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MODELLING OF DYNAMIC BEHAVIOUR OF FIBRES AND CABLES

Polach P.[*], Hajžman M.[**], Bulín R.[***]

Abstract: *In this paper there are presented some possible approaches suitable for the modelling of the fibre and cable dynamics in the framework of various mechanical systems: force representation of a fibre, a point-mass model and an absolute nodal coordinate formulation. Experimental measurements focused on the investigation of the fibre behaviour were performed on the assembled weight-fibre and weight-fibre-pulley-drive laboratory mechanical systems. These mechanical systems were modelled using some of the mentioned methods and simulations of the experimental measurements were performed. The simulations aim was to create a phenomenological model of a fibre (cable). The obtained results are discussed.*

Keywords: Fibre, Dynamic System, Phenomenological model, Experiment, Simulation.

1. Introduction

Fibres and cables can play an important role in designs of many machines. One of the most interesting applications is replacing the chosen rigid elements of a manipulator or a mechanism with fibres (cables). The main advantage of this design is the achievement of a lower moving inertia, which leads to a higher mechanism speed and lower production costs. Drawbacks can be related to the fact that fibres (cables) should be only in tension in the course of a motion. In this paper there are summarized possible approaches suitable for the modelling of fibre and cable dynamics in the framework of various mechanical systems and presented approaches of the modelling of a real fibre supported by validation with the results of experimental measurements.

Fibres and cables are used especially in the parallel kinematic mechanisms (e.g. Fahham et al., 2010; Taghirad et al., 2011). Cable-driven variants of the parallel kinematic mechanisms have further advantages, viz. a large range of motion, the possibility of antibacklash property (e.g. Agrawal et al., 2010) and an easy reconfiguration. Typical disadvantages of the fibre-driven parallel kinematic mechanisms are a relatively narrow frequency bandwidth of their feedback motion control and problems with the accurate positioning of an end-effector. A promising research development in solving these problems is the concept of multi-level mechanisms with a hierarchic structure composed of a parallel cable-driven mechanism for large and slow motions and an active structure connected to the mechanism platform for low and high frequency motions (Duan et al., 2011; Polach et al., 2018). The example of these mechanisms is QuadroSphere (e.g. Polach et al., 2014; see Fig. 1 left). The QuadroSphere is a tilting mechanism with a spherical motion of a platform and an accurate measurement of its position. Its position is controlled by four fibres; each fibre is guided by a pulley from linear guidance to the platform.

Experimental measurements focused on the investigation of the fibre behaviour were performed in two steps: on the assembled weight-fibre (e.g. Polach et al., 2014; see Fig. 2) and on the assembled weight-fibre-pulley-drive laboratory mechanical systems (e.g. Polach et al., 2018; see Fig. 3). The weight in these systems can be considered to be the end-effector. The aim of simulations of the experimental measurements was to create a phenomenological model of a fibre.

[*] Dr. Ing. Pavel Polach: Research and Testing Institute Plzeň; Tylova 1581/46; 301 00, Plzeň; CZ, polach@vzuplzen.cz; New Technologies for the Information Society, University of West Bohemia; Univerzitní 8; 306 14, Pilsen; CZ, ppolach@ntis.zcu.cz

[**] Assoc. Prof. Michal Hajžman, PhD.: Research and Testing Institute Plzeň; Tylova 1581/46; 301 00, Pilsen; CZ, hajzman@vzuplzen.cz; New Technologies for the Information Society, University of West Bohemia; Univerzitní 8; 306 14, Plzeň; CZ, mhajzman@kme.zcu.cz

[***] Ing. Radek Bulín, PhD.: New Technologies for the Information Society, University of West Bohemia; Univerzitní 8; 306 14, Pilsen; CZ, rbulin@ntis.zcu.cz

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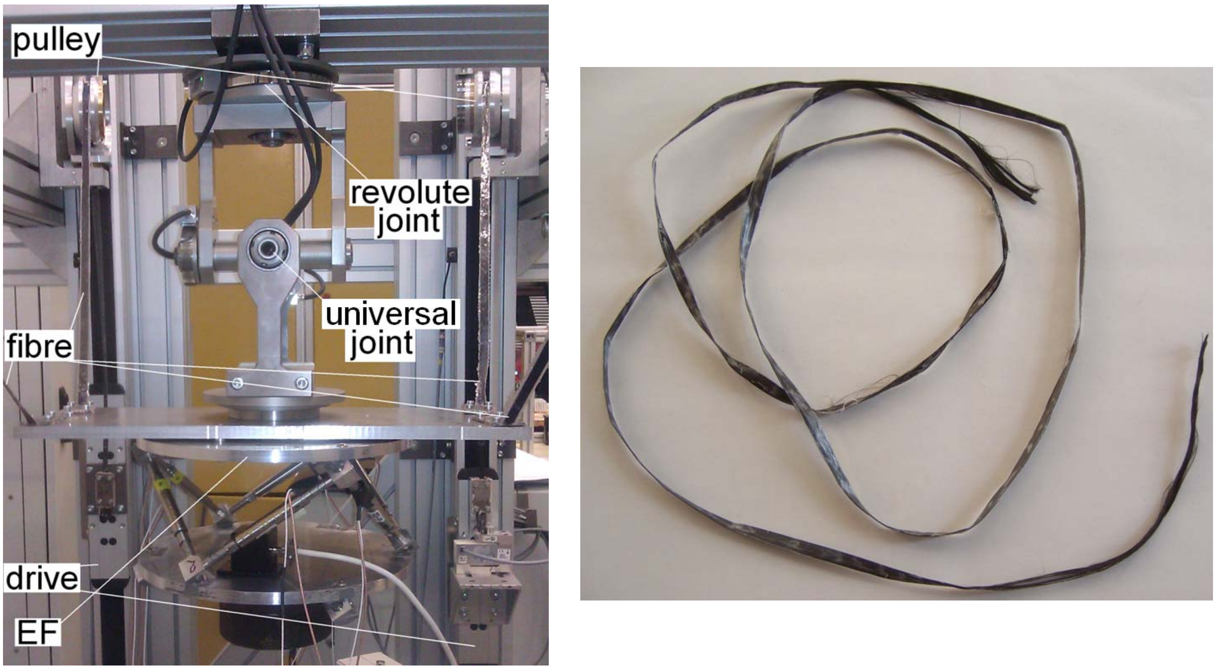

Fig. 1: The QuadroSphere tilting mechanism(EF = end-effector; left) and carbon fibre with a silicone coating (right).

2. Approaches to the modelling of fibres and cables in the mechanical systems

The fibre (cable, wire etc.) modelling should be based on considering the fibre flexibility and suitable approaches can be based on the flexible multibody dynamics (see e.g. Shabana, 1997; Lugrís et al., 2011; Gerstmayr et al., 2012).

There are many approaches to the modelling of flexible bodies in the framework of multibody systems. Comprehensive reviews of these approaches can be found in Shabana (1997) or in Wasfy (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 (1996).

The simplest way how to incorporate fibres (cables) in the equations of motion of a mechanism is the force representation of a fibre (e.g. Polach, 2015; Diao, 2009). The mass of fibres is supposed to be small to such an extent comparing to the other moving parts that the inertia of fibres is negligible. The fibre is represented by the force dependent on the fibre deformation and its stiffness and damping properties. A variable length of the fibre due to wiring can be easily described using the force approach. This way of the fibre modelling is probably the most frequently used in the cable-driven robot dynamics and control (e.g. Heyden, 2006; Zi et al., 2008).

A more accurate approach is based on the representation of the fibre using a point-mass model (e.g. Kamman, 2001; Polach et al., 2014; Ottaviano et al., 2015). The fibre can be considered either flexible or rigid. It has the advantage of a lumped point-mass model. Point masses can be connected by forces or constraints. The fibre wiring can also be simulated and a detailed model of a wiring mechanism can be observed. In the case of the manipulator mechatronic model consisting of fibres and the end-effector, whose motion is driven by fibres, utilization of the point-mass model of a fibre (cable) proved to be very prospective.

In order to represent bending behaviour of fibres their discretization using the finite segment method (Shabana, 1997) or so called rigid finite elements (Wittbrodt et al., 2006) is possible. Other more complex approaches can utilize nonlinear three-dimensional finite elements (Freire, 2006).

A very promising approach usable for the fibre (cable) modelling is a so called absolute nodal coordinate formulation (ANCF), which is based on the discretization of a fibre to nonlinear finite elements (Shabana, 1997; Gerstmayr et al., 2012; Liu et el, 2012; Hajžman et al., 2015). Absolute nodal positions and slopes are considered to be nodal coordinates of the ANCF elements. The formulation leads to the constant mass matrix and the highly nonlinear stiffness matrix. The model can be efficiently used for the investigation of various contact problems related to fibres or cables.

Another approach used for the creation of a general model involving fibres with distributed mass and time-varying length is based on Hamilton's principle, which serves for achieving a system of partial differential equations describing the fibre dynamics (Du, 2015). To solve the system of dynamic equations, the Ritz-mode method with polynomial shape functions is employed and the system of partial differential equations is converted into ordinary differential equations. The accuracy of the fibre model depends on the order of the used polynomial mode functions. This approach is suitable for the modelling of cable-driven manipulators with distributed mass flexible cables.

3. Laboratory experimental mechanical systems and identification of fibre model parameters

As it was already mentioned experimental measurements focused on the investigation of the fibre behaviour were performed in two steps: on the assembled weight-fibre (e.g. Polach et al., 2014; see Fig. 2) and the assembled weight-fibre-pulley-drive mechanical systems (e.g. Polach et al., 2018; see Fig. 3). A carbon fibre with a silicone coating (see Fig. 1 right, e.g. Polach et al., 2012) was used for the experiments. The simulations aim was to create the phenomenological model of a fibre. When looking for compliance of the results of the experimental measurement with the simulation results influences of the following system parameters were considered: the fibre damping coefficient, the fibre stiffness and the friction force between the weight and the prismatic linkage.

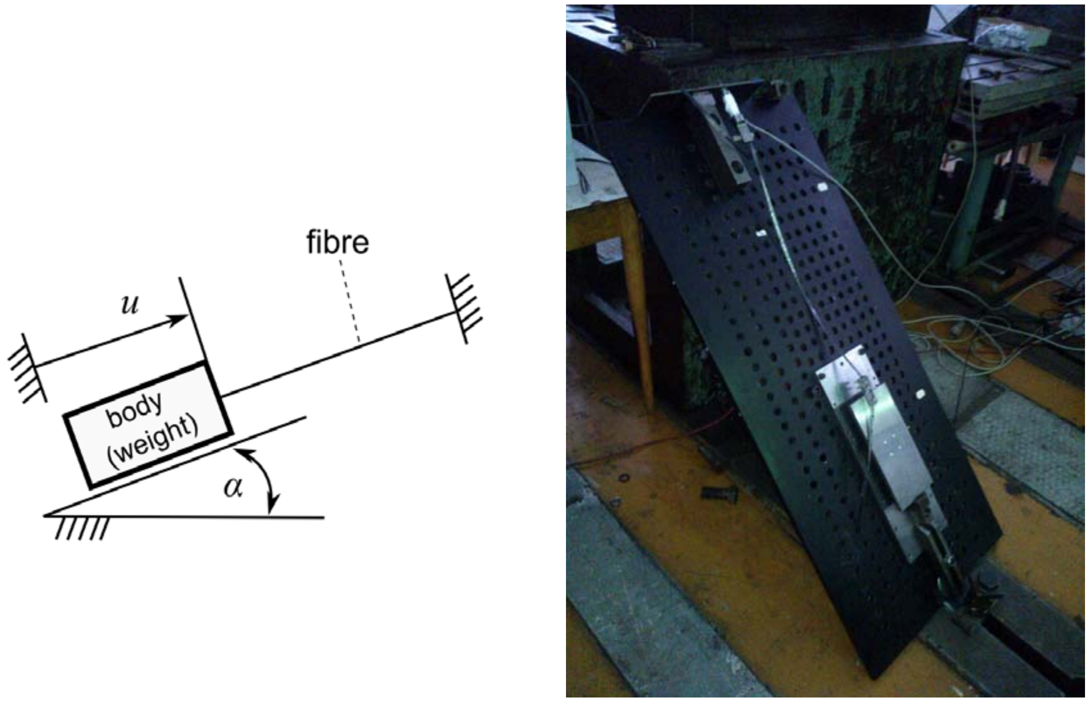

Fig. 2: Scheme and a real weight-fibre mechanical system.

Investigation of the fibre properties eliminating the influence of the drive and the pulley at weight-fibre mechanical system (see Fig. 2) was an intermediate stage before the measurement on the weight-fibre-pulley-drive test stand (see Fig. 3). The fibre was fixed in the upper end on a force gauge. At the other end of the fibre the already mentioned prism-shaped steel weight (i.e. of weight 3.096 kg) was fastened. The fibre length was 559 millimeters and its mass was 1.63 grams. The weight was lifted to a certain height (from 5 to 20 millimetres) and then let to fall in the vertical direction or to slide down the inclined plane. The angle of inclination of the inclined plane could be changed. The weight moved in a prismatic linkage. Time histories of weight position *u* (in the direction of the inclined plane; measured by means of a dial gauge) and of the force acting in the fibre (measured on a force gauge) were recorded using a sample rate of 2 kHz.

In the weight-fibre-pulley-drive system the fibre was driven with one drive (at the drive the fibre was fixed on a force gauge) and was led over a pulley and at its other end there was the same prism-shaped steel weight as in the weight-fibre system, which moved in a prismatic linkage on an inclined plane (see Fig. 3).

The angle of inclination of the inclined plane could be changed. The fibre length was 1.82 meters (the same type of a fibre as in the weight-fibre system; the fibre weight was 4.95 grams), the pulley diameter was 80 mm. Drive periodic exciting signals could be of a rectangular, a trapezoidal and a quasi-sinusoidal shape and there is a possibility of variation of a signal rate. Time histories of weight position *u* (in direction of the inclined plane; measured by means of a dial gauge), of drive position *x* (in vertical direction) and of the force acting in the fibre (measured by a force gauge at drive) were recorded using a sample rate of 2 kHz.

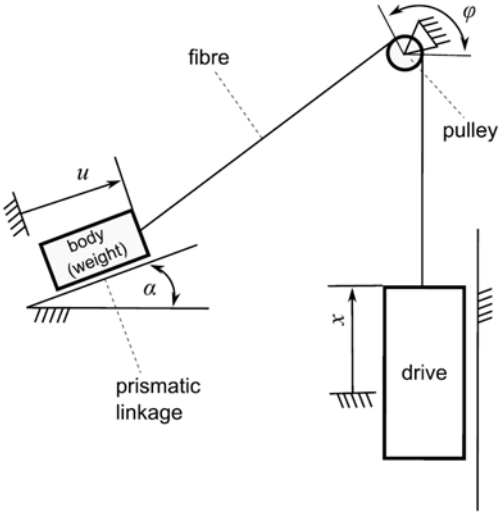

Fig. 3: Scheme and a real weight-fibre-pulley-drive mechanical system.

3.1. Weight-fibre laboratory mechanical system

Results of experimental measurements and simulations of two tested situations are presented (altogether 6 testing situations were simulated – Polach et al., 2013). In the presented cases the weight was let to slide down the inclined plane of alpha angle (see Fig. 2) α = 45 degrees (results in Fig. 4 and Fig. 5) and α = 30 degrees (results in Fig. 6). In the multibody model only one kinematic joint (prismatic linkage) is considered (between the weight and the base) with 2 degrees of freedom. The weight is considered a rigid body.

As it has been stated the value of the fibre damping coefficient, the value of the fibre stiffness and the friction force between the weight and the prismatic linkage were variable parameters at finding a suitable phenomenological model. The influence of those parameters on time histories of the weight position and also on time histories of the 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 measurement and the simulation results. Application of the approach based on the calculation of the statistical quantities, which enables to express directly the relation between two time series, appeared to be suitable for comparing two time series in various cases.

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

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

where μ_1 and $\mu_2(\boldsymbol{p})$ are the mean values of the appropriate time series. The correlation coefficient values range between zero and 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 a scalar value, which is obtained using a simple calculation.

Starting values at the phenomenological model creating were fibre stiffness measured on the tensile testing machine (Polach et al., 2012) and on the basis of the experience determined fibre damping coefficient. The starting friction force between the weight and the prismatic linkage was considered to be zero.

When looking for the fibre model, which would ensure the similarity of time histories of the weight position and time histories of the force acting in the fibre as great as possible, the fibre stiffness and the fibre damping coefficient were considered to be constant. The friction force course (in dependence on the weight velocity) was considered nonlinear. Especially the paper by Půst et al. (2011) served as a basis for the determination of the friction force course. The parameters values were "tuned" for the weight-fibre system model with the force representation of the fibre.

The monitored quantities at the experimental measurements and the computer simulations are presented in Figs. 4 to 6. In Tab. 1 and in Fig. 7 there are parameters of the phenomenological models of the weight-fibre mechanical system. The values of correlation coefficient $R(\boldsymbol{p})$ before and after "tuning" the parameters of the mechanical weight-fibre system model are presented in Polach et al. (2013). As it was already mentioned, the parameters values were "tuned" for the weight-fibre system model with the force representation of a fibre and not for the system models with the representation of the fibre by the point-mass model (this is evident from comparing the correlation coefficient $R(\boldsymbol{p})$ values for both types of the model – see Polach et al., 2013). Further, as evident from Tab. 1, identical values of the fibre stiffness and the fibre damping coefficient for all the simulations of the weight sliding down the inclined plane were independent of alpha angle. This approach seemed to be logical.

Tab. 1: Values of the stiffness and the damping coefficient of the fibre model.

Stiffness [N/m] of the fibre model		**Damping coefficient [N·s/m] of the fibre model**	
Starting value	**Final value**	**Starting value**	**Final value**
$305 \cdot 10^3$	$104 \cdot 10^3$	152.58	83.47

Course of the friction force was considered different for each plane incline (and, of course, different for the simulation of free falling weight, i.e. $\alpha = 45$ degrees). The smaller the plane inclined angle the larger the friction force – see Fig. 7. For the weight velocities lower than -0.1 m/s and higher than 0.1 m/s the friction force courses are constant. In the course of the friction forces the frictional drag of contact in the stick phase of loading before the beginning of the weight motion was taken into account (Půst et al., 2011; see Fig. 7).

It is evident from time histories of the monitored quantities given in Figs. 4 to 6 (and Polach et al., 2013) that the results of the simulation of the weight sliding down the inclined plane differ partly in connection with the utilization of various fibre models. Despite the fact that the fibre mass is very low in comparison with the weight mass it becomes evident in the longer time of the system transition to the equilibrium position when using the point-mass fibre model.

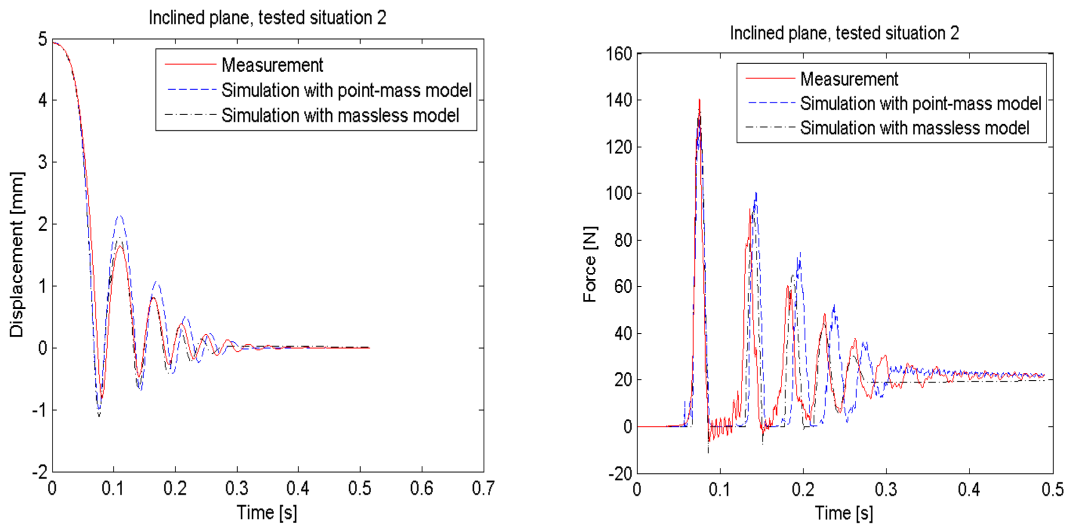

Fig. 4: Time histories at sliding down the inclined plane of alpha angle $\alpha = 45$ degrees, tested situation 2: the weight position (left), the force acting in the fibre (right).

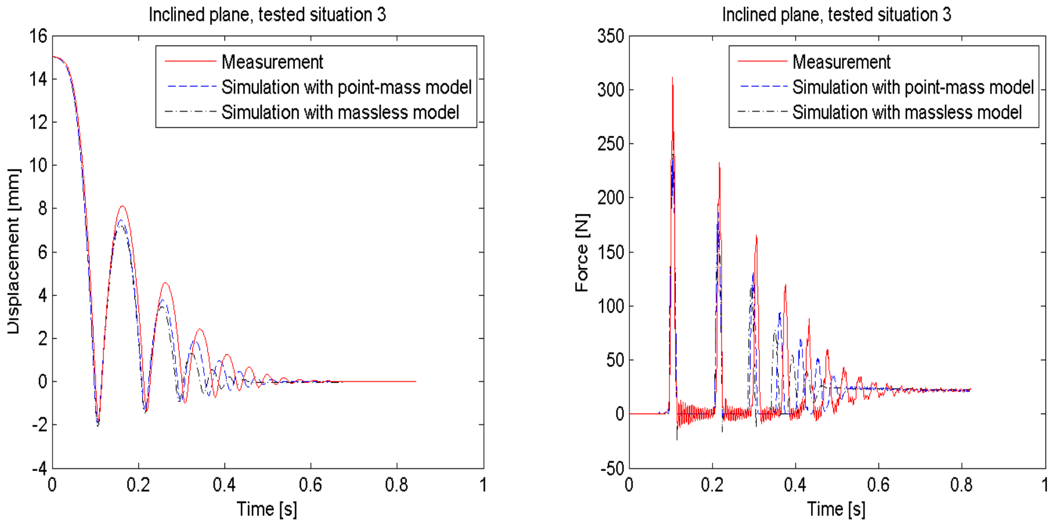

Fig. 5: Time histories at sliding down the inclined plane of alpha angle $\alpha = 45$ degrees, tested situation 3: the weight position (left), the force acting in the fibre (right).

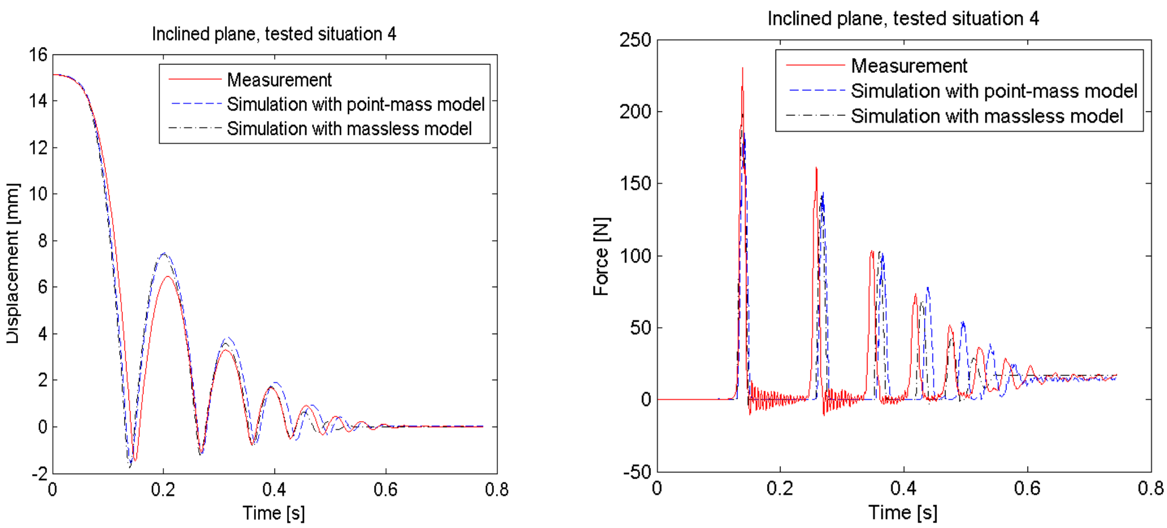

Fig. 6: Time histories at sliding down the inclined plane of alpha angle $\alpha = 30$ degrees, tested situation 4: the weight position (left), the force acting in the fibre (right).

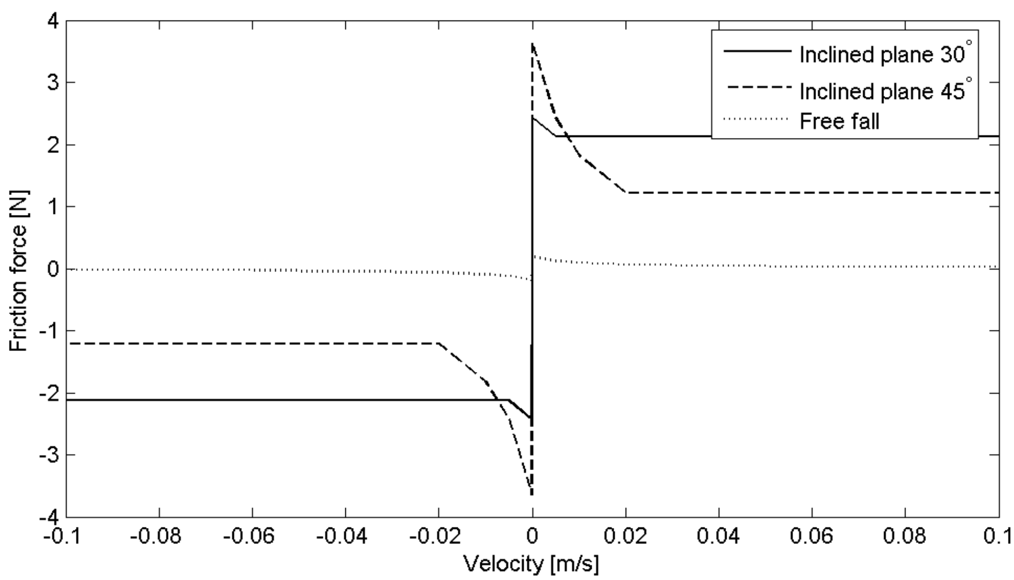

Fig. 7: Friction forces between the weight and the prismatic linkage.

3.2. Weight-fibre-pulley-drive laboratory mechanical system

The second step of the experimental measurements focused on the investigation of the fibre behaviour was performed on the assembled weight-fibre-pulley-drive mechanical system (e.g. Polach et al., 2018; see Fig. 3). In the presented case the angle of the inclined plane was $\alpha = 30$ degrees and the pulley-fibre angle was $\varphi = 150$ degrees (see Fig. 3). As already stated, drive periodic exciting signals could be of the rectangular, the trapezoidal (see Fig. 10 left) and the quasi-sinusoidal (see Fig. 9 left) shape and the signal rate variation was possible. Altogether 13 different situations were tested at this configuration of the assembled laboratory mechanical system.

The same system was numerically investigated using the multibody models. The same quantities as at the experimental measurements, i.e. time histories of the weight position and of the force acting in the fibre, were monitored. Results of the experimental measurements were compared with the computational results obtained using three types of the fibre model: the force model (Polach, 2015; Polach et al., 2017), the ANCF model (Bulín et al., 2017; Polach et al., 2018) and the point-mass model (Polach et al., 2020). Equations used for creating these models are given in the above mentioned literature.

Firstly, the phenomenological model of the force fibre model (considering e.g. influences of the fibre transversal vibration, etc.) suitable for the simulations with the weigh-fibre-pulley-drive mechanical system was created (Polach et al., 2017). The number of degrees of freedom in kinematic joints of the multibody model of the weight-fibre-pulley-drive system is 5. The weight, 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 the weight-fibre-pulley-drive model the course of the friction force was considered the same as at simulations with the weigh-fibre model (Fig. 7). The values of other parameters of the phenomenological model were determined in the same way as in the weight-fibre model, i.e. at simulations with the force model of the fibre and partly visually and partly on the basis of the value of correlation coefficient (see Eq. (1)). The fibre stiffness ($34 \cdot 10^3$ N/m) and the fibre damping coefficient (27.5 N·s/m) were considered to be system parameters of the phenomenological model (e.g. Polach et al., 2017). At simulating the experimental measurements for a "quicker" drive motion it was necessary to consider the velocity-dependent stiffness and the velocity-dependent damping "coefficient" in the fibre model for the calculation of dynamic response of the system (e.g. Polach et al., 2017). Frequencies of drive motion – i.e. frequencies of drive periodic excitation signal – higher than 1 Hz are designated as "quicker" drive motions, frequencies of periodic drive motion lower than 1 Hz are designated as "slower" drive motions.

In the multibody model of the weight-fibre-pulley-drive using the ANCF fibre model, the pulley is modelled as a rigid body with one degree of freedom (rotation), the fibre is modelled as a deformable body and is discretized using the ANCF planar L2T2 beam elements (Bulín et al., 2017). 18 ANCF elements in total were used for the fibre discretization, 10 elements of which are used to discretize the fibre section wrapped around the pulley in order to properly model the contact interaction. 8 remaining elements were used to discretized two long straight fibre sections between the weight and the pulley and between the pulley and the drive. An in-house modelling tool in the MATLAB system based on the proposed modelling methodology was created. The fibre Young modulus is considered to be constant and is determined based on the fibre stiffness of the phenomenological model and the fibre cross-section (0.001 x 0.01 m). Proportional damping was used.

The model of the weigh-fibre-pulley-drive mechanical system with the point-mass fibre model is the same as model of this system with the force fibre model, except the fibre. The point-masses in the fibre model are unconstrained and are connected by spring-damper elements. At present, the fibre is modelled using 7 point-masses.

At the "slower" drive motion simulations (see Figs. 8 and 9) performed with the point-mass model the results are in a better coincidence with the results of experimental measurements than the results obtained using the force model considering any phenomenological model. The coincidence of the results obtained using the ANCF method and the experimental results is comparable with that obtained using the point-mass model.

A particular signal defining the motion of the drive and time history of the measured position of the weight at the "quicker" drive motion is in Fig. 10 (the measured motion of the drive served as an input signal for the numerical simulations). At simulating the “quicker” drive motion (see Fig. 10) with the point-mass fibre model, the results are predominantly in a worse coincidence with the results of experimental measurements than the results obtained using the force model with the velocity-dependent stiffness and the velocity-dependent damping “coefficient”.

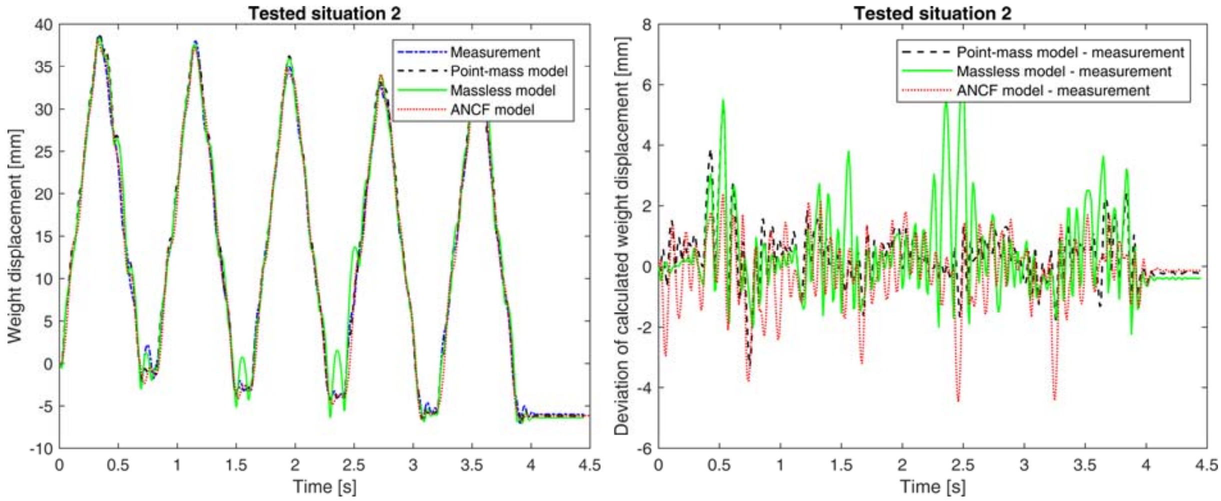

Fig. 8: Time histories of the weight displacement at the “slower” tested situation (left) and deviation of the calculated weight displacements from the measured displacement (right).

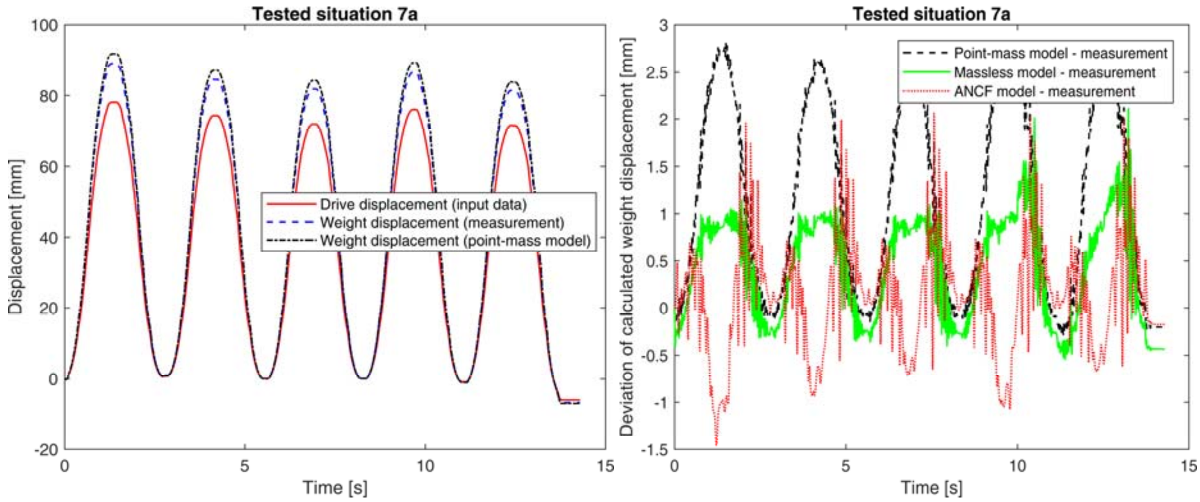

Fig. 9: Time histories of the drive and the weight displacements at a “very slower” tested situation (left) and deviation of the calculated weight displacements from the measured displacement (right).

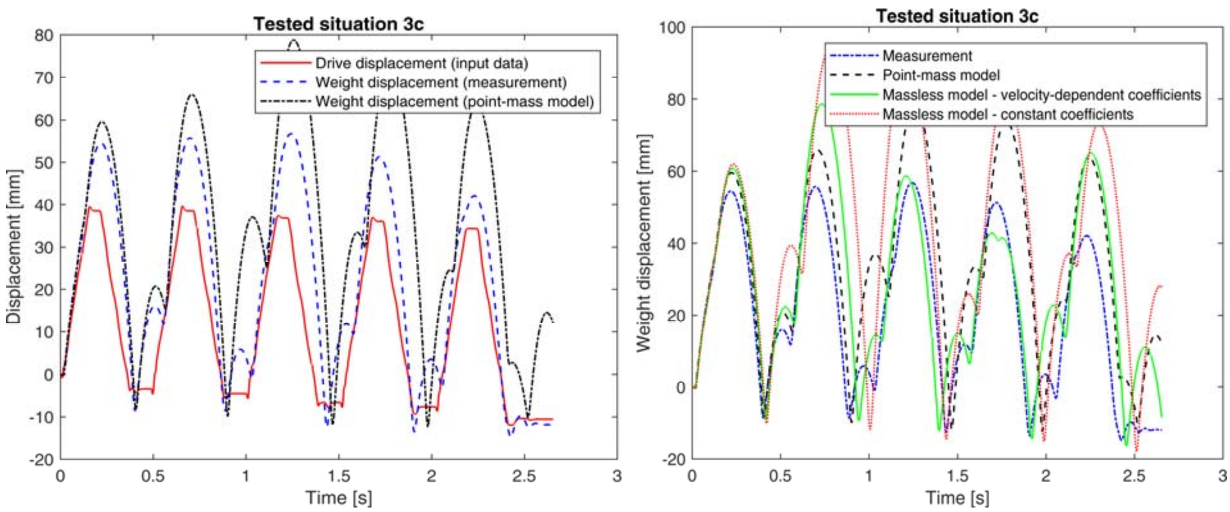

Fig. 10: Time histories of the drive and the weight displacements at the “quicker” tested situation.

4. Conclusions

This paper summarizes some possible approaches suitable for the modelling of the fibre and the cable dynamics in the framework of various mechanical systems: the force representation of the fibre, the point-mass model and the absolute nodal coordinate formulation (ANCF).

The weight-fibre and the weight-fibre-pulley-drive mechanical systems were chosen as an example of the application of the above-mentioned numerical methods. Those systems were chosen because experimental measurements focused on the investigation of the fibre behaviour were performed on them. The simulation aim was to create a phenomenological model of the fibre that would be utilizable in the 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.

It is evident from the achieved results that the general phenomenological model of the fibre was not determined. General influences of the individual parameters on the system behaviour, which are usable for all systems containing the weight-fibre subsystem(s), were assessed. Suitable fibre models, but only in dependence on the definite simulated test situation, were determined. In the case of the investigated simple weight-fibre mechanical system the created models are dependent on the angle of inclination of the (inclined) plane on which the weight moves. It is obvious that it would not be possible to generalize the created models either for the weight-fibre-pulley-drive mechanical system or for the other similar systems.

Future work will be focused on improving the point-mass model of the fibre and modelling its interaction with the pulley (the advantage of this approach is supposed to be in a precise physical interpretation of the problem and in a short computational time). The investigation of the influence of nonlinearity, time-variability and dynamic couplings among the fibre, the manipulated end-effector and the mounting structure will continue in development of complex dynamic models of the sophisticated active structures. Qualitative studies in order to reveal and describe important properties of the composed multi-level mechanism from the point of view of control algorithm demands will be performed.

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