COMPARATIVE ANALYSIS OF BELL SOUNDS FROM SEVERAL ROMANIAN ORTHODOX MONASTERIES AND CHURCHES

C. OANCEA[1], CONSTANTIN GHEORGHIES[2], SIMONA CONDURACHE-BOTA[2]

[1] *"Dunarea de Jos" University of Galati, Faculty of History, Philosophy and Theology, 800201 Galati, Romania*

[2] *"Dunarea de Jos" University of Galati, Faculty of Sciences, 800201 Galati, Romania*

Abstract: *Church bells are particular musical instruments, whose sound perception, known as pitch, is more complex than of those instruments belonging to a classic orchestra. Bells' design and specific proportion of materials used for casting them make each bell unique in its resulting acoustics. This article presents a comparative analysis of the sounds emitted by 5 ringing bells from 5 different Romanian monasteries and churches, by means of complex sound analysis programs, called Wanaval and Sigview, respectively. The spectrograms of the recorded bells ringing are displayed. The partial frequencies were identified and subsequently both simple and multiple correlations were performed between the following sound parameters: frequency, amplitude and intensity. The data were also statistically analyzed, by calculating the average, minimum and maximum values and the standard deviation, respectively. Even though all the analyzed bells have similar size, weight and even wall thickness, their musical characteristics are clearly different one from another, proving the uniqueness of each church bell.*

Keywords: *church bell, partials, frequency, amplitude, sound intensity*

1. INTRODUCTION

Bells are percussion musical instruments, to whom a note or a set of notes on a musical scale are assigned to, which identifies and differentiate between them and which is used to judge whether a bell is "in tune" with others in a chime (i.e. a group of bells sounding together). But since old times, bells are also features of the universal human culture, appearing both in religious rituals and in exceptional tour clocks all over the globe. Church bells represent more or less massive structures, made mainly of a copper - tin alloy, whose best designing; casting and maneuvering are reached nowadays as a result of deep scientific research [1-6].

The oldest bells in Romania are found in the churches from Sântana Nirajului, Şeica Mare and Cotmeana, dating from the 14th century. The best known church bells from the first half of the 15th century are: one at the Roman Catholic church of Cristur and two at the Cozia monastery, dating from 1403 and 1413, respectively. More numerous are the bells preserved from the second half of the 15th century, especially those donated by Stefan cel Mare to the Moldavian monasteries: to Putna, in 1484 and 1490, to Voronet in 1488, and to Bistriţa in 1490 and 1494 [7, 8].

Complex analysis of both the emitted sounds of church bells and of the multiple parameters influencing the acoustic performances of the bell is required for optimum manufacturing and it is the subject of numerous recent studies [1-6, 9, 10].

This article presents the analysis of ringing bells belonging to 5 Romanian monasteries and churches, by means of specific complex acoustic analysis programs, called Wavanal and Sigview, respectively. The study takes part from a big project including the analysis of the sounds emitted by 25 church or monastery bells all over Romania. The bells chosen for the analysis presented here have a three notes harmony: DO2 C2, RE2 D2 and MI2 E2, as it can be seen from Table 1. The same table also contains the names, weight and diameter of each of the 5 bells. Each sound recording lasted 65 seconds.

Table 1 Names, notations and characteristics of the bells analyzed within this article

No.	BELL'S LOCATION	Diameter, [cm]	Weight, [kg]
1.	"Saint Nicholas" Monastery from Călui, Olt (sound no.5)	76 68 61	260 185 144
2.	"Saint Archangels Mihail şi Gavriil" Monastery from Caşin, Bucharest (sound no.7)	76 68 61	260 185 130
3.	"Sleeping of God's Mother" Monastery, from Izvorul Mureşului, Miercurea Ciuc (sound no.8)	76 68 61	260 185 130
4.	"Saint Archangels Mihail and Gavriil" Orthodox Church from Căiuţi, Oneşti, Bacău (sound no.15)	76 68 61	260 185 130
5.	"Saint Pious Parascheva" Orthodox Church from Matca, Galaţi (sound no.20)	76 68 61	260 185 130

2. THEORETICAL NOTIONS

Pitch is one of the four major auditory attributes of sounds, together with loudness, timbre and the location of the sound source. It can be defined as the perceived fundamental frequency of a sound [10]. Only after the Fourier analysis was developed, people could attempt to explain the pitch of complex sounds on a scientific basis. Definitely, the Fourier transform (FT) procedure leads to the identification of all the individual frequencies contained within a complex sound [9].

A *partial* is defined as an identifiable frequency in the sound of a bell, arising from a mode of vibration of the bell. In the case of a bell's sound spectrum, the partials are spaced at fractional multiples of the fundamental frequency. Nevertheless, these sounds can be represented by the sinusoidal partials and noise model, when the frequency of each partial is recorded, along with its amplitude and phase. The *upper partials*, known also as *overtones* represent sounds of frequencies which are multiples of the fundamental frequency of the sound. The first six overtones have special names: *hum, prime, tierce, quint, nominal* and *superquint* [10].

The Fourier transform of a complex sound is generally plotted as amplitude versus component frequencies. But also, another plot can be used to present the spectral composition of a complex sound, namely sound intensity level versus wavelength. As it is known, the *sound intensity, I* or acoustic intensity is defined as the sound power per unit area. The SI unit *of acoustic intensity* is W/m^2. *The sound intensity level*, L_I is the magnitude of sound intensity expressed in logarithmic units (decibels), being given by the next formula:

$$L_I = 10 \cdot \ell og_{10} \frac{I}{I_0} \qquad (1)$$

where I_o is the reference intensity, generally taken as 10^{-12} W/m^2.

In the case of church bells, the reference intensity is that of the nominal, whose intensity level is, thus, equal to zero.

3. EXPERIMENTAL DETAILS AND RESULTS

The files of the sounds recorded from the 5 churches and monasteries given in Table 1, having either .wav or .mp3 extensions were imported and Analyzed in the Wanaval and Sigview computer programs.

With the Sigview program, full interpretation of the sound signals in real time was achieved, in terms of spectral analysis, statistical functions and comprehensive graphics solutions for 2D or 3D correlations.

The *additive analysis and synthesis of sounds* can add-up the individual partials identified by FT of a complex sound, in order to rebuild the part of the original sound with no noise content, known as the *witness sound* or *sound control*, which can be used for comparison with the original sound. This can be done by means of the Wanaval program. In the case of the study presented here, the recorded church bells' sounds were compared with a *sound control* sample having the same musical characteristics, DO 2, RE 2 and MI 2 as the analyzed original sounds. The Wanaval program allows for the analysis of bell sounds using a personal computer. It provides facilities for graphical display of recorded bell sounds, identification of partial frequencies and synthesis of bell sounds from a list of partials. It also allows complete determination of the harmonic character of a bell using the facilities available on any multi-media home PC and the exploration of the way that changing the tuning of a bell changes its resulting sound.

In the following the intensity level will be simply denoted as *intensity*, and, thus, it will be expressed in decibels (dB).

Fig. 1 presents the resulting spectrum of partials of the analyzed sounds in amplitude versus frequency plot, as resulting from the FT of the sound records. Instead, Fig. 2 gives the intensity (in dB) against frequency plot for the same sounds as compared to the sound control, denoted as the 6th. One can notice from Figs. 1 and 2 that the graphs are identical, both in amplitude and in intensity for 2 groups of church bells: 1). for the sounds nos. 5, 7 and 8; 2). for the sounds nos. 15 and 20 and for the sound control. This is due to the fact that the bells in each of the two groups have approximately the same characteristics (size and weight), as given in Table 1.

Changes in the sound intensity in for each of the considered main partials are analyzed in Fig. 3. The range of fluctuations for the values of the sound intensity are summarized in Table 2, where ΔI represents the intensity fluctuation range, in dB, for each individual partial, Ip, scs denotes the intensity in dB of the sound control sample; Ip, 15 and Ip, 20 represent the intensity (levels) of the partials, expressed in dB, also, corresponding to nos. 15 and 20 recorded sounds from church bells (see Table 1 for bells' numbers). The following overlapps are noticed both from Table 2 and from Fig. 3a in the case of tierce, for sounds nos. 15 and 20 and for the sound control (0.00 dB); from Fig. 3b in the case of quint, for sounds nos. 15 and 20 (-14.49 dB).

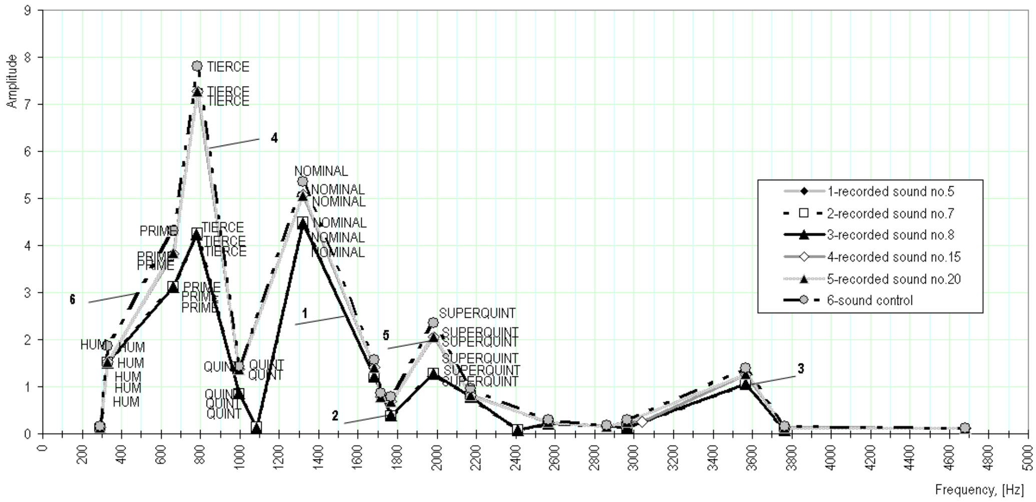

Fig. 1. Frequency dependence of the amplitude of the main partials versus sound control sample (no. 6)

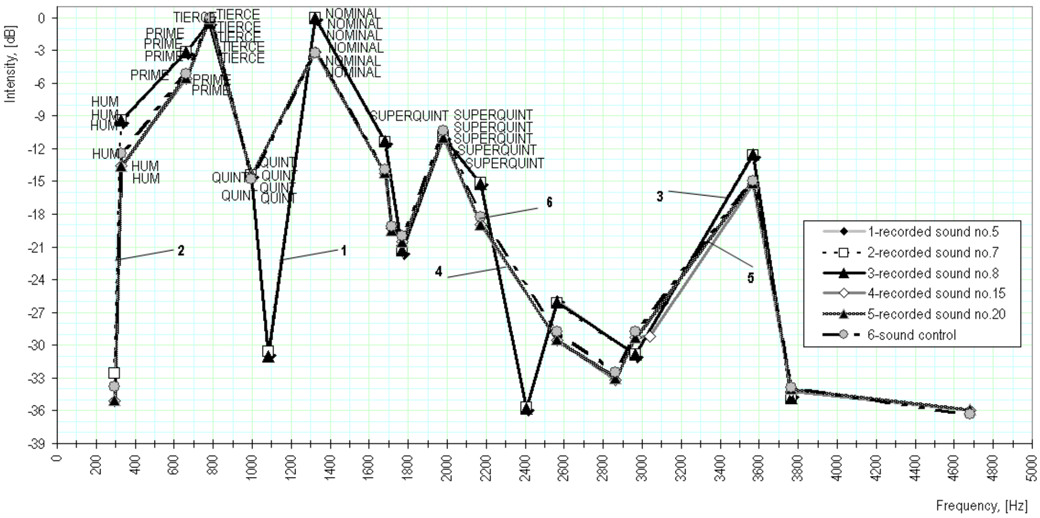

Fig. 2. The influence of frequency variation on the intensity of the main partials recorded versus sound control sample (no. 6)

Table 2 Variation in sound intensity (levels) for the analyzed church bells sounds and for the synthesized sound control

No.	Partial name	ΔI, (dB)	Ip, scs, (dB)	Ip, 15, (dB)	Ip, 20, (dB)
1.	hum	- 9.44 ÷ - 13.59	- 12.45	- 13.55	- 13.59
2.	prime	- 3.15 ÷ - 5.59	- 5.15	- 5.59	- 5.54
3.	tierce	0.00 ÷ - 0.49	0.00	0.00	0.00
4.	quint	- 14.31 ÷- 14.76	- 14.76	- 14.49	- 14.49
5.	n ominal	0.00 ÷ - 3.28	- 3.28	- 3.12	- 3.15
6.	superquint	- 10.40 ÷ - 10.99	- 10.40	- 10.95	- 10.99

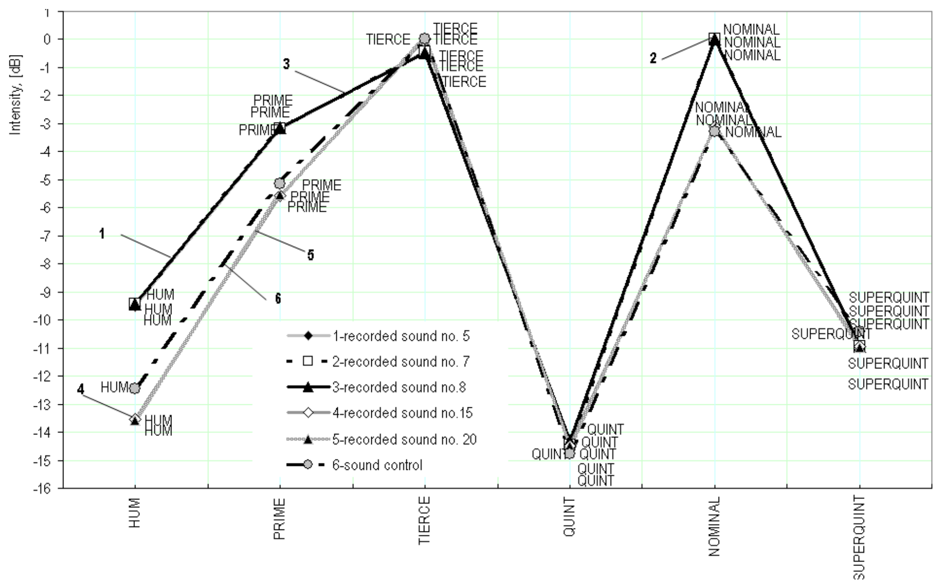

Fig. 3. Changes in sounds intensity depending of the analyzed main partials

Fig. 4 presents the variation of the standard deviation intensity for each of the original church bell recorded sounds and for the sound control.

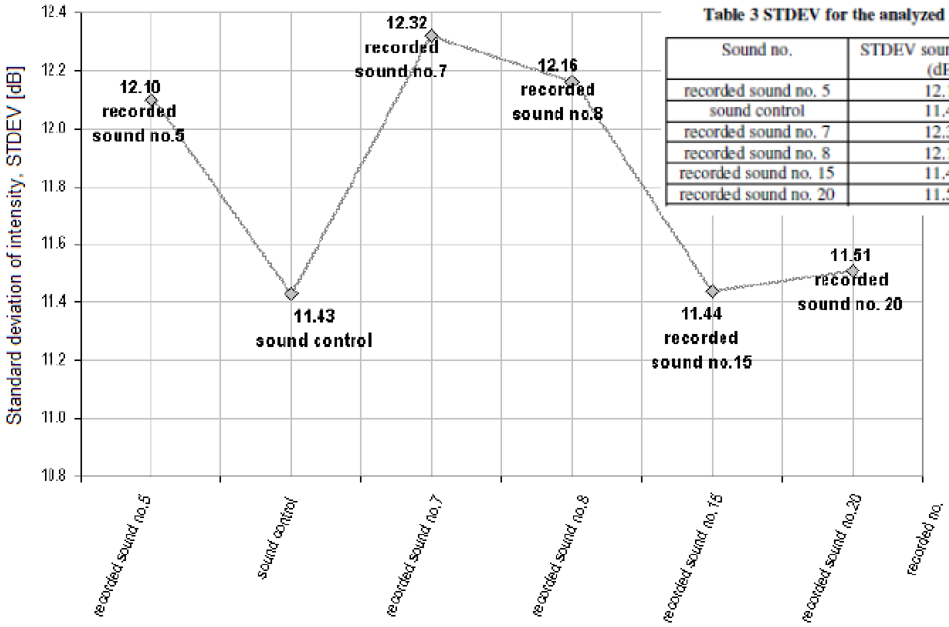

Table 3 STDEV for the analyzed sounds

Sound no.	STDEV sound intensity (dB)
recorded sound no. 5	12.10
sound control	11.43
recorded sound no. 7	12.32
recorded sound no. 8	12.16
recorded sound no. 15	11.44
recorded sound no. 20	11.51

Fig. 4. Variation of STDEV of intensity for the analyzed characteristic sounds

The standard deviation, STDEV expresses the degree of spread of a set of N data, x_k around their mean value, $\overline{x}$, being given by the following expression:

$$\text{STDEV} = \sqrt{\frac{\sum_{k=1}^{N}\left(x_k - \overline{x}\right)^2}{N}} \qquad (2)$$

The STDEV of the sound intensity can be also noticed in Table 3, for each of the 6 analyzed sounds (5 church bell sounds and one control sound).

For the sounds analyzed within this article, one can notice from Fig. 4 that the STDEV varies between 11.43 and 12.16 dB, depending on the characteristics of the analyzed sounds.

Two main aspects are noticeable from Fig. 4: 1). There is the same range of the STDEV values, between 12.10 and 12.32 dB for nos. 5, 7 and 8 recorded sounds; 2). The STDEV ranges between 11.43 and 11.51 dB for the cases of the sound control sample and of the nos. 15 and 20 recorded sounds.

4. CONCLUSIONS

The sounds of church bells from 5 churches and monasteries in Romania were analyzed in terms of amplitude, intensity level, frequency of partials and the corresponding standard deviations. Even though, in groups, the analyzed bells posses the same geometrical characteristics (size and weight), being tuned into the same 3 notes harmony of DO RE MI, their corresponding acoustic characteristics are different. Even slight changes in a bell's weight leads to a change of its amplitude and intensity against frequency, i.e. on the sound spectra, which imply a different perception of their sounds. This proves the uniqueness of each bell, given by a multitude of parameters, not only its size, weight and musical harmony. Thus, the precise acoustic analysis for church bells opens widely the possibility to cast and choose from a range of bells, the ones that match better the demands of the buyer, according to the results from such complex sounds investigations as presented within this article.

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