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Vibroacoustic heritage monitoring with a standalone system

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ABSTRACT
This paper describes the results of the 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, performing spaces and areas of historical relevance. 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.

Section: RESEARCH PAPER

Keywords: vibroacoustic landscape; cultural heritage; applied physics; sensors

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1. INTRODUCTION

The definition of cultural heritage evolved along the years to include both its tangible and intangible components [1]. In the case of "acoustical heritage", scholars increased the number of parameters used as measurable descriptors related to the fruition of sound, as intangible heritage [2]. However, the intangible dimension of acoustic heritage is not limited to sound itself, but includes also the space where the experience of music is made, that can have specific characteristics in relation to its function [3].

The "acoustical heritage" can be subject to variations along time, due to the change of lifestyles, environmental conditions, social and cultural changes, modifying the context and conditions of fruition of the cultural heritage itself [4]. 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) [5]. The definition of 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 specific 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 related to acoustics 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 descriptors of sounds, studies of acoustics related to cultural heritage spanned from the vibro-acoustic characterization of music instruments [6], to the acoustic characterization of ancient settlements [7], performing spaces, such as theatres [8], sacred spaces [9] or even cities [10]. 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 [11]. However, the attention of researchers concentrated only on the audible range of vibration frequencies, neglecting the measure of infrasound vibrations [12]. 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 are, at least, three. The first is that some objects (like music instruments) or spaces (like cities) can be characterized by different frequency spectra, depending on the existing vibroacoustic 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 [13], [14]. 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 [15]. 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, whose data can be collected 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.

The second section will describe the system constituents and key sensors. At the end of the same section, the measure point used as case study will be identified. Section 3 will be focused on a summary of the obtained preliminary results derived from the measures. Section 4 will be dedicated to a discussion of the obtained results under the light of the introduced definition of vibroacoustic landscape, considered as an extension of the soundscape definition given by the International Organization for Standardization. Finally, Section 5 will outline the man conclusions of the performed work.

2. 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. The study of cultural heritage aims at understanding the principles and the techniques that led to the creation of tangible or intangible artworks, localizing them in their space and time.

Cultural heritage professions are deeply evolving in parallel to our understanding of cultural heritage and on innovative approaches, proposed and validated by different researches and applications. For example, in the case of historical monuments and sites maintenance and preservation, research works implemented different monitoring approaches to collect and analyse multiple data aimed at enabling the predictive maintenance of monuments and sites. It is, therefore, clear, that such an extensive and multidisciplinary evolutionary process in the field of cultural heritage, directed towards these new relevant and complex objectives, is based on the availability of high quality multi-disciplinary and multi-parametric data.

This need inevitably triggered the evolution of classical monitoring systems into real-time and/or in-time systems. These systems, in fact, are 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, are fully adaptive, modular, and also transportable. This modular system design allows to implement a distributed monitoring of multiple parameters, depending on the user requirements and on the evolution of results and of modelling. Under this perspective, monitoring system require a design, which must be focused on three important aspects:

a. Quality and accuracy of sensing and of data acquisition, with standard interfaces;
b. System modularity and scalability;
c. System robustness with regard to critical environmental conditions and long operational time requirements.

The scientific research activity of our group in the field of cultural heritage started many years ago with the monitoring of archaeological monuments. The idea of developing a multi-disciplinary, modular and adaptive distributed monitoring system was conceived in year 2015, 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 [16]. This system, based on the use of broadband high-sensitivity 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, inside the Paestum and Velia archaeological Park in Paestum (Italy). The system operating on the Neptune Temple, in its basic configuration, consists of 34 seismic sensors (displacement sensors) distributed along three different levels 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 user requirements [17].

The standalone system version used for these first tests of the urban vibroscape measurement, produced by Advanced Scientific Sensors and System (Adv3S™), 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 its simplified version, up to 120 sensors of different typologies (seismic, acoustic, magnetic, environmental, etc.).

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

Table 1. Main technical characteristics of the National Instruments™ 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

Table 2. Main characteristics of the Adv3S™ horizontal seismometer model SE-10HL.

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

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

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)

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) produced by Advanced Scientific Sensors and Systems (Adv3S™). It consists of a mechanical monolithic oscillator (model GK19A – class EB-100), based on the Watt's Linkage architecture [18]-[20], 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 Adv3S™.

The microphones, used as acoustic pressure transducers, are the free-field microphones model 4190 from Brüel & Kjær™, being not only suited for class 1 Sound Level Meters, but also for any high-precision acoustic measurement.

Type 4190 microphone requires an external polarization voltage. Consequently, the system was integrated with NEXUS 2690 from Brüel & Kjær™ for the microphone pre-polarization and signal pre-amplification. The main technical characteristics of the microphones 4190 are detailed in Table 3.

Field measures were conducted from February to June 2022. The standalone system was located inside a masonry building in the urban historical center of Napoli (Italy), close to a main road characterized by a high traffic load and by the passage of a subway line under the same area. Figure 1 identifies, through an aerial image, the selected sampling point and the sampling area.

Figure 1. Aerial view of the measure area in the historical centre of Napoli (Italy), with the 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.

3. RESULTS

Displayed results consist in a graphic representation of a subset of displacement and acoustic data, serving as representative examples of urban vibroscape and its characteristics. The data were acquired from two couples of orthogonally-oriented SE-10HL seismometer and 4190 microphones. Sensors were oriented along the North-East and North-West directions, respectively. Collected data span a temporal length of about 1160 minutes (0.8 days) starting from June 26, 2022 at 14:29:03 (UTC+1), with a sampling frequency of 50 kHz.

Figure 2 shows the set of displacement and acoustic pressure data acquired along a day by the two sensors positioned in along the North-East direction, parallel to the main road leading to the Napoli central zone.

The figure clearly shows the large differences in noise forcing between daytime and nighttime, caused by the variability of

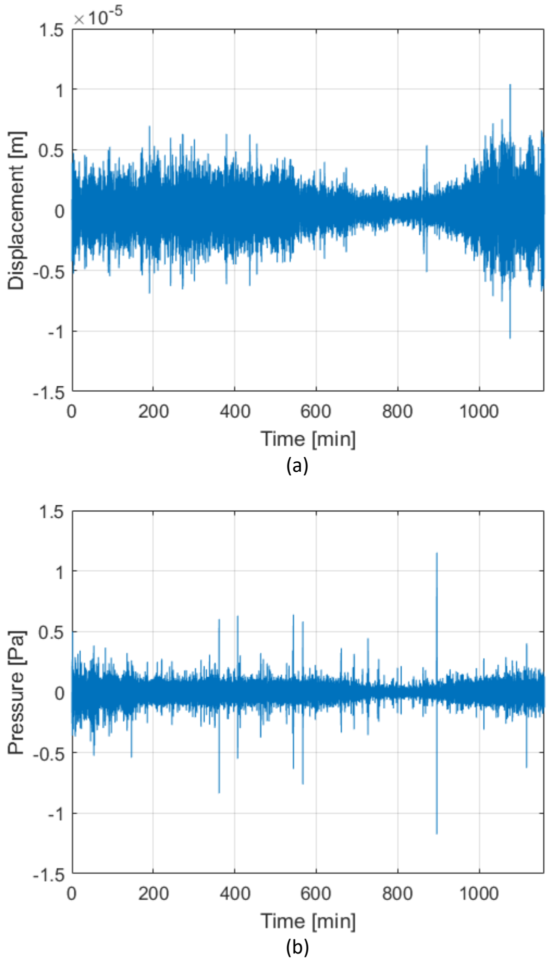
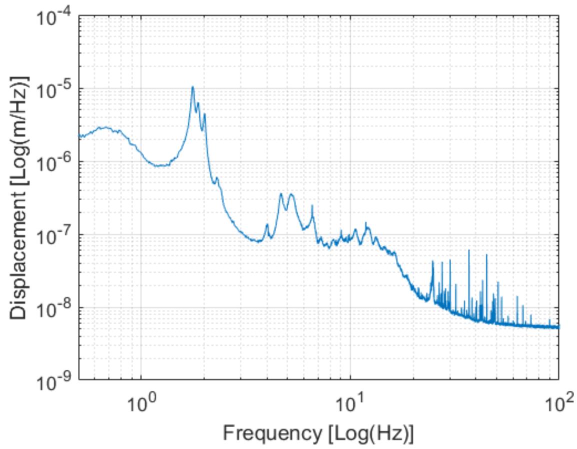
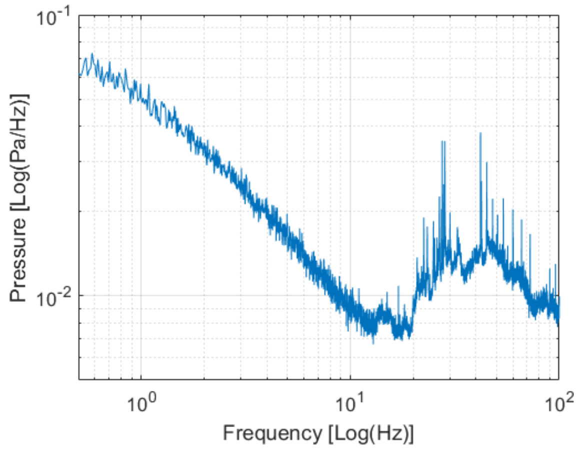


Figure 2 Displacement (a) and acoustic pressure (b) signals measured along a day for a pair of coupled horizontally-directed sensors.

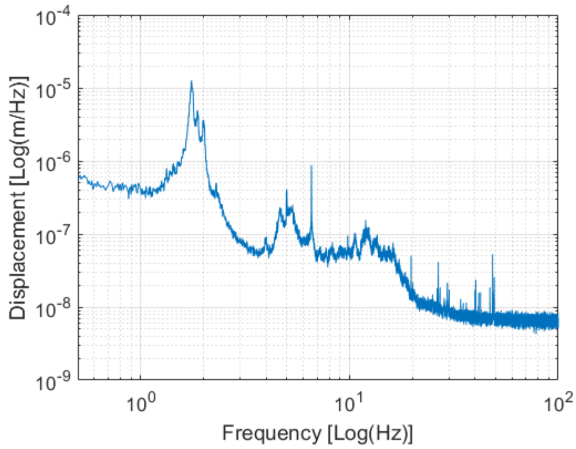


(a)

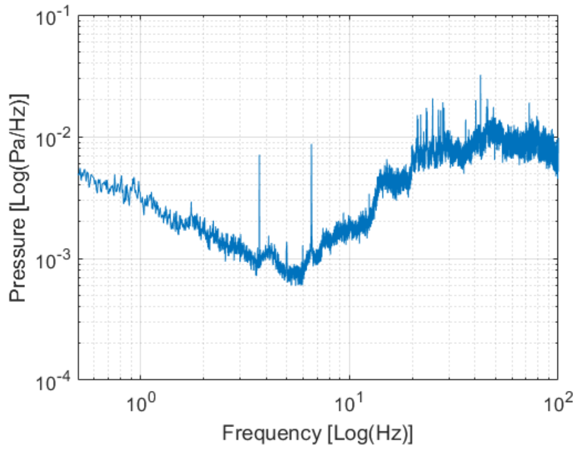


(b)

Figure 3. Frequency spectra of displacement (a) and acoustic pressure (b) signals derived from the data shown in Figure 2.



(a)



(b)

Figure 4. Night-time frequency spectra of displacement (a) and acoustic pressure (b) signals for the NE oriented couple of sensors. Measures are limited to a period of two hours during the night-time.

existing anthropogenic sources, being especially active during the day.

Figure 3 shows the frequency spectra of displacement and acoustic noise signals reported in Figure 2 in the frequency band 0.5 Hz – 100 Hz.

The spectral representation of displacement signal clearly shows many resonance frequency peaks and bands, depending on the seismic and anthropic noise background forcing. However, some peaks have also a counterpart in the acoustic pressure spectra, being a potential signature of the acoustic transmission along different solid paths, such as the building walls. 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 only in terms of environmental load, but also as an input mechanical forcing, in the same way as the seismic noise, that propagates through the structure (churches, theatres, caves, etc.). The effects of such a multiple-inputs multiple-outputs system dynamics is also the cause of an intangible vibroacoustic effect, being characteristic of the intensity and distribution of vibroacoustic sources, as well as of the place where these effects are detected.

Figure 4 and Figure 5 show the frequency spectra of acoustic and displacement signals for the two couples of independent sensors, limited to a period of two hours at night-time. The two couples are referred to their spatial orientation toward NE and NW.

In particular, Figure 4 refers to the NE oriented sensors, while Figure 5 refers to the NW oriented sensors. The frequency spectra allow to identify the presence of probably-related peaks, associated to different forcing bands in both the couples of spectra. This is especially true for the peaks in the region between 3 Hz and 7 Hz, being visible in both figures, and for the region between 20 Hz and 50 Hz, even if less evident.

This preliminary observation will require a deeper analysis to demonstrate, in a quantitative way and in agreement with a structural model of the building, the effectiveness of the hypothesized coupling and the effects discussed above.

4. DISCUSSION

The results of the performed field tests show some interesting features related to the acoustic pressure and displacement signals recorded inside a building in the historical centre in Napoli.

The recorded signals from each pair of sensors, being coupled according to their directionality related to the building and main road orientation, display a clear difference between their day and night amplitudes. In particular, an evident signal reduction appears at night-time, as expected due to the reduction in number, distribution and intensity of the existing anthropogenic sources during night-time.

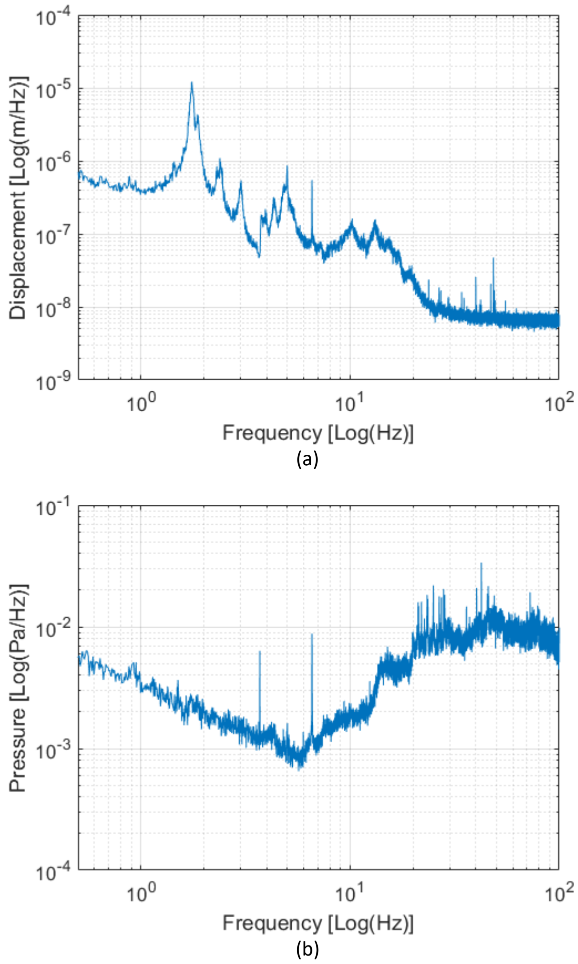


Figure 5. Frequency spectra of displacement (a) and acoustic pressure (b) signals for the NW oriented couple of sensors, limited to a period of two hours during the night-time.

What is, instead, more interesting, being in line with the aim of this research on the vibroacoustic characterization of cultural heritage sites and assets, is that the two signal sources do not appear to be uncoupled. In fact, the experimental results clearly indicate that it is already possible to hypothesize a coupling and a *de facto* interchange between the causes and effects of acoustic pressure and seismic signals, especially in the low frequency band domain. Considering the specific case study reported in this work, the literature reports that the greatest structural response in the case of masonry buildings, is included in the range between 1 to 10 Hz [21], [22]. The structural response peak, falling within this frequency range, is visible in Figure 3 and Figure 4. However, in the same figures other peaks are also visible, depending on other factors. Thus, outside of the considered range (i.e., below 1 Hz and above 10 Hz, the broadband seismometer can detect mechanical vibrations of different origin, including both natural and anthropogenic sources).

In particular, the obtained results, showing the connections between low-frequency vibrations and acoustic pressure signals, suggest that the current investigations on soundscape should be expanded to include the characterization of mechanical vibrations domain at lower frequencies. In fact, from one side, the relevance of soundscape was already recognized by International Organization for Standardization (ISO) in 2014, that defined Soundscape as "acoustic environment as perceived or experienced and/or understood by people, in context" [23]. 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 [24]. This approach was already applied in relation to cultural heritage sites and to urban spaces, as reported in the literature [25]-[27]. However, past works never included the assessment of the lower frequencies vibration domain in the characterization of different spaces, sites or other cultural assets. Conversely, the obtained result suggest the correctness of expanding the measure from the soundscape to the whole vibroacoustic landscape.

5. CONCLUSIONS

This work shows the preliminary results obtained from the measurement, with a standalone system, for the characterization of urban vibroacoustic landscape inside a building located within the historic area of the city centre of Napoli. The spectral analysis suggests a mutual influence between displacement and acoustic pressure signals, showing the effectiveness of the tested solution for the characterization of the vibroacoustic landscape.

The application of the proposed standalone solution could serve, in the future, to monitor the vibracoustic signals, with the aim of characterizing ancient monumental architectures and other assets of historic and cultural interest, as well as cultural heritage sites and historic areas. Such an activity could serve to characterize the monitored assets or sites under the perspective of intangible cultural heritage, considering the vibroacoustic landscape as a specific feature of the observed area, site or asset, as discussed in the introduction.

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