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Suitability of MEMS accelerometers for continuous monitoring of railway bridges – a case study

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ABSTRACT

Continuous monitoring of transportation infrastructures has significantly contributed to the management of new systems, by taking advantage of new tools in the field of Operational Modal Analysis (OMA). It also plays a crucial role in ensuring the safety and structural integrity of old railway bridges. Traditional monitoring systems, while reliable, are often expensive, complex, and require significant maintenance, limiting their widespread application. In this context, MEMS (Micro Electromechanical Systems) accelerometers have emerged as a promising alternative, offering a cost-effective, robust, and autonomous solution for Structural Health Monitoring. Due to the growing importance of continuous monitoring of structures in Civil Engineering, this article aims to explore new measurement systems and sensor solutions for Structural Health Monitoring of bridges, using as a case study one of the steel bridges in the Beira Alta international railway line in Portugal. The main objective of this study is to evaluate the dynamic behaviour of the Trezói Bridge through operational modal analysis and assess the viability and suitability of MEMS accelerometers in a continuous monitoring system installed in a structure of this type. By considering the results of ambient vibration tests carried out with MEMS accelerometers, as well as the measurement of the bridge's dynamic behavior over an year of operation, this type of accelerometers demonstrated high reliability, autonomy, and effectiveness, overcoming key challenges associated with traditional monitoring solutions, such as cost and maintenance. This paper details this case study, exploring accessible, scalable, and sustainable solutions that contribute to infrastructure management with credible performance.

Keywords: Operational modal analysis, MEMS accelerometers, Railway bridges, Continuous dynamic monitoring

1. INTRODUCTION

Structural health monitoring of civil infrastructures, and especially bridges, is a subject that deserves the attention of many international research projects [1]. Recent technological advances have contributed to making the installation and operation of permanent dynamic monitoring systems more practical, useful and economical [2].

Based on these advances, continuous identification of structural parameters through analysis of responses to environmental excitation at critical points has become a key strategy in monitoring the structural health of bridges. Along with Operational Modal Analysis plays a crucial role in identifying the modal parameters of a structure under service conditions, further supporting efficient management and maintenance of bridge infrastructure [3].

The development and validation of tools for the automatic identification of modal parameters based on the structural responses during normal operation is fundamental, as the success of subsequent damage detection algorithms depends on the accuracy of the modal parameter's estimates [2].

In this context, this article aims to publicize the instrumentation solutions that have been used on the Trezói bridge, an old metal railway bridge in Portugal, for monitoring dynamic parameters over time. This paper presents the architecture of the developed sensors, as well as the signal processing used to evaluate the data continuously measured.

2. DESCRIPTION OF THE BRIDGE

The Trezói Bridge (Figure 1) is one of the six largest on the Beira Alta railway line, connecting Portugal to Spain. Built by the German company Fried Krupp, it was inaugurated on August 20, 1956. This riveted steel structure spans 126 meters, featuring two inverted Warren truss girders with a constant width of 4.40 meters. Its supports allow free rotation, restricting longitudinal movement toward Guarda while permitting controlled deformation toward Coimbra. The bridge incorporates "I-shaped" cross girders and stringers for added strength, along with maintenance corridors on the upper deck and within the structure.



Figure 1. Trezói Bridge

3. AMBIENT VIBRATING TEST

The identification of modal parameters in bridges can be performed through dynamic tests of different types [4 5]. In this study, the ambient vibration test was used (Figure 2), which involves only the measurement of the structural response under ambient excitation, in this case without traffic.

During the ambient vibration test, accelerations in three directions (lateral, vertical and longitudinal) were measured at 9 points of the bridge, using six seismographs. Two sensors worked as fixed stations, while other were guided through the rest of the bridge. The acquisition time for each setup is 25 minutes, acquiring at a frequency of 100Hz.

The frequency spectra recorded by the seismographs showed some peaks with greater amplitude in the frequency range from 0 to 7 Hz (Figure 2), which corresponds to the natural frequencies of the superstructure. In the lateral direction three clear peaks appear, the first one at 2.93 Hz, the second at 3.66 Hz and the third one at 3.89 Hz. While at the vertical frequency there is a very clear first peak at 5.46 Hz. Another peak at 6.06 Hz was also identified and it corresponds to the torsional mode of the structure.

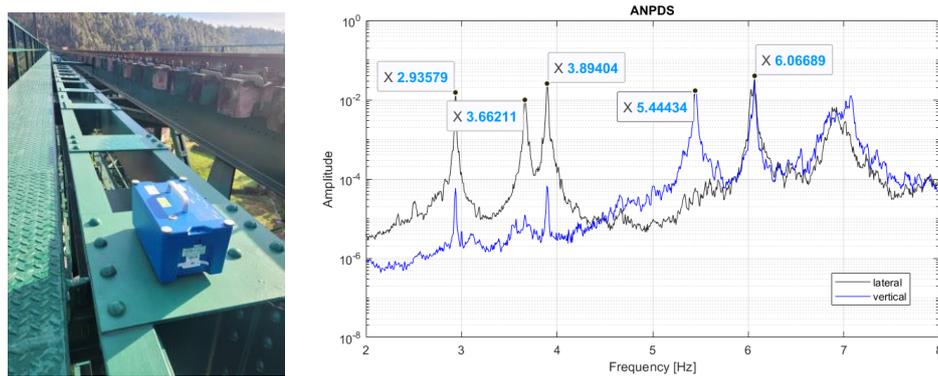


Figure 2. Seismograph in the test and Average Normalized Spectrum (ANPSD)

In this study, two methods were used to identify the modal parameters; the Peak-Picking method was used for an initial assessment of the data and evaluation of frequency content, which was followed by a second analysis resorting to the application of the Covariance-driven Stochastic Subspace Identification (SSI-Cov) method [6 7 8]. The mode shapes obtained with the Peak-Picking method shown in Figure 3 and Figure 4, together with numerical results [9], for comparison, showing a good agreement between them.

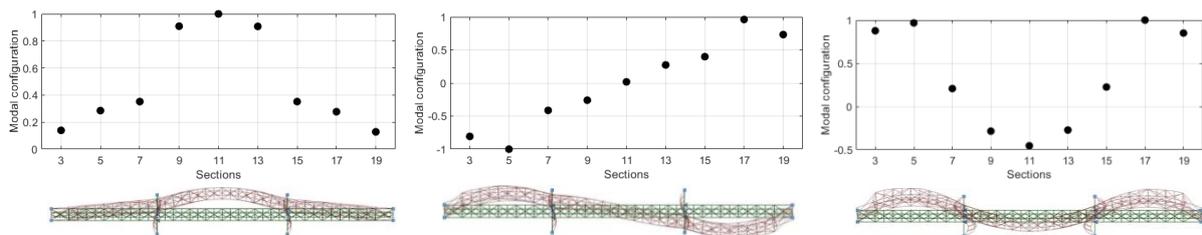


Figure 3. Lateral view of the first 3 lateral modes

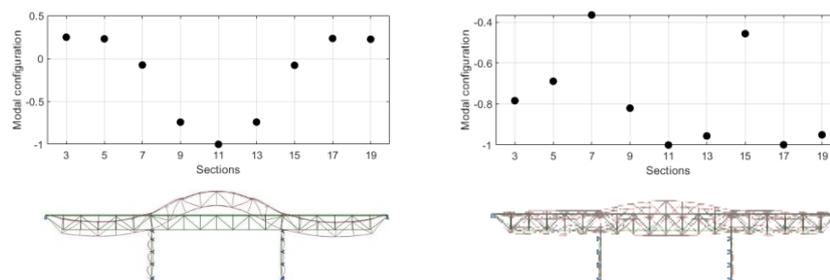


Figure 4. Top view of the first vertical (on the left) and torsional (on the right) modes

As mentioned before, the analysis performed with the Peak-Picking method was complemented with the application of the SSI-Cov algorithm, to further validate the results. Every 2 model orders from 10 up to 100 were considered, which resulted in the stabilization diagram presented in Figure 5. Additionally, the mode shapes obtained are presented in Figure 6, with lateral and vertical modal ordinates represented in different colours. A good agreement was obtained between the two methods, both in terms of frequencies and mode shapes.

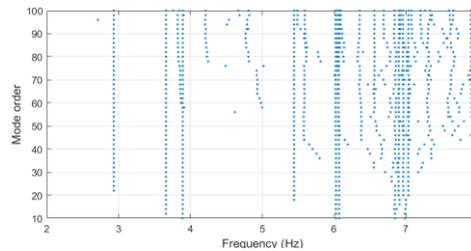


Figure 5. Stabilization diagram obtained with the SSI-Cov method

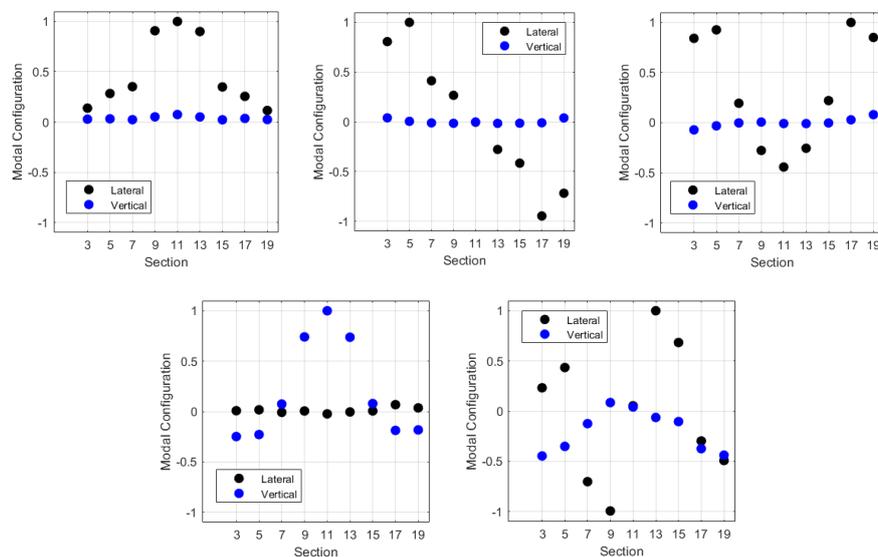


Figure 6. Mode shapes obtained with SSICOV

4. CONTINUOUS MONITORING SYSTEM

Continuous bridge monitoring systems, along with dynamic testing, are used to validate design concepts, assess the state of the structure, evaluate behaviour under loading and to perform damage detection based on vibration analysis. In the case of bridge monitoring, the determination of vertical displacements is one of the most important issues [10]. In this sense, a new measurement system was developed and implemented to evaluate the railway bridge based on measurements of the structural response to ambient vibration and the passage of trains. The system records signals related to the conditions for which the bridge is being monitored.

In this sense, the devices chosen for installation in the structural monitoring of the Trezói Bridge belong to a new generation of sensors. This system requires no long cables and is easy to install. Therefore, the aim of this research in this field is to develop instrumentation for measuring real structures that meets the requirements and overcomes the disadvantages of the traditional heavy measuring systems [11].

The used devices (Figure 7) are composed of a tri-axis MEMS accelerometer which is commanded by means of an AT mega microcontroller. The MEMS accelerometer is of digital type integrating a 20-bit ADC, and includes internal antialiasing filters, programmable frequency rate and dynamic range. This system is powered by 5 batteries of 3400 milliamps capacity each, enabling an autonomy of 3.3 months

in continuous operation. The accelerometer adopted is of the MEM (microelectron mechanical) type, ADXL355 from Analog Devices Company.



Figure 7. Accelerometer modules

In the context of the Operational Modal Analysis of the structure, four accelerometers were fixed to the bridge in sections 4 and 11, in the middle of the first span from Trezói side and in the middle of the structure. Two devices were installed at upstream side (A1 and A2) and other two at downstream (S3 and S4). The selection of these sections was decided based on the results of the ambient vibration test in order to capture the modal components of the first vibration modes of the structure, indicated in the figure with the yellow arrow.

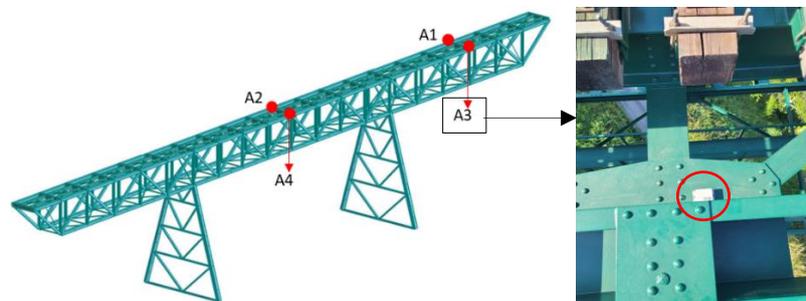


Figure 8. Location of the accelerometers in the structure

5. EVALUATION OF DYNAMIC BEHAVIOR OVER TIME

In order to continuously track and confirm the modal properties of the first 5 vibration modes of the structure and to observe the remaining modes of the bridge, an automated operational modal analysis was performed. Figure 9 presents the raw results for a pre-tracking analysis performed between August/23 and October/23. The processing of the acceleration signals allowed to evaluate the evolution of the dynamic properties for each vibration mode during this period. It is possible to observe the evolution of the natural frequencies for the modes previously identified, which show short-term variations over time, probably due to the influence of temperature.

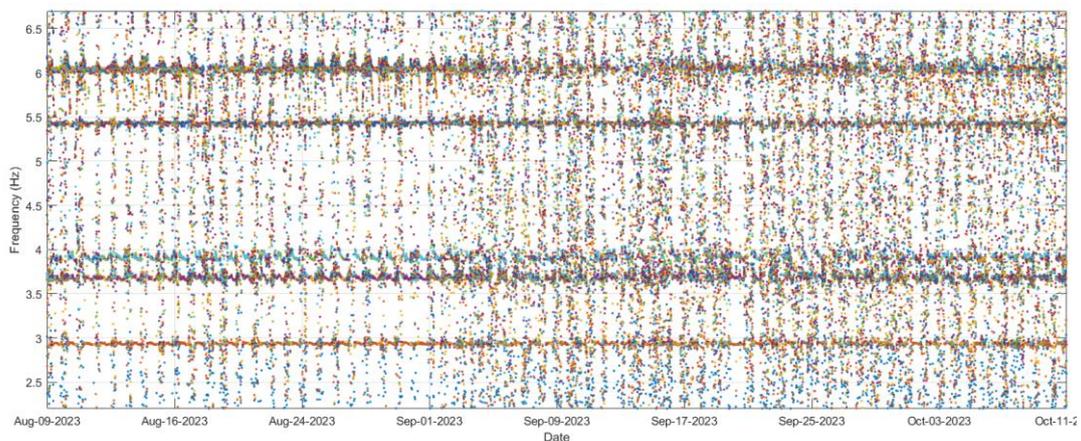


Figure 9. Evolution of natural frequencies for 3 months

Nevertheless, a more detailed analysis in time reveals the occurrence of periodic misidentifications of natural frequencies. This can be explained by the very low vibration levels verified during the night, as shown by the evolution of the RMS of the accelerations presented in Figure 10. Additionally, Figure 10 presents the ANPSD functions obtained for a pair of signals acquired at midnight and at noon, showing that in the first case, the spectra is dominated by noise. However, even with these difficulties, the results of the continuous analysis showed excellent performance, as presented in Table 1.

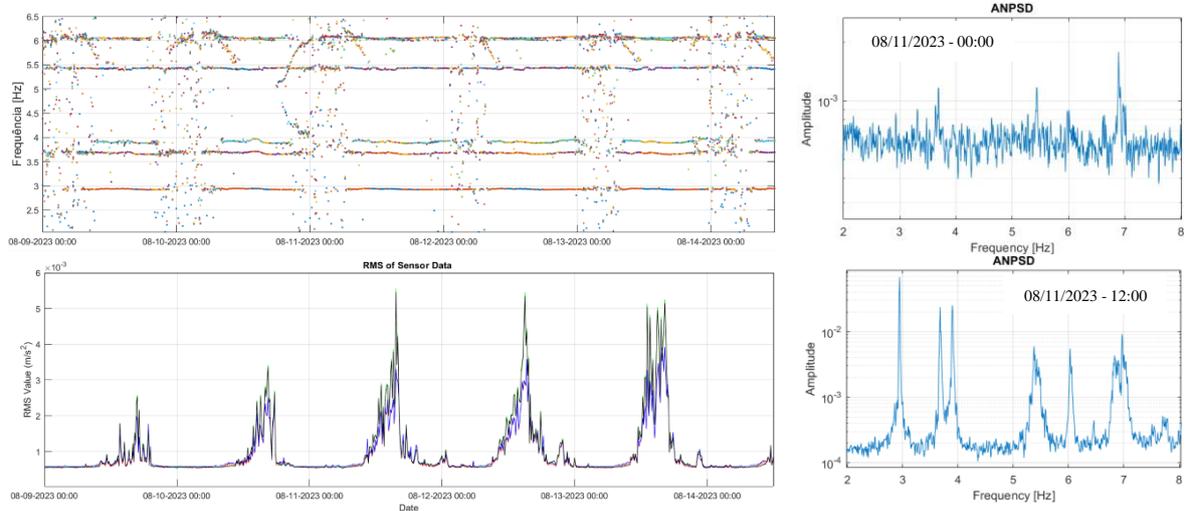


Figure 10. On the left: time association between the misidentification of natural frequencies (top) and low excitation (bottom). On the right: spectra at midnight (top) and spectra at noon (bottom).

In addition to the continuous tracking of modal properties (Figure 11), a detailed evaluation of natural, damping, and the Modal Assurance Criterion (MAC) was conducted over the analyzed period (see Table 1). This approach allowed for quantifying the stability of the extracted modes and identifying variations that could influence the dynamic behaviour of the bridge. The average MAC was found to be around 0.90, indicating a high level of correlation between the identified modes and the reference modes. This information is essential for validating the consistency of the extracted modes and monitoring potential structural changes over time.

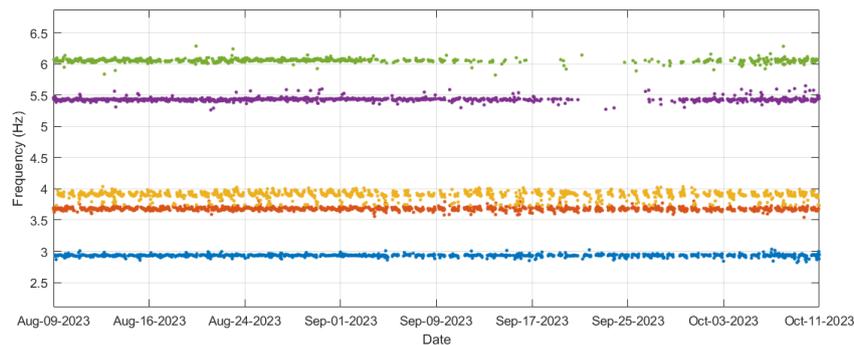


Figure 11. Continuous tracking of the first 5 modes natural frequencies.

The objective in this moment is to make a preliminary check of the quality of the acceleration signals acquired continuously at Trezói bridge, making and identification of modal parameters over time and compare them to the results of the initial ambient vibration test performed with seismographs. Comparing the natural frequencies of the structure identified in the ambient vibration test, with the continuous analysis, the results show a difference of less than 1% (see Table 1).

Table 1. Ambient Vibration Test and continuous monitoring: comparison and average results

Mode	Ambient Test [Hz]	Average frequency [Hz]	Difference (%)	Average Damping (%)	Average MAC
1	2.94	2.93	0.34	0.61	0.98
2	3.66	3.68	0.54	1.15	0.98
3	3.90	3.89	0.26	1.28	0.93
4	5.44	5.42	0.37	0.37	0.96
5	6.06	6.05	0.17	0.35	0.81

Analyzing the first modes, lateral, vertical, and torsional continuously, it is possible to observe that the MEMS sensors produce results showing an excellent correlation with the test results, allowing to conclude that the accelerometers used in this application are suitable for continuous monitoring of the Trezói bridge. Comparing the results by the Peak-Picking method, on 08/13/23, from accelerometers A1 and A2 (Fig 18) in sections 4 and 11, it is possible to conclude a good agreement exists between them.

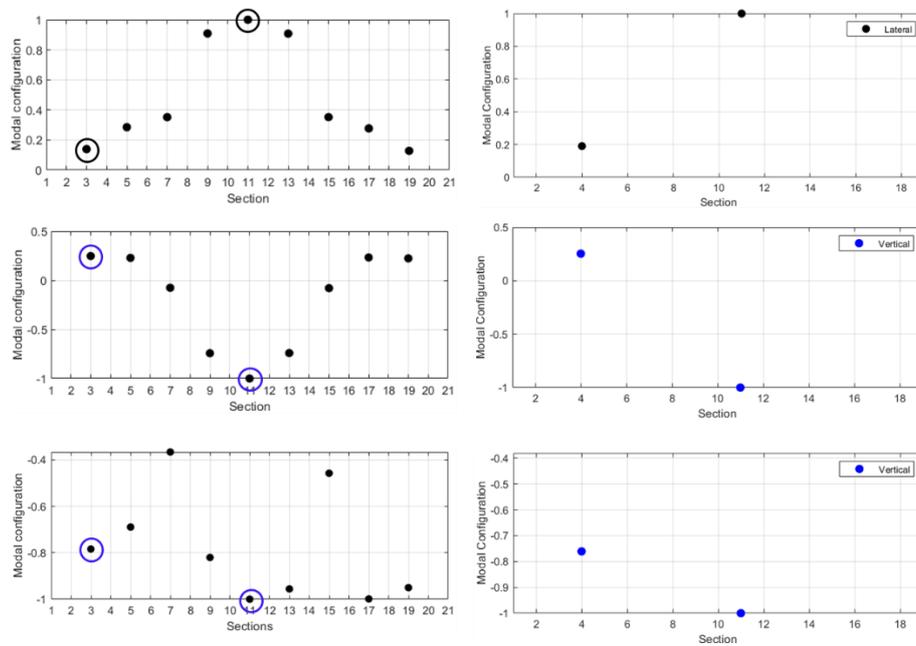


Fig. 11. Comparison between the mode shapes obtained with the Ambient Vibration Test using seismographs (on the left) and using the MEMS accelerometers (on the right)

6. CONCLUSIONS

The study conducted at the Trezói Bridge demonstrated the effectiveness and reliability of MEMS accelerometers for continuous structural health monitoring. Through ambient vibration testing and year-long data acquisition, the accelerometers successfully captured the modal properties of the bridge, showing high accuracy in identifying natural frequencies and dynamic behaviour.

Overall, the results highlight the potential of MEMS accelerometers as a cost-effective and scalable solution for railway bridge monitoring. The system's autonomy, ease of installation, and strong correlation with traditional monitoring methods make it a promising alternative to more expensive and maintenance-heavy solutions. Despite some challenges, such as reduced excitation during the night affecting identification accuracy for a few hours, the continuous monitoring approach proved to be robust and consistent. These findings support the adoption of MEMS-based monitoring systems for infrastructure management, contributing to the long-term safety and reliability of aging railway bridges.

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