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Broadband vibroacoustic fingerprint of a historic building chamber concert room in Napoli (Italy)

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Abstract – Tangible and intangible elements of cultural heritage are interconnected in supporting the growth of sustainable and resilient urban lifestyles. In the case of sites of historical and archaeological relevance, some spaces were conceived and designed to host specific practices (e.g., religious, musical, theatrical, political, etc.). However, the reasons for designing those historical spaces in a certain way often remain substantially unknown, due to the lack of available documental sources related to their design and planning. In the case of intangible vibroacoustic characteristics of a certain space, part of this information may be retrieved by specific measurements. For this reason, we have started a preliminary experimental activity, aimed at characterizing the vibroacoustic fingerprint, i.e. the vibro-acoustic site-specific features, of a private chamber concert room, located inside a historic building in the center of Napoli (Italy). For such a purpose, acoustic measurements were integrated with broadband vibration measurements though a dedicated monitoring system for identifying the vibroacoustic fingerprint of the room, using time-series and frequency-based analyses.

I. INTRODUCTION

The tangible and intangible dimensions of cultural heritage are interconnected elements, which support the growth of sustainable and resilient urban lifestyles [1]. In particular, the intangible cultural heritage, as defined since year 2003 by UNESCO [2], contributes to shape the identity of a place and its inhabitants, increasing the sense of belonging and the care for cities, especially in the case of sites of historic and cultural relevance. In this sense, the awareness about the nature and site-specific characteristics of intangible cultural heritage, also related with site-specific practices and on the effects of sensorial perceptions occurring in a certain space, triggers the effectiveness of participatory actions toward the protection and valorization of historical urban centers [3].

Tangible elements, such as architectonic features [4], interact with intangible factors, such as acoustic characteristics [5], actively shaping a site-specific *genius locus* [6]. However, audible-range vibrations are just a limited part of mechanical vibrations generated and propagated in the environment and perceived by humans. In fact, airborne and ground-borne infra-sound vibrations with a frequency below 20 Hz can be perceived through human bodies, producing feelings of discomfort, which we often do not know how to rationally explain. On the other hand, sitting on the sand near the seashore, listening to the breaking of the waves or to the slow motion of the trees due to wind, produces feelings, often capable to generate an increased level of well-being in individuals, as proved by the positive results in using infrasound vibration therapy in the case of patients affected by neurodegenerative diseases [7, 8]. This is why a previous study extended the domain of investigation of intangible cultural heritage to the vibroacoustic landscape [9], defined as the totality of mechanical vibrations generated by natural and anthropogenic sources, characterizing a certain place.

In the case of sites of historical and archaeological relevance, certain spaces were conceived and designed to host specific practices (e.g., religious, musical, theatrical, political, etc.). However, the reasons for designing those historical spaces in a certain way often remain hidden, due to the lack of any available written source related to the design and planning of those spaces. This is why it can be difficult to disentangle the elements of planning with a prevailing symbolic content, like the orientation of some religious buildings, from those having a functional reason, such as in the case of the acoustical design of a theatre. Moreover, it would be desirable to understand whether some functional elements in spatial planning could be strictly connected to symbolic ones. This is why a physical characterization of some site-specific environmental variables could support a better understanding related to the design of historical sites and the life of communities that inhabited those areas.

For this task, multidisciplinary dedicated research in the field is needed, aimed at understanding the initial reasons, as the environmental, cultural and temporal context (cultural, economic and technologic), for which a certain space was designed and planned for specific uses in a certain way and, eventually, why it evolved in a certain way along the time.

Although such an evolutionary approach sounds very appealing in theory, it is very difficult to become operational, often due to the lack of available documental sources, being relevant for retrieving the necessary information and knowledge to the place under study. Nevertheless, often, similarity with other structures of the same period and comparative analyses of the used techniques can be a relevant starting point for a progress in this field.

However, a further step can be taken to obtain some details on site-specific measurable features that were not directly documented or known at the time of construction. With this goal in mind, we have started a pilot experimental activity, aiming at characterizing the vibroacoustic fingerprint [10], i.e. the vibro-acoustic site-specific features, of a historic building private concert room located in the center of Napoli (South Italy). For such a purpose, traditional acoustic measurements were integrated with broadband vibration measurements, with the aim of identifying the current vibroacoustic state of a room, designed for chamber music, in a private historical building, based on sampling and elaboration of time histories and frequency-based analyses.

II. MODELING APPROACH

A. *The model*

A spatial vibroacoustic model must take into full account not only the geometric and physical characteristics of the space, but also its interactions with both external and internal forcing factors. The mechanical noises of natural and anthropic origin, interacting with the building walls, constitute a vibratory (i.e., displacement) source that, exciting the air in the room, generates an extended acoustic noise background (e.g. pressure changes in the audible range), filtered by the acoustic response (e.g. resonance modes) characteristic of that space, in which the music listeners are fully immersed.

These forcing factors shouldn't be identified according to their typology or frequency band, but under the unifying view of mechanical (pressure) forces. Therefore, both anthropic (e.g., acoustic noise due the traffic) and natural noise (e.g., wind forcing and seismic noise) can be fully included in a model driven by a general amplitude forcing, independent from their frequency band classifications (e.g., infrasound, sound and ultrasound).

This reclassification is relevant, because it allows a very general and effective analysis on the goals an architect may have conceived, that is especially true for relevant public spaces, like theatres such as ancient Greek and Roman ones, where some effects and some forcing factors were probably taken into the due account or used to create special atmospheres or effects.

The internal forcing, instead, is the sum of acoustic sources (e.g. musical instruments) and of extra forcing due to the physical presence of the listeners. For this reason, it assumes a great relevance the measurement of what in optics is known as dark noise, that, in our case, is the noise present and typical of the place, the so-called background acoustic noise. The latter includes, of course, infrasound, sound and ultrasound bands, perceived by listeners in contact with the basement and immersed in space (air).

The scheme of the space under test with the position of the musical instruments, in our case a piano, and of the sensors of the monitoring system, is shown in Figure 1. The space is limited by internal walls (50 cm thick), by doors, separating the room from other internal spaces, and by an external wall (70 cm thick) with a balcony, linking the internal and external spaces.

We have built a simplified model, considering the room as an acoustic resonator, consisting of an empty parallelepiped (910 cm × 640 cm × 430 cm) filled with air at room temperature. The steady state solution of the acoustic equations can be described in terms of modes, allowing a more effective interpretation of the results.

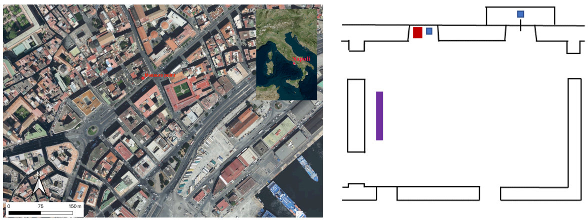

Fig. 1. Aerial view with scale and North orientation of the historical center of Napoli (Italy), with measure point evidenced as red dot (left); Scheme of the chamber concert room with the positions of piano (violet), seismometers (red) and microphones (blue) (right).

There are three different typologies of modes, classified in terms of number of reflections from the wall surfaces: axial (2), tangential (4), oblique (6). A synthetic expression describing all the modes is

$$f_{n_1 n_2 n_3} = \frac{v_s}{2}\sqrt{\left(\frac{n_1}{l}\right)^2 + \left(\frac{n_2}{w}\right)^2 + \left(\frac{n_3}{h}\right)^2} \qquad (1)$$

where v_s is the speed of sound in air, l, w and h are the length, width and height of the room, respectively, while n_1, n_2, n_3 are the integers, that identify each single mode. In particular, two indexes set to zero identify an axial mode, one index set to zero identifies a tangential mode, all indexes different from zero identify an oblique mode.

Another relevant parameter is the reverberation of the acoustic waves from the wall, ceiling and base in connection with resonance modes (acoustic response). This phenomenon makes the spectral response of the space to this forcing non-uniform and sometimes unpleasant, due to an increase of its acoustic noise background. This is highly undesirable as it does not allow a faithful reproduction of sounds and yet it is an effect that cannot be fully cancelled. It is the acoustic fingerprint of a room, that evolves along the time together with the transformation occurring to the space, such as the change of furniture (e.g. tapestry, frames, etc.), and strongly dependent on the reflection coefficients of the walls.

Furthermore, extending this reasoning to acoustic sources, the physics of acoustic waves shows that groups of waves close in frequency may give origin to beats – in practice, other perceived frequencies – generated by the combination of those signals. This effect may also be wanted, for example during musical performances. Let's think, for example, to the classical bi-cord, consisting in the emission of two different notes, that, combined (due to beats), generate new perceived notes, not only in the acoustic band, but also in the infrasound band. This is rarely the case of a room conceived for chamber music, as the one described here. However, it becomes very relevant especially in religious spaces like churches, characterized by very low frequency resonance modes, that can be excited in presence of large instruments, such as pipe organs, so that the infrasound generated during musical performances may couple with its acoustic and structural modes.

Finally, it is important to underline that the generality of the approach described above allows its direct application to both closed spaces, like churches and theaters, and open spaces, like the ancient Greek and Roman theaters.

III. INSTRUMENTS AND METHODS

B. Instruments

The standalone system is based on a compact and modular DAQ system powered with external batteries to minimize the low-frequency noise effects. The basic DAQ unit is a 24-bit National Instruments^{TM} FieldDAQ, model FD-11603. The data, acquired by the DAQ units, down-sampled at 5 kHz, are synchronized and collected through a dedicated Ethernet line by a Standard PC Unit running Windows 11 acting as data acquisition, storage a distribution system, controlled and synchronized through the Ethernet Link by a dedicated User Interface (Supervisor), developed by Adv3S^{TM}.

Table 2. Broadband mechanical seismometer Adv3S^{TM} *SE-10HL and SC-10HL key technical data*

Model	**SE-10HL**	**SC-10HL**
Res. Freq.	3.80 Hz ± 10%	0.80 Hz ± 10%
Readout	LVDT	LVDT
Band	DC – 100 Hz	DC – 1 kHz
Sensitivity	72 V/mm ± 10% $< 10^{-8}$ m/$\sqrt{\text{Hz}}$ (3.5 Hz < f < 0.1 kHz)	12 V/mm ± 10% $< 5 \cdot 10^{-9}$ m/$\sqrt{\text{Hz}}$ (0.8 Hz < f < 1 kHz)
Output	± 10 V (range)	± 10 V (range)

The configuration used for this pilot experiment consisted in one DAQ module, equipped with 4 horizontal broadband mechanical seismometers (displacement sensors) and 2 microphones (acoustic sensors), extending and optimizing the original system conceived to characterize the vibroscape in urban context [11].

Two different models of broadband seismometers were used, based on the same technology, the SE-10HL the SC-10HL from Adv3S^{TM}, whose main characteristics are shown in Table 2. These seismometers are highly directional, high-sensitive, characterized by oscillators based on the Watt's Linkage architecture and LVDT readout system. The microphones are Brüel & Kjær^{TM} free-field model 4190 for high-precision acoustic measurement, pre-polarized and pre-amplified with NEXUS 2690 device, again from Brüel & Kjær^{TM}, whose main technical characteristics are detailed in Table 3.

Table 3. Brüel & Kjær^{TM} free-field microphone key technical data

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

C. Site Measurements

The monitoring system was installed close to external wall of the room.

Fig. 2. a) Picture of internal section set-up of the monitoring system used for the experiment consisting in 4 seismometers and 1 microphone (top); b) particular of the 4 seismometers (bottom).

The broadband mechanical seismometers were positioned in the so-called window space, so that they are de facto positioned on the external walls of the building to optimize their interaction with the outdoor environment.

Their position was mutually orthogonal for each couple of sensors, with the first one oriented at 300° NW direction and the second one at 210° SW direction.

The internal microphone was placed close and parallel (300° NW) to the first couple of seismometers, while the other one was positioned outside on the balcony (120° SE) to collect the external pressure noise. A picture of the internal section of the system is shown in Figure 2.

IV. RESULTS

The monitoring system sensitivity can be qualitatively appreciated in the detection of the 3.2 magnitude earthquake occurred in Southern Albanian Coast (Albania) at 2023-05-18 23:17:06 (UTC +02:00) Italian time with geographical coordinates 40.2060 (lat.), 19.4560 (long.) at a depth of 15 km [12]. Figure 3 shows the signal detected by the 300° NW oriented seismometers, with a clear definition of the P and S waves. The relatively high background noise is due to the seismometers position (the fourth floor in the city center of Napoli). Note the presence of another single large peak due to a local anthropic event.

The characterization of the chamber music room vibroscape (acoustic background) has been obtained from the analysis of night-time data. In absence of internal noise sources, the background internal vibroacoustic noise is generated only by external noise sources (natural and anthropic), like for example ground-borne (e.g. micro seismic activity) and airborne (e.g. wind).

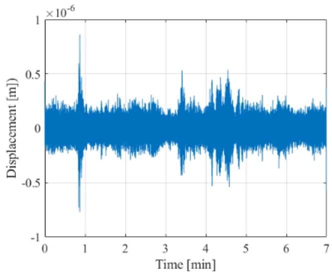

Fig. 3. Albania earthquake signal of 2023-05-18 at 23:17:06 (UTC+2:00) Italian time as detected by the EW Seismometer (time origin 23:16:19).

The spectral characteristics of a subset of the acquired data at night (one seismometer and both microphones) are shown in Figure 4 and Figure 5.

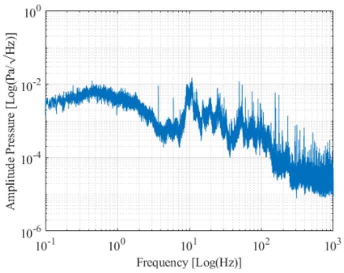

Fig. 4. Amplitude Mean Fourier Density Spectrum of internal microphone 4149 B&K^{TM}.

V. DISCUSSION

D. Data Analysis

Figure 4 shows the Amplitude Mean Fourier Density Spectrum of the internal microphone signal, that is actually the acoustic background internal noise of the space, in the band 0.1 – 1 kHz. This shape is, *de facto*, the fingerprint of the room, generated by both the seismic and acoustic external forcing, shown in Figure 5.

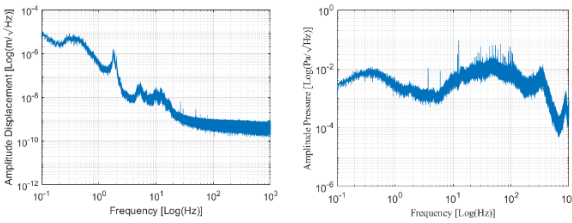

Fig. 5. Amplitude Mean Fourier Density Spectrum: (a) seismometer SC-10HL Adv3S^{TM}; (b) external microphone 4149 B&K^{TM}.

The presence of many peaks in the whole band, whose number increases with frequency, is a consequence of the excitation of the resonance modes of the room. A direct application of Equation 1, considering the specific room dimensions and the speed of sound at the room temperature allows the evaluation of their number, typology and frequency. Small differences in frequency and some other close peak appearing in the picture are due to the presence of furniture and tapestry in the room, etc., that partially modifying the effective room dimensions (the free acoustic space) have effects on the acoustic paths.

On the other hand, Equation 1 does not explain the presence of peaks below about 18 Hz, that is the natural resonance mode with the lowest frequency. Part of the frequency peaks appearing in the band 1 - 20 Hz can be explained considering that the concert room is linked to other rooms on the same floor through doors. Thus, these frequencies appear to be generated by the different additive combinations of nearby room volumes. This means that a vibroacoustic study, aiming at determining the background noise, must always take into account the influence of contiguous spaces, whose effects depend on the typology of the linking elements (e.g. doors, walls, ceiling, etc.). In our case, this background noise component is generated by the interaction of the different rooms through doors and lays in the infrasound region. Thus, even if it is not perceived as an acoustic signal, it still interacts with human bodies fully immersed in air.

The direct comparison among outdoor and indoor noises as measured by the two microphones shows some peaks forcing the walls and propagating internally, only partially attenuated, if not coincident with the room acoustic resonance peaks. Furthermore, some peaks are in correspondence of the building mechanical resonances: micro-seismic noise excite the building resonances, that in turn excite the air inside the room, contributing to the background acoustic noise.

Nevertheless, for completeness, it is relevant to remind that the microphones are integral to the basement, so that, part of the noise is directly introduced in the microphone. A further confirmation can be found in the density spectra pictures, comparing both the data collected through the seismometers and microphones. A large frequency bump appears in the low frequency region. This noise is due to the sea waves, as known from geophysical observations [13, 14], being visible due to the closeness to the sea and depending, in the range 0.1-1 Hz, on the existence of non-linear forcing by standing swell at the sea surface in both pelagic and coastal regions. The fact that that the bump is generated by an external source is confirmed by the fact that the same shape is visible also on the outdoor, while the indoor signal is generated by a partially-different vibroacoustic forcing.

VI. CONCLUSIONS

Tangible and intangible elements of cultural heritage are interconnected, sometimes being conceived and designed to host specific practices. However, the reasons for designing those historical spaces in a certain way often remain hidden, due to the lack of available and reliable documental sources related to their planning. In the case of the acoustic field, this information can be retrieved only through specific measurements.

For this reason, we have started a preliminary experimental activity, aiming at characterizing the vibroacoustic fingerprint of a private chamber music concert room, located inside a historic building in the center of Napoli (Italy). We have, therefore, integrated broadband pressure forcing (acoustic) with displacement (seismic) measurements within a dedicated monitoring system, aiming at identifying the vibroacoustic fingerprint of the room, using time-series and frequency-based analyses.

The experimental results confirm the existence of a site-specific vibroacoustic fingerprint, generated, in agreement with the Theory of Systems, by the mutual interaction of vibroacoustic sources with the existing spaces, characterized by different physical characteristics. Finally, it is relevant to underline the generality of this approach, which can be applied to different real contexts, both indoor, such as in the case of churches and theaters, and outdoor, as in the case of ancient Greek and Roman theaters.

VII. ACKNOWLEDGEMENTS

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