

Non-invasive dating of historical church bells through vibroacoustic matching of musical temperaments

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Abstract – This study presents a non-invasive methodology for the chronological assessment of historical church bells based on vibroacoustic analysis and musical temperament matching. The method involves recording each bell’s acoustic emission, extracting the main spectral components, and comparing them to theoretical frequency sets derived from historical temperaments. Applied to eight bronze bells from Salerno Cathedral, dating from the 13th to the 19th century, the approach successfully identified a correspondence between each bell’s tonal profile and the temperament systems historically in use during its presumed period of origin. The results show a stratified pattern, with quarter-comma meantone tuning in the medieval bell and just temperament in most early modern specimens. Equal temperament appears in 19th-century examples. This confirms that tonal structures may serve as chronometric markers and opens a new direction in archaeometric research by recovering intangible heritage embedded in sound, without requiring any material intervention.

I. INTRODUCTION

The accurate dating of historical church bells presents a significant challenge, particularly when inscriptions are missing, or archival documentation is incomplete. Traditional dating methods often rely on stylistic analysis or metallurgical studies, which may not always yield precise results. For example, a study demonstrated how compositional analysis can trace technological changes across centuries in bronze alloys used in bells [1]. Bronze bells from the Western Zhou period (China) were analyzed using optical microscopy, SEM-EDS, ICP-EDS, and portable XRF to study composition and manufacturing techniques [2]. A 20th century bronze bell in Asyut, Egypt, was studied through SEM-EDX, XRD, and FTIR to assess both composition and degradation [3]. Electrochemical Impedance Spectroscopy (EIS) was used to evaluate corrosion layers (patinas) on 19th-century bronze bells, revealing details about their exposure history and

environmental impact [4].

While these methods provide valuable insights, they typically require material sampling, which is not always feasible or acceptable in the context of cultural heritage conservation. Nevertheless, non-invasive methodologies — such as modal characterization and geometric reconstruction — have been employed for the structural and acoustic assessment of historical bells, enabling the identification of vibrational properties and morphological features without compromising material integrity [5].

However, to date, the only study that formalized an archaeometry approach, that can be applied for supporting the dating of church bells is the one based on the vibroacoustic analysis and musical temperament matching, conducted on eight bronze bells from Salerno Cathedral, dating from the 13th to the 19th century [6]. This study aims to contribute to the field of archaeometry, describing the metrological non-destructive vibroacoustic technique that can support such a dating procedure, which can be particularly valuable for bells lacking inscriptions or other identifying features, offering a new avenue for historical and musicological research. The approach is based on the verified hypothesis that the dominant tuning system reflected in a church bell frequency peaks emission can serve as a complementary indicator of its period of manufacture. Thus, by matching the spectral characteristics of a bell to specific historical temperaments, we aim to establish a correlation between tuning practices and chronological context.

This approach does not seek to replace existing dating methods, but rather to complement them by providing an additional layer of analysis. Based on the intrinsic acoustic properties of bells, we can gain insights into the historical tuning practices and, by extension, the likely time frame of a bell’s creation. In particular, the methodology involves recording the bell’s sound, performing spectral analysis to identify prominent partials, and comparing these frequencies to the theoretical intervals of various historical temperaments. A close match between the bell’s spectral data and a specific temperament may suggest a temporal

association, given the historical periods during which certain temperaments were prevalent.

II. MATERIALS AND METHODS

A. Bell tuning in its historical and technological context

The tuning of a church bell is an intrinsic part of its manufacturing process and is fundamentally determined by the bell's geometry—specifically its profile, thickness distribution, and diameter-to-height ratio [5]. These physical parameters govern the distribution of vibrational modes that, in turn, define the audible partials contributing to the bell's tonal identity. During the final stages of bell production, fine-tuning is often performed by removing material from the inner surface to adjust the frequencies of key vibrational modes, especially those associated with the strike note and its harmonic spectrum [7].

Despite being a practical procedure grounded in craftsmanship, bell tuning inherently requires a reference system. This reference allows any musical instrument maker or player to determine whether a given partial is “in tune” relative to a fixed pitch or interval structure.

Past studies assumed that during the medieval period, such reference systems were informal, empirical, and unstandardized, more reliant on auditory experience than on codified musical principles. For example, based on the available documental sources, church bell started to be tuned according to a defined procedure only since the 17th century [8]. However, musical tuning reference systems, known as temperaments, were already formalized in antiquity, from the time of Pythagoras. In fact, musical scales theory developed around the mathematical relationships between pitches, leading to the definition of temperaments based on rational frequency ratios. By the medieval period, theoretical frameworks such as Pythagorean tuning and, later, meantone temperaments were well known among theorists and musicians.

This is why it was hypothesized that the apparent disconnect between these theoretical systems and their application to bell tuning derived from a possible lack of written sources or considering that bells, due to their inharmonic overtone structure, could not meaningfully adhere to musical temperaments.

The hypothesis explored in this study is that bell founders, consciously or not, tuned bells according to culturally accepted musical temperaments of their time, aligning the geometry of the bell structure to produce a sound that could be recognized as ‘harmonic’ in relation to the accepted cultural standards of the place and times in which they were built.

B. Measure and data analysis

The proposed methodology is designed to characterize the tonal properties of historical church bells by extracting their vibrational signature and comparing it to theoretical pitch structures derived from documented historical

temperaments. The procedure is entirely non-invasive and consists of four main steps: acoustic data acquisition, spectral analysis, temperament modeling, and comparative evaluation.

Each bell was recorded in situ, under controlled excitation. Excitation was performed the original clapper, to ensure consistency with the bell's intended mode of vibration. Flat-frequency recordings were carried out using the UMIK-I linear omnidirectional condenser USB microphone, characterized by a flat frequency response in the 20 Hz–20 kHz range. Recordings were made at a sampling rate of 44100 Hz and a 24-bit resolution to ensure accurate capture of the harmonic content. The recorded audio signals, recorded in uncompressed *.wav form.

Acoustic recordings were post-processed in MATLABTM R2024b. The signals were normalized and segmented to isolate the initial transient and steady-state portions of the bell's emission. Short-Time Fourier Transform (STFT) and Welch's method were employed to obtain high-resolution spectra. The frequency components corresponding to the main partials—typically the hum, prime, tierce, quint, and nominal—were identified through peak detection algorithms, using both energy thresholding and harmonic clustering techniques. Only stable peaks were retained for comparison.

Reference pitch sets were constructed for a variety of historical temperaments: Pythagorean tuning, quarter-comma meantone, sixth-comma meantone, just intonation, and 12-tone equal temperament. Each temperament was modeled starting from a root frequency coinciding with the nominal of the analyzed bell. From this root, the expected theoretical frequencies of the other partials were computed according to the mathematical definitions of each temperament system. All theoretical values were calculated in Hz.

The extracted spectral peaks were compared with each theoretical temperament model by computing absolute frequency deviation metrics in Hertz (Hz). For each identified partial, f_i , the corresponding theoretical frequency, $f_{i,ref}$, was calculated based on the structure of the given temperament, using the bell's nominal as the root reference tone. The deviation for each partial was then computed as:

$$\Delta f_{\%} = \frac{f_i - f_{i,ref}}{f_{i,ref}} \quad (1)$$

An average absolute deviation across all relevant partials was calculated for each temperament. The temperament yielding the lowest overall deviation was considered the best acoustic match. A deviation threshold of $\pm 5\%$ of the corresponding theoretical frequency was adopted to determine whether a partial was acceptably in tune with a given temperament structure. In addition to average deviation, the consistency and clustering of deviations across all partials were qualitatively evaluated to verify the presence of a coherent temperament structure rather than isolated coincidences. This ensured that the inferred match

was not the result of random alignment but of an underlying tuning logic traceable to historical practice.

Once the best-fitting temperament had been identified, the corresponding historical period of its documented use was adopted as the inferred dating range of the bell. While this association does not provide an absolute chronology, it offers a culturally and acoustically grounded temporal attribution. For example, a strong match with quarter-comma meantone suggests a likely origin between the 16th and early 18th centuries, whereas alignment with Pythagorean tuning is typically associated with medieval tonal systems prior to the emergence of systematic tonal harmony. In this way, the temperament serves as an acoustic proxy for dating, particularly valuable in cases where traditional epigraphic or archival data are lacking.

C. Salerno cathedral bells tuning matching

To test the proposed methodology, the non-invasive vibroacoustic characterization and temperament-matching procedure was applied to the complete set of historical bells installed in the bell chamber of Salerno Cathedral (Campania, Italy). The ensemble comprises eight bronze bells suspended on the upper level of the cathedral bell tower, each differing in size, inscription, and documented origin, having construction dates ranging from the 13th to the 19th century.

The bell reference numbers used in this study are as follows: Bell 1 – C³, 1824, Rossi and Ripandelli; Bell 2 – F³, 1535, Giordano; Bell 3 – B³, 13th century, anonymous; Bell 4 – C⁴, 1734, Astarita; Bell 5 – D⁴, 1782, Garzia; Bell 6 – Gb⁴, 1782, Garzia; Bell 7 – F⁴, 1745, anonymous; Bell 8 – A⁴, 19th century, anonymous.

Each bell sound was recorded in situ using the standardized procedure described in sub-section B. The corresponding sound emissions were processed via spectral analysis to extract the dominant tonal components (partials). The number of tonal components identified in the audible range (20 Hz – 20,000 Hz) varied between 7 and 21, depending on the pitch and physical characteristics of each bell. Full details of the spectral analysis, including frequency values, number of matched tones, and partial distributions, are available in the literature [6].

III. RESULTS AND DISCUSSION

A. Results

The temperament-matching procedure was applied to the full spectral dataset obtained from the eight bells of Salerno Cathedral. For each bell, the extracted partials were compared to frequency sets derived from five historical temperaments: Pythagorean, just intonation, and meantone temperament in its 1/4, 1/3, and 1/6 comma variants, as well as 12-tone equal temperament.

The best-fitting temperament for each bell was identified based on the minimum average absolute deviation in Hz between measured and theoretical frequencies, within a

matching tolerance of $\pm 5\%$. As detailed in the literature [6], the following associations were established: Bell 1 (C3, 1824) – Equal temperament; Bell 2 (F3, 1535) – 1/4 comma meantone; Bell 3 (B3, 13th century) – Pythagorean; Bell 4 (C4, 1734) – 1/4 comma meantone; Bell 5 (D4, 1782) – 1/4 comma meantone; Bell 6 (Gb4, 1782) – 1/4 comma meantone; Bell 7 (F4, 1745) – 1/4 comma meantone; Bell 8 (A4, 19th century) – Equal temperament.

The number of matched frequency peaks per bell ranged from 5 (Bell 8) to 15 (Bells 1 and 2), significantly exceeding the canonical five partials (hum, prime, tierce, quint, and nominal) currently used for bell tuning verification. All matched frequencies deviated by no more than $\pm 3.73\%$ from their theoretical values.

The results show a clear chronological stratification consistent with historical documentation and stylistic attribution. Early bells (e.g., Bell 3) aligned with Pythagorean intervals, characteristic of medieval modal theory, while most of the 16th–18th century bells matched quarter-comma meantone systems—used widely in Renaissance and early Baroque Europe. Bells from the 19th century (Bells 1 and 8) corresponded closely to equal temperament, which became the dominant system from the late 18th century onward.

B. Discussion

The consistent alignment between measured bell spectra and historical musical temperaments provides compelling evidence that tuning practices across centuries were not arbitrary, but rather informed—implicitly or explicitly—by culturally dominant acoustic frameworks. While previous scholarship suggested that bell tuning as a structured practice only emerged in the 18th century [8], the results from this study suggest a much earlier adoption of coherent tonal reference systems.

The prevalence of 1/4 comma meantone temperament among the 16th–18th century bells supports the hypothesis that bell founders aligned their tuning practices with those already established in contemporary instrumental music. Meantone temperament, particularly in its quarter-comma form, was widely adopted in keyboard and fretted instruments to achieve consonant thirds and functional harmony across a subset of keys. The presence of this temperament in bell spectra further suggests a convergence of musical standards across instrument classes.

Similarly, the Pythagorean alignment in Bell 3, one of the oldest in the set, points toward a pre-Renaissance sound ideal where pure fifths dominated, and harmonic consonance was governed by intervallic simplicity rather than harmonic progressions.

The use of spectral temperament matching as a chronometric tool introduces a new avenue for the dating of bells, especially when inscriptions are missing or unreliable. While not a replacement for stylistic or

metallurgical analysis, this method complements traditional approaches by embedding the sonic fingerprint of each bell into a broader historical and musicological framework. It reinforces the notion that tonal structure constitutes an intangible trace of cultural and technological knowledge encoded into material objects.

Finally, the approach is replicable and scalable. Provided that spectral peaks are cleanly extracted, the method can be extended to other bells and bell towers, contributing to the systematic mapping of historical tuning practices across time and geography. This highlights the potential of vibroacoustic metrology not only for acoustic diagnostics but also for historical reconstruction and heritage interpretation. The spectral analysis of the eight bells from Salerno Cathedral reveals a consistent alignment with meantone temperament systems, particularly the 1/4 comma variant. This observation suggests that historical bell founders employed tuning practices that prioritized consonant intervals, especially pure thirds, over the equal spacing of semitones characteristic of equal temperament.

IV. CONCLUSIONS

This study demonstrates the effectiveness of a non-invasive vibroacoustic methodology for investigating the historical tuning systems of church bells and assessing their potential as chronological indicators. By combining spectral analysis with historical temperament modelling, we introduced a replicable framework that allows for the tonal characterization of bells in relation to culturally and temporally situated musical systems.

Applied to the eight historical bells of Salerno Cathedral, the method revealed a consistent alignment between each bell's vibrational spectrum and a specific historical temperament. The matches were coherent with the known or estimated dating of the bells, thus supporting the hypothesis that tuning practices—whether intuitive or explicit—were shaped by culturally dominant acoustic norms. In particular, the identification of Pythagorean tuning in the oldest bell and quarter-comma meantone in most Renaissance and Baroque examples suggests that tonal aesthetics, long considered primarily relevant to instrumental music, also played a formative role in bell making.

The key contribution of this approach lies in its ability to recover intangible cultural information embedded in sound: tuning as both a physical adjustment and a sonic expression of historically situated musical knowledge. Where inscriptions and documents are absent, the tonal identity of a bell can now serve as an acoustic proxy for dating and classification, opening new directions for archaeometry, musicology, and heritage science.

Moreover, this method preserves the integrity of heritage artefacts. By avoiding invasive sampling and relying entirely on sound recordings, it offers a sustainable tool for heritage monitoring, documentation, and interpretation. Its

applicability to other bell towers and historical contexts promises to enrich our understanding of the acoustic dimension of cultural heritage across different regions and periods.

In conclusion, vibroacoustic metrology—when coupled with historical music theory—proves to be a powerful instrument for decoding the sonic imprint of past craftsmanship, enabling a deeper integration of material and immaterial heritage analysis. Future developments may include expanding the comparative database of temperaments, automating the spectral-matching procedure, and integrating psychoacoustic models to further refine the interpretive accuracy of the method. The spectral investigation of the bells of Salerno Cathedral confirms the presence of structured tuning systems, with a strong prevalence of meantone temperament characteristics across specimens dating from the 13th to the 19th century. These findings offer compelling evidence that bell founders, even in the absence of formal documentation, were applying culturally informed acoustic principles during manufacturing.

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