

Standalone detector for vibroacoustic heritage monitoring

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Abstract – This paper describes the results of preliminary application tests for a stand-alone prototype data acquisition system. The system was developed for monitoring and characterizing the vibroacoustic landscape and, in particular, the vibroacoustic heritage, such as music instruments or performing spaces. The tests, performed on a building in the historical center of Napoli, show a possible interconnection between acoustic and displacement signals, as external forcing of the monitored structure, with exchange of the cause-and-effect roles, especially at low frequency.

I. INTRODUCTION

The definition of cultural heritage evolved along the years to include both the tangible and intangible components of civilization [1].

Scholars, introducing the concept of “acoustical heritage”, witnessed their gradual awareness about the relevance of acoustic parameters as a relevant experiential factor in the fruition of heritage [2]. Moreover, the intangible dimensions of cultural heritage can be characteristic of a certain space [3]. However, the “acoustical heritage” can be subject to variations along time, due to the change of lifestyles, environmental conditions, social and cultural changes. Thus, physical, historical and social factors should be considered together within a given scenario to identify whether certain acoustic characteristics of a given place could be considered as an immaterial component of cultural heritage.

Such a connection was especially recognized with the year 2003 UNESCO convention for the Safeguarding of the Intangible Cultural Heritage (ICH). ICH integrated the material dimensions (instruments, objects, artifacts and cultural spaces) with the immaterial ones (i.e., practices, representations, expressions, knowledge, skills). In the case of acoustics, audible sounds should be seen as a mean of interaction, eventually conveying a semantic content, originated by given objects in a certain space, sometimes requiring certain practices or skills to be produced. In the case of music, sounds are produced in a certain space with the aid of music instruments and developing certain performing skills, conveying a message to the listeners.

Another example might include the sound of prayers in a sacred space, where specific practices are performed for ritual purposes, involving the participants to the rite through the use of sounds (voice or music). It becomes clear, then, that the study of acoustic heritage can encompass several disciplines, ranging from physics, for the measure and characterization of objects, instruments, artifacts or spaces, to psychology, to infer some details about the perceptual dimensions of sounds.

Considering the physical dimension of sounds, studies of acoustics related to cultural heritage spanned from the vibro-acoustic characterization of music instruments [4] to the acoustic characterization of ancient settlements [5], performing spaces, such as theatres [6], sacred spaces [7] or even cities [8]. In the case of cities, Scholars introduced the term of sound landscape, contracted as soundscape, as the totality of audible vibrations generated by natural and anthropogenic sources, characterizing a certain place. However, the attention of researchers concentrated only on the audible range of vibration frequencies, neglecting the measure of infrasound vibrations. Instead, it would be relevant to include the overall characterization of vibration landscape (i.e., vibroscape), being the totality of vibrations generated by natural and anthropogenic sources, characterizing a certain place. Thus, future studies should expand their domain to the “vibroacoustic landscape” and to the “vibroacoustic heritage”.

The potential reasons for considering such an extension to the “vibroacoustic heritage” are at least three. The first is that some objects (like music instruments) or spaces (like cities) can be characterized by different vibration and acoustic spectra, depending on the existing vibroacoustics sources and the environmental conditions of a certain place. Moreover, vibrations, including both the infrasound and the audible frequencies range, exert an influence on human health and well-being. On the other side, ancient authors developed different theories related to sounds, which were purposefully used to convey specific messages or to obtain specific psychological reactions [9]. This implies an awareness about certain expressions, knowledge and skills, thus pertaining the domain of immaterial cultural heritage of certain contexts.

Given the potential interest to investigate the vibroacoustic heritage from a physical perspective, the first obstacle to

overcome is the availability of integrated sensing technologies for such a purpose. Thus, the aim of this work is to present the integration, into a stand-alone solution, of displacement and acoustic sensors for a simultaneous data collection for the characterization of the vibroacoustic landscape, eventually becoming applicable in other domains pertaining the characterization of vibroacoustic heritage, such as music instruments or performing spaces.

II. INSTRUMENTS AND METHODS

As stressed in the previous section, the definition of cultural heritage has evolved along the years to include both the tangible and intangible components of civilization, aiming at understanding their goals, as well as the principles and the techniques that led to the creation of artworks, tangible or intangible, localizing them in their space and time.

Nevertheless, cultural heritage is also deeply evolving in its classical activities, like, for example, maintenance and conservation of historical monuments. The latter, in particular, is evolving towards approaches aimed at predictive maintenance processes based on the analysis of collected data through tailored monitoring systems designed for this purpose.

It is, therefore, clear, that such an extensive and multidisciplinary process of evolution of the cultural heritage towards these new relevant and complex objectives requires high quality multi-disciplinary data.

This inevitably triggered the evolution of classical monitoring systems into a real-time and/or in-time systems, capable to acquire a large and distributed number of parameters with bands and sensitivities determined by the required application, from one side, but, on the other side, fully adaptive and modular, and also transportable, to allow its evolution according to the evolution of results and of modeling. This new approach requires a new interpretation of a monitoring system, whose design must be focused on three important aspects:

- quality and accuracy of sensing and of data acquisition, with standard interfaces;
- system modularity and scalability;
- system robustness with regard to critical environmental conditions and long operational time requirements.

Our group scientific research activity started many years ago, with archeological monuments monitoring. The idea of developing a multi-disciplinary, modular and adaptive distributed monitoring system was conceived with the development of a first prototype of broadband low-frequency high-sensitivity monitoring system for the Trajan Arch in Benevento (Italy), aimed at tuning a FEM (Finite Element Model) of the Arch in year 2015 [10]. This system, based on mechanical monolithic seismometers (displacement sensors), was the first step of a path leading to an effective adaptive modular distributed monitoring system, capable to integrate different typologies of

sensors, like the one now permanently installed and operational since 2021 on the Neptune Temple in Paestum (Italy), consisting, in its basic configuration, of 34 seismic sensors (displacement sensors) distributed along the three layers of the temple (foundations, stylobate and architrave), but already set up for further expansion both in terms of number and typology of sensors according to the data analysis results [11].

The standalone system version used for these first tests of the urban vibroscape measurement, produced by Advanced Scientific Sensors and System (Adv3STM), consists of a high-quality compact size, low power consumption, transportable DAQ system powered with external batteries and equipped with two highly directional horizontal high-sensitivity broadband mechanical seismometers (displacement sensors) and two high-quality directional microphones (acoustic sensors). This systems, remotely controllable and fully expandable, is capable to acquire in this simplified version up to 120 sensors of different typologies (seismic, acoustic, magnetic, environmental, etc.).

The DAQ is based on the 24-bit National InstrumentsTM FieldDAQ, model FD-11603, whose characteristics are detailed in Table 1, based the Ethernet standard for data acquisition and remote control of the units.

Table 1. Main technical characteristics of the National InstrumentsTM model FD-11603 DAQ

Number of channels	8 analogic input channels
ADC type	24 bits – Delta Sigma
Input voltage range	± 10.5 V
Sampling Rate Maximum	102.4 kSamples/s
Sample mode	Simultaneous
Accuracy	± 30 ppm maximum

The acquisition system, in turn, was connected to a portable computer running Windows 10 operating system in order to collect the data for further elaboration. The remote configuration, synchronization, data acquisition, real-time data presentation and control are performed through a dedicated graphical interface (Supervisor), developed by Adv3STM.

The mechanical monolithic seismometer (SE-10HL), used for this first application of (displacement) vibroscape monitoring, is a real horizontal seismometer (no force feedback control configuration) from Advanced Scientific Sensors and Systems (Adv3STM). It consists of a mechanical monolithic oscillator (model GK19A – class EB-100), based on the Watt’s Linkage architecture [12–14], equipped with a high-sensitive LVDT readout system. The relevant technical characteristics of the seismometer SE-10HL are detailed in Table 2. The acquisition system, in turn, was connected to a portable computer running Windows 10 operating system in order to collect the data for further elaboration. The remote configuration, synchronization, data acquisition, real-time data

presentation and control are performed through a dedicated graphical interface (Supervisor), developed by Adv3STM.

Table 2. Main characteristics of the Adv3STM horizontal seismometer model SE-10HL.

	<i>Model SE-10HL – class EB-100</i>
<i>Basic architecture</i>	<i>Monolithic Folded Pendulum (Pat.)</i>
<i>Configuration</i>	<i>Seismometer (open loop)</i>
<i>Natural Frequency</i>	<i>3.80 Hz ± 10%</i>
<i>Readout</i>	<i>LVDT</i>
<i>Band</i>	<i>DC – 100 Hz</i>
<i>Sensitivity</i>	<i>72 V/mm ± 10%</i>
<i>Spectral Sensitivity</i>	<i>< 10⁻⁸ m/√Hz (3.5 Hz < f < 100 Hz)</i>
<i>Output Signal (dual)</i>	<i>± 10 V (range)</i>

The microphones are, instead, free-field microphones, model 4190 from Brüel & KjærTM not only suited for use in class 1 Sound Level Meters, but also for any high-precision acoustic measurements. Type 4190 microphone requires an external polarization voltage. Consequently, the system was integrated with NEXUS 2690 from Brüel & KjærTM for microphone polarization and signal preamplification. The main technical characteristics of the microphones 4190 are detailed in Table 3.

Table 3. Main technical characteristics of the microphone model 4190 from Brüel & KjærTM

Open-circuit Sens. (250 Hz)	50 mV/Pa
Band	6.3 Hz – 20 kHz
Output Signal (dual)	± 10 V (range)
Lower Limiting Freq. (-3 dB)	1 to 2 Hz
Dynamic Range	14.6 – 146 dB
Polarization Voltage	200 V (external)

III. RESULTS

Field measures were conducted from February to June 2022. The standalone system was located in the urban historical center of Napoli (Italy), close to a main road of the historical center, characterized by a high traffic load and by the passage of a subway under the same area. Fig. 1 identifies the sampling point and the sampling area. Displayed results consist in a graphic representation of a sub-set of displacement and acoustic data, serving as representative examples, of urban vibroscape and its characteristics. The data, acquired from SE-10HL seismometer and 4190 microphones, orthogonally oriented in couples, in the North-East and North-West directions, respectively, span a temporal length of about 1160 minutes

(0.8 days) starting from June 26, 2022 at 14:29:03 (UTC+1), sampled at a frequency of 50 kHz.



Fig. 1. Aerial view of the measure area in the historical center of Napoli (Italy), with measure point evidenced as red dot. Scale and North orientation are reported within the view. On the top-right, the position of Napoli municipality in Italy.

Fig. 2 shows the full set of displacement and pressure data acquired by the two sensors positioned in along the North-East direction, parallel to the main road leading to the Napoli central zone. The two figures clearly show the large noise forcing difference between daytime and nighttime.

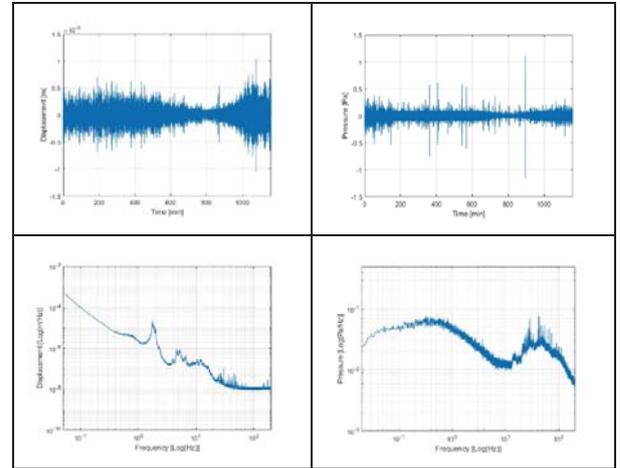


Fig. 2. Displacement (left) and Acoustic noise (right) signals (above) and frequency spectra (below) measured along a day.

Very interesting, instead, is the result of a global spectral analysis, evaluated in the band 0.05 Hz – 200 Hz. The spectral displacement clearly shows many resonances (and bands) frequencies, classically due to the seismic and anthropic noise background forcing. However, peaks, with a counterpart in the pressure spectra, are also visible, being a potential signature of the solid path transmission of

acoustic noise through the building itself. Therefore, the structure, *de facto*, acts as a complex multiparametric system, characterized by multiple inputs and multiple outputs, according to the viewpoint of Theory of Systems. These observations open the possibility of studying the acoustic response, not as natural environmental load, but as an input forcing, in the same way as the seismic noise, that propagates through the structure (churches, theatres, caves, etc.) potentially generating also “intangible acoustic” effects.

Fig. 3 shows the acoustic and displacement noises for the two couples of independent sensors. It is interesting to note the presence of probably related peaks in the two couple of measurements, such as forcing bands, in both the couples of spectra. Of course, this observation requires a deeper analysis to demonstrate in a quantitative way and in agreement with the structural models, the coupling and the effects we discussed above.

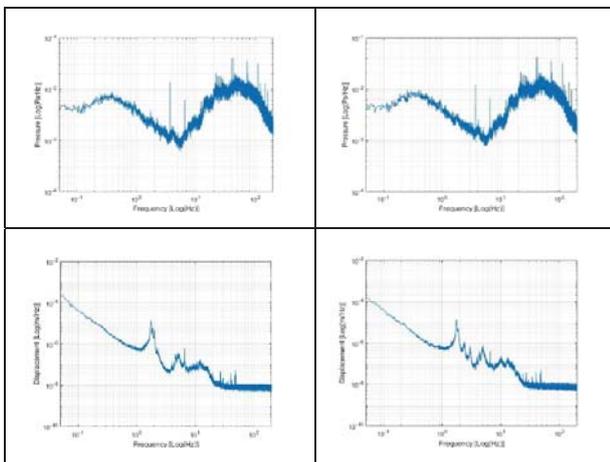


Fig. 3. Displacement and acoustic noise measured for two hours at nighttime (left side): acoustic (top-left) and displacement (bottom-left) spectra of the NE oriented couple sensors; right side: acoustic (top-right) and displacement (bottom-right) spectra of the NW oriented couple of sensors).

IV. DISCUSSION

The results of field tests performed show interesting features in connection with the acoustic and displacement noises on a building of the historical center in Napoli.

The four sensors, oriented in couple of two, show the difference of amplitude of the vibroacoustic noise during the day, with an evident reduction at nighttime, as probably expected due to the fact the vibroacoustic noise in an urban situation is mainly generated by anthropic noise.

What is, instead, more interesting, being in line with the aim of this research on vibroacoustic noise related to cultural heritage, is that the two independent noise sources do not appear to be uncoupled. In fact, experimental results clearly indicate that it is already possible to hypothesize a

coupling and a *de facto* interchange of the causes and effects between acoustic and seismic noises, especially in the low frequency band.

The obtained results, showing the connection between vibrations and acoustic noise measures, suggest that the current investigations on soundscape should be expanded to include the low-frequencies mechanical vibrations domain. In fact, from one side, the relevance of soundscape was already recognized by International Organization for Standardization (ISO) in 2014, which defined Soundscape as "acoustic environment as perceived or experienced and/or understood by people, in context". Relying on the qualification of human perception in relation to acoustic sensations, psychoacoustic evaluations obtained with soft metrology approaches are, then, turned into physical assessment with a hard metrology approach [15]. This approach was already applied in relation to cultural heritage sites and to urban spaces was already proved in the literature [16–18]. However, past works never included the assessment of low-frequency vibration domain in the characterization of different spaces and sites.

V. CONCLUSIONS

This work shows the interesting, although preliminary, results obtained from the measurement with a standalone system for the characterization of urban vibroscape in connection with the effects on a historical building.

The spectral analysis suggests a mutual influence between displacement and acoustic signals, showing the effectiveness of tested solution for the characterization of the vibroacoustic landscape. The application of such a solution could serve, in the future, to monitor the vibroacoustic noise, with the aim of characterizing ancient monumental architectures and historic areas also under the perspective of intangible cultural heritage, as discussed in the introduction.

VI. ACKNOWLEDGEMENTS

Marco Casazza acknowledges the financing of his working position through the Italian Ministry of University PON fund, Azione IV.4 Asse IV “Istruzione e ricerca per il recupero – REACT-EU”. Authors wish to thank the firm Advanced Scientific Sensors and Systems (Adv3S™) for providing the instrumentation necessary to make the measurements presented in this work.

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