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COMPARISON OF LONG-TERM AND AD-HOC MONITORING SYSTEMS FOR SYSTEM IDENTIFICATION IN STRUCTURAL HEALTH MONITORING)

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Abstract. *The rapid development of new monitoring technologies in recent years is crucial for the wider implementation of Structural Health Monitoring (SHM), especially given the deteriorating condition of many bridges worldwide. This study contributes to this field by comparing a permanent long-term monitoring system and an ad-hoc monitoring system applied to a newly constructed steel arch bridge with a main span of 48.8 m and an arch height of 8 m. The bridge is equipped with several strain gauges used for continuous monitoring. In parallel with the permanent system, the ad-hoc monitoring system was deployed for a short-term, multichannel measurement campaign, during which Operational Modal Analysis (OMA) was performed using recorded accelerations. Natural frequencies obtained from both systems were compared to evaluate the effectiveness of each approach for system identification. The study highlights the advantages and limitations of long-term and ad-hoc monitoring and provides recommendations for optimal application in future SHM practice.*

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1 INTRODUCTION

The structural integrity and long-term durability of transportation infrastructure are critical components of modern engineering management [1]. Among various structural forms, steel arch bridges are widely utilized for their aesthetic appeal and efficient load-bearing capabilities. However, these structures are subject to continuous degradation due to environmental factors, material fatigue, and increasing traffic loads. To ensure safety and optimize maintenance costs, the implementation of Structural Health Monitoring (SHM) systems has become essential practice in civil engineering, providing deep insights into overall structural performance and seismic capability [2, 3].

Traditional bridge assessment often relies on periodic visual inspections or short-term "ad-hoc" measurement campaigns. While these methods provide a high-resolution snapshot of a bridge's dynamic properties—such as mode shapes and natural frequencies, they often fail to capture the continuous influence of environmental fluctuations, such as temperature changes [4, 5]. This has led to the development of Permanent Monitoring Systems (PMS), which utilize smart sensor deployments to provide real-time, continuous data over the entire lifecycle of the structure [6, 7]. Because temperature gradients significantly affect natural frequencies, updating baseline finite element models using recorded data is essential for accurate health assessment [8]. In tandem, operational modal analyses often rely on accelerometers to detect dynamic anomalies and structural mode shape shifts [9, 10].

This paper focuses on the monitoring and dynamic characterization of a newly constructed steel arch bridge with a main span of 48.8 m and a total width of 15.93 m. The primary objective is to evaluate the effectiveness of a minimalist PMS setup compared to high-density ad-hoc acceleration measurements. The study explores whether a system with a limited number of sensors—specifically strain gauges—can successfully identify the bridge's natural frequencies and track their evolution under different environmental conditions.

The investigation is divided into two main parts: first, the analysis of long-term data from the permanent system, including the comparison of results between sub-zero January temperatures and mild April conditions; and second, the validation of these findings through an ad-hoc campaign using highly sensitive seismic accelerometers. By comparing these two approaches, this work aims to demonstrate that permanent and ad-hoc systems serve as complementary tools, providing both the long-term environmental context and the detailed modal data necessary for a comprehensive structural health assessment.

2 DESCRIPTION OF THE BRIDGE

The bridge consists of a composite reinforced concrete deck supported by a steel arch structure and vertical hangers (Fig. 1). The geometry is defined by a main span of 48.8 m and an arch height of 8 m (Fig. 1). With a total width of 15.93 m, the cross-section provides a 9.9 m wide carriageway and pedestrian sidewalks on either side (Fig. 2). Hanger spacing is uniform at 6 m throughout the central portion of the span, transitioning to 9.4 m segments at the supports.



Figure 1: Picture of the investigated bridge.

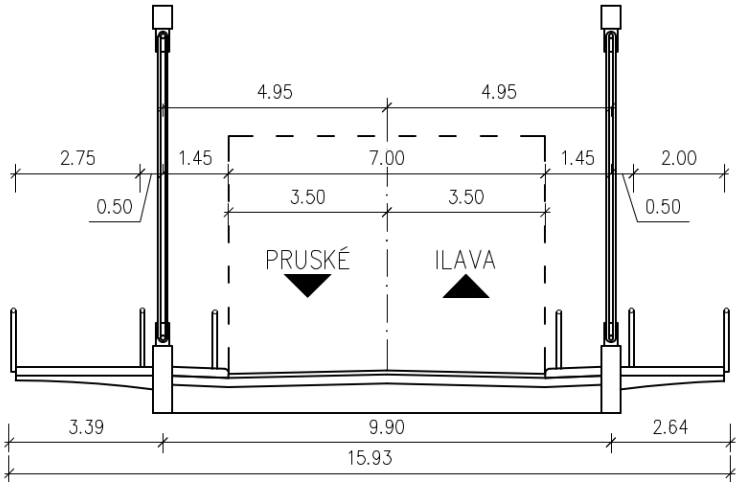


Figure 2: Cross-section of the bridge.

2.1 Permanent monitoring system

The Permanent Monitoring System (PMS) system continuously processes data from selected sensors via an on-site control computer, which transmits a streamlined dataset to the cloud in real-time. These results, comparing measured values against theoretical expectations, enable bridge authorities to assess structural health. In this setup, two strain gauge channels (SG1 and SG2, see Fig. 3 are active on both main girders, alongside temperature (TM1 and TM2) and traffic video recordings (REC1) at Fig. 4.

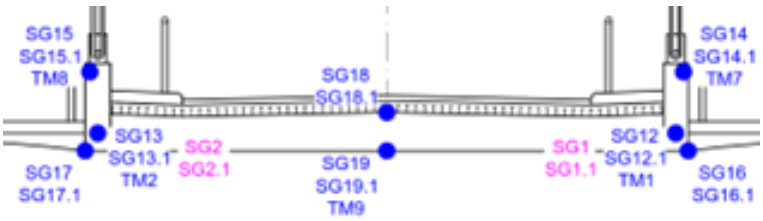


Figure 3: Cross-section of the bridge with strain gauges from PMS (SG1 and SG2) and other sensors.



a)



b)

Figure 4: Traffic video recording REC1: a) synchronized camera, b) a passage of the bus from REC1 in January.

2.2 Ad-hoc monitoring system

During the measurement campaign the system consists of controlling computer and DAQ module in order to measure 4 channels. This module allowed us to measure simultaneously four signals of acceleration. Specifically, highly sensitive seismic accelerometers were used. Due to that fact, it was possible to analyze just ambient vibrations caused by wind, pedestrians, cyclists or passing vehicles. During the campaign two setups were used. One covering also measurement of vibration of one hanger and the other one was measuring vibration close to SG2 on the opposite side.

3 DATA ANALYSIS

The goal was to compare performance of identification of dynamic properties from different quantities, strains and accelerations. They are both analyzed in this chapter. Data were in both cases processed similarly to ensure comparability. During measurement in April (accelerometers and strain gauges) the temperature of the structure reached approximately 19 degrees. In the case of results from strain gauges in January, the situation was totally different. The temperature was below zero, around -1.5°C.

3.1 Strains from permanent monitoring system

The free decays were analyzed to obtain the frequency response of the bridge using measured strains. Using Fast Fourier Transform signals were transformed from time domain to frequency domain. Then, results from strain gauges SG1 and SG2 are shown in Fig. 5. According to them, Tab. 1 was prepared and it describes the identified natural frequencies. The numbering is chosen only according to identified natural frequencies, and they do not consider the order from a numerical model (it was not scope of this paper).

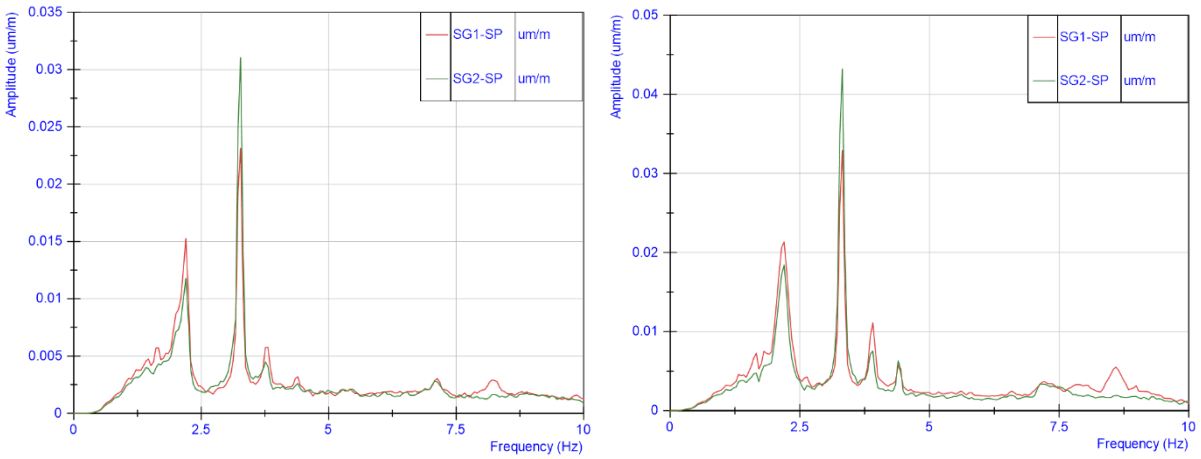


Figure 5: Frequency response obtained from strain gauges: measurement in a) April, b) January.

No.	Natural frequency from April (Hz)	Natural frequency from January (Hz)
1	-	-
2	2.20	2.20
3	-	-
4	3.27	3.32
5	3.79	3.91
6	4.39	4.39
7	-	-

Table 1: Natural frequencies identified during strain gauges measurements.

So, the order is only used to be able to compare results from strain gauges also with the results from accelerometers described and analyzed in the next subchapter. As can be seen in Tab. 1, natural frequencies no. 1, 3 and 7 were not identified due to horizontal vibrations. The results were then limited to vertical bending and torsional mode shapes, respectively to their natural frequencies.

3.2 Accelerations from ad-hoc measurement

The data logged during the campaign in April using accelerometers was processed in the DIAdem software using the own developed code. Specific steps are described in article [11] in more detail. The difference was in limit values used: e.g., a 0.5 Hz high-pass filter, a 10 Hz low-pass filter, and a sampling frequency was also reduced to 50 samples/s from the original 2048 samples/s as the hardware option. Fig. 5 shows the frequency response using the setup 1 which was previously explained in chapter no. 2.2. Each part (a), b), c), d)) represents one data record.

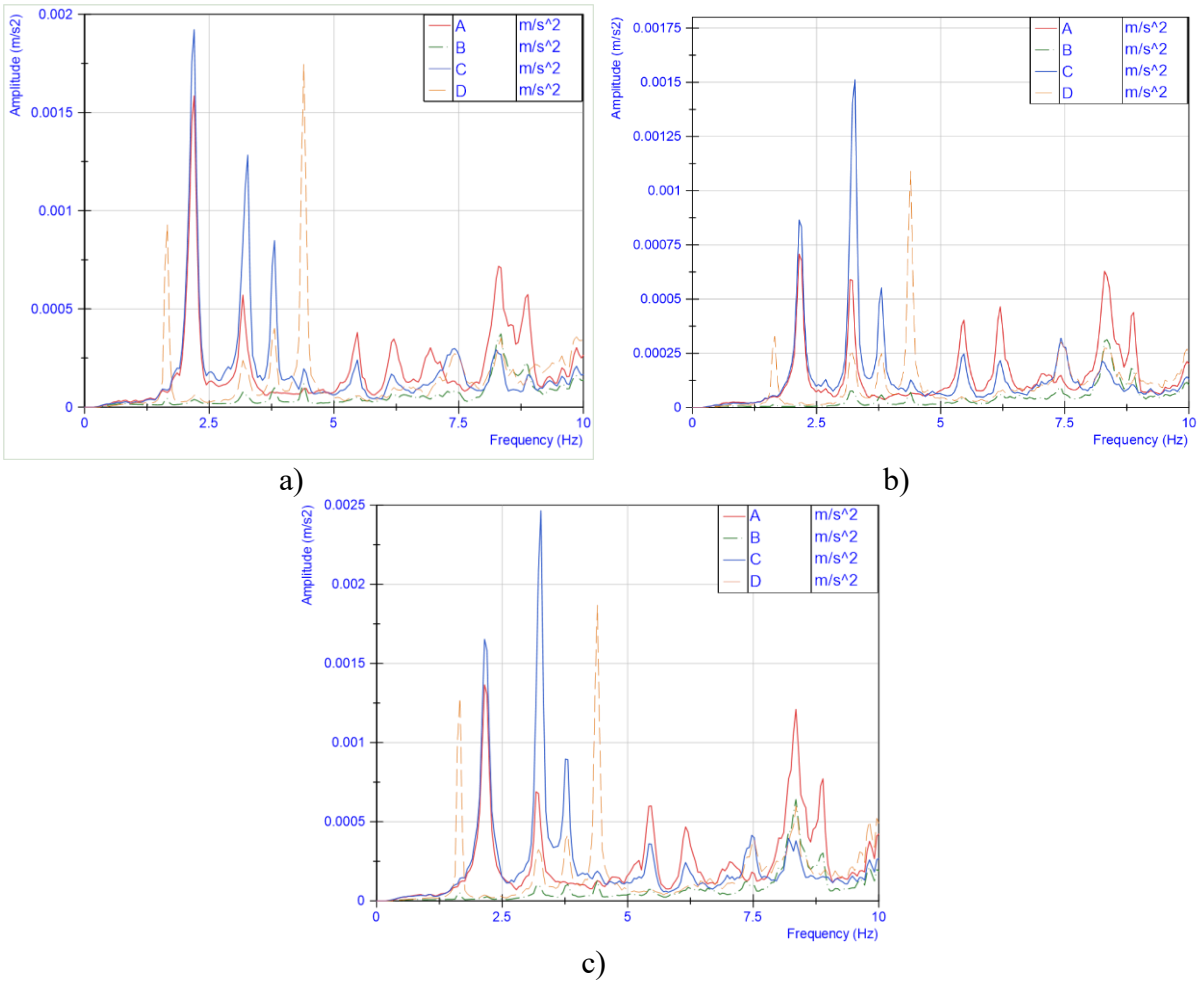


Figure 6: Frequency response obtained from accelerometers in setup 1: a) data no. 1, b) data no. 2, c) data no. 3.

No.	Natural frequency from data no.1 (Hz)	Natural frequency from data no.2 (Hz)	Natural frequency from data no.3 (Hz)
1	1.66	1.66	1.66
2	2.20	2.15	2.20
3	3.17	3.22	3.20
4	3.27	3.27	3.27
5	3.81	3.81	3.81
6	4.39	4.39	4.39
7	-	-	-

Table 2: Natural frequencies identified during ad-hoc measurement in April (setup no. 1).

In the case of setup no. 1, it was possible to identify also mode shapes and corresponding natural frequencies for horizontal vibrations. Due to sensor B installed in the horizontal direction on the main girder but also due to the sensor on the hanger, again deployed in the horizontal direction. Using this limited equipment, we were unable to identify torsional mode shapes.

The same approach was also used in the case of setup no. 2. In this case the first natural frequency disappeared. Respectively, very weak evidence could be found in the case of sensor B (green dot-dashed line). The orange line is in this case intact because this sensor in the case of setup no. 2 is located close to the SG2 (on the opposite main girder). So, results on Fig. 6

from sensors A and D should be similar in the case of the natural frequency of 2.2 Hz which represents the first bending mode shape. The sensors C showed little greater amplitude because it was located on the main girder (the same side as the sensor A) but very close to the middle point of the span.

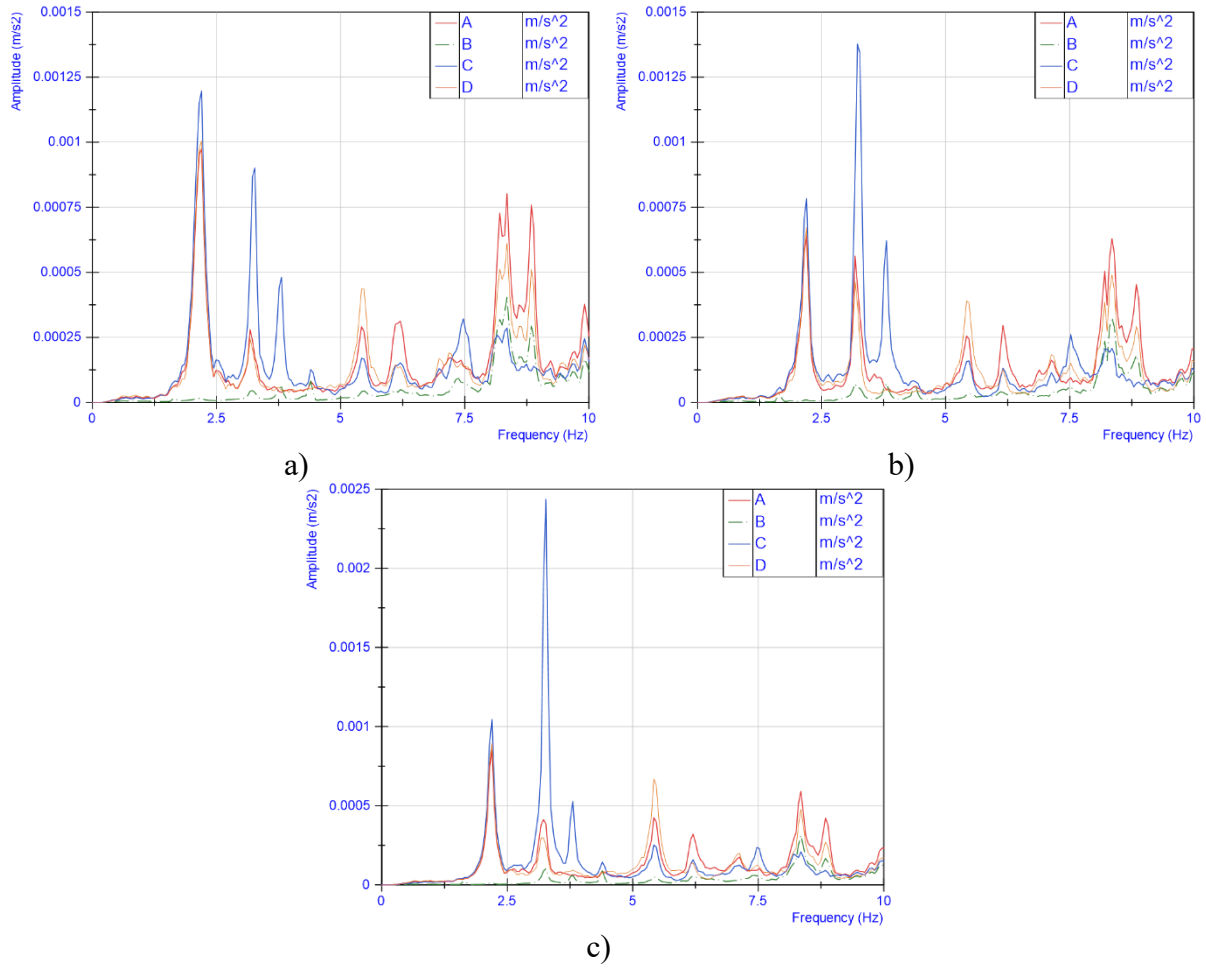


Figure 7: Frequency response obtained from accelerometers in setup 2: a) data no. 1, b) data no. 2, c) data no. 3.

No.	Natural frequency from data no.1 (Hz)	Natural frequency from data no.2 (Hz)	Natural frequency from data no.3 (Hz)
1	-	-	-
2	2.20	2.20	2.20
3	3.22	3.17	3.17
4	3.27	3.27	3.22
5	3.81	3.81	3.81
6	4.39	4.39	-
7	5.49	5.45	5.42

Table 2: Natural frequencies identified during ad-hoc measurement in April (setup no. 2).

Because of the missing sensor on the hanger, the first frequency was missed in the identification in the case of setup no. 2. On the contrary, the 7th frequency was found just in this case.

4 COMPARISON OF RESULTS

In Tab. 3, the identified frequencies were averaged in the case of acceleration measurements. The results from strain gauges were taken just from Tab. 1 as they were.

No.	Natural frequency from setup no.1 (Hz) / ACC	Natural frequency from setup no.2 (Hz) / ACC	Natural frequency from April (Hz) / Strain gauges	Natural frequency from January (Hz) / Strain gauges
1	1.66	-	-	-
2	2.17	2.20	2.20	2.20
3	3.20	3.19	-	-
4	3.27	3.25	3.27	3.32
5	3.81	3.81	3.79	3.91
6	4.39	4.39	4.39	4.39
7	-	5.45	-	-

Table 3: Natural frequencies identified during ad-hoc measurement in April (setup no. 2).

According to the results, PMO showed that also limited equipment (in order to save expenses) can be valuable to identify some dynamical parameters. Thanks to the right locations they can monitor a lot of natural frequencies. On the other hand, it is not possible to identify mode shapes and in this case the usage of dense layout of sensors is unreplaceable. But these two approaches can be complementary. Besides that, some small differences in natural frequencies in the various periods of the year could be found even from two sensors. Then, such a small permanent monitoring system can be valuable insight into the environmental effect on dynamic parameters.

5 CONCLUSIONS, DISCUSSION

The investigation of the steel arch bridge demonstrates that the integration of Permanent Monitoring Systems (PMS) and ad-hoc measurement campaigns provides a comprehensive understanding of structural behavior. Based on the comparative analysis of strains and accelerations, the following conclusions are drawn:

- Efficiency of Limited Instrumentation: The results indicate that a minimalist permanent monitoring setup, consisting of only two strategically placed strain gauges, can identify a significant portion of the bridge's natural frequencies. This suggests that cost-effective systems can provide valuable continuous data for structural health monitoring when sensor placement is optimized.
- Complementarity of Monitoring Approaches: While the permanent strain-based system excels at long-term data collection, it proved unable to identify horizontal vibrations or specific mode shapes. Conversely, the ad-hoc acceleration measurements provided the high-density data necessary for mode shape identification. Therefore, these two methodologies are most effective when used as complementary tools.
- Environmental Influence on Dynamics: A comparison between January and April datasets revealed a clear correlation between ambient temperature and dynamic properties. The natural frequencies identified in sub-zero temperatures (January) were consistently higher than those measured at 19°C (April). This underscores the PMS's ability to capture the impact of environmental variables on the bridge's stiffness and overall dynamic response.

- Sensor Placement Sensitivity: The ad-hoc campaign highlighted that the detection of specific frequencies is highly dependent on sensor location. For instance, the first natural frequency (1.66 Hz) was only detectable when sensors were placed directly on the bridge hangers. This reinforces the necessity of preliminary numerical modeling or high-density ad-hoc testing before finalizing a permanent sensor layout.

In summary, even a small-scale permanent monitoring system offers critical insights into the long-term structural integrity and environmental sensitivity of bridge structures, though it should be supplemented by periodic high-resolution vibration testing for complete modal characterization.

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