Indirect assessment of tension force in cables equipped with TMDs

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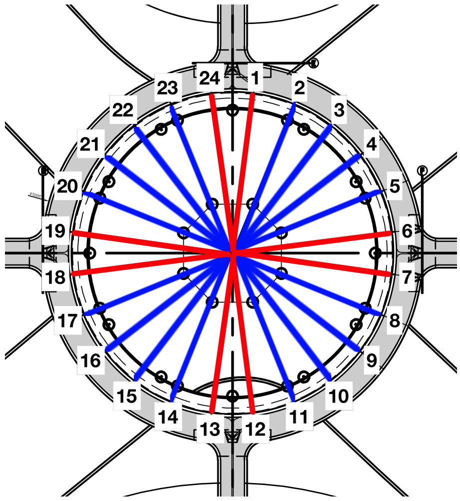
Abstract. In this paper, an indirect method to obtain the actual tension force in stay cables is presented. It is based on a combined experimental and numerical approach, where the experimental measurement of the first natural frequency of the cable is combined with a FE model of the cable to finally obtain an estimate of the actual tension force. The method is suitable to be applied to cables eventually equipped with tuned mass dampers. It is here presented referred to an application case, the stays of the Hovenring Bridge. Being those cables endowed with two tuned mass dampers, the well-established indirect method based on the string theory cannot be applied to the present case. Therefore a new approach is proposed: it makes advantage of a FE model of the cable, made by equivalent tensioned beam elements and includes the effects of the dampers through equivalent mass-spring-damper systems. A complete description of the method is presented along with its validation through a comparison with a direct measurement of the tension force in 4 cables.

1. Introduction

When dealing with cable-suspended structures, it is essential to have an accurate estimate of the tensile force on the cable elements. This is first to guarantee the structural safety of the structure but also to allow for the scheduling of the maintenance operations. Looking at the existing techniques to estimate cable tension, direct methods are available along with indirect ones. The first, also called static methods, consists on using load cells or a hydraulic jack to directly measure the tension force. The accurate estimation we can get from them is usually counterbalanced by high costs and accessibility to the anchorage system, which may result in the bridge closing to the traffic for several days. An alternative approach is to rely on the so-called indirect methods, which allow the estimation of the tension force from the measure of the natural frequencies of the cable. For this reason, they are also called vibration methods. The existing literature proposes several experimental and theoretical studies for the indirect estimation of the tension force. The simplest ones rely on the taut string theory, which proposes a very simple formula to relate the measured natural frequency to the actual tension force in the cable [1]. This simplified method neglects the bending stiffness of the cable and, to overcome this problem, the Bernoulli-Euler beam theory can be applied. By applying this approach, Fang and Wang [2] proposed a practical formula in a simple explicit form to estimate cable tension, neglecting sag-extensibility by using the frequencies relative to antisymmetric or higher vibration modes of the cable. Other studies inclusive of the sag effects can be found in [3, 4, 5]. Park et al. [6] focused instead on the indirect estimation of the tension force in the double-hanger cable system, introducing a new frequency-based system identification technique inclusive of the

(a) The bridge



(b) Top view of the bridge and cable numbering

Figure 1: Hovenring Bridge

flexural stiffness of the system. In 2015, Wang et al. [7] studied the main cable for a suspended bridge, introducing a new approach based on the continuum model to estimate the main cable tension force from measured natural frequencies. Main cable tension force is affected by hangers and stiffening girder, so they proposed to consider the differential equation of motion governing the vertical vibration of a cable by considering an additional translational spring constant term to reflect the effects induced by hangers and girder.

The literature survey allows highlighting that there exist several indirect approaches to estimating actual tension force value in different types of structures. However, in case we want to study a cable equipped with dampers, the application of the taut string theory or analogous approaches based on the transverse vibration equation is not straightforward.

In this paper, a methodology to obtain an indirect estimation of the actual tension force in the cable equipped with tuned mass dampers (TMDs) is proposed. Specifically, the method is described and applied to the stays of the Hovenring Bridge (Figure 1a). It is based on the experimental measurements of the first natural frequency of the cable that is then used to obtain the estimation of the tension force through a FE model. The proposed method will account for the structural and geometrical properties of the cable and will include dampers' contribution. The method has been developed to obtain a prediction of the actual tension force and to allow for the scheduling of re-tensioning operations, if required. The desired accuracy of the method is 5% for the force estimation. Being the tension force estimation based on the measurement of the first natural frequency and being $f_1 \propto \sqrt{T}$, this implies having ≈2% accuracy on the frequency estimation.

Despite here referred to the Hovenring Bridge, the present methodology is general and applicable to any other case.

2. Hovenring Bridge description

The Hovenring is a roundabout flyover for bicycles placed in Eindhoven, the Netherlands. The structure is a bridge with a closed-box girder deck that realizes the "ring" with an outer diameter of 72 m, as shown in Figure 1a. The deck is suspended by means of 24 inclined stay cables, equally spaced along the deck. All the stays are connected to a 70-m high central steel pylon.

2.1. *The cables*

The 24 stay cables are 53 m long and are equally spaced along the deck. They consist of fully locked coils (diameter of 50 mm) with adjustable cylindrical sockets with threaded rods (M100x6 on the deck side and M72x4 on the pylon side), spherical nuts, and spherical washers. The inclination angle of the cables is 55° with respect to the horizontal. Cables located in correspondence of the lateral abutments have a nominal tension $T_1 = 705kN$ while the remaining 16 have a nominal tension $T_2 = 470kN$. Figure 1b shows the top view of the bridge and cable numbering: red cables are the ones with the higher nominal tension. To prevent wind-induced vibrations, each cable is endowed with two TMDs, specifically designed to protect modes up to 25Hz. For a detailed description of the design and installation of the dampers, the reader is referred to [8].

3. Methodology

The indirect assessment of the tension force in the stays of the Hovering Bridge is based on the following methodology:

- starting from the FE model of the stays already available from a previous study [8], equivalent models for the TMDs are designed and implemented in the numerical model
- experimental free vibration tests are performed on each cable to identify the first natural frequency
- a direct measurement of the tension force is performed in 4 cables with a jacking system
- a validation of the new cable FE model inclusive of the TMDs is performed by comparing the "direct" measurement of the tension value with the one predicted by the numerical model
- the tension force in the remaining 20 cables is estimated by letting it free to vary in the FE model until the numerical estimation of the first natural frequency matches the experimental finding

3.1. *The FE model*

Each cable is modelled using an equivalent tensioned beam finite-element scheme. Specifically, all the elements the stay is made of (threaded bars, washers and sockets) are modelled in the computational domain. Proper mesh refinement is adopted close to the constraints, being the locations interested by the maximum bending of both threaded bars and the cable itself. Boundary conditions are set at the washer-nut interface locations. Because of friction and the high tension force, the spherical nuts and washers act more as clamps than as hinges. Therefore, a hinge and a lumped torsional stiffness are considered for a realistic model of the constraints. The equivalent torsional stiffness values are determined by means of a best-fitting procedure between the experimental and numerical modal shapes of the system [9]. In the FE cable model, each TMD is modelled as 2 Degrees of Freedom lumped mass models, as shown in Figure 2. The parameters $\mathrm{M}_{1,2}$, $\mathrm{K}_{1,2}$ and $\mathrm{R}_{1,2}$ of the equivalent 2DoFs models are identified by matching the experimental transfer function of the dampers with the one from the simplified model, both in terms of magnitude and phase. As an example, the transfer function comparison for the low-frequency damper is shown in Figure 3. Table 1 summarises 2DoFs parameters.

3.2. *Free decay: experimental setup*

During the on-field campaign, each cable is instrumented with a triaxial accelerometer placed at 10 m from the cable socket, as shown in Figure 4. The measurement system consists of a Lord G-Link-200 sensor (Figure 5), that has an onboard triaxial MEMS accelerometer allowing high-resolution data acquisition with low noise. The accelerometer is installed such that two

Table 1: Lumped mass models' parameters

		TMD #1	TMD #2
M_1	[kg]	5	4.93
M_2	[kg]	7	5.1
K_1	[N/m]	3.99E+03	2.12E+03
K_2	[N/m]	1.17E+04	887.91
R_1	[Ns/m]	55.96	22.25
R_2	[Ns/m]	280.22	21.31

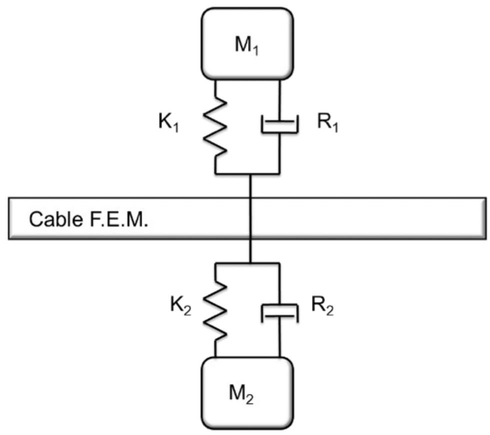


Figure 2: TMDs implementation in the FE model with 2 equivalent 1DoF systems

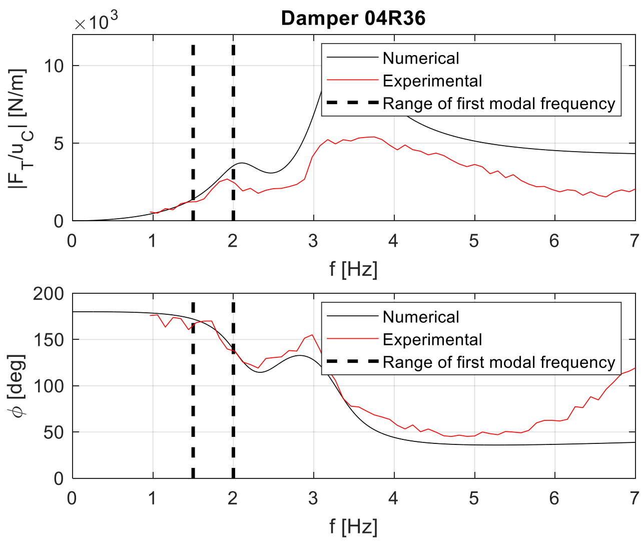


Figure 3: TF comparison for the low-frequency damper

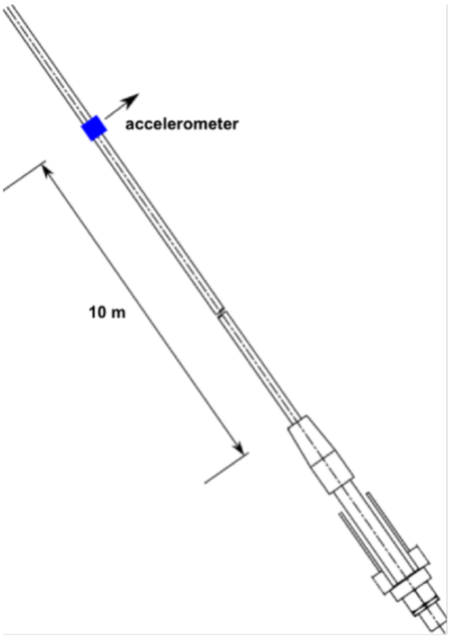


Figure 4: Accelerometer position on the cable.

Figure 5: The Lord G-Link 200 accelerometer installed on the cable.

(y and z) out of three axes are parallel to the excitation directions. The sampling frequency is 128Hz and the acquisition time is 100s. The free decay test method is used to identify the first natural frequency of the cable. It consists of exciting the cable by hand in the neighbourhood of the first mode frequency; then, once a steady condition of the vibration mode is reached, the cable is let to move freely. The operator responsible for the cable excitation was on a cherry picker (total mass about 7600 kg), standing on the bridge, close to the cable to be excited.

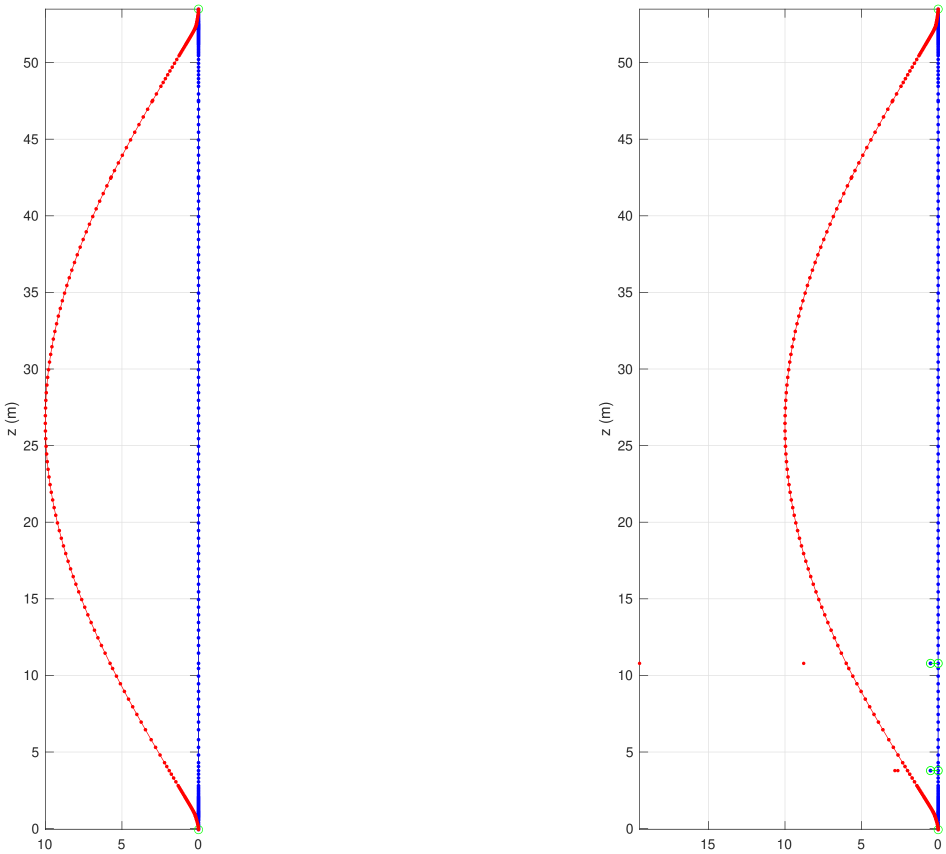
4. Results

4.1. FE cable model: TMDs effects on the first natural frequency

Being the cable FE model used to obtain the estimation of the actual tension force, it is important to ensure that it correctly reproduces the dynamics of the cable. To this purpose, detailed modelling of each component (sockets, washers and threaded bars) is included along with the dampers. Natural frequency and mode shapes are computed in the FEM, including the effects of the equivalent mass-spring-damper systems used to model the dampers. The resulting first natural frequency is smaller than the one for the corresponding undamped case. Figure 6 shows the comparison of the first mode shape and frequency with and without dampers for cable #5. Such a result is obtained considering as tension force the nominal value (T = $470kN$).

4.2. Free decay analysis

The time history of the decay motion is recorded by the accelerometer clamped to the cable and allows for the identification of the first mode frequency and damping ratio. Specifically, the first eigenfrequency detection is performed post-processing the decay time histories of the accelerations through the zero-crossing method to identify the frequency as a function of time. Vibration frequency is checked for two orthogonal directions. As an example, Figure 7 shows the time history of the free decay response of the accelerometer for cable #5 and the magnitude of its Hilbert transform in logarithmic scale (Figure 8) that is used to estimate the damping coefficient h_1, being the latter proportional to the slope of the curve as a function of time. Estimation of



(a) Undamped system $- f_1 = 1.782 Hz$ (b) Cable with TMDs $- f_1 = 1.764 Hz$

Figure 6: Cable FE model, first mode shape of undamped system (a) and with TMDs (b).

the damping ratio associated to the first mode is shown in Figure 9; Figure 10 reports instead the average results from the zero-crossing method for the eigenfrequency identification.

The time history in Figure 7 is characterized by time intervals with different envelope characteristics. Those differences are then reflected in the magnitude of the Hilbert transform, in the damping ratio and frequency estimation. Specifically, the following differences are highlighted:

- the first time interval (0–15 s) is characterized by the highest oscillation amplitude, associated with the highest damping ratio ($h_1 = 6.8‰$) and frequency estimation ($f_1 = 1.801 Hz$, the average over that time range). Such behaviour is ascribable to the high amplitudes, responsible for cable elongation and so increased tension force with respect to the rest configuration. For the analyzed cable, motion amplitude at the accelerometer location is $\approx 7.5 m/s^2$ over the first cycles; this corresponds to $0.1m$ oscillation amplitude at the anti-nodal location. Assuming that the mode shape is the one shown in Figure 6b, the cable elongation is equal to 0.001%, implying an increase of 3.1kN in the tension value (i.e. 0.6% with respect to the actual value) for the largest amplitudes. Such variation affects both the first eigenfrequency and the damping ratio.
- in the interval 15–33 s, oscillations' amplitude decays slightly less. In this time range, the TMDs are in their standard operative conditions. The damping ratio is decreased ($h_1 = 5.4‰$) with $f_1 = 1.792 Hz$, as shown by the grey dashed line in Figure 10. In the

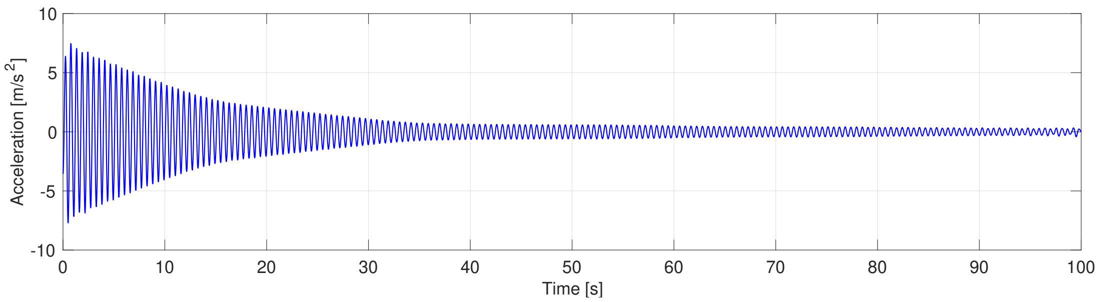


Figure 7: Time history of free decay response as recorded by the accelerometer

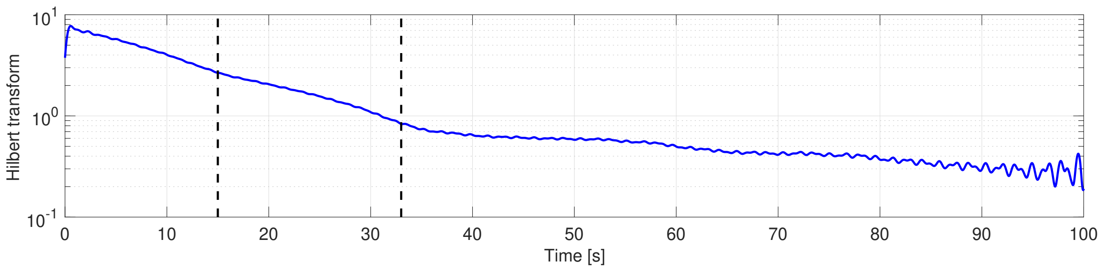


Figure 8: Magnitude of Hilbert transform as a function of time, mode 1 of cable 06.

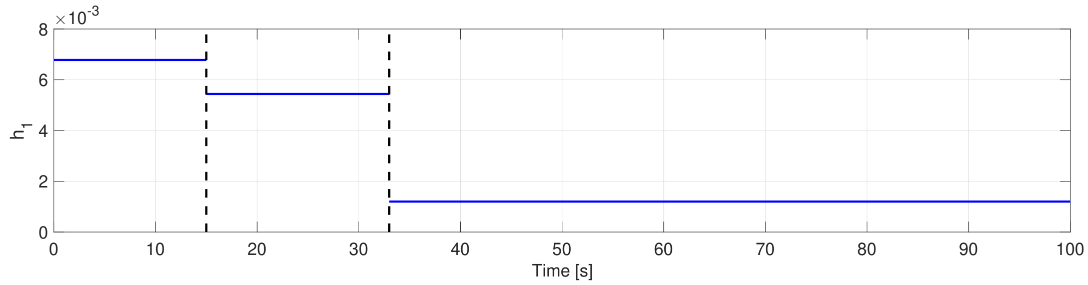


Figure 9: Damping coefficient for the first mode as a function of time

same figure, the dash-dotted lines mark the $\pm 2\%$ of the mean frequency in this time range. This is to show the variability in the frequency computation to guarantee a 5% error in the tension force estimation.

- in the last interval, small oscillations' amplitude are observed and the TMDs are less efficient. This results in a lower damping ratio ($h_1 = 1.2‰$) and slightly decreased estimation of the first eigenfrequency $f_1 = 1.78Hz$.

It is clear that the cable frequency changes depending on the motion amplitude and on the TMDs operative conditions.

The experimentally estimated eigenfrequency must be then compared to the one from the numerical model. The FEM of the cable includes the dampers that are correctly working and considers constant tension force. As a consequence, the experimental frequency to be considered is the one from the 15–33 s time range, where the TMDs are in their operative conditions, and therefore their equivalent lumped model is representative of their effects.

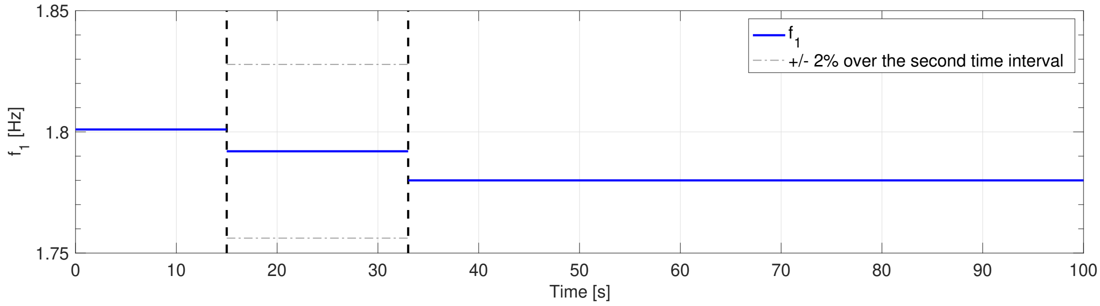


Figure 10: First eigenfrequency estimation as a function of time

4.3. Comparison between nominal and actual tension force in the stays

The experimental detection of the first eigenfrequency is performed for all the stays of the Hovenring Bridge. Then the experimental findings are used to proceed with the tension estimation. Specifically, the input tension force in the FE model of each stay is varied until the numerically estimated first eigenfrequency matches the experimental value. Table 2 summarizes the results: all the cables are listed, along with their nominal tension force, the experimental measures of the frequency and the outputs from the FEM (frequency and actual tension force). Cables that have been used for validating the FEM are reported in bold: for them, it is available also the direct (experimental) measure of the tension force that is performed by means of a jacking system. In addition, for all the cables not located in correspondence of the lateral abutments (i.e. the ones with lower nominal tension force), a correction to the numerically predicted tension force is applied to account for the increase of tension due to the weight of the cherry-picker used to reach the excitation location. Such correction is estimated as equal to the weight component of the cherry-picker along the cable direction, uniformly distributed over the 4 cables in each quarter. Due to the restraining scheme of the bridge, no correction is applied to the cables located over the lateral abutments.

5. Conclusions

This paper presents an indirect method to effectively estimate tension force in cables equipped with TMDs with an accuracy of 5%. It relies on a combined experimental and numerical approach: starting from measured frequency, the tension force is estimated through the FE model of the cable. The method has been here presented as applied to the cables of the Hovenring Bridge, a flyover roundabout in Eindhoven that has 24 inclined stays, each of them equipped with two TMDs. The procedure the method is based on foresees the experimental detection of the first natural frequencies of the cables, performed by means of free-decay tests. The output of the experimental campaign allowed highlighting the way motion amplitudes affect the first eigenfrequency detection; specifically, for the highest amplitudes, some non-linear effects due to an increased tension force in the cable have been observed. Then, it has been found that for the smallest amplitudes, the TMDs in the cable were not efficient, inducing differences in the eigenfrequency and damping ratio for the first mode. Such experimental findings were then used along with the FE model of the cables. Such model is based on tensioned beam elements, and includes different types of elements to properly model cable sections close to the constraints, characterized by sockets, threaded bars and washers. The connection with both the tower and the deck is modelled through equivalent hinges plus lumped torsional stiffness. Moreover, each TMD is modelled in the FEM as equivalent 2 Degrees of Freedom lumped mass models. The estimation of the tension force in the cables is finally achieved by letting it free to vary in the FE model until the numerical estimation of the first natural frequency matches the experimental

Table 2: Summary of the first natural frequency and tension force estimation for the stays of the Hovenring Bridge. Cables used for FEM validation are reported in bold.

Cable		Experimental		Numerical			Error
#	Nominal T [kN]	Freq. [Hz]	Tension [kN]	Tension [kN]	Correction [kN]	Corr. Tension [kN]	[%]
Cable 01	705	2.015	-	616.4	0	616.4	-
Cable 02	470	1.775	-	490	15.3	474.7	-
Cable 03	470	1.938	545.3	570	15.3	554.7	-1.7
Cable 04	470	1.597	382.2	394.1	15.3	378.8	0.9
Cable 05	470	1.792	-	488.9	15.3	473.6	
Cable 06	705	1.87	545.3	546.2	0	546.2	-0.2
Cable 07	705	1.955	577.9	581.6	0	581.6	-0.6
Cable 08	470	1.84	-	528.1	15.3	512.8	-
Cable 09	470	1.755	-	465.3	15.3	450	-
Cable 10	470	1.903	-	565.3	15.3	550	-
Cable 11	470	1.615	-	391.7	15.3	376.4	-
Cable 12	705	1.94	-	588.8	0	588.8	-
Cable 13	705	2.045	-	635.9	0	635.9	-
Cable 14	470	1.773	-	488.6	15.3	473.3	-
Cable 15	470	1.685	-	427.4	15.3	412.2	-
Cable 16	470	1.798	-	503.2	15.3	487.9	-
Cable 17	470	1.86	-	524.8	15.3	509.5	-
Cable 18	705	1.915	-	573.5	0	573.5	-
Cable 19	705	1.94	-	571.9	0	571.9	-
Cable 20	470	1.673	-	433.8	15.3	418.5	-
Cable 21	470	1.79	-	485.3	15.3	470	-
Cable 22	470	1.8	-	504.5	15.3	489.2	-
Cable 23	470	1.7	-	436	15.3	420.7	-
Cable 24	705	1.887	-	556.9	0	556.9	-

finding. The method as presented provides an accurate indirect estimation of the tension force in an efficient way, without the need for direct force measures. To further improve the model, authors are working on the inclusion of temperature effects in the estimation of the tension force, by relying on sets of experimental data acquired in different periods of the year.

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