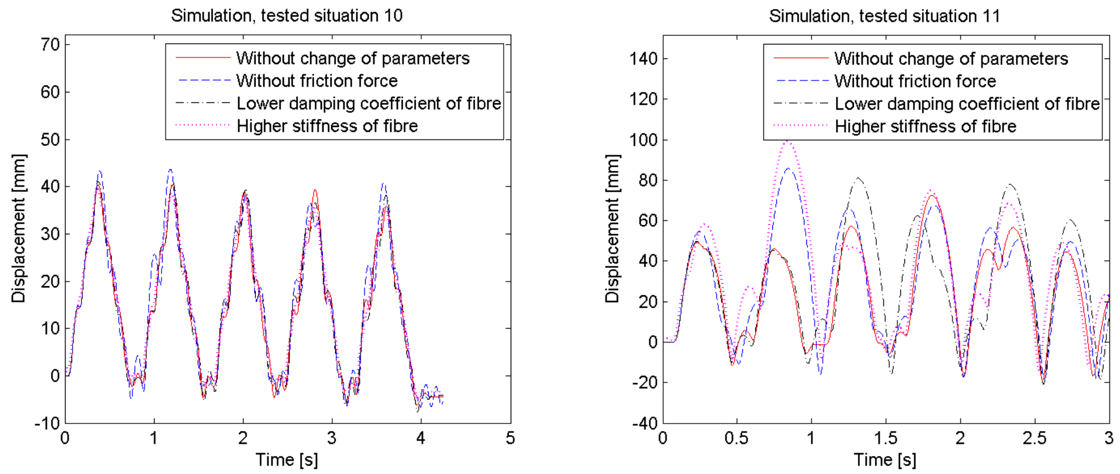


Fig. 9: Time histories of the weight displacement at "quicker" tested situations (asymmetric position of the weight, the weight with added mass), influences of model parameters. (taken from Polach et al., 2014).

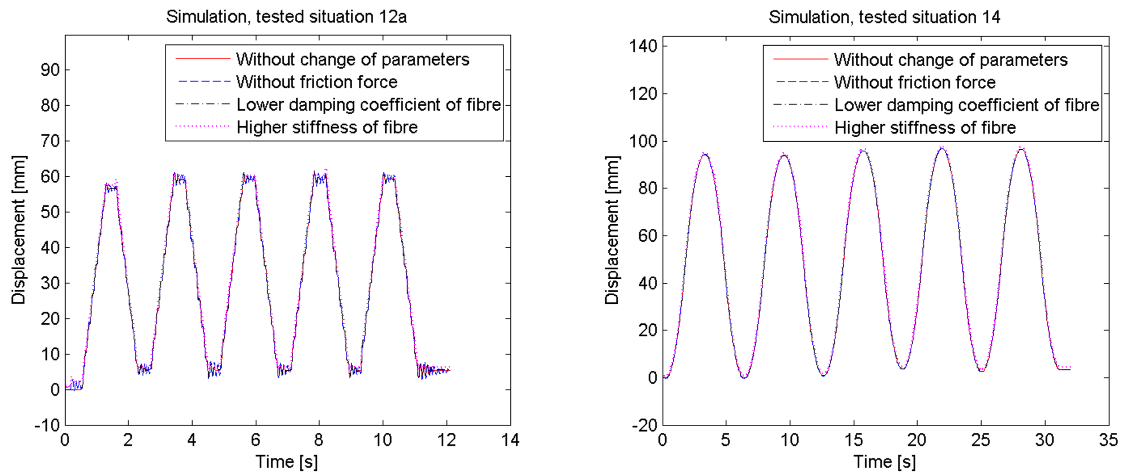


Fig. 10: Time histories of the weight displacement at "slower" tested situations (asymmetric position of the weight, the weight with added mass), influences of model parameters. (taken from Polach et al., 2014).

The highest frequency of drive motion (i.e. the highest frequency of input signal) at investigation of the weight-fibre-pulley-drive system is 2 Hz (see Fig. 5 and Fig. 6). This frequency of drive motion is much lower than natural frequencies of the computer model of linearized system in an equilibrium position. Natural frequency corresponding to the weight vibrations of the system with weight without added mass is 25 Hz and natural frequency of the system with weight with added mass is 15.25 Hz. It means that in case of weigh vibration at "quicker" tested situations the excitation of resonant vibrations is not concerned, but vibrations that are given by strongly nonlinear behaviour of a fibre (as it has been already stated, fibres are able to transfer only tensile force, in "compression" they are not able to transfer any force), which can even have the character of chaos, are involved.

Time histories of the weight displacement recorded at the experimental measurements and computed at the computer simulations at "slower" tested situations are approximately identical (see Fig. 4a and Fig. 7b). Unlike the weight displacement at symmetric position with respect to the vertical plane of the drive-pulley symmetry (Polach et al., 2013c; Polach et al., 2013e) the local extremes are not of the same magnitude (Polach et al., 2013d; Polach et al., 2014). The cause of differences in local extremes of time histories of the weight displacement was (probably) an incorrect calibration of a dial gauge used for the measurement of weight displacement (the differences occurred in all cases at the investigation of the weight-fibre-pulley-drive system, at which the position of the weight was asymmetric with respect to the plane of a drive-pulley symmetry (Polach et al., 2013d; Polach et al., 2014); at measurements at which the position of the weight was symmetric this problem has not occurred (Polach et al., 2013c; Polach et al., 2013e)). But this fact cannot be 100% verified because immediately after the measurement the experimental stand was dismounted. At simulating the experimental measurements at the "slower" drive motion the monitored time histories of the weight displacement are identical independently of the fibre stiffness, the fibre damping coefficient and the friction force (between the weight and the prismatic linkage) – see Fig. 10.

At the "quicker" tested situations the measured and the computed time histories of the weight displacement are of the same character (see Fig. 3a and Fig. 5). At simulating the experimental measurements at "quicker" drive motion the local extremes of the monitored time histories of the weight displacement are dependent on all the phenomenological model parameters (i.e. on the fibre stiffness, the fibre damping coefficient and the friction force) – see Fig. 9.

At all the simulations when changing the computational model the time histories of dynamic force acting in the fibre are different (more or less) but their character remains the same. From Fig. 3b, Fig. 4b, Fig. 6 and Fig. 8 it is evident that time histories of dynamic force acting in the fibre are not suitable for searching for the parameters of the fibre phenomenological model. It follows from the fact, that the phenomenological model of fibre is to cover, as it has been stated, e.g. influences of fibre transversal vibration, "jumping" from pulley etc. As it does not include those phenomena physically (but by the change in the already introduced model parameters), it is evident, that it is not possible to expect that the introduced time histories of dynamic force acting in fibre will be of the same course.

Time histories of the monitored quantities at tested situation, at which the weight was without added mass, and at tested situation, at which the weight was with added mass, given in Fig. 5 and Fig. 6, were recorded at identical drive motion. Similarly, time histories given in Fig. 7 and Fig. 8 were recorded at other identical drive motion. As to the influence of the added mass to the weight on the experimental measurements and computer simulations results, a higher mass is manifested in higher magnitudes of time histories of the weight displacement at the "quicker" situations (see Fig. 5). At the "slower" situations a higher mass of the weight does not influence the magnitudes of time histories of the weight displacement in any way (see Fig. 7). The added mass of the weight is shown in higher magnitudes of dynamic forces acting in the fibre independently of the input signal rate (see Fig. 6 and Fig. 8).

From the obtained results it is evident that parameters of the fibre phenomenological model must be, in addition, considered dependent on the speed of the weight motion (i.e. simultaneously on the input signal rate).

For searching for the parameters of the fibre phenomenological model it is necessary to use the results of experimental measurements with the "quicker" drive motion. The possibility of performing experimental measurements with other time histories of drive motion or with a different geometrical arrangement of the experimental stand will be analysed.

5. Conclusions

The approach to the fibre modelling based on the force representations was utilised for the investigation of the motion of the weight in the weigh-fibre-pulley-drive mechanical system. The simulation aim is to create a phenomenological model of the fibre, which will be utilizable in fibre modelling in the case of more complicated mechanical or mechatronic systems. The created phenomenological model is assumed to be dependent on the fibre stiffness and on the fibre damping coefficient.

Development of the fibre phenomenological model will continue. From the obtained results it is evident that parameters of the fibre phenomenological model must be, in addition, considered dependent on the speed of the weight motion. The question is if it is possible to create the phenomenological model like that.

In addition it must be stated that the model of the fibre-pulley contact appears to be problematic in the computational model.

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