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Subjective evaluation and an objective measure of a church bell sound quality

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ABSTRACT

The research described in this paper attempts to give an answer to a very old question about a good sounding bell. To this end, a large number of listening tests were performed in which ten bells were compared in pairs to investigate whether bells could be evaluated by subjective sound quality. Furthermore, two new parameters that can be used for objective evaluation of bell sound quality are proposed: the nearest ideal bell deviation and the percentage of the sound energy contained in the first five partials. The ten bells were compared based on the values of the introduced objective parameters. The paper presents correlation of the subjective and the objective analysis, demonstrating applicability of a novel method for bell sound quality assessment.

1. Introduction

Nearly all natural musical instruments produce a sound with a harmonic or quasi-harmonic structure, whereby the majority of the dominant components have frequencies that are near-integer multiples of the fundamental frequency [1,2]. The human auditory system tends to perceive a single pitch, which, for most of the tones with a complex harmonic structure, corresponds to the fundamental frequency. A single integrated sound image, consisting of harmonic components, including their build up and decay rates, mainly affects the instrument tone quality. In contrast, sound of a bell consists of inharmonic overtones, called partials, whose frequencies correspond to the frequencies of natural vibrational modes of the bell [1–8]. Although such a rich inharmonic structure is expected to create several pitch sensations, when a bell is struck, there is usually one tone that is predominantly heard and that tone is called the strike note [1–8]. However, an additional pitch sensation (usually called the secondary strike note) [1,2,9] fuses together with partial overtones into the characteristic sound image, determining the aesthetic experience of a bell sound.

Bells have been an important part of almost every culture in history [2,4]. Due to their characteristic inharmonic sound as well as the habit of listening to bells on special occasions, the sound of a bell induces a very specific experience for a listener. Thus the question of how to define a pleasant sounding bell is very old. Throughout the history people have been trying to determine how a bell should sound considering the physical characteristics and limitations of a bell, and comparing the sound of various bells [6]. According to the oldest theory of a tuned bell, the first five partials dominantly influence the sound of a bell and its strike note. In case of the traditional Western minor-third church bell, the first five partial ratios of a tuned, or the so-called ideal bell, are 1:2:2.4:3:4 [1–7]. These partial ratios provide clearly heard strike note which is particularly important when bells are used as musical instruments in carillons. On the other hand, Orthodox church bells are considered to be rhythm rather than melody instruments, thus precise melodic tuning was not so important or even desirable [10–12]. Putting aside the cultural differences, two principal questions arise: (1) does the same bell induce a similar aesthetic experience among various listeners and, thus, (2) is it possible to arrange a group of different bells according to their subjective sound quality by assigning a single quality score to each bell.

The first goal of the research described in this paper was to answer the questions posed above. For that purpose, the well-known method of paired comparison subjective testing was used [13–17]. Considering the number of all paired combinations for a given number of bells and the reasonable duration of a single listening test, ten different church bells were chosen. Eight of them were selected from a database, which includes about 150 old and new bells from Serbian Orthodox churches, and the two others were almost ideal Western church bells. The ten bells were

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compared in pairs (worse/better bell) by way of listening tests. A blind listening test was performed with two groups of subjects: a group of musically experienced subjects and a group of subjects without music education. Selected subjects were of Serbian cultural heritage and it is assumed that they were exposed to both Eastern Orthodox and Western cultural influence resulting in relatively unbiased basis for their judgment. A detailed description of the listening test is given in Section 2 of the paper.

The positive outcome of the listening test motivated the second goal of the research: introduction of a quantitative measure of a bell sound quality as a single number parameter, taking the listening test results as the main indicator of a bell sound quality. Two such parameters were considered: the first was introduced as a measure of deviation from the nearest ideal bell [18], and the second was defined as the energy comprised in the first five partials of a bell. The demand for such a parameter arises from the need to evaluate a great number of old church bells, most of which are not even close to the ideal [19], as well as to provide guidelines for the bell design in bell foundries in order to improve the sound of new cast bells. The objective parameters are described in Section 3. The comparison between the subjective and the objective analysis of the 10 bells is given in Section 4 of the paper. Concluding remarks are presented in Section 5.

2. Listening test

Assuming that a listener can tell which of the two bells sounds more pleasant, the authors decided to arrange a group of bells according to their subjective sound quality, investigating whether a particular bell could be labeled as “a good sounding” or “a bad sounding”. In order to obtain relevant results, a listening test with a large number of subjects needed to be performed, and a reasonably large number of bells had to be chosen.

2.1. Analyzed bells

The bells for the analysis were chosen from a database of recorded bell sounds. The database includes about 150 old and new bells from Serbian Orthodox churches. The bells were recorded from an approximately two meter distance with a standard condenser 1/2″ measurement microphone. The sampling frequency was 44.1 kHz with 24 bit resolution. Some of the bells were recorded from below as well. The bells were rung by hand with their own clapper. The recorded bells showed considerable differences in objective characteristics (partial frequencies and amplitude ratios, as well as partials decay times), from completely dissonant bells to bells with partials frequencies arranged in an almost ideal manner.

In order to cover a wide range of different bell sounds 10 signals were chosen for the listening test. The main characteristics of the ten bells are presented in Table 1. Eight of them were chosen from the database: 7 bells (B1, B2, B3, B6, B7, B8, B9 in Table 1) being recorded laterally, while the signal denoted by B10 represents the sound of the same bell as the signal B9, the only difference being that the B10 was recorded from below the bell. Since the objective analysis of the signals B9 and B10 showed different relative ratios of the partial amplitudes, it was particularly interesting to compare the subjective evaluations of these two signals. Three of the eight bells were new bells cast in a local Serbian bell foundry, while five others were old bells. The remaining two signals, denoted by B4 and B5, which were downloaded from the web site of the bell foundry Glockengießerei Perner–Passau [20], had partials content quite close to the ideal.

The bells presented in Table 1 are arranged by the fifth partial frequency in ascending order. According to the simplest theory on the strike note of a bell, stating that the strike note corresponds to the frequency of the octave below the fifth partial [1–3,8,9], the arrangement of the bells in Table 1 corresponds to sorting by the strike note frequency.

It has been shown previously that the strike note phenomenon and the subjective experience are closely associated with the sound of the bell during the first second after the strike [19]. In accordance to that, the duration of all sound signals was cut to 1 s. The signal was faded out after 600 ms so that a sudden cutoff of the signal would not influence the test results.

2.2. Bell comparison and the result analysis procedure

In the listening test the method of paired comparison was used [13–17]. The 10 selected bell sounds were compared in pairs, each pair of bells being compared exactly once by each subject. Hence, a test for one subject consisted of 45 unordered comparisons. In each comparison the “better” sounding bell was assigned 1 point, while the “worse” sounding bell was assigned 0 points. In the case where both bells induced a similar aesthetic experience each bell was assigned 0.5 points. The results of the paired comparisons were converted to quality scales using two different methods.

In the first, intuitively simple method of mean preference scores [16], the results were processed in the following way. For each subject tested, the total number of points was calculated for each bell, thus the maximum number of points for a bell equals the total number of bells decreased by 1 (in case of this study it was 9). The total number of points for a bell was calculated as a sum of points the bell got from each subject tested. For the comparison of the listening test results and the values of the introduced objective parameters the total number of points for a bell *Bi* was transformed to fit into the range (0, 1) as:

$$AvgBellScore_{Bi} = \frac{TotalPoints_{Bi}}{(NumOfBells - 1)NumOfSubjs}, \quad (1)$$

where $TotalPoints_{Bi}$ is the sum of points the bell *Bi* got from all subjects, *NumOfBells* presents the total number of analyzed bells (in this

Table 1
Characteristics of the bells used in the listening test.

No.	Bell origin	Bell characteristics		Objective analysis				
		Age	Weight [kg]	1st part. [Hz]	2nd part. [Hz]	3rd part. [Hz]	4th part. [Hz]	5th part. [Hz]
B1	Jovanović Bell Foundry	Old	722	199	299	371	459	592
B2	Kremenović Bell Foundry	New	800	177	274	371	511	635
B3	Monastery Grgeteg	Old	500	207	331	455	581	775
B4	Perner–Passau Bell Foundry, G4	New	720	193	393	468	587	781
B5	Perner–Passau Bell Foundry, H4	New	350	242	490	587	727	980
B6	Popović Bell Foundry	Old	214	264	511	630	786	1066
B7	Russian bell	1883	85	374	606	797	980	1082
B8	Monastery Ostrog, smaller bell	Old	<100	334	678	802	974	1330
B9	Kremenović Bell Foundry	New	70	355	732	861	1001	1378
B10	Kremenović Bell Foundry (B9 bellow)	New	70	355	732	861	1001	1378