TECHNISCHE MECHANIK, Band 25, Heft 1, (2005), 9-16
Manuskripteingang: 05. Mai 2004

Bell Chime, Dragon Washbasin, ...
--- Modern Scientific Information Hidden in Ancient Chinese Science and Technology

Da-Jun Wang

In China, many ancient cultural relics are indeed treasures that combine arts with engineering technology and science. As the carriers of ancient science and technology, they are rich in sophisticated scientific information. Modern science is needed to reveal it. Furthermore, new scientific phenomena, methods and results may be discovered, which is helpful to the development of modern science.
In this paper, the properties of mechanics discovered by investigating the bell chime and dragon washbasin are represented. Some interesting modern research topics motivated from this study are described.

1 Introduction

The famous British scientist, author of the monumental work < Science & Civilisation in China >, Joseph Needham thought that science and technology in ancient China is a cave of glittering treasures.

This, I feel, is a valid statement, moreover some treasures have not been revealed and some need to be re-recognized, re-discovered and re-evaluated. Due to being rich in sophisticated scientific information, modern science is needed to reveal these treasures.

New scientific phenomena, methods and results may be discovered in this study, and helpful to the development of modern science.

Two examples are illustrated in this paper: Bell-chime, the musical bells in ancient China; Dragon washbasin, a plaything used in the ancient Chinese royal court.

2 Ancient Chinese Music Bells --- Bell Chime

2.1 Background on Culture

Great importance was attached to ceremonial music in ancient China, music was not only entertainment but also an important means of education and state administration.

An important history book < Historical Records > suggests that music has two functions: internally it corrects people's minds and externally it distinguishes nobleness from humbleness.

Ancient Chinese musical instruments were classified into eight types: metal – bronze bell, stone – stone chime, earth such as Xun, leather – drum, silk – various of stringed instruments, wood – zhu, etc, gourd – mouth organ, and bamboo – panpipes. The bells were placed at the head of all ancient Chinese instruments. Bells were not only the most important instrument but also the symbol of power. The bell chime had both entertaining and social functions and played an important and particular role in Chinese history.

In about 1,100 B.C., bell chime appeared in China, this kind of music bell possess particular shape. The cross section of a bell is not usually round, but oblate, made up of two pieces of circular arc, see Fig. 1. So it was called oblate bell. About a thousand years later, bell chime reached its prime. The bell chime of Marquis Yi of State Zeng (see Fig. 2) is so far the best bell chime unearthed in China. This set of bronze cast bells is composed of sixty-four music bells with a total weight of 2.5 Tons. They are hung on a L-shaped bell rack in three rows. They are of superb workmanship. This set of bells has come into being in about 433 B.C..

2.2 Music Performance

There are two unique attributes associated with the oblate bell: dual tones and short sound duration.

Each bell can generate two tones and hence it was given the name “dual tones bell”. When struck at the “middle gu” point and the “side gu” point, the bell generates two music sounds of different pitches. The interval between the two tones is harmonic, a major or minor third. The advantage of the dual tone bell is obvious. It enlarges the bell’s function in performance and save material in its manufacturing.

This oblate bell is different from the round bell used in religious services, which has a very long duration. When a round bell is struck, its vibration lasts a long period of time, thus prolonging the sound generated, for fast-tempo melodies, the sound waves interfere with each other so that no music is produced. On the other hand, the vibration of an oblate bell lasts a shorter period of time, so it is suitable for fast-tempo melodies.

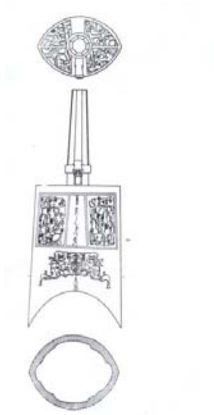


Figure 1. The oblate bell

Figure 2. Bell chime of Marquis Yi of State Zeng

2.3 Scientific Mechanism of Dual Tones: Qualitative and Quantitative Mode Analysis

Why can the oblate bell generate dual tones? The reason lies in its unique shape, whose cross-section is not round but oblate.

For a convenience to explain the principle, we shall start from the difference between the round ring and the oblate ring.

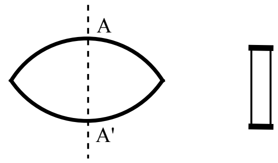
An even round ring is an axi-symmetric structure. When struck at a point, the response, free vibration, is a superposition of all modes. The main component of free vibration is the first mode, the fundamental frequency of sound generated is the fundamental frequency of the ring. When struck at another point, on account of the ring's axi-symmetry, the fundamental frequency of the sound generated is the same with that when struck at the original point. So the round ring can only generate a sound with same fundamental frequency, no matter at what point it is struck.

The case of an even oblate ring is different. It is not axi-symmetric but mirror symmetric with respect to the symmetric line AA' crossing the middle part of the ring. See Fig. 3(a).
The natural modes of this symmetric structure can be divided into two groups: the first group, $\phi_{si}, i = 1,2,...$ are symmetric with respect to the symmetric line associated with a series of natural frequencies, $f_{si}, i = 1,2 ...$. The second group, $\phi_{ai}, i = 1,2,\cdots,$ are anti-symmetric associated with another series of natural frequencies $f_{ai}, i = 1,2,\cdots,$ see Fig. 3.

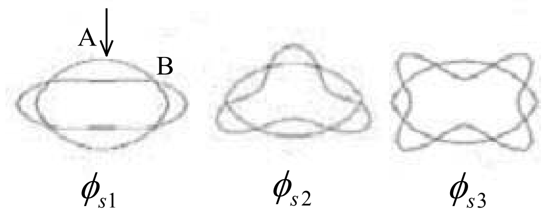
It should be noted, the cross points of ring and symmetric line are one node of all anti-symmetric modes, called middle points, noted by A in Fig. 3.

When the ring is struck at a middle point, the response of the ring is a superposition of all symmetric modes only, the main component is the first symmetric mode, its associated frequency is the fundamental frequency of the sound generated.

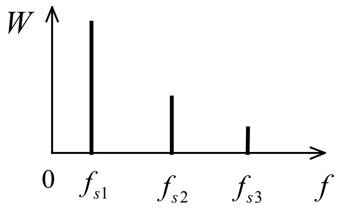
The most interesting fact is that when the another struck point is designed to be positioned right on the node of the first symmetric mode, point B in Fig. 3, this mode will disappear in the vibration response, the associated natural frequency also disappears in the sound generated. In this case, the main component of vibration response is the first anti-symmetric mode, the fundamental frequency of this sound is the natural frequency of the first anti-symmetric mode. Doing so, two sounds with two different fundamental frequencies can be generated. The key is that the two struck points should be positioned on the node of the first symmetric mode and the first anti-symmetric mode respectively.



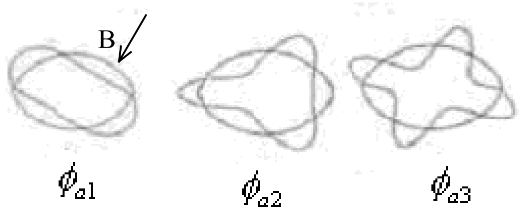
(a) Symmetric line of the oblate ring



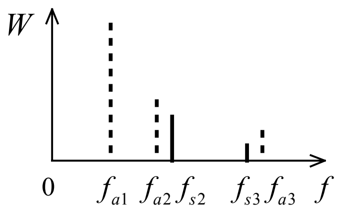
(b) Symmetric modes



(c) Amplitude spectrum of displacement response when the ring is struck at point A



(d) Anti-symmetric modes



(e) Amplitude spectrum of displacement response when the ring is struck at point B

Figure 3. Natural modes and response of an oblate ring

The case of the round bell and oblate bell is similar to that of the round ring and oblate ring, but much more complicated. No matter at what point the round bell is struck, the sound generated has the same fundamental frequency as it is an axi-symmetric structure.

An oblate bell is not an axi-symmetric structure, but a mirror symmetric structure with two symmetric planes. One plane YOZ crosses the middle part of the bell, the other XOZ is perpendicular to it. The modes of the bell can be divided into symmetric and anti-symmetric modes with respect to YOZ plane (see Fig. 4).

If the "middle gu" point is designed to be positioned on the symmetric plane, it is also located on the node line of all anti-symmetric modes. When the bell is struck at this point, the vibration response is a superposition of all symmetric modes, main component being the first symmetric mode, while the associated natural frequency is the fundamental frequency of the sound generated.

If the "side gu" point is designed to be positioned on the node line of the first symmetric mode, when struck at this point, the vibration response is a superposition of all modes, except the first symmetric mode, and the associated natural frequency disappears in the sound generated. The main component of vibration response is the first anti-symmetric mode, while the associated natural frequency is the fundamental frequency of the sound generated. By designing the bell as described above, two sounds with different fundamental frequency can be generated. Designing the bell with an appropriate shape and size, two musical tones with major and minor third interval can be generated.

The modes and natural frequencies of the smallest bell of the bell chime of Marquis Yi were obtained by FEM computation. Applying the symmetry of structure, the computation of frequencies and modes of the whole structure can be reduced to that of four substructures. The DOF of one substructure is ¼ of that of whole structure. The computation cost of an eigenvalue problem is proportional to the cubic of DOF. So the computation cost can be greatly decreased. The details are represented in Wang Dajun et al. (2003).

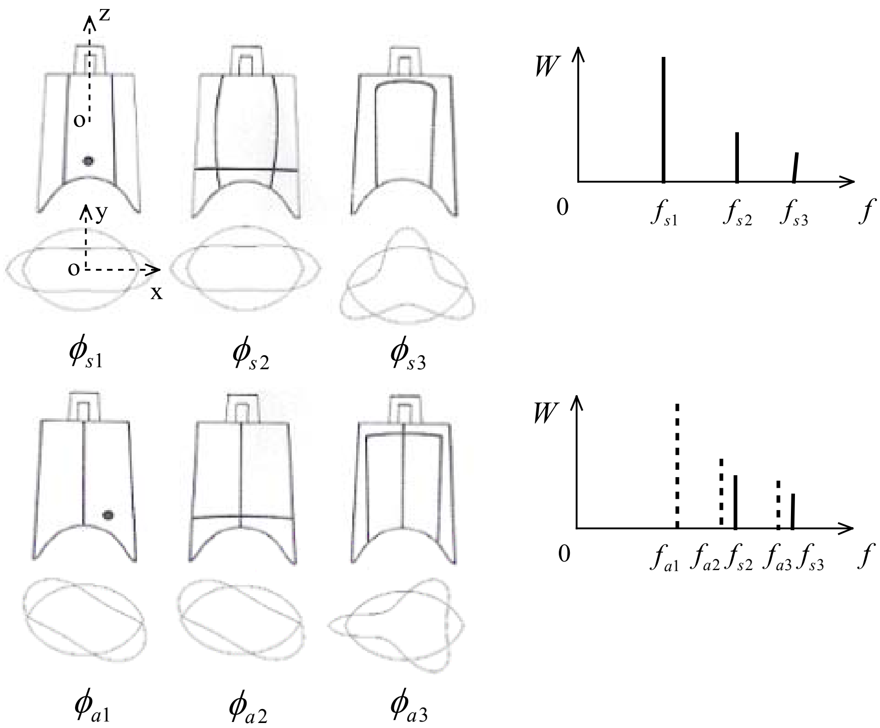


Figure 4. Natural modes and response of an oblate bell

2.4 Scientific Mechanism of Short Duration: Material Damping and Sound Radiation

Why is the duration of sound generated by oblate bell short?

In order to explain this phenomenon, an appropriate experiment was designed. Four circular cylindrical steel shells of the same material and size were used. Three of which were pressed into oblate shape, each with different oblateness. The other shell remained with a round cross-section. Each of the four bells was struck both in a vacuum and in air and the sound duration was measured. In the vacuum, the decay of the sound had nothing to do with the bell's shape, while in the air a difference occurs in their sound duration. The oblateness of one of the three oblate shells is close to that of the common oblate bell. The damping coefficient of this shell is three times of that of shell with round cross-section. That is to say the duration of this oblate shell is one third of that of the circular cylindrical shell.

This phenomenon shows that oblateness of the shell is irrelevant to the energy dissipation caused by the internal friction within the material, but it affects the energy decay from acoustic radiation through the air.

3 Scientific Mystery of Dragon Washbasin

3.1 Enjoying the Interesting Motion of Water in Washbasin

The Dragon Washbasin (Fig. 5) and Fish Washbasin are playthings in the ancient Chinese royal court, and are cast in bronze. Those with dragon shapes cast inside are called Dragon Washbasins. Those with fish shapes are called Fish Washbasins. If the basin is filled with water and its handles are rubbed with one's hands, the basin will make a sweet buzzing sound. Rice-shaped ripples will appear near the four symmetric points on the wall of the basin. If the handles are rubbed harder, four fountains of water drops will spurt up from these points. The maker of the basin cast the mouths of the dragons or the fish just toward these four points. It makes the fountains looks as if they are coming from these mouths. With a skilful hand, the fountain may appear from six, eight, and even fourteen points, see Fig. 6.

The waves, fountains and shimmering dragons present quite an interesting picture. This interesting and mysterious phenomenon has attracted the interest of many people including scientists.

Figure 5. A dragon washbasin and a fish washbasin

Figure 6. Spurting up of four, six and fourteen fountains of water drops

3.2 Dragon Washbasin Phenomena Research

The study of "Dragon Washbasin phenomena" has highlighted three areas of research: The motion of the water-shell system caused by the rubbing action; the surface waves of water in an elastic vessel; generation of low frequency water waves caused by high frequency excitation.

(a) Mechanism of vibration of the basin

Some people think that the mechanism of vibration of the basin is caused by resonance.

Is it resonance? Evidence suggests not. As shown in Fig. 6, in the case of generating four fountains in a fish washbasin, the frequency of vibration of the basin is about 100 Hz. For six fountains, the frequency increased to 300 Hz. For fourteen fountains, the frequency of vibration is as high as 940 Hz. Obviously the frequency of motion of the human hand can not be so high. In fact the hands need not move back and forth to produce the same phenomenon.

The phenomenon is not resonance, but a non-linear vibration, known as self-excited vibration. A typical example is playing the violin. The principle of self-excited vibration can be illustrated for the system with a single degree of freedom (DOF). As the dry friction coefficient is related to the relative velocity between objects. The effect of rubbing the system is equivalent to a negative damping when the velocity of the system is small, but positive damping when the velocity is large, the system will cause a steady motion whose frequency is close to the natural frequency.

The mechanism of generating sound and producing fountains in the Dragon Washbasin is similar, however, much more complicated. The model of this problem is given as follows:

The basin filled with water is regarded as a water-shell coupled system, the hands are regarded as a single DOF system, the motion of the two systems is caused by friction between them, see Fig. 7. At first the natural modes of water-shell system are required to be found experimentally. Then the equations for vibration of the two systems is established. The cubic non-linear velocity terms appear in these equations. The details are represented in Liu Xijun et al. (1998, 2001).

The results from the experimental and numerical studies were obtained.

When the natural frequency of the "hand system" is close to the natural frequency of the second symmetric mode of the basin, the self-excited vibration occurs; the shape and frequency of motion of water-basin system are close to this mode and its associated natural frequency respectively. In this case six fountains of water appear, see Fig. 8.

When the natural frequency of "hand system" is close to the natural frequency of the fourth symmetric mode of the water-basin system, self-excited vibration also occurs. The shape and frequency of motion of water-basin system is close to this mode and its associated frequency respectively, so fourteen fountains of water are produced, see Fig. 9.

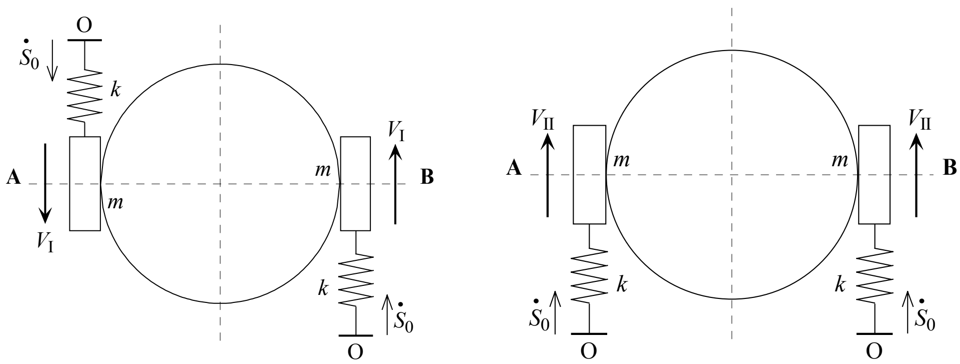
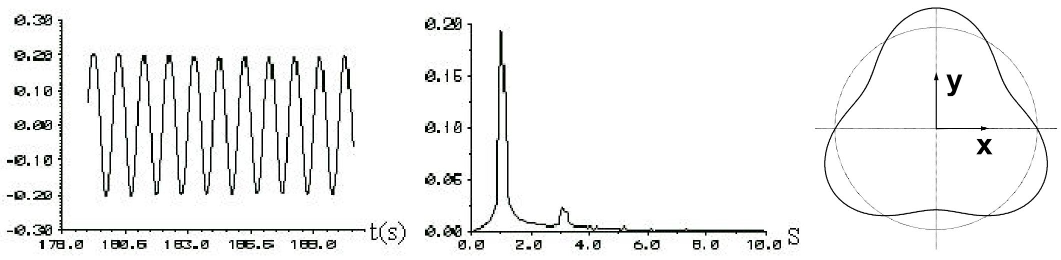


Figure 7. The model of two systems

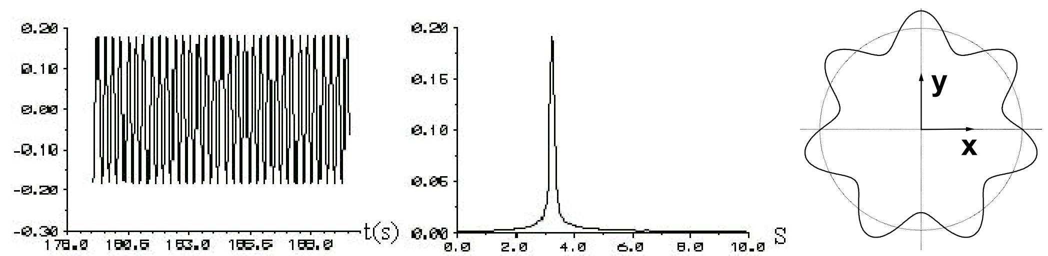


(a) Time history of displacement response at one point of washbasin

(b) Amplitude spectrum of displacement response at one point of washbasin

(c) Motion shape of washbasin

Figure 8. Spurting up of six fountains caused by self-excited vibration



(a) Time history of displacement response at one point of washbasin

(b) Amplitude spectrum of displacement response at one point of washbasin

(c) Motion shape of washbasin

Figure 9. Spurting up fourteen fountains caused by self-excited vibration

(b) The beautiful but complicated motion of water inside the basin

The motion behavior of the water surface changes with the magnitude of motion of the shell. When the motion of the shell is very small, the motion of whole system is linear. With an increase in amplitude of the shell, the secondary waves appear in water surface and the water fountains appear (Shen and Yeh, 1997; Hsieh, 1997; Shang and Shen, 2000).

(c) Generation of gravity water wave with low frequency in an elastic vessel subjected to lateral excitation with high frequency

In the experiment of the mode of the washbasin, we discovered an interesting and important phenomenon. When the frequency of excitation is 115 Hz, resonance occurs; the frequency of motion of the water surface is also 115 Hz. When the frequency of excitation increases to 118 Hz, the motion of water surface suddenly changes into gravity waves with a frequency of 3 Hz and large amplitude. This is a strong non-linear behavior. A series of experiments for cylindrical shell filled with water were carried out. For example a glass cylindrical shell is filled with water (Qing-Ding Wei et al.,1997), when the exciting frequency is 259.4 Hz, resonance occurs, the motion shape of the water surface is the corresponding part of mode, of the water-shell coupled system, with a $\cos 2\theta$ component. When the exciting frequency increases to 266.7 Hz, the motion shape of water surface is close to the Bessel function $J_0(K_0, r)$ associated with a frequency of 2.77 Hz. This motion is close to the first order mode of the gravity water wave in rigid cylindrical tank. The motion of the shell has a beat with a frequency of 2.77 Hz.

Various patterns of motion of water surface can be generated under different frequencies and intensity of exciting force.

According to our theoretical analysis, this phenomenon is basically a Hopf-bifurcation of a dynamic system; it has, however, particular significance and difficulty as it is a fluid-structure interaction system. So far three research problems have been motivated from studying the "Dragon Washbasin phenomenon", they all belong to significant problems of modern science. Some new results have been revealed, and some problems are still open.

4 Remarks

The two examples discussed here, bell chime and dragon washbasin, show a strong relationship between antiquity and modern day science. Ancient Chinese science and technology are rich in sophisticated scientific information, modern science is needed to reveal it; new scientific phenomena, methods and results may be discovered and helpful to development of modern science; Re-evaluation of ancient Chinese science and technology may result from these new discoveries.

Acknowledgment

This work is supported by the National Natural Science Foundation of China (Grant No. 60034010 and 10172064). The author is also grateful to Mr. Yung-Yen Wong and Mr. La-Ke Young in Hong Kong for their help. Special thanks are due to Professor X.J. Liu and J. Chen for their cooperation, some of the text in this paper is extracted from the papers published with them.

References

Chang, C.C.; Shen, M.C.: Nonlinear capillart-gravity waves under an eage condition. *J. Eng. Math.* 38, (2000), 391-402.

Hsieh, D.Y.: Water waves in an elastic vessel. *ACTA MECHANICA SINICA* (English series), Vol. 13, No. 4, Nov. (1997), 289-303.

Liu Xijun, Wang Dajun, Chen Yushu: Self-excited vibration caused by dry friction between two elastic Structures. *ACTA MECHANICA SINICA* (English series) 14, (1998), 319-327.

Liu Xijun, Wang Dajun, Chen Yushu, Zhang Li, Huang Qinghua, Li Junbao: High-order self-excited vibration induced by dry friction between two elastic Structures. *ACTA MECHANICA SINICA* (English series) 17, (2001), 340-347.

Qing-Ding Wei, Da-Jun Wang, Bin Yan, Xiang-Dong Du, Jun Chen: A Visualization study on water spray of Dragon Washbasin. Chapter eleven, Atlas of Visualization III, Edited by the Visualization Society of Japan, CRC Press, (1997), 169-179.

Shen, M.C.; Yeh, N.S.: Exact solution for forced capillary-gravity waves in a circular basin under Hocking's edge Condition. *Wave Motion*, 26, (1997), 117-126.

Wang Dajun, Chen Jian, Wang Huijun: The feature of the dual tones of Chinese music bells. *Mechanics and Its Application* (In Chinese), 25, (2003), 12-16.

Address: Prof. Da-Jun Wang, Dept. of Mechanics and Engineering Science, Peking University, Beijing, 100871, P.R. China.
e-mail: djwang35@yahoo.com.cn