Validating the DLR Cables Library with Experiments and Parameter Optimization

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Abstract

The advantages of modelling and simulation are widely known: Optimizing systems before production, generating alternatives in a few clicks, reducing costs, monitoring, digital twin, etc. The quality of the simulation depends heavily on the quality of the modeling, making it an essential task. The DLR Cables library, which we presented in another work, allows the simulation of steel cables, focusing on use cases where their dynamic behavior is of interest, such as cranes and elevators, but also special motion systems using cables and amusement rides. There, the numerical approach based on finite elements is explained in detail and it is also shown that some simplifications are accepted in order to improve the computational effort. This paper presents the crucial tasks of validation and parameterization of the model, specifically focusing on the material properties of bending stiffness and bending damping. To achieve this, a series of experiments were carried out on four different cables. Optical systems are used to record the cables and to compare them with the simulation. For some of the experiments, we were able to show a good match between reality and simulation, but it also became clear that a linear approach may not be sufficient depending on the application.
Keywords: Modelica, Steel Cables, Validation

1 Introduction

In this paper, we present our results of a validation campaign for a Modelica library that can be used to simulate steel cables, the DLR Cables library (Bellmann, Seefried, and Bernhofer n.d.). The focus of that library was primarily on computational speed, as our approach to describing a cable through multiple discrete bodies coupled together becomes computationally intensive with the standard Modelica Multibody Library (Otter, Elmqvist, and Mattsson 2003). Therefore, in our approach, cable elongation, cable torsion, and cable bending are considered separately with simplified equations of motion. This leads to an error that needs to be estimated.

For the validation campaign presented here, existing measurement systems are utilized. The goal is to validate the modelling of a cable in order to be able to simulate more complex systems, where the dynamic behavior of a cable is crucial, like Jomartov et al. (2023), Katliar et al. (2017), Elhardt et al. (2023), and Yan et al. (n.d.).

In the second section, the cable model is outlined briefly, and the potential parameters are listed, including those already available and those to be determined through experiments. Section three presents two different measurement setups and the methodology for evaluation, as well as the results from the measurements. The paper concludes with a discussion of the results and future endeavors aimed at further improving cable modelling.

2 Cable Model and Available Data for Parameterization

Modelling a steel cable is a complex task. In the paper "The DLR Cables Library" (Bellmann, Seefried, and Bernhofer n.d.), we present an approach where a cable is divided in a defined number of elements that are connected in a row. To model the behavior of the cable, the calculation of elongation, bending and torsion are separated. This reduces the computational time compared to an approach using the standard Modelica Multibody components but physical effects are also lost, the influence of which will also be investigated in this validation study. Additionally, depending on the task, different levels of complexity can be used for the three main components.

In the literature, there are various approaches for identifying cable behaviour and to obtain information for parameterization. For cable elongation, data from the manufacturer is usually available. Here, a defined length of cable is clamped in a test rig and subjected to various tensile loads. The resulting elongation is recorded and stored in a table. Such a potential nonlinear characteristic curve can be represented in the presented model. The axial damping along the cable is currently implemented as a linear case. For cable bending, various setups can be found in the literature, which either measure the resistance force of the cable depending on lateral deflection (Z. Chen et al. 2015) or analytical or numerical considerations for bending stiffness are carried out (Zhu, Ren, and Xiao 2011; Papailiou 1995). In the library, a more complex model is available that takes the curvature into account and thus becomes nonlinear for larger bending. The parameters for bending stiffness and bending damping are single values (no lookup table). For torsion we use a simple linear stiffness and damping model. For bending and torsion, data acquisition is not easy. Due to the missing parameters and the uncertainties resulting from the modeling, validation is unavoidable. The study of cable research shows more effects that are not implemented until now, for example damping due to interwire friction (Spak, Agnes, and Inman 2013; Y. Chen, Meng, and Gong 2017) or variable bending stiffness due to axial load (Papailiou 1995). These are not implemented in the current model and can be considered for further refinement if needed.

3 Experimental Setup and Parameter Identification

At DLR, highly versatile and precise laser measurement systems are available, therefore a test rig setup has been devised to utilize the existing equipment to record the behaviour of different steel cables as accurately as possible and compare it with our model (Häusler 2019). The following setup was used for four different steel cables from Pfeifer, see Table 1. The manufacturer provided detailed data for the stiffness of the cable. The focus of the following experiments was on the bending stiffness and bending damping.

Name	D [mm]	Weight q_0 [$\mathrm{kg\,m^{-1}}$]
10 P 524	10	43
16 P 524	16	110
20 P 524	20	172
16 PN 152/9	16	104

Table 1. Cables used for the experiment. The P 524 cable has a plastic coated steel core while the PN 152/9 has only a steel core. Both have an ordinary lay.

3.1 Experiment 1: Horizontal Clamped Cable

To identify static parameters, a short piece of cable is clamped horizontally in a holding device. The aim is to check the extent to which the bending beam theory applies to such a short piece and to determine the Modulus of Elasticity on the basis of the measured values, see Fig. 1.

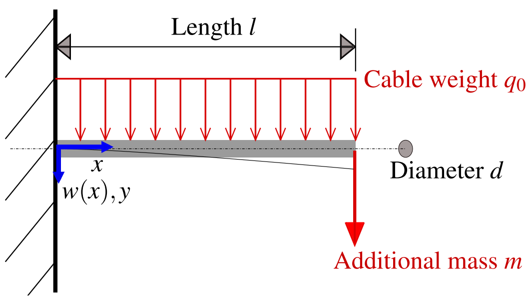

Figure 1. Using beam theory for a short piece of cable to get the Modulus of Elasticity.

Different masses m are applied to the free end of the piece of cable. A line laser scanner (Keyence LJ-V7300) measures the deformation of the cable section. Hysteresis behavior was observed during the tests. Depending on whether the weight tends to be deflected upwards or downwards, different positions result after releasing the weight, see Fig. 2. This indicates a kind of static friction in the cable. Since this is not currently represented by the cable model, the mean value is used for further consideration.

In Fig. 3, the mean deflections over the distance from fixed clamping are shown with different additional masses m for the four cables.

From these measurements, the Modulus of Elasticity can be calculated (Byskov 2013). At this moment, we've used a simple approach with small deformations.

For the constant load from the cable, the deflection of the beam can be described by

$$w_{q_0}(x) = \frac{q_0 l^4}{24EI}\left(6\left(\frac{x}{l}\right)^2 - 4\left(\frac{x}{l}\right)^3 + \left(\frac{x}{l}\right)^4\right), \quad (1)$$

for the additional mass m it is

$$w_m(x) = \frac{mgl^3}{6EI}\left(3\left(\frac{x}{l}\right)^2 - 4\left(\frac{x}{l}\right)^3\right). \quad (2)$$

with g the gravitational constant and

$$I = \frac{r^4\pi}{4} \quad (3)$$

the second moment of area for a cylindrical cross section with a radius r of the cable. Combining Eq. (1) and Eq. (2) with $w(x) = w_{q_0}(x) + q_m(x)$ and solving for E leads to

$$E(x) = \frac{q_0 l^4}{24w(x)I}\left(6\left(\frac{x}{l}\right)^2 - 4\left(\frac{x}{l}\right)^3 + \left(\frac{x}{l}\right)^4\right) + \frac{mgl^3}{6w(x)I}\left(3\left(\frac{x}{l}\right)^2 - 4\left(\frac{x}{l}\right)^3\right) \quad (4)$$

Fig. 4 shows the resulting Moduli of Elasticity for the cables. The first 5 cm are not meaningful but then the curves align and show an approximately constant behavior, which was used for parameterization in the library, see Table 2. It is planned to carry out further measurements with more complex theories and other bending tests like presented in Cao and Wu (2018) or Z. Chen et al. (2015).

Name	D [mm]	E-module [$\mathrm{N\,m^{-2}}$]
10 P 524	10	0.65×10^8
16 P 524	16	1.9×10^8
20 P 524	20	2.1×10^8
16 PN 152/9	16	1.75×10^8

Table 2. Experimentally obtained Moduli of Elasticity

3.2 Experiment 2: Free Swinging Cable

To measure the dynamic behavior of the cables, we use a very precise laser tracking system (Leica AT 960). A 8m cable is mounted on the ceiling in our lab. A mass of 10 kg is added at the free end of the cable. For the experiment,

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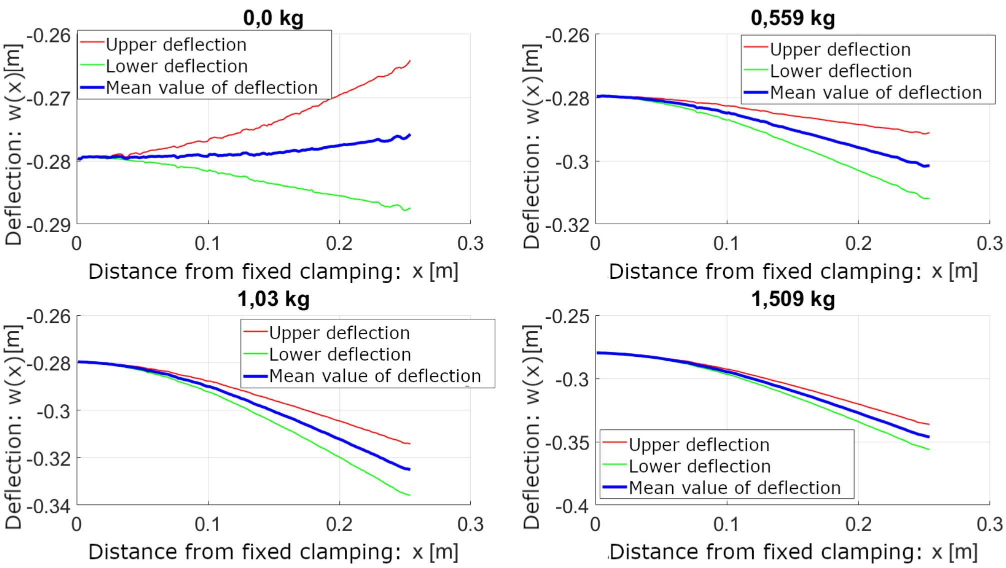


Figure 2. Experiment 1: Upper and lower deflection of cable with different weights at the free end of the cable. Because of static friction, the cable rests at different positions depending on the direction. Here, the deflections of PN 152 are shown.

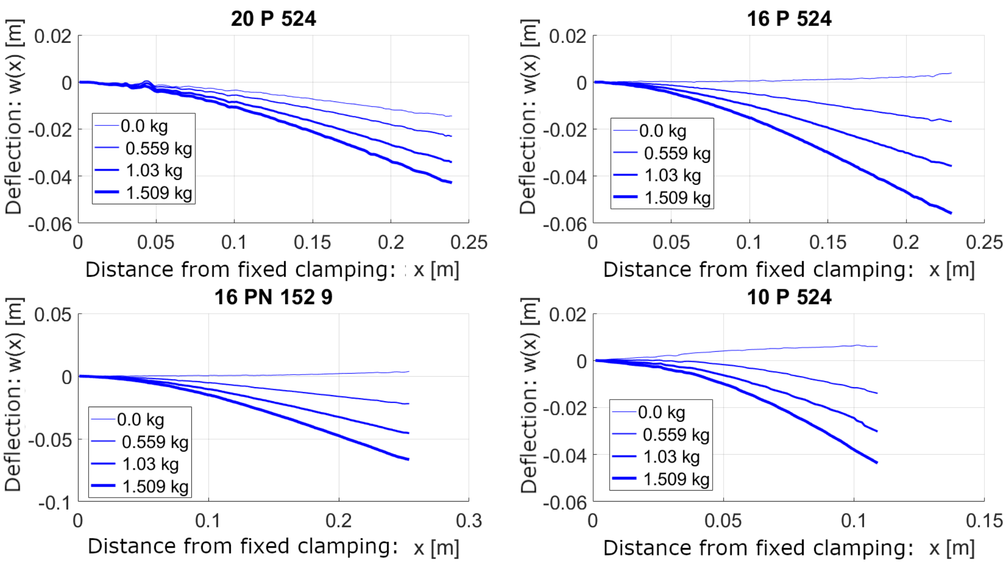


Figure 3. Experiment 1: Mean deflections of the cable section with different weights at the free end.

we put the free end of the cable to five different positions and release the end. This way, the cable swings in different but repeatable ways. A marker for the laser tracker is attached at the cable on nine different positions. The laser tracking system can only track one target at the same time, so there are 45 runs to do for each cable. Figure 5a shows the cable with the different starting positions and the positions of the markers for the laser tracking system. Figures 5b and 5c show two different starting positions for the cable and the evolution of the swinging behavior. With such different starting positions, excitation at various frequencies within the cable can be achieved. These are harmonics and the decay of these movements helps to identify the cable bending and damping.

On the modelling side, we also use a 8m long cable with the same mass at the end. The number of elements is set to 50, so that the transitions between the discrete cable elements match the positions of the markers. The error

$$e_1(t) = (r_{E,1}(t) - r_{S,1}(t))^2 \tag{5}$$

describes the time dependent distance of the position of the cable in the experiment, here at marker '1', $r_{E,1}(t)$, and the corresponding position of the cable in the simulation, $r_{S,1}(t)$. The integral of $e_1(t)$ describes the cost function

$$J_1 = \int_0^{t_e} e_1(t)\,\mathrm{d}t \tag{6}$$

and is taken to find the optimal parameter for the damping bending by minimizing J_1. For a more complex optimization, where all positions of the markers are optimized at

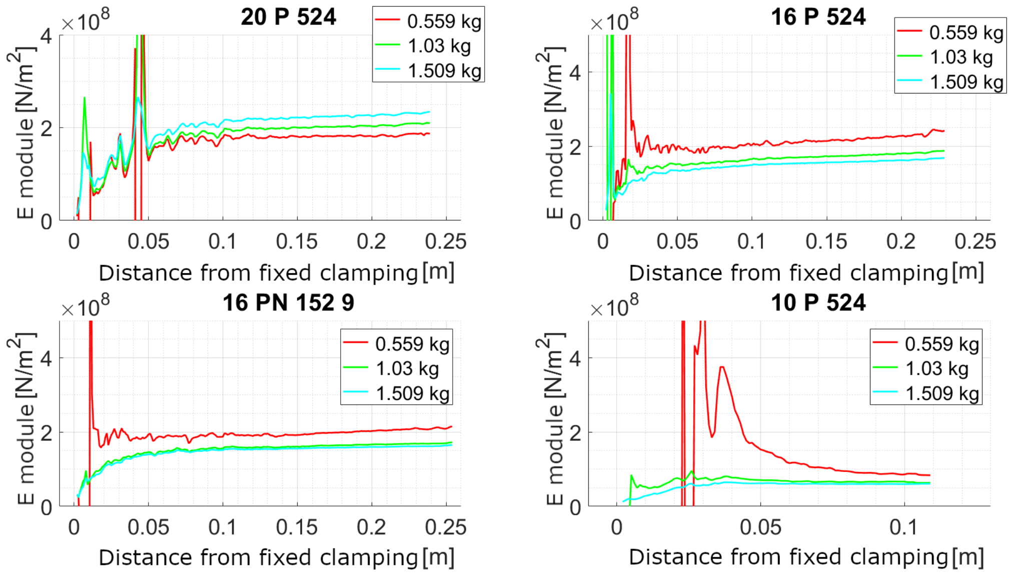
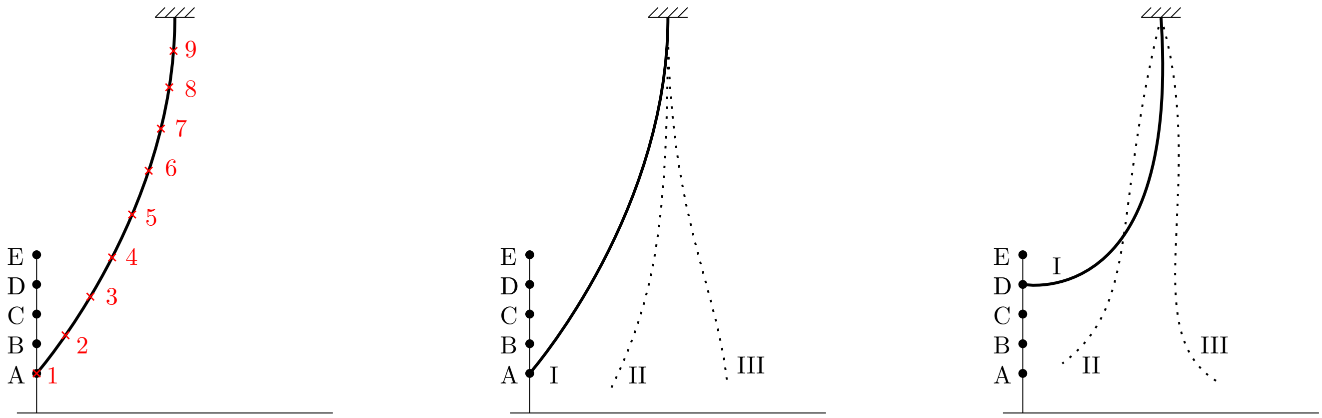


Figure 4. Moduli of Elasticity of the different cables depending on their distance to the fixed clamping



(a) Numbering of starting positions (A to E) and positions of the marker of the laser tracker (1 to 9).

(b) Example of swinging cable with starting position A (I). After a few milliseconds, the cable has the configuration II and then III.

(c) Example of swinging cable with starting position D (I). After a few milliseconds, the cable has the configuration II and then III with strong harmonics.

Figure 5. Experimental setup of the 8m long cable mounted at the ceiling with different starting positions.

the same time, the cost function expands to

$$J = \int_0^{t_e} e_1(t) + e_2(t) + \ldots + e_9(t)\, \mathrm{d}t. \tag{7}$$

In Fig. 6, the model is shown of that optimization to measure the difference between the recorded first marker position and the corresponding point at the cable, here at the additional mass. The optimization is implemented with the *DLR Optimization library* (Pfeiffer 2012). The optimization variable is the parameter for the bending damping, d_bend.

In Fig. 6b the output of an optimization is shown where a small change of the bending damping leads to a very precise match of the simulated and the real movement. Here, the cable was released at the starting position A.

The cable is then deflected both in the simulation and in the test and released from the start position ’E’. After a short time, the oscillation behavior of the lowest point ’1’ is very similar to the previous case. On the other hand, clear changes can be seen at position ’7’, see Fig. 7a. It is also easy to see that the simulation and the measurement do not match well in terms of the amplitude of the harmonics. Even after renewed optimization, see Fig. 7b, the result is not as good as expected.

4 Discussion and Conclusion

The validation of simulation models is crucial in order to be able to rely on the results. In a first step, the parameters for bending stiffness and bending damping were deter-

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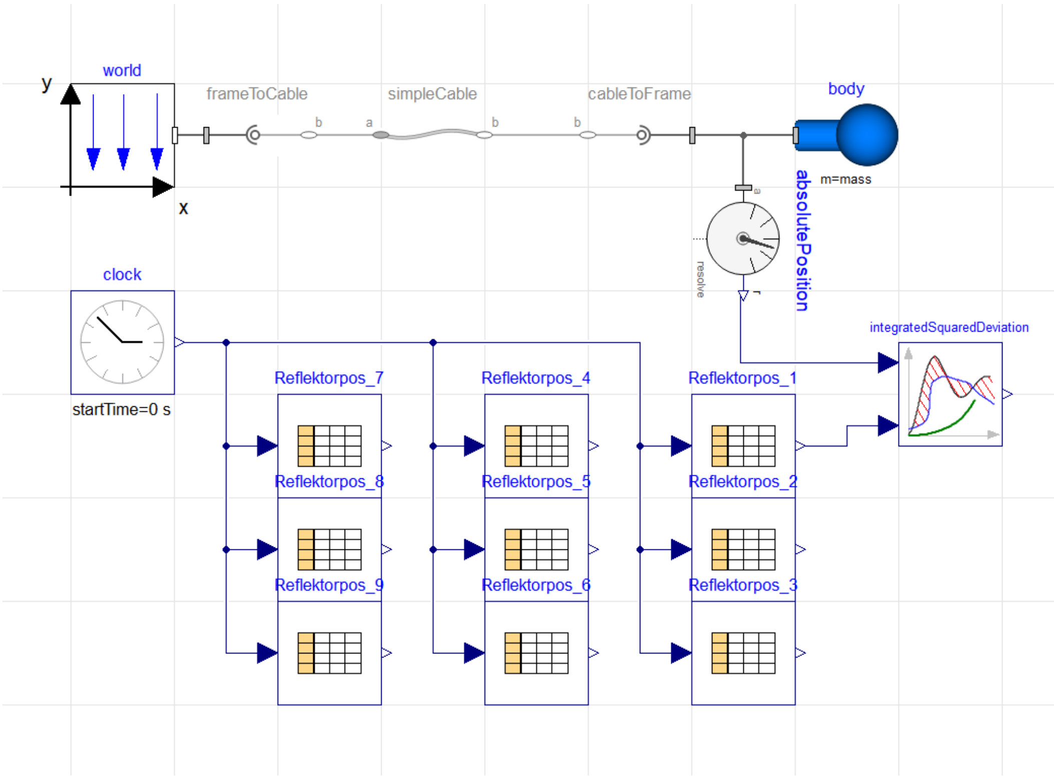
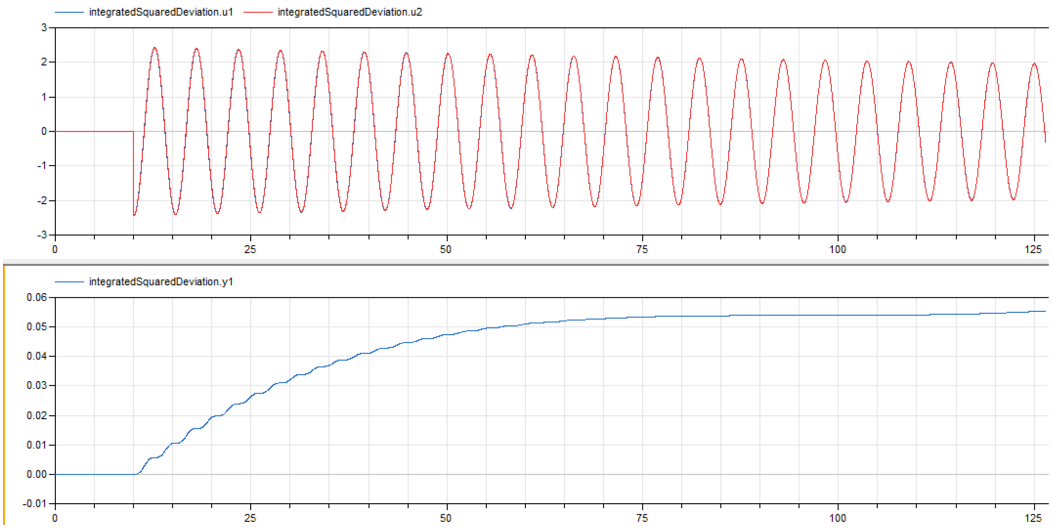


(a) Modelica model to run an optimization with the *DLR Optimization library* (Pfeiffer 2012). Here, only the position of the additional mass is compared in simulation and from real measurements, that have been recorded and are used here as a lookup table.



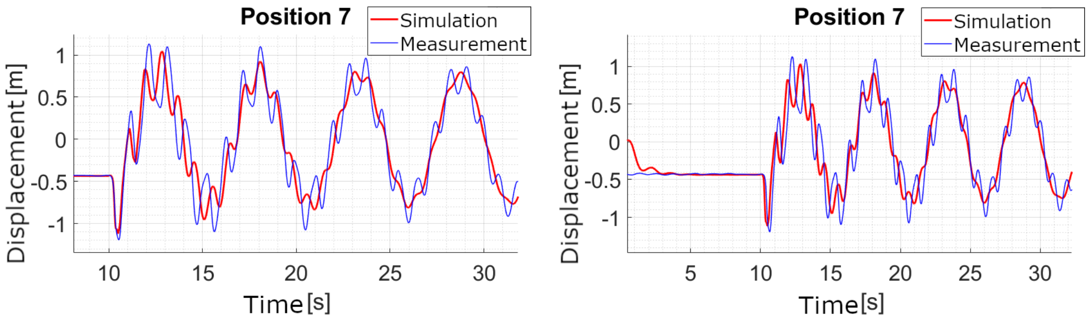
Evaluation 100:

Tuner parameters	name	value	difference to start	min	max
	d_bend	0.063	2.778e-3	0.04	0.1

Criteria	name	scaled criteria	diff. to start	unscaled criteria	usage	demand value
0 1 2 3	integratedSquaredDeviation.y1	0.061	-95.7%	0.061	minimize	1
0 3 6 9	**Sum of squared criteria**	3.736e-3	-99.8%			

(b) Result of the optimization shown in Fig. 6. A small change of the bending damping parameter `d_bend` leads to a very good match between the measured, real swinging of the cable and the simulation.

Figure 6. Model made in Dymola of a cable simulated with the Cables library and compared to real measurement. The position of marker '1' and the starting position is 'A' is shown, see Fig. 5a. The comparison is used to optimize the bending damping parameter.



(a) Comparison of simulation and measurement for a cable, started at position 'E'.

(b) Comparison of simulation and measurement for a cable, started at position 'E'. Even after optimization, the curves of the higher frequency do not match well.

Figure 7. Comparison of a swinging cable P 524 with 10 mm diameter simulated with the Cables library and real measurement. The position of marker '7' and the starting position is 'E' is shown, see Fig. 5a.

mined experimentally in this work and transferred to the simulation model using an optimization-based method. For simple pendulum movements, the agreement between the simulation model and reality is very good. In the case of excitation, where higher frequencies also occur in the cable itself, the simulation shows a sufficient fit with the reality but can still be improved, for example by choosing a more complex model. Changing the number of elements did not improve the results thus the authors assume that the modelling itself need to be updated if such complex motions are of interest.

An extension of the bending model with a lookup table for stiffness and damping to enable non-linearity could help to improve the accuracy of the simulation compared to the reality. Furthermore, according to literature, the effect of axial load is high so that those experiments should be made, too. At the moment, another validation is carried out using the Motion Suspension System - MSS (Elhardt et al. 2023) and the results will taken into account to refine the modelling of the cable.

References

Bellmann, Tobias, Andreas Seefried, and Thomas Bernhofer (n.d.). "The DLR Cables Library". In: *Asian Modelica Conference 2024*.

Byskov, Esben (2013). *Elementary Continuum Mechanics for everyone: with applications to Structural Mechanics*. Vol. 194. Springer Science & Business Media.

Cao, Xin and Weiguo Wu (2018). "The establishment of a mechanics model of multi-strand wire rope subjected to bending load with finite element simulation and experimental verification". In: *International Journal of Mechanical Sciences* 142, pp. 289–303.

Chen, Yuanpei, Fanming Meng, and Xiansheng Gong (2017). "Study on performance of bended spiral strand with interwire frictional". In: *International Journal of Mechanical Sciences* 128-129, pp. 499–511. ISSN: 0020-7403. DOI: 10.1016/j.ijmecsci.2017.05.009.

Chen, Zhihua et al. (2015-10). "Experimental research on bending performance of structural cable". English. In: *Construction and Building Materials* 96, pp. 279–288. ISSN: 0950-0618. DOI: 10.1016/j.conbuildmat.2015.08.026.

Elhardt, Ferdinand et al. (2023). "The Motion Suspension System–MSS: A Cable-Driven System for On-Ground Tests of Space Robots". In: *IFToMM World Congress on Mechanism and Machine Science*. Springer, pp. 379–388.

Häusler, Leonhard (2019). "Identifikation und Modellierung von Stahlseilen". Bachelorarbeit. Hochschule München. URL: https://elib.dlr.de/139717/.

Jomartov, Assylbek et al. (2023-03). "Simulation of suspended cable-driven parallel robot on SimulationX". In: *International Journal of Advanced Robotic Systems* 20.2. ISSN: 1729-8814.

Katliar, Mikhail et al. (2017). "Nonlinear model predictive control of a cable-robot-based motion simulator". In: *Ifac-papersonline* 50.1, pp. 9833–9839.

Otter, Martin, Hilding Elmqvist, and Sven Erik Mattsson (2003-11). "The New Modelica MultiBody Library". In: *3rd International Modelica Conference*. Ed. by Peter Fritzson. LIDO-Berichtsjahr=2003, pp. 311–330.

Papailiou, Konstantin O (1995). "Bending of helically twisted cables under variable bending stiffness due to internal friction, tensile force and cable curvature". In: *Doctor of Technical Sciences thesis, ETH, Athens, Greece* 168.

Pfeiffer, Andreas (2012). "Optimization library for interactive multi-criteria optimization tasks". In.

Spak, Kaitlin, Gregory Agnes, and Daniel Inman (2013-01). "Cable Modeling and Internal Damping Developments". In: *Applied Mechanics Reviews* 65.1. DOI: https://doi.org/10.1115/1.4023489.

Yan, Fei et al. (n.d.). "Dynamic modelling and parameter identification for cable-driven manipulator". In: *Current Science* 116.8 (), p. 1331. ISSN: 0011-3891. DOI: 10.18520/cs/v116/i8/1331-1345.

Zhu, W. D., H. Ren, and C. Xiao (2011-04). "A Nonlinear Model of a Slack Cable With Bending Stiffness and Moving Ends With Application to Elevator Traveling and Compensation Cables". In: *Journal of Applied Mechanics* 78.4. DOI: https://doi.org/10.1115/1.4003348.

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