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Influence of the mass of the weight on the dynamic response of the asymmetric laboratory fibre-driven mechanical system

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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 is asymmetric with respect to the vertical plane of drive-pulley symmetry. 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 a multibody model. The influence of the mass of the weight and the influence of the weight asymmetry on the coincidence of results of experimental measurements and the simulations results are 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, experiment, computer simulations

1. Introduction

The replacement of the chosen rigid elements of manipulators or mechanisms by fibres or cables [3] 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. [7, 30]) in the course of a motion.

Experimental measurements focused on the investigation of the fibre behaviour were performed on an assembled weigh-fibre-pulley-drive system [20, 21, 24]. A 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 drive-pulley symmetry (in presented case asymmetric position is considered, see Fig. 1). It is possible to add an extra mass to the weight (in presented case the added mass is considered). The same system is numerically investigated using a multibody model created in the *alaska* simulation tool [14]. 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

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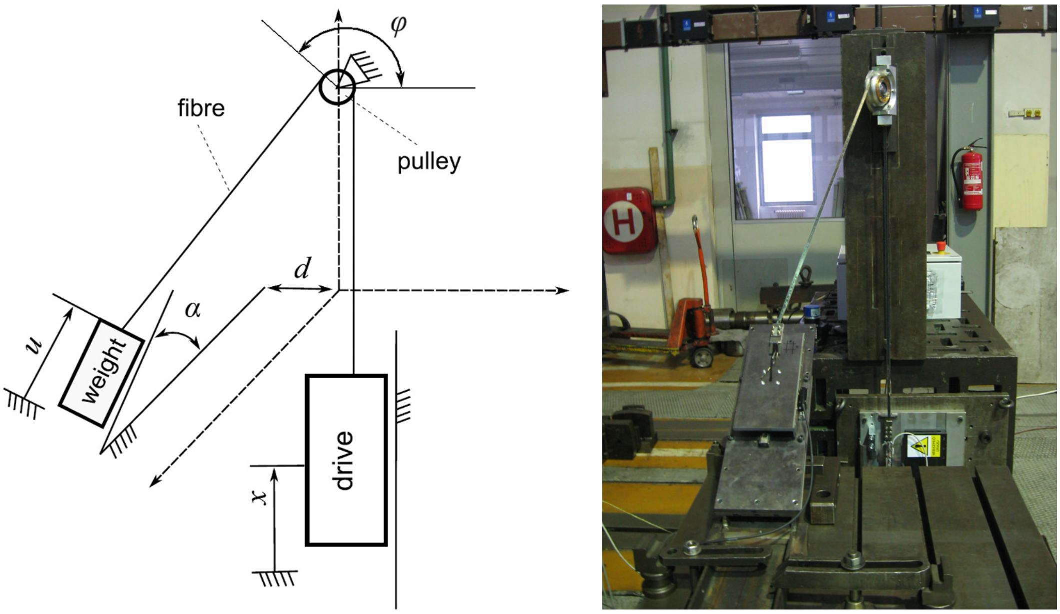


Fig. 1. Scheme and a real weight-fibre-pulley-drive mechanical system with asymmetric position of the weight

modelling in the case of more complicated mechanical or mechatronic systems. A spherical tilting mechanism named QuadroSphere (see Fig. 2) is an example of such a mechatronic system, at which the phenomenological computational model of fibre will be utilized. The QuadroSphere is a mechanism with a spherical motion of a platform and accurate measurement of its position. The platform position is controlled by four fibres; each fibre is guided by a pulley from linear guidance to the platform (see Fig. 3).

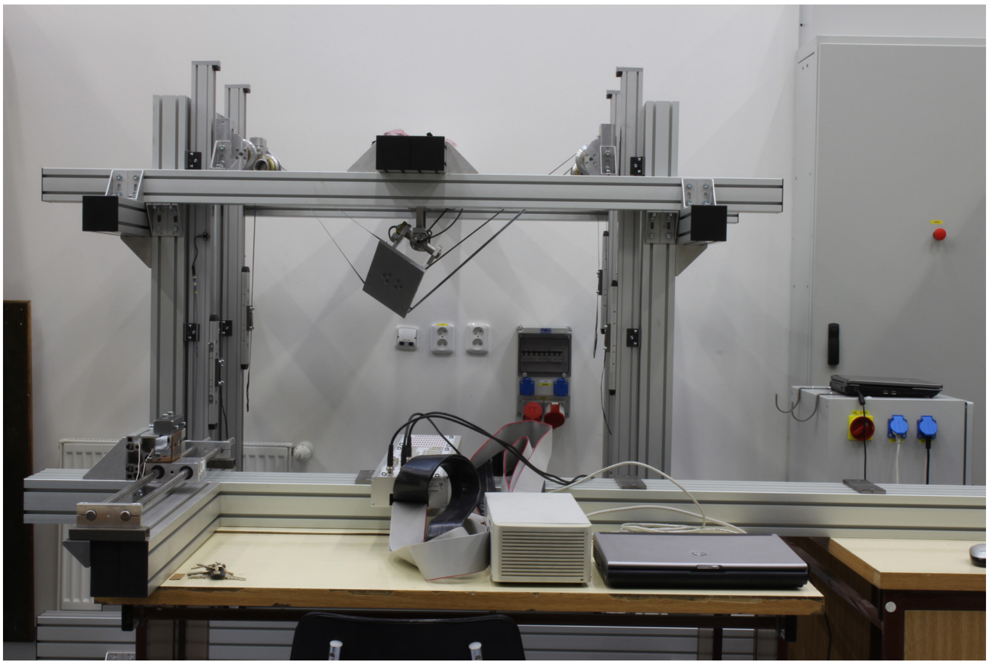


Fig. 2. The QuadroSphere spherical tilting mechanism

Fig. 3. Detail of the QuadroSphere platform

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 [18] and [19]. The paper continues investigating the weight-fibre-pulley-drive system given in [20] and [24] where the position of the weight was symmetric with respect to the plane of a drive-pulley symmetry, and in [21], where the position of the weight was asymmetric and the weight was without added mass.

2. Experimental stand

Originally it was supposed that for the experimental measurement focused on determining the phenomenological model 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. [17]). 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 [22].

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. [22]) 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 [20, 24] or asymmetric [21] with respect to the vertical plane of drive-pulley symmetry (as it has been already mentioned asymmetric position is considered in this paper). 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 (as it has been already mentioned the added mass is considered in this paper). The angle of inclination of the inclined plane could be changed (in this case the angle is $\alpha = 30.6$ degrees and the pulley-fibre angle is $\varphi = 124$ 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 [15]. 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 [9] should be based on considering the fibre flexibility and suitable approaches can be based on the flexible multibody dynamics (see e.g. [6, 28]). 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 [8]. Comprehensive reviews of these approaches can be found in [28] or in [31]. Further development together with other multibody dynamics trends was introduced in [27]. Details of multibody formalisms and means of the creation of equations of motion can be found e.g. in [1, 29].

The simplest way how to incorporate fibres in equations of motion of a mechanism is the force representation of a fibre (e.g. [4]; the massless fibre model). 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. [11, 33]). The fibre-mass system fulfils all requirements for modelling the fibre using the force representation of a fibre. A more precise approach is based on the representation of the fibre by means of a point-mass model (e.g. [12]). It has the advantage of a lumped point-mass model. The point masses can be connected by forces or constraints. In order to represent bending behaviour of fibres their discretization using the finite segment method [28] or so called rigid finite elements [32] is possible. Standard multibody codes (SIMPACK, MSC.ADAMS, alaska etc.) can be used for this purpose. Other more complex approaches can utilize nonlinear three-dimensional finite elements [5] or can employ the absolute nodal coordinate formulation (ANCF) elements [6, 10, 13, 28].

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 the pulley etc. The weight (with added mass), the pulley, the cradle of pulley and the drive are considered to be rigid bodies [21]. The number of degrees of freedom in kinematic joints is 6. A planar joint between the weight and the base (prismatic linkage), a revolute joint between the cradle of pulley and the base, a revolute joint between the pulley and the cradle of pulley and a prismatic joint between the drive and the base (the movement of the drive is kinematically prescribed) are considered. Behaviour of this nonlinear system is investigated using the *alaska* simulation tool [14].

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 simulation results 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 [18, 19]. 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 [18] 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 fibre stiffness and 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 [2, 25]). A general phenomenological model of the fibre (at "quicker" tested situation [20, 21, 24]) was not determined, but general influences of individual parameters on the system behaviour, which are usable for all systems containing fibre-mass subsystem(s), were assessed. A suitable fibre model, but only in dependence on the definite simulated test situation, was determined.

"Starting" values at the phenomenological model creating are, identically with [19], fibre stiffness measured on a tensile testing machine [22] ($94 \cdot 10^3$ N/m) and fibre damping coefficient derived on the basis of experience ($46.9\ \mathrm{N \cdot s/m}$). The "starting" friction force between the weight and the prismatic linkage is considered to be zero [20].

Final values were calculated on the basis of the final values determined in [20] and are the same as in [20, 21] and [24] (stiffness $= 34 \cdot 10^3$ N/m, damping coefficient $= 27.5\ \mathrm{N \cdot s/m}$). Friction force course determined at investigating the weight-fibre mechanical system [19] with the angle of inclination of the inclined plane $\alpha = 30$ degrees (see Fig. 4) was applied in the model of the weight-fibre-pulley-drive mechanical system [20, 21, 24].

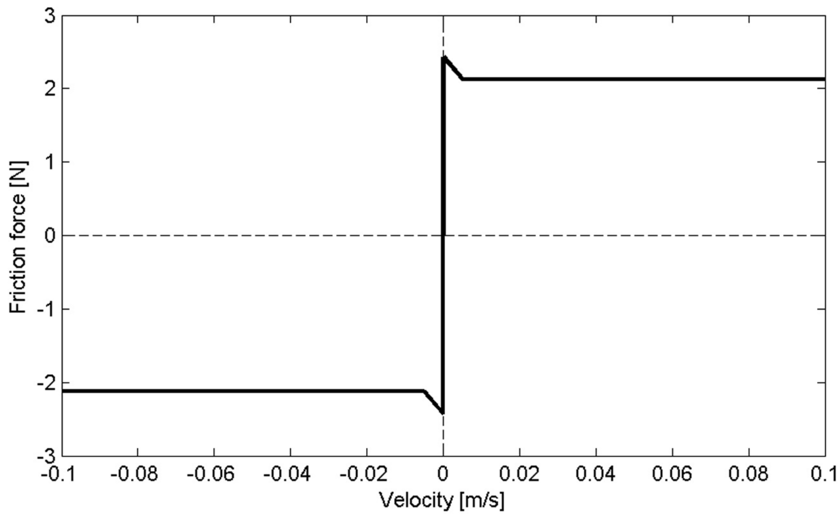


Fig. 4. Friction force acting between the weight and the prismatic linkage

Results of experimental measurements and simulations of four tested situations are presented (altogether twelve situations were tested). Two tested situations at a "quicker" drive motion (situations 10 and 11) and two situations at a "slower" drive motion (situations 12a and 14) are presented in this paper (see time histories of drive motion in Figs. 5, 8b and 11b). Frequencies of drive motion (i.e. frequencies of input signal) higher than 1 Hz are designated as "quicker" drive motions, frequency of drive motion lower than 1 Hz are designated as "slower" drive motions.

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. [16, 23].

Correlation coefficient $R(p)$ [26] defined for two discrete time series $x^{(1)}$ (the time history recorded at experimental measurement) and $x^{(2)}(p)$ (the time history determined at simulation with the multibody model; function of investigated parameters p) was calculated

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

where μ_1 and $\mu_2(p)$ 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 be put as the problem of the minimization of the objective function in the form

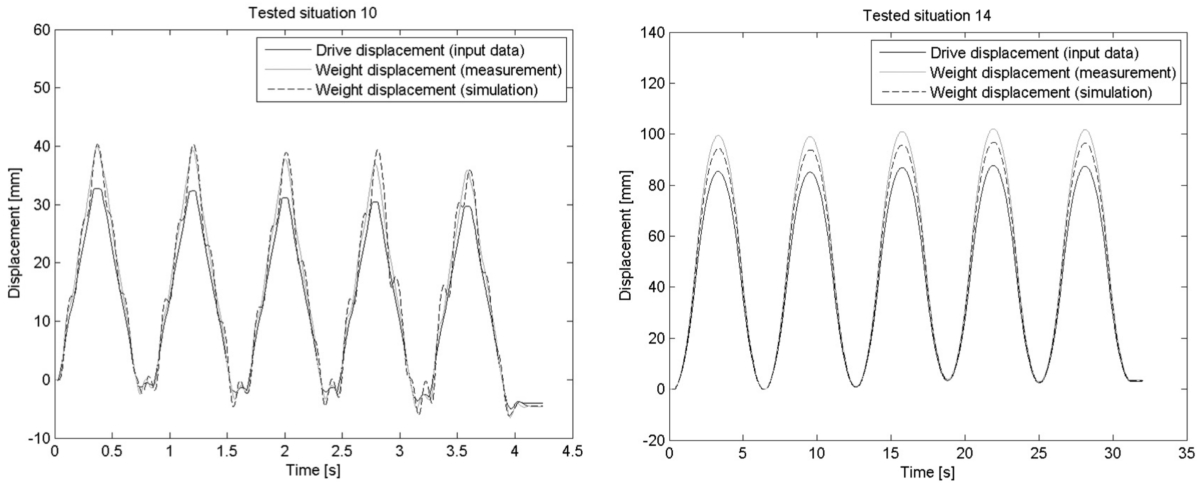
$$\psi(p) = (1 - R(p))^2. \tag{2}$$

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. 5 to 16. In Table 1 there are values of correlation coefficient $R(p)$ for the "starting" values of parameters and for the values of parameters of the mechanical fibre-mass system model taken from [20].

Table 1. Values of correlation coefficient $R(p)$ [–]

Tested situation	Shape of an input signal	Comparison of time histories of the weight displacement		Comparison of time histories of dynamic force acting in a fibre	
		"Starting" value	Final value	"Starting" value	Final value
10	trapezoidal	0.999 300	0.991 8	0.054 69	0.546 9
11	trapezoidal	0.006 408	0.746 5	0.121 60	0.285 3
12a	trapezoidal	0.999 900	0.999 4	0.010 47	0.499 0
14	quasi-sinusoidal	1.000 000	1.000 0	0.032 60	0.830 6



a) b)

Fig. 5. Time histories of the weight displacement, a) at "quicker" tested situation 10, b) at "slower" tested situation 14

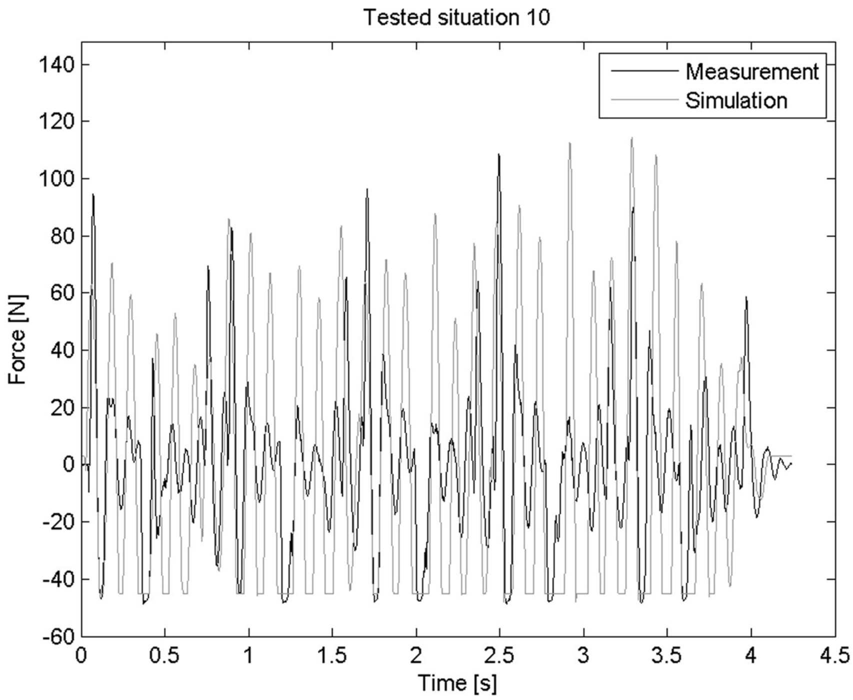


Fig. 6. Time histories of the dynamic force acting in a fibre at "quicker" tested situation 10

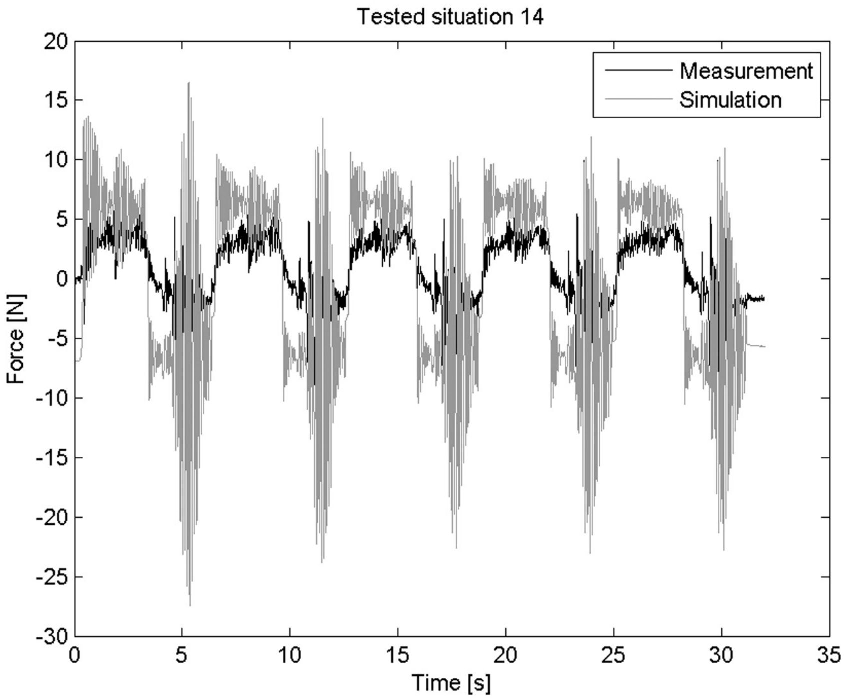
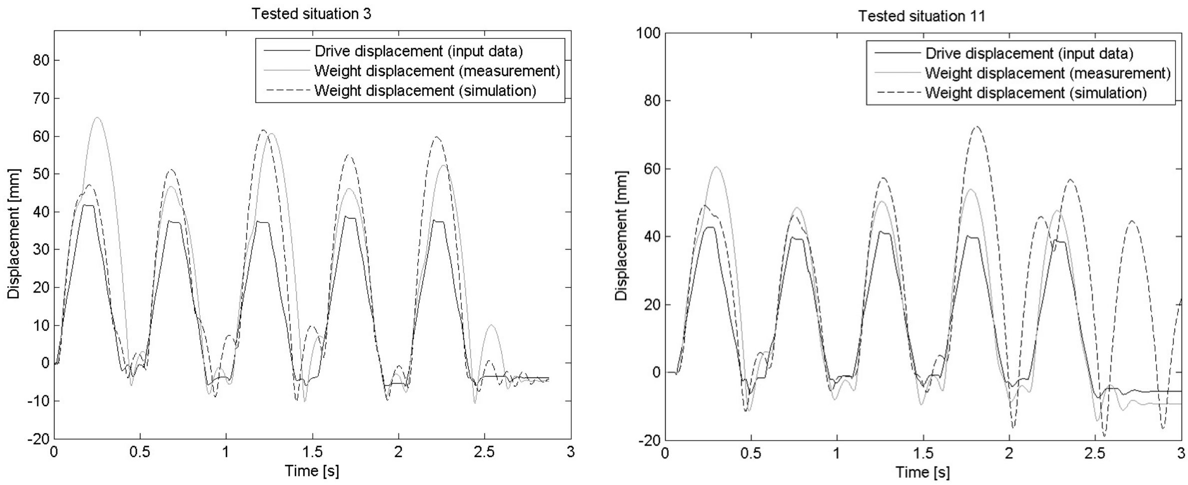


Fig. 7. Time histories of the dynamic force acting in a fibre at "slower" tested situation 14



a) b)

Fig. 8. Time histories of the weight displacement at "quicker" tested situations, influence of the mass of the weight, a) situation 3 (weight without added mass — taken from [21]), b) situation 11 (weight with added mass)

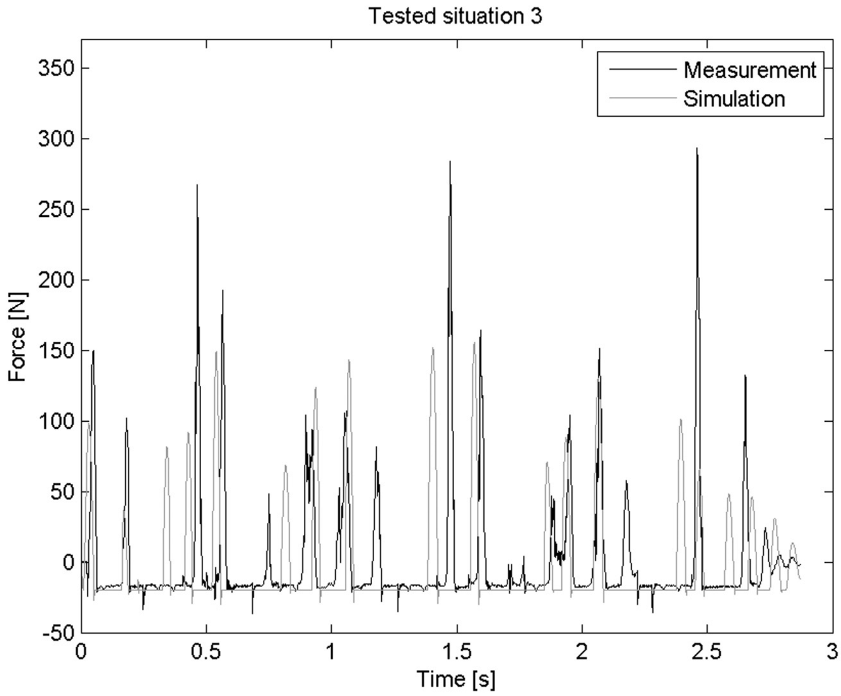


Fig. 9. Time histories of the dynamic force acting in a fibre at “quicker” tested situation 3, weight without added mass (taken from [21]), influence of the mass of the weight

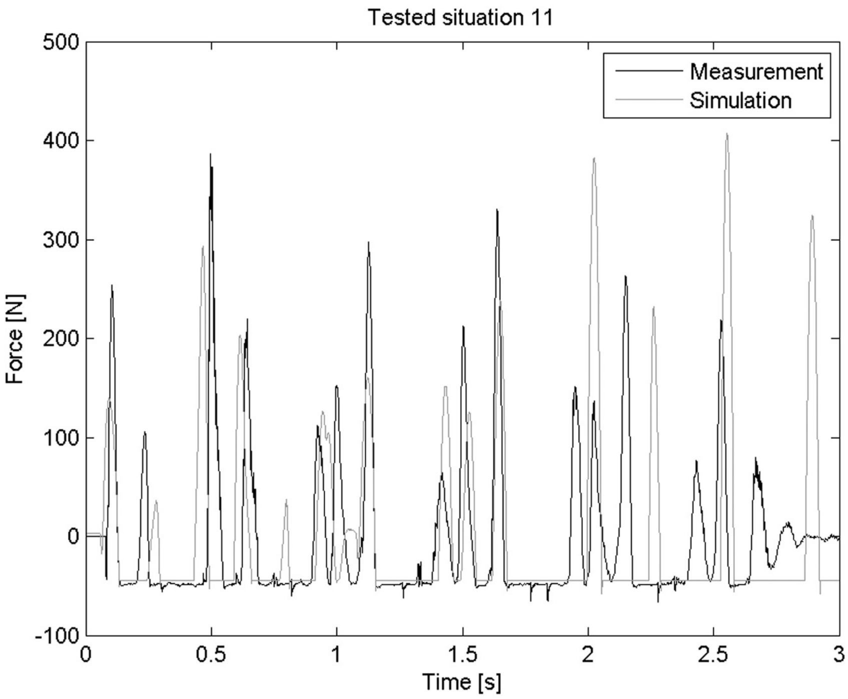
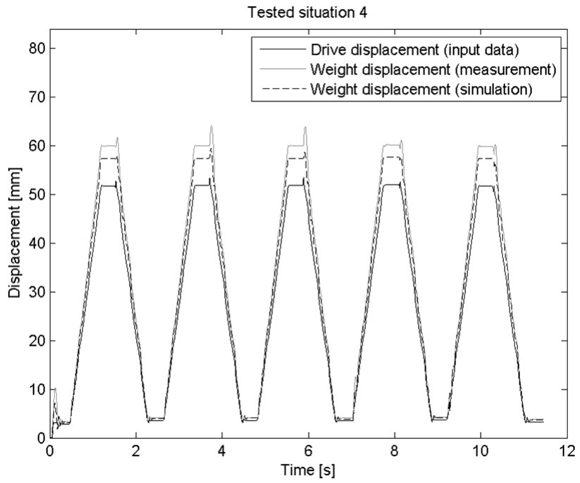
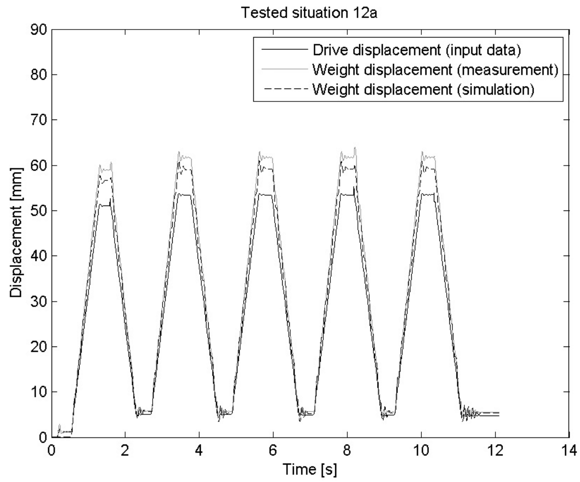


Fig. 10. Time histories of the dynamic force acting in a fibre at “quicker” tested situation 11, weight with added mass, influence of the mass of the weight



a)



b)

Fig. 11. Time histories of the weight displacement at "slower" tested situations, influence of the mass of the weight, a) situation 4 (weight without added mass — taken from [21]), b) situation 12a (weight with added mass)

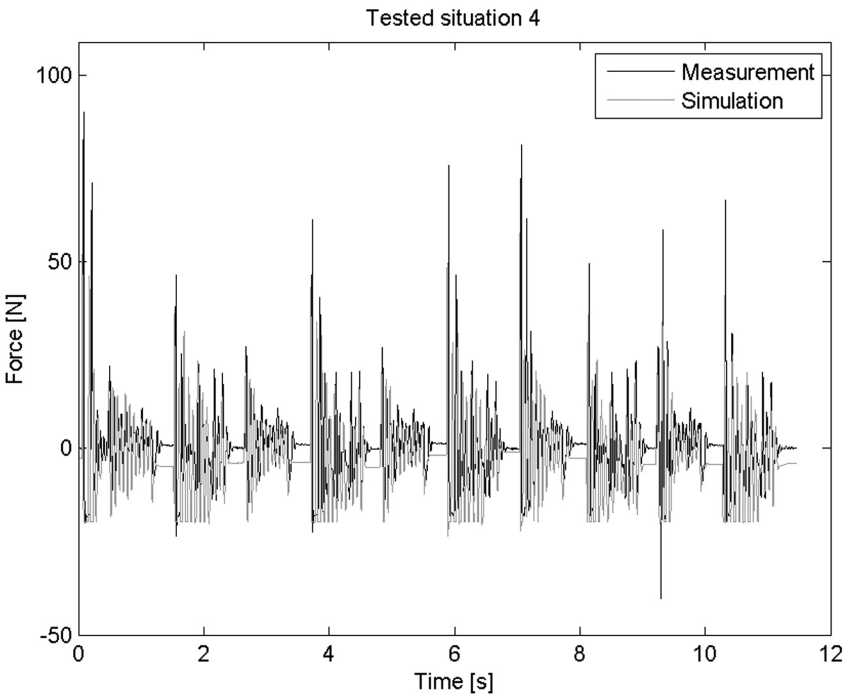


Fig. 12. Time histories of the dynamic force acting in a fibre at "slower" tested situation 4, weight without added mass (taken from [21]), influence of the mass of the weight

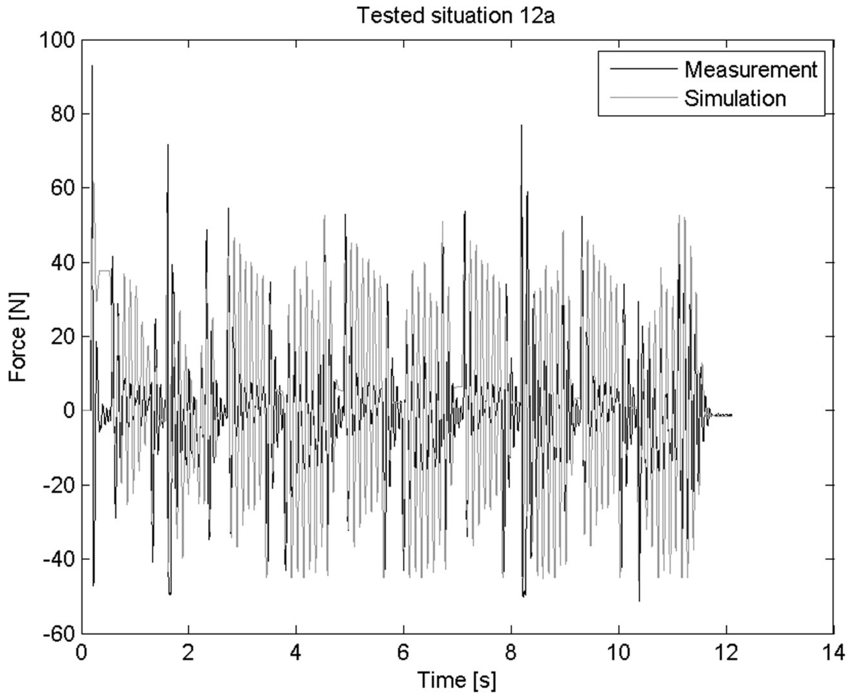


Fig. 13. Time histories of the dynamic force acting in a fibre at "slower" tested situation 12a, weight with added mass, influence of the mass of the weight

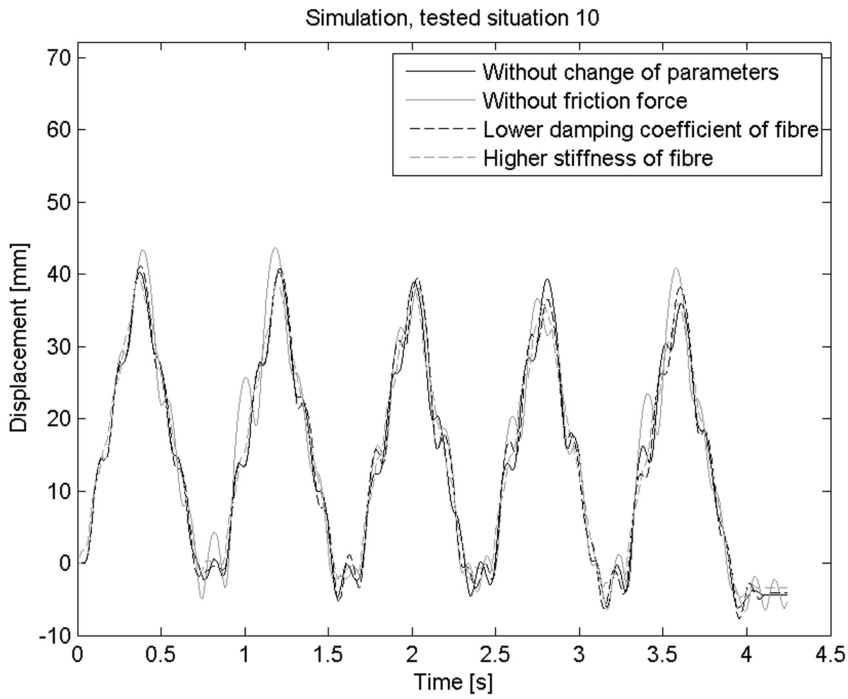


Fig. 14. Time histories of the weight displacement at "quicker" tested situation 10, influence of model parameters

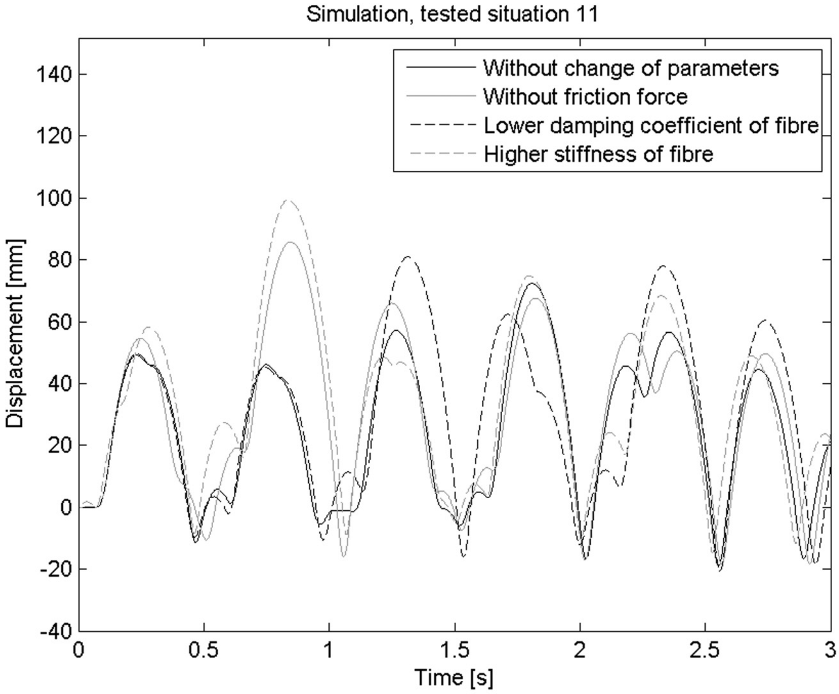
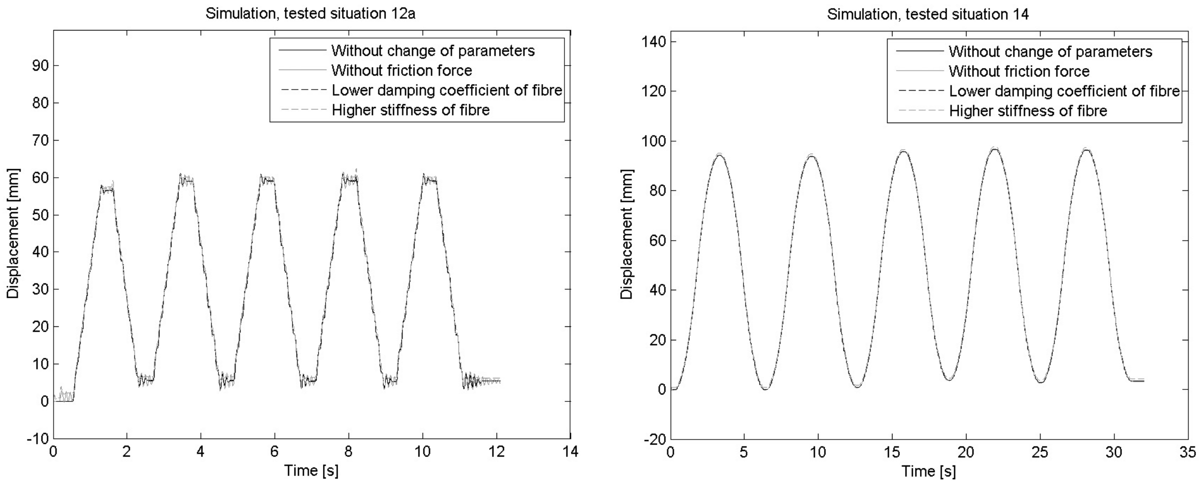


Fig. 15. Time histories of the weight displacement at "quicker" tested situation 11, influence of model parameters



a) b)

Fig. 16. Time histories of the weight displacement at "slower" tested situations, influence of model parameters, a) situation 12a, b) situation 14

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 situations 3 and 11 (see Figs. 8 to 10). 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.

In Figs. 5a and 6 there are given time histories of monitored quantities at tested situation 10. Though this situation is specified as a “quicker” one, it still is not a typical “quicker” situation. In the record of time histories of the weight displacement in Fig. 5a the results of the measurement and that of the simulation seem to be identical, but in reality they are influenced by the parameters of the phenomenological model, with which the simulation had been performed (see the following paragraph). Time histories of the dynamic force acting in a fibre in Fig. 6, determined at measurement and using the simulation, are of the same character. 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 14 are shown in Figs. 5b and 7. A typical “slower” situation is concerned. In the record of time histories of the weight displacement in Fig. 5b measurement and simulation results seem to be more different than at simulating “quicker” situation 10 mentioned in the previous paragraph. The cause of differences in local extremes of deflections 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 [21]; at measurements at which the position of the weight was symmetric this problem has not occurred [20, 24]). But this fact cannot be 100 % verified because immediately after the measurement the experimental stand was dismounted. Time histories of the dynamic force acting in the fibre in Fig. 7, determined at measurement and using the simulation, are of the same character. The reason of different course of time histories of the dynamic force acting in the fibre is the same as in the case of tested situation 10. The character of time histories of the dynamic force acting in the fibre shown in Fig. 7 is seemingly visually more different than the character of time histories of the dynamic force acting in the fibre shown in Fig. 6. But it is necessary to realize that lower magnitudes of the dynamic force by orders are concerned.

Time histories of the weight displacement at “quicker” tested situation 3, at which the weight was without added mass [21], and at tested situation 11, at which the weight was with added mass are shown in Fig. 8. An identical drive motion was used at those tested situations. Similarly, time histories of the weight displacement at “slower” tested situation 4, at which the weight was without added mass [21], and at tested situation 12a, at which the weight was with added mass, are shown in Fig. 11. At those tested situations an identical drive motion was also used. Figs. 9, 10, 12 and 13 show time histories of dynamic force acting in fibre for those identical tested situations. As to the influence of the added mass to the weight on the experimental measurements and computer simulations results, a higher mass is shown in higher magnitudes of time histories of the weight displacement at the “quicker” situations (see Fig. 8). 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. 11). The added mass of the weight is shown in higher magnitudes of dynamic forces acting in the fibre independently of the input signal rate. The higher the mass of the weight the higher the influence of the input signal rate (see Figs. 8 to 10, 12 and 13).

Time histories of the weight displacement given in Figs. 14 to 16 inform about the influence of the change in the phenomenological model parameters (i.e. the fibre stiffness, the fibre damping coefficient and the friction force) on the course of these time histories. When finding out the influence of individual parameters value of only one parameter was changed, other ones remained unchanged. “Starting” value (already mentioned in this paper) was used as the parameter changed value. From Fig. 16 it is evident that 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). At the “quicker” tested situations (10 and 11) the measured and computed time histories of the weight displacement are of the same character (see Figs. 5a and 8b). At simulating the experimental measurements at “quicker” drive motion (see Figs. 14 and 15) 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). All findings given in this paragraph correspond to the results obtained in previous investigation of the weight-fibre-pulley-drive [20, 21, 24].

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 (the same finding as in [20, 21] again). From Figs. 6, 7, 10, and 13 and Table 1 it is evident that time histories of dynamic force acting in the fibre are less suitable for searching for the parameters of the fibre phenomenological model.

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. on the input signal rate).

For searching for the parameters of the fibre phenomenological model it would be useful to perform more experimental measurements with the “quicker” drive motion. In reality the “quicker” drive motion is limited on the one hand by its parameters (limited amplitudes of the drive displacements and limited drive speed) and on the other hand by the danger of the weight “flinging out” of the prismatic linkage (during one test measurement at a higher drive speed it really occurred). 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. Conclusion

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 a 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, on the fibre damping coefficient and on the friction force acting between the weight and the prismatic linkage in which the weight moves.

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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