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► **To cite this version:**

Carlo Rainieri, Danilo Gargaro, Giovanni Fabbrocino. Vibration-Based Monitoring of Tensile Loads: System Development and Application. EWSHM - 7th European Workshop on Structural Health Monitoring, IFFSTTAR, Inria, Université de Nantes, Jul 2014, Nantes, France. hal-01021062

HAL Id: hal-01021062

<https://inria.hal.science/hal-01021062>

Submitted on 9 Jul 2014

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VIBRATION-BASED MONITORING OF TENSILE LOADS: SYSTEM DEVELOPMENT AND APPLICATION

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ABSTRACT

The in-situ evaluation of the tensile load in cables and tie-rods plays a primary role in the continuous monitoring and health assessment of strategic as well as historic structures. The main advantage of the indirect determination of cable forces from dynamic tests in operational conditions is the opportunity to achieve accurate, cheap and fast quality checks in the construction phase (after pre-stressing), and safety checks and structural maintenance over the structure lifespan.

Based on the most recent developments in the field of operational modal analysis, an automated system for continuous monitoring of axial loads based on dynamic measurements has been developed. The system consists of a distributed measurement system based on programmable hardware and wireless modules, and of a centralized data processing server for the estimation of the tensile loads in the monitored cable from records of its dynamic response to ambient vibrations. The experimental identification of the flexural modes in terms of natural frequencies and mode shapes is used to solve an inverse problem for the identification of the axial loads. A prototype of the SHM system has been installed to monitor the tensile load in one of the cables of a sample steel arch. Preliminary experimental results from continuous monitoring of the cable are discussed pointing out the effect of environmental factors.

KEYWORDS : *Automated operational modal analysis, tensile load, cables.*

1 INTRODUCTION

The in-situ assessment of the tensile load is of interest for cable-stayed bridges or large steel arches, as well as for ancient masonry vaults and arches. The inverse problem associated to the evaluation of the tensile axial force from vibration measurements has been investigated in several studies because of its promising applicative perspective in the context of non-destructive testing and Structural Health Monitoring (SHM). The main advantage of the indirect determination of cable forces from dynamic tests in operational conditions is related to the opportunity to achieve accurate, cheap and fast quality checks in the construction phase (after pre-stressing), and safety checks and structural maintenance over the structure lifespan [1].

An extensive literature review pointed out that the available vibration based methods for the estimation of tensile loads in cables and tie-rods usually take advantage of the known input applied by an impact hammer [2, 3, 4] and eventually of the results of a numerical model [5]. The application of a known input by an impact hammer is theoretically more relevant in the case of tie-rods and relatively small tensile loads, since the reduced amplitude of vibration requires high performance sensors but the dimensions of the sensors (which determine their sensitivity) must be kept as small as possible to minimize the effect of the mass of the sensors on the dynamic behavior of the member. Since the reduction of the dimensions typically negatively affect the performance of

the sensor, a trade-off between performance and weight has to be pursued when output-only modal identification techniques are applied to estimate the tensile load in tie-rods.

Methods able to take into account the effect of the mass of the sensors and the uncertain boundary conditions in the estimation of the tensile load have been recently developed (see, for instance, [6]), thus making the continuous monitoring of tensile loads in tie-rods based on vibration measurements more attractive. On the other hand, the increasing availability of high performance accelerometers and the fast development of output-only modal identification techniques have revealed Operational Modal Analysis (OMA) as a profitable alternative for vibration based monitoring of tensile loads [7]. The increasing spreading of reliable and robust automated OMA procedures [8, 9, 10], able to provide accurate modal parameter estimates, fosters the development of vibration based systems for tensile load estimation and monitoring.

In the present paper, the development of a vibration based monitoring system for continuous tensile load estimation is illustrated. Some experimental results obtained after the installation of the monitoring system on one of the cables of a sample steel arch are also presented, and the influence of environmental factors is discussed.

2 THE VIBRATION BASED MONITORING SYSTEM

A vibration based SHM system for continuous monitoring of tensile loads has been recently developed. It consists of a distributed measurement system based on programmable hardware and wireless modules, and in a centralized data processing system for the estimation of the tensile loads in the monitored elements starting from records of their dynamic response to ambient vibrations. The architecture of the system is depicted in Figure 1. A prototype of the SHM system has been installed to monitor the tensile load in one of the cables of a sample steel arch (Figure 2).

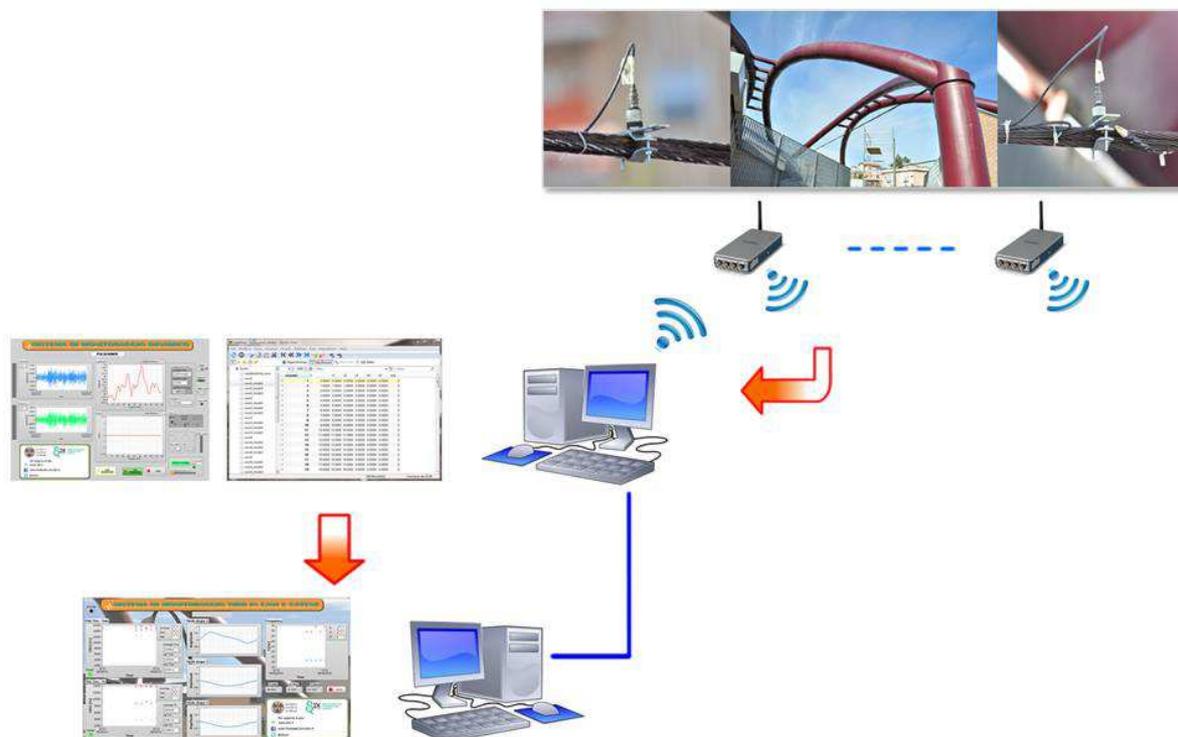


Figure 1: Architecture of the axial force monitoring system

Four piezoelectric accelerometers are installed on the cable. They are wired to a wireless data acquisition module from National Instruments™. The distributed data acquisition modules (at

least one module for each monitored element) are managed by a software developed in LabView environment. The collected raw data are stored into a local MySQL database. Each monitored element has an individual table of its own in the database for data storage. When the number of monitored elements is very large, the data acquisition task can be fragmented among a number of local servers.

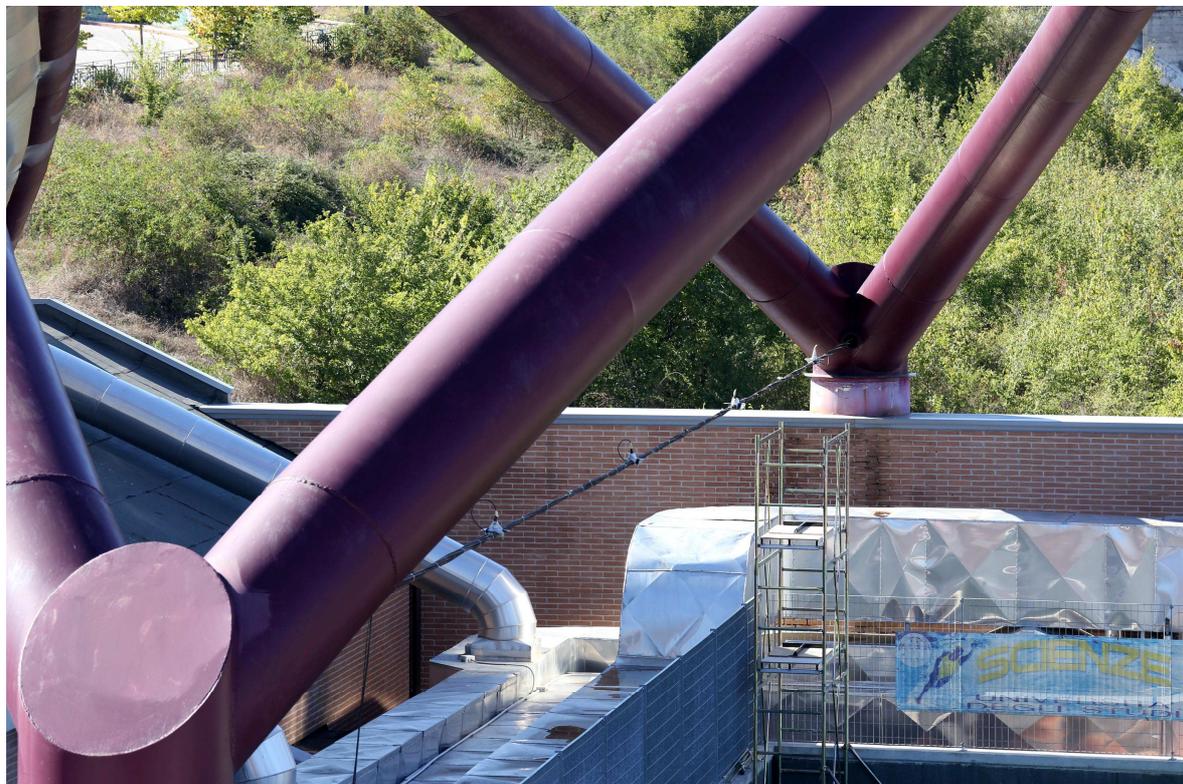


Figure 2: The monitored cable

A central server collects time histories of the dynamic response of given duration and carries out the automated identification of the modal parameters. The algorithm for automated output-only modal identification [10] is based on the combination of different OMA techniques in order to make easier the analysis and interpretation of the stabilization diagram.

The modal parameter estimation is carried out by applying the Stochastic Subspace Identification (SSI) method [11, 12] to the source correlations obtained from the Second Order Blind Identification (SOBI) [13, 14] procedure resulting in a relevant simplification in the identification of the physical poles. In fact, the correlation of the sources can be interpreted as a free decay response of the equivalent Single Degree Of Freedom (SDOF) system corresponding to a mode, and they can be analyzed by covariance-driven modal identification algorithms. The preliminary, approximate separation of the modal contribution simplifies the analysis of the data and the interpretation of the stabilization diagram, because the modal information is extracted from univariate time series, which theoretically include information about one mode at the time (however, in the practice, noise or minor contributions from other modes can be present).

The physical poles are separated from the spurious poles by means of clustering techniques [15] and mode validation criteria. The final values of the natural frequency and damping ratio for the identified modes are obtained by a sensitivity analysis with respect to the number of block rows i in SSI, for a given value of the maximum model order in the stabilization diagram. The cluster characterized by the minimum variance of the estimates when i ranges in a certain interval with a

certain step Δi is then selected as the one providing the best estimate of the modal parameters for a given structural mode [16]. Mode shape estimates are finally obtained from Singular Value Decomposition (SVD) of the output Power Spectral Density (PSD) matrix at the previously estimated frequency of the mode [17].

The key feature of the algorithm is the lack of any analysis parameter to be tuned at each new monitoring application. Its performance in terms of accuracy and reliability of estimates has been investigated through extensive tests based on simulated data and real measurements [10]. The analysis of the obtained results pointed out that the algorithm carries out automated output-only modal identification in a very robust way. In fact, a success rate larger than 99% has been obtained.

Very accurate natural frequency and damping ratio estimates have been obtained for different values of the signal-to-noise ratio. Moreover, based on an appropriate selection of sensor locations, it has been proved that the automated modal identification algorithm is able to accurately identify the modal parameters of the structure under investigation even in the case of a few measurement points. The identified dynamic properties are used to estimate the tensile load. For the herein discussed application, the tensile load is evaluated according to the following equation:

$$f_n = \frac{n}{2l} \sqrt{\frac{N}{\rho}} \quad n = 1, 2, \dots \quad (1)$$

assuming that the influence of the bending stiffness EI and the end constraints is negligible with respect to the tensile load; f_n is the natural frequency of the n -th mode and l its length. Sets of experimental results obtained after the installation of the monitoring system on one of the cables of a sample steel arch are illustrated in the next section. Estimates of the tensile load close to the design value in operational conditions have been obtained.

3 MONITORING RESULTS AND ENVIRONMENTAL EFFECTS

Preliminary monitoring results obtained right after the installation of the previously described monitoring system on one of the cables of a sample steel arch are illustrated in this section. In particular, the analyzed data have been collected in the period from December 2nd, 2013 to December 12th, 2013 (approximately ten days of continuous monitoring).

The position of the four sensors installed on the monitored cable has been defined according to the results of an output-only modal identification test carried out a few weeks before the installation of the monitoring system. Ten sensors were used in that case to estimate the mode shapes with a good spatial resolution (Figure 3a). Among the ten positions adopted for the dynamic identification test, four of them have been selected as sensor locations for permanent monitoring of the cable. In particular, the positions of the four sensors have been selected in a way able to ensure the possibility to distinguish the mode shapes of the fundamental modes. This objective has been accomplished by installing the sensors at positions #3, #5, #7 and #9, as pointed out by the fact that the corresponding AutoMAC matrix for the first three modes is characterized by negligible off-diagonal terms (Figure 3b). This condition, together with the presence of four modes only in the investigated frequency range (from DC to 10 Hz), ensures that the contributions of the first three modes are well separated [14].

Figure 4 shows the trend of the natural frequency estimates for the fundamental mode; the same trend characterizes also the higher modes. Variations in the order of about 3% with respect to the average value (2.55 Hz) of the natural frequency can be observed. The monitoring results in terms of tensile load estimates are shown in Figure 5. In agreement with Equation (1), a trend similar to that of the natural frequency characterizes the axial load. Figure 4 also clearly shows that the swing of the estimates systematically recurs over the different days, with a sudden drop at about eleven o'clock in the morning and a gradual increase in the late afternoon until the maximum value reached during the night. Thus, the variations of the natural frequency estimates can definitely be addressed to environmental factors and, in particular, to thermal effects.

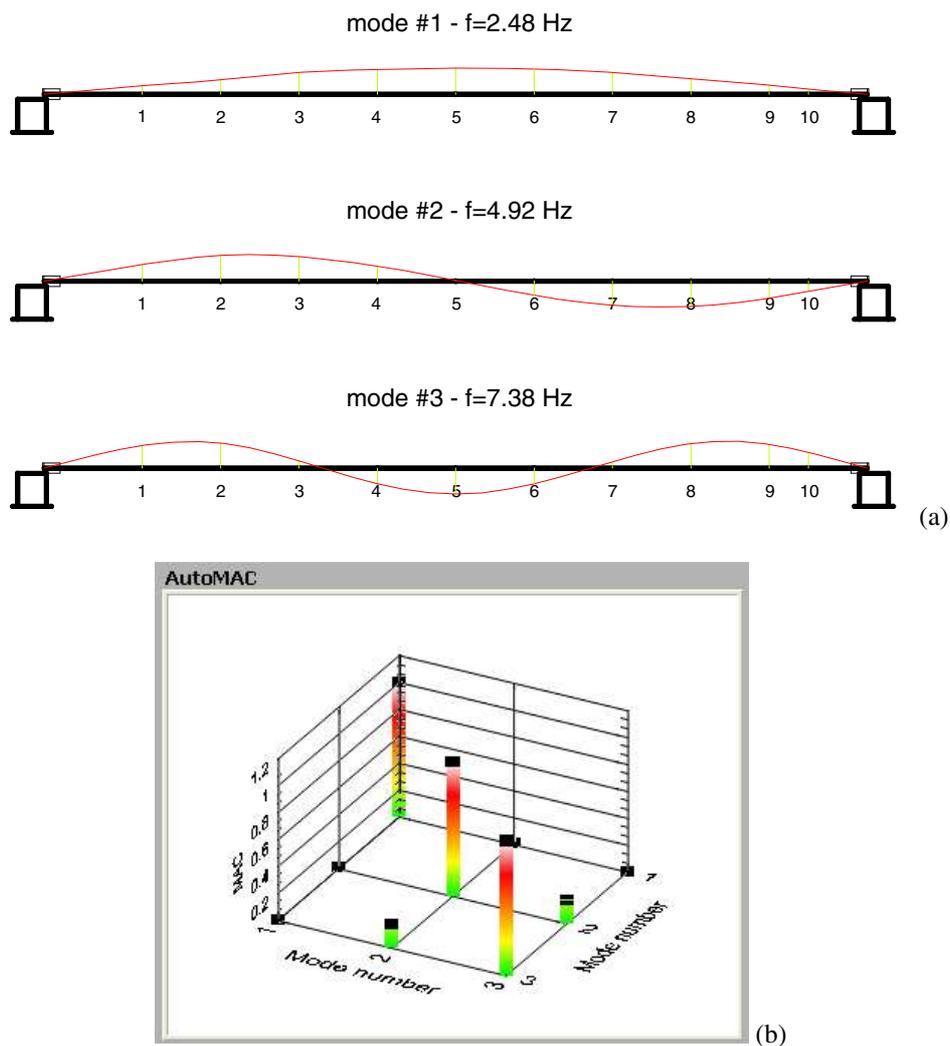


Figure 3: Sensor layout for the OMA test (a) and AutoMAC matrix using only sensors #3, #5, #7 and #9 (b)

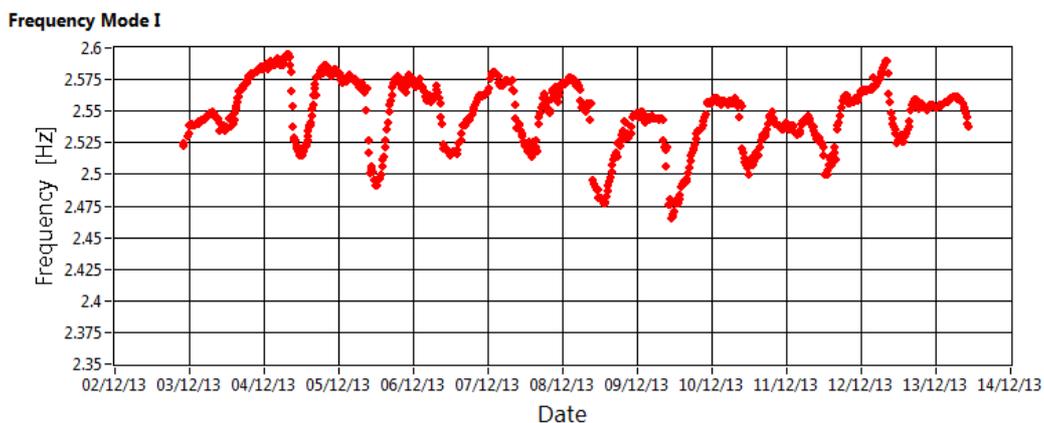


Figure 4: Variations of the natural frequency of the first mode over time (from December 2nd, 2013 to December 12th, 2013)

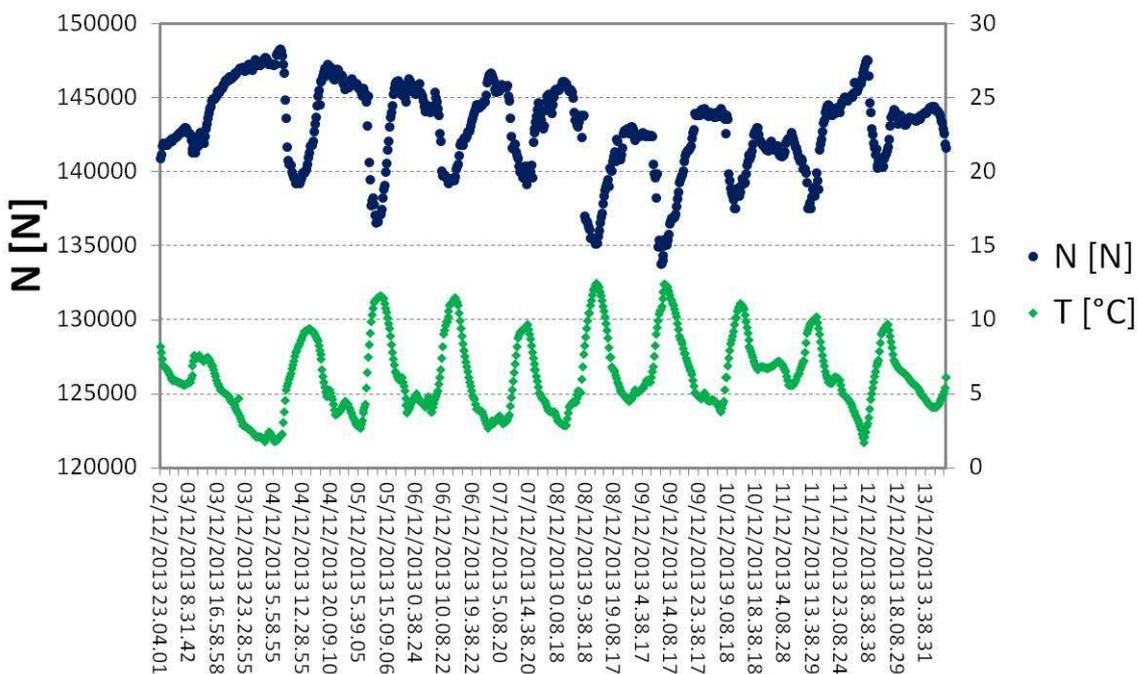


Figure 5: Tensile load in the cable and local temperature T (from December 2nd, 2013 to December 12th, 2013)

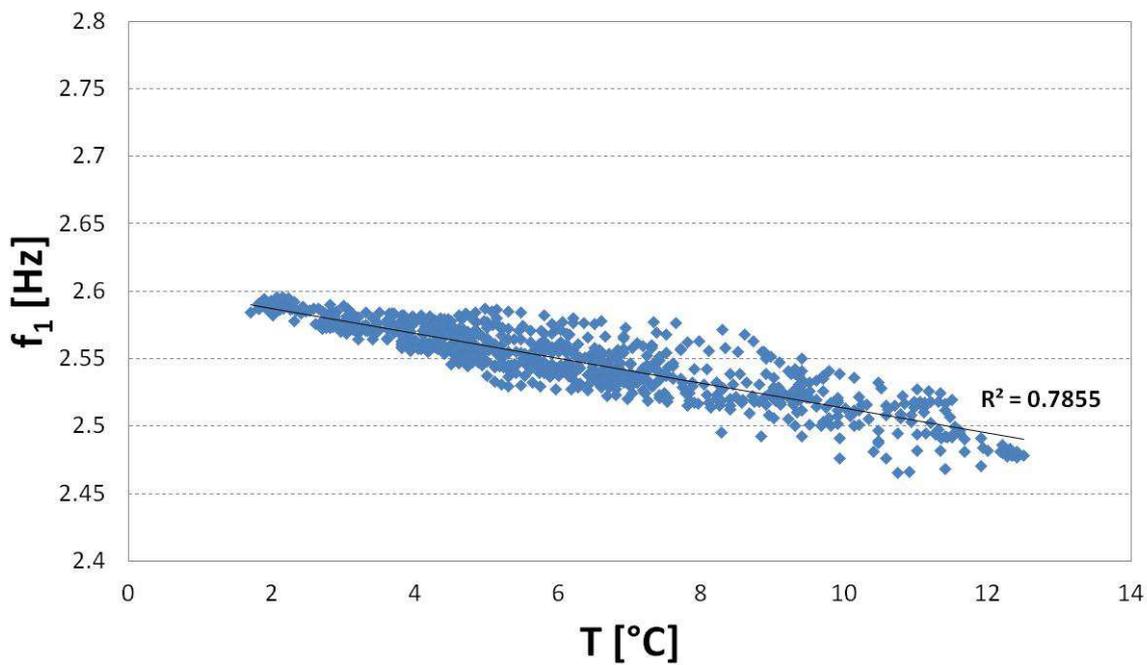


Figure 6: Variation of the natural frequency of the first mode against temperature

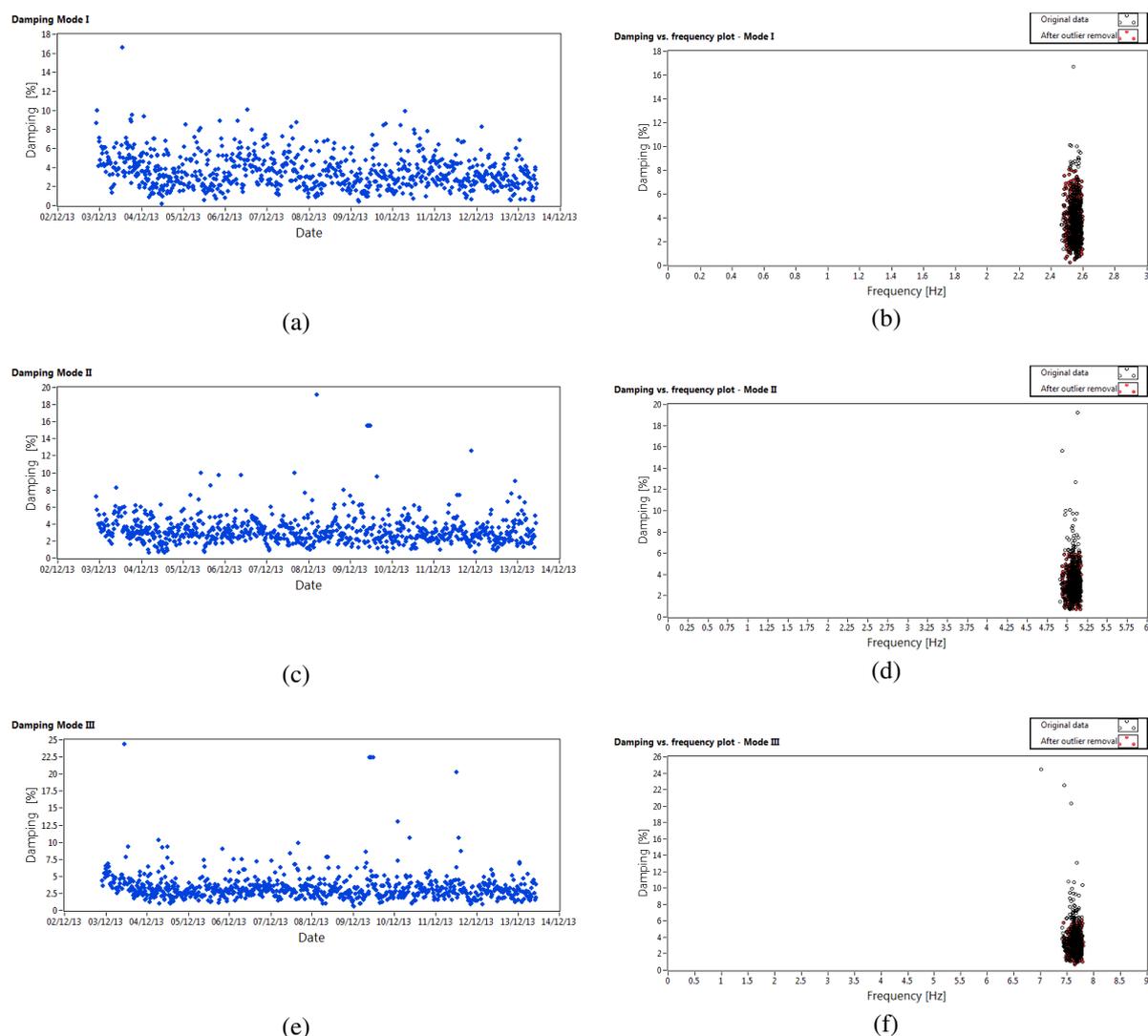


Figure 7: Time evolution of damping ratio and damping vs. frequency plot for mode I (a, b), II (c, d), III (e, f)

Comparing the load estimates with the values of temperature in the area recorded by the local meteorological station (source: www.meteomolise.it), slight increases in the tensile load when the temperature decreases can be observed, and vice versa (Figure 5). The remarkable influence of temperature on the estimates has been checked by plotting the estimates against the local temperature. Figure 6 shows that there is a basically linear relationship between natural frequency estimates and temperature over the observed period of time.

The monitoring results in terms of damping ratio estimates are shown in Figure 7a, Figure 7c and Figure 7e. In this case it is not possible to observe a clear influence of the temperature. Moreover, the damping estimates are more scattered than the natural frequency estimates. Apart from the inherent variability of damping estimates, their variation can be probably associated to the amplitude of vibration rather than to the temperature; however, further investigations are in progress on this aspect. Nevertheless, it is important to note that only a few outliers can be observed among the modal parameter estimates (Figure 7b, Figure 7d, Figure 7f), thus confirming the effectiveness and reliability of the automated OMA algorithm.

For a more detailed characterization of the effect of environmental and operational factors, the monitoring system has been recently complemented by temperature sensors, and rms values of

accelerations are being stored in the database together with the modal parameters and the tensile load estimates.

Nevertheless, the herein illustrated preliminary results are definitely encouraging. They remark the effectiveness of the system, and a database of modal properties, tensile loads, temperature and vibration amplitude is going to be populated. A long-term validation of the performance of the system is also in progress.

4 CONCLUSIONS

A system for continuous monitoring of tensile loads has been presented. It takes advantage of an effective algorithm for automated output-only modal parameter identification, and its distributed architecture for data acquisition makes the system fully scalable, so that it can be applied to monitor a large number of elements at the same time. Encouraging results have been obtained from its implementation in a real application, pointing out the influence of environmental and operational factors and the need to complement the system with temperature sensors.

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