Finite Element Analysis and Gong Acoustics

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ABSTRACT: Finite Element Analysis is used to predict the effect of a range of variations of gong geometries on modal frequencies. This data is evaluated in relation to experience in gong manufacture by a variety of methods and its implications for new instruments discussed.

1. INTRODUCTION

During this century advances in the fields of musicology, acoustics and human cognition have created new theoretical contexts in which European musical traditions may be interpreted alongside the musical traditions of many other cultures. In acoustics (now including musical and psychoacoustics) these advances enable us to re-address questions of the relationships between instrumental timbre, musical form, and the perception of pitch, consonance and harmony.

For example, western orchestras evolved with the exclusion of instruments with non-harmonic overtones since it was thought they would interfere with the harmonic concerns of composers [1]. Through exposure to non-western instrumentation, electronic sound generation and sound recording technology composers are now exploring complex sound sources and instrumentation in compositions no longer structured by eighteenth and nineteenth century European harmonic concerns. While composers such as Harry Partch built entirely new instrument ensembles to explore such interests [2], others have been deeply involved in computer programming and electronics.

Finite element analysis (FEA) modelling has been applied to the design of novel idiophones for use within conventional European musical contexts [3-6]. For example, an entire carillon of bronze bells with major instead of minor third partials has been designed and cast [4-6]. Computer programs which physically model musical instruments through FEA modelling have recently been developed for electronic music synthesis [7,8]. These programs offer a range of models of physical systems such as stretched strings and membranes, wooden and metal bars, resonators and various excitation mechanisms. Novel, virtual instruments may then be generated for use in computer composition.

The instruments described in this paper embrace new musical possibilities by exploring the timbral implications of a range of gong geometries, inspired by instruments from diverse musical traditions, through FEA modelling. This is compared to acoustic spectra for instruments designed and manufactured by the author utilising various contemporary manufacturing technologies, for a range of novel performance, cultural and architectural contexts.

2. INSTRUMENT DESIGN AND ANALYSIS

Very little literature is available on the manufacture and acoustic behaviour of tuned gongs [9-14]. These instruments are features of traditional musical ensembles from Indo-China to Indonesia. They vary greatly in shape and may range in size from about 150 mm to greater than 1 metre in diameter [15]. Throughout South-East Asia musicians and craftspeople have manufactured instruments by whatever means were available, with most of their efforts remaining poorly documented. Manufacturing methods include casting or forging in various copper based alloys [16-18] or more recently (usually for economic reasons) forging in mild steel or fabrication from sheet steel. Metal spinning of sheet steel was successfully used by the author for the manufacture of a range of gongs for a set of outdoor installations.

In order to investigate which elements of shape are essential to producing certain relationships of vibrational overtones, a simple series of FEA experiments were carried out on gong shape models beginning with a flat disk. This data will be discussed with reference to direct experience with the manufacture of tuned gongs.

Acoustic spectra have been measured for gongs from sets of just-tuned cast bronze and spun steel gongs which were made recently in Melbourne without the aid of FEA modelling. Spectra for the bronze gongs vary substantially due to variation in shape and size (the set crosses three octaves), and to dimensional irregularities created during manufacture and whilst tuning by hand grinding. All the gongs had cylindrical rims for ease of manufacture.

Figure 1 shows the acoustic spectra recorded about 100 milliseconds after excitation of three small gongs of less than 300 mm diameter. The first two spectra are of gongs spun from 1.2 mm mild steel sheet, the second of which had a boss beaten into it to raise the fundamental frequency to a specific pitch (a boss is a raised hemispherical dome in the centre of the gong's surface). The third spectrum is of a gong which was cast with a boss in silica bronze. The fundamental frequency was lowered to the required pitch by thinning the gong's surface with a grinder.

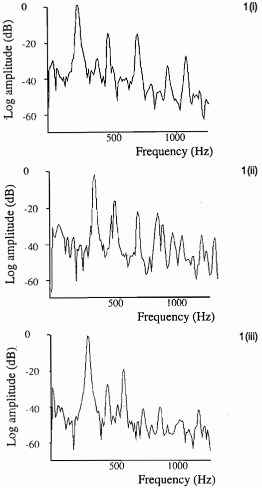

Figure 1. Acoustic spectra recorded 100 ms after excitation of:

i) Spun steel gong (286 mm surface diameter and 100 mm deep rim),

ii) Spun steel gong as above with 50 mm diameter, hemispherical boss,

iii) Cast silica bronze gong (225 mm diameter and approximately 2 mm thick surface, 55 mm deep and 5 mm thick rim, and 65 mm diameter and approximately 5 mm thick hemispherical boss).

The instruments were digitally recorded using the Macromedia Deck version 2.5 sound editing program and a Sennheiser MD 441 dynamic microphone. Excitation was by striking the instruments with padded mallets. The microphone was held above the top surface along the axis of symmetry of the gongs at a distance of about 500 mm. Short time Fourier transforms were performed by the AnnaLies version 4.2PPC program written by David Hirst and Thomas Stainsby for Macintosh computers at La Trobe University [19].

Table 1 includes frequencies of the first six major spectral peaks observed between 50 and 400 milliseconds after excitation with the ratios of these frequencies to the fundamental of each gong expressed numerically or as an octave equivilent just interval. The percentage deviation of the numerical from the just intervals is also given. The instruments were developed for just-tuned ensembles and their partials are described in this way to indicate the degree of consonance of their partials. Carillon bell partials are similarly related to intervals in Western musical scales. For comparison, the tempered major third is 3.5% sharper than the just interval 5/4, which is its closest consonant interval.

Table 1. Modal frequencies and ratios derived from acoustic spectra.

GONG		**SPECTRAL PEAK**						
		1	**2**	**3**	**4**	**5**	**6**	**7**
Flat	**mode***	2,0	0,1	3,0	4,0	1,1	2,1	0,2
Steel	**f (Hz)**	252	422	498	622-662	738	984	1223
	f/f (1)	1	1.67	1.98	-	2.98	3.91	4.85
	just ratio	1	5/3	2/1	?	3/2	2/1	5/4
	% deviation	-	0	-1.0	-	-0.7	-2.3	+1.2
Steel	**f (Hz)**	370	540	723	878-925	1080	1380	-
with	**f/f (1)**	1	1.46	1.95	-	2.92	3.73	-
boss	**just ratio**	1	3/2	2/1	?	3/2	2/1	-
	% deviation	-	-2.0	-2.5	-	-2.6	-6.7	-
Bronze	**mode**	2,0/0,1	1,1	3,0	4,0	2,1	0,2	?
	f (Hz)	298	597	891	1110	1190	1404	1699
	f/f (1)	1	2.00	2.99	3.72	3.99	4.71	5.70
	just ratio	1	2/1	3/2	15/8	2/1	7/6	7/5
	% deviation	-	0	-0.3	-0.1	-0.3	+0.9	+1.5

* The assigning of modes is based on FEA modelling data presented later. The first number refers to the number of nodal lines, the second to the number of nodal rings of each mode.

The spectrum of the steel gong with boss was typical of gongs in this set. Their pleasing tonal qualities may be attributed to the closeness of the principal overtones to consonant intervals. The metal thickness and gong geometry was decided upon from experience in fabricating gongs from steel sheet. The cast bronze gong was chosen as an interesting example from a range of gong spectra. In other gongs of similar dimensions in this set the lowest two modal frequencies were close, causing occasional difficulties in pitch definition.

Suprisingly there is little difference between the spectral data for the two steel gongs shown in figure 1. Beating the boss into the gong raised the frequency of all the principal radiating modes by almost the same multiplier. Figure 2 shows plots of data obtained in FEA modelling experiments to explore the effects of adding bosses of various size and thickness to circular plates. In these experiments increasing boss sizes had the greatest effect on the 2,0 mode.

Examination of the data in table 1 does show a greater frequency increase in the 2,0 mode than the 0,1 mode when the boss is added. This results in a smaller just interval between the first two modes of this gong. The next four intervals are not greatly changed by the addition of the boss. Increases in internal tension in the metal surface due to the introduction of the boss were not accounted for in the FEA experiments. This added tension would increase modal frequencies, and comparing the spectral data in table 1 with the FEA data in figure 2 suggests that it is an important factor in the behaviour of these gongs.

FEA modelling was performed using the vibrational analysis package of Pro-Engineering's Mechanica Structures (version 13) program. Since the instruments being modelled have thin walls, the models were constructed as shells of prescribed thicknesses. Models used parameters for phosphor bronze (Young's modulus (Y) of 103 GPa, Poisson ratio (P) of 0.34 and density (D) of 8,900 kg/m^3), or low alloy steel (Y=200 GPa , P=0.27 and D=7,800 kg/m^3).

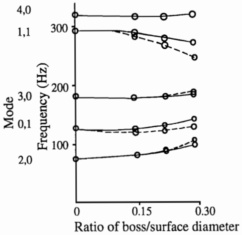

Figure 2. Plots of FEA predicted frequencies for various modes versus the ratios of the diameters of hemispherical bosses to the surface diameter of 1.2 mm thick mild steel circular plate models. Broken lines are plots of data for 2.4 mm thick bosses.

Doubling the thickness of the boss slightly raises the frequencies of modes with nodal diameters, but lowers the frequency of modes with nodal rings, including the 1,1 mode. This may be attributed to increased stiffness for the former modes and increased mass loading for the latter. A similar mass loading effect reported by Rossing [11] was proposed as the mechanism by which a boss could bring the first two modes with nodal rings into an octave relationship. As a boss is beaten into a steel gong the metal being worked thins and work hardens. This will have no effect on mass loadings but the stiffness will be effected in a complex way, since the thinning will reduce stiffness, but work hardening will increase it.

The present data shows that a boss of up to 30% of the surface diameter and twice its thickness has a relatively minor impact on the timbre of cast or spun gongs. In forged gongs beating out the boss pulls out any buckles in the surface and evenly thins it by stretching the metal. This may at first lower the fundamental frequency of the gong until the surface is uniform at which point the pitch will begin to increase with increasing surface tension and stiffness as described above. Bosses are an important feature of sets of tuned gongs in that they assist the maker to tune forged gongs and the player to strike the centre of the gong when playing fast passages.

Most gongs, whether of specific pitch or not, have rims. Data from FEA experiments are used in figure 3 to show the large impact rims have on the timbre of gongs without bosses.

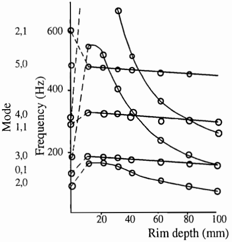

Figure 3. Plots of FEA predicted frequencies (in Hz) for various modes of 1.2 mm thick and 286 mm surface diameter mild steel gong models versus rim depth (in mm.).

The frequencies predicted for modes with nodal diameters only (2,0, 3,0, 4,0 etc.) increase dramatically with the introduction of even a small rim due to increased stiffness in the plane of vibration. As the rim size is increased, these frequencies quickly reach maxima before rapidly decreasing. When the rim depth is about 1/3 the size of the surface diameter (80 mm) they are close to the frequencies predicted for a freely vibrating circular disk. The 5,0 mode also behaves in this manner but is not shown in the figure for reasons of clarity and scale.

The introduction of a rim had less affect on the three modes with nodal circles shown in the figure (even though they may also contain nodal lines). Inspection of the FEA displacement contours for these modes revealed much smaller vibration amplitudes in the gong rims than was predicted for modes without nodal circles. Changes in the rim size therefore did not increase stiffness in regions of the gong which would affect the frequencies of these modes as much as the modes without nodal circles.

The data shown in figure 3 indicates that the two principal types of modes of vibration in gongs may be tuned independently of each other, and suggests rim to surface size ratios worthy of further investigation to produce musically interesting timbral results. Furthermore, modes with nodal diameters only were predicted to have their greatest displacement in the rim, so varying the metal thickness of the surface should have much less effect on them than modes with nodal rings. Figure 4 shows a plot of the FEA predicted frequencies of various modes for three different ratios of metal thickness in the surface compared to the rim.

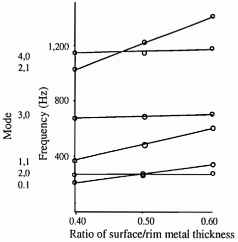

Figure 4. Plots of FEA predicted frequencies for various modes versus the ratio of metal thickness in the surface compared to the rim for phosphor bronze models based on the bronze gong described in figure 1.

Most Indonesian gongs have rims in the shape of inverted, truncated cones (see figure 5). From the preceding discussion it would be expected that increasing the angle of the rim from vertical would affect the modes with nodal diameters only more than those with nodal rings. This is confirmed by the data shown in figure 6. Predicted frequencies for modes with nodal diameters only increase sharply while frequencies for modes with nodal rings remain nearly constant with increasing rim angles.

Two types of rim shapes on gongs in the central Javanese gamelan are shown in figure 5. Rims of the second shape may be up to twice as deep as on comparably pitched gongs of the first. The second shape is found on the highest pitched gongs in the ensemble (in the top octaves of the bonang panerus and barung), which play the more complex elaborations of melodic material. Interestingly, it is also found on the highest pitched gongs usually used for defining rhythmic cycles in the music (kenong) [20]. Kenong are pitched within the same octave as the lower octave bonang barung gongs, and so the rim shape would appear to have an important role in creating timbral distinctions between gongs with the same pitch but differing musical function, and gongs with similar musical functions but tuned an octave apart.

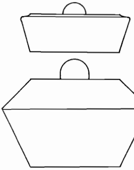

Figure 5. Two rim types found on central Javanese gamelan gongs.

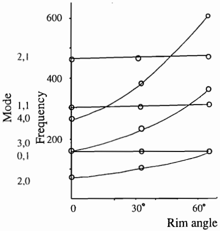

Figure 6. Plots of FEA predicted frequencies for various modes versus the angle from vertical of the rim on 1.2 mm thick, mild steel models with 0.35 rim depth to surface diameter ratio.

3. DISCUSSION

The predicted frequencies of the FEA experiments for gong models based on manufactured gongs did not match the acoustic spectra for these gongs due to various effects of the manufacturing processes which are difficult to accurately model. However when the results are taken in combination they indicate how the near harmonic overtone spectra recorded for these gongs have been produced by the right combination of physical properties. More experiments with actual cast and spun gongs will be necessary to precisely correlate computer models with the behaviour of gongs.

An important aspect of instrument design not addressed by modelling with FEA programs is the radiation efficiency of predicted vibrational modes. Antiphase source distributions will interact to reduce radiation efficiency if the sources are within about half of one wavelength, and such effects will occur to significant degrees for most vibrational modes in gongs. The front and back faces of the surface of a gong contain principal radiating regions emitting in antiphase [16], which are isolated to some extent by the rim. These effects are highly complex to predict and would require more detailed study with prototype instruments to fully understand. Clearly the air volume contained by the rim and the floor when the gongs are suspended horizontally is too large to be an efficient resonator.

The data presented in this paper was the result of personally funded research (generously assisted by a number of universities) aimed at developing a flexible design protocol for instruments to be used in a range of new musical, cultural and architectural contexts. Although significant advances have been made, more work will be necessary to accurately correlate computer predictions with physical instruments. This task will be assisted by the application of highly reproducible, modern manufacturing technologies in metal forming, casting and milling, and more sophisticated analytical methodologies.

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