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Cathedral bell's San José de Cúcuta: Heritage and acoustics

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Abstract. The objective of this research was to analyze the characteristics of the bells and dynamic particularities of the bell tower of the cathedral of San José de Cúcuta, Norte de Santander, Colombia. The research had a mixed methodological approach, using a simplified numerical model of the structure. The spectrum of structural response is determined, analyzing according to the bells, magnitudes of the function of variable forces, with the time that they introduce on the structure with their own weight, speed of rotation and inertia; the most unfavorable dynamic amplification factor and response for quasi-static analysis for forces is determined. It is concluded that the bell of greater weight introduces greater efforts in the tower, being the location of the bell a direct incident factor.

1. Introduction

The study of bells, your acoustics, is in turn of a broad field of immaterial heritage interest for its contribution to the soundscape [1] and church history. Woodside [2], mentioning Schafer, he defines sound landscape as any acoustic field [3] that can be studied by the set of sounds of a specific place, be it a country, a city, a neighborhood, or an enclosure. He insists on the importance of sounds and their eventual or intentional interaction with referents of the social environment where they are produced, thus being an indicator of the evolution of a society [4]. In addition, they coin the term "sound marks" [5] as a heritage sound that is unique and possesses qualities that make it recognizable by the community. The investigation has as objective analyze the characteristics materials and technical details of the bells and the dynamic characteristics of the belfry tower of the cathedral of San José de Cúcuta, Colombia.

2. Methodology

The research had a mixed approach, with descriptive and historical method [6]. The case study focuses on the San José de Cúcuta Cathedral, located in the Santander Park in downtown San José de Cúcuta, Colombia and built at the end of the 18th century. In order to apply the modal superposition method for the dynamic analysis valid for mass matrix inertia force vector damping force systems with viscous damping [7], manifested in Equation (1), where {m} represents the system mass matrix, {k} the stiffness matrix, {x} the displacement vector. Geometric simplifications are made on model, having as hypothesis that the tower is disconnected from the rest of the ship to be built in different stages tower and ship.

$$\{m\} - \{x\} + \{k\} * \{x\} = \{0\} \qquad (1)$$

The analyzed system has a very low damping coefficient, so the frequencies of the free vibration coincide with a system without damping. To determine the characteristics of the hoods, the Heyman and Therefall procedure [8] is followed, in order to adjust the numerical model through tests [9]. Casolo's works set the main frequencies in tension and bending between 0.62 Hz and 2 Hz for thin towers [10]. An iterative process is carried out to adjust the model and achieve 1120 degrees of freedom so that the first vibration mode of the numerical model and the real structure coincide. The four bells have metal yokes of bronze with manual tilting, suspended in metal beams anchored diagonally in the tower; the bells do not rotate at constant speed as they are independent, the mathematical simulation of the movement is carried out considering the bell as a physical pendulum that oscillates freely around its axis, with the pendulum in its maximum position the potential energy initiates the movement with speed of each bell according to the number of clapper blows during one minute dividing by two, this movement introduces on its support horizontal and vertical forces variable with time, transmitted to the support bar and to the structure of the tower. The weight, (Equation (2)) determined by the diameter Ø in meters elevated to the cube multiplied by a constant value of 579 in Colombia [7].

$$\text{Ø}^3 \text{ x } 579 = \text{kg} \qquad \text{Bell Colombia} \tag{2}$$

$$\text{Ø}^3 \text{ x } 357 = \text{kg} \qquad \text{Bell Roman} \tag{3}$$

In the case of the Roman bells (Equation (3)) the formula varies according to the characteristics of the profile and the thickness of the bells, the constant being 357, *i.e.* 40% less, when making these calculations the weight of the bell is excluded, since then the weight of the yoke must be added, in the case of a wooden bell, it can weigh three quarters of the total weight of the bell, while if it is made of iron it will have approximately half the weight of the bronze [11].

3. Results

The bells of the cathedral of San José de Cúcuta, Colombia, is locate in one of the towers on the western margin, on the third level, whose rectangular floor plan with a semi-occupied interior finish, not only made up the highest construction in the city, but also constituted the greatest sound instrument of the town in the twentieth century, allowing until today, the exit of the sound through its two pairs of Romanesque openings on each side. This tower was designed as a resonance box [1], strategically elevated to spread at a greater distance the sonority of the ringing of the holy mother bell, of the major bell Sacred Heart, less bell Saint Louis, and the medium bell, called for the purposes of this study Saint Joseph, heard in a large part of the city. The characterization of the bells in terms of their approximate weight, is recorded in 500 kilograms, 800 kilograms, 80 kilograms and 90 kilograms respectively, so it does not have a remarkable weight, but its resonance (Table 1), as compared with some bells notable sizes antiqued such as the bell "Cantabona" in Germany (11th century) weighed about four tons, and "Maria Gloriosa" of the Cathedral of Erfurt, founded in 1497, weighs thirteen tons [2].

In the distribution of the bells within the hall or nave, variables of acoustic and constructive type, structural and functional intervene. The conjunction of these variables defines the arrangement of the bells according to their number, dimension, tuning, drive system, use and orientation in relation to the immediate and distant urban space. In general, the bells are placed in the openings of the room, the biggest below the smallest or sharpest, ensuring a greater range of sound, the foregoing, determines possibilities and limitations in the operation of the glasses and in the sound quality of the instrument of the tower and of the urban space in which it is inserted.

The epigraphy and inscription of the bells, provides information about these, such as, for example, to whom it is consecrated, date of smelting, among other data, which can be of help for their identification. The typography has varied from the first bells with adorned font style to an ordinary font, consistent with the stylistic periods of classical, gothic, victorian and modernity. This last case concerns at least three of the bells of the cathedral, with epigraphs (Table 1) entitled technical card of the bells. This particularity, of the epigraphy, reveals the origin of the bells, whose founder Luis

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Tristancho and sons, with ample trajectory in the country, and whose fifth generation of Nobsa's bellmakers, in interview affirm that their work was learned from their ancestors, and they, in turn, from Euphrasio Tristancho, who more than two centuries ago took first hand the instructions of the Spanish Juan de Gauss, who introduced this industry in Colombia. The descendants of the Tristancho, preserve the art combining the copper, bronze and tin, which are subjected to temperatures of 1200 degrees centigrade to melt them, the technique they use is called lost mold, because the last for a bell only melts once and breaks; hence, there are no two similar bells in the world.

Table 1. Technical details of the bells.

Description				
Name	Holy Mother Bell	Major bell Sacred Heart	Less bell Saint Louis	Medium bell Saint Joseph
Epigraphy	"Holy Mother of God pray for us. Year. 1947". Company logo: Luis Tristancho and sons B/ col."	"Sacred Heart of Jesus Holy Temple of God have mercy on us. Luis Tristancho and sons Bucaramanga 1947".	"Saint Louis" 1952"	
Size	90 cm high, 1.10 cm diameter medium base	1.10 cm high, 1.27 cm diameter large base	55 cm high, 57 cm diameter Small base	45 cm high, 70 cm diameter small base
Side	13 cm	15 cm	6 cm	Smooth
Weight	500 kg	800 kg	80 kg	90 kg
Material	Copper, bronze and tin	Copper, bronze and tin	Copper, bronze and tin	Copper, bronze and tin
Year of smelting	1947	1947	1952	Unknown
Smelter	Luis Tristancho and sons	Luis Tristancho and sons	Unknown	Unknown
Place of melting	Bucaramanga	Bucaramanga	Unknown	Spain
Yoke	Steel cable	Steel cable	Steel cable	Steel cable
Clapper	Metallic	Metallic	Metallic	Metallic
Touch mechanism	Manual touch	Manual touch	Manual touch	Manual touch
Profile	English	English	English	Dutch fleming

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In the case of the bells of the cathedral of San José de Cúcuta, Colombia, whose manual touch have marked time signals, summons to mass, festivals and solemnities, even civil tolls, among others, reveal a sonorous landscape to which vital elements are related, in addition to the bells themselves, such as the yokes, clapper, the height at which they are arranged, orientation, structure of the tower, which modify its sound. Around 1923, in the book of current accounts of the cathedral of San José de Cúcuta, Colombia, there is evidence of the existence of a bellman who at that time had a salary of three pesos a month, a situation that changes after the liturgical reduction to which the second Vatican council contributed. In this regard, author includes it as one of the causes of the disappearance of the bell ringers towards the sixties, where traditions such as the manual ringing of bells systems were renounced [6]. However, in the cathedral of San José de Cúcuta, Colombia, the tradition of the manual ringing is preserved, becoming a communicative language that for more than 70 years has forged a sonorous landscape in the daily life of San José de Cúcuta, Colombia.

Given the characteristic of the tower and the four bells installed, the effect is considerable as the lighter weight bells are introduced into the tower with greater stresses than the heavier ones where stability is guaranteed, although local cracking effects may occur in the vicinity of the hood attachment points. The height of the tower is 35 m of which the first 18.7 m are occupied by the cane or base of the bell tower. This first section is of square section of 6 m on the outside and wall 1.25 m thick. The octagonal bell tower rests on the walls of the cane and has a height of 3 m ending internally in the dome, above finds the top of the tower that ends at about 35 m above ground level.

3.1. Acoustic analysis

The structure located in the center of the polygonal room with perimeter bells suspended at dissimilar heights, has four bells of different sizes, organized in triangle as a whole, the shortage is observed as a tuned set or rails to support harmonics. The space has a relatively cubic volume with rounded encounters in plan but not in section. In Cúcuta the average diameter is 134 cm, presenting a stable average diameter and weight in relation to the number of bells. The sorority of the city is emphasized by the plurifocal writing for which the major bell is used as a grave pedal which, by densifying the sonic mass [11], assures the permanence of the retouch whose parts are tuned with a certain oscillation, in an approximate note of C, increased by the climatic condition of the city, which influences the increase in intensity and distribution of the sound wave of this urban space.

The two large bells, “Santa Madre” and “Sagrado Corazón”, are placed on the same face, two to the access plaza and two to the opposite side on a face adjacent to the previous one. The disposition of this set reflects certain attention to the immediate urban space in which the cathedral is inserted, in which, the bells of greater size are oriented to the access of the cathedral. Analyzing the sound of the bell depends on the internal structure and profile, where the most important parts that are part of the sound are harmonics of a fundamental, therefore, also those that have a frequency multiple of the fundamental. To them it is necessary to add some partial inharmonic [6] , that unlike the harmonics do not follow the same rule [5] the relative amplitude of the partial has as main factor the location of the mallet, according to it, in the cathedral would be recognized in the touches partial profiles hum, premium, fifth, and k nodal circles (Table 2) such that they transmit a frequency on 4 and 6 meridians and the number “n” of their meridian nodes 0 or 1, peripheral wave with m=2 meridians, RIR-Ring vibration mode with a deviation between 0.5% to 5% of the desired frequency.

Analysis of the set formed by four bells, with a difference of proportional diameter between them, shows that each bell has a different relation with respect to the ideal, which causes that, beyond the own tuning, the relative one is disproportionate. Similarly, the arrangement in four levels, generates effect in the effort transmitted to the tower by the weight and operation of the bells of greater to smaller diameter for the case of the small, which, as the smaller bells are placed above the larger ones, these larger, on the other hand, the high frequencies propagate in a straight line, as opposed to the low frequencies that do it omnidirectional [3], in this way the high frequencies when they are placed on the low ones, diffuse linearly their partial ones without finding obstacle in the propagation of their sound.

Table 2. Analysis of bell vibration modes.

Analysis of bell vibration modes				
Bells	Holy Mother	Sacred Heart	St. Louis	St. Joseph
hum	Mi 3 -11	do 3 +02	Do 5+00	sib 3-45
hum frec	154	131	273	225
prima	Do 5-49	re 4+13	Do 6+00	reb 5-07
3a	sol 4 +13	fa #4-18	523	si 5-46
3a frec	389	366		961
5a	Do 5+36	si 4-42	sol 6+01	do 6+49
5a frec		480		1075
nominal	sib 5+37	mib 5+24	mi 6-25	Do 6+08
nom frec	667	631	1299	1267
diameter	110	127	57	70

Nevertheless, there is a disposition of the two medium bells that makes possible the interference of sonorous waves in their joint action; in the same way, the greater bell was disposed above the greater size and the smaller bell is disposed under one of the holes of the tower, which hinders the sonorous propagation, in spite of it, it is reported clear and intense listening. Although the structural behavior of the tower motivates the disposition of the glasses in height, certain dispositions indicate the lack of attention in some acoustic requirements. According to Equation (1), the values of the Eigen frequencies have a $w_1 = 0.014\sqrt{\frac{E}{\rho}}$ (rad/s), $w_2 = 0.0131\sqrt{\frac{E}{\rho}}$ (rad/s), $w_3 = 0.0273\sqrt{\frac{E}{\rho}}$ (rad/s), $w_4 = 0.0225\sqrt{\frac{E}{\rho}}$ (rad/s), for common brick with density 1600 Kg/m^3, normal resistance between 0.8 MPa and 2.4 MPa, and for its elasticity mode of $9.5 * 10^6\omega^2$ $(\frac{N}{m^2})$. Own frequencies in the system then oscillate between 0.62 Hz and 2 Hz, in a model of four masses with three degrees of freedom with average modulus of elasticity of $1.5 * 10^6$ $(\frac{N}{m^2})$ finally converges for 1150 degrees of freedom to $5.2 * 10^6$ $(\frac{N}{m^2})$. As a consequence of the oscillatory movement of each bell, horizontal and vertical forces variable with time are introduced on the supports, transmitted to the structure of the tower, which presents great rigidity in the direction of its longitudinal axis. Frequency analysis allows to deduce that the bell that presents greater proximity in its first harmonic is Sacred Heart, hence it is the one that presents greater problem. The values of the amplification factor allow us to conclude that, in a quasi-static analysis, the forces introduced by the Sacred Heart bell are the most unfavorable for the structure, given the arrangement in the same beam together with the other medium-weight bell and its location above the lighter one (Table 3).

Table 3. Harmonics, amplification factor and horizontal force introduced by each bell.

Name	1	2	3	Dynamic amplification factor	Horizontal force N
Holy Mother of God	0.40	0.90	1.40	2	4000
Sacred Heart of Jesus	0.61	1.25	1.90	27	40000
St. Louis	0.70	1.50	2.10	11	7500
Saint Joseph	1.00	2.00	0.10	1	180

The evaluation of the tension state of the tower allows us to affirm that the high own weight of approximately $1.7 * 10^7$ N presents in its base a composite bending problem in which the compression tension is the predominant value.

4. Discussion

The analyzed dispositions agree with Francesc Llop in his study of bell towers conserving references of polygonal plants as in regions of Aragon and La Rioja in Spain [12], as well as in his study the bell tower is located in the center. In relation to the type of covering of the room, it is required the construction of a false vault whose curvature favors the reflection of the sound and its propagation to the outside. Likewise, the disappearance of the angles improves the reflection of the partial bells and increases the power. In the case of the historic Spanish bell San José, has wall diameter thinner and therefore its notes are more serious, than the other of a similar diameter, San Luis, but has walls thicker [5]. The difference is not only of note height, it is also of sound power, the thicker the walls the bell is sharper and as also the mass is greater, the sound power grows [5]. As it is pointed out in ontological texts [13], solemn was the ringing of three o'clock in the afternoon, given by the small bell of the cathedral, which, by means of interpolated blows on the alley camp, remembered the passion, in memory of which and of the victims of the earthquake, the devotees prayed three creeds, kneeling, in the streets. On the other hand, despite having high dynamic amplification factors, the horizontal forces introduced by the tipping do not present a relevant magnitude with respect to the bending rigidity of the tower. The factor that boosts the value is due to the fact that the bells are not well balanced, so the Sacred Heart bell must be relocated under the bell Holy Mother, around a common support beam, the speed move 20% away from the first frequency of the tower itself. However, structural safety is guaranteed. In this case, the bell of greater weight introduces greater effort, it becomes necessary to design anchors from the bells to the tower for the efforts calculated through dynamic analysis, being the Sacred Heart the one that presents greater horizontal forces.

5. Conclusions

The bells of the cathedral of San José de Cúcuta, Colombia, located in one of the towers of its facade, formed the highest, symbolic construction and acoustic instrument of greatest resonance in the city in the twentieth century. The ringing of the bells gives life to the so-called "sonorous marks" as a unique patrimonial sound that has qualities that make it identifiable by the community. However, the arrangement of the two bells “Santa Madre” and “San José” allows the interference of the sound waves in their actions. In the same way, it is deduced that the bell that presents greater proximity in its first harmonica is the Sacred Heart, of there that is unfavorable for the structure, for its disposition in the same ray next to the other bell of medium weight and given its location above the one of smaller weight. Due to the above, the structural forces introduced in the bells do not significantly affect the structural safety of the tower. Thus, the design of the bell connections must be reconsidered and arranged to improve the structure and sound conditions.

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