

Ambient vibration data for SHM of historic structures

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ABSTRACT: Structural health monitoring (SHM) based on ambient vibration sources is suitable for historic buildings due to its rapid, non-invasive and reliable approach. It is a consolidated methodology for testing construction and a good alternative in Life Cycle Assessment (LCA), for estimating structural behavior over time. This research shows the effectiveness of ambient vibration data in assessing the structural health monitoring of heritage. By analyzing this data, changes indicating damage or deterioration can be detected, enabling continuous monitoring without extensive and invasive physical tests.

The research includes case studies of historic masonry arch bridges in Venice (Italy), showcasing the practical applications of ambient vibration monitoring. Results indicate that this method can accurately identify structural issues and provide early warnings. Furthermore, this data helps in the calibration and validation of numerical models, enhancing structural assessments accuracy, and potential application for Machine Learning. The findings emphasize the importance of vibration-based monitoring techniques to ensure the longevity and safety of historic structures and contribute to the preservation of cultural heritage.

1 INTRODUCTION

Structural health monitoring (SHM) is essential for the preservation of historic buildings, monuments and bridges, particularly those in culturally significant cities like Venice. Traditional monitoring methods often involve invasive techniques that can damage these structures. Ambient Vibration Monitoring (AVM), a non-invasive and rapid approach, offers a promising alternative for assessing the structural integrity and ensuring the longevity of cultural heritage. AVM measures the natural vibrations of a structure, caused by environmental factors such as wind and traffic, to assess its health without any physical intervention, forming a robust strategy for long-term structural monitoring and data archiving.

Research has demonstrated the effectiveness of AVM in a variety of heritage structures (Russo, 2013a) (Russo, 2013b) (Boscatto, et al., 2015) (Castellaro, et al., 2017) (Sorrentino, et al., 2018), for instance the assessment of the Rialto Bridge in Venice underscores the practical applications of AVM in detecting early structural issues and providing timely warnings (Russo, 2016). Further studies validate AVM's reliability in updating structural models and identifying parameters under seismic activities, emphasizing its role in preserving historic constructions without causing damage. (Luş, et al., 1999) (Boscatto, et al., 2015) (Ceravolo, et al., 2014)

Additionally, De Stefano et al.'s comprehensive review of SHM techniques highlights the relevant experiences on SHM of historical heritage in Italy (De Stefano, et al., 2016), while the works of Gentile et al., and Castellaro provide evidence of AVM's application in monitoring and assessing seismic vulnerability (Gentile & Saisi, 2006) (Castellaro, 2016).

Venice, with its complex network of over 400 bridges, exemplifies the importance of innovative monitoring techniques like AVM. These bridges, many dating back centuries, are vital not only for the city's functionality but also for maintaining its cultural heritage. The adoption of AVM in Venice provides valuable insights into the health of these structures, ensuring their preservation for future generations.

By monitoring the dynamic properties of these structures, AVM helps detect changes indicating damage or deterioration, enabling continuous monitoring without extensive physical tests. (Ivanovic, et al., 2000) (Godarzi & Hejazi, 2025) This method enables early warning systems based on detected anomalies while also facilitating the creation of a consistent data archive useful for machine learning and rapid interventions.

2 RESEARCH'S AIM

SHM is crucial for conserving historical buildings, as they are often subject to natural deterioration and damage due to age and exposure to environmental factors. This study focuses on utilizing ambient vibrations, a non-destructive method, for SHM in historical buildings. The research demonstrates how Operational Modal Analysis (OMA) (Brincker & Ventura, 2015) (Brincker, et al., 2007) plays an essential role in vibration-based SHM, providing a cost-effective approach to monitor the dynamic behavior and structural integrity of historic buildings over time. By identifying changes in natural frequencies and modal shapes, OMA helps detect and track any damage or deterioration, offering critical information for the maintenance and conservation of these important cultural heritage constructions.

OMA techniques are widely applied to determine the dynamic parameters of historic buildings, even though these structures are often complex and filled with mechanical and physical uncertainties. The most intuitive technique used for these purposes is Peak Picking (PP) (Naderpour & Fakharian, 2016), which identifies strong responses near the structure's natural frequencies from the peaks in the power spectral densities computed for the time histories recorded at the measurement points.

The time histories need to be converted into the frequency domain for practical reasons and computational requirements, and for this purpose, the Fast Fourier Transform (FFT) (Cooley & Tukey, 1965) is mostly preferred to ensure a fast and accurate conversion.

This study uses AVM methods to conduct in-situ tests in ten historic masonry arch bridges located in Venice, in the zone which is indicated in Figure 1. The PP identification technique is applied to measured data, and by processing them, dynamic parameters such as frequency, damping coefficient, and modal shape can be determined, which can then be filled into 3D geometric models to reconstruct the overall behavior of the bridge in the future.

3 EXPERIMENTAL IN-SITU PROGRAM

The research employed digital lightweight 3d velocimeters, known as Tromino®, to collect ambient vibration data from ten historic bridges in Venice. Measurements were taken using three Tromino®, during early morning hours, between 2 AM and 7 AM, to minimize ambient noise interference due mainly to walking. One of the three devices is set in the half span of the bridge and the other two are placed on the first and third quarter length of the bridge, to gather more extensive data from each bridge.

Each acquisition had a duration of 16 minutes, with a sampling frequency of 128 Hz, consisting of three components: two horizontal and one vertical. Dynamic monitoring, based on natural vibration sources like wind, and the waves of the water, was harnessed via a dynamic identification process to determine frequencies, damping coefficients, and modal shapes.

TROMINO®, which is a portable ultra-light acquisition system developed by Moho World s.r.l., based in Venice, can record ambient noise in a frequency range from 0.1 to 200 Hz with high digital resolution of approximately 24-bit. One of its main benefits is its lightweight (1.1 kg) and small size (10 x 14 x 8 cm), allowing it to be placed anywhere in the construction.

4 SIGNAL PROCESSING AND FEATURE EXTRACTION

The ambient vibrations captured by TROMINO® are amplified, converted into digital form, and transferred to an internal memory card (e.g., 16 GB). It is then analyzed on a PC using Grilla®

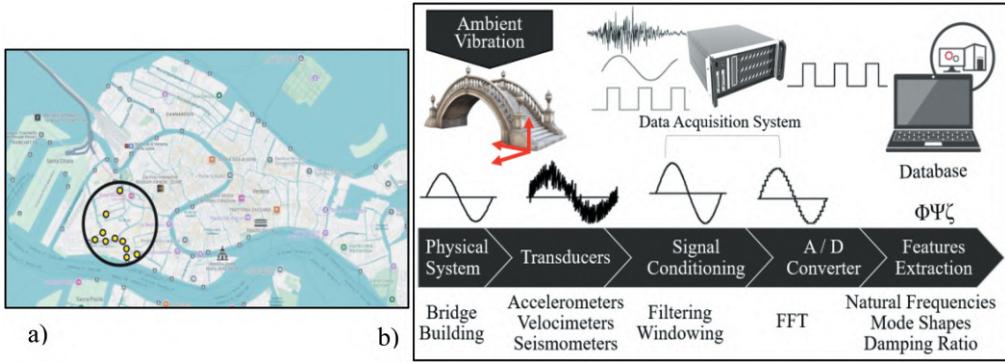


Figure 1. a) Map of ten chosen masonry bridges in Venice, b) Ambient vibration monitoring flowchart.

software, which provides routines for spectral and H/V analyses, following the European SESAME project directives (SESAME, 2004). The software employs the FFT to convert the signal from the time domain to the frequency domain, facilitating signal processing operations. By calculating the Fourier spectra of the horizontal (H) and vertical (V) components of the signal, practitioners can derive essential insights about site resonance frequencies and other critical dynamic properties (Nakamura, 1989).

The mathematical formulation of this Fourier Transform operator is described as follows (Eq.1,2), where f represents frequency and t denotes time:

$$h(t) = \int_{-\infty}^{+\infty} H(f)e^{i2\pi ft} df \quad (1)$$

This can also be expressed more compactly as $h(t) = F[H(f)]$, where F denotes the Fourier Transform. In this context: $h(t)$ is a time-domain function that describes the system's response or behavior, t is the variable function, F is the Fourier Transform Function, and $H(f)$:

$$H(f) = \int_{-\infty}^{+\infty} h(t')e^{-i2\pi ft'} dt' \quad (2)$$

The pair $h(t)$ and $H(f)$ are related by the Fourier Transform and its inverse, forming what is often referred to as a Fourier pair. These functions are interconnected such that their combined behavior preserves information, with the product of their variables equaling 1.

This property enables the Fourier Transform to be expressed in a summation form for discrete systems or periodic signals, as follows (Eq.3):

$$h(t) = \sum_{n=-\infty}^{+\infty} c_n e^{i2\pi n f_0 t} \quad (3)$$

Here, c_n are the Fourier coefficients, and f_0 is the fundamental frequency of the periodic function.

For functions with a period T that approaches infinity (i.e., non-periodic signals), the fundamental frequency f_0 approaches zero. In such cases, the summation form transitions into the integral representation, making the Fourier Transform applicable to both periodic and non-periodic functions.

The natural frequencies of the building are identified through a simple peak-picking strategy. Initially, transients are manually removed with a specific tool, and the Fourier spectrum is then calculated by dividing the signal into non-overlapping windows of 20 seconds. Each window is detrended, tapered, padded, fast Fourier transformed, and smoothed with triangular windows with a width of 1-3% of the central frequency. Additionally, three other windows (rectangular, cosine, and Konno & Omachi) are available. The elaborated recordings can be exported in ASCII or SAF format, allowing the analysis of individual signal components (e.g., N-S, E-W, U-D) or just the velocity/acceleration data.

5 DYNAMIC IDENTIFICATION PROCEDURE

The AVM approach involves several steps, including instrumentation and data acquisition, signal processing and feature extraction, data interpretation and analysis, and damage detection. A typical monitoring system comprises sensors, a Data Acquisition System, and a database for data collection and storage. The signal is pre-processed with operations such as filtering, windowing, and decimation before being converted from analog to digital via an A/D converter. Finally, the signal is collected, stored, and processed by OMA identification algorithms to extract the system's dynamic features, such as main peaks, mode shapes, and damping ratio. (Figure2) These steps help in accurately identifying and analyzing the modal parameters of the structure. The collected data are processed through Grilla® software, which implements Fourier Spectrum Analysis and the PP algorithm to identify modal frequencies and mode shapes of the system.

The damping coefficients were estimated through the “half-power bandwidth” method (Chopra, 2016) by the following equation (Eq.4):

$$\zeta = \frac{f_b - f_a}{2f_n} \quad (4)$$

where f_a and f_b are the frequencies before and after the frequency value f_n , at which there is a peak amplitude P of the Fourier spectrum, with amplitudes of $P/\sqrt{2}$.

6 EXPERIMENTAL RESULTS

This section presents the results obtained from the in-situ investigation and dynamic monitoring, including the frequencies, and damping coefficients. Figure 2 shows the sensor placement on the bridges and the acceleration spectra of the first bridge, with three orthogonal components. Figure 3 shows the acceleration spectra diagrams of all ten bridges, with only the vertical component, since in dynamic monitoring of bridges, the consideration of vertical flexion motion and relative damping is of interest and essential. The properties of the main vibration modes for the bridge structures are shown in Table 1. Unlike buildings, interpreting mode sequences in bridges is more complex due to the diversity in shapes, materials, and anchorage points to the ground. These factors lead to a larger number of observable modes. However, the pick frequencies, dominant mode and the damping ratio, where possible, are mentioned in Table 1.

All the monitored bridges are arch type, and as we know, the first flexural mode with high amplitude will not appear at the mid-span, and the amplitude at the 1st and 3rd quarter-spans are expected to be higher. Figure 3 shows that in most of the cases, this pattern is happening. In almost all the diagrams, at least one flexural mode is clear, however only in bridge no. 10, the data is unclear and the amplitude stays the same at almost all frequencies with very small peaks.

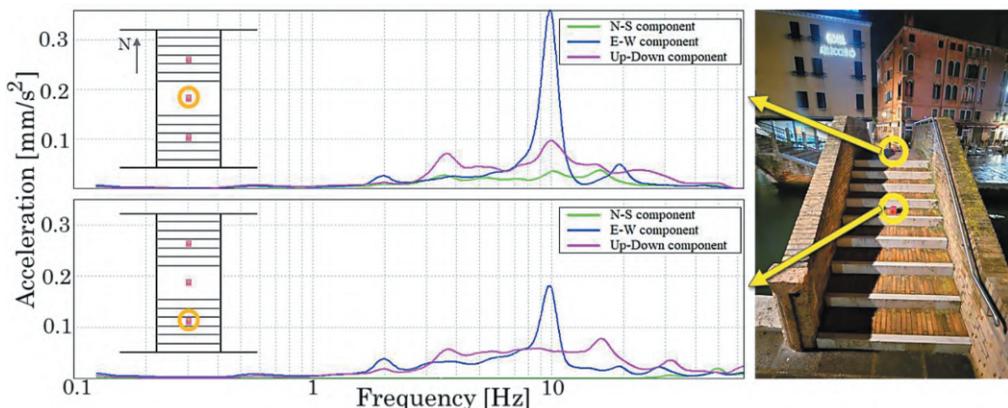


Figure 2. Acceleration spectra of ponte cosetti in three components, by AVM.

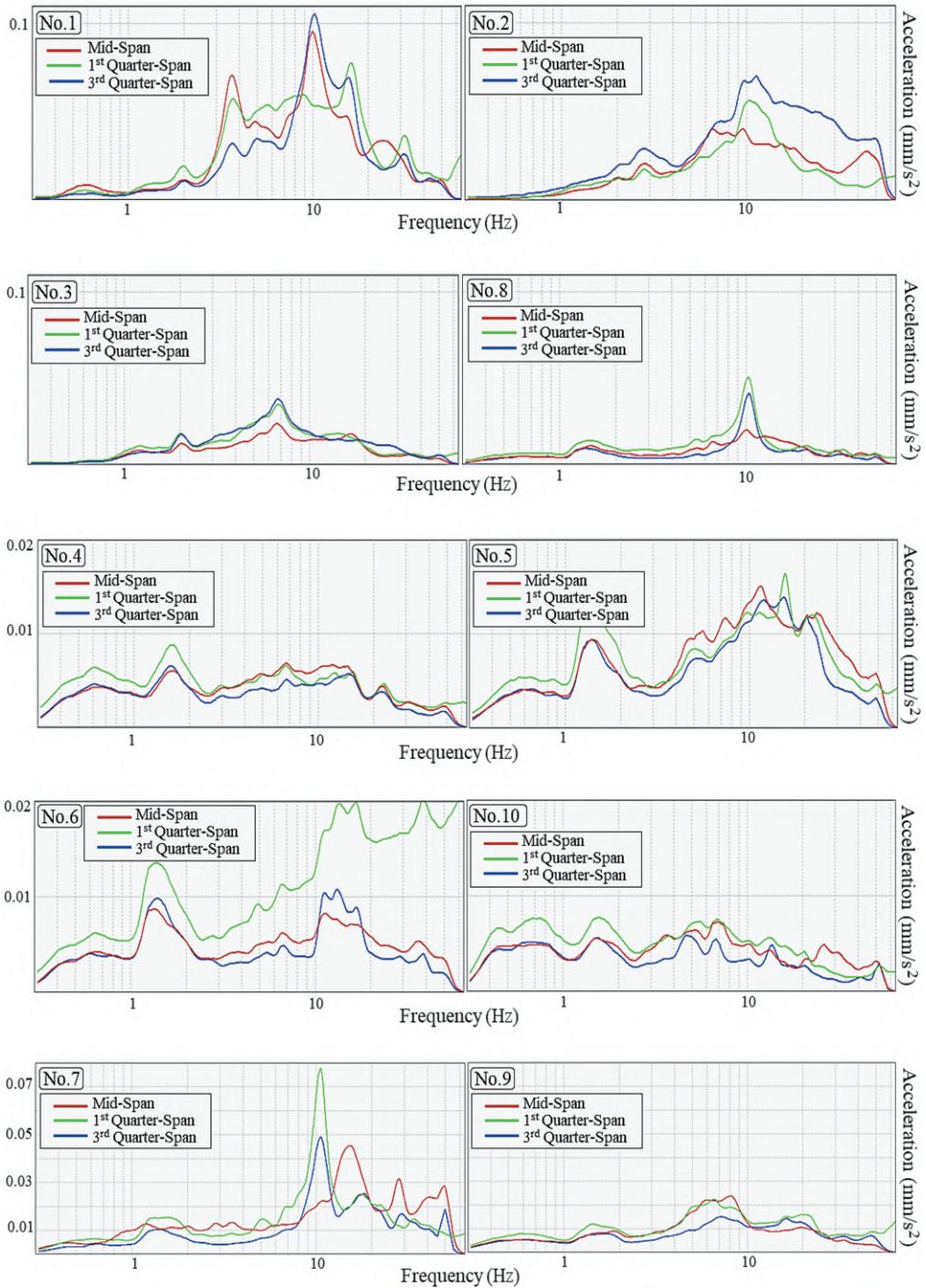


Figure 3. Acceleration spectra of vertical component, by AVM of bridges No.1 to 10

A visual inspection was also conducted on these ten masonry arch bridges and their condition of conservation was preliminarily classified as indicated in Table 1. The evaluation was based on visible damages such as weathering, mortar loss, cracks, vegetation growth, erosion, and settlement. For example, bridges in Poor condition showed significant mortar loss,

Table 1. Main properties and vertical vibration frequencies for the monitored masonry arch bridges.

No.	Photo of the Bridge	Bridge Name	Level of Conservation	Dimensions (m)			Peak Frequencies (Hz)	Dominant Mode	Damping Ratio (%)
				Length	Width	Height			
1		Ponte Cosetti	Poor	7.75	2.22	2.10	0.62		-
							2		-
							3.6		10.9
							10.2	Flexural	14.2
							16		-
2		Ponte Santa Maria Maggiore	Poor	10.23	3.59	2.85	2.72		-
							9.6	Torsional	-
3		Ponte de le Terese	Fair	9.30	4.12	2.05	2.05		10.7
							6.64	Flexural	18.9
							16.5		-
4		Ponte S. Nicolò	Fair	8.06	4.33	2.10	0.61		-
							1.65	Flexural	19.8
							6.7		-
5		Ponte De La Piova	Fair	8.06	3.78	2.35	1.4		22.3
							5.15		-
							7.4		-
							11.4	Torsional	-
6		Ponte dell' Angelo Raffaele	Good	8.37	4.35	2.30	1.35	Flexural	26.4
							13.4		-
7		Ponte de la Madalena	Poor	9.73	4.35	1.90	1.23		-
							10.5	Flexural	7.67
							15		16.7
8		Ponte De S. Sebastian	Fair	12.44	5.35	2.03	1.47		23.5
							5.4		-
							10	Flexural	
9		Ponte de San Basegio	Poor	9.92	3.60	2.08	0.6		-
							1.87		-
							8.1	Torsional	-
							16.23		-
10		Ponte Sartorio	Good	8.22	3.04	2.69	0.7		-
							1.53		-
							3.65		-
							6.86		-

cracks, and weathering, while those rated Fair had minor damages like limited vegetation or small cracks. Bridges rated Good were generally well-maintained with only negligible issues. The level of conservation for each bridge is provided in Table 1.

The damping ratio is calculated based on the “half-power bandwidth” method, where possible, and the results are presented in Table 1. This method has indeed certain limitations and

clear, narrow resonance peaks are needed to accurately calculate the damping ratio. Therefore, it was not possible to calculate the damping at all peak frequencies, since as can be seen in the amplitude spectrums, some peaks are not sharp enough.

The bridges in Venice pose unique challenges for dynamic analysis. Their relatively short span and close proximity to buildings of up to five stories significantly influence the spectral response. In general, the vibration spectra could be complicated by the dominant frequencies of nearby structures, which may interfere with the bridge's natural frequencies. This interference makes peak identification challenging and complicates the diagnosis of mode shapes.

7 CONCLUSIONS

This study applied Ambient Vibration Monitoring (AVM) to ten historic masonry arch bridges in Venice, serving as the first phase of a larger campaign involving over 100 bridges. Data were collected using three Tromino® and analyzed with FFT to identify primary flexural frequencies and calculate damping ratios where possible. Challenges arose due to environmental factors and level of structural conservation, which complicated spectral analysis and mode identification. Based on this research, the key findings are:

- The bridges' damping ratios were strongly influenced by their conservation levels. Bridges in good condition (e.g. Bridge 6) exhibited the highest damping ratio (26.44%), suggesting well-preserved materials dissipate energy effectively. While bridges in fair condition showed moderate damping ratios, ranging from 23.47% (Bridge 8) to 10.71% (Bridge 3). Bridges in poor condition, such as Bridge 1 and Bridge 7, had the lowest damping ratios, with values as low as 7.67% and 10.88%, attributed to significant damage, including cracking, mortar loss, and material degradation. This trend also aligns with the width-to-length ratio of the bridges, as Bridge 6, with one of the highest ratios, exhibited the highest damping, while Bridge 1, with the lowest ratio, had one of the lowest damping values.
- The acceleration spectra data indicates that all bridges exhibited at least two distinct peak frequencies during the 16-minute monitoring, suggesting the presence of multiple vibration modes contributing to their dynamic behavior. For six bridges (No. 1, 2, 5, 7, 8, and 9), the dominant peak frequencies were observed between 8 to 11 Hz (10.2 Hz, 9.6 Hz, 11.4 Hz, 10.5 Hz, 10 Hz, and 8.1 Hz respectively). These frequencies, all around the 10 Hz range, are relatively high for masonry bridges but expected and consistent with their low width-to-length ratio. Additional observed vibration frequencies for each bridge are presented in Table 1.
- Most bridges exhibited a notable short peak frequency below 1 Hz, indicating a possible torsional mode, especially in bridges No. 1, 4, 5, 6, 9, and 10. Among the six bridges with a dominant mode around 10 Hz, bridges No. 1, 7, and 8, exhibited flexural modes, while bridges No. 2, 5, and 9, displayed torsional modes. Additional flexural and torsional modes are evident in Figure 3. For instance, bridge No. 1, exhibited its first torsional mode at 0.6 Hz, its first flexural mode at 2 Hz, a second flexural mode at 3.6 Hz, and another at 10.2 Hz. Bridge No. 2 showed a flexural mode at 2.72 Hz and a dominant torsional mode at 9.6 Hz. Bridge No. 3 experiences its first and second flexural modes at 2.05 and 6.64 Hz and bridge No. 4 has a first torsional mode at 0.61 and the first and second flexural mode at 1.65 and 6.7 Hz. These results emphasize the influence of structural proportions and conservation conditions on mode distribution, where bridges with higher width-to-length ratios and better conservation states tend to exhibit distinct modal characteristics at lower frequencies, while slender or deteriorated bridges show higher-frequency modes with less energy dissipation.
- Despite challenges, AVM successfully identified natural frequencies, damping ratios, and mode shapes for these masonry arch bridges. The technique proves effective for monitoring structural health while preserving cultural heritage, ensuring minimal intrusion.
- The half-power bandwidth method showed limitations in accurately calculating damping ratios, especially for broad or unclear peaks in the spectral graphs. Future work will try to employ the Random Decrement Technique, which is an effective method for estimating the damping, originally developed for aerospace applications (Cole, 1973) and later adapted for civil engineering (Jeary, 1986). This method averages segments of a structure's response to

random inputs, such as wind or traffic loads and by isolating the response due to initial displacement, it provides a reliable estimate of the damping ratio, which makes it a valuable tool for the dynamic analysis, ensuring accurate damping evaluation under ambient excitations.

- This study is part of a larger monitoring campaign targeting over 100 masonry arch bridges in Venice, over the next two years. The collected data will form a comprehensive database for applying Machine Learning techniques, enabling advancements in damage detection, early warnings, and rapid intervention strategies for preserving cultural heritage.

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