Dynamic Monitoring of a Cable-Stayed Bridge: Monitoring System and First Results

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Abstract. The Éric Tabarly bridge in Nantes is a 210m long cable-stayed road bridge crossing the Loire River, that was inaugurated in 2011. It is composed of a 27 m wide steel deck divided into two spans by a 57 m high steel pylon, being the main span 143m long. In the context of the European Research Project DESDEMONA (DEtection of Steel DEfects by Enhanced MONitoring and Automated procedure for self-inspection and maintenance), the bridge has been equipped with a dynamic monitoring system, constituted of 16 uniaxial accelerometers installed both on the deck and on the Pylon, with accelerations being recorded with a sampling rate of 100 Hz. This paper describes the dynamic monitoring system installed in the bridge and the results achieved during the first months of operation, including the characterization of vibration levels (maximum and effective values) as well as the automatic identification of the bridge modal properties. Finally, the effects of operational and environmental conditions on modal properties are studied.

Keywords: Bridge Engineering, Operational Modal Analysis, Structural Health Monitoring, Operational and Environmental Effects.

1   Introduction

Nowadays, the development of monitoring systems capable of detecting damage at an early stage is one of the primary topics of research related to civil engineering structures due to the large number of equipments built during the past century that are reaching their expected lifetime [1] [2]. This field has also gained importance within recently built structures, being the installation of vibration-based monitoring systems occurring more commonly right from the moment when the structure starts operating, which allows for a better characterization of its behaviour evolution on the long run, providing essential information for a small percentage of the primary investment.

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These systems are based on the identification of the modal properties of the most important vibration modes of the studied structures and are considered one of the most reliable monitoring procedures to be implemented in civil engineering structures, being able to operate even under very low vibration levels [3]. The modal properties of a structure are directly connected to their mass and stiffness, representing accurate indicators of their global condition. For the past decade, vibration-based systems have been implemented in quite distinct types of structures, from bridges to wind turbines [4] [5], including buildings, bell-towers and concrete dams [6] [7] [8].

Vibration-based monitoring systems are especially suitable to detect structural alterations due to the sensitivity of natural frequencies to these changes. However, civil engineering structures are usually subjected to varying operational and environmental conditions, which affect the structure behaviour and more specifically their modal properties [9]. Moreover, data variability due to the effects of such external conditions is normally of higher magnitude than the variability due to small damages, thus it is essential to minimize the effects of operational and environmental conditions on natural frequencies in order to obtain features that are suitable for the timely detection of novel structural behaviour due to the occurrence of small damages.

In this context, this paper presents a brief description of the dynamic monitoring system installed in the Tabarly bridge, in Nantes, and the results obtained over one year of continuous dynamic monitoring, including the characterization of vibration levels, modal identification and the tracking of modal properties. Finally, concluding remarks regarding the developed works are presented.

2   Instrumented Bridge and Monitoring System

The Éric Tabarly bridge in Nantes is a 210 meters long cable-stayed road bridge crossing the Loire River, that was inaugurated in 2011. It is composed of a 27 meters wide steel deck divided into two spans by a 57 meters high steel pylon, being the main span 143 meters long (see Figure 1).

In 2016, a first set of instrumentation has been installed to monitoring the vibration behaviour of the bridge. Consequently, 16 uniaxial accelerometers have been installed in the bridge with 2 different acquisition zones: 8 accelerometers were located in the deck and another 8 accelerometers in the pylon. Data are acquired through a *PEGASE* generation 2 acquisition card marketed by A3IP company under University Gustave Eiffel license, for each of the two zones. Each acquisition card exports voltage measurements at a sampling frequency of 100 Hz.

Silicon Designs 2210 accelerometers are being used, which can collect accelerations from -10 G to 10 G and are usable up to a 700 Hz acquisition frequency. In the deck, each slot contains two uniaxial accelerometers, with the first along Y and the second along Z. At the section X3 there are two accelerometers along Y. In the pylon, three of the eight accelerometers follow the direction of axis Z, while the others are installed along X direction.
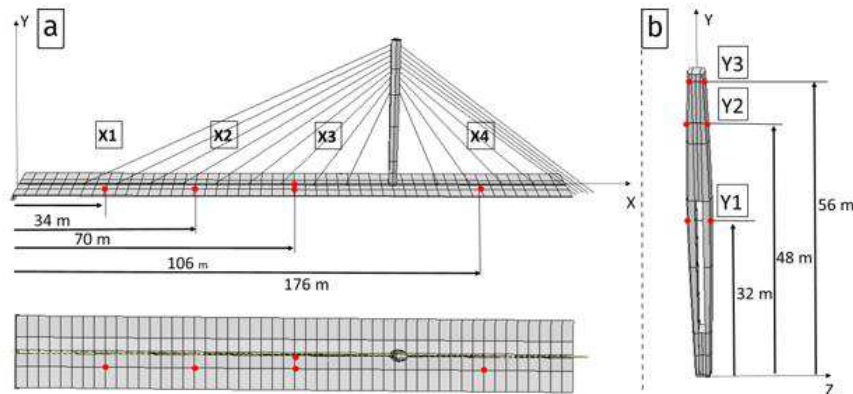
Fig. 1. Representation of the bridge, with red dots showing the location of the accelerometers: a) detail of the deck; b) detail of the pylon.

3 Continuous Dynamic Monitoring

3.1 Characterization of vibration levels

The vibrations in the bridge are mainly due to the road traffic crossing it daily, and to the action of the wind. The root mean square (RMS) of the accelerations measured by each sensor were calculated for every hour of data, allowing to characterize the intensity of the measured vibrations, to access the quality of the results and to detect eventual sensor malfunctions. This processing was performed for the entire monitoring period, though the evolution of the RMS over time is represented in Figure 2 only for the period between 15/07/2018 and 01/09/2018, so that a clearer figure could be achieved, facilitating the analysis of the results. Data from the deck and from the pylon was represented separately, and each of the respective 8 measuring channels is represented by a different colour.

In the case of the deck, a clear division is verified between the results obtained from the five sensors measuring vertical accelerations (Y direction in Figure 1) and from those measuring lateral accelerations (X direction in Figure 1), with the intensity of the vertical ones being 5 to 10 times higher. It is also possible to distinguish a pattern of five days with higher accelerations followed by two days with decreased accelerations, which is in complete correspondence with working days and weekends. This pattern is also visible with the results obtained from the pylon, though not as clear as with the deck.
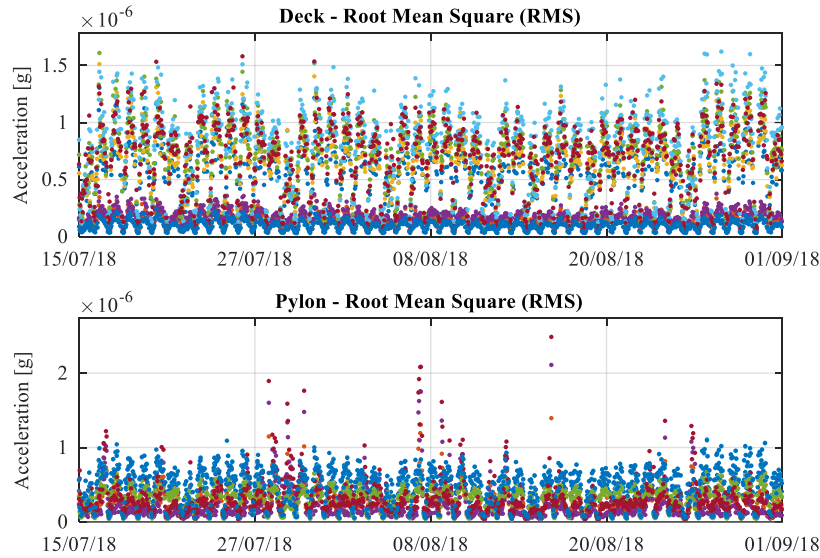
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Fig. 2. Vibration levels measured in the Deck and in the Pylon between 15/07/2018 and 01/09/2018.

3.2   Automated Operational Modal Analysis

There are several methods that can be used in the performance of operational modal analysis, which may be automated in different ways. For instance, the application of the singular value decomposition to each time series of accelerations, and the assembly of the sample first singular values, allows the construction of maps where colours are used as a function of energy intensity, thus providing approximate estimates of the natural frequencies of the structure and their evolution over time.

This strategy was applied to the same time-series measured in the deck that were used to build Figure 2, resulting in the colourmap presented in Figure 3, where warm colours (red) are associated with higher values. There are several horizontal red alignments between 0 and 8 Hz, corresponding to the deck's natural frequencies, indicating the existence of more than 15 vibrations modes. These alignments are very-well defined up to 4 Hz, with increased visual uncertainty for higher frequency ranges. A closer analysis of the colour map allows to perceive a wave-like variation of the natural frequencies over time, which is most likely due to the influence of daily temperature oscillations.

After this preliminary and straightforward analysis, a second automated approach that relies on the combination of the Covariance-driven Stochastic Subspace Identification (SSI-Cov) method with a routine based on cluster analysis, was used to continuously track the structure's modal properties. The theoretical background of this methodology is carefully explained in [10].

Since quite different monitoring periods were available for the deck and for the pylon, the time-series measured in these two substructures were analysed separately.
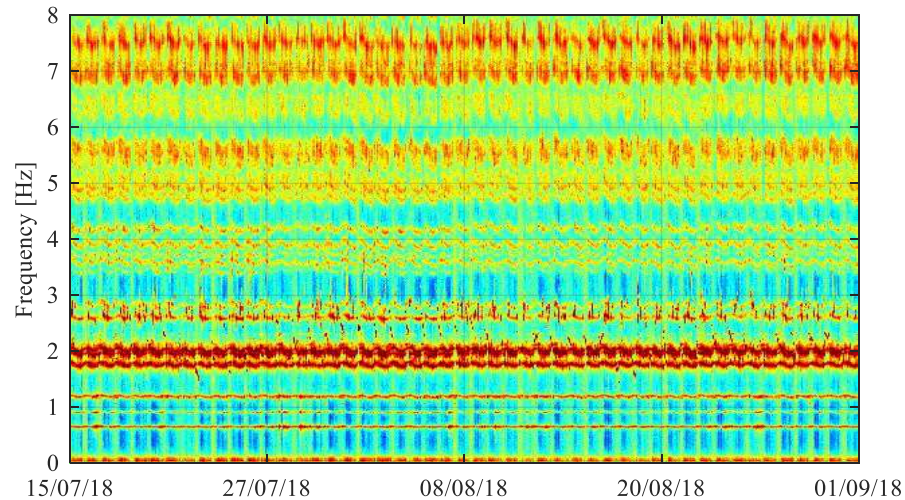
Fig. 3. Colour map with the frequency evolution of the deck between 15/07/2018 and 01/09/2018

In the case of the deck, it was possible to identify and track 18 vibration modes, between 20/04/2018 and 10/09/2018, with identification rates within the available files higher than 90 %, for most of the tracked modes.

These results are resumed in Table 1, where the mean and the standard deviation of each modes' natural frequency and damping are presented together with the Modal Phase Collinearity (MPC) [11] obtained from their mode shapes. These modes can be found between 0.6 Hz and 7.5 Hz, with increasing standard deviations from lower to higher modal orders, mostly because of external conditions. In turn the obtained damping ratios vary between 0.5 % and 1.5 %, as it was expected. Most of the identified vibration modes are real and present MPC values close to 1, though there are a few modes with MPC below 0.90, indicating relevant complex components in their mode shapes.
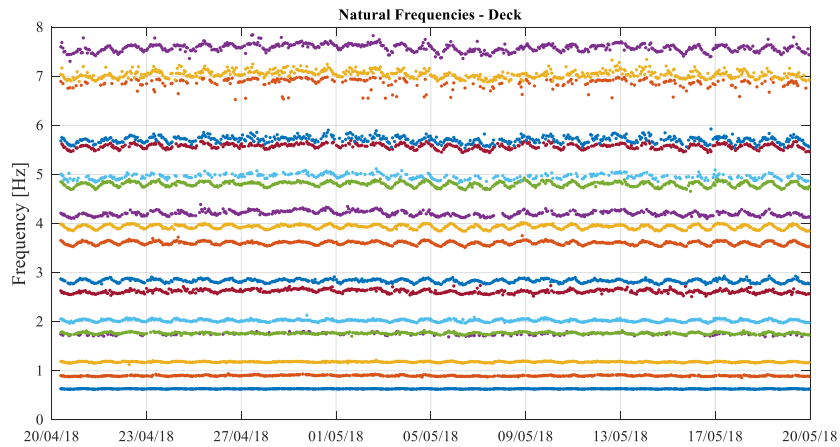
The evolution of the deck's identified natural frequencies is presented in Figure 4 for one month, where each colour represents a different vibration mode and each point results from the analysis of hourly data. Such as in the case of Figure 3, well-defined horizontal alignments are observable, though in this case with higher accuracy for the whole studied frequency range. Only the fourth mode (represented in purple) is hardly detectable due to frequency proximity to the fifth mode (represented in green). Once again, regular variations on natural frequencies are visible, which are consistent with daily temperature fluctuations.

The procedure used for the automated identification of modal properties was repeat for the time-series of accelerations recorded on the pylon over one year, between 13/07/2017 and 10/09/2018. Similar results were obtained with 17 modes being identified between 0.5 Hz and 10.5 Hz. Damping ratios are also contained between 0.5 % and 1.5 % and only two modes consistently presented MPC values below 0.90.

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Table 1. Deck: modal properties and identification success rates between 20/04/2018 and 10/09/2018.

Mode	Frequency [Hz]		Damping [%]		MPC	Success Rate [%]	
	Mean	Std	Mean	Std		Full Period	Available Files
1	0.63	0.004	0.56	0.266	1.00	72.4	99.8
2	0.89	0.010	1.22	0.827	0.97	66.7	91.9
3	1.17	0.011	0.85	0.436	1.00	72.5	99.9
4	1.73	0.022	1.01	0.567	0.71	17.2	23.7
5	1.75	0.020	0.80	0.434	0.92	68.7	94.8
6	2.01	0.025	0.80	0.370	0.96	72.3	99.6
7	2.60	0.034	0.94	0.492	0.96	70.5	97.2
8	2.81	0.037	0.88	0.364	0.92	70.4	97.0
9	3.57	0.040	0.84	0.247	0.90	71.7	98.9
10	3.90	0.046	0.84	0.247	0.92	71.9	99.2
11	4.17	0.043	1.05	0.477	0.89	62.8	86.6
12	4.76	0.055	1.14	0.294	0.92	71.9	99.1
13	4.93	0.053	1.05	0.395	0.81	42.4	58.5
14	5.53	0.057	1.19	0.292	0.55	60.4	83.4
15	5.66	0.071	1.33	0.453	0.68	66.9	92.3
16	6.82	0.076	0.97	0.265	0.13	34.4	47.5
17	6.99	0.072	0.86	0.206	0.82	70.9	97.7
18	7.52	0.079	1.05	0.239	0.92	71.8	99.0

Fig. 4. Evolution of the natural frequencies of the deck between 20/04/2018 and 20/05/2018.

The evolution of the natural frequencies of the pylon is presented in Figure 6 for the entire monitored period. The distinction between modes is clear once again, with

higher data variability in the modes of higher order. In this case, since over one year of data is represented, it is possible to observe a seasonal wave on natural frequencies, due to the effect of temperature. Daily fluctuatinos were observed as well, though these are not detectable in Figure 5, due to the dimension of the sample. The blank space during April 2018 corresponds to a period of system maintenance.

Finally, a primary analysis of the environmental and operational conditions affecting the dynamic behaviour of the bridge was performed. The whole set of natural frequency estimates obtained for the second mode of the pylon were represented as a function of ambient temperature. A linear relation was found between the two variables, though a coefficient of determination of only 0.6 indicates that other variables may significantly affect the natural frequencies of the pylon.
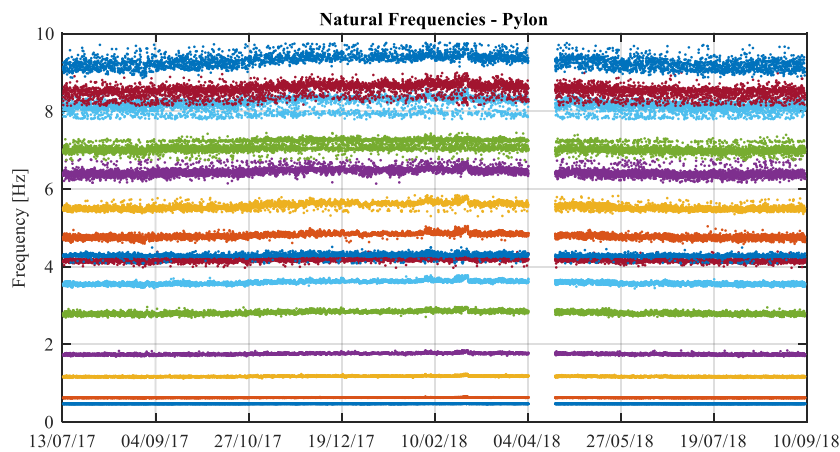

Fig. 5. Evolution of the natural frequencies of the pylon between 13/07/2017 and 10/09/2018.
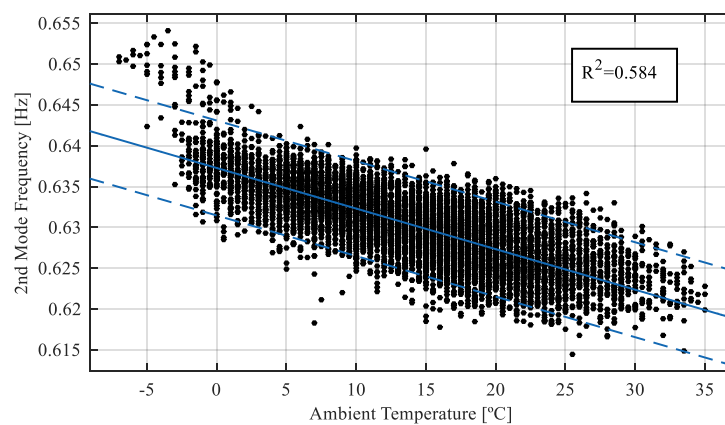

Fig. 6. Relation between natural frequencies and ambient temperature.

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4   Conclusion and Future Developments

An efficient and detailed evaluation of civil engineering structures in real time require proper monitoring systems to remotely assess their condition. In that sense, the vibration-based monitoring system described in this work present a real, proven solution for this issue. The monitoring system provided quality time-series of accelerations that allowed an accurate identification of modal properties. Most of the data files missing were due to periods of system maintenance.

A separate analysis of deck and pylon was performed, due to divergencies in the available data for these two substructures. The analysis of vibration levels showed that higher accelerations are measured in the deck, in the vertical direction, when compared to the lateral direction and to the pylon, and that the excitation of the structure decreases on weekends, probably due to the reduction in traffic crossing the bridge.

Good results were achieved in terms of modal analysis, with a large number of vibration modes being tracked and identification rates above 90 % in most modes. It was also verified that a few modes present relevant complex components in their mode shapes. Finally, both seasonal and daily fluctuations were observed on the natural frequencies and a linear relation was found between these properties and ambient temperature.

The results obtained with this study demonstrate the suitability of vibration-based monitoring systems based on automated modal identification to provide features that are able to characterize the evolution of the condition of a structure. Methods suited for data normalization will be used in the future to minimize the effects of temperature, and other external variables affecting the bridge, on natural frequencies, which combined with the monitoring of the bridge for a longer period would simultaneously permit to better analyse this structure and to conclude about possible variations of the structural condition and more accurately assess potential damage situations. The present work acknowledges as well the necessity to analyse the complex components of mode shapes in order to achieve an efficient modal tracking.

Acknowledgments

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