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METROLOGICAL REQUIREMENTS FOR THE BROADBAND VIBRO-ACOUSTIC MONITORING SYSTEM OF THE SAN PIETRO A CORTE CHURCH BELL TOWER, SALERNO, ITALY

1. Introduction

The vision of cultural heritage, originally associated to the idea of inherited properties, has evolved into a completely new one, reflecting the multidisciplinary and synergic interconnection of archaeological, historical, cultural, architectural and environmental elements, synthesis of its material and sensorial dimensions (Vecco 2010; Tavares, Alves, Vásquez 2021). This semantic evolution, which impacted on the UNESCO definition of cultural heritage, is opening new scenarios in the evaluation of heritage assets, aimed at understanding a place-related identity on the basis of the urban morphology, architectural styles, buildings techniques and environmental scenarios (United Nations Educational, Scientific and Cultural Organization, UNESCO 2022).

Despite its attractiveness, the application of this new vision to real contexts has some inherent difficulties. In the specific case of built heritage and public spaces, it largely depends on the availability of information about the relation between their design, functions and use, often lost over the centuries. From an archaeological perspective, this knowledge would be highly relevant, since the study about the functions of materials, objects and spaces is the key to the interpretation of past events and to the understanding of the habits and material history of people. This approach is coherent with the functional (i.e. processual) method in archaeology, often based on the adoption of comparative assessment in the study of materials, objects and spaces both in space and in time, aiming at understanding their function (Coles 1966; Deetz 1977; Baker 2013).

This vision, that triggered a transition from a static-contemplative to a dynamic-planning approach for the preservation and valorization of cultural heritage, is paving the road to new relevant multidisciplinary questions and approaches (Mrak 2014). In parallel, the inherently multi-disciplinary awareness about the intersection between material and symbolic (sensorial) elements is requiring the development of new methods and tools, based on measurements and the experimental evidence, aimed at supporting new interpretations of the archaeological evidence, as well as suggesting new historical hypotheses.

For such a purpose, landscape can be explicitly or implicitly used as a suitable functional unit, not only from an archaeological perspective, but also in the context of heritage studies (Vecco 2010; Tavares *et al.* 2021). In fact, the functionality of spaces, conceived for specific practices (e.g., religious,

Fig. 1 – The Longobard bell tower (left) of the San Pietro a Corte Church, Salerno (Italy).

political, military, etc.), allow to integrate a description of material features and intangible elements related to the environment, in which the spaces or structures are located. Among the intangible environmental parameters, that can be experimentally measured, modelled and interpreted through a multi-disciplinary vision, the vibroacoustic features of a landscape, known as vibroacoustic landscape (the totality of mechanical vibrations, both of natural and anthropic origins, in the infrasound and audible frequency regions), as defined in the literature (Barone *et al.* 2023), are assuming a very important role. In fact, the vibroacoustic landscape is a generalization of the acoustic landscape (the 'acoustic environment as perceived or experienced and/or understood by people, in context'), also known as 'soundscape', already used in the process of study and valorization of the cultural heritage (Yelmi 2016; Bartalucci, Luzzi 2020).

This generalization depends on two reasons. From one side, the traditional focus on the audible frequency range (20 Hz-20 kHz) has led to an artificial subdivision within this field of physics, depending on the different technical applications of acoustics, often associated to human health, with respect to the measure of vibrations, being of interest for geophysicists. This is why subsequent studies on spatial acoustic characterization have been termed 'soundscape', reflecting a consideration for human auditory capabilities. On the other side, the human body is able to interact and react also to lower (infrasound) vibration frequencies (Persinger 2014; Singh, Singh, Kalsi 2020). Thus, these broadband airborne, and ground-borne mechanical vibrations of natural and anthropic origin should be considered and characterized together, while vibroacoustics should become the new general disciplinary framework for these experimental and theoretical physical studies. With this respect, the development of a new standalone solution (Casazza *et al.* 2023), integrating new classes of vibration sensors capable to provide effective measurements in support, allowed us to extend our analysis to the vibroacoustic landscape. Its application to the sensorial dimension of cultural heritage guided us to investigate the vibroacoustic fingerprint of objects and the site-specific vibroacoustic characteristics in relation to the evolving features of the heritage assets under study (Barone *et al.* 2023; Casazza *et al.* 2023).

The approach to the study of the vibroacoustic features for a site is contextualized here to the Longobard complex of San Pietro a Corte in Salerno (Italy), the ancient chapel of the Longobard Palace of Prince Arechi II, an integral part of the complex that is believed to have served as the city's governing palace until the Angioian age (Fig. 1) (Fiorillo 2020). In particular, considering the San Pietro a Corte bell tower vibroacoustic fingerprint characterization as an interesting case study, due to its cultural relevance and to the availability of archaeological data, this work aims to describe the application of a suitable integration between the vibroacoustic monitoring system and a digital model via a suitable optimization process.

This integration not only enriches the background to support the historical interpretations of the site in relation to the monument known transformations, but also aids in elucidating the structural dynamic behaviour of the bell tower. Consequently, this general approach, described through an application, furnishes heritage managers and specialists with critical insights, enabling the identification of optimal strategies for the effective preservation and conservation of the historical structure. Within this research purpose, this work aims to detail an innovative integrated monitoring and modelling method, named Dynamic Finite Element Modelling (DFEM), whose initial phases will be described and applied here.

The next sections will introduce the method we are using for this study, underlining the critical points that deserve more attention and defining the characteristics number of the starting measurements points, determined following all the preliminary known information from the historical sources and technical inspections.

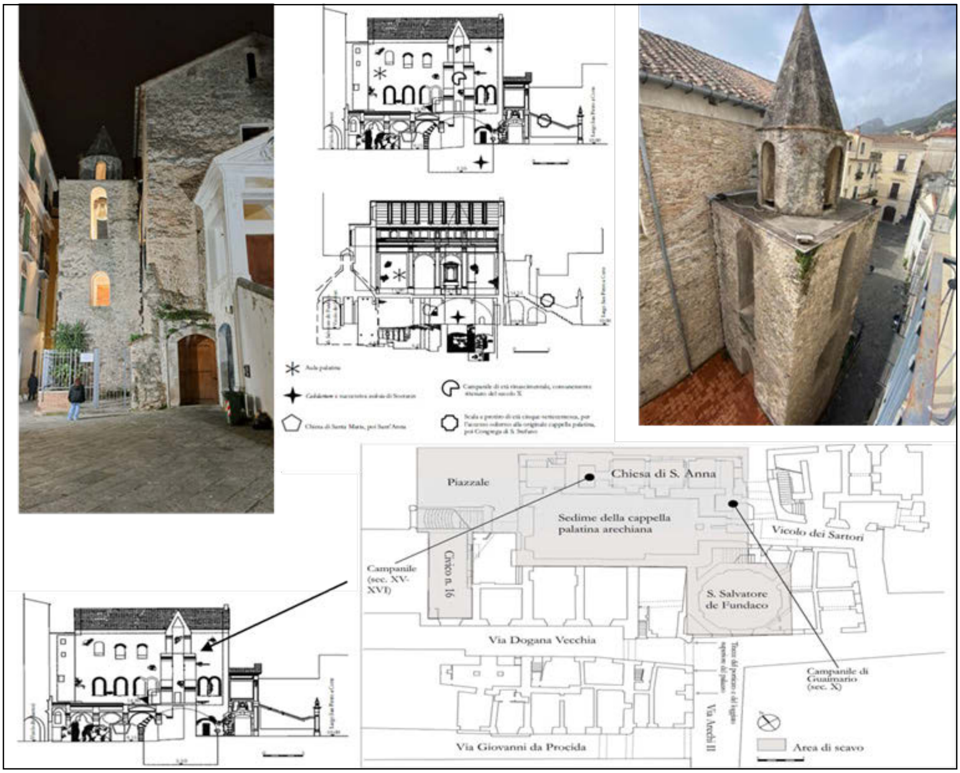

Fig. 2 – Architectural stratification of the the San Pietro a Corte complex (Salerno, Italy), based on the surveys Prof. Arch. Mario Dell'Acqua.

2. Materials and methods

2.1 *San Pietro a Corte and its bell tower*

The San Pietro a Corte complex (Fig. 2), located on a small square along via Antica Corte, in the Salerno city historical centre, is positioned slightly above the seafront. The site is structured on three levels. In the lower one, the two rooms of a building of the 1st-2nd century A.D., which, according to the archaeological reconstructions, might have been a *frigidarium* and an *apoditerium* of a thermal facility, which cannot be defined yet with certainty whether it was either public or private (Peduto, Fiorillo, Corolla 2013). The archaeological investigations, coordinated, since year 2018, by Fiorillo in collaboration with the local Soprintendenza, revealed the conversion to a cemetery function of the cold pool, from the 5th century onwards, categorically ruling out the possibility that the room had been transformed into an early Christian church, as previously assumed. The cemetery function of the area continued until the 6th-7th century, until when it was interrupted by a dramatic event, as evidenced by the archaeological remains in several urban sites within the city of Salerno, that were investigated by the Soprintendenza in the 1990s (Iannelli 2012). This event caused the collapse of the vaults, as evidenced by the twisting of one of the spandrels of the cross vault, that covered one of the rooms. Later, during an early medieval reorganisation of the space, only the barrel-vaulted room was affected, which housed the basin.

The mutating political events induced the Benevento duke, Arechi II, to undertake a more ambitious and extensive project, integrating a large part of the surviving thermal structures from the 1st-2nd century AD into the building complex, that was to house the Benevento court, when it moved to Salerno. In fact, the ongoing and yet-unpublished research work are showing that, between the 1st and 2nd century AD, in the position where the bell tower stands today, there was a rectangular building in *opus listatum*, being slightly less than three metres wide and not less than four metres high, which endured until the 8th century. This structure, in the Arechian period, due to its position, had a function compatible with a documental archive. On these remains, which were never demolished, it is possible that the first bell tower of the palace church was built, being identifiable with the 'small but beautiful' one mentioned in 10th century sources (Westerbergh 1956). The event, that affected the northern wall of the chapel at the time of Guaimarion, caused its collapse and the subsequent reconstruction, based on a partial reuse of the older structures as foundations and, where these had not been preserved, a special filling with stones and soil. Conversely, it has been hypothesized that the current inclination of the bell tower toward North could derive from an ancient soil slip, which probably caused the collapse of the third order of the tower and the subsequent construction of a non-tilted tower cap. In year 2022, after its restoration, a year 1456 bell belonging to the San Pietro a Corte complex has been installed within the second order of the tower.

The historical and cultural significance of the site is underlined by its role in the traditions of the Salerno Medical School, where the ceremonies for conferring doctoral degrees took place in the 15th century inside the palatine chapel of San Pietro a Corte and that of St. Catherine of Alexandria, the patron saint of the Salerno School (Della Monica *et al.* 2013). It is very likely that in the previous three centuries the ceremony took place in the hypogean rooms, also based on the descriptions provided by Sinno in his *Catalogue of Diplomas*, in which he mentioned those conferred in '*sacratissima aede Sancti Petri ad Curtim*', and the presence of St. Catherine of Alexandria, whose image was frescoed several times inside the rooms as early as the Norman age, becoming the protector of the Medical Schools in Europe from the 14th

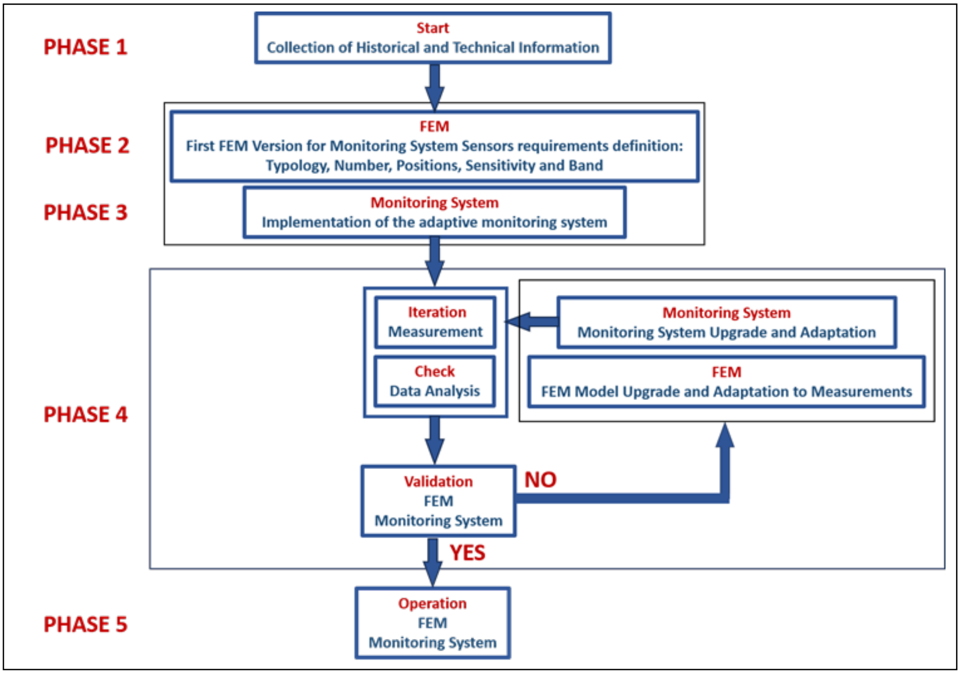

Fig. 3 – Synthetic Flow Diagram describing the dynamic FEM (DFEM) modeling procedure.

century onwards (Fiorillo 2013) and also a symbol of protection for the city, being represented in such a guise in a room in the tower of Salerno castle.

2.2 *Method*

The Dynamical Finite Element Modeling (DFEM) method consists in an iterative sequence of optimization phases, leading to a coherent integration between a Finite Element Model (FEM) and a modular monitoring system, performed through the adaptation and calibration of the FEM according to measurement results, paralleled by the adaptation and modular integration in terms of positions and number of sensors of the distributed monitoring system, based on FEM predictions (Fig. 3).

The first phase of this procedure consists of the collection of all the historical and technical information about the structure under study. The second phase aims at the production of the first version of the FEM, used to produce a first guess on the expected monitoring system technical characteristics in terms of sensors numbers and types. There are different digital tools and commercial software, which can be used to produce a FEM for the design and visual dynamic behaviour representation of complex structures or components. These models are well known and widely used in the cultural heritage field, also supporting the implementation of archaeo-seismological models (Hinzen 2005; Caputo *et al.* 2011; Guerra *et al.* 2017; Galassi *et al.* 2022). The Phase 2 enables to fix the preliminary installation criteria, followed by the installation of the monitoring system in an initial configuration (Phase 3). This provisional setup is implemented, together with the model, through an iterative optimization process (Phase 4). Following this optimization, as classically defined in the field of Operative Research, Phase 5 initiates the operation of the integrated digital and physical monitoring framework, collectively forming a 'phygital system', constituting the standalone evolution of 'phygital sensors' described in the literature (Barone *et al.* 2023; Casazza, Barone 2023; Schiavi *et al.* 2023).

The initial stages (Phase 1 and Phase 2) are crucial for determining the measurements conditions and specifying the preliminary selection of sensors, including their sensitivity and frequency requirements, for a modular, distributed monitoring system. An understanding of the asset's structural health and preservation status is vital to identify installation constraints and manage risks to the heritage asset within a constrained budget. This consideration is essential for the procurement of advanced sensors and the remote operation of the monitoring system. Preliminary field surveys and data collection, followed by modeling and simulation, underpin this strategic approach. Within this framework, modelling and simulation, following a preliminary field survey and data collection, can support this innovative choice (Casazza, Barone 2023). The preliminary results, that are presented here, are a summary of these two phases.

Finite Element Models (FEMs), traditionally employed in planning and structural stability assessments, often in conjunction with Building Information Modelling (BIM) software, have been innovatively applied to produce a first guess on vibration signal characteristics, such as amplitude and frequency. This approach facilitates the alignment of a heritage asset expected structural response with the selection and placement of sensors. This reverse application of FEMs has been successfully implemented in designing a monitoring system for an ancient Greek colonnade and in analysing various cultural heritage structures, including bridges, buildings, and churches.

2.3 *DFEM preliminary modelling*

During the DFEM Phase 1, two field visits were undertaken to evaluate the structural health of the heritage asset and identify any potential constraints on the installation and operation of the monitoring system. In parallel, preliminary vibration measurements were collected through a portable Bluetooth accelerometer (Model BWT901CL, produced by WIT MotionTM). The surveys also aimed to gather an initial set of geo-referenced images for creating a

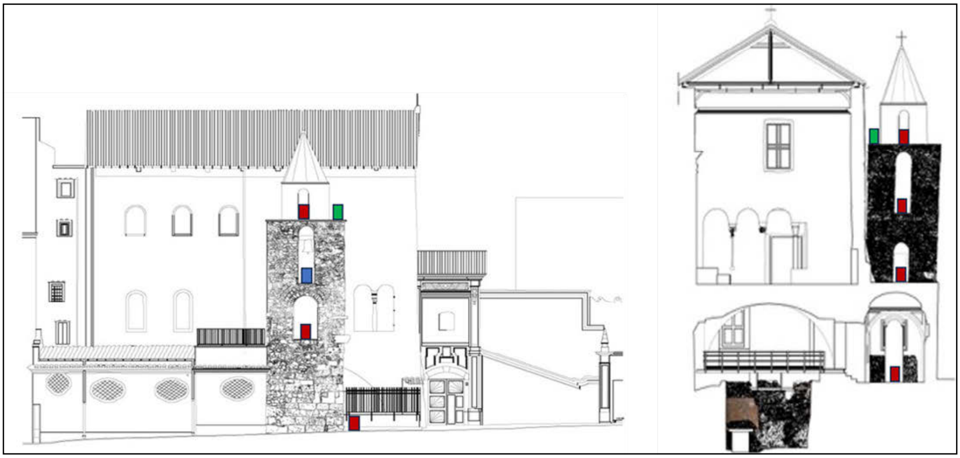

Fig. 4 – Identified preliminary measure points (Bell Tower – left: north side; right: east side) – red square: four displacement sensors and an acoustic sensor (five degrees of freedom); blue square: four displacement sensors (four degrees of freedom); green square: meteorological station.

preliminary Finite Element Model (FEM). Instead of collecting more detailed data through advanced methods, like cameras on Unmanned Aerial Vehicles (UAVs) or LiDAR, a smartphone was deemed sufficient for this initial phase. The geo-referenced photographs were processed to generate rudimentary 3D models through the software Metashape by AgisoftTM. The method for using a smartphone to derive a preliminary 3D model is described in the literature (Heng Siong, Ariff, Razali 2023). Then, the 3D model was exported to a commercial FEM software (Abaqus, produced by SIMULIATM) to produce the preliminary structural dynamics simulations, as the Phase 2 of DFEM process. In particular, the model was discretized through 3D brick elements, while the model mechanical properties for the masonry structure were preliminarily parametrized according to the literature (Ceroni *et al.* 2009; De Silva *et al.* 2018). The simulations, performed to assess the expected displacement and acceleration signals, were obtained following a procedure previously defined in the literature (Casazza, Barone 2023).

2.4 *DFEM Monitoring System initial requirements*

The preliminary and approximate results produced by the FEM need to be integrated with other considerations. First of all is that the structure acts as a filter for the external vibroacoustic signals of natural (e.g., wind, sea waves, etc.) and anthropic (e.g., vibrations generated and altered by different sources, like engines or transportation means, and transformed by structures and infrastructures and the urban texture), transforming the input signals into a different output in terms of signal amplitude and frequency spectrum (Barone, Casazza 2023). The wide frequency range of input and expected output signals suggests a preferential use of broadband sensors.

Second, the monitoring system design is based on structural response, that can be described through its dominant modes. These modes are the base (orthogonal) functions that, according to the Theory of Systems, have the most relevant weight in the description of the dynamical behavior of the bell tower in its multi-dimensional mode spaces (Varricchio, Damasceno Freitas, Martins 2013; Varricchio *et al.* 2015; Ni *et al.* 2016). A preliminary analysis of the expected bunch of dominant modes, also based on previous studies, shows that the slow motion of this typology of structure is mainly determined by the angular displacement (low frequency motion), while the transversal displacement has relevance at higher frequency (high frequency motion) (Ivorra, Pallarés 2006; Ivorra, Pallarés, Adam 2011; Milani, Clementi 2021). Therefore, an effective description of the dynamical behavior of the bell tower requires the acquisition of both the signals typologies.

3. Results and discussion

Based on the outcomes from the preliminary Finite Element Model (FEM), which highlighted areas of anticipated maximum displacement and acceleration signals, and incorporating operational constraints along with the dominant modes model, initial installation sites for monitoring equipment were determined, as depicted in Fig. 5. These locations are slated for further refinement in subsequent phases of the Dynamic Finite Element Method (DFEM) process.

The red squares in the figure define the positions of four displacement sensors (two translational and two angular), orthogonally oriented each other, together with an acoustic sensor (five degrees of freedom). The blue squares consist of four orthogonally oriented (four degrees of freedom) displacement sensors (two angular and two translational). The green square defines the position of the meteorological station, necessary for the acquisition of other relevant information (wind speed and direction, temperature, pressure, humidity, rain, etc.). Each point partly synthetizes the different structure degrees of freedom relative to the level of the tower. On the other side, the effective position of each sensor will be chosen according to the availability and quality of each position point.

Considering the preliminary survey and modelling results, integrated with the structural dynamic considerations, we identified the most suitable sensors for the DFEM of San Pietro a Corte. In particular, we opted for using a set of monolithic mechanical seismometers without force feedback, capable of providing an output signal proportional to the displacement signal. In addition to well-known characteristics of high sensitivity and bandwidth in the low

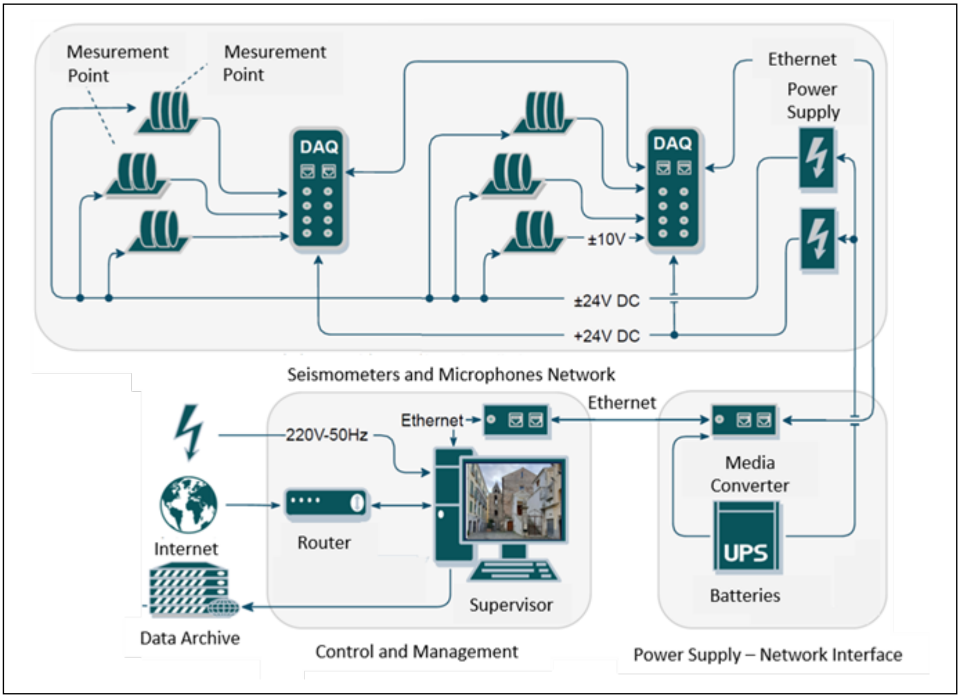

Fig. 5 – Scheme of the adaptive and modular distributed monitoring system developed for the monitoring system of the bell tower of *San Pietro a Corte* complex.

frequency region, this class of sensors allows the simultaneous extraction of both translational and angular signals (Barone, Giordano 2015, 2018a, 2018b, 2022). In this way, it will be possible to halve the number of physical sensors, simplifying the acquisition system (DAQ), while keeping the number of degrees of freedom unchanged. Moreover, this class of sensor allows a non-invasive positioning, even considering its very limited dimensions. Sensors will be positioned on stone tiles (to guarantee their stability), in turn placed on the measurement points, without any anchoring or gluing, to avoid any risk of damage for the monument.

The SE-10HL monolithic horizontal seismometers, produced by Advanced Scientific Sensors and Systems (Adv3S™) and featuring a mechanical monolithic oscillator (model GK19A – EB-100 class, Watt's Linkage architecture) with a high sensitivity LVDT readout system, were selected as the optimal commercial choice for this application. This seismometer has been previously employed in cultural heritage conservation efforts, including the monitoring of the Trajan Arch in Benevento (Italy) and as a central element in the permanent distributed monitoring system for the Temple of Neptune in Paestum (Salerno, Italy) (Petti *et al.* 2017, 2023). However, in case of need for higher sensitivity measurements evidenced during the Phase 4 of DFEM, the chosen sensors will be substituted with the SC-10HL sensor. Considering the characteristics of the sensors and the broadband frequency range of acoustic signals that could be detected in an urban context, the choice of acoustic sensors is oriented toward I-class model 4190 Brüel & KjærTM 1/2” free-field microphones, used for high-precision acoustic measurement. The microphone signals can be pre-polarized and pre-amplified with Brüel & KjærTM NEXUS 2690 device.

The adaptive modular distributed monitoring system (Fig. 5) has been effectively employed across various cultural heritage applications (Barone, Casazza 2023; Barone *et al.* 2023; Petti *et al.* 2023). This versatile system is designed to accommodate a diverse array of sensor types, including seismic, acoustic, electromagnetic, and meteorological sensors. Its modular nature is facilitated by an Ethernet network, which enables the integration of numerous 24-bit data acquisition (DAQ) local stations. Each station, specifically the FD-11603 FieldDAQ class by National InstrumentsTM, supports up to eight 24-bit channels with a sampling rate up to 100 kHz. The system is connected to a workstation for efficient data management and storage, complemented by a specialized graphical interface (Supervisor), such as the one developed by Adv3STM, for system oversight. To reduce the electromagnetic interference, the entire setup is powered by batteries.

The specialization of the system for the bell tower monitoring is relatively simple. In fact, considering the total number of distributed degrees of freedom (14) plus the slow frequency sampling channels of the weather station, the architecture can be limited to only two DAQs, guaranteeing, in this way, a maximum of sixteen degrees of freedom, while still maintaining its full modularity and adaptivity. It must be stressed that the preliminary design of the monitoring system and its digital model counterpart, defined during Phase 1 and Phase 2 of DFEM, requires to be mutually optimized, as part of Phase 4, after the installation and activation of the monitoring system (Phase 3), to produce a fully-operational phygital system (Phase 5) that can contribute to the assessment of the tower bell structural health and to the study and characterization of the vibroacoustic landscape characterizing the surrounding area (Barone *et al.* 2023).

4. Conclusions

The integration of material and immaterial aspects in cultural heritage interpretation, thanks to a multi-disciplinary analysis of existing evidence, is exemplified through this study, aimed at supporting the vibroacoustic characterization of the San Pietro a Corte complex bell tower through an innovative method, the Dynamical Finite Element Modeling (DFEM). The DFEM method aligns with classic optimization techniques through an iterative process, adjusting the model based on empirical data and subsequently refining the monitoring system set-up to fit model predictions. Based on preliminary field surveys, the preliminary phases of DFEM procedure allowed to determine the key parameters for a distributed monitoring system design, as a premise to the iterative optimization between the monitoring system and the structural model applied to the bell tower vibroacoustic fingerprint profiling.

This work on DFEM constitutes a part of bell tower comprehensive vibroacoustic study, in the framework of past and current studies of San Pietro a Corte complex, which might produce new perspectives for the characterization of the urban history and the urban texture evolution of Salerno, informing also potential conservation and valorization strategies, as advocated by the Soprintendenza.

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ABSTRACT

This study employs a multi-disciplinary holistic approach to analyze the vibroacoustic fingerprint of the San Pietro a Corte Longobard complex bell tower (Salerno, Italy), using the Dynamical Finite Element Modeling (DFEM) optimization method introduced here. The DFEM aims at mutually optimizing the integration between a modular monitoring system and a digital model, creating an adaptive 'phygital system' through a holistic, multi-disciplinary approach. This work, focusing on the initial phases of DFEM procedure, allowed us to design a preliminary monitoring setup, being supported by field surveys. The use of this phygital system could better inform, in the future, the actions needed to protect the immovable heritage assets and produce new data to support novel interpretations of existing material evidence.