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LYRA: a novel autonomous monitoring solution for long and short bridge stays and hangers

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Abstract
The determination of the tension in cable-stayed and tied-arched bridges has been a concern for authorities for decades in order to verify the integrity of the structures. The increasing age of the bridges and the recent collapse of several of them across Europe is making their monitoring more important than ever. Nowadays, the analyses usually rely on sparse on-site measurements of the strain or of the direct force when hangers are replaced (i.e., a few times in the lifetime of the structure) or on the use of accelerometers and the simple taut string theory, which ignores the bending stiffness of the cable and its boundary conditions, to measure the tension (usually at best once a year). As a result, damages can be detected late and the measured data depends on the environmental conditions during the measurement (traffic, temperature, wind,…)

In this paper, we first describe LYRA, a novel autonomous bridge monitoring solution based on wireless accelerometers and on an advanced mathematical model of the hangers. The accelerometers measure the response of the hangers to environmental solicitations six times a day and dispatch the data to a central station. Then, the station computes the tension of the cables from the time response of the sensors by means of a robust algorithm, which is an extension of the simple taut string theory for flexible anchors and/or non-negligible bending stiffness. Finally, the measured tensions are uploaded on a webserver, where they can be monitored from any apparatus with an internet access, and alerts are automatically generated if tensions outside of pre-set boundaries are measured. The capabilities of the system and the necessity for a model that takes bending effects into account are finally demonstrated on three stays of the Wandre, Obsersvatoire (Liège) and Harchies bridges.

Keywords: cable, bridge, monitoring, LYRA, vibrations

1 Introduction

Cable-stayed bridges are common practice in civil engineering and are widespread all over the world. To ensure their safety and avoid failure such as those that occurred in Toulouse (2018) or Genova (2019), governing authorities often perform periodic inspections of the cables, which are a good indicator of the integrity of the bridge as an issue usually leads to a redistribution of the loads [1,2,3,4].

The Lanaye bridge, located at the border between Belgium and the Netherlands, for instance, is inspected by the Service Public de Wallonie (SPW) about once a year. This procedure allowed to detect a crack-corrosion failure in one of the stays and to replace the cable before the occurrence of more severe problems [1] (see Figure 1). Such corrosion induced failures are a worldwide concern even though every precaution and protection measures are taken when assembling the strands and rods that compose the bridge cables [4,5,6].

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Bridge inspections are often quite sparse (about once a year/bridge in Belgium) and usually rely on cumbersome vibration measurement setups with wired accelerometers, very long cables and on the taut string theory [3,4], which completely neglects the bending stiffness of the instrumented cable and can lead to large errors for small and/or stiff cables.

In this paper, we introduce the LYRA, a fully autonomous cable tension monitoring solution that greatly simplifies the measurement campaigns. It is suitable for long term monitoring, and provides accurate tension estimates for cables, irrespective of their bending stiffness. The LYRA comprises wireless sensors placed on each instrumented stay and a solar powered central station which aggregates the measurements, computes the tension using advanced algorithms, and finally upload the data on a cloud server. The necessity to consider the bending stiffness in the model will be assessed on three stays (Wandre, Observatoire and Harchies) characterized by different length to cross-section ratios.

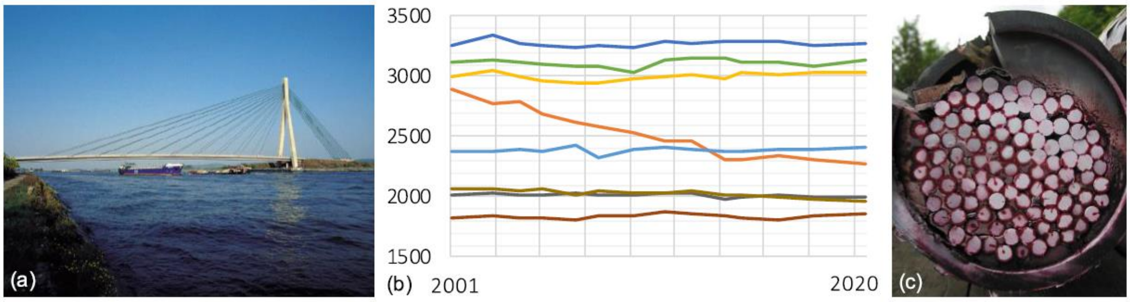

Figure 1: Photograph of the Lanaye bridge (left), tension variation between 2001 and 2020 in 8 instrumented stays (middle) and photograph of the cross section of a damaged stay (right)

2 Hardware solution of the LYRA

The hardware solution of the LYRA comprises three main components, which function together to provide a full monitoring solution (see Figure 2). Wireless accelerometers first measure the response of the instrumented cables to environmental solicitations such as traffic or wind. They dispatch the acceleration measurements to a solar powered central station, which computes key processing indicators (KPIs) from the acceleration measurements, saves the data to an internal database, and finally uploads the relevant data on a cloud server. Finally, a web application, available on any device with an internet connection, is used to display the data and to send alarms when the KPIs reach user defined thresholds.

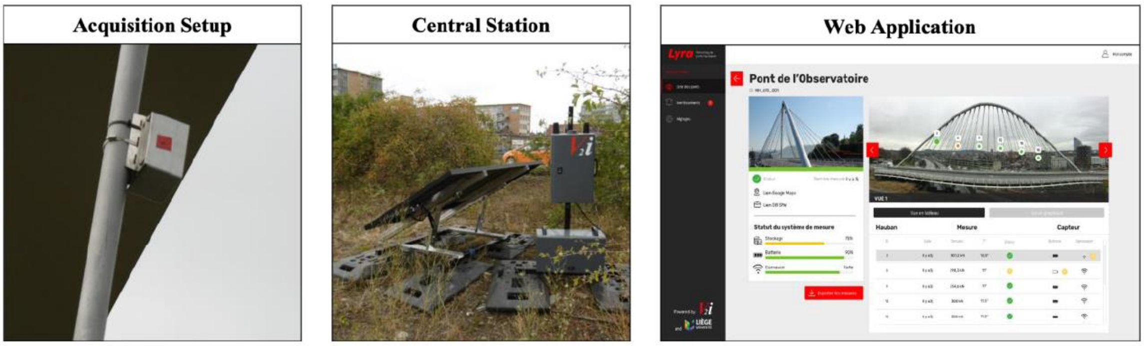

Figure 2: the LYRA solution, comprising wireless sensors (left), a central station (middle) and a cloud solution (right)

2.1 Central station

The central station has three main functions. First, it controls the acquisition system. Several strategies are implemented to minimize the risk of collision or loss of packages. For instance, the station activates the sensors one after the other according to a specified schedule. A quality index is associated to the time series depending on their signal-to-noise ratio and the stability of the wireless connection. It allows to determine confidence levels for the subsequent identification of tensions or to directly discard some measurements. The sensors are also able to keep a part of the signal on their internal memory for a few seconds to transmit it correctly even though the connection with the station is intermittent.

Second, the station processes the acceleration measurements received from the wireless sensors and computes the tension in the cables.

Third, the station acts as a relay by uploading and organizing raw data received from the acceleration and the temperature sensors but also the tension estimates and information about the remaining capacity of the batteries, both on an online server and on its own on-site database.

In addition, some parameters are embedded inside the memory of the station and can be modified either by direct access, or via the cloud. Typically, it encompasses the length and mass of the cables that are necessary for the tension identification. Apart from that, the sampling frequency, the duration of acceleration measurements, their timing, and the modal identification parameters (see section 3.1) are defined there as well.

The central station can either be powered by the network or using a solar panel, for remote applications. As both sources of power are usually intermittent, an internal battery powers the station during the losses and a smart controller prevents the battery from fully discharging.

2.2 Wireless nodes

The acceleration measurements are performed using wireless sensors, which have many advantages. First, it does not require pulling wires along the whole bridge to link the sensors with the central station. Second, it allows the sensors to be easily placed far enough from the bridge deck to prevent vandalism issues. Third, it avoids adding mechanical weak points to the network, such as wires which are in addition complicated to repair or to replace.

The sensors are powered by special D-size batteries with low self-discharge and high robustness to temperature variations. These batteries are sufficient to record five-minute long signals, four times a day, for ten years, at least. The sensor and battery assemblies have then been placed inside IP66 rated, waterproof and UV-resistant casings whose internal structure has been 3D printed according to our needs. They also contain a temperature sensor with an accuracy of 0.25°C, an antenna, and the electronics necessary to communicate with a central station.

Finally, the casings are clamped to the stays by means of U-shaped metallic elements which can be adjusted to fit the diameter of the instrumented cable. In order to ensure that the natural frequencies of the cables are well distinct from those of this acquisition system, it has been tested on a shaker. It has been shown that the sensor resonates at very high frequencies, that are hardly ever excited when dealing with ambient vibrations.

2.3 Cloud solution

Finally, a web application dedicated to the monitoring of axial forces in the stays and the hangers of cable supported bridges has been developed. It allows to visualize the variation of the tension in each cable by means of tables or graphs and it sends automatic warnings if an issue is detected on the central station (e.g. a power loss) or if the tension in an instrumented cable is outside specified limits.

3 Tension identification procedure

The tension in each instrumented cable is identified in two steps: first the natural frequencies of the cable are automatically computed. Then, the resulting tension is computed using a mathematical model of the instrumented stay and the previously measured frequencies.

3.1 Frequency identification

The natural frequencies of each instrumented cable are computed from their response to ambient excitations (wind, traffic,…) by means of the "crystal-clear" version of the Stochastic Subspace Identification (SSI) algorithm and stabilization diagrams [7,8]. Examples for the Wandre, Observatoire and Harchies bridges are discussed in section 6.

3.2 Tension identification

The parametric model of a cable with length L, mass per unit length μ, cross section stiffness EI and tension H attached in each end by supports of dimensionless rotational stiffnesses ρ_i and translational stiffnesses ρ_i^* is illustrated in Figure 3. Solving the equations of motion of this cable provides a relationship between F(n), the n[th] natural frequencies identified from the acceleration measurements, and the tension.

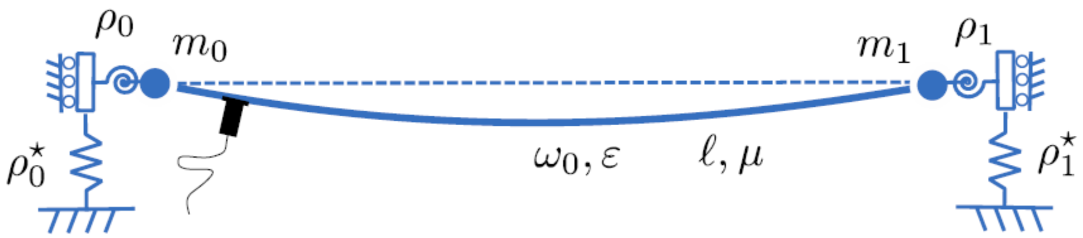

Figure 3: Parametric model of a cable

Depending on the value of ε, the non-dimensional bending stiffness of the cable, which is defined as

$$\varepsilon = \sqrt{\frac{EI}{HL^2}} \quad (1)$$

three different methods can be used to obtain the tension H in the cable from the natural frequencies.

If $\boldsymbol{\varepsilon} = \mathbf{0}$, the cable has no bending stiffness, the F(n)/n curve is a horizontal line, and the taut string theory [3,4] directly provides a relationship between the tension and the estimated natural frequencies

$$F(n) = n \times \frac{1}{2}\sqrt{\frac{H}{\mu L^2}} \quad (2)$$

which can be easily solved using a least square fitting on the measured natural frequencies or using only one frequency. This method is the most used by authorities for bridge monitoring [1].

If $\boldsymbol{\varepsilon}$ is small, the perturbation method can be applied to the equations of motion of the cable, and an asymptotic solution, which also directly links the tension in the cable to its natural frequencies can be derived as

$$F(n) = \frac{1}{2}\sqrt{\frac{H}{\mu L^2}}\left(n + 2np\varepsilon + \left(\frac{\pi^2 n^2}{2} + 4p^2\right)\varepsilon^2\right) + ord(\varepsilon^3) \quad (3)$$

where p is a dimension-less parameter that takes the stiffness of the supports into account and has values $p = 0$ if the cable is hinged-hinged and $p = 1$ if the cable is clamped-clamped. This formulation can also easily be solved using a least-square fitting on the measured natural frequencies, where parameters H and ε are variables and p is fixed. Note that if $\varepsilon \to 0$ in the asymptotic solution (equation (3)), the formulation degenerates to that of the taut string (equation (2)). As a result, if at least 3 frequencies are measured, the asymptotic solution should always be used in lieu of the taut string.

If $\boldsymbol{\varepsilon}$ is large, typically over 3%, the asymptotic model is not valid, and it is suggested to use a semi-analytic model. This model relies on solving an inverse problem by means of an optimization algorithm (differential evolution). Many more details about the derivation of the asymptotic and semi-analytic models are available in the paper of Foti et al. [9]. Note that the equations of motion of the semi-analytic model are identical to those used to derive the asymptotic model and it can therefore be used as a reference case.

3.3 Identification strategy implemented in the LYRA

The identification strategy implemented in the LYRA is depicted in Figure 4 and relies on the frequency identification techniques described in section 3.2 and on both the asymptotic and the semi-analytic models:

1. The natural frequencies of the cable are extracted from acceleration measurements using SSI.
2. Asymptotic solutions are computed from the measured natural frequencies assuming the cable is either hinged-hinged or clamped-clamped. If the results are close and if the bending stiffness is small, the computation is over: it is not necessary to refine the tension estimation.

3. If $\varepsilon > 3\%$ or if both asymptotic models provide different outputs, the asymptotic model is not valid and the semi-analytic model is used, with initial conditions obtained from the asymptotic solution assuming p = 0.5 (intermediate solution between fully hinged and fully clamped).
4. If $\varepsilon > 10\%$, it might be possible to identify the parameter "p" rather than fixing it to 0.5. Several computations with variable "p" are performed and if they converge, this solution is kept. Otherwise, solution (3) is chosen.

This identification strategy therefore makes use of the asymptotic model to save computational time and energy when ε is small (which can be critical for remote applications), and of the semi-analytic model when more accuracy is needed.

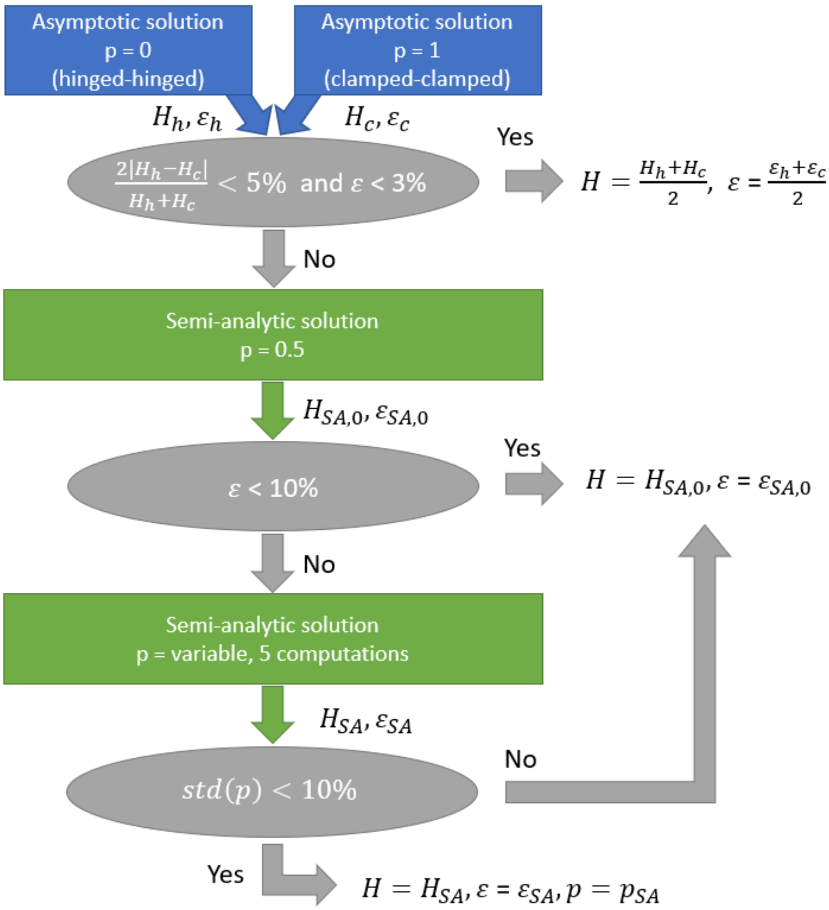

Figure 4: Identification strategy implemented in the LYRA

4 Test cases

The performance of the proposed identification algorithms is assessed on three typical bridges in Belgium which have been instrumented with the LYRA. To keep this paper short, only 1 stay per bridge is presented next, although large scale monitoring operations are common practice with the LYRA (the 30 stays of the Lanaye bridge are currently being monitored for instance). The goal is to illustrate the impact of the bending stiffness of the cable on the measured tension so 3 very different stays have been chosen:

1. Stay 38 of the Wandre bridge (see Figure 5) is 174 meter long, has a mass per unit length of 79.9 kg/m, has a very small bending stiffness, and has been monitored between August and October 2020.

2. Stay 15 of the Obervatoire bridge (see Figure 6) is 20 meter long, has a mass per unit length of 12.6 kg/m, is an intermediate case in terms of bending stiffness, and has been monitored between December 2019 and January 2020.

3. Stay 2 of the Harchies bridge (see Figure 7) is 4.42 meter long, has a mass per unit length of 25.3 kg/m, features a significant bending stiffness, and has been monitored between January and March 2020.

Figure 5: Photograph of the Wandre bridge (stay 38 is highlighted in red). Photograph from [10].

Figure 6: Photograph of the Observatoire bridge (stay 15 is highlighted in red)

Figure 7: Photograph of the Harchies bridge (stay 2 is highlighted in red)

Table 1: Summary of the measurement results

		Wandre	Obervatoire	Harchies
Taut string Least Square	Tension [kN]	4677 ± 89	373 ± 7	1498 ± 65
	Error [%]	~ 0	+ 15	+ 85
	ε [%]	-	-	-
Taut string F(1)/1 or F(2)/2	Tension [kN]	4684 ± 109	343 ± 12	838 ± 19
	Error [%]	~ 0	+ 7	+ 33
	ε [%]	-	-	-
Asymptotic model (p=0.5)	Tension [kN]	4654 ± 122	322 ± 15	663 ± 17
	Error [%]	~ 0	~ 0	+ 10
	ε [%]	0.5 ± 0.6	2.6 ± 0.2	8.5 ± 0.3
Semi-analytic model (p=0.5)	Tension [kN]	4657 ± 105	321 ± 15	600 ± 58
	Error [%]	-	-	-
	ε [%]	0.2 ± 0.4	2.6 ± 0.5	11.0 ± 1.1

Table 1 summarizes the tensions identified on all three bridges with all four methods and Figure 8 to Figure 10 plot the measurement results. The errors computed are the difference between each case and the semi-analytic case, which is the most advanced model proposed in this paper. The confidence intervals provided are the 2-σ values, which indicate the bounds within which 96% of the measurements are found.

The measurement results obtained on the Wandre bridge are displayed in Figure 8. For this cable, modes 2 to 6 are clearly identified on the PSD but mode 1 is not (top left). The F(n)/n curves are completely flat, i.e. the cable behaves as a taut string (top right). The bending stiffness parameter (bottom left) is identified only with the asymptotic and semi-analytic model as the taut string assumes zero stiffness, and a large spread is observed, which illustrates that it is useless to identify this parameter when it is very small. The identified tension (bottom right) is nearly identical with all four proposed models.

The identification results on the Observatoire bridge are depicted in Figure 9. This time modes 1 to 6 are clearly identified (top left) and the resulting F(N)/N curves increase from ~4.1 to ~4.5 (top right). The bending stiffness is small but identifiable (~2.5%) and, as expected, the asymptotic and semi-analytic models yield similar results (bottom left). The identified tensions show that taking bending stiffness into account is critical for this cable (bottom right) as the taut string theory overestimates the tension by 7 to 15% depending on the chosen modes (black and red curves). Nevertheless, the stiffness is sufficiently small to use the asymptotic model.

Figure 10 finally depicts the results obtained on the Harchies bridge. The PSD of the response (top left) shows that 5 modes are identified and that there are clearly not evenly spaced. The resulting F(n)/n curves (top right) indeed increase from ~20 to ~35 in 5 modes only. This time, the bending stiffness is sufficiently high to invalidate the hypotheses of the asymptotic model as values of 8.5% and 11% are identified (bottom left). The tension (bottom right) is only properly estimated by the semi-analytic model. The taut string theory is completely off (+33 to +85%), and the asymptotic model leads to a slight overestimation (+11%). Even though the bending stiffness is higher than 10%, the identification of the tension is stopped at step 3 of the algorithm (see 3.3) because the stiffness parameter p does not converge.

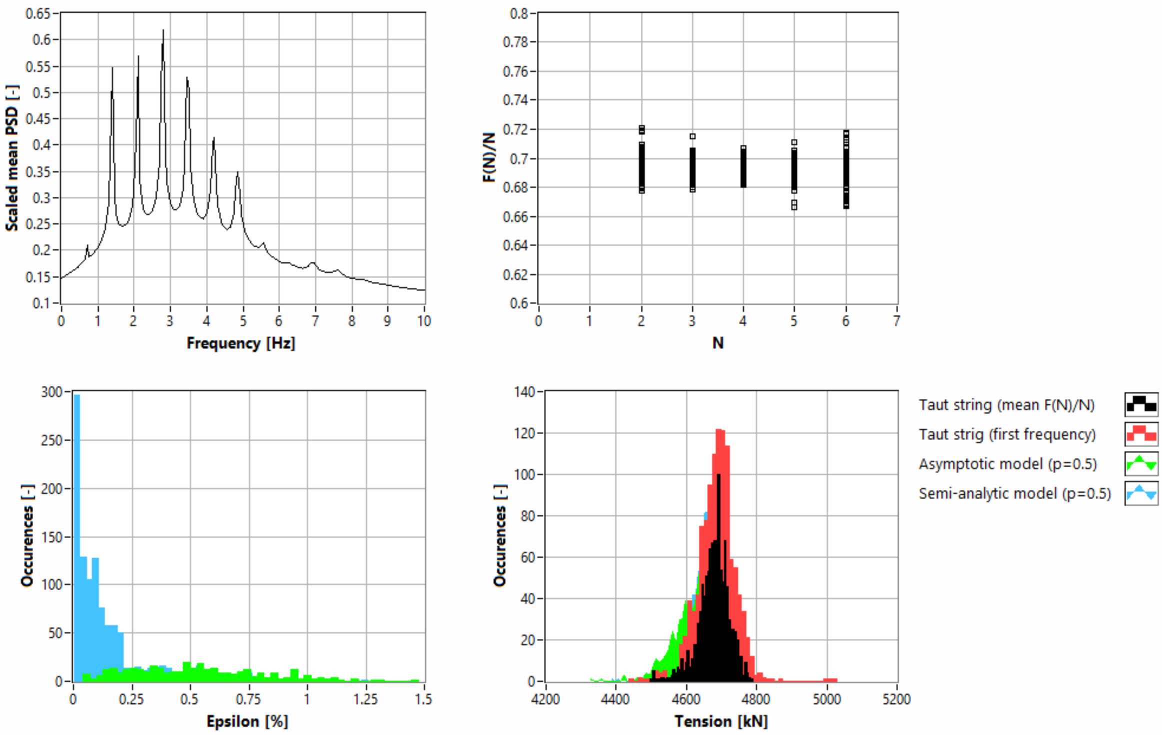

Figure 8: Identification results on stay 38 of the Wandre bridge (1136 measurements from 19/08/2020 to 19/10/2020)

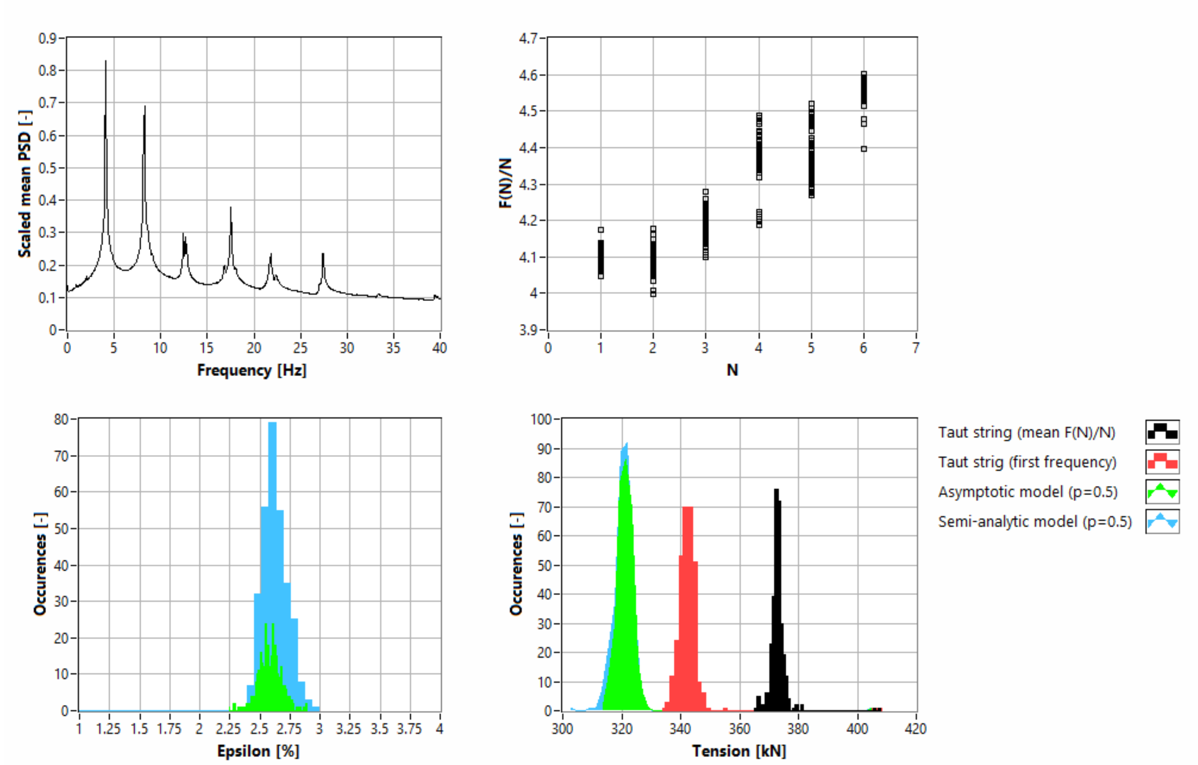

Figure 9: Identification results on stay 15 of the Observatoire bridge (304 measurements from 06/12/2019 to 03/01/2020)

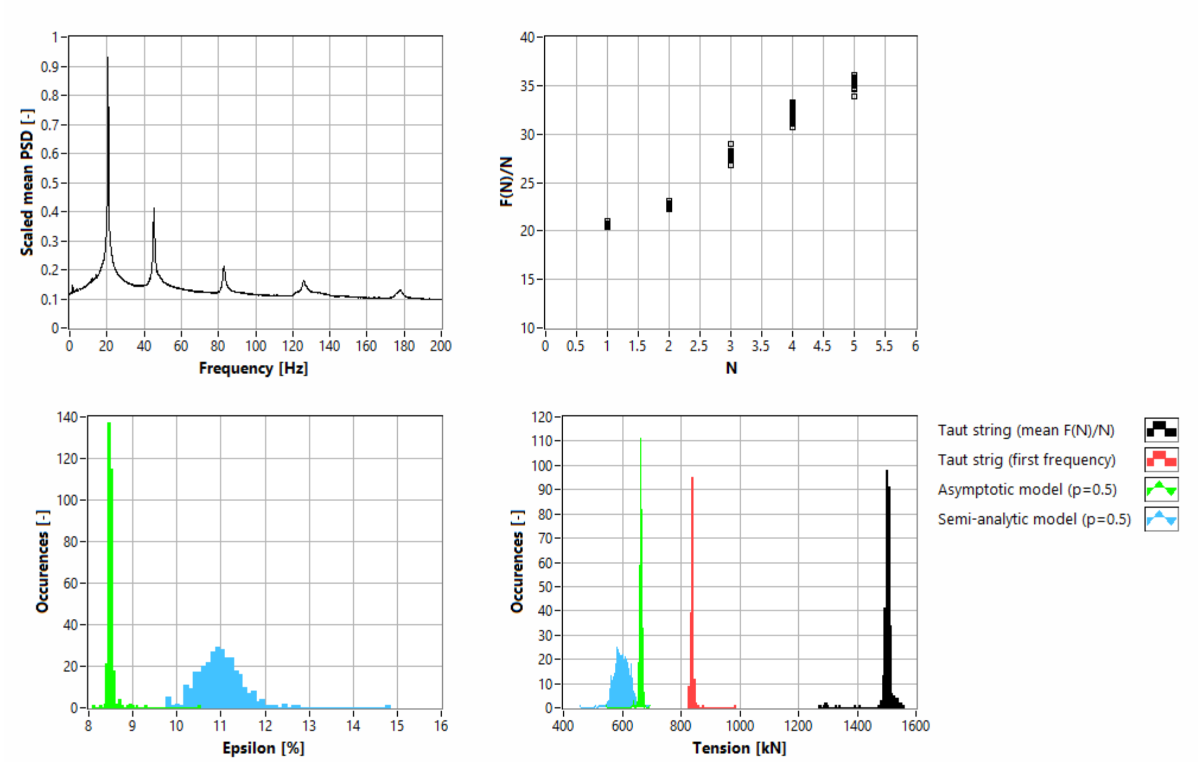

Figure 10: Identification results on stay 2 of the Harchies bridge (311 measurements from 31/01/2020 to 11/03/2020)

5 Conclusions

This paper first presented the LYRA, a novel autonomous solution for bridge cables tension monitoring. The LYRA employs wireless accelerometers to ease the installation procedure, a solar-powered central station for potential remote installations, a cloud solution to access the data remotely. A powerful identification algorithm that takes the bending effects into account and is capable of measuring accurately the tension in stays irrespective of their length and anchorage conditions.

The capabilities of the LYRA are demonstrated on three bridges in Belgium with small, moderate, and high bending stiffness, which illustrates the necessity for advanced computation models when tackling short hangers, as the taut string model leads to errors up to 85% in tension estimation.

Acknowledgements

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