FIFTH INTERNATIONAL CONGRESS ON SOUND AND VIBRATION

DECEMBER 15-18, 1997
ADELAIDE, SOUTH AUSTRALIA

Invited Paper

THE BELL -- WHERE DO WE STAND TODAY?

Hervey Bagot

Bagot Bellfoundries
Box 421, North Adelaide SA 5006

ABSTRACT

The Western bell has a 1000-year history of development as a musical instrument. The technical improvements in that time have been a mixture of serendipidity and science. An historical overview is given in this presentation, and some current problems and research mentioned.

About the year 1000 cast bronze bells for use in belltowers began a development from the cylindrical shape borrowed from the East. From then to the present day seven important stages can be seen:

(1) movement to a new (flared) shape which would give an identifiable musical note -- by about year 1200;

(2) appreciation of the design laws for bells in a musical scale (without resort to mechanical tuning) — by 1500;

(3) understanding the vibrational complexities of the bells, leading to the possibility of harmonic tuning -- before 1700;

(4) description (without understanding) of the modal content of the bell -- by 1950;

(5) revelation of the physical significance of the vibrational modes -- by 1980;

(6) building on the past to design and modify bells, using the mathematical and computational tools now available -- from 1980;

(7) improving understanding of correct voicing of bells to good effect -- also in our day.

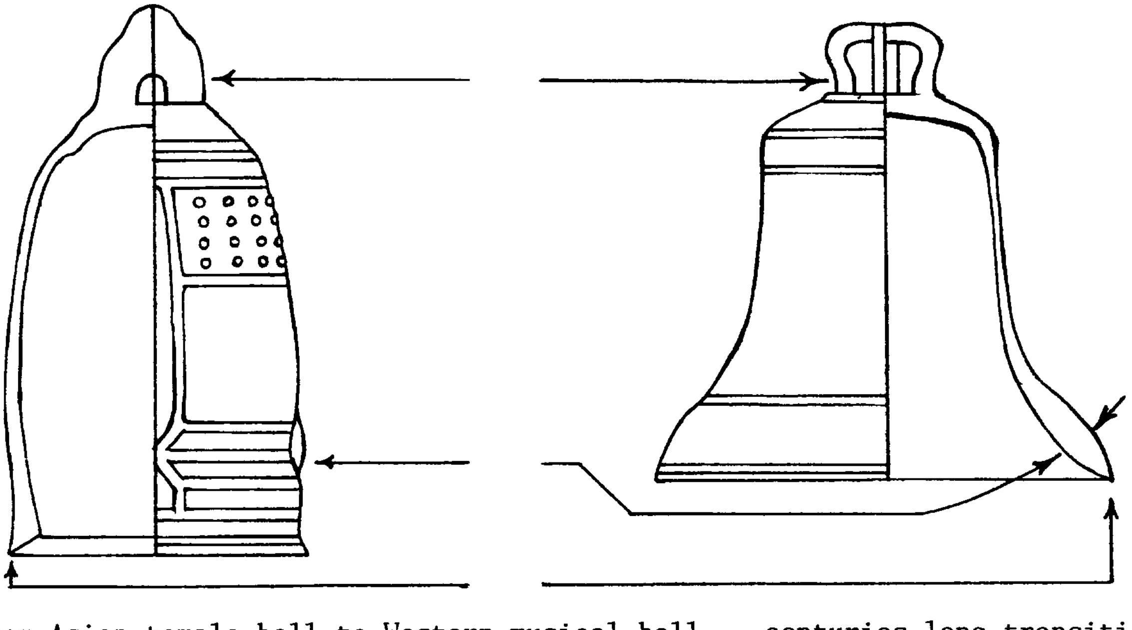
Acknowledgment: The line diagrams on the next succeeding two pages were derived as follows -- (a) Comparison of Oriental and Western bell, from P. Price in "Studies in Japanese Culture II" (University of Michigan 1969). (b) Bell profiles, K. Kramer in "Die Glocke u. ihr Geläute", München 1990.

We stand today at the end of a millenium of development which has seen the Western bell traverse a difficult journey from signal-giver to well-recognized musical instrument. By the "bell" is to be meant for this paper primarily the cast-bronze tower bell as used in, for instance, the 54-bell carillon at Sydney University (basis bell about 2 m mouth diameter, 4300 kg mass, strike-note frequency 206 Hz), the 8-bell change-ringing (swinging) peal at St Peters Cathedral, Adelaide (basis bell about 1.5 m mouth diameter, 2000 kg mass, strike-note frequency 262 Hz), and the 5-bell clock chime at GPO Adelaide (basis bell about 2400 kg). There are many hundreds of examples of such installations in the world today (though not all as heavy as the above).

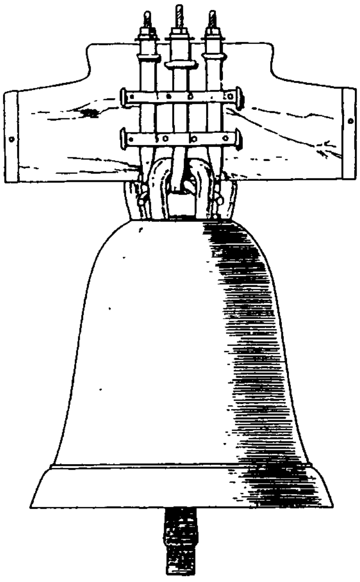
Over the millenia the bell-making process itself has not changed much -- put simply, a volume has to be accurately defined and then molten metal poured in to create a net shape! However, the design of that shape in the West has pre-occupied bellfounders -- its creation and understanding are the subject of this paper.

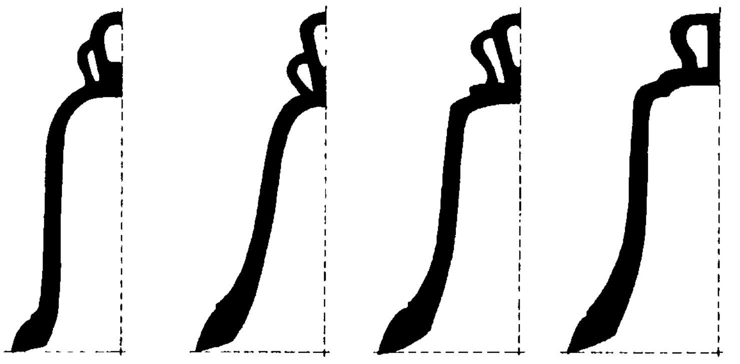
Part of carillon, Sydney University

Before 1000 AD Irish missionary saints had carried with them rudimentary bells formed from sheet metal and with an internal clapper to make a percussive sound. About the year 1000 the larger, heavier cast-bronze bell of cylindrical shape (or the concept of it) arrived in the West from the East via trading routes. The Chinese had already several centuries BC perfected the making of large bronze temple bells (of the cylindrical shape) and smaller chime bells of non-circular section in tuned musical sets -- such as the 65-bell set found in 1978 in the tomb of Marquis Yi (433 BC).



From Asian temple bell to Western musical bell -- centuries-long transition.





Beehive, 12th c. Sugarloaf, 13th c. Transition, 14th c. Gothic 3-tone 15th c.

(At left - Mintard bell (Germany), 11th c.)

Our story starts with the bell's use as instrument of warning rather than of music, and the surviving examples in the West from the 11th century make no concession to musical sensibilities. An example is a bell in Mintard (Germany) in "beehive" profile (1075 mm mouth diameter, appr. 900 kg mass). This bell is the oldest bell in Germany still mounted and serving as a rung bell. Note that a thickening at the rim (which was internal to Asian temple bells) has become external since the hung clapper needs a flat impact area. This thickening later developed into the "soundbow", a significant feature and essential to the creation of the Western bell as we know it today. The partial tones in these early bells are not concordant, and often it is not easy to say what "note" the bell has.

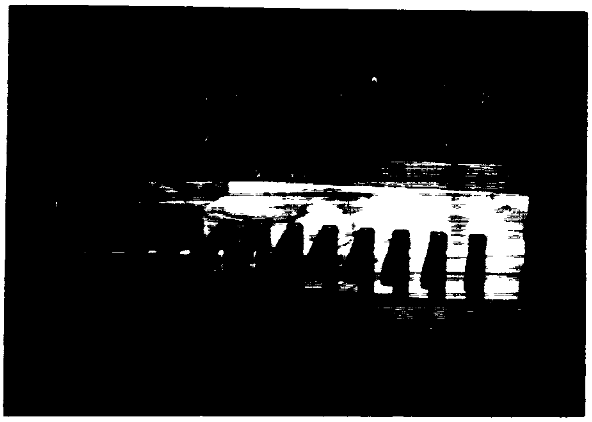
In the 12th century some experimentation with the bell's geometry occurred, and by about year 1200 we see the emergence of a new shape, flared, thicker in parts, known as the "sugarloaf" form. It may be that the development in shape and thickness was driven as much by physical strength requirements as by musical considerations and improved foundry techniques. At all events the musical effect was better -- the bells had a recognizable note, though other tones were not concordant. A 2-bell peal at Niederthalhausen (Germany), about years 1190 and 1230, is a rare surviving example (bell mouth diameters 775 and 700 mm, masses around 200 kg).

A transition occurs now towards a more nearly vertical waist and squarer shoulder. Surviving from year 1311 we have the rich-sounding "Henry" bell at Bamberg (Germany) (1800 mm mouth diameter, 5200 kg mass), an early manifestation of the so-called "Gothic 3-tone" profile in which three important tones in the bell are in satisfying concordance at last. By this time the "correct" laws of proportion have been discovered. Numerous great bells from the 14th and 15th centuries survive, culminating in the "Maria Gloriosa" of Erfurt (Germany), year 1497 (mouth diameter 2580 mm, mass 11450 kg), one of the most beautiful bells ever made.

The 15th century also saw attention turned to the design laws for progression of bells in a musical scale. It needed only a few decades for the law of "dynamic similarity" to be recognized, especially by the Maria Gloriosa bellfounder, Gherd van Wou, who has given us numerous bell-peals from this time. The year 1500 is the high point in the medieval bellfounding art. With good foundry technique, the founder knew now that the musical note of the bells was in inverse relationship to the dimension, and he had only to vary the profile "photographically". Usually the bells came out nearly correct to note as cast, and "tuning" was not considered. The same similarity rules are used for bell peals today, though mechanical tuning is commonly now done in order to satisfy critical ears and also to put into good concord the bells of a particular town where more than one peal might be heard from any standpoint.

We turn now to another period of development in the bell art, with a new high point approached in about the third quarter of the 17th century by carillon builders, especially the Hemony brothers of The Netherlands. Up to now we have spoken only of pealing (swinging) bells, but it is true that in 14th century Flanders some examples of small bell-chimes existed in the new town towers made possible by commercial success. Such chimes (of just a few bells, mounted statically) were usually sounded from a weight-driven mechanism, and the bells were probably not very musical. They signalled the time.

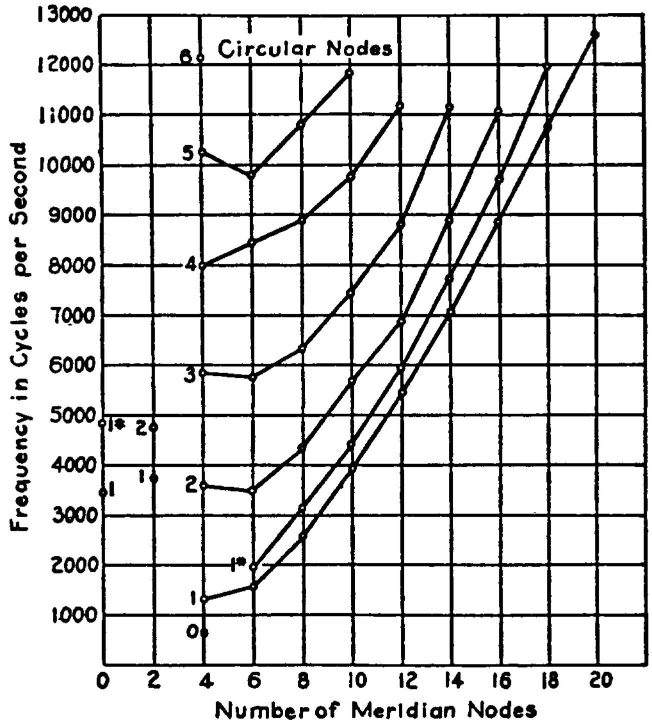
However, by about mid 15th century we see an increase in the numbers of bells in such installations and (up to a point) their musicality, and the bells were being played from a baton keyboard (photo at left). By about 1530

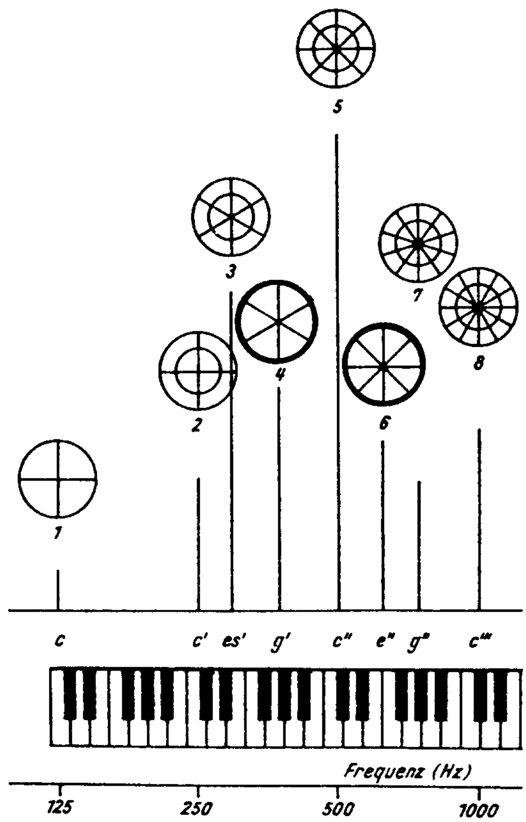


the "carillon" had extended to two octaves (about 18 bells), but the music was still melodic only. With increasing numbers of bells, accurate tuning became an issue. From 1600 we see experiments in tuning the "note" of a bell, by either "shortening" (chiselling the sharp lip) to raise the note slightly, or by "hewing" (chiselling the soundbow to thin it) to lower the note. However, there was no real understanding of the reasons for the results gained, such as they were. About this time the French mathematician Mersenne had described the overtones in a vibrating string. An analytical approach now to the bell sound was pioneered by an Utrecht carillonneur, Jacob van Eyck (who was related to Christiaan Huygens). Van Eyck discovered how to elicit the tones in a bell by external selective stimulation -- he whistled them to appear! -- and thus to identify them. His next step was to propose that tuning could indeed be achieved by modifying the bell shape. Exactly how this knowledge was used by the Hemony brothers in their carillons (of around 1650-1675) is not clear. It is known, however, that they had men rotate the bells on a vertical axis (mouth upward) for the tuning process in which the bells had been made initially a little too thick. The improvements in tuned result made possible the chromatically tuned carillon at this time (3 octaves in extent, about 35 bells). The bells approached today's standard more accurately than ever before (as in the musical figure at right, which is a clear expression of the Gothic 3-tone principle).

Further, deeper understanding of the bell's workings now has to wait until nearly the 20th century. Lord Rayleigh in 1890 (Ref. 1), with the simple aids of hammer, voice, organ pipe, adjustable tuning fork, and Helmholtz resonator, elicited tones and mapped nodal meridians and nodal circles on the bell body. He found some theoretical explanation for the existence of the nodal lines.

F.G. Tyzzer in 1930 (Ref. 2) was able to describe and classify many "partial tones" in the bell using more modern electrical equipment for tone stimulation and recording. Grützmacher's 1959 representation (Ref. 3) of bell

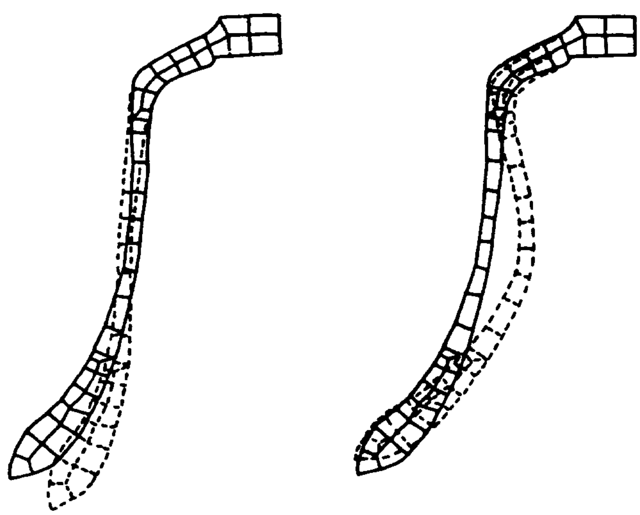




Bell-mode representations of Tyzzer (above) and Grützmacher (right).

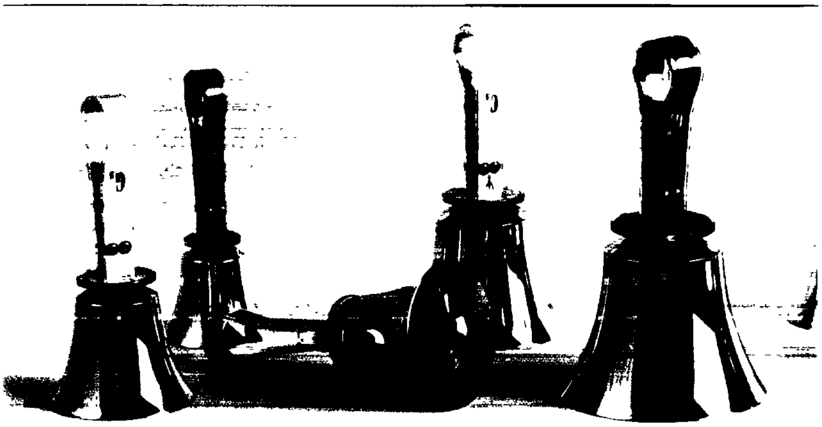
modes is effective. These classifications, however, remained empirical only and without physical explanation.

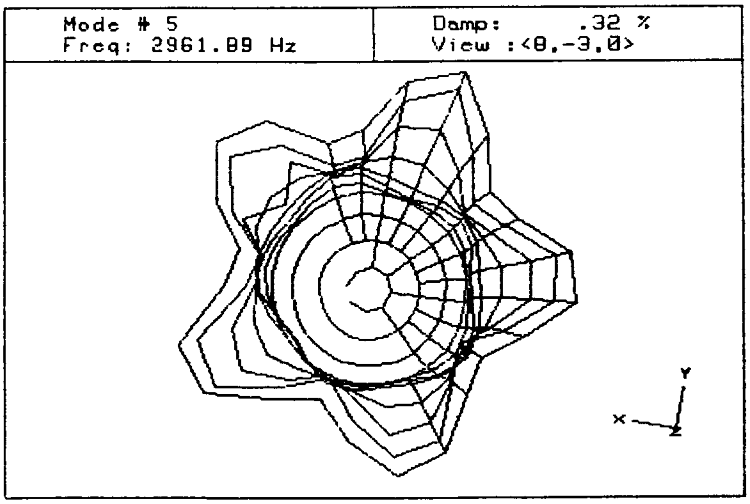
Rational understanding had to await the arrival, in the last quarter of our century, of powerful enough mathematical and computational tools for the solution of this near-intractable problem. Finite-element analysis is basic to this, and R. Perrin and T. Charnley, of Loughborough (UK) have proposed a physical basis for the behaviour of the bell. They classify the normal modes (which are mostly radial-inextensional) into two physical types, the "ring driven" (the soundbow driving the motion) and the "shell driven" (the soundbow anchoring the motion). These concepts are very helpful in an understanding of the bell's sound, its radiation, and the tuning possibilities.



"Ring driven" and "shell driven" bell modes (after Perrin and Charnley, Ref. 4)

Such researches have now made it possible for the bell not only to be described but also to be prescribed. The Dutch bellfounders Royal Eijsbouts now regularly employ finite element design in their bells, both for refinement of existing patterns and for creating bells in different tonalities as required. A recent success (1995) has been the control of certain accidentally degenerate higher tones in large carillon bells, improving the tone.





Some brief mention should be made also of the musical handbell, now quite popular with musical groups in the USA, Britain, and Australia. Some useful new insights have been gained, by experimental application to this class of bell, of modal analysis and time-average holographic interferograms (e.g. at the musical acoustics research laboratory of Prof. T. Rossing at DeKalb (USA).

A better-radiated sound in handbells has been pioneered recently by the Malmark company (USA), in their development of certain large aluminium alloy bells which radiate better into air due to the different material and dimensions. There is better radiation matching to surrounding air.

The story draws to a conclusion. But not without a mention of the materials used in bells. Metals other than the simple bell bronze (80Cu/20Sn) have been tried, such as irons and steels from the mid 19th century to our time, and some very good examples exist especially where correctly "voiced" (see below). However, the iron and steel profiles cannot be the same, either in curve or in size, as for bronze, because of differences in physical properties and acoustical matching to air. Steel bells must be larger than bronze bells for the same note, and this is doubtless a consideration where belfry space is limited. The simple binary copper-tin bronze (first used by the Chinese millenia ago) has generally reigned supreme, largely because of its low internal friction. There have been exceptions in our time, when local shortages of tin forced use of complex copper alloys including zinc/silicon.

The bell has thus arrived as a quite well understood, serious musical instrument. Numerous bellfounders are active in the world today (mostly in Europe), and are busy. Some are active in research, both practical and theoretical. Modern technical understandings of every kind permit attention to be turned to improvement of the bell even further. Better foundry methods are bringing sounder castings, hence longer reverberation times in the bells. New ideas about "voicing" (materials and shape for clappers) open up a new field of possibilities -- we can helpfully view the bell's sound as based on a Fourier transform of the force-time envelope (of clapper impact) over the frequency spectrum of the bell.

Sound "shaping" (i.e. reverberant belfry design) is another area for improvement, somewhat neglected in the past. Modern architectural materials allow quite good control of reverberation as a function of frequency, including in the high-frequency domain where it may be desirable to remove shrill starting transients before broadcast of the sound from a tower.

Questions about the metallurgy persist. Does a bell's sound change over time? -- due perhaps to a very slow phase transformation (from the hard delta intermetallic Cu31Sn8 to another hard phase, the epsilon Cu3Sn).The intermetallics (hard) and the solid solution (ductile) together provide the character of the bell metal in the proportions of copper and tin used. Some experiments in 1996 by the present writer (using four musical handbells each of about 300 g mass, in a vacuum oven) have confirmed his earlier result with a 50 kg tower bell. Annealing for a few hours at 600 degrees Celsius (cf. the 520 degree transformation temperature for the hard delta phase), and slow cooling, led to a lowering of the lowest-mode tone frequency by about 15 cents (100 cents = 1 semitone = 6% frequency change). However, holding the handbells for 100 hours at 300 degrees (cf. the 350 degree transformation temperature for the hard epsilon phase), and slow cooling, led to a <u>rise</u> in frequency of 5 cents (prior anneal at 600 degrees) or 10 cents (no prior anneal at 600 degrees). There also appeared both a coppery colouration and a yellowish colouration on the previously polished golden bronze surfaces, suggesting perhaps a release of copper atoms in a transformation . It is hoped to carry this study further with metallurgical and other tests.

Dr A. Lehr (Netherlands)(Ref. 5) has recently enquired whether centuries-old bells might have undergone changes to internal structure due to their history of millions of soundings. He has reported also the effects on tuning of small, old carillon bells in The Netherlands -- marine industrial atmospheres in some Dutch locations had caused conversion of a bell's surface metal to salts which were shaken off by the active sounding of the bell. This led to a thinning of the bell profile and a lowering in tone frequencies, putting the smaller bells in a carillon out of tune with the larger which were much less affected.

A mystery in the psychoacoustical "strike note" remains -- lower-register bells in a carillon have a strike note but higher register ones (e.g. as pictured above) do not. Yet the musical note-progression appears monotonic to the ear as the bells are sounded through the scale.

Research into many aspects of bells continues, and we can look forward to more published work in the technical journals and in the magazines of the European bell museums and of campanological societies around the world.

REFERENCES

1. Lord Rayleigh, "On bells". Philosophical Magazine (1890), <u>29</u> (No. 176).

2. F.G. Tyzzer, "Characteristics of bell vibrations". Journal of the Franklin Institute (1930), <u>210</u>, 55-66.

3. M. Grützmacher, "Das Teiltonspektrum einer Glocke". Gravesaner Blätter (1959), <u>4</u>, 124-8.

4. R. Perrin and T. Charnley, "Normal modes of the modern English church bell". Journal of Sound and Vibration (1983), <u>90</u>, 20-49.

5. A. Lehr, "Campanologie" (in Flemish). Nationaal Beiaardmuseum, Asten 1996.