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Short Paper

STUDY OF VIBRATION AND SOUND CHARACTERISTICS OF A COPPER GONG

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ABSTRACT

The gong, a Chinese traditional musical instrument, is generally made of copper in a circular shape. The finite element model of the gong is first constructed to perform theoretical modal analysis (TMA). So, the natural frequencies and corresponding mode shapes can be obtained. Experimental modal analysis (EMA) is also carried out. Results show that both natural frequencies and mode shapes match quite well between TMA and EMA. The radiated sound spectra of the gong are also measured and compared with the vibration modes to identify its principal frequency of radiated sound. Through the validated finite element model, the effect of geometric dimensions and material properties of the gong on its vibration modes and sound characteristics is also studied.

Key Words: gong, vibration, sound, modal analysis, finite element analysis.

I. INTRODUCTION

The copper gong is one of the important Chinese traditional musical instruments. The famous I-Lan Lin-Wu Big Gong (Wang, 1986) in I-Lan, Taiwan, possesses localized characteristics and has a special sound due to its traditional manufacture procedures. Technicians usually make most traditional Chinese musical instruments based on experience. There are few studies investigating their vibration and sound characteristics. In this paper, both theoretical and experimental analyses of the gong's vibration behavior related to its sound characteristics are presented.

Bretos *et al.* (1999) adopted the finite element method to model the free plates and box of a violin, excepting the neck. Through the validated finite element model, the adjustment of violin modal properties can be numerically predicted and fitted to desired resonance peaks. Facchinetti *et al.* (2003) applied finite element analysis (FEA) and experimental mode analysis (EMA) to study the vibration behaviors of reed and pipe in a clarinet. The holographic interferometer was used to observe the vibration modes and eigenfrequencies of the reed. The experimental results showed that some reeds had strong asymmetries; the cause of modal asymmetries lies most probably in the lack of homogeneity of the cane used for the reed due to its natural character. To understand the vibration behavior of musical instruments and their sound mechanisms, experimental measurement techniques are necessary. Skrodzka and Sek (2000) adopted the traditional experimental modal analysis technique to get modal frequencies, modal damping ratios and their corresponding mode shapes of a loudspeaker under different working conditions. The vibration frequencies and mode shapes for a semi-cone woofer and a tweeter were observed. They also studied location effect of the sound box on the speaker quality. This work adopts FEA and EMA to study the vibration characteristics of a copper gong. The sound frequency response is also measured to find the relationship between the dynamic modes and sound qualities. From the verified finite element model, the effect of geometry dimensions and material properties on the principal

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Table 1 Dimensions of copper gong

Variable	H_1 (m)	H_2 (m)	D_1 (m)	D_2 (m)	t (m)	θ
Value	0.03	0.0145	0.0615	0.1125	0.002	15.87°

Table 2 Material properties

Properties	Young's modulus, E (N/m^2)	Density, ρ (kg/m^3)	Poisson's ratio, ν
Copper gong	7.22×10^{10}	9472	0.34

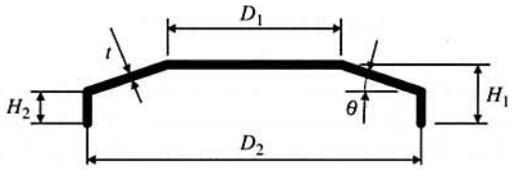
frequency of the gong is also analyzed. The objectives of this work are listed as follows:

1. Create the finite element model for the copper gong and perform the finite element analysis to get the modal parameters and frequency response. At the same time, experimental tests are conducted to obtain the test data for the copper gong. The results including natural frequencies, mode shapes, and frequency response functions were compared between finite element analytical results and experimental data. These procedures can make sure of the correctness of the finite element model.
2. The impact on the gong comes from different striker materials and in different locations. The sound frequency response of the copper gong is then measured to find the relationship between the dynamic modes and sound qualities.
3. The finite element model, verified by the experimental data, will be extended to do more designs and vibration analysis. Different geometric dimensions and materials of gongs will be subjected to finite element analyses. All of these parameters, related to the modal parameters and sound characteristics, investigated to improve the sound qualities of copper gongs and will help manufacturers to make high quality copper gongs.

II. FINITE ELEMENT ANALYSIS

The picture of a Chinese traditional copper gong is shown in Fig. 1(a), and the structure is depicted in Fig. 1(b). The geometric dimensions and material properties are listed in Tables 1 and 2, respectively. The grid of the copper gong for experimental modal testing is plotted in Fig. 2. ANSYS finite element code is applied to perform the modal analysis for the copper gong. The finite element model is shown in Fig. 3. 3-D shell elements are selected to generate the finite element model. In the test, the copper gong is hung up by a nylon tape; therefore, the free-free boundary conditions are applied in the finite element analysis for comparison with the test results.

(a) Traditional Chinese copper gong



(b) Geometric dimensions of copper gong

Fig. 1 Structure and dimensions of the copper gong

III. EXPERIMENTAL WORK

1. Experimental Modal Analysis

In this study, the impact hammer and the accelerometer are used as the actuator and sensor, respectively, to excite and measure the gong frequency response functions, through the electric charge amplifier connected to A and B input modules of BK-3550 frequency spectrum analyzer. The first step in the experimental test is to set up a BK-3550 frequency spectrum analyzer. The frequency range is assigned to be 0-800 Hz, and the resolution is 800 lines. Fig. 2 shows the gong grid. There are 33 test points distributed on the surface of the copper gong. The accelerometer is fixed at point

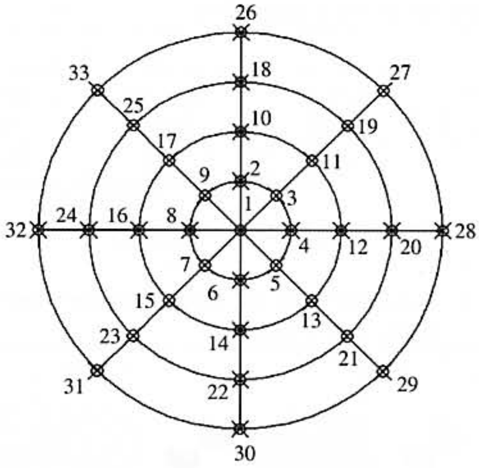


Fig. 2 Grid of copper gong for EMA

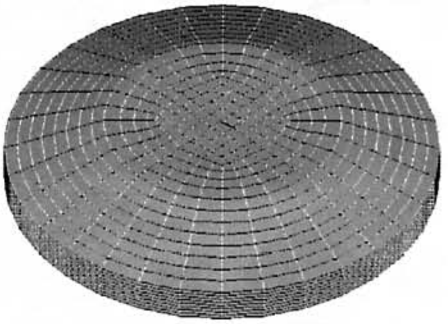


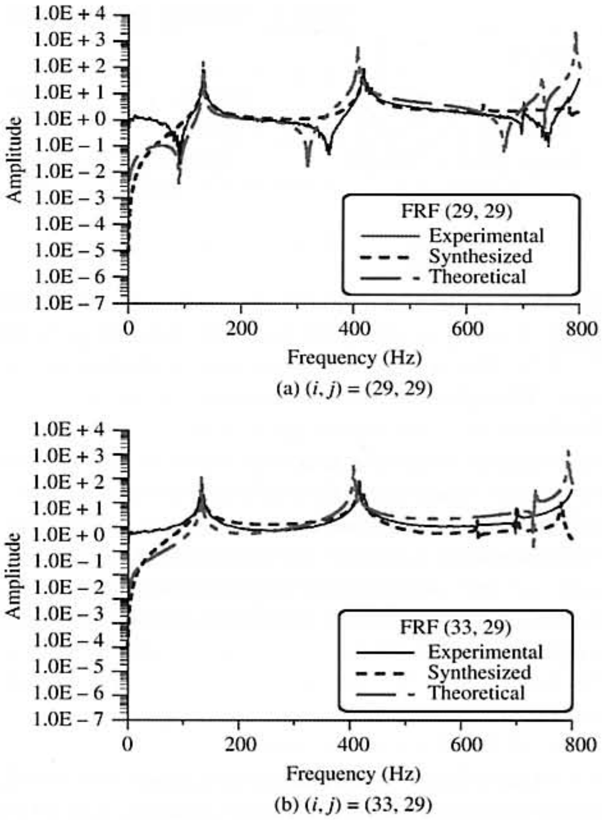
Fig. 3 Finite element mesh of copper gong

29, while the impact hammer will hit each point in-turn. After 33 test points were hit, 33 sets of frequency response functions were obtained. Those functions were combined and processed for curve fitting through CADA-PC software to obtain the modal parameters of the copper gong.

2. Sound Measurement

The microphone is connected to the channel B input module of frequency spectrum analyzer, and the channel A input module will be connected to the impact hammer. The position of microphone relative to the gong has no specified standard. In this test, the distance of the microphone from the copper gong will be within 3-5cm to ensure the radiated sound is higher than background noise.

In testing, the BK-3550 frequency spectrum analyzer is set up first. The range of frequency will effect the acquisition time of the signal. In general, the wider the range of frequency is, the shorter the acquisition time will be. In this test, the peak value of frequency less than 800Hz will be our concern, so the range of frequency setup is set to 1600Hz. In sound measurement, two issues are concerned. The first is the knocking location of the hammer. Let the rubber hammer knock the copper gong at 4 different locations along the radius from the center of the copper gong. The second is the effect of different tip head materials of hammer on the radiated sound. The hammer materials used in the test will be steel, wood, plastic, and rubber.



(a) $(i, j) = (29, 29)$

(b) $(i, j) = (33, 29)$

Fig. 4 Comparison of frequency response functions

IV. RESULTS AND DISCUSSIONS

1. Model Verification

In this section, frequency response functions and modal parameters are compared with each other to verify the finite element model.

(i) Frequencies Response Function (FRF)

The FRF obtained from testing, compared with results obtained from FEA is plotted in Fig. 4. One can observe that the FRF curves are comparable and agree reasonably. The frequency response function is observed with two typical conditions: (1) the response measuring point (j = 29) is the same as the

Table 3 Natural frequencies (Hz) obtained from FEA and EMA

Mode	1	2	3	4	5	6	7
FEA	132.57	132.96	412.33	426.83	429.82	835.03	859.20
EMA	132	137	414	423	428	628	700
Error(%)	-0.40	2.94	0.40	-0.90	-0.43	-17	-22.70

knocking point ($i = 29$); (2) the response measuring point ($j = 29$) is different from the knocking point ($i = 33$). The result for the first case is plotted in Fig. 4(a). The resonant and anti-resonant frequencies can be observed. The higher deviation at the beginning of frequency response function between the test and FEA came from the different boundary conditions.. The results of the second case are shown in Fig. 4(b). The resonant frequencies for both methods agree very well, but the anti-resonant frequencies do not appear due to different locations between knocking point and accelerometer position.

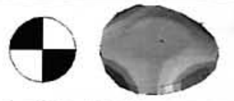
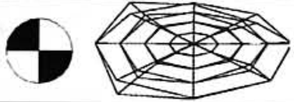
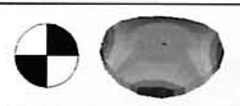
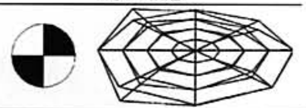
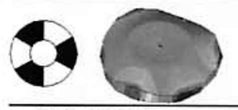
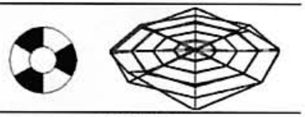
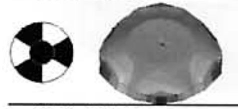
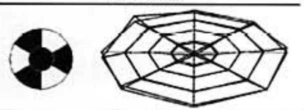
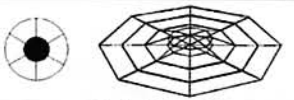
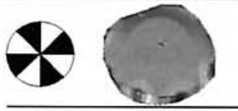
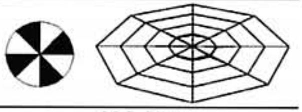
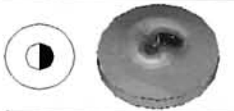
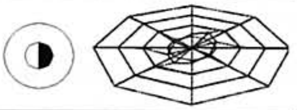
(ii) Modal Parameters

The natural frequencies obtained from FEA, which involved the optimization process, and EMA are listed in Table 3. The first five frequency values for FEA and EMA agree very well. The error percentage is under 3%. That the 6th and 7th frequencies obtained from FEA are much higher than those obtained from EMA may be due to complex surface concavity in the hand-made gong.

The first seven mode shapes observed from EMA and FEA are listed in Table 4. Several observations and physical interpretations are as follows:

1. For the first two modes, the natural frequencies are very close to 132 Hz in FEA. As one can see, their corresponding mode shapes are axi-symmetrical, because the gong is an ideal circular curvature plate in the finite element model. In EMA, the first two natural frequencies reveal slight difference due to the imperfect axisymmetry. For the 1st and 2nd EMA mode shapes, only one corner node at the right-bottom reveals bad data, not matching the FEA mode shape. However, the vibration characteristics can be seen matched accordingly. It is noted that there are two nodal diameter lines across the gong center. These two modes can be characterized as the first circumferential bending modes of the gong. The radiation efficiency of these modes is generally small (Fahy,1985).
2. The third and fourth modes are also axisymmetry modes except that there are three nodal diameter lines. The middle flat circle of the gong reveals a volumetric mode that is beneficial to the sound radiation. For the skew annulus of the gong, there appears to be a second circumferential bending mode.

Table 4 Comparison of mode shapes between FEA and EMA

Mode	FEA	EMA
1	 132.57 Hz	 132 Hz
2	 132.96 Hz	 137 Hz
3	 412.33 Hz	 414 Hz
4	 426.83 Hz	 423 Hz
5	 429.82 Hz	 428 Hz
6	 835.03 Hz	 628 Hz
7	 859.20 Hz	 700 Hz

Note: ● = mode shape upward; ○ = mode shape downward

3. The fifth mode is mainly the volumetric mode for the middle flat circle and is almost still for the skew annulus. This type of vibration mode can radiate sound most efficiently. As discussed later, the principal frequency of sound made by the gong is right at this frequency.
4. The sixth mode shows four nodal diameter lines

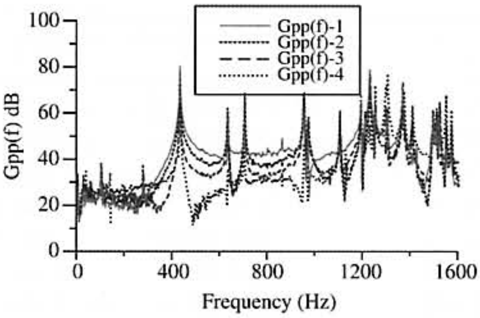


Fig. 5 Sound pressure level of copper gong for different knocking points

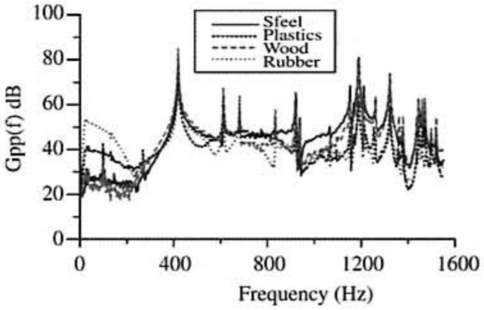


Fig. 6 Sound pressure level of copper gong for different impact heads

along the skew annulus, and the seventh mode reveals one nodal diameter line along the middle flat circle of the gong, while the skew annulus is almost still.

5. In the point of view of sound radiation efficiency, the fifth mode can radiate more efficiently than others and is the dominant mode for sound radiation.

2. Sound Characteristics

The tests for the sound characteristics of copper gong include two types. The first is that the copper gong is knocked at different locations. The second is that different impact hammers are applied to produce the sound.

The sound characteristic curves responding to different knocking points are plotted in Fig. 5. Gpp (f) denotes the auto spectrum of radiated sound in dB *re* 20×10^{-6} Pa. The labels 1-4 indicate the knocking points. For Gpp(f)-1, the knocking point is at the center of the copper gong, Gpp(f)-2 is at 1/3 of the radius, Gpp(f)-3 is at 2/3 of the radius, and Gpp(r)-4 is at the outer edge of the copper gong. Some observations are made as follows:

1. The maximum peak value of Gpp(f) is at $f = 423$ Hz, and the amplitude is lower when the knocking point is far from the center of the copper gong. It can be realized that the hit position on the mode shape maximum response can excite more sound radiation than a hit elsewhere.
2. The other two peak values below 800 Hz are at $f =$ 628 Hz and 700 Hz which are related to modes 6 and 7, respectively. The amplitudes at the two peaks are lower than that of $f = 423$ Hz, because these two mode shapes reveal circumferential bending modes which can result in radiated sound cancellation phenomena (Fahy, 1985).
3. There are three structural modes near $f = 423$ Hz. The most relevant is Mode 5 the volumetric mode which can radiate efficiently. Modes 3 and 4 can also contribute to sound radiation significantly for their frequencies close to Mode 5 are due to the inclined angle design of the skew annulus. The frequency at $f = 423$ Hz can be characterized as the principal frequency of the gong.

For further understanding the relationship between the impact hammers with the sound characteristics of gong, different materials of impact hammers such as steel, plastic, wood, and rubber are applied to strike the gong. Results are plotted in Fig. 6, and the peak values of sound are also at frequency of 423Hz. In general, the vibration amplitude is smaller at high frequency range when the hammer material becomes soft. For low frequency range, the softest material such as the rubber tip head reveals the highest sound level. The wood hammer can result in the highest amplitude in the frequency range of 400Hz to 900Hz. This is why the wood stick is normally used in playing the copper gong.

3. Geometric Dimension and Material Properties Effect

For more understanding of the geometric dimensions and material properties' effects on the sound characteristics of the copper gong, finite element models are created with different geometric dimensions. Table 5 lists the natural frequencies for different cases. Case A denotes the original dimensions of the copper gong. Three different dimensions of copper gong are analyzed. Case B is double size of the original D_1, D_2, H_1, H_2, t. Case C is double the size of the original D_1, D_2, H_1, H_2. Case D is double the size of t. Case E uses the original dimensions but steel material properties. Table 5 shows the first seven natural frequencies for those cases and is discussed as follows:

1. There is no surprise that increasing the size dimensions will generally lower the natural frequencies such as Cases B and C. To increase the thickness of the gong will result in higher natural frequencies such as Case D.
2. For higher stiffness material, such as steel, in Case

Table 5 Natural frequencies (Hz) for different dimensions and material properties

CASE	A	B	C	D	E
Mode	Original dimension (copper)	Double size of original D_1, D_2, H_1, H_2, t	Double size of original D_1, D_2, H_1, H_2	Double size of original t	Original dimension (steel)
1	132.57	66.28	39.60	216.51	350.21
2	132.96	66.30	39.75	216.76	350.29
3	412.33	208.29	113.75	652.89	1100.50
4	426.83	208.90	121.52	657.15	1104.20
5	429.82	210.21	127.21	722.10	1110.60
6	835.03	384.83	222.71	1189.00	2033.20
7	859.20	402.53	235.38	1192.00	2126.70

E, the natural frequencies are higher than those of Case A for a copper gong.

3. For the gong considered in this work, the principal radiated sound frequency is dominated by modes 3, 4, and 5 as discussed previously. That these three modal frequencies are close to each other is the key design philosophy. Cases C and D do not maintain this characteristic properly. The inclined angle of the skew annulus, the size of the middle flat plate, and the thickness of the gong need proper selection to get good quality of principal sound frequency.
4. This work did not simulate the sound radiation of gong theoretically; therefore, the sound radiation pattern could not be obtained for different mode shapes. Instead, a simple sound pressure measurement to identify the high level response at some modal frequencies allows one to predict and explain the sound radiation pattern based on the vibration modal properties of the gong.

V. CONCLUSIONS

In this work, the finite element model of a Chinese copper gong is generated, and the vibration characteristics of the gong obtained from this model are verified by experimental modal tests. The sound characteristics of the copper gong are also investigated. The following summarize the present work.

1. The natural frequencies obtained from FEA can get good agreement with those of experimental tests. The principal frequency of 423Hz can be identified from the sound measurement and also observed in finite element analysis. Due to the successful prediction of FEA, the finite element model can be extended to do the other analysis to understand the vibration and sound characteristics of gongs.
2. The results obtained from FEA in high frequencies show much difference from EMA. The major reason is that the copper gong is hand made. There are many concavities and convexities on the surface of the copper gong. This may result in the deviation for high frequencies between FEA and EMA.
3. The analyses and tests get the same results, that the highest sound pressure level is observed at frequencies of 423 Hz. So the principal frequency of the sound of the gong can be obtained by FEA. There are three modes including modes 3 to 5 contributing to the sound radiation of the principal frequency.
4. Based on the experimental results, the sound characteristics have a close relationship with the modal parameters. The sound characteristics of the musical instrument can be predicted through vibration analysis.
5. In finite element analysis, structural dimensions and material properties of the gong can be changed to understand the effect on the vibration behavior and sound characteristics. Through these analyses, the gong structure can be modified to improve its sound characteristics. This method is also useful for other musical instruments.
6. This work may be the first attempt to theoretically and experimentally study the dynamic and sound radiation characteristics of a Chinese copper gong. The gong plays an important role in Chinese opera, festivals and celebration events to show joyful feelings and vigorous affection. Actually, there are many types of gongs with different shapes and sizes. For complex structures like gongs, it is difficult to conclude solid design rules in selecting dimensions or even different shapes. With the help of CAE software, like ANSYS used in this work, and EMA technique, this paper validates the analytical finite element model that can be easily redesigned. To further refine the design rules is outside the scope of this work. For example, Yun-Lo that is made of a series of different sizes of gongs can play different tones like a percussion instrument.

Although the gong has been used as an instrument for hundreds of years, gong manufacturing is mostly based on manufacturer's experience. Through gongs' scientific study, the authors hope to introduce analysis and experimental techniques to gong makers and improve sound quality.

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