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Dynamic Monitoring of Composite Steel–Concrete Viaducts Using Short Accelerometric Records: Potential and Limitations.

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Abstract

Structural Health Monitoring (SHM) is an increasingly crucial issue in civil engineering. Many structures like bridges and viaducts nowadays are older and show signs of structural deterioration that can potentially affect structural safety. One of the most popular monitoring techniques is dynamic monitoring under environmental vibrations using Operational Modal Analysis (OMA) techniques.
The application of OMA techniques usually requires the recording of accelerometer signals of consistent time duration. Consequently, a large storage space, expensive cabled solutions and lots of data traffic are required for such purpose.
In the last years, cheap wi-fi accelerometers begun to be installed on bridges providing short length accelerograms. This paper explores the feasibility and the quality of dynamic identification of composite steel-concrete bridge decks based on short-duration accelerometer recordings (slightly longer than 100 seconds) recorded at specific times of day.
Furthermore, the outcome of using a small number of sensors on the results of dynamic identification is studied.
The article highlights the potential and critical issues of dynamic monitoring based on short-term accelerometer recordings and a limited number of sensors.
The results obtained show that short duration of accelerometer recordings cannot be used with a traditional OMA approach but may allow for dynamic identification with acceptable results if properly treated.
The second critical aspect is related to the limited number of sensors, which, for the purposes of a model-driven monitoring approach, makes the model updating of the digital twin particularly complex.

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1. Introduction

The infrastructure assets of many western Countries were largely developed between the 1950s and the 1980s. As a result, a significant portion of these structures has now exceeded its original design life and is showing increasing signs of aging and deterioration. This condition has raised important concerns regarding structural safety and serviceability, especially for strategic infrastructures such as highway bridges and viaducts (Neves et al. (2005), Frangopol et al. (2007).

In this context, Structural Health Monitoring (SHM) represents a fundamental tool to assess the condition of existing structures and to ensure their long-term safety and durability (Farrar and Worden (2012)). In recent decades, interest in both static and dynamic monitoring has grown significantly (Bertagnoli et al. (2023), Bertagnoli et al. (2024), Ferrara et al. (2024)), driven by the evolution of measurement technologies and the increasing availability of advanced control systems (Bertagnoli et al. (2020), Imperiale et al. (2024)).

At the same time, technological progress and the decreasing cost of sensors have made it possible to monitor increasingly complex structures in a more continuous and detailed way. The spread of low-cost accelerometers, Internet of Things (IoT) devices, and cloud-based data storage has opened new opportunities for large-scale monitoring of bridges and other infrastructures (Bertagnoli et al. (2020), Swartz et al. (2009)). In parallel, the development of numerical models, such as finite element models, has become essential for the interpretation of monitoring data and for understanding the structural behavior under different operating conditions (Ferrara et al. (2024), Sun et al. 2025).

However, despite these technological advances, the large-scale implementation of SHM in civil engineering remains in its early stages. Unlike other engineering sectors — such as automotive and aerospace — where monitoring systems are standard and fully integrated, civil structures are rarely equipped with permanent sensing networks. In contrast, bridges and viaducts, though equally vital to safety, are often monitored only when specific structural issues arise.

One of the main obstacles to the wider diffusion of SHM systems lies in the management of the vast amount of data produced by dense sensor networks. Even though the cost of individual sensors has dropped dramatically, the acquisition, storage, and processing of large quantities of data require considerable computational and economic resources. Despite the decreasing cost of sensors, the data infrastructure required for their management and operation remains expensive, constituting a significant limitation for many infrastructure owners and public administrations.

As a result, current research is exploring simplified yet efficient monitoring strategies, capable of reducing both data volume and system complexity while maintaining a minimum reliable diagnostic accuracy using Operational Modal Analysis (OMA) do short under-sampled accelerograms and other techniques related to small data handling.

While the application of OMA to civil structures is well established in the literature, it typically requires long-duration acceleration recordings to ensure reliable identification and adequate frequency resolution (Ranieri and Fabbrocino (2014), Peeters et al. (2001)). This inevitably generates large datasets that are not always practical to handle, especially in continuous and large-scale monitoring systems.

In the present accelerations were recorded over time windows slightly longer than 100 seconds at a sampling frequency of 80 Hz. Such recordings were collected at fixed regular intervals throughout the day.

The authors are aware of the empirical guidelines commonly adopted in Operational Modal Analysis, which recommend recording 1000 to 2000 times fundamental mode period. Some studies have shown that natural frequencies can be reliably estimated even with a few hundred cycles, whereas damping generally require much longer recordings (Banfi & Carassale (2016), Christensen et al. (2019)). In the present work, the signal length corresponds to 384 cycles of the first identified mode, much shorter than those typically used in conventional OMA. The aim of the paper is to investigate the limits of OMA when short and information-poor accelerograms are employed, and to show that only through careful signal selection, meaningful information on the dynamic behavior of the structure can still be obtained.

Moreover, the monitoring campaign was performed with a limited number of accelerometers, positioned to capture the fundamental dynamic behavior of the structure.

In summary, this work aims to highlight both the potential and limitations of dynamic identification approaches based on short-term acceleration recordings and a reduced number of sensors. The results demonstrate that reliable modal parameters can still be extracted under these simplified acquisition conditions, offering valuable insights for cost-effective and scalable monitoring of bridges and viaducts.

2. Case study description

The case study concerns the Fiorenza Interchange, a major motorway junction located in Milan, in northern Italy. The interchange connects two of the most important highways in the national network: the A4 Venezia–Torino and the A8 Milano–Laghi. Some of the overpasses of the interchange are affected by noticeable vibration phenomena induced by traffic loads. These effects are particularly evident during the passage of heavy vehicles. Some light forms of structural degradation, mainly concentrated around the expansion joints is also present. As a result, a detailed dynamic investigation was considered necessary to better understand the structural response.

The interchange is composed of six viaducts, identified by a numerical code and a color in Figure 1: 2A2 (green), 223 (red), 210 (yellow), 233 (blue), 2B4 (orange), and 243 (violet).

Fig. 1. Layout of the highway interchange.

Fig. 2. View of the underside of a generic 4-beams and a 2-beams viaduct.

The decks of all six viaducts are composite steel–concrete beam girders. Some of them consist of two longitudinal steel beams (viaducts 210, 2B4, 2A2, and 243) while two others count four longitudinal steel beams (viaducts 223 and 233). These two structural configurations are illustrated in Figure 2. The length of the spans varies from 25 m to 36 m. The piers are made of circular columns and they are founded on shallow foundations.

The spans are isostatic using a peculiar gerber scheme based on a tensed pendulum system. The support system on the piers is quite unusual; a detail is shown in Figure 3. One span rests directly on the circular columns, while the adjacent span is connected by the pendulum to the span that rests directly on the columns.

The monitoring system consists of a network of triaxial wireless accelerometers. Each accelerometer is battery-powered with an operating autonomy of up to four years, ensuring long-term monitoring capability with minimal maintenance. The sensors configuration parameters can be remotely modified from the central monitoring unit. Since they operate through a wireless communication system, no wired connections are required, significantly reducing installation costs and time.

Each sensor measures acceleration along three directions — vertical, longitudinal, and transverse — with a sampling rate of 80 Hz. The acceleration values are expressed in milligravity (mg) units. The sensors were installed at four locations along the deck: at midspan (L/2), quarter span (L/4), one-eighth span (L/8), and near the support.

The scheduled acquisition mode consists of recordings with a duration of 102.4 seconds, corresponding to 8192 samples per axis for each triaxial accelerometer at 80Hz. These are pre-programmed acquisitions, automatically performed at fixed time intervals defined by the user (for example, every 1, 2, 6, 12, or 24 hours). This type of acquisition will be used by the authors to estimate the natural frequencies and other modal parameters of the structure under ambient vibration conditions.

A second acquisition mode activated on this structure is the triggered acquisition mode. Each sensor can activate himself whenever the measured acceleration exceeds a predefined threshold value. Each triggered acquisition lasts 12.8 seconds, corresponding to 1024 samples per axis at 80Hz. The threshold level can be remotely configured via a web-based monitoring platform. This type of recording can be useful for capturing transient events, such as the passage of heavy vehicles or other impulsive excitations that can significantly influence the dynamic response.

For each viaduct, the monitoring system was installed on only one or two spans, depending on accessibility, structural configuration and budget limits. This approach allowed the study of recurrent portions of each structure, while maintaining a limited number of sensors and a manageable amount of data.

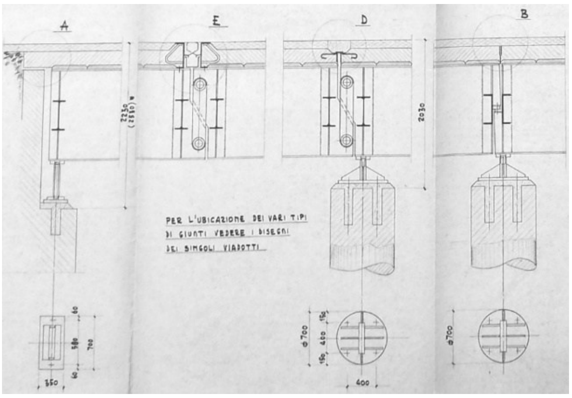

Fig. 3. Original drawings of the gerber tensed pendulum system.

3. Methodology

Each of the two acquisitions described in the previous paragraph provides complementary information about the structural behavior. The methodological approach is therefore divided into two parts:

- The analysis of triggered accelerations, focused on the evaluation of the peak-to-peak dynamic response and its temporal evolution;
- The analysis of scheduled accelerations, aimed at identifying the natural frequencies and mode shapes of the structures based on 102.4-second recordings.

A first analysis was performed on the acceleration records generated by the triggered acquisition mode. For each sensor, the peak-to-peak acceleration was computed from every triggered accelerogram. These values represent the maximum dynamic response recorded during individual excitation events.

All the peak-to-peak acceleration values were then grouped on a monthly basis, and for each month the maximum peak-to-peak acceleration was selected. The resulting time series, representing the monthly maximum acceleration, was then plotted to evaluate its temporal evolution over the entire monitoring period.

This approach allows detecting possible seasonal trends in the structural response — for instance, variations correlated with temperature — as well as identifying anomalous vibration patterns that could be associated with changes in structural stiffness or local damage. It thus provides a simple but effective indicator for assessing the long-term dynamic stability of the monitored viaducts.

The second part of the analysis concerns the accelerograms recorded through the scheduled acquisition mode: 102.4 seconds 80 Hz acquisitions taken every 6 hours. A flow chart of the procedure is provided in Figure 4.

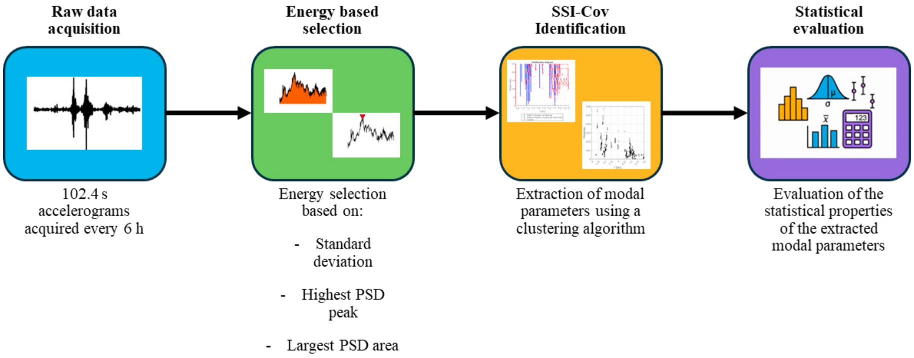

Fig. 4. Workflow of scheduled accelerograms recordings.

Performing Operational Modal Analysis (OMA) on the entire dataset would require an extremely high computational effort. Therefore it was considered sufficient to perform a small set of OMAs per month to track the evolution over time of the dynamic properties of the monitored viaducts. The accelerometric data were grouped on a monthly basis for each structure. Within each month, the most energetic accelerograms were selected using three complementary criteria:

- The highest standard deviation of the acceleration time history;
- The largest area under the Power Spectral Density (PSD) curve;
- The highest peak of the PSD function.

The input signals are first filtered to remove noise (low-pass at 10 Hz). Then, for each acquisition, the three energy-based indicators are calculated separately along the vertical, longitudinal, and transverse directions.

After identifying the most energetic accelerograms according to each criterion, the corresponding recording dates are compared to find the most recurrent acquisition times across the three methods. For each viaduct, the synchronous accelerograms (same date and hour for all sensors) corresponding to these recurring acquisition times are selected for OMA. To avoid potential outliers and to ensure redundancy, the OMA is not performed on a single set of accelerograms, but rather on the three most energetic sets identified each month.

For each month, the natural frequencies, damping ratios, and mode shapes of the monitored systems are calculated using the SSI-Cov (Stochastic Subspace Identification – Covariance-driven) algorithm. This method generates stabilization diagrams that can vary significantly in clarity depending on the signal-to-noise ratio of the analyzed accelerograms. The stable pole alignments are automatically extracted using the DBSCAN clustering algorithm, which identifies dense clusters in the frequency-damping space. Once the stable modes are identified for each month, a comparison across all months of the year is performed to identify recurrent modes.

Finally, for each identified frequency, the following statistical indicators are computed: the number of occurrences, the mean value, the standard deviation, and the coefficient of variation.

This procedure allows for a systematic and automated identification of the dynamic characteristics of the monitored viaducts and their temporal evolution over the year, providing a reliable foundation for long-term vibration-based monitoring with limited data acquisition requirements.

In parallel with the analysis of the measured accelerations, finite element (FE) models of the monitored viaducts were developed to perform a model updating process aimed at refining the numerical representation of the structures based on the experimentally identified dynamic characteristics. The numerical models were created using both beam-type and shell-type elements, to accurately reproduce the composite steel–concrete behavior of the decks and the stiffness contribution of the slab. The beam elements were employed to represent the longitudinal steel girders and transverse crossbeams, while the shell elements were used for the reinforced concrete deck.

4. Results and Discussions

The results reported here refer to the 2A2 viaduct. The analyses provided similar results for the other viaducts.

Figure 5 reports the monthly trend of the maximum peak-to-peak accelerations measured in the vertical direction for all accelerometers installed on viaduct 2A2. Sensors are mounted on the edge girder of span 4 (C4) and span 5 (C5) at L/8, L/4, and L/2; two additional sensors (P5 N and P5 S) are placed on the two columns of the pier between the two spans.

The curves show that the largest vertical accelerations are generally observed at L/4 and L/8 while mid-span (L/2) exhibits slightly lower amplitudes. This spatial pattern is consistent with the first vertical bending modes of the deck: quarter-span locations tend to experience higher curvature/acceleration than mid-span for the dominant traffic-induced response on the edge girder. The pier sensors record very low vertical accelerations, as expected at support regions where vertical motion is restrained.

Over Jan-2023 - Oct-2024, the vertical acceleration levels are remarkably stable, with only modest seasonal fluctuations (slightly higher in winter, lower in summer), plausibly caused by temperature-dependent structural behavior. Monitoring of expansion joints confirmed the increase of stiffness in summer due to complete closure of the joints. No persistent drifts or abrupt changes are evident, suggesting no progressive loss of stiffness in the monitored spans during the observation period. Overall, the results indicate a consistent vertical dynamic response across sensors and months, and they validate the effectiveness of the triggered-acquisition approach for tracking peak responses with limited data volume.

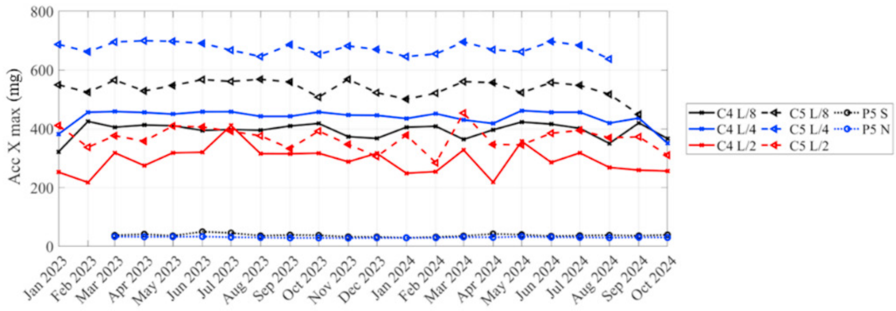

Fig. 5. Maximum monthly peak-to-peak accelerations of viaduct 2A2.

Dynamic identification was performed once per month on the three most energetic synchronous recordings selected according to the procedure described in the previous section. All the identified modal parameters were then aggregated on an annual basis, and the vibration modes were extracted using clustering algorithms.

The average natural frequency of each identified mode and the corresponding confidence bands are reported in Figure 6, monthly, during the years 2023 (left) and 2024 (right) for the viaduct 2A2. Each black dot represents a frequency identified through OMA from the most energetic synchronous accelerogram sets, while the solid lines indicate the average frequency values and the shaded bands correspond to the confidence intervals derived from the statistical distribution of the results.

Some differences may be observed in the average frequencies and in the amplitude of the confidence intervals, but the authors believe they are solely related to the statistical sample and do not indicate any monotonous and/or continuous change in the dynamic behavior or structural condition of the viaduct.

Two recurring vibration modes are consistently identified throughout the monitoring period, with average frequencies of 3.74 Hz and 3.99 Hz, respectively. These frequencies represent the most dominant vibration modes of the structure and remain substantially stable over time.

Figure 7 illustrates the modal shapes corresponding to the two identified modes. In the figure, the black line represents the undeformed configuration of the structure, the red line indicates the mean modal shape obtained by averaging all the modal shapes clustered within the mode, while the grey lines show the individual modal shapes belonging to the same cluster.

Overall, the results confirm the stability of the identified modal parameters over two consecutive years and validate the reliability of the adopted short-duration OMA approach for long-term vibration-based monitoring.

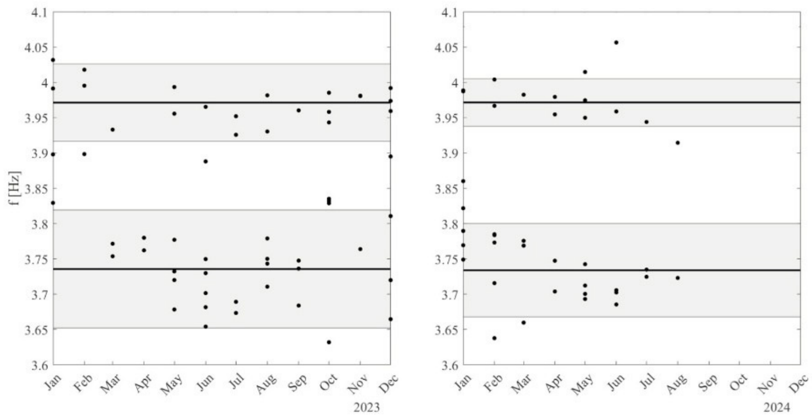

Fig. 6. Viaduct 2A2. Identified frequencies.

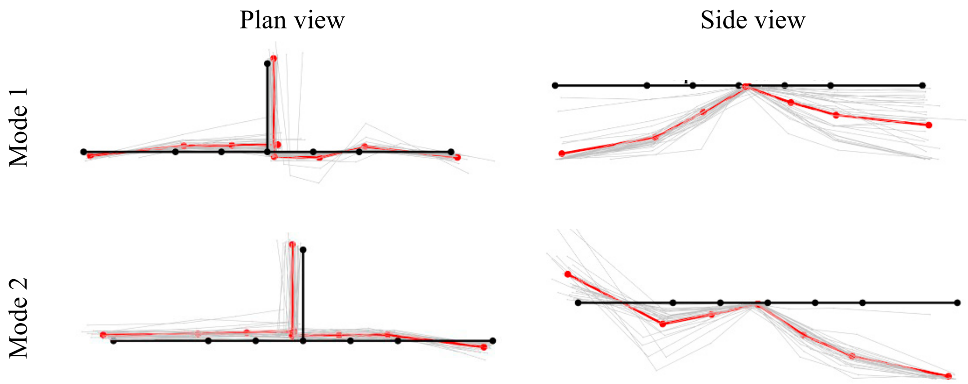

Fig. 7. Viaduct 2A2. *Modal shapes of the identified modes*.

The comparison between the experimentally identified modal parameters and those obtained from the finite element models proved to be particularly challenging. The numerical models exhibited several closely spaced vibration modes, both in terms of frequency and modal shape, which makes the interpretation of the numerical dynamic behavior complex.

Due to the high similarity between adjacent numerical mode shapes, establishing a clear and unambiguous pairing between the experimental and numerical modes requires careful evaluation and did not lead to a clear conclusion.

5. Conclusions

This study presents an application of a Structural Health Monitoring (SHM) system, focusing on the potential of short-duration dynamic recordings and a limited number of sensors for long-term vibration-based monitoring.

Two complementary analysis procedures were implemented: the triggered acquisition analysis, based on the evaluation of monthly peak-to-peak accelerations, and the scheduled acquisition analysis, aimed at the identification of the modal parameters through short 102.4-second recordings. The results demonstrated a stable dynamic response over time, with only minor seasonal variations attributable to environmental conditions.

The OMA-based identifications provided consistent modal frequencies across two years of monitoring, confirming the reliability of short recordings for structural characterization. Meanwhile, the numerical modelling highlighted the complexity of the system's dynamic behavior, due to several closely spaced modes, making the model updating process still a work in progress.

Overall, the study confirms that a cost-effective SHM strategy combining limited instrumentation, short-duration acquisitions, and robust data processing can successfully capture the essential dynamic features of complex bridge structures, providing a solid foundation for the assessment of the structural safety of the bridges.

On the contrary, the lack of quantity of instruments, the poor quality of the accelerometric information retrieved and the peculiar dynamic properties of the bridges did don allow to find a clear correspondence between f.e.m. numerical and experimental modes. A much higher number of sensors on each span, longer acquisitions and higher sampling would have been necessary to accomplish this task.

As a conclusion a model driven OMA requires higher quality data, whereas the data driven approach presented in this paper can be useful to study the evolution over time of some key parameter without the computational and economic burden of traditional OMA techniques.

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