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Vibroacoustic characterization of a chamber music concert room in the context of the urban texture

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ABSTRACT
The integrated interpretation of the tangible and intangible dimensions of cultural heritage assets is challenging, since much of the required information is often lost or difficult to find. In particular, when coming to the functional planning of historic spaces or archaeological sites, documental or archival sources are scarce or even absent. Consequently, to support the interpretation of these functional design and planning elements, which are related to the life of communities that inhabited those areas, quantitative methods, such as a physical characterization of site-specific environmental variables, may assume a great relevance, like in the case of the vibro-acoustic properties conceived for specific uses or performances, as theatres, cathedrals or other public spaces. With this goal in mind, we have started a pilot experimental activity, aiming at characterizing the vibroacoustic fingerprint, i.e. the vibro-acoustic site-specific features, of a historic building private chamber music concert room, located in the centre of Napoli (South Italy). This work, based on the integration of different sensors and modelling tools, has allowed to observe the site-specific vibroacoustic features not only in relation to the geometric features of the space, but also in relation to the surrounding urban landscape morphology. Consequently, the results have evidenced the presence of a site-specific vibroacoustic fingerprint, related to how the structure and the surrounding urban morphology were planned. The applied integration of a unifying model, previously validated in the literature, and of broadband vibroacoustic measures, has allowed to evidence some quantitative elements, that, characterizing the interaction between spaces and the people living them, constitute a possible basis for interpreting the heritage intangible components (design according to functional and/or symbolic purposes) in relation to different structural urbanistic and architectural elements (tangible heritage).

Section: RESEARCH PAPER

Keywords: vibro-acoustics; applied physics; intangible cultural heritage; vibroacoustic landscape; geometrical physics

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1. INTRODUCTION

The vision of cultural heritage changed during time, as a result of a semantic evolution, which originated at the end of the 18th Century AD, when heritage meant inherited properties. Since then, the idea of cultural heritage evolved, reflecting also new multi-disciplinary visions, based on an innovative and synergic interconnection of archaeological, historical, cultural, architectural and environmental elements, synthesis of its tangible and intangible dimensions [1], [2]. This semantic evolution is reflected in the UNESCO definition of cultural heritage, which finally included its intangible dimension [3]. This paved the way to new scenarios in the evaluation of heritage assets, which promote also the sustainability of cities [4], contributing to the definition of a place-related identity on the basis of the urban morphology, architectural styles, buildings techniques and environmental scenarios, as well as to the well-being of urban dwellers. In fact, the awareness of the nature and site-specific characteristics of intangible cultural heritage triggers the effectiveness of participatory actions toward the protection and valorisation of historical urban centres [5], contributing to actively shape a site-specific *genius loci* [6].

Although this new vision appears very attractive, it has some inherent difficulties, when coming to its objectivity. In fact, the relation between measurable place-related parameters and their perception and reception by people depends on the ability of relating the objects, spaces, functions and uses, which, in turn, depends on what we know, from documents and other archival sources, about how spaces, their symbolic meanings and destination of use were conceived at different spatial scales (from the building scale to the different landscape scales). In the case of historical or archaeological sites, these details are often lost or, at least, difficult to find. This is the reason for a great interest by archaeologists, who try to study the functions of materials, objects and spaces to interpret past events for understanding the habits and material history of people in the past, in agreement with the functional (i.e., processual) method in archaeology [7], [8], which often adopts a comparative assessment of studied materials, objects and spaces both in space and in time, with the aim of understanding their function [8], [9].

Based on a limited availability of documental sources, the interpretation of functional (i.e., how different spaces was conceived for certain specific practices) and symbolic (i.e., objects as symbols of power, religion, culture, etc.) elements cannot rely only on an aesthetic basis. Instead, this interpretation should stem from a better knowledge of structural and spatial parameters within an inclusive spatial unit of investigation, being able to capture the inter-related and co-evolving human-environment dynamics. This is why landscape is often used as a complex functional unit of archaeological investigation [10]. Within this spatial (i.e., landscape) unit, different quantitative characterization can be performed to assess the co-evolving human-environment dynamics, not only with the purpose of supporting existing interpretations of built heritage, but also to produce new multi-disciplinary research questions.

With this respect, the measure of vibroacoustic parameters con be performed to characterize an extended spatial unit, connecting also the physical (tangible) and symbolic (intangible) elements of cultural heritage. It is not a case that the study of soundscape, known also as sound landscape or acoustic landscape, as “acoustic environment as perceived or experienced and/or understood by people, in context”, has become popular in the process of cultural heritage studies and valorisation [11], [12]. In the case of heritage structure, for example, acoustics was relevant for ancient Greek theatres and other performance spaces, which were built based on an accurate knowledge of this discipline, despite its prevailing implicit nature, reflecting not only a clear relation between their structure and their function (i.e. a space for performance), but also as public space used to express cultural, political and religious feelings.

The characterization of soundscape, determined within the human audible frequency band (20 Hz - 20 kHz), is limited with respect to human sensory range of mechanical vibrations which extends also to lower vibration frequencies [13], [14]. This is also confirmed by the use of infra-sounds in therapeutic applications [15]–[17]. This is why works should extend to include also airborne and ground-borne mechanical vibrations at lower frequencies of natural and anthropic origin.

Following the same line, a previous study extended the domain of investigation to include, first, the vibroscape, and, then, the vibroacoustic landscape, as the totality of mechanical vibrations, potentially experienced by people, within a specific spatio-temporal context of intangible cultural heritage to the vibroacoustic landscape [18], [19]. Similarly, we defined the vibroacoustic fingerprint as the object- or site-specific vibroacoustic characteristic related to the evolving characteristics of the heritage asset under study [20].

In the domain of cultural heritage studies, this integrative vision is still infrequent. In fact, experimental and theoretical studies of audible and lower-frequency mechanical vibrations generally attracted the interest of two different communities of scholars. From one side, past acoustics studies ranged from the experimental characterization either of music instruments [21], [22] or of specific performance spaces, like theatres or cathedrals [23], [24]. They also included the implementation of acoustic models and simulations, used for the virtual reconstruction of sounds and perceived sound in specific settings [25], [26]. Moreover, the characterization of the acoustic emission for different materials is used as a non-destructive technique in the context of heritage object monitoring and characterization [27].

On the other side, vibrations are studied in relation to heritage objects, structures or sites mainly to characterize their dynamic behaviour for assessing their structural health [28]. Existing studies include the monitoring [29], [30] and modelling [31]-[33] of immovable heritage assets, which extend to simulations, based on Artificial Intelligence techniques [34], [35]. The measure of vibrations is used also for the diagnosis of potential degradation processes for heritage objects [36].

Conversely, only a few studies integrated the study of audible and lower-frequencies vibrations. In particular, a couple of works reconstructed the expected vibro-acoustic behaviour of historic bells, based on its complete 3D scanning, finite-element modelling and sound synthesis simulations [37], [38]. However, these researches were prevalently oriented toward simulations. A past work, based on previous researches on finite element modelling and experimental vibration analyses applied to the study of violins and violin-making techniques, integrated the experimental measures of the vibrational properties and the acoustic emission of a violin [20]. Finally, another research integrated the on-site and laboratory acoustic and vibration measures with modelling in the case of a historic theatre [39]. Based on current Scopus and Web of Science databases records, no other published peer-reviewed study in vibro-acoustic applied to the cultural heritage is currently available in the literature.

Integrating experimental and modelling considerations in the field of vibro-acoustics applied to the cultural heritage, this work focuses on the experimental characterization of the passive vibroacoustic response of a private chamber music concert room, located in the centre of Napoli (South Italy), in relation to its surrounding environment. The data are interpreted considering the interactions between the chosen heritage asset (i.e., the concert room) and the environment, together constituting the observed vibroacoustic landscape. Then, a site-specific vibroacoustic model is proposed, proving the potential interactions between the urban morphology and the existing built heritage. Such a modelling approach, extendable to other heritage contexts, has allowed to define the vibroacoustic landscape in relation not only to the tangible architectural characteristics of the site, but also to its passive response, which depends, from one side, on the position of the asset within the urban context, and, on the other side, on the structural and architectural design of the heritage asset, which in turn depends also on its desired functional characteristics in relation to site-specific practices (i.e., music playing), that constitute the intangible dimension of the chosen heritage asset.

The next section will introduce the method used for this study, based on the use of advanced vibro-acoustic sensors integrated into a system, and on a simple vibroacoustic model. Furthermore, the case study for which the vibro-acoustic metrological characterization is conducted, in the context of cultural heritage studies, will be described. The third section will describe the experimental results obtained through the performed vibration and acoustic measurement. Then, the second part of the section will present the interpretation of the experimental results under the light of the proposed model, which was previously discussed from different perspectives in the literature. The fourth section will discuss the implications of the obtained results on previous studies focused on the characterization of the vibro-acoustic fingerprint and the vibro-acoustic landscape. Moreover, the potentiality of these implications will be extended to the domains of cultural heritage and ecology studies. Finally, the concluding section will highlight the major findings, the ongoing and future directions of research.

2. METHOD

2.1. Vibroacoustic fingerprint measurement system

The choice of vibroacoustic sensors, integrated into a coherent standalone system to measure the passive vibroacoustic signals depends on the input signals expected characteristics. In the case of urban vibroacoustic signals, past works evidenced the presence of sub-hertz frequencies down to 0.04 Hz, with meaningful variations between day and night recordings.

Based on a modular design, the standalone monitoring system, powered with external batteries, is based on a 24-bit National Instruments™ model FD-11603 FieldDAQ unit, used to acquire the data. Then, after down-sampling at 5 kHz, data were synchronized and collected through a dedicated Ethernet line by a Standard PC Unit, running Windows 11, acting as data acquisition, storage and distribution system. The system was controlled and synchronized through the Ethernet Link by a User Interface (Supervisor), developed by the company Adv3S™.

On the basis of the expected input signal characteristics, as well as on past experimental campaigns [18], the version used for this experiment consisted in a single DAQ module, equipped with 4 horizontal broadband mechanical seismometers (displacement sensors) and 2 microphones (acoustic sensors), extending and optimizing the original version of the system conceived to characterize the vibroscape in urban context. Two different models of broadband seismometers were chosen, based on the same mechanical technology [40], [41]. In particular, the selected broadband vibration sensors were the SE-10HL and the SC-10HL models, both produced by Adv3S™, characterized by high directionality and sensitivity, due to their mechanical monolithic oscillators, based on the Watt's Linkage architecture, coupled with a sensitive LVDT readout system (Table 1).

The two acoustic sensors were I-class model 4190 Brüel & Kjær™ 1/2" free-field microphones, used for high-precision acoustic measurement. The microphone signals were pre-polarized and pre-amplified with NEXUS 2690 device, produced by Brüel & Kjær™. The microphone main technical characteristics are detailed in Table 2.

Table 1. Broadband mechanical seismometer Adv3S™ SE-10HL and SC-10HL key technical data.

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

Table 2. Brüel & Kjær™ model 4190 free-field microphone key technical data.

Technical feature	Parameter value
Open circuit sensitivity (250 Hz)	50 mV/Pa
Frequency band	6.3 Hz – 20 kHz
Output signal (dual)	± 10 V (range)
Lower frequency (-3 dB)	1 to 2 Hz
Dynamic range	14.6 – 146 dB
Polarization voltage	200 V (external)

2.2. Building location and measure site key features

The private chamber music concert room is located at the fourth floor of a masonry palace, prevalently built using the Neapolitan yellow tuff, typical of many masonry buildings in Campania Region [42], in the historical centre of Napoli (South Italy) (Figure 1).

The urban texture, surrounding the building where the concert room is positioned, is characterized by the presence of one of the main streets of Napoli of the historical centre, named Corso Umberto, and a small square, piazza Ruggiero Bonghi, on the opposite site of Corso Umberto with respect to the building.

The room structure and the positions, within the room, of a piano (purple mark) and of the monitoring system sensors (red and blue marks) are shown in Figure 2.

Figure 1. Aerial view of part of the city centre of Napoli (South Italy). The measure point and the nearby Ruggiero Bonghi square are identified.

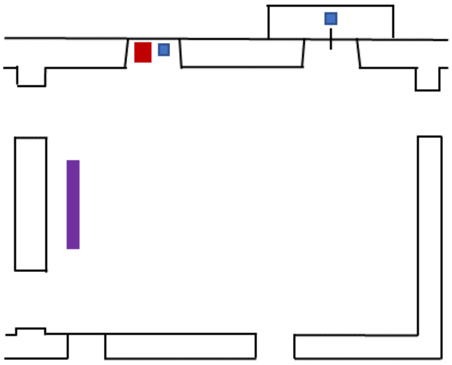

Figure 2. Positions of seismometers (red), microphones (blue) and a piano (purple) inside the chamber music room.

The chamber music concert room has a parallelepiped shape, with approximate dimensions of 9.10 m (length) × 6.40 m (width) × 4.30 m (heigh). The space is limited by internal walls (50 cm thick), by doors, separating the room from other internal spaces, and by an external (south) wall (70 cm thick), with a window and a balcony, bordering the external spaces facing toward Corso Umberto.

2.3. Sensors positioning

The monitoring system was installed close to external wall of the room, facing Corso Umberto and Ruggiero Bonghi square (see Figure 1 for reference). The broadband mechanical seismometers were positioned in the window space close to the external walls to optimize their interaction with the outdoor environment. Each couple of sensors were placed orthogonally, with the first one oriented toward 300° NW direction and the second one toward 210° SW direction.

One microphone was placed indoor to capture indoor sounds and noise, while another one was placed outdoor. In particular, 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 acoustic vibrations. A picture of the internal section of the system is shown in Figure 3.

2.4. Model

The vibro-acoustic modelling of a space requires the correct determination not only of its physical and geometric characteristics, but also of the external and internal forcing elements. In fact, the observed physical interactions between a structure, like a historic building, and the environment are fundamentally governed by mechanical forces of both anthropic (e.g., urban traffic, human activities, etc.) and natural (e.g., wind, micro- or macro-seismic activity, sea waves, etc.) origin. These mechanical forces, acting upon the building boundaries, as well as on all the other surrounding structures and infrastructures that shape the urban environment and its morphology, induce vibrations, whose amplitude and frequencies are modified by two main factors. From one side, vibrations are influenced by each structure, depending on its materials, mechanical properties and resonance modes, triggering a specific vibro-acoustic response on the monitored building. On the other side, vibrations depend by the time-evolving interaction among the different existing structures. The resulting vibroacoustic signature, equivalent to the dark noise in optics, includes, as a whole, infrasound, sound and ultrasound acoustics and displacement signals, that interact with anyone staying in that space, in contact with the basement and immersed in space (air).

Figure 3. Monitoring system set-up: (top) 4 seismometers and 1 microphone; (bottom) detail of the 4 seismometers.

Any person found in that space experiences this vibroacoustic background, whose characterization could be very useful not only for determining the functional characteristics of a certain space, but also for supporting different or innovative historical interpretations related to the implicit knowledge on spatial and functional planning in relation to the implicit knowledge, that is identified both as immaterial cultural heritage and as ecological wisdom [43] in the case of ecology studies.

The chamber music room was modelled as an empty parallelepiped acoustic resonator, filled with air at room temperature. In this way, the steady state solutions can be described in terms of modes, appearing as resonance frequency peaks observed from performed measures. In particular, a parallelepiped acoustic resonator is characterized by three different mode types, classified in terms of number of reflections from the wall surfaces: axial (2), tangential (4), oblique (6) [44]. The resonance frequencies can be computed using the classical Rayleigh formula [45], whose synthetic expression for the steady state equations in the case of closed acoustics resonators is:

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

where v_s is the speed of sound in air, l, w and h are the length, width and height of the room, while n_1, n_2, n_3 are the positive 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.

The resonance model of the room wouldn't be sufficient alone to explain the observed frequency peaks. Instead, secondary resonance vibration peaks depend on the presence of different urban components, such as road pavements and other structures or infrastructures, that, in turn, being excited by different sources, can generate vibrations of the indoor environment and its structure [46]. In particular, streets can be assimilated to acoustic wave guides with an open upper side [47]. As assessed by previous works, this model is proved to be valid, since typical wavelengths are small compared to typical macro-length scales of street widths/lengths and building heights [48], [49]. The main road (i.e., corso Umberto) and the roads in the vicinity of the measure point, being surrounded by buildings, can be described as a canyon-like shape acting as wave-guide, which, being open at the top, has a fixed height of $h \to \infty$. Then, the resonance modes of the road can be limited to two main natural frequencies. In particular, its dimensions were approximated to l ≈ 1680 m (length) and w ≈ 25 m (width).

However, other surrounding roads could be included, applying the same reasoning. Moreover, other partially-confined outdoor spaces, such as squares or courtyards, can be included for defining the secondary peak frequencies, applying the same reasoning, as confirmed by the literature [50]. This is the case of piazza Ruggiero Bonghi, that is found on the other side of corso Umberto with respect to the measure site, whose dimensions are $l \approx 46.5$ m (length) and $w \approx 28.80$ m (width).

In synthesis, this unifying model, based on previous literature evidences, evaluates, in a simplified way, the vibroacoustic response of the chamber music concert room due to three independent noise sources: two external forcing sources (the two acoustic wave guides excited and resonant to environmental and anthropic noise forcing) and the internal resonance modes noise enhanced by the room. While the expected room resonance modes are characterized by frequency higher than 18.90 Hz, then according to our hypothesis, many of the lower frequency modes – in particular, those of Ruggiero Bonghi square – should be visible in the measured room frequency spectrum, due to the vicinity of the historical palace to this resonator.

Due to the largely-different physical dimensions of these spaces, the mode sets are distributed on different bands, often appearing as very close each other, making their experimental identification more difficult. However, based on this unifying theoretical model, it is possible to affirm that, due to the proximity of the low frequency modes of Corso Umberto (0.1 Hz ÷ 10 Hz), it is possible to expect a measured signal characterized by a continuous spectrum, depending on low frequency noise anthropic and environmental noise forcing, where frequency peaks or higher bands might appear, as a signature of different resonance phenomena.

3. RESULTS

3.1. Monitoring system sensitivity

The quality of the monitoring system and the high sensitivity of the seismometers can be 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, as reported by the Italian National Institute of Geophysics and Vulcanology.

Figure 4 shows the signal detected by the 300° NW oriented seismometers, with a clear definition of the P and S waves, despite the relatively high background displacement noise due to the seismometers position (Napoli city centre). It is also interesting to note the presence of an isolated large peak, probably due to a local event of anthropic origin.

3.2. Vibro-acoustic measures

The density spectra of a subset of the acquired data at night from the two microphones, the internal one (300° NW) and the external one (120° SE), and from the SC-10HL seismometer, oriented parallel to the internal microphone (300° NW), are shown in Figure 5. The measurements were made with all the internal doors, windows and balcony closed, but with the window and balcony tapestry open, in order to measure the vibroacoustic noise effects in the real and original conditions. In particular, the subset shows the pressure mean spectral density, measured both by the internal (Figure 5 a)) and external (Figure 5 b)) microphones 4149 by B&K^{TM}, together with the amplitude mean spectral density displacement measured by the seismometer SC-10HL by Adv3S^{TM} (300° NW), using only the night-time data. This choice aims at minimizing the internal noise sources, necessary to guarantee the measurement with good approximation of the internal background vibroacoustic noise, as prevalently caused by external noise sources (both natural and anthropic).

3.3. Geometric vibro-acoustic model interpretation for the experimental results

As discussed before, the vibroacoustic response (i.e. the acoustic signal spectral noise) in the concert camera room due to three independent noise sources: Corso Umberto, Ruggiero Bonghi Square and the concert room (internal modes). This observed signal is a measure of the indoor space acoustic background noise, corresponding to the acoustic space fingerprint of the room. Figure 5 a) shows the amplitude mean

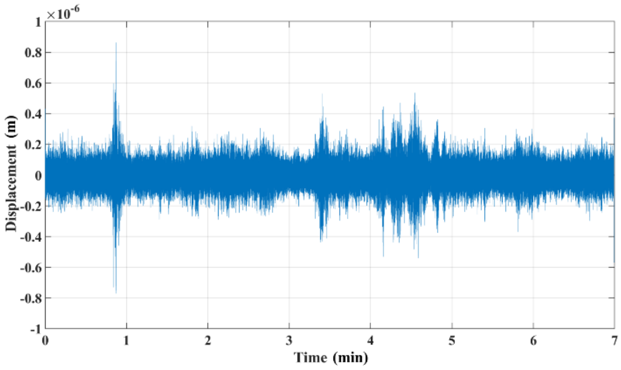

Figure 4. Albania earthquake, recorded on May 18, 2023 at 23:17:06 Italian time (UTC+2:00), as detected by the EW Seismometer (time origin 23:16:19).

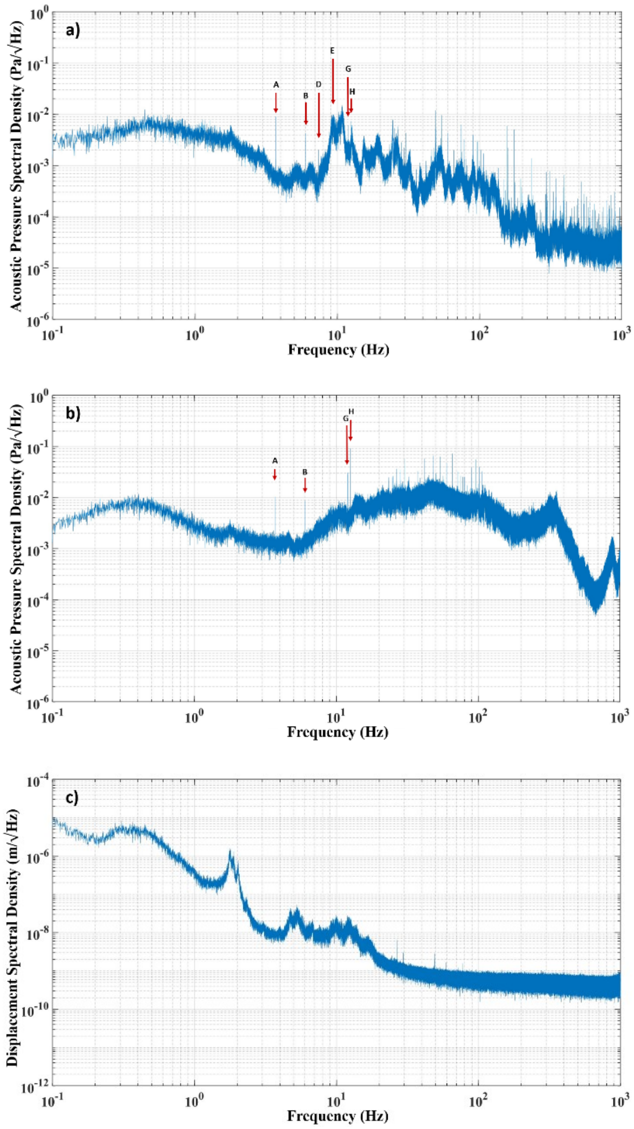

Figure 5. a) Pressure mean spectral density measured by the internal microphone 4149 by B&K^{TM}; b) Pressure mean spectral density measured by the external microphone 4149 by B&K^{TM}; c) Displacement mean spectral density measured by seismometer SC-10HL by Adv3S^{TM} (300° NW).

Fourier density pressure spectrum of the internal microphone signal in the band 0.1 Hz ÷ 1 kHz.

The natural oscillation modes may be clearly individuated in Figure 5 a) within the large number of peaks present in the frequency spectrum, whose number, as expected, increases at the increasing of frequency (higher order modes). Since this equation refers to an empty ideal parallelepiped, observed small differences in the peak frequencies and the appearance of other peaks, close to the main ones, are expected, depending on the presence of furniture and tapestry in the room, which alter the free acoustic paths dimensions. The same discussion is valid, when extended to the windows and balcony accesses, each characterized by passing space of the same external wall width. Besides a single peak, due to the first resonance mode of the balcony at about 70 Hz, all the peaks are positioned beyond 150 Hz. Consequently, this explains the excitation of resonant modes in the medium frequency (150 Hz – 1 kHz) visible in Figure 5 a), that are instead not present in Figure 5 b).

However, Figure 5 a) shows also the presence of signal peaks at frequencies lower than 18.90 Hz. These peaks cannot be explained by Equation (1) considering only the room size. Instead, they should be explained, as discussed in the literature [46], as secondary resonance peaks related to other geometric factors, depending on external forcing sources related to the urban texture and the surrounding structures.

In particular, based on the size of Ruggiero Bonghi square, Table 3 highlights how some of the lowest resonance modes relate to the square sizes, based on the application of Equation (1) with $h \to \infty$. These peaks are identified in Figure 5 a) and Figure 5 b) through an alphabetical coding from A to H.

The previous reasoning can be furtherly extended to include also the longitudinal resonances frequency of corso Umberto, acting as an acoustic waveguide. In fact, the longitudinal dimension (about 1680 m) of this road makes it an effective low frequency (infrasound) acoustic resonator. According to the predictions of Equation (1), the first longitudinal axial mode has a frequency of ≈ 0.1 Hz. This corresponds to the large spectral bump in the (0.1 ÷ 1 Hz) band, present also at night, being visible in Figure 5. Considering the vicinity of the sea with respect to the measure point, this bump can be explained considering the excitation of corso Umberto resonance frequencies generated by the sea waves signal interacting with the coast. In fact, the sea-cost interaction frequency has a typical range between 0.1-1 Hz, as confirmed by previous literature studies [51], [52].

Continuing the analysis of the seismometer amplitude spectral density, Figure 5 c) highlights the presence of many large peaks in the band (1 Hz ÷ 18 Hz). These peaks correspond to the building mechanical resonances. In particular, the observed micro-seismic noise of natural and anthropic origins excites the building resonances, that, in turn, excite the air inside the room, generating forced internal oscillations at different frequencies, contributing, in this way, to the background vibro-acoustic noise. In fact, the shapes of these building resonances are clearly visible in Figure 5 a), but are totally absent in Figure 5 b).

Table 3. Lowest resonance modes of Ruggiero Bonghi square acoustic resonator. From left to right: the theoretical modes, the measured modes and their coding for representation in Figure 5 a) and Figure 5 b).

Model-based frequency peaks in Hz	Measured frequency peaks in Hz	Figure 5 ID codes
3.7097	3.701	A
5.9896	5.999	B
7.0453	7.068	C
7.4194	7.403	D
9.5353	9.556	E
11.9792	12.000	F
12.5404	12.538	G
14.0907	14.021	H

4. DISCUSSION

The results of the experimental vibro-acoustic characterization of the chamber music concert room, coupled with a unifying interpretative model, evidenced that the considered space vibro-acoustic performance depended not only on how it was planned (i.e., the structure), but also on where and how it was placed. Obviously, a complete interpretation of the experimental measures on the basis of the proposed model would be impossible, due to the multiplicity of urban structures surrounding the building where the chamber music concert room is located. Moreover, the presence of non-linear phenomena, that might determine the presence of other peaks embedded in the same signal, would not be explained. Despite these facts, the model is enough accurate to explain the main experimental findings of this study and of previous works.

The evidences emerging from this work have many implications. The first is that a vibroacoustic landscape, as defined at the beginning of this work, really exists. In fact, besides the random presence of different input sources, the most important forcing of a place, as proved in the case of chamber music concert room, might not be completely casual, since they would be limited to their temporal duration. Conversely, the characterization of a space cannot be confined to its vibroacoustic behaviour as a function of its shape. Instead, this enclosed space, with its shape, designed on the basis of different structural and functional elements, should be considered together its surrounding spaces, being a portion of landscape. This justify the use of landscape, in the context of archaeology and cultural heritage studies, as a unifying complex element to be studied holistically.

The second implication is that vibroacoustic fingerprint of a structure or an object cannot be disentangled from their spatial context. In the case of the room fingerprint, frequency peaks are also justified in relation to the forced oscillations generated by secondary resonance frequencies. Conversely, at higher frequencies, the external forcing appears to drastically reduce, due to a limited presence of higher frequency resonant modes, being also masked by the resonant modes of surrounding rooms in the historical building.

It is important to underline that the generality of the approach described above allows its direct application to other closed and open spaces of interest for heritage studies, like churches, theatres, temples, monasteries, historical buildings in rural or urban areas or even larger urban spaces. In fact, although applied here in a simplified form, the same model can be adaptively extended to different structures or spaces, allowing to obtain a basic vibroacoustic model, which can be verified experimentally based on the measured vibroacoustic signal spectra.

Finally, the evidence of a vibro-acoustic interaction between the urban texture and a place, designed for specific purposes, opens the space to new historical hypothesis on the presence of an ecological wisdom, as the “ability to integrate ecological theory and practical experience to understand the landscape system on specific sites to produce real and permanent goods” [43]. In the case of spatial planning, the choices for designing and building the existing heritage structures in different ways, depending not only on their functions but also on their structure and position, might be an indirect evidence of the capacity, based on a repeated practice, to select these parameters on the basis the site-specific landscape features. This, in turn, might be related to the desire to reproduce specific positive or negative experiences and sensations, which we could attribute to the vibroacoustic landscape characteristics of a certain space, such as a concert room or hall, a theatre, a church, a monastery, or even an urban historic centre, shaped by its buildings and infrastructures.

5. CONCLUSIONS

This work characterizes the vibroacoustic behaviour (i.e., vibroacoustic fingerprint) of a private chamber music concert room, located inside a building in the historical centre of Napoli (South Italy). The use of high sensitivity broadband vibration and acoustic sensors, integrated into a system, allowed to detect the structural response of the concert room. However, the experimental study, integrated with a simple model, confirmed the hypothesis of previous works, evidencing the presence of an interaction between the urban morphology and its components (structures and infrastructures) and the space under study. In particular, this interaction has the nature of a forcing on the room, triggered by the resonance of specific urban components (in the case studied, one of the main roads of the historic centre, facing the building under study, and a square in the close vicinity) to vibro-acoustic signals of natural and anthropic origin. This evidence further confirms the existence of a real vibro-acoustic landscape.

This connection among different cultural heritage elements existing within a certain space motivates not only the structural, but also the functional design of certain spaces, conceived to host specific practices. A further element might include also the choice of position within the design. This coupling between physical spaces, structures and functions pertains to the integration of material heritage with its immaterial counterpart. However, the reasons for planning the shapes, functions and positions of historical spaces in a certain way often remain hidden, due to the lack of available and reliable documental sources related to their planning.

This is why only high-sensitivity broadband multiparametric measures, coupled with models and metrological procedures can overcome the existing lack of knowledge and understanding on the ecological wisdom, the planning and building skills of past civilizations. For this reason, considering the challenging goal, we started the experimental activity from a relatively simpler structure, that of a private chamber music concert room, in integration with a standalone vibroacoustic monitoring system, being the portable compact version of a previous system, already applied in the context cultural heritage studies.

The obtained results, based on the application of advanced sensors integrated into systems, can allow us to delve, both quantitatively and qualitatively, some multidisciplinary aspects pertaining cultural heritage structures and infrastructures. In fact, based on the accurate use of multiple high-sensitivity broadband sensors, it might be possible, in the future, to support the interpretation of spatial and structural planning, as well as the building practice, of past civilizations, also in the absence of specific sources, following a general application approach to contexts. The elements subject to interpretation might range from the reasons that led architects of the past to choose the positioning of a structure in a place, to the architecture shapes, the type of construction, the use of materials in different contexts, both for closed structures, as in the case of churches and theatres, and for open or partially open structures, as in the case of ancient Roman or Greek theatres or amphitheatres.

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