

# The Sound Emission of the Bell Tower of the Salerno Cathedral in Medieval Europe between Architectural Structure and Bell Construction Techniques

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**Abstract** – This study aims at understanding the intangible design principles that may have directed the design and construction of the Bell Tower of the Salerno Cathedral. The starting point is the hypothesis, already well demonstrated in previous papers, that this bell tower is one the key source elements of a largely distributed network of communication and government of the territory based on the acoustic transmission of information, relying on sources and repeaters (bells towers of monasteries, churches, towers and castles), synergically coordinated by Normans and Benedictines.

In particular, the study focuses on the top part of the Bell Tower, the turret, that housed the bells during the Norman period. The results demonstrate that the turret behaves as an acoustic resonator matched to the bell's sound emission, to maximize and concentrate the acoustic emission in defined directions, changing the vision on the level of acoustic knowledge and the quality of implementations in the Norman period.

## I. INTRODUCTION

A modern vision of cultural heritage is a synthesis of both tangible and intangible dimensions, expressing the historical power and the meaning of a monument through its integrated and synergic multidimensional representation, within the context of a historical-evolutionary interpretation [1,2].

A reinterpretation of the past, that integrates synergistically, but independently, current tools and cultural approaches, may largely contribute to the formation of effective interpretative hypotheses, aiming at describing both its tangible and intangible identity within the framework of archaeological, documentary and metrological evidence.

The vibro-acoustic metrology vision becomes, therefore, an independent and innovative element of proposition and

quantitative validation of interpretative hypotheses, fully consistent with the archaeological and documentary approach, directing the formulation of functional hypotheses for understanding historical assets.

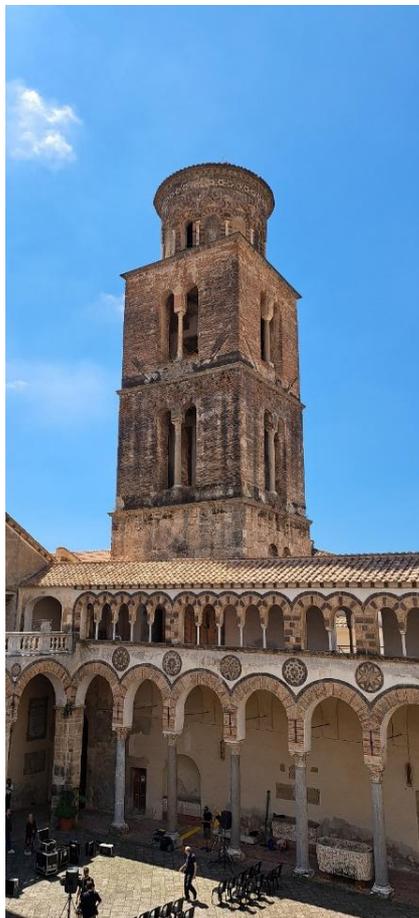
In the last few years, the introduction of vibro-acoustic metrology in the cultural heritage field, is contributing to overcome limited technical views in the process of defragmentation of the cultural elements in the interpretation of historical monuments, recovering the historical unity of vision: acoustics waves (acoustics) and seismic oscillations (mechanics) are reclassified as pressure waves, overcoming the modern cultural divisions in frequency bands, one of the great limitations in studying and understanding the cultural heritage. For example, the technical-anatomical division of acoustics into bands (infrasound, sound and ultrasound) is one of these great limitations. In fact, overcoming the fragmentation of research and culture in the field, historically due to an independent evolution of these two disciplines, can allow us to find elements of synthesis useful for broader interpretations and more general visions of a monument, interconnecting different disciplines within the archaeological context.

Such a vision, complementary to the classic archaeological-documentary one, may provide new elements for understanding the architecture and the function of the bell towers in the Norman period, between the dominion of the Longobards of the South (Duchy of Salerno) and the subsequent reign of Frederick II of Swabia.

In particular, this work analyzes the role of the bell tower of the Cathedral of Salerno as a source element of a network of communication and government of the Norman territory based on the acoustic transmission of information using the bells housed in the bell towers of monasteries and churches, but also positioned on castles' towers, acting as acoustic sources and repeaters, coordinated by the

Benedictine abbeys [3].

In the context of the initial development of bells and the need to implement a very efficient political-military religious communication network, both the positioning of the bell towers and the acoustic emission power of the bells themselves became very important. The latter had a strong development in the Norman period and in the period of maximum flowering of the Benedictine order in the South of Italy. The Benedictine monks, the most technologically advanced ordo in that period in Europe, had already developed very advanced casting techniques for the implementation of bells, as demonstrated by the first European treaty on the casting of bells of Teophylus Presbiter [4].



*Fig.1. The Bell Tower of the Cathedral of Salerno*

On the other hand, in a system of acoustic transmission of information the identification of the main signal sources (frequently multidirectional), key elements of the entire governance network, became necessary. This reasoning leads directly to the bell tower of the Cathedral of Salerno, the most important bell tower in Salerno in the Norman

period and, therefore, presumably also the main source of the acoustic “governance”.

In the following sections, the study of the bell tower of Salerno will be presented, focused mainly on its turret, providing a completely new interpretation (tangible and intangible) of the architectural design and functionality of the bell tower itself, and of its turret. In fact, the latter can be seen as complementary and essential to the bells since it acts as a harmonic sound board on which the bell itself is tuned, functioning as a resonant acoustic amplifier and element of directional sound emission.

This new vibroacoustic interpretation of the architectural design of the bell tower, in very close relation with the bell and its sound actuation methods, highlights an acoustic and technological knowledge of the Normans of the South, probably the most advanced Normans in Europe in that period, like the cultural background and knowledge of the Salerno Medical School. This aspect has never been highlighted before, simply because the bell tower of the cathedral of Salerno has not been interpreted, in an intangible way, as derived from the knowledge of the time, on the basis of the historical and cultural context, in connection with the presence in Salerno of Byzantine workers.

## II. THE BELL TOWER OF SALERNO CATHEDRAL

The Cathedral of Salerno was built in Romanic style between 1076 and 1085 after the conquest of the city by Roberto d’Hauteville, during the archbishopric of Alfano I, a Benedictine monk. The cathedral was consecrated in June 1084 by Pope Gregory VII, a guest in exile in the city.

The monumental Norman bell tower, an important testimony to the Byzantine-Norman fusion of the period, was built more than half a century later, commissioned by Guglielmo da Ravenna, archbishop of Salerno from 1137 to 1152, previously archbishop of Capua, as shown by the epigraph on a stone plaque walled into its southern front.

This bell tower, leaning against the southern side of the cathedral's quadriportico, rises almost 52 meters in height with a base of about 10 meters per side. Its structure is very simple, composed of four cubic stages, ending with a cylindrical turret with a hemispherical dome.

The structure of the bell tower follows the classic dictates of the statics of the structures of the period. The first two stages of the tower are made of thick blocks of travertine, positioned on a solid base, while the next two stages are made of brick blocks, lightened on all sides by large-mullioned windows, that unload the weight laterally on the corners. The cylindrical turret has vaulted lateral openings, surmounted by round arches intertwined with regular alternation, functional to support the load of the dome.

The appearance of the bell tower unquestionably highlights the difference in style between the first stages of the bell tower itself and the last stage, the turret, where the bells were presumably positioned in the 12<sup>th</sup> century, as

documented in the book by Pietro da Eboli “Liber ad honorem Augusti” (also known as *Carmen de Rebus Siculis or Carmen de motibus Siculis*) [5], a work dedicated to Henry VI, which reports that the bell tower contained three bells inside.

Considering the typical size of the bells of the 11<sup>th</sup> and 12<sup>th</sup> centuries, it is possible to assume that all three bells could have been housed inside the turret. Currently, the bell tower houses eight bells, all cast after the construction of the bell tower itself. The largest two are housed inside the last stage, while the remaining six are housed inside the turret. Table 1 summarizes the main characteristics of the bells positioned on the Norman bell tower and their position inside the tower structure.

Table 1. The bells of the Bell Tower of the Cathedral of Salerno

Year	Bell-maker	Note	Sound System	Position
1824	Rossi e Ripandelli	C <sup>3</sup>	Falling Clapper	Last stage
1535	Giordano	F <sup>3</sup>	Falling Clapper	Last stage
XIII cent.	Unknown	Bb <sup>3</sup>	Flying Clapper	Turret
1734	Astarita	C <sup>4</sup>	Flying Clapper	Turret
1782	Garzia	D <sup>4</sup>	Flying Clapper	Turret
1782	Garzia	Gb <sup>4</sup>	Flying Clapper	Turret
1746	Unknown	F <sup>4</sup>	Flying Clapper	Turret
XIX cent.	Unknown	Ab <sup>4</sup>	Flying Clapper	Turret

### III. THE TURRET OF THE BELL TOWER

The study started from a geometric analysis of the bell tower turret aiming at reconstructing its geometry to understand its construction choices (intangible heritage) decoupling the metrological approach from the aesthetic-symbolic expression, widely analyzed and discussed over the centuries. For the first time, we studied the possible relationship existing between the structural and acoustic functionality of the turret. In fact, the acoustic sources (bells) were contained inside the turret, which would appear, following a coherent vibroacoustic approach, as a sound box, similarly to the dynamic acoustic behavior of a classical acoustic musical instrument.

The structure of the dome is geometrically very simple as it consists of a hollow cylinder covered by a substantially spherical dome. Starting from the lower half of the cylinder, twelve vaulted open windows allow the outside propagation of the sound emitted by the internal sources (bells). These windows are oriented isotropically in different directions (at multiple angles of 360/12°), some of them closed following subsequent restorations, for reasons presumably related to the statics of the turret itself. The external part of the cylinder presents several

intertwined arches, a light but effective structure to support the hemispherical dome.



Fig. 2. The turret of the Bell Tower of the Salerno Cathedral.

The external geometric structure is equal to the internal one, since the internal space is also cylindrical with a hemispherical vault. The bells, positioned inside the turret, act as extended sources, whose sound is propagated outside through the twelve isotropically-oriented windows of the turret. The main internal geometric dimensions of the turret are shown in Table 2.

Table 2. Main geometric dimensions of the turret of the Bell Tower of the Cathedral of Salerno.

Turret Geometric Parameter	Measured
Inner Radius	2.80 m
Lateral Height	6.40 m
Total Height	8.90 m
Hemispheric Dome Radius	2.80 m
Window Geometric Parameter	
Total Height	2.40 m
Lateral Height	1.80 m
Width	1.00 m

The simple geometric shape of the turret and the geometric dimensions, reported in Table 2, allow to synthesize an acoustic model simple but sufficient to demonstrate the behavior of the turret as an acoustic resonator matched to the bell’s sound emission. It is, anyway, important to consider that, although no documental historical source, describing the inner side of the turret, has been found, it is not improbable that the inner side of the turret was covered with acoustic reflecting material, like wood, to improve the acoustic properties of the turret, whose role will become evident in the following sections.

#### A. The XIII century bell

Limitedly to the XIII century bell (Fig. 3), considering its closeness to the time of the bell tower construction, we have evaluated the match between the spectral emission of this bell and the structural response of the turret of the bell tower, starting from the structure geometry, as previously done in other studies [6,7].



Fig. 3. Photo of the XIII century bell. Note that this bell is not positioned in the center of symmetry of the turret but moved to one side of it.

The XIII century bell was acoustically characterized through an acquisition, carried out with a simple Samsung A53 cell phone, fully sufficient in relation to the objectives of this study. In fact, the emission frequencies of bells are generally higher than 100 Hz and the analysis is based only on values of the emitted frequencies, so that the amplitude of the signal frequency has not relevant role.

### B. The turret acoustic modes

The shape of the turret allows us to identify two geometric elements linked to its symmetry. The center of the spherical cap and the axis of symmetry of the cylinder. In particular, the center of the spherical cap appears to be positioned on the central axis of the cylinder. Furthermore, the radius of the cylinder would appear to coincide with the radius of the spherical cap. From the point of view of geometric acoustics, this means that the positioning of an extended source in the center of symmetry, such as a bell, would put it in an acoustic-geometric privileged position, the dome acting as an acoustic reflector of the sound emitted by the bell, keeping the acoustic rays in phase and pumping energy on the radial resonance modes.

Continuing with the acoustic-instrumental interpretation of the turret, the cylindrical geometric structure generates stationary acoustic waves whose frequencies are determined by its geometric dimensions. For sake of simplicity, assuming for the turret a cylindrical shape, then its cylindrical acoustic modes can be of three types: radial, azimuthal and longitudinal.

In fact, the solution of the acoustic wave equations in

cylindrical coordinates leads to defining the internal resonance frequencies of the cylinder,  $f_{jmq}$ , synthesized by the relation

$$f_{jmq} = \frac{v_s}{2\pi} \sqrt{\left(\frac{\alpha_{jmq}}{R}\right)^2 + \left(\frac{q\pi}{L}\right)^2} \quad (1)$$

where  $v_s$  is the sound speed in air,  $R$  and  $L$  are the radius and length of the cylinder,  $j$ ,  $m$  e  $q$  are the indices (non-negative integers) referring to the eigenvalues of the radial, azimuthal and longitudinal modes, respectively, and  $\alpha_{jmq}$  is the  $j$ -th zero of the  $m$ -th Bessel function derivative.

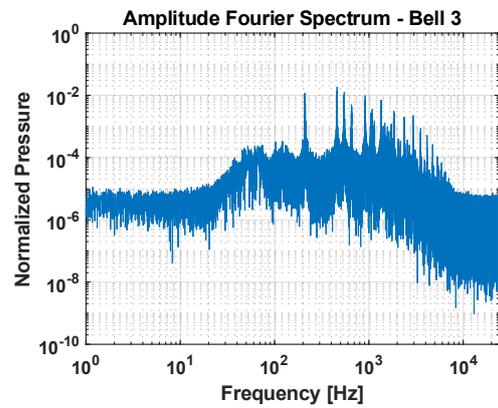


Fig. 4. Fourier Spectrum of the recorded audio signal of the XIII century bell. Note the large number of high-frequency peaks due to excitation of the turret inner modes.

An exact evaluation of the acoustic resonance modes, that considers, in a non-approximate way, the presence of the hemispherical dome, can be carried out with better precision using acoustic numerical ray tracing techniques. However, also this refined approach would lead to the consideration that the best harmonic behavior of the turret can be obtained only if the source (bell) is matched to the acoustic resonator (turret).

### C. Source-resonator coupling

The acoustic model shows that the maximum acoustic emission of the turret is obtained for bells, whose acoustic emission modes match the acoustic resonance modes of the cylindrical turret. Although measurements indicate that the current radius of the turret is 2.82 m, there is no certainty that it was the radius at the time of the bell tower's construction, because of the many alterations, restorations, and consolidations occurred over the centuries. To account for this historical uncertainty, the turret radial modes have been evaluated for a radius spanning the range [2.70 m ÷ 2.90 m]. This analysis has shown that there are values of the radius for which the acoustic modes of the turret are very close to the acoustic modes of the XIII century bell, confirming the possibility of a “projected” matching between the source (bell) and the resonator (turret).

Table 3. The first twenty radial acoustic resonance modes (and the ratios between the bell acoustic modes with respect to the second one) of the turret of the bell tower of Salerno Cathedral evaluated assuming  $R=2.70$  m.

Mode	Turret Frequency [Hz]	Bell Frequency [Hz]
1	77.47	
2	141.84	
3	205.69	210.78
4	269.39	
5	333.01	
6	396.61	
7	460.18	460.39
8	523.74	548.00
9	587.28	
10	650.83	653.43
11	714.37	
12	777.90	
13	841.44	
14	904.97	915.29
15	968.50	
16	1032.0	
17	1095.6	1085.48
18	1159.1	1144.56
19	1222.6	
20	1286.1	
21	1349.7	1346.64

What has been stated becomes particularly evident if we compare the second and third column of Table 3, where the main frequencies of the XIII century bell spectral acoustic emission are also reported.

#### IV. CONCLUSIONS

This study aimed at understanding the intangible design principles that may have directed the design and construction of the Bell Tower of the Salerno Cathedral, focusing on the top part of the Bell Tower, the turret, where the bells were probably housed in the Norman period.

The results demonstrate that the turret behaves as an acoustic resonator matched to the bell's sound emission, maximizing and concentrating the acoustic emission in defined directions. Therefore, the turret is complementary and essential to the bell sound emission, behaving as a resonant acoustic amplifier and sources of directional emission of the sound.

This new intangible acoustic interpretation of the architectural design of the bell tower, in very close relation with the bell and its sound actuation methods, highlights

an acoustic and technological knowledge very advanced in Europe in that period, as a unique synthesis of Norman, Norman, Byzantine and Benedictine knowledge.

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