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ACOUSTICS OF HISTORICAL CHINESE BELLS

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1. INTRODUCTION

Many ancient Chinese bells, some more than 3000 years old, remain from the time of the Shang and Zhou dynasties. Most of these bells, being oval or almond-shaped, sound two distinctly different notes, depending upon where they are struck. Although small ornamental bells may have existed in India, Assyria, and Egypt as early as 2000 BC, the bells that remain from these early civilizations do not compare to the ancient Chinese bells in size or in quality.

After the 3rd century AD, round temple bells gradually replaced two-tone bells. Although mainly of bronze, large iron bells appeared in some temples around the 12th century. Many cities placed large bells in towers to announce the time of day. The largest known Chinese bell, standing over 4.5 m high, was cast in the 15th century during the reign of the Ming emperor Yongle. In this paper, we discuss the acoustical behavior of some ancient two-tone bells and also some of the round temple bells.

2. BELLS IN ANCIENT CHINA

The earliest known Chinese bells are small clapper bells of clay and copper from the third millennium BC. Beginning with the early Bronze Age (ca. 2000 BC), however, bronze became the material of choice for cast bells, as it remains to this day. The art of casting bronze developed to a high level of sophistication during the Shang dynasty (1766-1123 BC). Most bells were cast using the "piece-mold" technique, which began with a core model of the intended bell in clay. This model served as the imprint for the outer molds, which were produced by applying a layer of clay to the model surface. The outer molds were removed from the model in sections and fired. After firing, the outside of the core model was scraped down to leave a gap of the desired bell thickness between the core and the outer mold. The piece-mold technique was particularly convenient for casting oval or almond-shaped bells, which became the bells of choice, probably because of their two-tone acoustical behavior [1,2].

Although all ancient Chinese musical bells are similar in overall shape, they may be distinguished in four main classes:

nao, with arched rims and large tubular shanks which supported them in the mouth-upward position;
yongzhong, similar in shape to nao but with a ring or loop affixed to the shank so that they could be hung downward, slightly tilted toward the player;
niuzhong, identical in body shape to yongzhong but suspended vertically from simple u-shaped loops;
bo, with level rims and sometimes elaborate suspension devices from which they hang vertically.

Examples of these four classes are shown in Fig. 1.

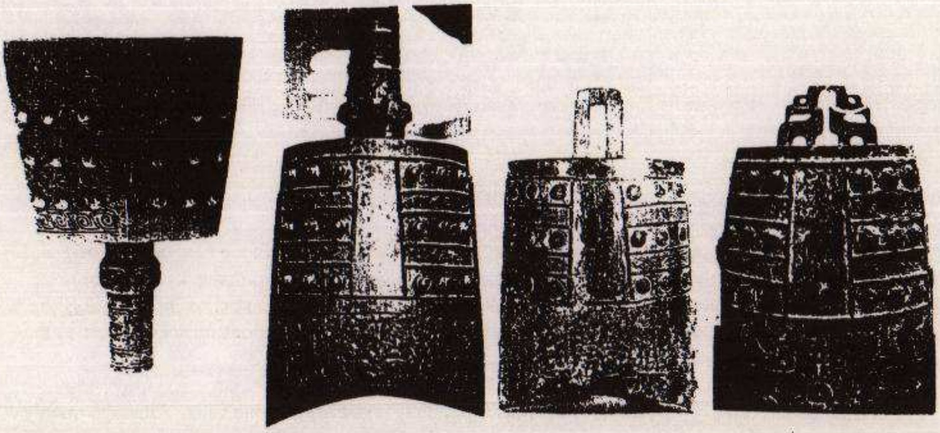

Fig. 1. Examples of four classes of ancient Chinese bells: a) *nao*; b) *yongzhong*; c) *niuzhong*; d) *bo*.

Ancient Chinese bells were richly decorated. One of the most notable decorative features are the *mei* or nipples, large or small, generally arranged into 4 groups of 9, as can be seen in Fig. 1. Within each group of 9 are 3 rows of 3 *mei* each, separated by *zhuan* or ridges. The *gu* or striking area is often richly decorated, and Chinese characters are often engraved in the area between groups of *mei*. Parts of a typical bell are identified in Fig. 2.

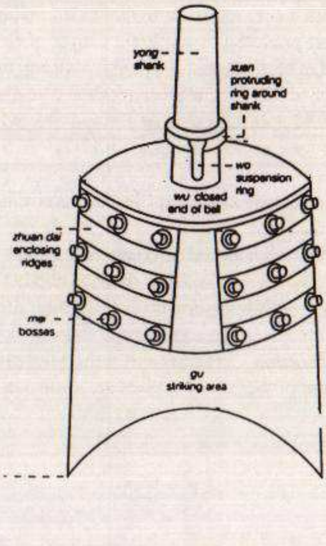

Fig. 2. Parts of a traditional Chinese two-tone bell.

The art of designing and casting ancient bells reached its peak during the Western Zhou (1122-771 BC) and Eastern Zhou (770-249 BC) dynasties. Bell chimes occupied a prominent position in ancient Chinese ritual orchestras. Bells became status-defining objects. It is hardly any wonder that persons of wealth and power coveted bell chimes for their burial tombs.

Most musical bells were manufactured in scaled sets or chimes. They were probably used in all sorts of rituals, as well as in musical performance. Chimes of bells were frequently buried in the tombs of royalty and noblemen, and that is how large numbers of ancient bells have been well preserved through the ages. The most remarkable set of bells discovered to date is the 65-bell set discovered in the tomb of Zeng Hou Yi (Marquis Yi of Zeng) in 1987. These richly-inscribed bells, survived in excellent condition since about 433 BC due to the tomb filling with water. Also found in the tomb were bamboo flutes, panpipes (*xiao*), mouth organs (*sheng*), plucked string instruments (*qin*), drums, and stone chimes.

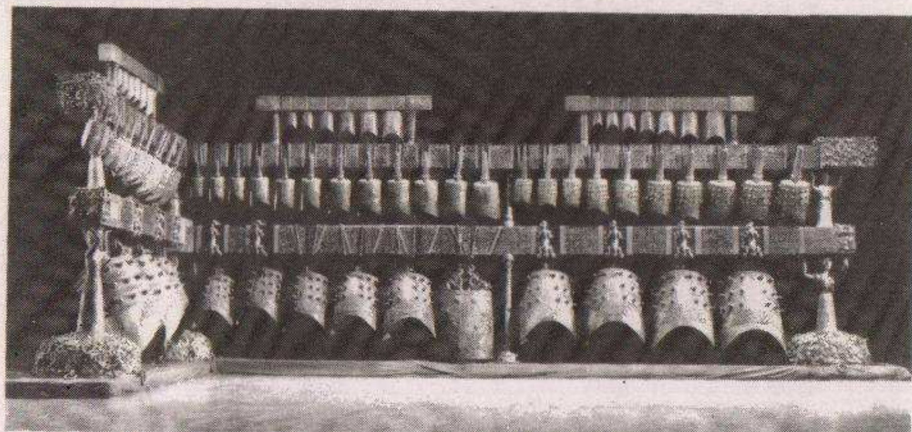

Fig. 3. Chime bells from the tomb of Zeng Hou Yi in Hubei province

Study of the Zeng bells and many other sets of bells has provided musicologists with a great deal of understanding about ancient Chinese customs of musical theory and performance. The richly inscribed Zeng bells provided information about their intended pitch in terms of ancient pitch standards or *lü*. The musical system documented by the Zeng inscriptions gives the names of twelve moveable notes or *yin*, not unlike the do, re, mi of Western tradition. To the four simple *yin* names, *gong, shang, zhi,* and *yu*, are added suffixes such as *jue*, which raises a note by a major third and *zeng*, which raises it by two major thirds [2].

3. VIBRATIONAL MODES OF ANCIENT TWO-TONE BELLS

When struck by its clapper or by a hammer, a bell vibrates in a complex way. In principle, its vibrational motion can be described in terms of a linear combination of the normal modes of vibration whose initial amplitudes are determined by the distortion of the bell when struck. Each partial in the spectrum of the radiated sound corresponds to a normal of vibration.

In a round carillon bell or church bell, it is customary to denote a normal mode of vibration by the number of complete nodal meridians m and the number nodal circles n. The principal modes (m,n), given names such as *hum* $(2,0)$, *prime* $(2,1)$, *third* (3,1), etc., are carefully tuned to the desired frequencies. Similar normal modes are observed in almond-shaped Chinese bells, but because of its elongated shape, each mode becomes a doublet, which we designate as $(m,n)_a$ or $(m,n)_b$, as shown in Fig. 4a. The b-mode has a node at the spine or *xian*, while they a-mode has an anti-node at this location. Striking the bell at the center of the broad face will preferentially excite modes have an anti-node there, such as the $(2,0)_a$, $(3,0)_a$, etc., while striking it about halfway toward the *xian* or spine will preferentially excite modes such as $(2,0)_b$ and $(3,0)$

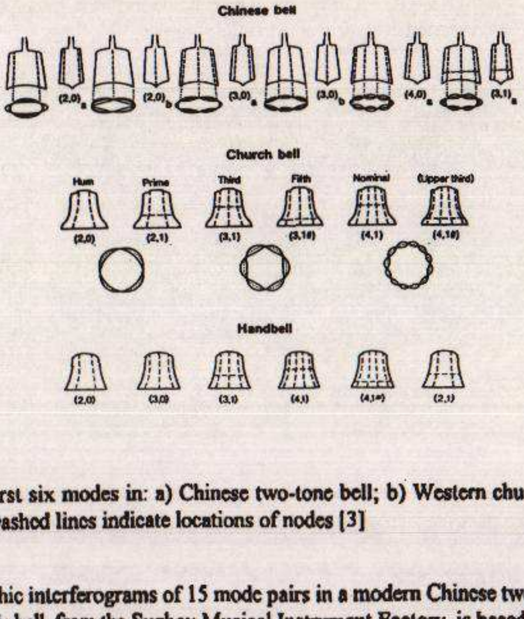

Fig. 4. First six modes in: a) Chinese two-tone bell; b) Western church bell; c) tuned handbell. Dashed lines indicate locations of nodes [3]

Holographic interferograms of 15 mode pairs in a modern Chinese two-tone bell are shown in Fig. 5. The shape of this bell, from the Suzhou Musical Instrument Factory, is based on ancient bells. The ratios of the B-mode to the A-mode frequencies range from 0.89 to 1.19 for the various mode pairs. In most cases, the B-mode has a higher frequency than the A-mode, as in ancient Chinese bells previously studied [5]. The largest splittings occur in the $(2,0)$ and $(4,1)$ mode pairs, although no consistent pattern of mode-splitting size is noted [1]. The thickness of the bell varies from about 9 mm at the center of the faces to 15 mm near the ends. On the inner surface of the bell are six grooves, each approximately 10 mm wide and 10 mm deep. Similar grooves, sometimes found on ancient bells, can have a substantial effect on the mode doublet splitting (and hence on the interval between the A- and B-tones). The fundamental $(2,0)_b$ and $(2,0)_a$ modes, which largely determine the pitches of the two tones are tuned to a minor-third interval (frequency ratio 1.20).

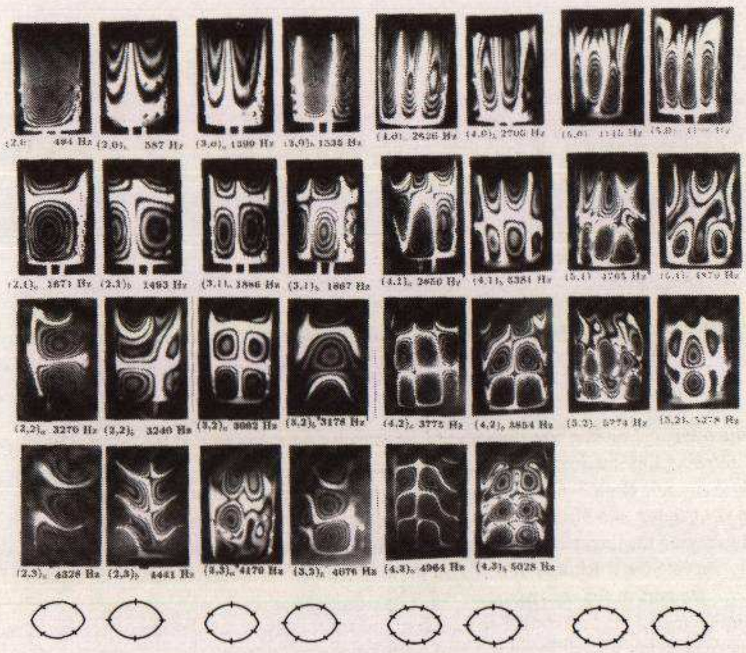

Fig. 5. Holographic interferograms of 15 mode pairs in a modern Chinese two-tone bell [5].

4. INTERVAL BETWEEN THE TWO TONES

The inscriptions on the Zeng Hou Yi bells indicate two intended intervals between the A-tone and B-tone, corresponding to a major third and a minor third in Western notation. In fact, the interval was difficult for ancient bell founders to control to a high degree of accuracy. The measured intervals for the 65 bells, indicated in Fig. 6, show some clustering around 300 cents (minor third) and 400 cents (major third), but they range from about 210 to 490 cents.

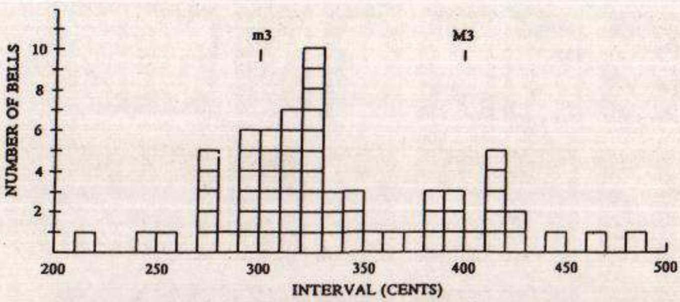

Fig. 6. Histograms showing distribution of A-tone/B-tone intervals in Zeng Hou Yi bells. Intervals are expressed in cents (1/100 of a semitone on the scale of equal temperament) or 1/1200 of an octave [1].

An important question is how the ancient Chinese bell casters controlled the interval between the two tones. The following four methods might have been used:

1. By a suitable choice of the width-to-depth ratio, or the eccentricity of the bell;
2. In *yongzhong* and *niuzhong*, by controlling the height of the arch (*yu*) at the rim;
3. By varying the thickness of different parts of the bell wall during casting;
4. By varying the thickness of different parts of the bell wall after casting, i.e., cutting grooves or troughs in the cold metal.

A priori, one might expect the first method to have been the most convenient. Frequency ratios of mode pairs in almond-shaped cylinders with different width-to-depth ratios are shown in Fig. 7. Frequency splitting ratios in both the (2,0) mode (solid curve) and the (3,0) mode (dashed curve) increase with eccentricity, as expected. This has been further confirmed by finite-element calculations on bell shapes [6].

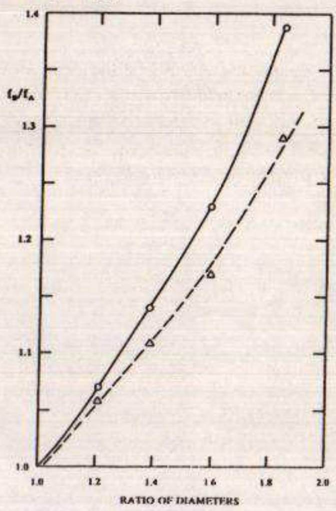

Fig. 7. Frequency splitting ratios of mode pairs in almond-shaped cylinders with different width-to-depth ratios. Solid curve is for the *(2,0)* mode, dashed curve for the *(3,0)* mode [7].

The mode intervals in the Zeng Hou Yi bells are shown in Fig. 8 as a function of the width-to-depth ratio. In the middle row of bells, the measured intervals are quite close to the intended intervals (1.20 or 1.25, respectively, for minor or major third bells). However, there is little or no correlation with the width-to-depth ratios, which range from 1.29 to 1.37 for both groups of bells. In the upper row (filled circles) and bottom row (open circles and triangles), there is not only a lack of correlation between interval and width-to-depth ratio, but the measured intervals do not follow the intended intervals very well either. Note that there are no intended major-third bells in the upper row.

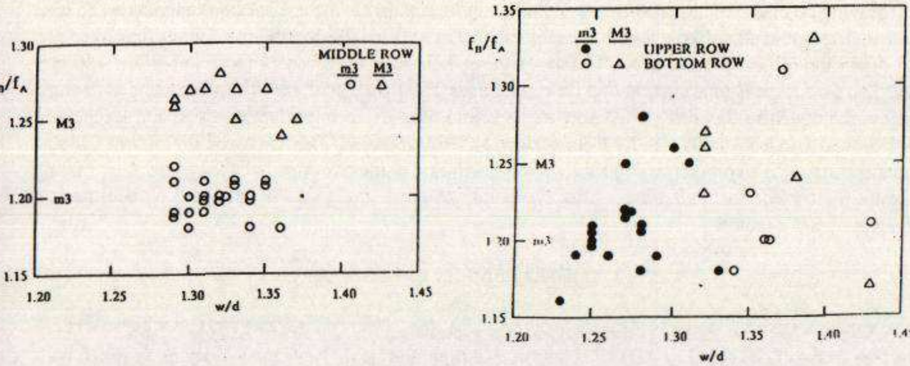

Fig. 8. Interval between A- and B-tones as a function of length-to-depth ratio in the Zeng Hou Yi bells. a) bells in the middle row; b) bells in the upper and bottom rows [1].

Other sets of chime bells show similar behavior. Intervals between the A-tone and the B-tone for all published bells are shown in Fig. 9. There is little, if any, correlation. Apparently, the bell founders did not depend upon the width-to-depth ratio or eccentricity to control the interval between tones.

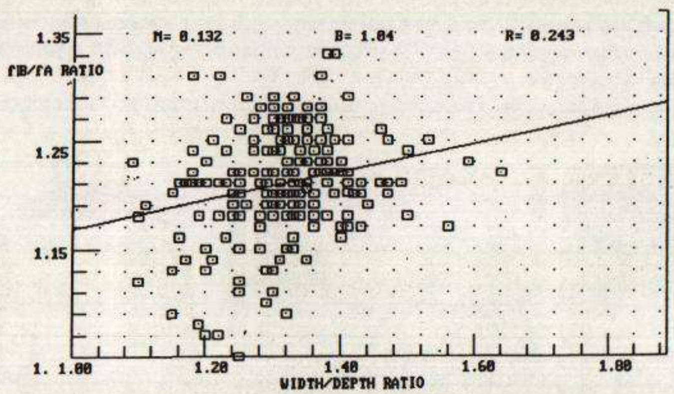

Fig. 9. B-tone/A-tone intervals for 205 Chinese bells

How about the height of the *yu* (mouth cutup) and the thickness contour? Our studies of over 200 bells for which physical measurements are available failed to show any real correlation between these parametrs and the A-tone/B-tone interval either [8]. Did they rely on fine tuning after casting, perhaps by selective thinning or by cutting grooves in the bell? It is difficult to determine, after all these years, whether the bells were carved after casting or whether tuning grooves were added. Relatively few bells have been carefully examined on the inside, and corrosion over the years has obscured surface details.

Having no electronic instruments or reliable tuning standards, the ancient bell founders could tune only by ear. It is not at all unlikely that they cast many bells, selected the ones whose sounds they liked and melted down the others to be re-cast. Tuning of the A-tone may have been a more important selection criterion than the A-tone/B-tone interval. In the case of bells that were inscribed with a note name at the time of casting, the match to this designated note name would become an important criterion for acceptance, although the match in many bells was far from perfect, as we have noted. However well the ancient Chinese bell founders were able to predict or control the tone separation in the two-tone bells they cast, their casting skills were remarkable for their time. After thousands of years, many of the bells still remain musical instruments of high quality!

5. ROUND TEMPLE BELLS

Although two-tone chime bells continued to be cast during the Qin dynasty (221-208 BC) and even into the Han dynasty (206 BC- 220 AD), their importance rapidly waned. New musical styles, in which bells played little or no role, were gaining favor. The few two-tone chime bells remaining from this period appear to be of a quality inferior to the bells from earlier periods. At the same time, expansion of the empire put the Chinese into close contact with cultures of central Asia, including India. With the spread of Buddhism from the third century, a new type of large temple bell, known in China as *fanzhong*, developed in East Asia.

Medieval East Asian temple bells are generally cylindrical or barrel-shaped with a circular cross-sections and a rounded top. They are considerably larger and thicker than the earlier chime bells, and wall thickness is more or less constant throughout the bell. Several temple bells are shown in Fig. 10. The rims of most early temple bells are mostly plane, but some Chinese temple bells have scalloped rims, rims with notches, or small protuberances that suggest tiny feet. The arched suspension device of *fanzhong* often takes the shape of a bent dragon. Their surface is divided into rectangular fields by a banded ornament that has been likened to the belt of a Buddhist priest's robe, and sometimes the strike points are marked by lotus-flower ornaments [9].

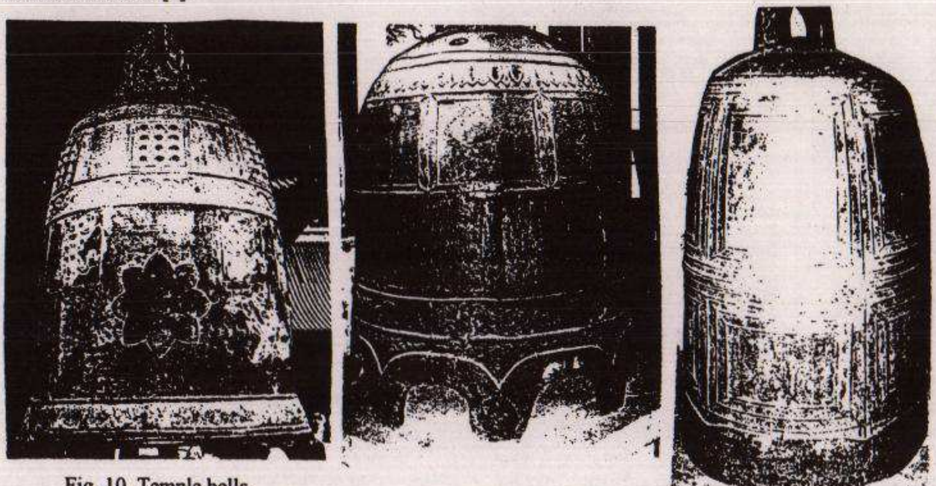

Fig. 10. Temple bells.

Temple bells, such as *fanzhong* in China and similar bells in Korea (*pŏmjong*), Japan (*bonshō*), Burma and Tibet, are generally considered to be patterned after Indian prototypes, but few, if any, bells of this age remain in India, so this remains an open question. In monasteries, both Buddhist and Taoist, *fanzhong* came to be used for both religious and secular purposes, such as signaling time of day. Successive waves of anti-Buddhist persecution resulted in melting down of temple bells, as well as bronze Buddha statues, and so few early bells remain. One of the oldest remaining *fanzhong*, dating from 545 AD, is now in the Nara museum in Japan. From the Tang dynasty (618-907 AD) onward, large bells were placed, together with drums, in towers at the center of every city to announced the beginning and the end of the day.

The casting of large temple bells in China reached its zenith during the Ming dynasty (1368-1620). The largest such bell, shown in Fig. 11, was cast during the reign of the emperor Yong-le (1403-1424). Its bronze body, 4.5 m high with a maximum diameter of 3.3 m, is inscribed with 227,000 characters of Buddhist sutra text; its mass is estimated to be 52,000 kilograms. It is displayed in the "Temple of the Great Bell" in Beijing.

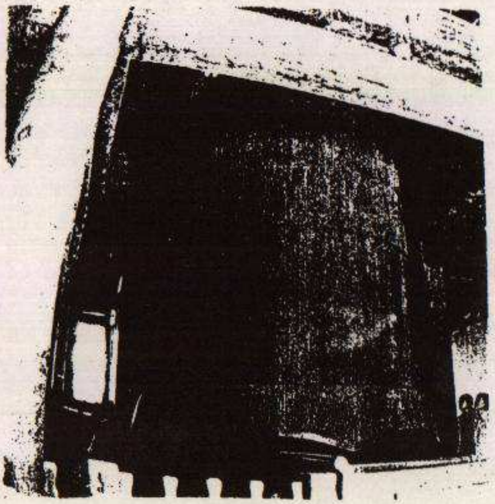

Fig. 11. Yong-le bell (15th century) in Beijing.

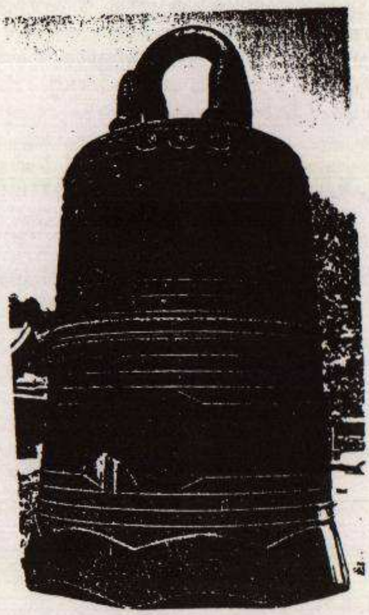

Fig. 12. Iron bell

6. IRON TEMPLE BELLS

From about the 12th century onward, many large bells in China were cast of iron, a much less expensive alternative to bronze. The better-sounding iron bells appear to have been of white cast iron rather than the more common grey cast iron [10]. The shapes and decorations of iron bells were quite similar to bronze bells. An iron bell is shown in Fig. 12.

Iron bells tend to be tonally inferior to bronze bells, largely due to the more rapid rate of sound decay. The faster sound decay with iron or steel bells is often attributed to greater internal loss the material, but this is not necessarily the case (steel, for example, has a low internal loss). A more important factor is the greater efficiency of sound radiation (and thus the greater loss rate of vibrational energy) due to the higher sound velocity in iron or steel. Due to this grater radiation efficiency, the sound of a steel bell is initially greater than a comparable bronze bell, but the sound dies away more rapidly.

7. ACOUSTICS OF TEMPLE BELLS

Few acoustical measurements have been made on *fanzhong* or temple bells. Most large bells in museums are displayed with their rim resting on a platform, and thus they cannot be sounded. Cai, et al. [11] were able to record the sounds of a number of *fanzhong* in the Great Bell Temple in Beijing, from which they measured the frequencies of many partials. However, they had no opportunity to relate these to modes of vibration of the bells.

Mode frequencies of the Yongle bell are shown in Fig. 13. The lowest mode of vibration in this large bell occurs at the very low frequency of 22 Hz [12].

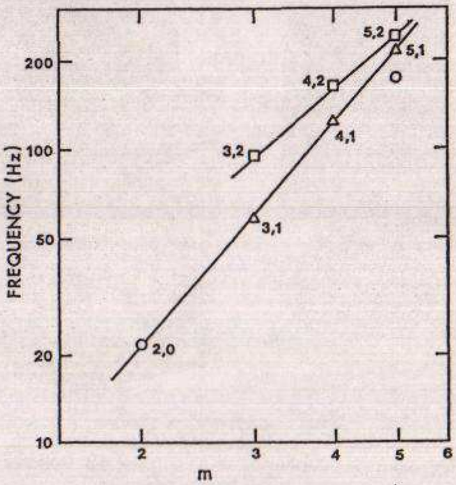

Fig. 13. Mode frequencies of the Yongle temple bell as a function of the number of nodal meridians *m* and nodal circles *n* (data from [12]).

8. CONCLUSION

Bells are a significant part of nearly every culture, and that of ancient China is no exception. During the Bronze Age, two-tone bells became important musical instruments. Many of these ancient bells still remain. After the 3rd century AD, round temple bells gradually replaced two-tone bells. Many cities placed large bells in towers to announce the time of day. Studies of historical Chinese bells continues to be a challenge to acousticians as well as archaeologists and musicologists.

The author thanks his many students and colleagues who have participated in studies of historical Chinese bells. Special thanks go to personnel at the Arthur M. Sackler gallery in Washington and the Shanghai museum in China for allowing access to their valuable collections of bells.

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