

Article

Acoustic Vases in Europe: A Review of Documentation, Approaches, Measurement Methodologies, and Preliminary Proposal for a Methodological Framework

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Abstract

Research on acoustic vases embedded in historical buildings has progressively developed through archaeology, architectural history, and acoustics, producing extensive documentation on their distribution, geometry, installation and possible acoustic role, with experimental evidence from in situ measurements, laboratory tests, and numerical analyses. However, documentation and measurement procedures remain highly heterogeneous, limiting reproducibility and comparative interpretation. Within this context, the present work proposes a preliminary methodological framework for future investigations. It reviews the principal European documentation, census, experimental, and numerical approaches identified by the authors. Particular attention is given to the recording system developed by Palazzo-Bertholon and Valière and to the experimental methodologies adopted in previous studies, including procedures, acoustic descriptors, and instrumentation. A possible extension of the “fiche d’information” is discussed to make geometrical, spatial, and installation-related data more explicit for comparative analyses, acoustic modelling, and measurement planning. A documented case study is used to illustrate the proposed organization of information, followed by a simplified acoustic simulation showing how structured data may support model construction and interpretation. The proposed procedure therefore combines simulation and in situ measurements, with standard and advanced investigation levels. The study is aimed at improving documentation quality, consistency, and comparability rather than providing definitive evidence of acoustic effectiveness.

Keywords: acoustic vases; archaeoacoustics; historical churches; acoustic simulation; measurement methodology

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1. Introduction

1.1. Background and Geographical Scope

Research on acoustic vases is based on contributions from various disciplinary fields, including archaeology, architectural history, and acoustics. The literature can be grouped into three complementary areas: geometrical and constructive characterization, acoustic interpretation, and experimental verification.

It is worth noting that the study is conducted within a European geographical context. The analyzed corpus should not be interpreted as an exhaustive inventory of all the possible documented buildings or occurrences encompassing vases. Nevertheless, it comprises the principal documentation, census, experimental, and numerical studies identified through the scientific, archaeological, and documentary sources described in Section 1.4.

The first area concerns the geometrical and constructive characterization of the devices. The available documentation provides a substantial amount of data regarding position, number, dimensions, and insertion techniques of the acoustic vases within buildings. These devices, often referred to as “pots”, are generally ceramic artefacts originally intended for common use, inserted into masonry with the neck flush with the internal surface and oriented toward the interior environment, with a predominant placement in the upper parts of walls and in vaulted structures, often in the choir and apse areas [1]. Configurations include linear distributions along walls, grouped arrangements between vault arches, and placements near openings [2]. Dimensional data show significant variability: historical repertoires report vases with heights of 25–32 cm and openings of 9–14 cm, while other contexts exhibit smaller elements (internal height 7–18 cm, diameter 5–8.3 cm) and spacing on the order of 1.8–2.5 m [3]. The number of pots per building ranges from a few units to over 100, with average values on the order of several tens in the most studied samples [1]. This variability reflects adaptation to specific architectural and construction conditions and the absence of standardized typologies.

The second area concerns acoustic interpretation. Historical sources explicitly attest to the use of pots for purposes related to the acoustic behavior of the worship space. Documents dated between the 15th and 17th centuries describe the installation of vases with the aim of improving the resonance of chant and voice. This intentionality is consistent with references to the Vitruvian tradition of “echea” and with the conception of the pots as resonant elements [4].

Nineteenth-century inventories documented the widespread presence of earthenware pots in English medieval churches and often interpreted these devices in relation to ancient acoustic vessels, although their actual function was not always established with certainty [5].

Early French research compared ancient echea with medieval acoustic jars documented in several churches, supporting the hypothesis of a possible historical continuity between classical resonators and medieval acoustic devices [6].

Subsequent critical analyses also examined vessels embedded within walls and beneath floors, suggesting that their possible acoustic function could be interpreted in relation to both Vitruvian sources and pseudo-Aristotelian explanations of resonance in enclosed spaces [7].

Later, synthetic accounts interpreted medieval acoustic vases as an adaptation of an ancient resonator tradition to enclosed and reverberant church spaces, where their function was associated less with precise tonal reinforcement than with the acoustic regulation of the interior environment [8].

In a broader historiographical perspective, the hypothesis of an acoustical tradition in European architecture has also been discussed in relation to recurring practices and phenomena, including resonators and acoustic effects produced by architectural geometry; however, this interpretation requires caution, since some effects may reflect intentional design whereas others arise inherently from structural form [9].

In medieval contexts, these devices are interpreted as means to modify acoustic conditions in environments characterized by high reverberation, with expected effects on spectral distribution and speech intelligibility [2]. Alongside this interpretation, the literature also reports constructive explanations (structural lightening of vaults, technological

requirements), particularly in Byzantine and Mediterranean contexts [10], indicating the coexistence of multiple functional interpretations. Structural and acoustic functions are recurring themes: acoustic vases are investigated both for the role in lightening vaults and for the resonant properties [11].

The third area concerns experimental and numerical assessment. Available studies have investigated the resonance of individual vases, their near-field response, and, less consistently, their influence on room-acoustic descriptors, mostly referred to reverberation. Reported effects are generally frequency-dependent, case-specific, and frequently comparable with measurement variability. The available evidence therefore does not provide a single quantitative estimate of the room-scale influence of acoustic vases.

1.2. Methodological Gaps

For this reason, comparative analyses require classification tools capable of systematically relating geometrical characteristics, insertion modalities, and potential acoustic implications.

In recent years, several studies have focused on this topic by developing rigorous classification and description systems that provide valuable structured datasets of documented cases.

Nevertheless, in the available records, some characteristics appear to receive limited emphasis or are not consistently reported, even if they were required during the collection stage. Given that the actual acoustic role of these artefacts is still unsettled, and that acoustic analyses through advanced simulation tools could help fill this knowledge gap, the available information should be made explicit and directly usable to support the construction of representative models.

Moreover, the existing literature provides several heterogeneous experimental investigations concerning these artefacts. Measurements have been carried out either in laboratory settings or in the buildings housing the vases, and experiments have been conducted close to the openings, sealed or unsealed, and within specific frequency ranges.

These approaches provide valuable information on the resonant behavior of individual artefacts and, in some cases, on their possible influence on the acoustic field of the hosting space. While the reported results are of considerable interest, their reproducibility and comparability are somewhat limited by the absence of a standardized methodology.

1.3. Objectives and Structure of the Study

The present paper addresses the aforementioned two methodological gaps. The first concerns the organization of documentation data in a form suitable for comparative and simulation-oriented analyses. The second concerns the absence of a structured procedure for assessing the acoustic influence of acoustic vases through coordinated documentation, modelling, and measurement activities.

Accordingly, the study first analyses the existing recording framework developed for the classification and census of acoustic vases, with particular reference to the work of Palazzo-Bertholon and Valière. The main experimental approaches reported in the literature are then critically considered in order to identify methodological limitations affecting reproducibility and comparability. The bibliographic research criteria are briefly described in sub-Section 1.4.

A possible extension of the existing recording system is then proposed. The aim is not to replace the original “fiche”, but to improve the explicit organization of geometrical, spatial, functional, and installation-related data for acoustically oriented analyses. A documented case study is then used to illustrate how information available in literature can

be structured within this framework. A simplified simulation-oriented application is subsequently presented to show how such structured information may support model construction and the interpretation of local acoustic effects.

Finally, the paper proposes a preliminary methodological framework for future investigations, integrating documentation, simulation, in situ measurements, uncertainty-aware interpretation, and possible advanced analyses.

The primary objective and novelty of the present work are therefore methodological. The paper does not aim to provide a definitive quantitative assessment of the acoustic effectiveness of acoustic vases, but to discuss how the organization and standardization of available information may support more reliable comparative studies, simulation-oriented analyses, and experimental campaigns.

On this basis, the following Section 2 examines the European classification and census framework developed by Palazzo-Bertholon and Valière, with particular attention to the information fields that may support comparative analyses and subsequent acoustically oriented investigations.

1.4. Literature Identification and Selection

The literature analysis was presented by means of a structured narrative approach. Sources were identified through bibliographic catalogues, institutional repositories, targeted searches of historical and scientific publications, and documentary material obtained through direct contacts with researchers active in the field. Publications were included when they provided original documentation, recording or classification procedures, experimental data, numerical methods, or methodological considerations specifically concerning acoustic vases installed in historical buildings. General studies on architectural resonators were retained only when their methods or results were directly relevant to the objectives of the present work.

The resulting corpus was conceived as a reasoned review aimed to identify the principal sources required to define the proposed methodological framework instead of providing a further systematic review or a complete census of European occurrences. Documentation, classification, and recording approaches are examined in Section 2, whereas experimental and numerical methodologies are discussed in Section 3.

2. State of the Art on the Classification and Census of Acoustic Vases

A structured attempt to establish a systematic classification and census of so-called “acoustic vases” in medieval buildings is represented by the research program led by Palazzo-Bertholon and Valière since 2005 and progressively consolidated through contributions extending to 2022 [12–14]. These researchers have worked over several years, primarily on French case studies, while also analyzing acoustic vases installed in historic buildings and churches across Europe.

The integration of contributions from different geographical areas (France, Switzerland, Germany, Italy, Byzantine and Mediterranean regions) shows that acoustic vases were distributed over a broad temporal and geographical range, with applications in Romanesque, Gothic, and Byzantine buildings [10,15]. Inventories indicate several hundred documented buildings, with significant concentrations in the French context and broader European distribution [1]. Typological variability, spatial distribution, and dimensional differences represent consistent features of the documentation.

The 2007 contribution [12] represents the first explicit proposal of a structured inventory model. The authors identify the fragmentation of previous studies—ranging from archaeological descriptions to erudite reports and isolated acoustic tests—and introduce a normalized data collection system. The census integrates three pre-existing inventories and extends them through systematic field investigations.

The classification scheme operates on multiple levels. At the building scale, the recorded parameters include building type (monastic, parochial, civil), geographical location, presumed construction date, interior volume, structural typology (vaulted or timber roof), and conservation state. At the device scale, the inventory records the number of vases (observed and presumed original), spatial distribution within the enclosure (choir, nave, chapels), installation height (upper walls, vaults), geometric arrangement (linear, triangular, clustered), typology of vase, material, volume, neck diameter, neck length, and depth.

A specific contribution of the 2007 framework [12] is the explicit separation of evidence types. Sources are classified as:

- archaeological evidence (in situ observation, ceramic typology, architectural context);
- historical textual sources (chronicles, construction accounts, liturgical references);
- acoustical investigations (laboratory reconstructions, in situ resonance measurements).

The inclusion of standardized recording sheets (“fiche d’information” and “fiche d’enregistrement”) formalizes this structure and establishes traceability between each recorded parameter and its documentary origin. This represents the first methodological model for the technical cataloguing of acoustic vases.

A 2016 contribution, developed in [13], extends the census to a broader European scale and introduces a clearer aggregation strategy. Cases are organized by country and building typology, while distinguishing between physically preserved devices and documentary attestations. The dataset is no longer presented as a simple list of occurrences, but as a structured corpus enabling statistical aggregation and comparative interpretation.

The developments discussed in the following period and revisited in [14] consolidate the classification by introducing a critical evaluation of the quality of evidence. Studies are differentiated according to methodological robustness: descriptive reports without measurements, frequency measurements of individual vases, comparative “open/closed” tests, and investigations lacking replicable protocols. This step introduces a hierarchy of evidentiary reliability within the census.

Across the aforementioned contributions, the classification evolves from inventory compilation (2007) to a structured European census and, subsequently, to methodological stratification of evidence. The common framework is based on four principal aggregation axes:

- Chronological aggregation: distribution of devices between the 11th and 16th centuries.
- Spatial aggregation: location within the architectural volume and installation height.
- Quantitative aggregation: number of vases as a function of building volume.
- Acoustic aggregation: resonance frequency ranges and their relation to building size.

Within the corpus identified in the present review, no alternative European-scale classification framework with comparable technical detail was identified. The Palazzo-Bertholon and Valière framework therefore represents the most extensively developed system identified in the reviewed literature for the structured cataloguing and methodological organization of acoustic-vase documentation.

This framework provides the methodological basis for further systematic cataloguing initiatives and for the integration of dispersed documentary sources into a coherent acoustical database.

On the basis of this extensive and long-term research activity, which has gathered substantial knowledge and documentary evidence concerning the installation of acoustic vases, an extended technical recording template “fiche d’enregistrement” derived from the 2007 interdisciplinary framework [12] is proposed in the current research.

The proposal of an updated template is intended to supplement existing records with more precise data on geometrical features, in particular dimensions, installation conditions, and the number and position of vases. Additional parameters related to geometry, installation, and acoustic behavior help to improve cross-site comparability, ensure measurement traceability, and enhance the robustness of statistical and acoustical analyses.

An online platform, available at <http://archeoacoustique.labo.univ-poitiers.fr/>, (accessed on 20/05/2026) extends the research by providing access to a continuously updated inventory of buildings containing acoustic vases. The database also allows the reporting of newly identified cases. For new entries, the required data follow the same structure as the existing fiche and are therefore fully consistent with the previously defined framework. Within the section “Description of the building”, the information to be provided includes the name of the building (church dedication or commonly used designation), the building type (church, secular building, other), and photographic documentation or sketches of the site. Within the section “Observation of the acoustic pots”, the required information includes whether only simple openings are visible in the masonry or whether actual pots are attested, the number of observed pots (or openings), the place of conservation (in situ or deposited in a museum or another institution, with specification), the location of the pots within the building (nave, choir, side chapels, or other areas), and their level of insertion (at human height, in the upper parts of the walls, or within the vaults). This section is complemented by photographic documentation or sketches of the pots and by any additional remarks considered relevant.

Although the Palazzo-Bertholon and Valière framework represents the most extensively developed European-scale inventory identified in the reviewed literature, its primary purpose remains descriptive and documentary.

Consequently, several types of information potentially relevant for physically based analyses and reproducible acoustic investigations are not always formalized in a directly usable way.

Following the examination of the aforementioned framework—the most structured data collection on acoustic vases identified by the authors—this analysis investigates the experimental methodologies reported in the literature. Specifically, it focuses on the adopted measurement procedures, measured acoustic parameters, and instrumentation, in order to identify common elements for comparison among studies and possible methodological limitations.

3. Review of Measurement Methodologies for Assessing the Influence of Acoustic Vases

The function of acoustic vases remains only partially understood, despite historical sources attributing an acoustic role to these artefacts. One of the main reasons for this uncertainty lies in the strong heterogeneity of the experimental methodologies adopted in previous investigations and in the limited comparability of the results obtained.

Results indicate that acoustic vases behave as frequency-selective resonators, with resonance frequencies typically ranging between 100 and 500 Hz [16]. In studies conducted on samples of medieval churches, measurements show a reduction of Reverberation Time (RT) in frequency bands relevant to speech and a cumulative effect associated with the number of devices, with correlations between the number of pots, building volume, and characteristic frequencies [1,16]. Other studies highlight localized effects on the spatial distribution of sound energy and variations in clarity-related parameters (e.g., C_{50}), without systematic changes in global acoustic parameters [17]. The case of Noyon documents selected resonance frequencies (108 Hz and 141 Hz), without identifying a corresponding spatial distribution rule [18]. Overall, the experimental results are strongly case-dependent and do not yet provide a comprehensive assessment of the acoustic influence

of the vases. Moreover, many reported effects are limited in magnitude and may be comparable with the intrinsic variability of measurements performed in large and acoustically complex historical spaces.

A wide range of experimental methodologies has been adopted to evaluate the acoustic effectiveness of ceramic vases installed in historical buildings, particularly churches.

These methodologies include in situ measurements, laboratory experiments, numerical modelling, and hybrid approaches combining different techniques. The following overview summarizes some procedures adopted, the type of data collected, the obtained results, and the limitations highlighted in previous studies. The objective of this section is not only to summarize the obtained results, but also to identify recurring methodological limitations that may affect the interpretation and reproducibility of the reported observations.

3.1. Local and Near-Field Characterization of Individual Vases

It should be noted that systematic experimental investigations on acoustic vases in churches have been developed primarily by French researchers [19] and are largely based on in situ measurements combined with laboratory tests [20]. These studies mainly address the resonance frequency and near-field response of the vases rather than global room-acoustic effects. Measurements performed on approximately 50 churches, with usable data from 22 buildings and a total of 274 intact vases, show resonance frequencies in the range 80–450 Hz, with a mean value of 226 Hz, corresponding to the main spectral components of the human voice. Laboratory tests indicate amplification levels up to 25 dB inside the cavity, decreasing to approximately 6 dB at a distance of 0.10 m from the neck and becoming negligible beyond this distance, confirming a highly localized acoustic effect. In the case of Pommiers-en-Forez, where 29 vases are embedded in the vault, two dominant frequency ranges are observed around 160 Hz and 250 Hz. However, the high proportion of damaged elements and the absence of consistent room-scale measurements prevent a conclusive assessment of their global acoustic impact [20].

Field surveys have systematically recorded parameters such as the number of vases, their geometry, position, and resonance frequency. Experimental investigations typically combine laboratory testing and in situ measurements to characterize the vases as resonant devices. These analyses have been carried out using microphones positioned within the cavity, at the neck, at the outlet, and at approximately 10 cm from the opening, with broadband excitation signals used to derive frequency responses [20,21]. Case studies report configurations with 29 vases arranged in three rows and grouped into distinct classes corresponding to different resonance frequencies. More generally, vase diameters around 25 cm and quantities ranging from 1 to 100 per building are indicated.

Other studies focus on the development of measurement protocols suitable for field surveys. In a structured in situ investigation [22] covering 20 buildings, including monastic and parish churches with volumes ranging from 187 to 6056 m³ and up to approximately 100 vases, resonance frequencies are determined using a lightweight protocol based on broadband excitation (hand clap), with complementary tests using voice or without excitation. The response is recorded by a microphone mounted on a telescopic pole, allowing reproducible positioning at the vase opening.

Another study modelled the vases as Helmholtz resonators including both laboratory prototypes and in situ measurements [23]. Laboratory configurations with neck diameters between 20 and 50 mm and neck lengths between 8 and 60 mm, and overall dimensions up to approximately 0.15–0.19 m, show resonance frequencies ranging from about 200–210 Hz for larger geometries to 360–370 Hz for smaller ones. In situ measurements in Romanesque churches indicate resonance frequencies distributed between 200 and 350 Hz, with representative values around 232 Hz, highlighting the variability associated with

vase geometry. The work by Desarnaulds [3] compiles experimental evidence from previous studies together with original measurements conducted both in laboratory and in situ conditions. The methodologies include comparisons between active and occluded vases, variation of source and microphone positions, and the use of different excitation signals such as pure tones, complex signals, and speech. Global acoustic parameters, including RT, spatial distribution, and frequency response, are evaluated by comparing configurations with and without vases, where the “absence” condition is simulated by closing the vases with cork plugs. Laboratory tests on eight different vase shapes are carried out in anechoic and reverberation chambers to determine frequency response, resonance frequency, quality factor, and absorption. In situ measurements use impulse response techniques to evaluate parameters such as RT, Early Decay Time (EDT), speech transmission index STI, and C_{50} , with each measurement point obtained as the average of six acquisitions. The results show that the limited number of vases, typically around four per church, and their distribution prevent the detection of clear global acoustic effects, with only small and localized variations observed, often comparable to measurement uncertainty.

Individual resonating vases have been more frequently examined, rather than the whole church internal space. The acoustic response of each vase was studied by Godman [4] by exciting the system with sinusoidal sweeps, radiated by a loudspeaker positioned at a defined distance (approximately 1.5 m), while the response was recorded using a microphone placed near or partially inside the neck of the vessel to capture the resonance peaks. The tests were performed in an anechoic chamber to isolate the intrinsic behavior of the resonator, and the recorded signals were processed to derive impulse responses and frequency spectra. The objective was to identify the resonant frequencies and spectral response of the vases, and to evaluate their potential role as selective resonators capable of reinforcing specific frequency components of sound.

As aforementioned, most studies refer to measurements mainly carried out in situ on individual pots. In this context, it should be noted that in [18] a microphone was positioned very close to the opening (approximately 1 cm from the neck) mounted on a telescopic pole, with signal acquisition through a real-time analyzer. Excitation was generated using simple and repeatable methods, specifically handclapping for rapid estimation and broadband noise for a more complete characterization of the frequency response. The aim of the measurements was not to determine global room acoustic parameters, but to characterize the resonant behavior of the pots, particularly their resonance frequency, and to collect comparable data across a large number of cases. The results were then used to analyze frequency distributions, investigate correlations with church geometry, and assess whether these devices could contribute to the reduction of RT in frequency bands associated with the human voice.

3.2. *In Situ Open/Closed and Room-Scale Investigations*

When room-scale investigations are carried out, the characteristics of vases in terms of dimensions and acoustic behavior are often documented, for example Arns and Crawford in [24] report two relevant French cases.

At Saint-Chef, 45 vases installed in three rows produced a measurable change in RT only in the immediate vicinity of the vases and within a narrow frequency range when covered and uncovered conditions were compared. The same source identifies the Mercoire chapel as a case in which 14 ceiling pots were associated with frequencies between 166 Hz and 294 Hz. The chapel measured 7.65 m × 9.95 m and had a vaulted height of nearly 10 m, with hard and almost uninterrupted boundary surfaces. These observations indicate local and frequency-limited effects rather than a broader room-scale modification. In fact the observed acoustic effects are confined to limited frequency bands and, in some

cases, to regions close to the vase locations, resulting in measurable but perceptually marginal variations in sound level and intelligibility.

The difference between open and closed vases has been specifically investigated in controlled experimental conditions [18]. In a confined underground space of approximately 15 m² (about 38 m³), equipped with 64 acoustic vases, impulse and broadband excitation signals were combined with modal analysis using a distributed microphone network (8 microphones arranged on 3 planes with 31 cm spacing) and complemented by in situ singing tests. The acoustic analysis focused on frequencies below 300 Hz, with a Schroeder frequency of approximately 270 Hz and vase resonances in the range 95–160 Hz, grouped around 108 Hz and 141 Hz. The comparison between sealed (bouchés) and open (débouchés) configurations shows an increase in RT from 0.58 s to 0.71 s, with variations exceeding 60% at 125 Hz. In [18], the values of 0.58 s and 0.71 s correspond to mean reverberation-time values calculated from the individual results reported in Table 1 of the 2016 study [18]; they therefore represent aggregated values rather than the result of a single receiver position or a single frequency-band measurement.

Table 1. Operational organization of the proposed two-level extension of the recording framework (Ext. = extended; Mand. = mandatory; NR = not reported; Cond. = conditional).

Level	Item and Status in the Original Fiche	Proposed Operational Field	Data Format, Unit, or Allowed Values	Requirement	Evidence and Uncertainty	Intended Use
Main	Building identification already present	Unique record ID, building name, country, municipality, coordinates, record date	Controlled text, date, decimal coordinates	Mand.	Documentary and coordinate source	Record traceability
Main	Chronology and function mainly reported as text	Construction phases, original and current function, liturgical zone, documented musical practice	Date range; controlled categories; free text only when required	Mand.; NR allowed	Source and confidence level	Historical and functional interpretation
Main	Number of vases already requested	Observed number, presumed original number, and current preserved number reported separately	Integer; observed, reported, estimated	Mand.	Observation or documentary source	Quantitative comparison
Main	Position and disposition generally descriptive	Architectural zone, wall/vault/floor location, relative height, and distribution pattern	Controlled categories; relative height (h/H), where available	Mand.	Source and positional uncertainty	Spatial comparison
Main	Morphology and dimensions partly structured	Morphological class, total height, maximum diameter, opening diameter, neck length, and volume	mm, cm, or m ³ ; NR when unavailable	Mand.; NR allowed	Measured, reported, or inferred; dimensional uncertainty	Morphological comparison and preliminary resonance assessment
Main	Opening condition not consistently formalized	Open, partially obstructed, closed, damaged, inaccessible, or unknown	Controlled categories	Mand.	Survey date and photographic evidence	Measurement planning
Main	Photographs or sketches already requested	General interior view, contextual view, detailed image, annotated plan, and section	Image ID, author, date, and scale	Mand.	Source, authorship, and licence	Verification and comparison

Ext.	Building geometry often incomplete	Plan, sections, total volume, sub-volumes, and relevant surface areas	m, m ² , m ³	Cond.	Survey method and geometric uncertainty	Room-acoustic modelling
Ext.	Acoustic boundary properties generally absent	Material class, absorption coefficient ($\alpha(f)$), and scattering coefficient	Frequency-dependent values	Cond.	Measured, literature-derived, or assumed values; uncertainty	Definition of boundary conditions
Ext.	Internal vase geometry generally incomplete	Neck length and area, cavity volume, wall thickness, and orientation	mm, m ² , m ³ , degrees	Cond.	Measurement or estimation uncertainty	Helmholtz or impedance modelling
Ext.	Position generally qualitative	Exact (x,y,z) coordinates, spacing, and axis orientation	m and degrees	Cond.	Coordinate uncertainty	Spatially resolved modelling
Ext.	Measurement metadata absent from the documentary fiche	Source, receivers, excitation signal, calibration, repetitions, environmental conditions, and processing parameters	Standardized measurement metadata	Cond.	Instrumental and procedural uncertainty	Reproducibility of acoustic campaigns

Modal analysis indicates local amplification near the walls and redistribution of sound energy within the volume. Singing tests performed with four male voices report improved self-perception and harmonic fusion in the open configuration.

Similarly, investigations in Serbian Orthodox churches [25] concluded that the low resonant frequencies and narrow bandwidths of the ceramic vessels, typically numbering fewer than 25 per building, made a contribution to the overall room acoustics almost impossible.

Nevertheless, it is emphasized that the effectiveness of acoustic vases depends on their number, placement, and the architectural characteristics of space. Studies conducted in Swiss churches [26] report reductions in Clarity (C_{50}) and speech transmission index (STI) when the vases are open, with weak effects at low frequencies and variations that are generally not perceptible, despite resonance frequencies in the range 237–444 Hz.

Within a broader research framework [3,26] addressing both the acoustic behavior of ceramic pots and their interaction with architectural spaces, experimental investigations were conducted at two complementary scales: local characterization of the resonators and in situ measurements in churches. The latter were performed using an MLSSA system with broadband MLS excitation radiated by a loudspeaker, while the acoustic response was recorded at multiple source–receiver positions distributed between choir and nave, including points at the height of the pots and at listener level. Data acquisition was carried out with asynchronous DAT recorders and repeated several times for each position to ensure reliability, and the impulse responses were processed to derive the main room acoustic parameters, namely RT, EDT, C_{50} , and Speech Transmission Index (STI). Also in this case, a key methodological feature is the comparison between configurations with pots open and temporarily sealed with cork stoppers, allowing isolation of their contribution without altering the boundary conditions. Complementary sound pressure level measurements in 1/3-octave bands were also carried out at short distances from the pots using a sound level meter with broadband excitation representative of speech. While laboratory and local measurements indicate that the pots behave as frequency-selective resonators with amplification confined around their resonance frequency, the in situ results show that their influence on the acoustic field is negligible: no significant variations are

observed in RT and EDT, and only very small, spatially and spectrally limited changes are detected in C_{50} and STI, generally within measurement uncertainty.

Recent in situ investigations in the caveau phonocamptique of Noyon Cathedral [27] provide a detailed experimental framework combining geometric characterization, modal analysis, and perceptual evaluation. The chamber, with a volume of approximately 38 m³ and equipped with 64 ceramic vases, is analyzed using a distributed microphone network. Resonance frequencies are identified around 108 Hz and 141 Hz, associated with differences in vase volume. Reference [27] reports an overall RT increasing from 0.53 s with the vases closed to 0.67 s with the vases open, mainly in the 62.5–250 Hz bands. These values are not directly equivalent to the mean values of 0.58 s and 0.71 s derived from the tabulated results reported in [18]. Despite the different absolute values and aggregation procedures, both sources indicate an increase in RT when the vases are open.

Modal analysis indicates a reduction in spatial level differences, suggesting improved sound field homogeneity without significant variation in average sound level. Listening tests based on live vocal performances indicate limited but measurable acoustic effects, with perceptual impact depending on the type of signal [27].

3.3. Laboratory and Controlled-Resonator Investigations

Laboratory and controlled-resonator investigations have been used to isolate the intrinsic acoustic response of ceramic vessels and to evaluate their resonance frequency, absorption, sound re-radiation, and cumulative behaviour under repeatable boundary conditions.

Giron et al. [28] summarize evidence indicating that ceramic resonators investigated in Serbian Orthodox churches are generally characterized by resonance frequencies below 100 Hz and extremely narrow operating bandwidths. These characteristics restrict their possible contribution to limited low-frequency intervals and do not support a broad modification of the overall room-acoustic response. The available conclusions are also dependent on laboratory characterizations that do not fully reproduce the installation conditions of vessels embedded in historical masonry.

Laboratory measurements were performed on ceramic pots representative of those used in churches, but tested outside the building context, either as single elements or in small groups [29]. The acoustic characterization was carried out in controlled environments: in an anechoic chamber, the pots were excited using pure tones or broadband signals (e.g., pink noise) and the response was recorded with a microphone placed inside the cavity or at the opening, allowing the determination of the frequency response and resonance behavior. Additional tests were conducted in a reverberation chamber, where multiple pots (e.g., 30 units) were arranged in different spatial configurations to evaluate their sound absorption properties. Further measurements investigated the re-emitted sound field, including intensity and spatial radiation, by comparing open and closed configurations and analyzing the decay after signal interruption. The aim of these measurements was to determine the resonance frequency, absorption capacity, and radiation characteristics of the pots, and to assess their potential effect on sound fields (absorption, amplification, diffusion), rather than to measure the acoustics of entire churches.

Further investigations conducted in Greek Orthodox Byzantine churches analyze the influence of artificial resonators under controlled conditions [30]. Measurements in a real church were performed using up to 480 identical bottles placed on the floor in successive steps. In this case resonators were not part of the original masonry but artificially introduced. The acoustic field was characterized through impulse response measurements, obtained using an omnidirectional dodecahedral sound source driven by MLS and swept-sine signals, repeated multiple times to improve the signal-to-noise ratio. The response

was recorded with calibrated omnidirectional condenser microphones ($\frac{1}{2}$ "), a bidirectional microphone, and an artificial head for binaural parameters, positioned at fixed receiver locations and averaged over several points. Data were processed in 1/1 and 1/3 octave bands according to ISO 3382, allowing the evaluation of standard room acoustic parameters. The objective was to quantify how the progressive addition of resonators affects global acoustic indicators (reverberation, clarity, definition, spatial parameters) and to verify whether a significant improvement of acoustic quality could be achieved. The results show generally weak effects, with only slight reductions in RT and moderate increases in clarity (C80) and definition (D50), mainly around the resonant frequency.

The results indicate that the energy ratios C80 and D50 increase with the number of vases, while RT decreases at low frequencies because of high absorption. The most effective locations were reported in corners, domes, and vaults, where changes in diffusion may reduce sound focusing. Anyway, these experimental configurations do not reproduce the actual placement and boundary conditions of ceramic vases embedded in masonry, and therefore the results cannot be directly transferred to historical installations.

3.4. Numerical Modelling Approaches

Numerical approaches have also been employed to characterize the resonant behaviour of the vases. In the case of Pommiers-en-Forez [31], a fully numerical methodology combines local modelling of individual vases with global room-acoustic simulations. The response of single vases was evaluated using Matlab, where a monopole source is introduced to compute impedance, gain, and pressure fields in the frequency range 10–500 Hz. These simulations identify resonance peaks around 250 Hz for smaller vases and 190 Hz for larger ones, with pressure amplification up to approximately 15 dB near the neck (about 10 cm), rapidly decreasing with distance. The results are then incorporated into a global model developed in CATT-Acoustic, where vases are approximated by absorbing panels coupled with electro-acoustic sources. Human emitters are represented with hemispherical directivity, and receivers are distributed along the nave axis to analyze sound pressure level decay. More recently, a wave-based numerical study has been conducted [32] using a finite volume time domain (FVTD) approach, in which the acoustic field was solved in the time domain and the pots were introduced through impedance boundary conditions derived from measured responses and Helmholtz-type models. Despite this methodological advancement, such studies remain isolated, and the use of numerical simulation for the quantitative evaluation of room acoustic parameters in the presence of acoustic vases is still not widely established.

3.5. Cross-Study Synthesis and Methodological Limitations

Across the reviewed studies, the most consistent evidence concerns the frequency-selective response of individual vases and the rapid spatial decay of near-field effects. Evidence concerning room-scale modifications is less consistent. Reported variations depend on vase number and condition, frequency range, source–receiver configuration, spatial or spectral averaging, and building characteristics. The available literature therefore supports the occurrence of local and frequency-dependent phenomena but does not provide a homogeneous quantitative estimate of their room-scale magnitude.

The analysis of the reviewed literature suggests that the interpretation of acoustic measurements performed in churches containing acoustic vases should be approached with particular caution, especially when the observed differences are limited in magnitude.

Measurements of RT, resonance frequency, and other acoustic parameters in churches containing acoustic vases are intrinsically sensitive, as the observed variability cannot be unambiguously attributed to the system under investigation and may arise

from measurement conditions. In large-volume environments with complex geometries, the sound field is not perfectly diffuse and depends on source and microphone position. Even small spatial displacements can produce measurable differences in RT or in low-frequency bands, which are those of interest for acoustic vases. Temporal fluctuations in thermo-hygrometric conditions, background noise, and uncontrolled disturbances can affect the sound decay between successive measurements.

As a consequence, differences observed between configurations (open/closed pots, near/far positions) may be of the same order of magnitude as fluctuations induced by the measurement process. The dispersion of results does not necessarily represent a physical effect of the pots but may reflect the intrinsic variability of the measurement system, including instrumentation, positioning, and operating conditions.

In metrology, this dispersion is quantified as uncertainty; ISO/IEC Guide 98-3 (GUM) [33] defines it as the parameter characterizing the variability of values attributable to the measurand. This framework provides an interpretative reference without implying modifications to existing experimental procedures. In many of the reviewed studies, the magnitude of the reported variations appears comparable to the variability potentially associated with measurement conditions themselves.

Moreover, measurements in churches with acoustic vases derive from heterogeneous campaigns, often constrained by limited control of boundary conditions. The general principles outlined in ISO 5725-2 [34] and ISO 21748 [35] indicate that such dispersion should be considered when interpreting results.

Taken together, the reviewed studies do not indicate a univocal direction of change in reverberation-related descriptors. Both increases and decreases have been reported, depending on the investigated frequency range, source–receiver configuration, averaging procedure, number and condition of the vases, and characteristics of the building.

The available evidence therefore does not constitute a homogeneous or conclusive demonstration of a room-scale acoustic effect, but indicates the possible occurrence of weak, frequency-dependent, and spatially confined phenomena.

A similar interpretative framework can be extended to the measurement procedures typically adopted in churches, which are intrinsically influenced by the architectural and operational constraints of these environments. Existing studies show that measurement techniques are often significantly different in terms of equipment, source–receiver configurations, and selected parameters, leading to results that are not always directly comparable [36]. The spatial complexity of churches, combined with their large volumes and the variability of liturgical source positions, makes the definition of a unique measurement configuration difficult. Source locations may vary between altar, pulpit, choir, or organ, and each configuration produces a different sound field.

Quantitative analyses confirm that acoustic parameters exhibit spatial variability that depends on source–receiver distance and position. While RT tends to show relatively low dispersion, other parameters, particularly those related to early reflections and energy distribution, present larger variations that may exceed perceptual thresholds in some cases. This indicates that even within the same church, different measurement positions can yield non-negligible differences.

In the context of investigations on acoustic vases, this variability represents an additional layer of complexity. Differences observed between configurations (e.g., open versus closed pots or measurements taken near or far from their location) are superimposed on the inherent spatial fluctuations of the acoustic field. As a result, small variations in measured parameters may reflect either localized acoustic effects or the underlying variability associated with source–receiver arrangements and environmental conditions.

Consequently, the interpretation of experimental results in churches should account for the fact that measurement outcomes are strongly dependent on the adopted configuration. Within this framework, modest changes in parameters such as RT can be considered compatible with a possible influence of acoustic vases, while at the same time remaining within the range of variability expected from the measurement procedure itself.

Within this context, the standardization of both documentation procedures and experimental methodologies becomes particularly important for improving the reliability and comparability of future investigations. The following section outlines possible extensions to the data collection process, pursuing a twofold objective: improving the direct comparability of documented cases and enabling a more acoustically oriented assessment, including simulation-based investigations.

4. Improvement of the “Fiche D’enregistrement”

As discussed in Section 2, the template, proposed in [12] and successively refined and applied in [13] and [14], provides a structured and coherent framework for the census of buildings and acoustic vases, already integrating a wide range of descriptive, geometric, and contextual information derived from extensive field surveys and multidisciplinary studies. Over the last decades, this framework has supported the collection of a large and consistent dataset, including architectural documentation, spatial distribution, and measured characteristics of the pots, which has already enabled qualitative interpretations and, in several cases, quantitative and frequency-based analyses.

Within this documentary framework, the present proposal does not aim to redefine the existing scheme, but to consolidate and extend its analytical potential by introducing a more explicit formalization of data that are already partially available. The objective is to improve consistency, comparability, and direct usability of the dataset for physically based and statistical analyses, while preserving the structure and the interdisciplinary nature of the existing fiche. In this perspective, the proposed extension should not be interpreted as the definition of a new inventory system, but rather as an attempt to enhance the analytical usability of information that is already partially available in many documented cases.

The first extension concerns the building description. The fiche already includes architectural and geometric information derived from in-situ surveys; these data have supported interpretations related to building volume, typology, and spatial organization. The proposed development reorganizes these elements into a more explicit geometric-acoustic framework. It is based on standardized parameters such as sub-volumes, characteristic dimensions, surface areas, and material categories. This re-formulation would not introduce new information but would allow for a more direct integration of the dataset into room acoustics modelling and comparative analyses.

This approach would facilitate the transfer of archaeological and architectural documentation into simulation-oriented environments and comparative acoustic analyses.

A second improvement addresses the morphological characterization of the pots. Previous studies have already produced a substantial body of measurements and observations on dimensions, typologies, and acoustic behaviour. However, these data are not always recorded in a fully homogeneous way across different surveys. The proposed enhancement consists in structuring these already available measurements through a standardized set of geometric descriptors, complemented by consistent photographic and graphical documentation. This would facilitate systematic comparison between cases and strengthen correlations with resonance-related properties. Such standardization becomes particularly relevant in situations where the expected acoustic effects are limited and where reliable interpretation requires consistent comparison between different case studies and experimental campaigns.

A third refinement concerns the spatial description. The fiche already documents the position of the vases within the architectural and liturgical space, and this information has been extensively analysed in relation to building function and acoustic interpretation. The proposed step consists in expressing these spatial data through normalized variables, such as relative height, distribution across functional zones (e.g., choir, nave), and typology of insertion (walls, vaults). This does not introduce new categories but enhances the comparability and quantitative interpretability of spatial patterns already identified in previous research.

Through these targeted adjustments, the fiche evolves from a well-established descriptive and analytical tool into a more explicitly structured dataset, in which existing information is formalized and harmonized. This evolution increases its effectiveness for archaeological interpretation, statistical comparison, and physical modelling, while maintaining full continuity with the research framework already developed.

4.1. Two-Level Operational Structure of the Extended Recording Framework

The proposed extension is organized into two complementary levels, to distinguish the minimum information required for documentary traceability and cross-site comparison from the additional data required for acoustic modelling and reproducible measurement campaigns (Table 1).

The “main” recording level comprises the fields that should be reported for every documented case. The “extended” acoustic-modelling level is conditional and applies when numerical simulation, physical modelling, or in situ acoustic assessment is planned.

Existing information is retained and classified according to its current format: structured field, free-text field, requested but inconsistently completed information, information derivable from documentary material, or absent information. The proposed development then specifies whether each item requires conversion into a controlled variable, addition of a measurement unit, explicit evidence traceability, an uncertainty field, or a new data-acquisition activity. A mandatory field may therefore be recorded as “not reported” if the information is unavailable, thereby distinguishing between missing and omitted data

The following sub-sections provide detailed descriptions and insights into the proposed enrichment of the data collection process.

4.2. Building Description

The original recording scheme already defines a detailed set of fields covering the identification of the building, its geographical and administrative context, its historical development and dating, its functional and liturgical attribution, and its current state of conservation. Architectural information is documented through the type of plan and the overall volume, while the presence of acoustic vases is described in terms of number, state, position, and spatial arrangement within the building. At the scale of the individual objects, the fiche includes descriptive and dimensional data such as general morphology, volume, neck diameter (internal and external), neck height, as well as notes on dimensions, dating, and references, ensuring both documentation and traceability.

Starting from this already comprehensive structure, further additions can be introduced in order to improve the practical usability of the collected information, especially in cases where detailed metric data are not available. A first complementary element consists in the inclusion of graphical representations of the building, in particular a plan view and at least one section, even in simplified or schematic form. These representations do not require precise surveys but allow a clearer interpretation of spatial relationships, relative heights, and the overall architectural configuration in which the vases are inserted.

Additional historical and functional information may be recorded when available, including the original liturgical function of the architectural space and relevant historical documentation concerning the use of the building.

When documented, information on the musical practices originally associated with the building may also support the interpretation of the possible acoustic role of the vases.

4.3. Acoustic Vases Characterisation

A second addition concerns the documentation of the position of the vases. The existing textual fields describing position and disposition can be effectively complemented by systematic photographic documentation, including both close-up images of individual vases and wider views showing their placement within walls or vaults. In addition, annotated images or simple schematic drawings indicating the position of the vases within the architectural elements provide a more precise and immediately interpretable description than textual information alone.

A third addition relates to the characterization of the vases themselves. Alongside the dimensional parameters already recorded, it is proposed to include visual documentation such as frontal and lateral photographs, and, where possible, simple schematic drawings indicating the main dimensions. Even approximate representations, when consistently produced, significantly improve the comparability between different cases and support the interpretation of geometric variability.

A further complementary element concerns the recording of the functional state of the vases, in particular the condition of the opening (open, partially obstructed, or closed). This information can be directly observed during surveys and provides a relevant indication for subsequent acoustic interpretation, without requiring additional measurements.

4.4. Spatial, Functional, and Visual Documentation

Finally, the introduction of a minimum standard for visual documentation is recommended, including a general interior view of the building, images of the vases in context, and detailed views of representative examples. This approach ensures that the dataset remains informative and usable even when complete geometric or metrological data cannot be obtained.

These additions do not alter the structure of the original fiche but enrich it through the integration of graphical and visual information, improving the clarity, comparability, and interpretability of the collected data across different case studies.

A more explicit dataset can provide geometrical and positional information for analyzing sound propagation within the building. Consistent data on vase arrangement can support the definition of simplified acoustic configurations, in which the interaction with the sound field can be analyzed under controlled assumptions. An extended and structured dataset can therefore support the construction of preliminary input models and reduce the amount of additional documentary work. Nevertheless, targeted in situ surveys and material characterization may still be required, depending on the completeness and reliability of the available information and on the objectives of the numerical analysis.

It should also be noted that the aforementioned extensive survey work collected a vast amount of information. It appears that some of these data have not been included in the available database. Moreover, the current on-site format [37] is less demanding compared to previous campaigns. The advantage is that the database can be expanded even when only partial knowledge of a site is available. Nevertheless, the loss of detail could affect proper modelling in simulation software.

The proposed additions therefore aim primarily at improving methodological consistency and interoperability between documentation, experimental investigations, and simulation-oriented analyses. Obviously, they do not directly demonstrate the acoustic

effectiveness of the vases themselves. However, they could be the means to improve knowledge on these artefacts and to build detailed models and design specific acoustic measurement campaigns. The contextual data may facilitate the interpretation of future numerical and experimental investigations and support interdisciplinary analyses combining archaeology, architectural history, and building acoustics.

In the next section, a practical application of the proposed improvement is presented.

5. Application of the Recording Framework: “Fiche” Example

An application example is presented to illustrate how the information required by the “fiche d’information” can be systematically organized and how additional data available in the literature can be structured without modifying the original framework. The church of Saint-Arbogast in Oberwinterthur is selected as a representative case due to the availability of detailed and consistent documentation from multiple sources. The analysis first provides a comprehensive description of the church based exclusively on literature data, then compares the information required by the “fiche d’information” with additional elements that can be extracted from the same sources, and finally discusses observations on how these data can support a more structured use of the fiche and contribute to a possible extension of the recording framework.

5.1. Information on a Sample Church from Literature

The church of Saint-Arbogast in Oberwinterthur, in the Canton of Zürich, is identified in the sources as the *alte Kirche von Oberwinterthur*. The presence of acoustic vases (*Schallgefäße*) was already documented by Pfeifer (1904) [38], who reported the discovery of such elements within the building. Subsequent information is mainly derived from the studies of Desarnaulds and Loerincik [2,3], from the detailed observations of Schnyder (1979), from museum documentation related to the recovered materials, and from later analyses reported in works by Valière and Palazzo-Bertholon [39,40] and by Arras [41]. Figure 1 represents the vase shapes that can be found in the church (a), their position, and the plan of the building (b), with a reconstruction of its development over time (c).

From an architectural point of view, the building is a church in which the choir represents the reference space for the presence of the vases. According to Desarnaulds and Loerincik, the vases are located in the vaults of the choir, which is dated to the second half of the 12th century. The reconstruction of the construction phases, as reported in the scheme by Schmaedecke (Figure 1), shows that the complex derives from a stratified development including a stone church from the 10th century, a southern extension in the 12th century, further additions in the 13th century, and a transformation into a three-aisled basilica around 1260, with subsequent interventions continuing up to the 15th century.

During the restoration carried out in 1932, some vases were recovered and are now preserved in the regional museum of Winterthur, where three examples are documented. The sources also report the presence of 83 vases (Schnyder, 1979) [2,3], a value that Desarnaulds identifies as the highest among Swiss churches. With regard to their location, Desarnaulds and Loerincik indicate that the vases are situated in the choir, both in the vaults and in the back wall. The image of their distribution on the choir wall clearly shows their arrangement in the upper parts of the elevation, above the windows and close to the springing zone of the vault.

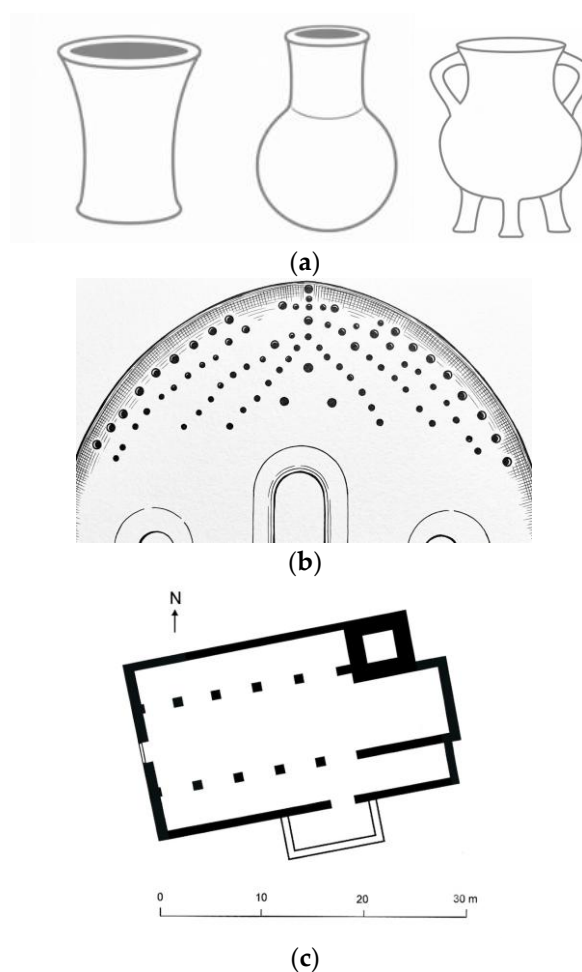


Figure 1. Author-produced schematic synthesis of the Saint-Arbogast documentation: (a) principal vase morphologies reconstructed from the descriptions and dimensional information reported in [3,38]; (b) schematic distribution of the documented openings in the choir, reconstructed from Schnyder (1979) and the iconographic sources cited in [2,3,39,40]; (c) simplified representation of the principal construction phases of the church, redrawn from Entopos, Wikimedia Commons, licensed under CC BY-SA 3.0, <https://creativecommons.org/licenses/by-sa/3.0/>) (accessed 20 May 2026). Image source: https://commons.wikimedia.org/wiki/File:Kirche_St._Arbogast_Bauetappen.jpg (accessed 20 May 2026) All panels were redrawn by the authors; dimensions and positions are approximate unless otherwise indicated.

The distribution of the vases is described by Schnyder as organized symmetrically in four parallel rows, arranged radially from a central cross-shaped configuration composed of four main elements and three associated ones. This configuration is also visible in the available iconographic documentation. Valière and Palazzo-Bertholon further report that, in the case of Oberwinterthur, the arrangement assumes an explicit symbolic meaning, with the formation of figures such as a cross, a triangle, and numerical groupings that can be related to musical or cosmological interpretations.

From a morphological point of view, Pfeifer (1904) [38] describes the presence of different shapes among the recovered vases: some exhibit a wide body with a narrow neck, while others have a more cylindric form with a rounded body and a straight neck. This difference is confirmed by the available images, which show two main types of vases, together with a further type characterized by the presence of small feet. The dimensions of the vases are reported by Desarnaulds on the basis of Schnyder's observations. The larger vases have a height ranging from 16 to 25 cm, a maximum diameter of about 20 cm,

and an opening of approximately 12 cm. The smaller vases have a height of about 10 cm, an opening of about 10 cm, and a base diameter of about 6 cm.

No information on the materials has been identified in the consulted sources; however, the representations and typology of the objects indicate that they correspond to ceramic artefacts.

From an interpretative perspective, the sources consistently attribute an acoustic function to the vases. Pfeifer explicitly uses the term *Schallgefäße* (acoustic vases), while subsequent studies place the system within the context of liturgical practices, particularly in spaces intended for singing. Arras further emphasizes that, in the case of Saint-Arbogast, the vases are also integrated into the decorative system of the interior surfaces, suggesting a relationship between acoustic function and symbolic meaning. The considered example shows an evolution of the building over time, a practice that was frequent in medieval churches. In such cases, where the original configuration included a specific number and arrangement of vases, the intended behavior of the artefacts cannot be easily deduced from measurements carried out today if the building's shape has changed over time and the current configuration differs significantly from the original one.

In these situations, it is evident that a simulation of the building's behavior could be highly beneficial, provided that the model is sufficiently accurate. Therefore, including detailed information on geometry, building evolution, and vase positioning could be pivotal in supporting in-depth analyses.

The selected example is therefore particularly suitable for illustrating how a historically documented case can provide sufficient geometrical and spatial information to support the construction of plausible simulation-oriented models, even without claiming a complete reconstruction of the original acoustic conditions.

5.2. Application of the Proposed Two-Level Recording Framework (Saint-Arbogast, Oberwinterthur)

Table 2 applies the Main and Extended operational fields defined in Table 1 to the Saint-Arbogast case. The purpose is to determine which variables can be populated from the available documentary and iconographic sources, which remain unavailable, and which types of acoustic or numerical analysis can be supported by the resulting record. Data status is classified as D (directly documented), S (reported in a secondary source), I (inferred from iconographic or typological evidence), or NR (not reported). Confidence is reported as high, moderate, low, or not assessable according to the nature and consistency of the available evidence.

Table 2. Application of the Main and Extended operational fields to the Saint-Arbogast case: available information, evidence status, confidence, and analytical implications.

Level	Operational Field (from Table 1)	Saint-Arbogast Information	Evidence/Status	Confidence or Uncertainty	Analysis Supported or Limitation
Main	Building identification	Église Saint-Arbogast; <i>alte Kirche von Oberwinterthur</i> ; Oberwinterthur, Canton of Zürich, Switzerland	D; [2,3,38–41]	High	Identification and cross-site traceability
Main	Construction chronology, function, and liturgical area	Multiple construction phases from the 10th to the 15th century; vases located in the choir; association with liturgical singing reported in the literature	S/D; architectural and historical sources	Moderate–High	Historical and functional interpretation

Main	Number of vases	83 vases reported by Schnyder; three recovered examples preserved in the regional museum of Winterthur	S; Schnyder as reported by Desarnaulds; museum documentation	Moderate	Quantitative comparison; current in situ number remains to be verified
Main	Architectural position and distribution	Choir vaults and rear wall; upper elevation; four parallel rows organized radially around a central cross-shaped pattern	S/D/I; textual and iconographic evidence	Moderate–High	Qualitative spatial comparison and distribution-pattern analysis
Main	Morphology and dimensions	Larger examples: (H = 16–25) cm, (D _{max} ≈ 20) cm, opening (≈ 12) cm; smaller examples: (H ≈ 10) cm, opening (≈ 10) cm, base diameter (≈ 6) cm	S; [3,38]	Moderate	Typological comparison and preliminary geometric assessment
Main	Current opening and conservation condition	Current condition of all in situ openings not reported	NR	Not assessable	Open/closed testing cannot be planned from documentary evidence alone
Main	Visual documentation	Images of vase typologies, distribution on the choir wall, and construction phases are available	D/S; cited iconographic sources	High for existence; positional scale not quantified	Visual verification and qualitative spatial interpretation; licences and source metadata must be completed
Extended	Complete building geometry	Construction-phase plan available; complete room dimensions, surface areas, and interior volume not reported	Partial; D/S and NR	Low–Moderate	Exploratory geometric model only; calibrated room-acoustic model not supported
Extended	Acoustic boundary properties	Material descriptions and frequency-dependent absorption/scattering data not reported	NR	Not assessable	Calibrated boundary conditions cannot be defined from the available record
Extended	Internal vase geometry	Opening diameters partially reported; neck length, cavity volume, wall thickness, and internal geometry not reported	Partial S; otherwise NR	Moderate for opening diameter; not assessable for internal geometry	Helmholtz or impedance-based modelling not supported
Extended	Exact coordinates and orientation	Approximate location and pattern derivable from iconography; exact (x,y,z) coordinates, spacing, and axis orientation not reported	I/NR	Low–Moderate	Qualitative or exploratory positioning only; spatially resolved model requires additional survey
Extended	Acoustic measurement metadata	No dedicated acoustic campaign for the current Saint-Arbogast configuration is documented in the sources used for the fiche	NR	Not assessable	A new in situ campaign is required for reproducible acoustic assessment

5.3. Comments and Observations

The “fiche d’information” provides a structured descriptive framework that allows the identification of the building, the presence of acoustic vases, their number, their location, and their general placement within the architectural space. In the Saint-Arbogast case, the Main-level fields can be populated to different degrees from the available documentary sources, whereas several Extended fields remain unavailable. The resulting record is suitable for documentary comparison and preliminary interpretation, but does not support a calibrated room-acoustic model or a resonator-resolved simulation without additional surveys. The same sources contain additional information that extends the descriptive level without introducing new data acquisition. The availability of a documented number of vases (83), their location within the choir, specifically in the vaults and in the back wall, and their placement in the upper parts of the structure provide users with a more detailed spatial interpretation than what is strictly required by the fiche. In this case, the position of the vases can be further specified in relation to architectural elements, as they are located above the choir windows and between the arches and the springing of the vault.

The iconographic documentation required by the fiche also enables a more detailed reading of the system. It reveals a non-random and highly structured distribution, described as a symmetric arrangement in four parallel rows, organized radially around a central cross-shaped configuration. This organization is directly observable in the available images and described in the sources.

In addition, the same sources provide morphological descriptions and dimensional ranges of the vases. Pfeifer reports the presence of different shapes, while subsequent studies document dimensional parameters for larger and smaller vases. These data introduce a level of typological and geometric detail that is not explicitly required by the fiche but can be directly derived from the recorded information and used for comparative purposes.

Symbolic interpretations associated with geometric arrangement, including references to the cross, triangular configurations, and numerical groupings, are also reported in the literature, together with the association of the vases with liturgical functions, particularly in spaces dedicated to singing. These aspects represent an additional layer of information that can be systematically recorded.

Overall, the Saint-Arbogast case shows that the information required by the original fiche can be enriched through a more explicit use of the same sources. The proposed improvement combines the formalization of information already present in the original fiche with conditional Extended fields required for acoustically oriented analyses.

At the same time, the available dataset remains limited with respect to global geometric data of the building, material characterization, and quantitative spatial parameters, which would be necessary for further developments oriented towards physically based analyses.

The availability of detailed information provides three operational advantages. First, it allows researchers to readily identify which types of analyses can be performed on a given building, without the need to consult all the associated documentation. Second, it enables a prompt assessment of whether the current configuration of the building can reflect the intended acoustic behavior of the vases, that is, whether the present layout is consistent with the period in which the vases were installed. Third, it facilitates direct comparisons between different case studies and supports the development of more accurate statistical analyses.

This aspect becomes particularly important considering that many of the acoustic effects reported in the literature are relatively small and potentially sensitive to differences in documentation quality, experimental setup, and interpretation criteria.

The value of a more explicit and structured fiche lies not only in supporting future simulations, but also in improving the robustness and comparability of experimental investigations carried out in different buildings and under different measurement conditions.

6. Example of the Use of a Detailed “Fiche D’information”—Acoustic Simulation

In this section an application example aimed at illustrating the use of a more detailed “fiche d’information” in the context of acoustic simulation is introduced.

The purpose of this section is not to provide a validated quantitative assessment of the acoustic role of the vases, but to illustrate how more detailed geometrical documentation could support the implementation of simulation-oriented analyses consistent with configurations observed in documented historical cases.

In fact, while the previous analysis has shown how a significant amount of structured information can already be extracted from the literature for documented cases such as Saint-Arbogast, the implementation of physically based models requires a further level of specification, particularly in terms of geometry, spatial discretization, and boundary conditions. For this reason, a reference case is constructed in the form of a simplified church model, similar but not equal to the original plan of Saint-Arbogast, defined so as to be consistent with the architectural and distributive characteristics observed in the surveyed buildings. The model includes a number of acoustic vases corresponding to values derived from empirical relationships reported in the literature and from considerations about the model volume.

This approach intends to highlight that, if the available information were more detailed, particularly with regard to the geometric and architectural characteristics of the building, it would be possible to give a first evaluation of the potential impact of the acoustic vases through simulation.

Such an extension would not only allow for a more accurate representation of the physical system, but also contribute to a deeper understanding of how these devices may have been used in historical contexts. Moreover, simulations can complement measurement activities, providing a unified assessment framework that will be presented in a subsequent section.

The resulting simulations should therefore be interpreted primarily as methodological examples, useful for discussing modelling requirements and possible analytical workflows, rather than as definitive evidence regarding the acoustic performance of the vases.

Accordingly, the numerical model evaluates the effect of an equivalent absorbing-area representation of the acoustic vases, rather than the physical behavior of the resonators themselves.

As discussed in Section 3.4, acoustic simulations aimed at quantifying the impact of the pots in historical churches are rarely documented in scientific literature

Nevertheless, the continuous advancement of simulation tools, the progressive reduction in calculation time, and the support of artificial intelligence in 3D modelling, may facilitate wider adoption of these approaches in future investigations, recommending their inclusion in a unified assessment framework.

6.1. Case Study

In the present application, a longitudinal church plan corresponding to a recurrent typology is considered. Two configurations are analyzed, in which acoustic vases are assumed to be installed either in the vault or in the vertical walls beside the apse. These arrangements reflect situations documented in several cases reported in the survey by

Valière and Palazzo-Bertholon [42], and the number of vases adopted in the model is consistent with the recurrent values highlighted in previous studies [16].

The referenced recording framework provides a structured basis for describing the position, number, and spatial distribution of the vases within the church, although such information is generally available only in an approximate form. In this context, the example emphasizes the relevance of more precise geometric and positional data—particularly those related to the architectural characteristics of the building—for defining the parameters that directly influence the simulation of sound propagation.

The number of acoustic vases in the model was defined based on the geometrical characteristics of the church (volume $V \approx 6000 \text{ m}^3$; it corresponds to the range of churches with pots, as in [14]), by applying the empirical relationships reported in the literature linking the number of pots, N , to the building volume, V , in m^3 , [16].

$$N = a V^{0.55}, \quad (1)$$

$$N = a V^{0.6}, \quad (2)$$

The parameter a is an empirical constant, assumed to be equal to 0.24 and to 0.15 for Equations (1) and (2), respectively.

The adopted dimensions should therefore be regarded as plausible approximations derived from recurrent configurations documented in the literature, and not as exact reconstructions of a specific historical building.

Applying (1) and (2) to the present case ($V \approx 6000 \text{ m}^3$), N is respectively equal to 29 and 28. By approximation N was assumed to be equal to 30 in the calculations, considering pots with an average opening diameter of 0.2 m. Referring to their distribution on the apse vault, they cover 1.6% of this surface. In a further simulation, with the pots located in the upper part of the vertical walls of the apse, they cover about 1.1% of the surface. Nevertheless, it must be underlined that the Equations (1) and (2) were derived considering churches with volumes lower than 6000 m^3 . In particular, Equation (2) was studied on the basis of 22 small churches and 7 additional churches, all presenting volumes lower than that of the case study (even if the precise value of that geometrical parameter was not possible to be ascertained from data contained in the cited works).

Comprehensive information on the recurring number of acoustic vases in churches with volumes around 6000 m^3 is currently not available. For this reason, multiple configurations were considered. In the present analysis the results obtained in the case of almost 3.2% surface coverage are presented. This condition corresponds to double the number of pots in the vault and triple that amount in the upper apse walls (60 and 90 respectively). Two surface materials were considered in order to represent the acoustic behavior of the church: a plaster finish applied to all surfaces, and a composite material assigned exclusively to those portions of the walls or vaults where acoustic vases are assumed to be present. This composite material combines the absorption properties of plaster with the contribution associated with the openings of the acoustic vases.

The equivalent absorption coefficient of each treated region was calculated as an area-weighted average of the absorption coefficient, α , assigned to the plaster and to the equivalent vase-opening areas. An absorption coefficient equal to 1 was deliberately assigned to the equivalent openings between 31.5 Hz and 250 Hz, while the plastered surfaces retained the absorption coefficients adopted for smooth plaster.

The value $\alpha = 1$ does not represent a measured absorption coefficient of an acoustic vase. It was adopted as a deliberately limiting assumption, corresponding to the maximum physically admissible absorption contrast between the equivalent openings and the surrounding plaster within the energy-based geometrical-acoustics model. The purpose was to determine whether the limited surface fraction occupied by the openings could

produce an appreciable room-scale variation. Therefore, the absorption mechanism represented in the model was maximized. As a result, minor changes under this extreme condition indicate that lower equivalent absorption values would produce equal or smaller effects through absorption alone.

Since the model uses an equivalent absorption approach, the calculation does not reproduce the resonance frequency, neck geometry, cavity volume, complex acoustic impedance, phase effects, sound re-radiation, or near-field response of actual Helmholtz-type resonators. As a result, it establishes a macro-scale trend but does not exclude localized resonant effects that operate beyond the assumptions of this simplified model.

With regard to plaster absorption, smooth plaster was considered in the simulations in order to make the effect of the acoustic vases' presence more evident. An absorption coefficient equal to 0.06 at 125 Hz was therefore assumed for the plastered surfaces. The 125 Hz band was selected because it lies within the frequency range in which acoustic vases are generally expected to act.

In Figure 2 the main geometrical features are represented, while in Table 3 the considered configurations are summarized.

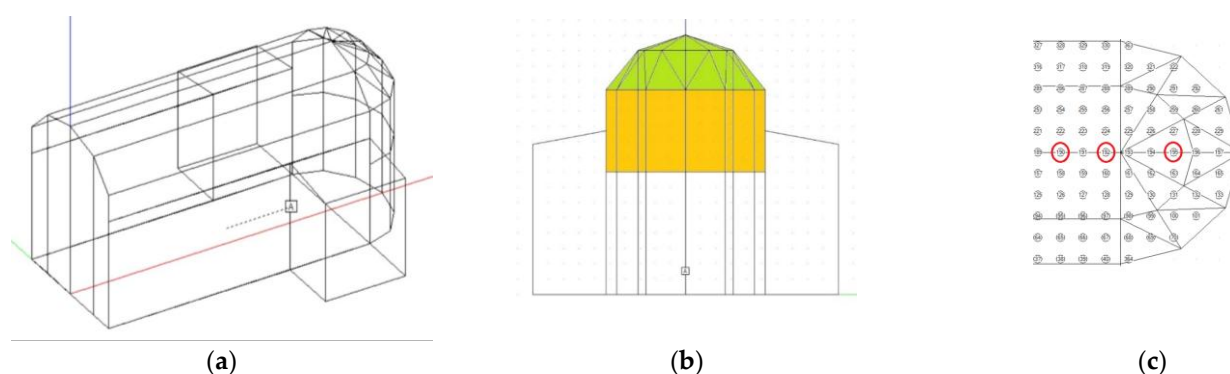


Figure 2. Church geometrical model: (a) 3D model, (b) Surfaces containing acoustic vases (the apse vault in green, the upper part of the vertical walls of the apse in yellow); (c) receivers' positions 190, 192, and 195 considered in the analysis of the results (red circles).

Table 3. Simulation cases: vases location, surface and mean absorption.

Case	Vases Location	N. Vases	Surface Coverage	Mean α
Base	No vases—Fully plastered surfaces	0	0%	0.06
W30	Upper vertical walls of the apse	30	1.1%	0.070
W90	Upper vertical walls of the apse	90	3.2%	0.090
V30	Apse vault	30	1.6%	0.075
V60	Apse vault	60	3.2%	0.090

A preliminary evaluation of the effect of the wall where the acoustic vases are supposed to be located was carried out through the analytical calculation of the RT using Sabine's equation, which yielded a value of 7 s. The results show that, in the analyzed cases, the RT variation is limited, with changes of approximately 0.04–0.05 s. Moreover, the Schroeder frequency was estimated considering the room volume of 6000 m³ and the calculated RT, obtaining a value of 68 Hz. Since this threshold is roughly half the frequency chosen the simulations (125 Hz) the dominance of modal behavior is effectively avoided.

The limited variations obtained through this preliminary analytical calculation are consistent with a significant part of the experimental literature, which generally reports weak or local acoustic effects associated with the presence of acoustic vases.

The simulations have been performed considering defined geometrical and acoustic boundary conditions. A sound source was positioned at a height of 1.5 m above the floor and analyzed in three different locations (S1–S3), useful for highlighting possible effects associated with the adopted equivalent absorbing-area representation of acoustic vases within the church volume. The sound field was sampled through 400 receiver points placed on a regular square grid, a portion of whose layout is illustrated in Figure 2c, at a height of 1.0 m.

As summarized in Table 3, five configurations are presented in relation to the distribution of absorbing surfaces:

- Base: the reference case with fully plastered walls;
- V30 and V60: the cases with vases applied to the apse vault (1.6% and 3.2% coverage, which correspond to 30 and 60 respectively);
- W30 and W 90: the cases with vases on the vertical walls of the apse in the upper part (1.1% and 3.2% coverage, which correspond to 30 and 90 respectively).

The source positions were defined as follows: in plan, S1 was located below the center of the main-nave ceiling, S2 below the apex of the apse vault, and S3 within the apse. All three source positions were located 1.5 m above the floor. The simulations were carried out using Ramsete software (version 3.14, [43]), based on geometrical acoustics and beam-tracing techniques for the modelling of sound propagation in enclosed spaces. The program represents the acoustic field by emitting a large number of pyramidal beams (hence the name Ramses, Ramsete in Italian) from the source, which interact with the surfaces through reflections and absorptions defined by the acoustic properties assigned to the materials. The geometry of the environment is discretized into planar surfaces, and each interaction modifies the energy and direction of the beams according to physical laws. The contributions of the beams reaching the receivers are integrated over time to reconstruct the impulse response and to evaluate acoustic parameters such as sound levels and reverberation characteristics, allowing the analysis of acoustic behavior as a function of spatial distribution and boundary conditions. For all simulations, identical calculation settings were adopted without randomization to ensure fully repeatable results under the same geometrical and boundary conditions.

When dealing with acoustic beams, instead of classical acoustic rays, it is important to use a large number of beams in order to minimize uncertainty when the beams impact on corners. In addition to the faster calculation speed compared to ray tracing, another advantage of using beams is related to the complete cover of the solid angle around sources without any superimposition of beams (as occurs for example with cone beams).

6.2. Results

The simulations showed no appreciable variations in the main acoustic parameters, between the reference plaster condition and the equivalent absorbing-area configurations, referring to Equivalent Level weighted A- LAeq (dBA)- and, at 250 Hz, T₂₀, Lrev, Ts, D₅₀, and C₅₀, in agreement with existing literature. However, the simulations highlighted a measurable influence on the EDT. Nevertheless, the magnitude of the observed variations remains limited and mainly spatially localized, coherently with many previous experimental investigations reviewed in the literature.

Given that EDT was the only parameter sensitive to these changes, the following analysis focuses specifically on this metric. It should be noted that, since the absorption contrast assigned to the equivalent openings was deliberately maximized, these calculated differences represent an upper bound of the room-scale effect attributable to absorption within the adopted model. Accordingly, this section describes the effects of different pot configurations and positions (represented by the adopted equivalent absorbing area) on

EDT, specifically considering the acoustic source S3. This source position was selected as the most representative because it corresponds to the possible location of a choir, which is the most likely intended target of the pots' acoustic influence.

The results should be interpreted in qualitative and comparative terms, consistently with the illustrative nature of the simulation framework adopted in the present study.

Figure 3 reports the exact EDT (125 Hz) values calculated at the three representative receiver positions (labelled 190, 192 and 195) indicated in Figure 2c. In the following figures, the EDT distribution over the entire church is shown by means of false-color maps, which are intended to illustrate the overall spatial distribution and the subtle qualitative variations among the analyzed configurations rather than the exact values at individual receiver positions. Figure 4 represents the EDT (125 Hz) behavior in the base-configuration, under the reference plaster condition (without pots).

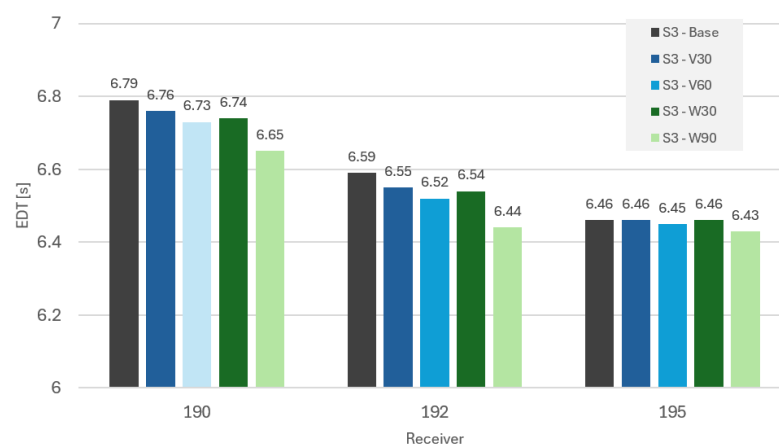


Figure 3. EDT (125 Hz) in all the conditions considered in the simulations.

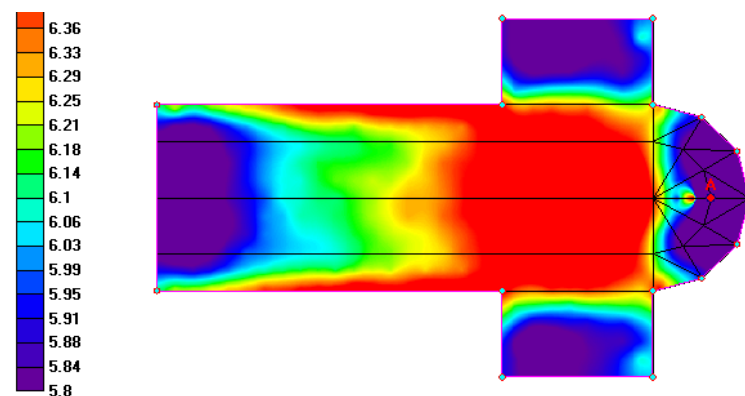


Figure 4. EDT (125 Hz) distribution without acoustic vases, in false colors on the church plan (left scale: EDT [s]).

The analysis of the above figure shows that higher EDT values, compared to those observed behind source S3, occur in the portion of the apse facing the central nave and near the walls. In particular, approximately one third of the apse is characterized by an EDT increase ranging from about 1% to 10%.

Figure 5a,b represent the EDT (125 Hz) distribution when pots are placed on the upper part of the vertical walls of the apse, considering configurations with 30 and 90 pots, respectively.

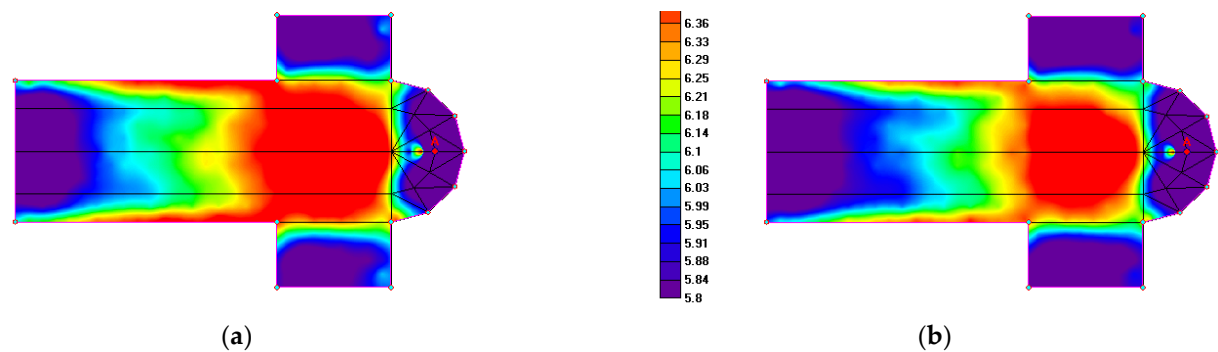


Figure 5. EDT (125 Hz) distribution, in false colours, with acoustic vases positioned on the upper vertical walls of the apse, (a) 30 pots, (b) 90 pots (scale: EDT [s]).

In both cases, the presence of acoustic vases modifies the overall EDT distribution. Compared with the reference plaster condition, the equivalent absorbing-area distributions on the upper apse walls produced changes in the EDT field mainly within the apse and in the corner regions adjoining the lateral chapels. The configuration with the larger treated area produced the larger variation; however, the differences remained modest and spatially localized. These results describe the response to the assumed equivalent boundary treatment and must not be interpreted as a prediction of the resonant behavior of actual acoustic vases.

As expected, the effect becomes more pronounced in configuration b). In particular, the zones located near the corners between the termination of the apse and the lateral chapels show a noticeable variation. Without pots, these regions were characterized by EDT peaks comparable to those observed in the first part of the nave, whereas the introduction of pots appears to mitigate the reverberation in these areas. This effect is more evident in configuration b), where the EDT increase decreases from 9.6% to 6.5%.

Figure 6 represents the influence of pots placed within the vault. The equivalent absorbing areas assigned to the apse vault also produced localized changes in EDT, although these were less pronounced than those calculated for the upper-wall configurations.

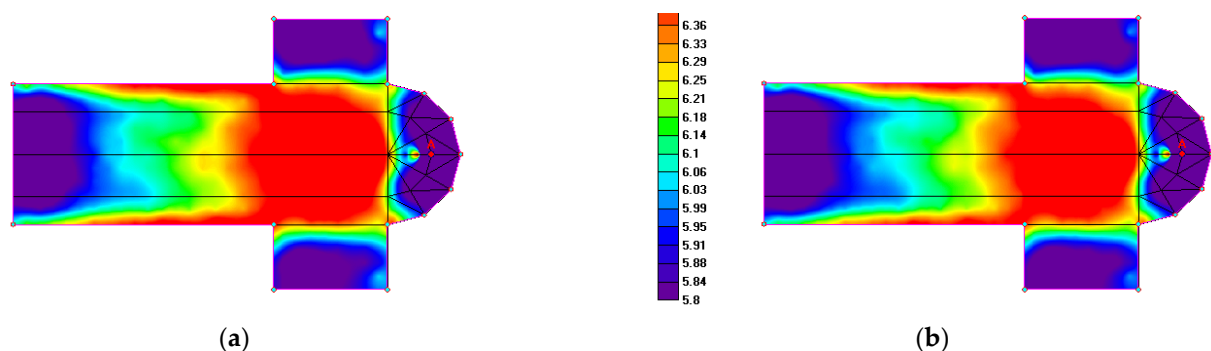


Figure 6. EDT (125 Hz) distribution, in false colours, with acoustic vases positioned in the vault. (a) 30 pots, (b) 60 pots (scale: EDT [s]).

The comparison with Figures 4 and 5 indicates that the presence of the acoustic vases in the vault actually has an influence on the RT, although it is less marked in comparison to that derived from their positioning on the walls. Nevertheless, these data do not quantify the specific Helmholtz-resonator response of the historical pots.

Also in this case, even if scarcely evident from the colors, configuration (b) shows a higher influence of the artefacts. This observation underlines the importance of accurate

documentation of the actual position and distribution of acoustic vases in historical buildings. In this configuration, the overall influence is less evident, although the reduction of EDT near the previously mentioned corner regions remains appreciable.

Overall, the simulations confirm that the influence of the vases is relatively limited, in agreement with previous literature findings. Nevertheless, the results suggest that their presence may contribute to local reverberation variations. In this case, the overall influence is less marked, while the reduction near the aforementioned corners is still appreciable, supporting the widespread and shared impression that the artefacts have a local influence. Detecting such effects requires highly controlled, reproducible, and spatially detailed measurements and calculations. Moreover, the simulation results highlight the influence of vase location, underscoring the importance of enriching the “fiche d’enregistrement” with more detailed information. Although the model is simplified, the results vary when the artefacts are virtually relocated from the vault to the upper portion of the apse’s vertical walls. The observed spatial localization of the variations also indicates that additional parameters particularly oriented to determine the local acoustic response may be analyzed in more detailed investigations.

Under the deliberately limiting equivalent-absorption assumption, the model produced only modest and spatially localized changes in EDT. These differences quantify the response to the assumed distribution of equivalent low-frequency absorbing areas; they do not represent a prediction of the resonant response of actual acoustic vases. Nevertheless, the fact that the calculated changes depend heavily on where these treated surfaces are located confirms how important it is to document the exact positioning and distribution of the openings.

These elements are brought together in the following section, where documentation, simulation, in situ measurements, and interpretation of results are organized into a coordinated procedure for the assessment of acoustic vases.

7. Proposed Methodological Approach for the Assessment of Acoustic Vases in Historical Churches

On the basis of the observations discussed in the previous sections, a quantitative assessment of the contribution of acoustic vases requires a reproducible and objective procedure. Such an approach is necessary to verify whether their presence produces measurable variations in the acoustic parameters of the church, and under which conditions these effects occur.

The proposed methodology is intended primarily to improve reproducibility, comparability, and interpretability in future investigations, rather than to demonstrate the acoustic effectiveness of the vases directly.

This approach combines two complementary components: simulation-based analysis and in situ measurement. The simulation component is intended to define reference configurations, introduce the acoustic vases into the model, identify potentially sensitive spatial regions, and support the selection of source and receiver positions. The measurement component is intended to verify experimentally whether the predicted variations can be detected under controlled and repeatable conditions.

Within this combined simulation–measurement approach, two levels of investigation are defined. Level I corresponds to a standard assessment procedure and includes the minimum set of operations required to obtain comparable results: definition of the reference acoustic configuration, introduction of the vases into the model, design of the in situ measurement campaign, open/closed comparison where feasible, and interpretation of the main acoustic descriptors. Level II corresponds to advanced investigations and is intended for cases in which the standard assessment identifies repeatable variations exceeding the expected measurement variability. This second level includes additional acoustic

descriptors, directional or spatial measurement techniques, and near-field analyses aimed at characterizing local, spectral, performer-related, or spatial effects.

7.1. Level I: Standard Assessment Procedure

This analysis refers to the environmental scale, considering the ensemble of existing vases, rather than the behavior of a single isolated element. The operational steps are outlined below.

Reference configuration—The first phase consists in defining an acoustic model of the internal environment without vases, assumed as the reference configuration. The model shall include the internal geometry (nave, possible side aisles, apse, roofing systems) and the acoustic properties of the surfaces, expressed in terms of absorption and scattering coefficients as a function of frequency.

The simulation aims to provide a prediction of the spatial distribution of acoustic parameters (EDT, T_{20} , T_{30} , C_{80} , D_{50} , etc.). Simulations are primarily intended to guide the identification of potentially sensitive regions and configurations to be investigated experimentally.

Introduction of acoustic vases—The second phase involves introducing the vases into the model through an equivalent representation consistent with the available data. When only partial information is available, the vases may be modelled as small surface areas characterized by frequency-dependent acoustic properties, distributed according to the observed positions (walls, vaults, apse area). The assigned parameters shall represent a frequency-selective behavior within the bands of interest.

A second simulation is then performed under the same conditions as the reference case. The comparison between the two configurations allows identification of differences between sound fields, expressed as variations of acoustic parameters and their spatial distribution, including possible resolution of local energy concentrations or non-uniform variations of RT.

Even limited or localized differences may be relevant in this context, provided that they can be distinguished from the variability associated with the measurement procedure itself.

Measurement campaign—The third phase concerns the design of the in situ measurement campaign and it is directly guided by the results of the simulation phase. Source and receiver positions shall not be defined solely based on geometry but selected to provide detailed coverage of the regions where the simulation indicates differences between the two configurations.

This includes both regions close to the surfaces containing the vases and areas where small variations of acoustic parameters can be observed, such as reductions in RT or energy concentrations.

Measurements shall therefore include both positions representative of the entire volume and targeted positions in areas where local variations are expected, even if not adjacent to the surfaces containing the vases. The measurement campaign shall follow established protocols for large-volume environments, with an adequate number of source–receiver configurations, repeated acquisitions, background noise control, and documentation of operating conditions, in order to allow subsequent uncertainty evaluation. Repeated acquisitions are particularly important to ensure the robustness and repeatability of the results. It should be also noted that in environments characterized by long decay times, temporal sampling intervals on the order of a few tens of milliseconds are generally sufficient for RT analysis. Wherever measurements aim to determine directly the C_{50} and C_{80} clarity indices and the Speech Transmission Index (STI), advanced systems based on Maximum Length Sequence (MLS) signals can be employed. Finally, an adequate sound

source with sufficient acoustic power shall be used to ensure an appropriate signal-to-noise ratio throughout the investigated volume.

Whenever technically feasible, measurements should be carried out both with open vases and with the same vases temporarily sealed, following procedures already adopted in previous investigations. The comparison between the two conditions represents one of the most direct approaches currently available for isolating the acoustic contribution of the vases while preserving all other boundary conditions unchanged.

As a possible extension of the measurement campaign, acoustic-camera measurements may also be considered when localized effects are expected near the surfaces containing the vases. This technique could support the time-resolved visualization of sound energy over short analysis intervals, on the order of a few tens of milliseconds, with the aim of distinguishing the contribution originating from the vase area from the energy reverberated by the remaining volume. Furthermore, it enables the analysis of local phase effects, addressing the interconnected nature of amplitude and phase modulations. Such a test would require short impulsive excitation and simultaneous analysis of the directions of arrival of sound energy as a function of time. Its practical applicability is limited by the low-frequency range involved, since the micro-phone array must have dimensions comparable with the wavelength of the lowest frequencies to be analyzed. Consequently, this approach should be regarded as an advanced and optional investigation, applicable only when suitable instrumentation and geometrical conditions are available.

Acoustic descriptors and results interpretation—The fourth phase consists of the critical processing of experimental data. The primary assessment should focus on room-acoustic parameters that have already been widely adopted in previous investigations and that can be measured according to established procedures. These include RT descriptors (EDT, T_{20} , T_{30}), clarity indices (C_{50} for speech and C_{80} for music), definition (D_{50}), STI, and sound pressure level distributions.

These descriptors are consistent with standardized room-acoustic practice, since reverberation, clarity, definition, and other room-acoustic descriptors are defined or discussed within ISO 3382-1, while STI is specifically defined by IEC 60268-16 for the objective assessment of speech intelligibility [44,45].

Their use is also consistent with church-acoustic measurement practice, where the selection of acoustic parameters and source–receiver configurations is explicitly linked to the spatial variability of measured results in large and architecturally complex interiors [36]. These descriptors allow the global acoustic behavior of the environment to be described and support the detection of repeatable differences associated with the presence of acoustic vases [3,26,27].

The analysis shall focus on low-frequency bands and on the bands identified by simulation as potentially sensitive to the presence of vases, as well as on the spatial regions where localized variations were predicted, consistently with previous studies reporting frequency-selective and localized responses of acoustic vases [3,16,26,27]. Acoustic parameters shall be evaluated per frequency band and per position, distinguishing mean values from spatial dispersion and variability across repeated measurements.

It is necessary to verify that observed differences exceed measurement uncertainty and are not attributable to normal data variability, due to non-uniformity of the sound field, source position, receiver position, signal-to-noise ratio, decay quality, and thermohygrometric conditions during acquisition.

This requirement is consistent with church-acoustic measurement guidelines, which emphasize the influence of source location, receiver distribution, repeated acquisitions, background noise, and decay quality on the reliability of measured parameters [36].

At the end of this phase, the analysis should identify the frequency bands and spatial regions where variations associated with the presence of acoustic vases can be distinguished from measurement uncertainty. If no such coherent variations are detected, the absence of experimental evidence should also be reported explicitly. Only when the observed variations consistently exceed the expected measurement variability and show spatial or spectral coherence should more advanced investigations be considered.

7.2. Level II: Advanced Investigations

When the Level I assessment identifies repeatable variations exceeding the expected measurement variability, additional acoustic descriptors may be considered in order to investigate more specific effects. These analyses should be regarded as a second level of investigation, aimed at characterizing local, spectral, performer-related, and spatial effects that may not be fully described by RT, clarity, definition, STI, or sound pressure level distributions alone.

The selection of these additional parameters should depend on the position of the vases, the expected frequency range of their action, the historical function of the architectural area, and the type of acoustic effect suggested by the preliminary results. In particular, acoustic vases located in choirs, presbyteries, vaults, corners, or other architecturally confined regions may require descriptors capable of representing performer feedback, local sound energy, spectral balance, and spatial impression. The following parameters may therefore be included in advanced investigations, even if they are not specific to acoustic vases, as complementary room-acoustic descriptors when Level I results suggest local, spectral, performer-related, or spatial effects. Their selection should not be interpreted as a fixed evaluation set, but as a case-dependent extension based on the expected physical mechanism, the architectural position of the vases, and the frequency range suggested by preliminary measurements or simulations [36,44].

Parameters:

- Support (ST) is relevant when acoustic vases are located in areas historically associated with singing activities, such as choirs, presbyteries, or monastic stalls. ST quantifies the amount of acoustic energy returning to the performer from nearby surfaces and therefore describes the acoustic feedback perceived by singers. Since several historical interpretations attribute to acoustic vases a possible role in improving vocal perception and harmonic blending during liturgical singing, ST may help determine whether measurable modifications occur in the immediate surroundings of the performers. The use of ST is supported by stage-acoustics studies, where such parameters were introduced to quantify the early reflected energy returning to performers and to relate measured room response to self-hearing conditions on stage [46].
- Strength (G) is suitable for investigating possible local increases or redistributions of acoustic energy. Historical literature occasionally suggests that acoustic vases may contribute to the reinforcement of speech or singing, although available evidence does not currently confirm this hypothesis in a general way. Since G quantifies the acoustic gain provided by the room relative to free-field conditions, it may offer useful information on localized amplification phenomena or on variations in the spatial distribution of sound energy. The parameter G is defined in standardized room-acoustic practice as a measure of sound strength relative to free-field propagation and is commonly used to describe the energetic contribution of the room to the received sound field [44,47].
- Bass Ratio (BR) provides an indicator of possible modifications of the low-frequency balance of the room. This parameter compares low-frequency RTs with mid-frequency RTs and is therefore relevant because acoustic vases are commonly interpreted as Helmholtz-type resonators operating mainly at low frequencies. BR may

help determine whether the vases contribute to changes in the low-frequency response of the space, including effects commonly associated with acoustic warmth. Although BR is not specific to acoustic vases, it is commonly used in auditorium acoustics to express the relative weight of low-frequency reverberation and is therefore suitable when frequency-selective absorption or resonance is expected in the 125–250 Hz bands [47,48].

- Brilliance (Br) may provide complementary information on spectral balance by considering the relationship between high-frequency and mid-frequency acoustic behavior. Although acoustic vases are expected to act mainly at low frequencies, selective low-frequency absorption may indirectly modify the perceived balance of the sound field. Together with BR, Br may therefore support the interpretation of spectral changes associated with the presence of the vases. Brilliance-related descriptors are commonly used together with low-frequency balance indicators to evaluate whether changes in RT modify the perceived spectral equilibrium between low-, mid-, and high-frequency bands [47,48].
- Lateral Fraction (LF) may be used when measurements or simulations suggest possible modifications of lateral reflections, sound diffusion, or sound focusing. LF quantifies the contribution of lateral sound energy and is commonly associated with spatial impression and listener envelopment. This descriptor may be relevant when acoustic vases are located in corners, vaults, domes, or other architectural elements where changes in reflection patterns may occur. The relevance of LF is supported by studies on early lateral reflections, which show that the lateral component of early sound energy is closely related to spatial impression and listener envelopment in enclosed performance spaces [44,49].
- Inter-Aural Cross-Correlation coefficient (IACC) may be considered as a complementary descriptor for spatial perception. IACC provides information on the similarity of the signals arriving at the two ears and is frequently used to assess spatial impression and listener envelopment. It may be particularly useful when the presence or distribution of the vases is hypothesized to influence diffusion, spatial uniformity, or the directional structure of the reflected sound field. IACC is commonly used as a binaural descriptor for spatial impression, since lower interaural correlation is generally associated with a broader and more enveloping perceived sound field [44].

Advanced instrumentation and near-field investigations may also be introduced when the Level I results or the additional descriptors indicate localized or directional effects.

As aforementioned, these techniques are not part of the minimum assessment level, but they may provide useful complementary information in acoustically complex historical spaces. They should therefore be considered optional tools for cases in which conventional omnidirectional measurements indicate localized, directional, or spatially non-uniform effects that require a more detailed description of the sound field [36,44].

Directional microphones, including figure-of-eight configurations, may be used to investigate directional components of the sound field and to support the evaluation of parameters related to lateral energy and spatial perception. Directional acquisition is particularly relevant when the objective is to separate lateral, frontal, or rear components of the reflected field, which may support the interpretation of LF, IACC, and other spatial descriptors [44,49].

Microphone arrays and Ambisonic systems may provide information on the directional distribution of acoustic energy and may be useful when the objective is to analyze diffusion, reflection patterns, or local sound-field modifications around the vases.

Array-based and Ambisonic techniques can provide direction-of-arrival information and spatial decomposition of the sound field, supporting the identification of reflection paths, diffusion patterns, and localized energy concentrations [50,51].

Binaural recording techniques may be considered when perceptual aspects, spatial impression, or listener-related descriptors such as IACC are included in the investigation. Binaural measurements are particularly appropriate when listener-related descriptors are required, because they reproduce the two-ear receiving condition needed for the evaluation of interaural quantities such as IACC [44].

Comparative near-field measurements may be performed by progressively positioning sources and receivers closer to the vases. This procedure may help identify localized phenomena that remain undetectable through conventional room-scale measurements.

This approach is consistent with previous investigations on acoustic vases, where measurements close to the neck or opening were used to identify resonance frequencies and localized amplification effects that were not clearly observable at room scale [18,20,21,26].

Equivalent near-field configurations may also be reproduced in simulation, by varying source positions and receiver positions in relation to the surfaces containing the vases.

They can therefore complement in situ measurements by testing whether localized effects predicted close to the vase openings remain spatially confined or can influence receiver positions representative of singers or listeners [31,32].

This activity may support the interpretation of local effects and may help define the most relevant positions for specific measurements.

The proposed advanced instrumentation is not intended to define a mandatory measurement protocol but rather to provide a flexible set of complementary investigation techniques, to be selected according to the architectural characteristics of the building, the research objectives, and the expected spatial extent of the acoustic effects.

7.3. Further Activities

A further stage may concern model calibration and historical reconstruction. This stage should not be interpreted as a simple verification of simulated values against experimental results, since the initial simulation primarily serves to guide the measurement campaign. Experimental data may instead be used to calibrate or validate the acoustic model, updating the properties assigned to surfaces and vases according to the obtained results. This calibration step is consistent with room-acoustic modelling practice, where measured impulse responses are commonly used to adjust boundary conditions and improve the correspondence between simulated and measured acoustic parameters [52].

A calibrated model may then be employed for subsequent reconstructive analyses, for example in cases where the original presence of vases is hypothesized in locations that are currently not visible, occluded, removed, or located within parts of walls, vaults, or architectural elements that cannot be directly inspected. In this perspective, the validated simulation becomes a tool for representing, with improved reliability, the acoustic field of the environment in a historical configuration different from the present one, contributing to the reconstruction of the original acoustic conditions of the church.

Overall, the proposed approach establishes a progressive methodological connection between historical documentation, geometrical characterization, numerical modelling, experimental verification, advanced acoustic analysis, and historical reconstruction.

8. Conclusions

Acoustic vases represent an interesting example of historical artefacts, extensively studied over time, yet still presenting a knowledge gap in terms of understanding their real impact on the soundscape of the buildings in which they are installed.

The present work primarily constitutes a methodological contribution aimed at discussing how the organization, formalization, and standardization of available documentation may support more reliable investigations on acoustic vases in historical buildings.

In particular, the study proposes a possible enhancement of the level of detail of the “Fiche d’Information” referring to buildings containing acoustic vases. This need arises from the observation that a considerable amount of available information is not currently fully exploited, although it could support more in-depth analyses of the acoustic behavior of these artefacts. More specifically, structured geometrical and positional information could facilitate the implementation of computational acoustic simulations, which are expected to become increasingly widespread in future investigations.

From this perspective, an example of enhanced data collection is applied to a case study, the church of Saint-Arbogast in Oberwinterthur.

Moreover, a detailed 3D model of a representative church containing vases was built to demonstrate the practical application of this dataset within the context of acoustic simulations. Using Ramsete, an illustrative calculation was performed at 125 Hz under a deliberately limiting equivalent-absorption assumption.

The simulations suggest that, under plausible geometrical assumptions, acoustic vases may contribute to local modifications of the sound field, although their overall influence appears limited and difficult to distinguish from normal spatial variability. These results concern only the absorption mechanism represented by the model and cannot be attributed to Helmholtz resonance or to the complete physical response of actual acoustic vases, including phase effects.

The simulation was intentionally conceived as an illustrative and simplified application example, aimed at showing how structured geometrical information could support future physically based analyses rather than providing a definitive quantitative assessment of the acoustic effectiveness of the vases.

Moreover, the study proposes a review of the main literature concerning measurements, evaluations, and analyses of acoustic vases. This analysis highlighted the absence of a widely adopted standard methodology for assessing their possible influence, as well as the fact that measurements can be affected by various sources of error due to the complexity of the buildings, the variability of thermo-hygrometric conditions, and the spatial positioning of sources and receivers.

Overall, the available results do not constitute a homogeneous body of evidence, which prevents a reliable and robust evaluation of the actual influence of the vases. As a contribution to addressing this methodological gap, a measurement–analysis methodology is proposed. The proposed approach integrates both acoustic simulations and on-site measurements with the aim of reducing empirical errors and refining building–vase models, thereby enhancing the comparability of results across different studies.

Therefore, the novelty of the present work lies in the integration of an improved documentation framework for the acoustic characterization of acoustic vases, and in the proposal of a coordinated assessment procedure specifically tailored to acoustic vases. This contribution aims to enhance methodological consistency, documentation quality, and the comparability of future studies on acoustic vases and related historical acoustic devices.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/acoustics8030056/s1>, Figure S1: title; Table S1: title; Video S1: title.

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