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Self-powered wireless structural sensors for long-term monitoring of bridges

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Abstract

The present work introduces the design of a self-powered wireless static and dynamic structural monitoring system developed by Wisepower Srl and deployed on some bridges along the S.S. 675 "Umbro-Laziale" (former "Civitavecchia - Orte" junction) since 2018. The most significant aspect of the developed monitoring system lies in the fact that it consists of a wireless network of MEMS accelerometers (noise spectral density in all axes: 22.5 µg/√Hz, and sensitivity: 3.9 µg/LSB) powered by energy harvesting systems, which can convert environmental energy (i.e. vibrations and light) into electrical energy collected in batteries, so extending the life and minimizing the maintenance cycles of the devices. Vibration-based energy harvesting is achieved through a non-linear resonator, which utilizes a wider spectrum of frequencies compared to traditional linear vibration energy harvesters owing to its non-linear dynamics. The efficiency of the system is further enhanced by the combination of solar panels, overcoming the limitations associated with traditional wiring or batteries, widening the lifespan of the electronics, and reducing the maintenance costs. The paper reports the analysis method and the data elaboration of some ambient acceleration records, validating the system for natural frequencies identification.

Keywords: Structural health monitoring; Bridge monitoring; Dynamic monitoring; Energy harvesting.

1. Introduction

Securing stable electrical supply to structural health monitoring (SHM) systems, including wireless sensor nodes and data transmission devices (Wang et al. (2018)), represents a formidable challenge. This is particularly critical for civil engineering structures like bridges in remote locations, where the access to the electrical grid is limited or non-

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existent. In these cases, integrating energy harvesting systems can provide several benefits, including self-sustainability and improved efficiency. Energy harvesting techniques can be applied to monitor various aspects of bridge health, including concrete strength, bolt tension, and scour damage (Fitzgerald et al. (2019), Chen et al. (2018)).

Vibrations from both environmental actions, such as wind or micro-tremors, as well as operational actions like vehicular traffic can be converted into usable energy by energy harvesting systems. In particular, piezoelectric vibration energy harvesters have become notably attractive for civil engineering applications (Clementi et al. (2022)), especially when exploiting more efficient non-linear dynamics, and wherever kinetic energy is variable in time and abundant at relatively low frequencies (Cottone et al. (2009)). Photovoltaic panels installed on the bridge surface or nearby structures also offers an attractive solution, being capable of capturing solar energy and converting it into electrical power. The combination of these energy harvesting technologies are particularly promising for developing self-sustainable monitoring systems, leading to more resilient and energy-efficient bridge SHM systems.

In this context, the vibration-based energy harvesting system patented by Wisepower has proved great potential for solving the problem of powering measurement devices in cases where wiring or the use of traditional batteries is limiting, inconvenient, or not feasible. Thanks to its energy recovery properties, carbon-neutral electricity is produced. The innovative solution has introduced a new approach that significantly increases the efficiency of energy conversion mechanisms compared to traditional methods.

2. Methods

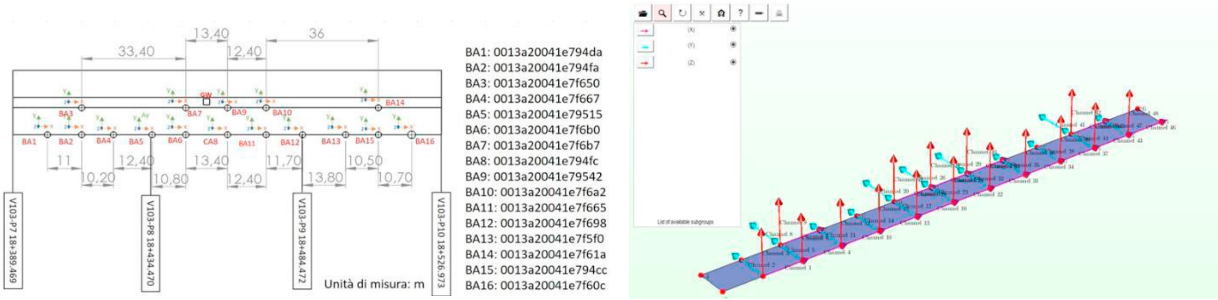
Wisepower sensor nodes provide a reliable, easy-to-mount, and cost-effective solution, which is designed for the dynamic and static SHM of large structures. Based on the MEMS technology, they measure: 3-axes accelerations; polar angles inclinations (sensitivity of 0.02°); and temperature (sensitivity of 0.5 °C). For this specific application, the sensor nodes are synchronized using GPS, data communication is performed by exploiting Zigbee connectivity, and the data are sent through a gateway to a remote server. Sensor operation and wireless connectivity do not rely on any battery replacement, being exclusively powered by solar and vibrational energy harvesting modules. Figure 1a shows one of the sensor nodes installed on the Biedano bridge. The bridge consists of 2 separate steel-concrete composite carriageways, each with a three-spans continuous beam static scheme (Figure 1b).

Ambient accelerations recorded in the Biedano bridge were analyzed using the P3P software (García-Macías et al. (2022)), a proprietary code of ANAS Spa developed by the University of Perugia in collaboration with Politecnico di Milano and the University of Padova, Universities that also participate in the FABRE Consortium since its establishment.

(a) (b)

Fig. 1. (a) Sensor installed on the bridge span. (b) Aerial view of the Biedano bridge (Google Maps).

On the bridge, Wisepower installed 16 triaxial accelerometers with self-powered MEMS technology, whose position is shown in Figure 2a, while Figure 2b shows the 48 measurement channels as inserted in the P3P software. The vibrations were acquired at a sampling frequency of 31.25 Hz and pre-processed to eliminate any linear drifts and frequencies outside the range from 0.2 to 12 Hz.



(a) (b)

Fig. 2. (a - left) Sensor layout on the bridge; (b - right) Definition of measurement channels.

After signal pre-processing, the modal identification of the bridge was carried out using the FDD (Frequency Domain Decomposition) technique. The channels were organized into subgroups of sensors distributed on each of the three spans. Subsequently, the power spectral density matrices of the accelerations were determined. The cross-spectral density function between two time-domain (t) acceleration signals $x_i(t)$ and $x_j(t)$ is defined as (García-Macías et al. (2022)):

$$S_{x_i x_j} = \mathcal{F}\{R_{x_i x_j}\} = \int_{-\infty}^{+\infty} R_{x_i x_j}(\tau) e^{-2j\pi f\tau}\, d\tau = \overline{\mathcal{F}\{x_i\}}\mathcal{F}\{x_j\}, \quad (1)$$

where $\mathcal{F}$ denotes Fourier transform, and $\bar{\bullet}$ stands for the complex conjugate operator. The FDD method starts with the calculation of the frequency-domain (f) spectral density matrix (Shynk (2012)):

$$\boldsymbol{S} = \begin{bmatrix} S_{x_1x_1}(f) & S_{x_1x_2}(f) & \dots & S_{x_1x_r}(f) \\ S_{x_2x_1}(f) & S_{x_2x_2}(f) & \dots & \dots \\ \dots & \dots & \dots & \dots \\ S_{x_rx_1}(f) & \dots & \dots & S_{x_rx_r}(f) \end{bmatrix}, \quad (2)$$

where r is the total number of channels analyzed. Once this matrix is constructed for different frequency values, its singular value decomposition is performed to conduct the modal identification. Specifically, the resonant frequencies can be estimated by selecting the peaks of the first singular value represented as a function of the frequency (Brincker et al. (2001)), while the complex-valued mode shapes are approximately represented by the first eigenvector evaluated at each resonant frequency.

3. Results and Discussion

The time series of the processed ambient accelerations are shown in Figure 3. These results show that the sensors exhibit a clear sensitivity to the passage of vehicle traffic loads, with a significantly high signal-to-noise ratio. The frequency domain analysis also shows a good response of the sensors. In particular, Figure 4 shows the existence of an energy concentration in the frequency range from 1.5 Hz to 5.5 Hz, with some resonance peaks compatible with the natural frequencies of the structure.

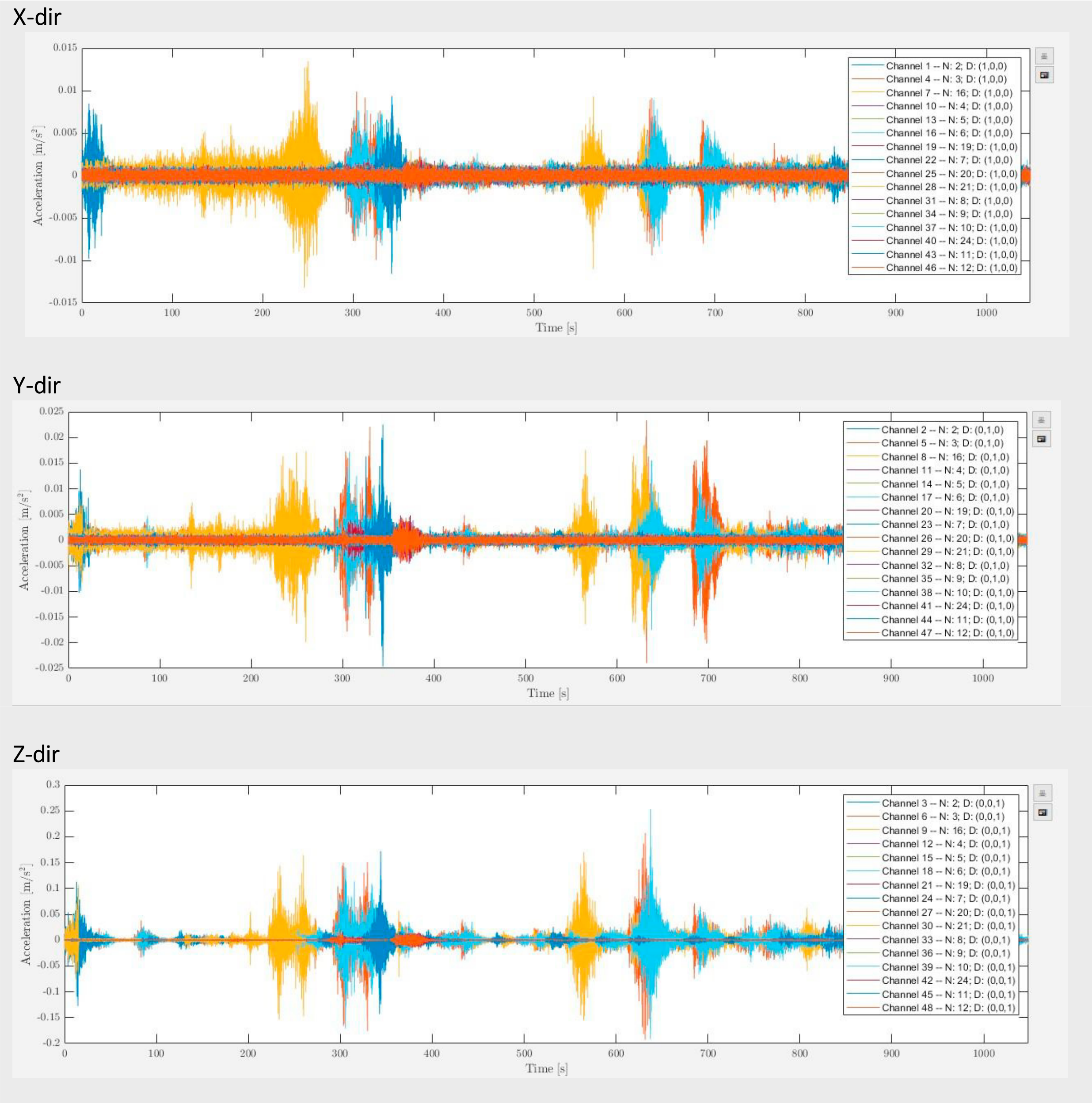


Fig. 3. Pre-processed ambient acceleration signals for the three directions X, Y and Z.

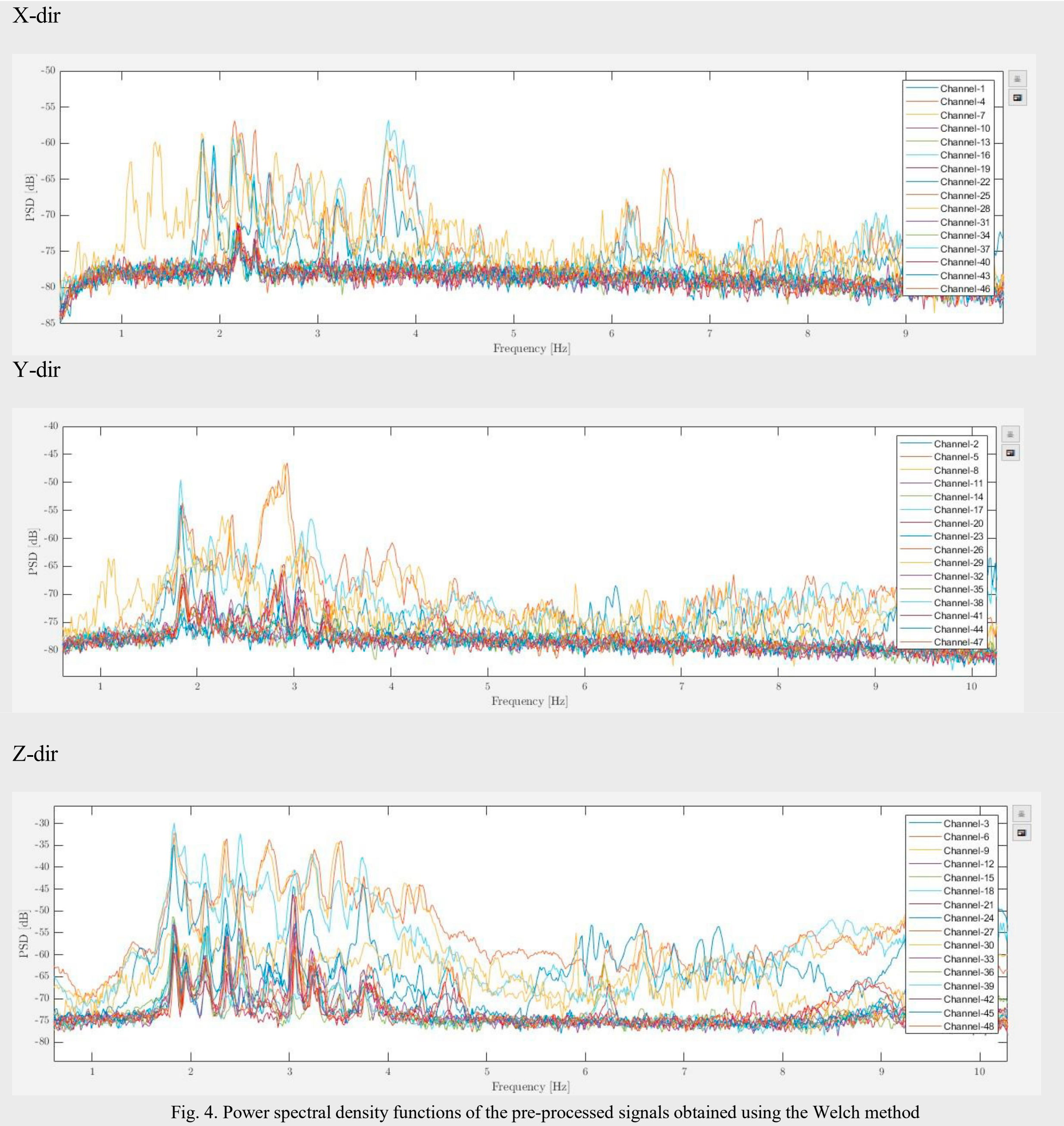
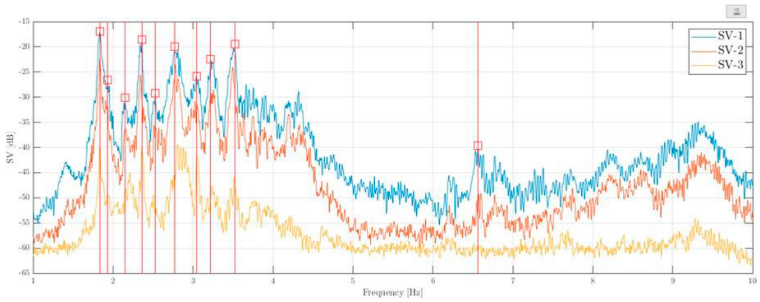
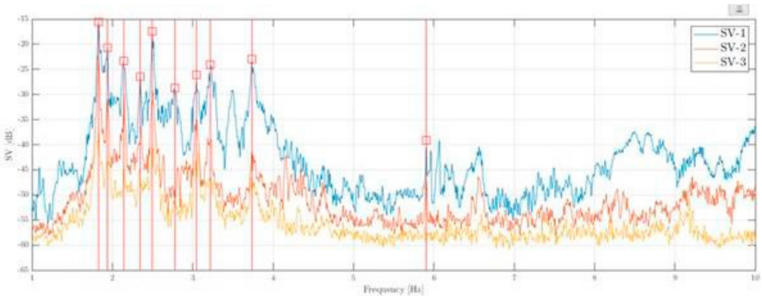


Fig. 4. Power spectral density functions of the pre-processed signals obtained using the Welch method (frequency resolution of 1.53e-3 Hz).

Span 1



Span 2



Span 3

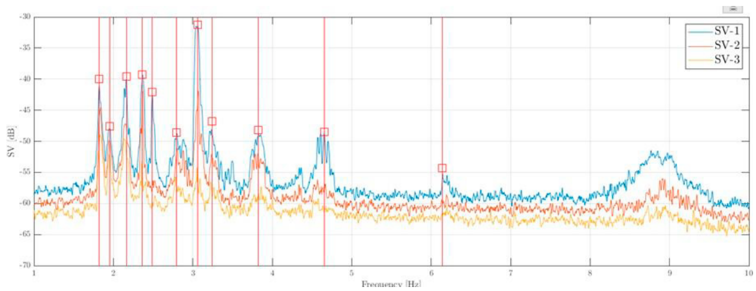


Fig. 5. Detection of resonant peaks of the first singular value of the power spectral density matrices for each span of the bridge.

Figure 5 shows the singular values for each span. The presence of several peaks in the frequency range from 1 to 10 Hz is clearly noticeable. The identified resonance peaks are summarized in Table 1 and compared with the natural frequencies identified in the structural testing campaign.

Table 1. Summary of the natural frequencies of the first 6 significant vibration modes obtained using the FDD technique.

Mode No.	Testing [Hz]	Software Elaboration P3P		
		Span 3 [Hz] November	Span 3 [Hz] March	Span 3 [Hz] June
1	18,65	18,387	18,272	18,196
2	19,69	19,341	19,379	19,569
3	-	21,515	21,414	21,629
4	-	23,613	23,499	23,651
5	28,12	27,695	24,948	24,872
6	62,50	62,599	62,256	61,417
7	-	65,613	65,613	-

To validate the identification of the modal shapes, a typical span is further analyzed. In particular, the data of the five sensors (15 channels) deployed on the third span (see Figure 6a) have been processed in an analogous way to what was presented above, both for the signal pre-processing phase (Figure 6b), and for the FDD technique (Figure 6c). Figure 6d shows the first six mode shapes obtained from the identification. A certain regularity of the mode shapes is observed, in particular the first two modes corresponding to first-order vertical bending modes with a certain asymmetry, most likely due to the structural continuity with the adjacent spans and the skewness of the deck. The mode shapes of the third and sixth modes suggest first-order torsional motions. Finally, mode shapes 4 and 5 are compatible with second-order vertical bending modes. In particular, it is worth noting that the MAC (modal assurance criterion) matrix of the identified mode shapes is almost perfectly diagonal, as it expected in the case of physical modes that are orthogonal to each other. This suggests the structural/physical nature of the identified modes and constitutes an indirect indication of the good quality of the obtained dynamic identification results.

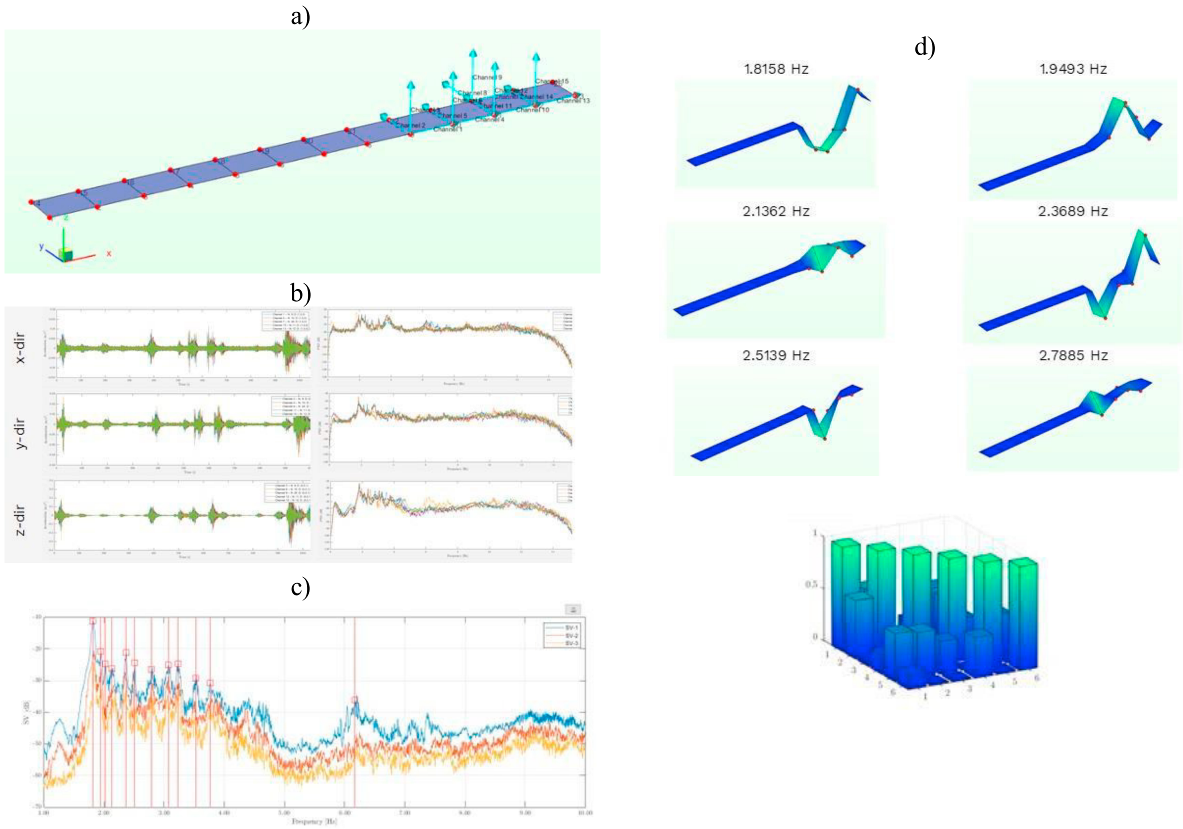


Fig. 6. (a) Definition of measurement channels in span 3. (b) Time series and power spectral density functions of the ambient acceleration records (frequency resolution of 7.33e-3 Hz) in span 3. (c) Detection of resonant peaks of the first singular value of the power spectral density matrices for span 3 of the bridge (set 2). (d) Identified mode shapes in span 3 of the Biedano bridge (set 2).

4. Conclusion

The conducted activities combined the data produced by the structural monitoring system based on Wisepower Srl's self-powered wireless sensors installed on the Biedano bridge, and the P3P software developed by the group composed of Politecnico di Milano and the Universities of Perugia and Padua for ANAS Spa. The study analyzed the ambient acceleration recordings from the field, and the presented results highlight, first of all, that the accelerometers show a strong sensitivity to vibrations induced by vehicle loads with a very good signal-to-noise ratio. In addition, it was possible to identify 6 natural frequencies for each span of the bridge. These natural frequencies are in line with those identified in the initial bridge characterization campaign, and they are consistent from one span to the adjacent ones. The mode shapes appear regular and in line with what is expected for this type of structures. They are also approximately orthogonal to each other as expected from a theoretical level.

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References

Fitzgerald, P.C.; Malekjafarian, A.; Bhowmik, B.; Prendergast, L.J.; Cahill, P.; Kim, C.-W.; Hazra, B.; Pakrashi, V.; OBrien, E.J. Scour Damage Detection and Structural Health Monitoring of a Laboratory-Scaled Bridge Using a Vibration Energy Harvesting Device. Sensors 2019, 19, 2572. https://doi.org/10.3390/s19112572

Chen Y, Xue X. Advances in the Structural Health Monitoring of Bridges Using Piezoelectric Transducers. Sensors (Basel). 2018 Dec 7;18(12):4312. doi: 10.3390/s18124312. PMID: 30544485; PMCID: PMC6308716.

G. Clementi, F. Cottone, A. Di Michele, L. Gammaitoni, M. Mattarelli, G. Perna, M. López-Suárez, S. Baglio, C. Trigona, I. Neri, "Review on Innovative Piezoelectric Materials for Mechanical Energy Harvesting" Energies, 15, 6227, 2022.

F. Cottone, H. Vocca, L. Gammaitoni, "Nonlinear Energy Harvesting" Phys. Rev. Lett, 102, 080601, 2009.

Hao Wang, Abbas Jasim, Xiaodan Chen, Energy harvesting technologies in roadway and bridge for different applications – A comprehensive review, Applied Energy, Volume 212, 2018, Pages 1083-1094.

García-Macías, E., Ruccolo, A., Zanini, M.A., Pellegrino, C., Gentile, C., Ubertini, F., Mannella, P. (2022). P3P: a software suite for autonomous SHM of bridge networks. Journal of Civil Structural Health Monitoring, in press, DOI 10.1007/s13349-022-00653-6

Shynk, J. J. (2012). Probability, random variables, and random processes: theory and signal processing applications. John Wiley & Sons.

Brincker, R., Zhang, L., & Andersen, P. (2001). Modal identification of output-only systems using frequency domain decomposition. Smart materials and structures, 10(3), 441.