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Hard vibroacoustic metrology for intangible cultural heritage: The case of church bells tuning

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***Abstract* – This work presents a vibroacoustic metrology approach to investigate the tuning systems of historical church bells as expressions of intangible cultural heritage. Focusing on eight bells from Salerno Cathedral, dated between the 13th and 19th centuries, we performed spectral analysis to identify partial frequencies and compared them against reference scales derived from five historical temperaments. Results indicate, prior to the 19th century, when the well-tempered system gradually became the standard tuning reference in Western music, a clear and repeated alignment with the 1/4 comma meantone system. This result suggests that bell founders relied on stable and culturally informed tuning references, transmitted through craft practice rather than written documentation. Thus, the act of tuning emerges not only as a physical adjustment, but as an immaterial expression of shared acoustic knowledge. In other words, the experiential knowledge developed by bell-makers, despite its uncodified nature, allowed to refine the construction techniques to obtain a repeatable result in terms of functionality with desired characteristics. By revealing this connection through a non-invasive analysis, the study contributes to the understanding, documentation, and safeguarding of the intangible sonic dimension of this cultural heritage object.**

I. INTRODUCTION

Church bells are more than instruments of sound. They are cultural artefacts whose resonance carries centuries of craft, symbolism, and communal identity. In recognition of this, UNESCO recently included manual bell ringing in Italy and Spain in the Representative List of the Intangible Cultural Heritage of Humanity, highlighting not only performance practices but also the embedded knowledge of bell production and acoustics [1].

The sound tuning, being the final phase of the bell manufacturing process, is among the defining features of its sonic identity. Tuning is not an accessory step, but a structural part of bell-making, involving the selective removal of material from the bell's inner surface to adjust its vibrational properties. This operation aims to achieve a perceptually harmonious spectrum of partials, traditionally aligned to a culturally-informed sense of consonance [2].

This procedure affects both the pitch and the relative amplitude of key vibrational modes, or "partials," and was historically executed without any known instrumental reference aid, relying solely on artisanal know-how [3]. As such, tuning constitutes both a material and intangible dimension of heritage: it alters the physical object while reflecting a transmission of empirical acoustic knowledge.

Despite its importance, bell tuning has rarely been documented in a systematic way. In particular, the historical evolution of their tuning temperaments, being the reference systems defining the frequency relationships among tones, has not been thoroughly examined through physical measurements. Prior literature dates the first confirmed use of tuned bells to the 18th century [4], although theoretical frameworks for temperaments existed much earlier. This gap limits our understanding of both historical practices and their alignment with evolving musical theory.

In this context, vibroacoustic metrology provides a rigorous approach for addressing this challenge. By applying spectral analysis to the sound emissions of historical bells, we can extract dominant tonal components and evaluate their correspondence to known temperaments. This study applies this approach to the bells of the Salerno Cathedral, spanning chronology from the 13th to the 19th century. The results reveal that temperament-based tuning was practiced well before what previously thought, suggesting a continuity between artisanal practice and theoretical developments in Western music. The method proposed here not only enhances our understanding of bell acoustics, but also opens new pathways for functional diagnosis, conservation planning, and the valorisation of acoustic heritage through scientific means.

II. MATERIALS AND METHODS

A. Measure and data analysis

The acoustic characterization of the bells was conducted using a non-invasive approach. Each bell was excited by its natural swinging motion, and the resulting sound emissions were recorded using a high-fidelity digital audio recorder equipped with a Class-I omnidirectional microphone UMIK-I. Recordings were made at a sampling rate of 96 kHz and a 24-bit resolution to ensure accurate capture of the harmonic content. Considering that the purpose of the measure was not to assess the sound intensity, but to perform a spectrally-linear recording, the microphone calibration was deemed unnecessary.

The recorded audio signals, recorded in uncompressed *.wav form, were converted and processed to perform a spectral analysis using Fast Fourier Transform (FFT) techniques to identify the fundamental frequency and its overtones. This procedure was performed using the software MATLAB, version 2024b. The spectral peaks corresponding to the bell's partials were extracted and considered as references for music scales, whose frequencies were determined based on different historical temperament references. The highest number of matches between measured frequency peaks and expected frequencies of music scales allowed to determine the reference temperament for each bell.

In particular, each identified tonal component was used to generate a full musical scale according to five historical temperament systems: equal temperament, just intonation (Pythagorean), and meantone temperament in three variants (1/4, 1/3, and 1/6 comma). The measured frequencies were compared to the calculated ones from these temperaments, and the best-fitting system for each bell was determined based on the number of tones within a ±5% deviation.

B. Salerno cathedral bells

The Cathedral of Salerno, officially known as the Primatial Metropolitan Cathedral of Saint Mary of the Angels, Saint Matthew, and Saint Gregory VII, stands as a significant monument in southern Italy. Founded by the Norman leader Robert of Hauteville, the cathedral was constructed between 1080 and 1085 and consecrated in 1084 by Pope Gregory VII, who was in exile in Salerno. The cathedral was built over a pre-existing early Christian church dedicated to Saint Mary of the Angels, which, according to tradition, housed the relics of Saint Matthew since 954. The design of the cathedral was inspired by the Abbey of Montecassino, reconstructed under Abbot Desiderius, and features a basilica plan with three naves, a transept, and a quadriportico.

The bell tower, constructed in the mid-12th century, exhibits Arab-Norman architectural elements and houses a collection of bells of varying ages and characteristics. The eight bells analysed in this study are located within this historic bell tower. Table 1 summarizes the key attributes of each bell. including the musical note, the known date or century of casting, and the bell-maker name, if known.

Table 1. Bell reference number, fundamental music note, construction year or century and bell maker(s) (if known)

Bell no.	**Musical note**	**Construction year or century**	**Bell-maker**
1	C^3	1824	Rossi/Ripandelli
2	F^3	1535	Giordano
3	B^3	13th century	Anon.
4	C^4	1734	Astarita
5	D^4	1782	Garzia
6	$G\flat^4$	1782	Garzia
7	F^4	1745	Anon.
8	A^4	19th century	Anon.

C. Tuning temperament

The development of musical temperaments has been a pivotal aspect of music theory, reflecting the evolving understanding of harmony and tuning systems throughout history.

In the medieval period, Pythagorean tuning was predominant, characterized using pure perfect fifths (frequency ratio 3:2). While this system preserved consonant fifths, it resulted in dissonant thirds, limiting its suitability for harmonic music. This tuning was particularly suited to monophonic and early polyphonic music, where the purity of fifths was paramount [5].

However, already in the Medieval period, as musical compositions became more harmonically complex, to address the perceived dissonance of thirds, meantone temperament was developed. This system tempered the fifths slightly to achieve more consonant thirds, enhancing the harmonic possibilities of keyboard and fretted instruments. This temperament evolved in the 16th and 17th centuries, facilitating the performance of music in a wider range of keys [6].

The Baroque period saw the emergence of well-tempered system, which allowed instruments to play in all keys with varying degrees of consonance. Unlike meantone temperament, which favoured certain keys over others, well temperament provided a more balanced approach, enabling composers to explore new harmonic territories [7]. By the 18th and 19th centuries, this temperament became the standard one.

III. RESULTS AND DISCUSSION

A. Results

The power spectral density (PSD) of the eight bells of Salerno Cathedral was calculated based on field recordings collected within the cathedral courtyard. The number of tonal components identified in the audible range (20 Hz – 20,000 Hz) varied between 7 (for the highest-tuned bell) and 21 (for the lowest-tuned bell). The tonal components on which the best-fitting computed scales were based are as follows: Bell 1: 244.250 Hz; Bell 2: 318.250 Hz; Bell 3: 914.125 Hz; Bell 4: 616.750 Hz; Bell 5: 688.625 Hz; Bell 6: 859.000 Hz; Bell 8: 974.813 Hz.

The number of matched tonal peaks with the respective temperaments ranged from 5 (bell 8) to 15 (bells 1 and 2), demonstrating that significantly more than the standard five partials, actually used to verify the tuning of a bell, can contribute to accurate temperament identification. All relative deviations between matched tones had relative deviations ranging between –3.25% and +3.73%. With this respect, it must be noticed that the smallest frequency variation that human hear is able to detect when comparing a pure musical tone of given frequency with another tone (this is called Just Noticeable Difference, JND) is characterized by mean absolute deviation of 0.5% from the initial note (i.e.: 1 Hz, if the initial tone has a frequency of 200 Hz; 10 Hz, if the initial tone has a frequency of 2000 Hz; and so on) [8]. Based on the available data and the music scales, computed on different temperaments to find the best matching, a variation of temperament reference would have been perceived, considering the JND thresholds at different frequencies.

B. Discussion

The spectral analysis of the eight bells from Salerno Cathedral reveals a consistent alignment with meantone temperament systems, particularly the 1/4 comma variant, until the 19th century, when the well-tempered system prevailed. This is why a variation of reference temperament was observed in the case of bells 1 and 8 (see Table 1). 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. The systematic reference couldn't have been casual, since a variation of temperament would have been perceived, even by an untrained human ear. Instead, the practical knowledge, developed through the experience, allowed bell makers to choose how to shape their bells to obtain a result that, depending on the culture of the time, was perceived as 'tuned'.

In fact, in campanology, the tuning of a bell is intrinsically linked to its shape and the precise removal of material during the finishing process. Each bell emits a complex series of partials, including the hum note, strike tone, tierce, quint, and nominal, which collectively contribute to its perceived pitch and tonal quality. Achieving a harmonious balance among these partials is crucial for producing a bell with a pleasing and musically useful sound.

The choice and evolution of reference temperaments in the analysed bells indicates a deliberate effort to fine-tune these partials to achieve specific harmonic relationships. The prevalence for meantone temperament in these bells aligns with historical practices observed in other musical instruments of the same periods. For instance, organ builders and harpsichord makers of the Renaissance and Baroque eras often favoured meantone systems to enhance the consonance of commonly used keys. This cross-instrument consistency underscores a broader musical aesthetic that valued the purity of intervals, particularly thirds, which are more consonant in meantone tuning compared to equal temperament.

Furthermore, the application of meantone temperament in bell tuning reflects an understanding of the psychoacoustic principles governing auditory perception. The strike tone of a bell, which is the dominant pitch perceived by the human ear, results from the complex interplay of its partials. By adjusting the frequencies of these partials to align with meantone intervals, bell founders could manipulate the perceived pitch and tonal 'colour' of the bell, enhancing its musicality and integration with other instruments tuned to similar systems.

IV. CONCLUSIONS

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.

The findings from Salerno Cathedral's bells contribute valuable insights into historical tuning practices and the acoustic considerations of bell founders. They highlight the sophisticated level of craftsmanship and musical understanding required to produce bells that not only served liturgical and timekeeping functions but also adhered to the prevailing musical standards of their time.

Beyond the physical characteristics of each bell, this study brings attention to their role as vehicles of intangible cultural heritage. The act of tuning—performed by ear, guided by tradition, and encoded in sound—is a non-material expression of knowledge passed across generations. Recognizing and analysing this tuning as a cultural trace embedded in the vibrational spectrum of bells provides a new pathway for preserving and interpreting the sonic heritage of religious and civic life.

By applying non-invasive vibroacoustic metrology, this work contributes to the broader effort of safeguarding intangible cultural assets, offering replicable tools for both scientific inquiry and heritage conservation.

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