Characteristic Tones and Modes of a Church Bell

Helmut Fleischer

Institute of Mechanics, University of the Federal Armed Forces Munich, Germany. Mail: helmut.fleischer@unibw.de

Introduction

The bell is a linear idiophone. Each partial tone corresponds to a partial vibration of the bell structure. Modern approaches allow for measuring or computing numerous vibration modes. Above all knowing the relevant modes is fundamentally important for the inverse problem of optimisation (Schoofs et al. [1]). Psychoacoustic experiments were performed using spectral reduction of the acoustic signal. The aim was to get an impression of how many and which partial modes are characteristic for a church bell.

Bell under consideration

Figure 1: Minor-third church bell considered in the investigation

The results refer to a small modern church bell (minor-third, strike note C_6, 37 kg bronze; made in Bavaria, *cf.* Figure 1). Details are given in [2].

Analysis of the bell sound

The psychoacoustic experiments described in the following were performed by Franziska Lenski during her diploma thesis. Inside a room the bell was hit with a hammer at the sound bow. In a distance of 4 m the sound was recorded on DAT and converted into a .wav-file. In contrast to a parallel study [3], an aurally-related analysis was performed using the program VIPER (VIsual PERception of audio signals), supplied by Cortex Instruments, Regensburg, Germany.

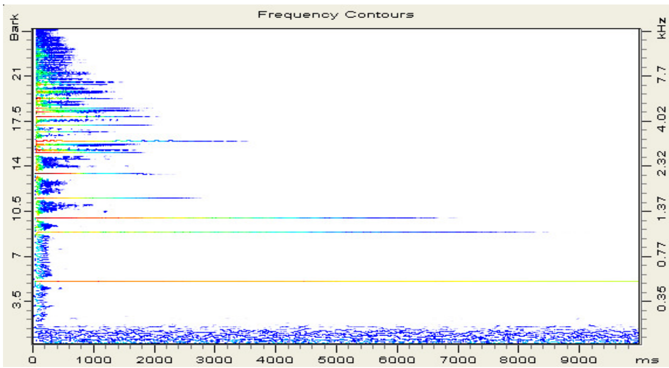

Figure.2: VIPER spectrogram of the original bell sound

The processing software accounts for basic findings of psychoacoustics; details are given in [2]. Figure 2 shows the original time-dependent VIPER spectrum. The components are plotted as a function of time (abscissa, 0 s - 10 s) and critical band rate (left ordinate, 0 Bark - 24 Bark) and frequency (right ordinate, 10 Hz - 16 kHz), respectively. Horizontal lines indicate tones. The level is encoded in colours (white and blue means low level, red high level).

Psychoacoustics: Pair comparisons

Resynthesis is provided by the software. Tentative experiments have shown that slight differences appear between the original and the resynthesised sounds which can be audible to a vigilant listener. So the resynthesised unmodified signal (Figure 2) was taken as a reference and compared to resynthesised signals, whose spectra had been reduced.

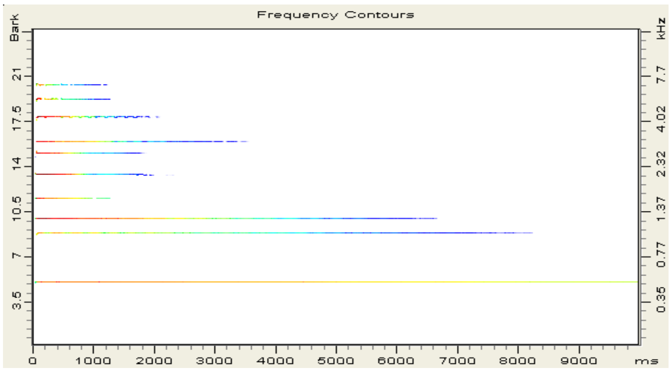

Figure 3: VIPER spectrogram of the bell sound considering masking and dropping all components below 45 dB

Pairs of sounds (3 s, 1 s break, 3 s), the original one and a spectrally reduced one, were binaurally presented via headphones at 80 dB. Ten subjects of different age, no bell specialists and most of them untrained, took part in the experiments. In a yes-no procedure they had to decide whether there was any difference audible or not.

The result was that the VIPER spectrum can further be reduced. No difference was audible in 60 percent between the original spectrum (Figure 2) and the reduced spectrum as shown in Figure 3. This means that ten partial tones represent a characteristic spectral core in a wider sense. They constitute a sound which cannot be distinguished from the original bell sound in the majority of cases. Transposing the spectrum by an octave and adding noise confirmed this finding.

Psychoacoustics: Likeness to a bell sound

In a second series the subjects had to solve a totally different task. They listened to single sounds resynthesised from VIPER spectra such as Figures 2 and 3. The spectra had been reduced to different extents. In a yes-no procedure the subjects were asked whether, in their opinion, the sound represented a bell or not. The main result is that the sound resynthesised from Figure 4 was fully judged as a bell sound. A similar result, which includes three further partials, was found by spectral synthesis disregarding phase relations [3].

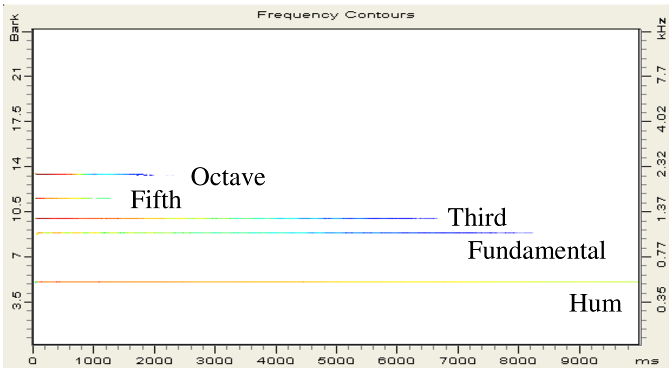

Figure 4: Reduced VIPER spectrogram of the bell sound containing the five partials of the principal region

The main result is that the tones of the principal region (hum or suboctave, fundamental or prime, minor third or tierce, fifth or quint. octave or nominal; see Figure 4), which are a subset of the ten partials in Figure 3, play a central role. A reduced sound containing these five partial tones is consistently perceived as a bell sound by all subjects.

Mechanics: Vibrations of the bell

Operating deflection shapes of the bell structure were investigated in the frequency range up to 5 kHz. The bell was excited at the inside of the sound bow by a mini shaker. A Laser Doppler vibrometer scanned the motion of the surface. Modal Analysis of the same bell [4] using impact hammer and accelerometer (fixed response) confirms that the results compare to the shapes and frequencies of eigenmodes.

Fourteen modes are compiled in Figure 5. The results of Laser vibrometry (blue) are superimposed to a black and white picture of the bell. The magnitude of the vibration, as measured in the direction of the Laser beam, is encoded in lightness. Dark blue denotes nodal lines and light blue antinodes. Results are arranged according to the number *m* of nodal meridians and the number *n* including, where necessary, location of nodal circles. Frequencies are normalised to the frequency of the 2,1-mode ($m = 2$ nodal meridians, $n = 1$ nodal circle), which generates the fundamental.

Discussion

In preparation of the psychoacoustic part of the investigation, the sound signal of the bell was analysed by means of an aurally-related software. The auditory spectra were reduced to different extents and resynthesised. Two series of hearing experiments were executed.

The first one was intended to find the audible part of the spectrum by comparing reduced signals to the complete one. The subjects had to indicate any difference. High congruence was found between the sounds according to Figures 2 and 3. If the sound includes the ten partials tones displayed in Figure 3, in the majority of cases subjects were not able to distinguish it from the complete bell sound as resynthesised from the spectrum of Figure 2. These ten components can be denoted as characteristic in a wider sense.

In the second series the subjects had to judge whether they associated a single sound to a bell or not. Thus, their expecta-

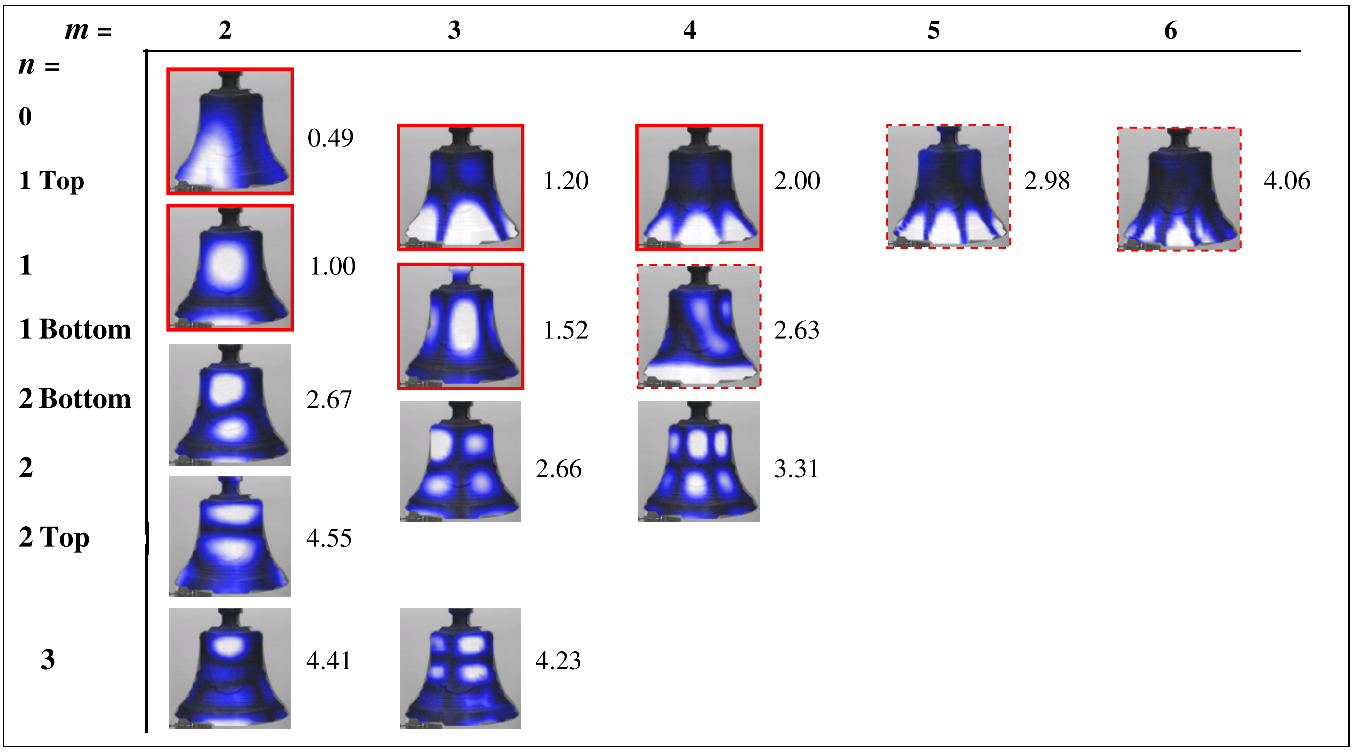

Figure 5: Operating deflection shapes (Chladni type) of the bell with the intervals normalised by the frequency of the fundamental

tions with regard to a bell sound were checked in order to find the indispensable spectral core. Not only the signal according to Figure 3 was fully categorised as a bell sound, but also the reduced spectrum of Figure 4.

This finding emphasises the significance of the principal region: The five partials hum, fundamental, (minor) third, fifth, and octave are characteristic for the bell sound in a closer sense. This fact, well-known in literature (e.g. [5], Lehr [1]), is once more approved by our investigation. In the main, the results agree with those of [3] based on an FFT analysis with subsequent additive synthesis disregarding phase relations. In this parallel investigation the five principal (plus additional three) tones proved sufficient for a good auralisation of a bell sound.

What this means in terms of the mechanical vibration can be taken from Figure 5. Each partial mode corresponds to a partial tone of the same frequency. Solid red frames indicate the modes, characteristic in a closer sense, that generate the five tones displayed in the reduced spectrum of Figure 4. Three further modes (tenth, twelfth and double octave, framed by broken lines) could play an additional role according to [3]. Another two tones/modes at 4.56 kHz (most probably the second on bottom of Figure 5) and 5.52 kHz (beyond the frequency range investigated and therefore not part of Figure 5) complete the core which is aurally relevant.

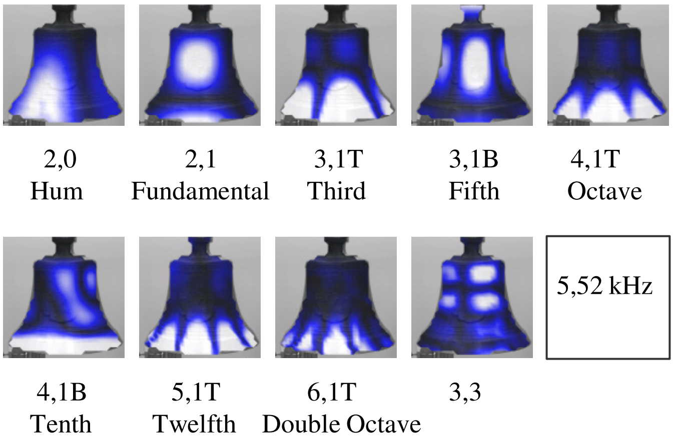

Figure 6: Characteristic vibration modes of the bell

The mechanical vibrations displayed in Figure 6 define different sets according to the psychoacoustic criteria. The modes are identified by the numbers *m* of nodal meridians and *n* of nodal circles. The character T ("Top") indicates that the nodal circle is close to the waist, B ("Bottom") that it is close to the sound bow. Terms used in campanology for the denomination of the corresponding partial tones are added.

The ten vibration modes of Figure 6, as a whole, generate the partial tones which proved as sufficient to constitute a sound indistinguishable from the original bell sound in the majority of cases. They can be regarded as characteristic in a wider sense. The five partial tones/modes in the upper row of Figure 6 are of special interest since they bear the actual information. They represent the very core, characteristic in a closer sense, which is indispensable for aurally identifying a sound as a bell sound.

Conclusions

The aim of the investigation was to identify the characteristic modes of a church bell by hearing experiments. While discussing the results it should be kept in mind that the experiments refer to a small bell, excited by a hammer. Hitting the bell by a clapper and investigating swinging larger bells could lead to different results.

Modern techniques (Modal Analysis [4,5] or Laser vibrometry; see Figures 5 and 6) allow for measuring numerous vibration shapes and frequencies. Numerical approaches (Finite Element Method [4,6]) enable computing a multitude of vibration modes. Inversely, optimisation tools [1] offer the possibility to give the partial frequencies and to find the corresponding bell structure.

Above all the optimisation task makes evident that it is fundamentally important to know the quantity and the types of the relevant modes. To identify the characteristic components, vibration measurements and hearing experiments were carried out in parallel. Aurally-related analysis and spectral reduction were applied to the acoustic signal. Subjects had to evaluate the resynthesised sounds, more or less reduced, in terms of two criteria. On the basis of the psychoacoustic results the role of the modes can be assessed.

The ten partial tones/modes assembled in Figure 6 proved as characteristic in a wider sense. They constitute a sound which can practically not be distinguished from the original bell sound.

For many applications this requirement can be weakened in the sense that the sound may be distinguishable from the original but must be plainly associated to a bell. With respect to this criterion the five partial tones/modes in the upper row of Figure 6 represent the very core. The hearing experiments indicate that these five to ten partial tones/modes constitute the bell spectrum and include the relevant information.

The range for choice depends on the setting of the task. The five partial tones/modes of the principal region (upper row in Figure 6) are indispensible to make a bell sound sound like a bell. Adding the five partial tones/modes in the lower row of Figure 6 completes the spectrum such, that the resulting sound practically compares to the original acoustic signal of the bell. However the choice may be, the selection is well motivated and avoids arbitrariness.

Literature

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