The Acoustics of Campaniforms

by Debbie Menken

Debbie Menken of the Summit Assembly of God Church in Roseville, Minnesota wrote this article for her final research paper for the Acoustics of Music Class at the University of Minnesota. As a member of AGEHR she was inspired to do this research because of her involvement in directing and playing of handbells. Her curiosity in the acoustics of their sound motivated her to do this paper for which she received an A!!

Campaniforms, bells, are extremely fascinating and complex musical instruments when analyzed in terms of physical acoustics. Tinntanabula, small bells and handbells in particular, have some unique characteristics different from tower bells. The matters most valid to acoustical considerations are: the scientific elements of bell manufacture, components of bell timbre, and the character of bell tone envelope and its relation to novelty rings. A more complete understanding of these topics commands an even greater respect and appreciation of bells.

Scientific Elements of Bell Manufacture

In early bell history when measurements and calculations lacked precision and the many mysteries of bells were not yet solved, much of bell founding was left to chance. In today's technological world bells are accurately designed with regards to metallurgy, dimensions, weight, shape and profile.

Bells are cast of bell metal, bronze, consisting of 80% copper and 20% tin. This alloy has been used for its inherent vibrating characteristics. Too much copper sharpens the pitch, and too much tin flattens the pitch and makes the bell brittle. History records accounts of experiments with silver and slight variations in the proportions of one metal to the other, but this is presumed to be because of impurities in the copper of ancient times. The refined copper of today affords a superior quality of casting.

The dimensions of a bell are essential to good bell timbre (tone quality), to good intonation, and to volume. Most bells are designed so that their height and diameter will determine pitch. If the dimensions of two bells are proportional but they differ in size, the larger bell will emit a lower pitch. The height of a tower bell should be approximately twelve times its thickness, and the ratio of diameter (at mouth) to height (to shoulder) should be approximately 15 to 11 ½, respectively. The history of church tower bells dichotomized when the lowland countries developed bells for harmonies and England had modified her bells to be best suited for chiming and the demands of change ringing. In order to facilitate dexterity in rapid change ringing, the English shortened their unwieldy tower bells to make them swing easier. Shortening sharpens the bell and makes it less rich by eliminating partials. Volume is proportional to size; a good tower bell can easily have a sound intensity level of 95 dB (decibels).

The frequency of the pitch of a bell is inversely proportional to the cube root of its weight.¹

\[ \text{bell} \approx \frac{3}{\sqrt[3]{W}} \]

In other words, all other factors remaining constant, the heavier the bell the lower the pitch.

Shape and profile of bells are of prime importance. Bells are to be thinnest at the sound bow, this thickness must be tapered upward to a third of the width or else the bell will sound dull and lack resonance. Bells in tune from the mold are said to have a “maidan peal;” this is rare and usually not desired, especially in handbells which are lathed and buffed to a jeweler’s polish. After a bell is cast, its characteristic form must remain through the tuning process; if the bell is flat, grinding the lower edge will raise the pitch and thinning the bell will flatten the pitch. Even though handbells sound one octave higher than written, due to their proportions, i.e., size, weight, and thickness, the pitch range of handbells is comparable to tower bells. Their size is smaller and weight is less (which would both cause the pitch to be higher), but the thinness of the bell compensates for size and weight.

and makes the pitch lower.

Old tower bells were tuned diatonically to the Pythagorean scale. The syntonic comma (the difference between true pitch of a Major third and the Pythagorean Major third) of that scale is 22 cents (hundredths of a semitone). This would be the error in intonation of a perfectly tuned primitive bell. Contemporary bell manufacturers, such as Schulmerich Carillons, whose factory I was privileged to visit and tour last summer, tune handbells chromatically in equal temperament and are accurate within 5 cents.

Modern bell quality can largely be attributed to the advancement of modern science and the achievements of bell manufacturers.

**Components of Bell Timbre**

Bell timbre is unique because of the partials it is comprised of. Most musical instruments sound more than one frequency simultaneously. These additional notes are called harmonics, overtones, or partials. In every tone there is the fundamental pitch (the most salient tone), the second harmonic, which is less intense and sounds one octave above the fundamental, the third harmonic, which is a fifth above the second or a twelfth above the fundamental, etc. Below are the first 16 notes in the harmonic series for low C:

The tone quality of an instrument is established by the presence and intensity of its certain emphasized overtones.

Pitch is described in terms of frequency, which means the number of oscillations (complete cycles of vibration) per second. A string playing middle C will vibrate back and forth about 264 times a second — C has a frequency of approximately 264 cps (cycles per second). The second harmonic is twice the frequency of the fundamental, the third is three times the fundamental frequency, the fourth — four times, etc. Therefore, if low C has a frequency of 66 cps, the second harmonic is 132, third 198, fourth 264, fifth 330, sixth 396, seventh 462, eighth 528, ninth 594, tenth 660, etc.

Harmonics are created by various modes of vibration. When a whole string vibrates the fundamental sounds, this is mode 1 (see A). When the string vibrates in two equal parts, sounding the second harmonic, this is called the second mode (see B). The points where the vibrations intersect are called nodes. The nodes are where the harmonics are located (see C). Usually all modes occur at once (see D). This is also the way wind instruments function, except that a column of air is the vibrating medium.

A pure tone, one without any harmonics, can be drawn on an oscilloscope as a sine wave (see A). The second harmonic has twice as many crests and troughs (see B) per the fundamental's period, the interval of time necessary for the wave to make one complete cycle. The third harmonic has three times as many per fundamental's period (see C), etc. When the fundamental and first harmonic sound together, the two waveforms are superimposed (see D). The subsequent waveform of the first three harmonics is more complex (see E), etc. Since the harmonic frequencies are integral multiples of the fundamental, the superpositions coincide to make waveforms in which each recurrent period is identical. Waveforms of this nature are called periodic.

Another relevant acoustical phenomenon is known as subjective tones. When two pitches are played together, third and fourth tones are heard. The addition of two frequencies produces a summation tone and the subtraction of the two creates a difference tone. For example, if F (approximately 176 cps) and C (approximately 264 cps) were played together, subjective tones F (approximately 88 cps) and A (approximately 440 cps) would also sound.

The acoustics of bells encompasses the domain of the harmonic series and subjective tones. Some
of the partials in a bell tone are not in the harmonic series; therefore, they cannot accurately be called harmonics or overtones. A good carillon bell sounds the strike tone (equivalent to the fundamental), the tierce up a minor third from the fundamental, the quint up a perfect fifth from the fundamental, the nominal up an octave from the fundamental, the upper tierce a major tenth above the fundamental, and the upper quint a perfect twelfth above the fundamental. In addition to the many partials above the bell, an octave below the fundamental can be heard which is called the hum tone. English tower bells vary in that the partials above the nominal are missing or too weak to decipher and that the hum tone is a major sixth below the fundamental. It is easily observable that all of these notes of carillon and tower bells do not fit into the harmonic series. Even if the hum tone were considered the fundamental, not all of the subsequent partials would be harmonics.

Tower bells are rich but hard to tune, the strike tone is usually flat, the hum tone is usually sharp but nominal is usually in tune. Slow passages permit all partials to be heard, but rapid passages mask most harmonics and strike tone leaving only the nominal discernible.

It is not known for certain if the hum tone (some question the strike tone also) is an actual vibration present in the air or if it could possibly be an aural illusion — a subjective tone. Even with a limited background in the frequencies of the harmonic series and in the formation of subjective tones, it is possible to test the probability of this hypothesis. A note with a frequency of 100 cps would have a harmonic series as follows (in relation to a bell):

<table>
<thead>
<tr>
<th>Frequency (cps)</th>
<th>Harmonic Number</th>
<th>Intervals from Fundamental</th>
<th>Bell Timbre Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Fundamental</td>
<td>Unison</td>
<td>Hum tone</td>
</tr>
<tr>
<td>200</td>
<td>Second</td>
<td>Octave</td>
<td>Strike tone</td>
</tr>
<tr>
<td>300</td>
<td>Third</td>
<td>Twelfth</td>
<td>Quint</td>
</tr>
<tr>
<td>400</td>
<td>Fourth</td>
<td>2 Octaves</td>
<td>Nominal</td>
</tr>
<tr>
<td>500</td>
<td>Fifth</td>
<td>2 Oct + M3</td>
<td>Upper tierce</td>
</tr>
<tr>
<td>600</td>
<td>Sixth</td>
<td>3 Oct + P5</td>
<td>Upper quint</td>
</tr>
</tbody>
</table>

The subjective tones, difference tone between any two adjacent partials, such as upper quint minus upper tierce (600-500), upper tierce minus nominal (500-400), nominal minus quint (400-300), and quint minus strike tone (300-200), would all produce the hum tone pitch of 100 cps. Any two partials one apart would create the strike tone of 200 cps: upper quint minus nominal (600-400), upper tierce minus quint (500-300). It is possible, therefore, that a bell is built on the approximate harmonic series of the hum tone which subjectively compensates for a missing fundamental.

Handbell harmonics are unlike tower or carillon bells in that they have only one prominent partial which is the twelfth and since it is within the harmonic series of the strike tone, it can be considered a harmonic or overtone. This enables handbells to ring chord progressions in major and minor keys with a minimum of dissonance. Also, the melody is not obscured by an abundance of partials. The handbell overtone, the twelfth, is equivalent to the quint (or upper quint depending on whether you consider the strike or hum tone the fundamental) in tower bells. In applying the subjective tone logic to handbells, it is apparent that a difference tone, twelfth minus fundamental (300-100), or 200 cps or the nominal (one octave above the fundamental), and a summation tone, twelfth plus fundamental (300+100), of 400 cps two octaves above the fundamental could be heard.

Experimenting with my own handbells I found that I could hear the strike tone very easily, and the twelfth by lightly damping the mouth of the bell. I also noted that the twelfth of one bell would excite the bell that is pitched one-twelfth above the first and vice versa causing sympathetic ringing. Hearing the subjective tones was much more difficult and ambiguous, but on several bells I do believe they were audible. The most interesting thing I experienced was hearing what I think was the twelfth above the twelfth.

Partials are created from a bell’s modes. The modes of bells differ from strings and columns of air because they have more than the single dimension of length. In that way, they are more like vibrating plates that have nodal lines and ventral segments (instead of nodes and antinodes). More than 400 vibrating plate modes were discovered by Chladni. The only difference between the vibration of a chime bar (flat plate) and a bell is that the bell plate is fastened on the middle and bent down on the sides. There are two classes of bell modes of vibrations: those with nodal lines that go up and down and those that go around, meridional lines. Partiala are thought to be located on those lines. Below is a drawing of the location of partials on a carillon bell.1

1Arts, Jan, Journal of the Acoustical Society of America, 10, 328 (1939).
1. Hum tone
2. Strike tone
3. Tierce
4. Quint
5. Nominal
6. Upper tierce
7. Upper quint

The hum tone sounds when the whole mass vibrates as one ventral segment; therefore, it has no nodal line.

In handbells, the fundamental-strike tone is formed at the lip and the twelfth is formed in the waist.

**Bell Tone Envelope**

The envelope of a tone is its attack (initiation) and decay (cessation) of sound. A bell tone is characterized by its sharp attack, rapid loss of volume, and richness, but its long duration. An oscilloscope rendering of a bell attack would be similar to this:

The great height of the vertical lines shows the amplitude of the attack, it is loud. It is observable that the attack is rich with harmonics. Since the lines are jagged, the nonperiodic waveform displays that the partials are not within the harmonic series. After 3, 7, and 12 seconds, the waveform grows smaller and smoother demonstrating the decay of non-harmonic partials and diminution of volume.

These drawings display bell tone envelope. As the length of time increases after the clapper has struck the bell, the sound becomes less intense but more pure. The attenuation (diminishing) of a bell tone is very long in duration. A good tower bell will still be 40 dB loud 40 seconds after struck. A bell does not grow silent absolutely gradually, but 2/10 of a second after it is struck it begins to pulsate. This was at once thought to be the result of the beating between two out-of-tune frequencies, but has been found to be from harmonics continuously building up to a maximum volume and then dying out. This is why bells have a built-in vibrato.

**The Acoustics of Handbell Novelty Rings**

Some handbell special effects have direct physical causes. Flippiscato (slapping the bells on the foam-padded table), pizzicato (plucking the clapper while on the table), and thumb damping (playing with gloved thumb on bell) change the envelope, the attack and decay, especially, of a bell tone to varying degrees; so much so that many audiences are very surprised with hearing such unexpected sounds come out of bells.

When a source of sound or a listener is in motion, sound waves reach the ear at a faster or slower rate than they were initiated, depending on speed and direction of the sound source, or listener. In this case the sound waves are perceived as traveling faster or slower than they really are. This results in raising or lowering of pitch. This phenomenon is known as the Doppler effect and is most familiar in the fluctuating pitch of an approaching and passing train whistle.

When a bell is rung in good form (and follows a smooth circular path), when a ringer uses vibrato, or when the ringer uses the gyro ring, the Doppler effect is causing the novel sounds. The most succinct example of the Doppler effect is found in tolling, which is accomplished by extending the arm, wrist and bell forward in a straight line after the strike and swinging the bell like a pendulum straight down, back and forward to ring position. Changing the location of the sound source so drastically results in the sound waves spreading out and piling up so much that an observable change in pitch is perceived.

My intrigue and captivation with the fascinating acoustical complexities of campaniforms is only surpassed by my love of their music. Bells and handbells are certainly two of the most beautiful sounding objects ever cast from bronze.

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2. Curtiss, A. N., JASA, 5, 163 (1933).