Analysis of just Noticeable Difference in Spectrum of Church Bell Sound

Aleksandra Samolov

Abstract — **Bells are specific sound sources. They have distinct, but, unlike musical instruments, inharmonious partials. These partials arise from modes of vibration of the bell and depend on dimensions and potential irregularities of the bell. Therefore, the question of a just noticeable difference in the church bell sound is of great importance. Analysis of subjective tests with synthetic sounds of two bells, different in size, is described in this paper. We report results for a just noticeable difference of partial frequency in the range 10-15 cents. Frequency dependence, is also, noticed.**

Keywords — **church bell, just noticeable difference, subjective test**

I. Introduction

PREVIOUS work of the same author showed preliminary results of a subjective analysis of the distinguishability of church bell sound imperfections. The goal of the initial research was to determine threshold values of just noticeable differences which appear in the course of introduction of frequency changes of certain partials. Results which were obtained in such preliminary analyses have shown that in predetermined conditions, just noticeable differences in such deviation exist within the range of 10-20 cent, depending on the frequency [1].

In the course of organization of that experiment, two important approximations were introduced. The first implied that all partials have constant amplitudes which do not change with time. In real sound of the bell, their amplitudes drop since they originate from subdued bell body oscillations. The second approximation implied that all five synthesized bell sound partials have equal amplitudes, although their amplitudes in the real bell sound are not identical to one another. Therefore, the first experiment was used only as an approximation of a real bell sound.

Literature shows results which indicate frequency change perception borders, that is, pitch of a tone. A just noticeable difference in frequency change perception of a pure sinus tone depends on the frequency [2]. In the range below 500 Hz, sense of hearing detects differences of approximately 1 Hz, while in the range above 500 Hz, the perceptibility range may be roughly described by a relation of $0.002f$. Additionally, several authors have confirmed the relevant fact that greater sensitivity to frequency changes exists in case of complex tones in comparison to simple ones [3]-[5]. Therefore, in the course of perception of musical tones which contain harmonics, sense of hearing detects a change of frequency in higher harmonics more easily than through a change of a basic tone. It was shown that musicians most commonly follow frequencies of higher harmonics while tuning [2].

By analyzing perceptibility of differences in the same intervals of different tonal systems, Hill and Summers determined perception borders at minor and major thirds [6]. They have determined that a change is perceptible at approximately 10 cent. Their results matched well the values determined by Parncutt and Cohen in their analysis of a similar issue [7]. Ternstroem and Sundberg have, by analyzing choir singers and manner in which a difference in a sound level of a single singer and the singers around him influence the difference in tone height, reached a mean value within a range of 8-10 cent, if both value levels were roughly 90 dB [8]. Additionally, Lottermoser and Meyer have discovered that it ranges from 20-30 cent [9], by analyzing basic tone dispersion in group singing.

By analyzing a just noticeable difference in the change of acoustic properties of different violins, Fritz and others have reached the conclusion that this value in frequency change varies within a range from 1.5% to 20%, depending on conditions in which the experiment was performed and whether the subjects which took part in the experiment were musicians or not [10]. Within that same research, authors reached the conclusion that tone height changes, when following a certain musical phrase, are less perceptible than in the course of observing such changes in a single tone. This is similar to the facts which are recognized in speech, in which case a change of central frequency of a single formant is more easily perceived in single vowels than in a sentence [11].

Moore and others, in their work related to the analysis of harmonics inharmonicity detection limits in complex tones, have reached a mean value of 4 Hz, for complex tones whose harmonics have equal amplitudes, and whose signals have equal durations. In another experiment performed by the same authors, signal durations were changed and it was noticed that a detection limit in higher harmonics increased as signal duration dropped, and it varies within 1 Hz to 40 Hz range. In lower harmonics the change is less pronounced and it is approximately proportional to the frequency change of harmonics [12].

Sound of a bell has complex contents, since it contains at least five important components with different

This paper was written during activities within the project 23046 supported by the Ministry of Science and Technological Development of the Republic of Serbia.

*Aleksandra Samolov is with the Military Technical Institute in Belgrade (sale1509@yahoo.com)

amplitudes, which begin with a characteristic transient and later in time drop, each with different speed. There is no data in literature about just noticeable differences in the quality of sound of church bells, besides the results of preliminary experiments with significant simplification of signals [1]. Therefore, it is not completely clear to which extent could the existing results from the literature be applied to the bell. Considering that, a series of experiments was performed, whose results are shown in this paper. Their purpose was to determine just noticeable differences of sounds of church bells.

II. Experimental procedure

Experimental research of just noticeable differences in the spectral structure of the church bell sound was performed based on synthesized signals, in order to enable a random variation of partial frequency value. Recording of two real church bells of different sizes, whose sound was recorded and analyzed, was taken as a basis for synthesis. Mass of the first bell was approximately 350 kg, with the lowest partial frequency of 131 Hz, which corresponds to the musical tone c (C3). Mass of the second bell was approximately 50 kg and the lowest partial frequency 659 Hz, which corresponds to the musical tone e″ (E5). These two values were taken as a basis for the synthesis of sounds of two ideal bells used in the experiment.

It is assumed that each of the two ideal bells has five important partials which are arranged in a characteristic manner with respect to the lowest (octave, third, fifth, octave). This choice ensures that signals of the two bells with five partials each cover the frequency range from 131 Hz, which is the frequency of the lowest bell partial, to 2637 Hz, which is the value of the highest partial frequency in the sound of the smaller bell. The frequency and musical pitch of all partials are shown in Table 1.

In signal synthesis, the relative ratio of initial partial amplitudes and speeds of their drop in time have been set to correspond to the values measured in the sound of real bells taken as models. Relative partial levels and drop time in synthesized sound are shown in Table 1. Partial levels were determined based on the effective values calculated in the initial 0.25 s of the signal, measured in comparison with the level of the lowest partial. Expressed drop time was defined as an interval in which a partial signal drops for 60 dB from its initial value. Drop time of the lowest partial in the sound of real bells is significantly longer than others. Since the duration of sound listening in experiments is 5 s, it is estimated that amplitude change of the lowest partial, due to a low drop speed, is not perceptible by the listener and it is considered to be a constant value. In order to avoid differences in initial partial phases, a phenomenon which may influence the envelope, „fade in“ with a duration of 1 ms was introduced at the beginning of the signal.

Table 1: Data on individual partials of both bells.

bell	***frequency (Hz)***	***musical pitch***	***relative level (dB)***	***drop time (s)***
bigger	131	C3	-8.9	/
	262	C4	-3.2	40
	311.13	E4	-5.8	30
	392	G4	-10.1	8
	524	C5	-5.4	15
smaller	659	E5	-5.8	/
	1318	E6	-4.3	9
	1567.98	G6	-5.4	7.5
	1975.53	H6	-4.7	5
	2637	E7	-9.4	3

Taking the synthesized signal sound of two bells as a basis, a group of signals was prepared, in which certain changes were introduced and which were reproduced for listeners. In them, a single partial frequency was varied in preset increments defined in cents, while the frequencies of others remained unchanged. The frequencies of partials were varied individually in increments of ±5, ±10, ±15, ±20, ±25, ±30, ±40 and ±50 cent. Changes were not introduced only in the frequency of the lowest partial.

A subjective analysis of just noticeable difference in signals prepared in this was organized with the participation of 10 subjects. Each of them had no less than eight-year musical education, as a warranty for understanding of dissonance term and recognition of differences in the bell sound. Age of the subjects was between 18 and 40. None of the subjects had previous experience in participating in experiments of the kind. Signal reproduction was performed by means of headphones under studio conditions, which ensured protection from possible disturbing surrounding sounds.

The analysis of perceptibility borderline at frequency change of one of the partials was performed in two experiments. In the first experiment, subjects listened prepared signals in which the frequency deviation of a certain partial was successively increased. Deviations were introduced with frequency increases and decreases, in aforementioned increments, up to ±50 cent. The duration of all individual signals was 5 s and they were reproduced for the subjects consecutively. Each first signal in a reproduced series was the sound of an ideal bell with partials set based on calculated ideal frequencies, while the subsequent signals had a changed frequency of one of their partials. Groups of signals were reproduced to the subjects randomly, stochastically with respect to introduced frequency changes, instead of increasing deviation sequence. This was done in order to avoid the effect of analytical focus on a variable partial. Subjects' task was to recognize the appearance of signals with an introduced frequency change.

The second experiment was performed in identical physical conditions, but in an A-B test form. Signal pairs were reproduced to the subjects, the first of which was a sound of an ideal bell, whose partials were at musically correct values of frequencies shown in Table 1 (Signal A), while the second signal from the pair represented the sound of the bell with changed frequency of a certain partial (Signal B). Signals in this experiment also had a duration of 5 s, with 3 s pauses. The sequence of signal pairs reproduction was random, in order to avoid analytical focus of the sense of hearing. So called „control pairs“ were reproduced occasionally during the test, where both signals, both A and B, had ideally set partial frequencies.

III. Results

Results of the analysis of a just noticeable difference in the bell sound from the first experiment are shown in Table 2. The first column shows the frequencies of partials of an ideal bell, the second shows the mean values of positive deviation at which the difference is detected, expressed in cents, while the third column shows the values of those deviations converted to a frequency in Hz. The following formula was used for calculation of those frequencies

$$a = b * 2^{\frac{n}{1200}} \qquad (1)$$

Results of the analysis of a just noticeable difference in the bell sound from the second experiment are shown in Table 3, whose columns have the same meaning as in Table 2.

Results of both experiments are shown in Figure 1, where deviation is expressed as the function of the correct frequency of the partial. Standard deviations of individual results obtained from answers of subjects who took part in the test are drawn in the diagram.

IV. Discussion

Experiments organized in this way were intended to enable an insight into just noticeable differences of the bell sound quality in two manners which usually occur in the course of listening: by means of evaluation of an isolated sound of a single bell strike and by its comparison with the sound of an ideal bell, all of which was achieved by the A-B test.

Results of the analysis of a just noticeable difference in the bell sound from the first experiment show that it exists within the range between 5 and 15 cent. In case of the smaller bell, that is, at higher frequencies, it varies within the 5 to 15 cents interval. Results obtained in this manner are compliant with the well known fact that ear shows a greater sensitivity at higher frequencies. Results which speak of the dependence of a just noticeable difference on the partial whose frequency is changed were obtained in the experiment. The results also indicate the dependence of a just noticeable difference on the manner of change, that is, whether the frequency of the partial was increased or decreased. In the first experiment, total results converge around a certain mean value amounting to 8 cents. Deviation from this value is noticed in results obtained for the bigger bell, namely in increases of partials.

Table 2: Result of analysis of just noticeable difference in the bell sound obtained in the first experiment.

bell	*change*	*ideal frequency (Hz)*	*mean value of deviation (cent)*	*frequency with deviation (Hz)*
bigger	increase	262	+11	263.67
		311.13	+10	312.93
		392	+15	395.41
		524	+15.5	528.71
	decrease	262	-9	260.64
		311.13	-8.5	309.61
		392	-9	389.97
		524	-10.5	520.83
smaller	increase	1318	+5.5	1322.19
		1567.98	+9.4	1576.52
		1975.53	+8.3	1985.02
		2637	+8.3	2649.67
	decrease	1318	-7.8	1312.07
		1567.98	-10.5	1558.5
		1975.53	-10.5	1963.59
		2637	-8.3	2624.39

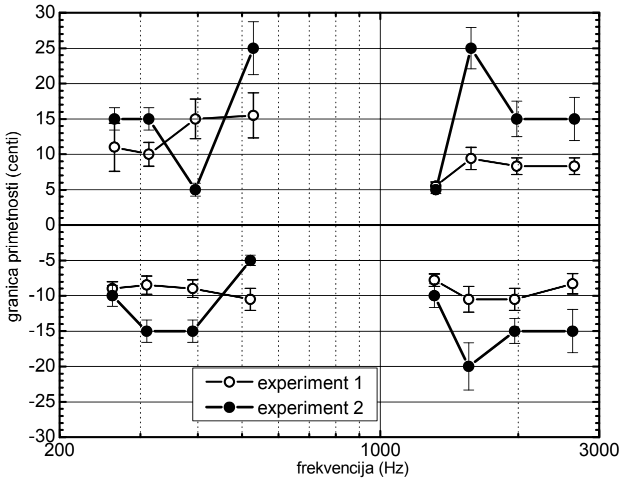

Fig. 1. Diagram of just noticeable difference in the bell sound. Bright dots represent results of the first experiment, while the dark ones represent results of the second experiment.

Results of the analysis of a just noticeable difference from the second experiment indicate that it exists within the 5 to 25 cents range. At higher frequencies, obtained results have higher values than in the first experiment. The greatest difference among the results was noticed in the third partial, the minor third. At lower frequencies, in the results which show a positive deviation, value increase is visible in the fourth (fifth) and fifth (octave) partial. The obtained value of deviation, expressed in cents, in the fourth partial is smaller than in the first experiment, but it is greater in the fifth partial. In the analysis of results of the bigger bell with a negative deviation, an increase in the fifth partial can be noticed, whose value is lower for a just noticeable difference than in the first experiment.

Due to the manner in which the test for analysis of a just noticeable difference in the second experiment was performed, it seemed logical that its value should be greater than the value from the first experiment. It was obtained by means of an A-B test, where subjects were asked to respond to the question whether they perceive the difference or not, and in case of analysis of this value in the first experiment, the first moment when the sound becomes unpleasant for hearing was sought for.

TABLE 3: RESULT OF ANALYSIS OF JUST NOTICEABLE DIFFERENCE IN THE BELL SOUND OBTAINED IN THE SECOND EXPERIMENT.

bell	***change***	***ideal frequency (Hz)***	***mean value of deviation (cent)***	***frequency with deviation (Hz)***
bigger	increase	262	+15	264.28
		311.13	+15	313.84
		392	+5	393.13
		524	+25	531.62
	decrease	262	-10	260.49
		311.13	-15	308.45
		392	-15	388.62
		524	-5	522.49
smaller	increase	1318	+5	1322.32
		1567.98	+25	1590.79
		1975.53	+15	1992.72
		2637	+15	2659.95
	decrease	1318	-10	1310.41
		1567.98	-20	1549.97
		1975.53	-15	1958.49
		2637	-15	2614.25

By comparing experimentally the obtained values with theoretical predictions [2], we have reached the following conclusions. At frequencies below 500Hz, compliance with theoretical data is good. Namely, according to literature, the difference in frequency in this area should amount to approximately 1 Hz. This value was also obtained experimentally, but in case of partials whose frequencies vary close to 400Hz, the value of frequency change increases and exists within the 3-4 Hz range.

It has been theoretically foreseen that, at high frequencies, the change amounts to 0.0002 f. Obtained values comply with that, and significantly supersede theoretical expectations. Namely, a theoretical frequency change should vary within 1-5 Hz range, while the difference achieved experimentally existed within the 4-18 Hz range.

In the aforementioned paper, Moore and other [12] authors discuss two manners of perception of complex sound inharmonicity. In lower harmonics (until the fourth in line), the changed harmonic stands out („is distinguished“) from the complex sound, while in higher harmonics this change is perceived as a „bit“ or sound sharpness. This phenomenon depends on the relationship of changed harmonic phases with the phases of other harmonics of the complex sound.

Since the signal envelope influences tone sharpness, and since from the frequency of approximately 20 Hz to the frequency of approximately 10 kHz sharpness increases for a factor of 50, we have concluded that it had one of important roles in the perception of differences in the sound of our signals. Namely, regardless of the partial which changed and its manner of change, an envelope shape change was noticeable. Literature also states [12], that the signal shape change which depends on the relative relationship of harmonic phases, influences the creation of „bits“, which are critical for the perception of inharmonicity of a complex sound.

Obtained values from both described experiments show good compliance with the results reached by others, mentioned in the Introduction of the paper.

The remaining unresolved issue regards the link of connection of a just noticeable difference in a bell's spectral structure with the value of partials and their drop times. Since no data has been found in the literature to support this, we deem that anomalies in the results could be explained by understanding the functional dependency of these values.

REFERENCES

[1] A. Samolov, M. Mijić, Subjektivna prepoznatljivost nesavršenosti zvuka crkvenog zvona-početna istraživanja, 16. Telfor, 2008, Beograd.

[2] H. Fastl and E. Zwicker, *Psychoacoustics-facts and models*. 3rd ed., Springer-Verlag Berlin Heilderberg, 2007., pp 185-188, pp 239-241

[3] N. Novitski, M. Tervaniemi, M. Huotilainen, and R. Naatanen, "Frequency discrimination at different frequency levels as indexed by electrophysiological and behavioral measures," *Cognitive Brain Research*, Vol. 20, June 2004, pp 26-36.

[4] C. Pantev, R. Oostenveld, A. Engelien, B. Ross and M. Hooke, "Increased auditory cortical representation in musicians," 1998., *Nature* (London) 23, pp 811-814.

[5] A. Shahin, D. Bosnyak, L. Trainor and L. Roberts, "Enhancement of neuroplastic P2 and N1c auditory evoked potentials in musicians," *J. Neurosci*. 23, pp 5545-5552.

[6] T. J. W. Hill and J. R. Summers, "Discrimination of interval size in short tone sequences," 2007., *J. Acoust. Soc. Am*. 121, pp 2376-2383.

[7] R. Parncutt and A. J. Cohen, "Identification of microtonal melodies-effects of scale-step size, serial order and training," *Percept. Psychophys*. 57, pp 835-846.

[8] S. Ternstroem and J. Sundberg, "Acoustics of choir singing," 1986., *Publications of Music Acoustic Committee of the Royal Swedish Academy of Music*, pp 12-22.

[9] W. Lottermoser and Fr. J. Meyer, "Frequenzmessungen an Gesungenen Akkorden," 1960., *Acustica* 10, pp 181-184.

[10] C. Fritz, J. Cross, B. C. J. Moore and J. Woodhouse, "Perceptual thresholds for detecting modifications applied to the acoustical properties of a violin," 2007., *J. Acoust. Soc. Am*. 122, pp 3640-3650.

[11] C. Lin and D. Kewley-Port, "Vowel formant discrimination for high-fidelity speech," 2004., *J. Acoust. Soc. Am.* 116, pp 1224-1233.

[12] B. C. J. Moore, R. B. Peters and B. R. Glasberg, "Tresholds for detection of inharmonicity in complex tones," 1985., *J. Acoust. Soc. Am.* 77, pp 1861-1867.

[13] D. A. Nikjeh, J. J. Lister and S. A. Frisch, "The relationship between pitch discrimination and vocal production: Comparison of vocal and instrumental musicians," 2009., *J. Acoust. Soc. Am*. 125, pp 328-338.