Acoustical characteristics of the Jing; An experimental observation using planar acoustic holography

Hyu-Sang Kwon*, Yang-Hann Kim* and Minhong Rim*

ABSTRACT

The Jing is a traditional Korean percussion instrument which plays a major role in Korean folk music. The distingishing feature of this instrument is its unique, long lasting low tone timbre. In this paper, we investigated the vibro-acoustic characteristics of the Jing. Our attention was focused mainly on finding out the physical variables that determine its unique sound. By understanding the way in which the Jing is manufactured, we were able to realize that the unique manufacturing and especially the tuning process by expert craftsman is responsible for the peculiar timbre the Jing produces. The experimental methods implemented to analyze the Jing were planar acoustic holography and direct measurements by accelerometers. The results from the holographic method and the direct measurements were in good agreement. It turned out that unlike most percussion instruments which have inharmonic partials, the Jing has harmonic partials which are responsible for its unique low-tone timbre. From the holographic representations of the modes, it is clear that the antinodes are located in the center of the Jing which is coincident with the typical striking location. In addition, intensity maps were constructed so that the specific acoustic energy flow can be visualized. It was also interesting to see the the circulation of energy intensity which corresponds to the rotating mode of the Jing.

Ⅰ. Introduction

The Jing is a traditional Korean percussion instrument which produces a very unique sound and there is no match for it any where in the world[1, 2]. The major objective of this paper is to give a physical explanation for all the magic behind the Jing's unique timbre. As the first step in our investigation, we visited a village where Jings are made by expert craftsmen and examined the manufacturng process and found out what could be the answer for the uniqueness of the Jing. It was the unique tuning process of the Jing which involved "ammering" its plate(Note the dents and surface inhomogeneity in Fig. 1)

The hammering process was in fact the most important procedure in making the Jing and this tuning process requires many years of experience and know-how. Actually only few very experienced craftsmen can do the tuning. It was a trial-and-error procedure where the craftsman hammered a certain part of the plate and listened to the tune it produced and went over the same procedure repeatedly until the sound it produced was satisfactory. Through careful observation, we were able to come up with the physical variables that were affected by the hammering of the Jing which we thought would be responsible for producing its unique sound. They were the thickness, surface inhomogeneity and material properties. In this paper though, we focused our attention on the effect of the thickness variation in the Jing which we thought was the major contributor to its unique sound.

The vibro-acoustic characteristics of the Jing was investigated experimentally, since the surface inhomogeneity of the Jing and its complex geometry made it almost impossible to use analytical or numerical methods. Even though the Jing's nonlinearity such as the pitch gliding is what makes it sound so unique[1], we focused our attention on the investigation of the linear behavior of the Jing; i.e. the reponse of the Jing when subjected to relatively small excitations. Planar acoustic holography: which enables us to obtain 3D field information from planar measurements of the sound fields, was implemented as the major experimental tool because it enables us to visualize the whole sound field around the Jing, as well as the vibration modes. An experiment using accelerometers was also performed in order to compare its results with those from the holographic method.

Ⅱ. Overview of Jing

As you can see in Figs.1 and 2, the Jing is composed of

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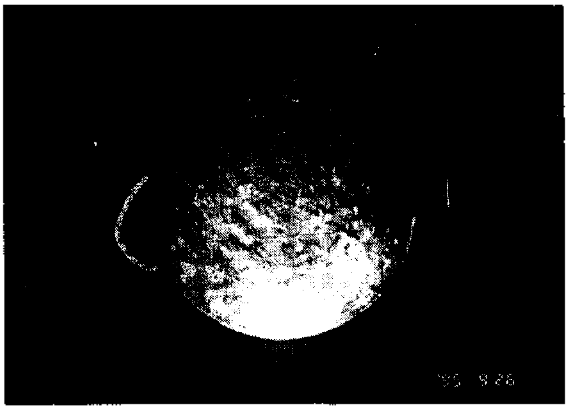
Manuscript Received: May 10, 1997.

a circular plate and a rim around it. The basic structure of the Jing looks pretty much like an ordinary percussion instrument, but after a careful observation some peculiar characteristics of the Jing can be realized.

The manufacturing process of the Jing is definitely worth mentioning, since its unique manufacturing process, especially the tuning process, is the key factor in determining its sound quality. The first part of the manufacturing process involves hot-rolling and hammering of a lump of brass into a flat circular shape of appropriate size. And then the outer edge is bent to form the rim while the lump is still hot. After the basic forming process, it is left in the open air to be quenched. The following step is the tuning process or as mentioned previously the "hammering process" which involves a trial-and error procedure in which an expert craftsman hammers a certain part of the plate and listens to the sound after each stroke. This procedure is repeated until the sound it produces is satisfactory to his ears. As can be expected, this is the most significant part of the whole manufacturing process which makes the Jing so unique. The irregular dents and rough surface from the hammering can be seen easily in Fig. 1. With more careful observation of Fig. 1, it is possible to notice that the dents are concentrated on the outer region of the plate which are responsible for the variation in the thickness and the curvature of the main plate. From the fact that there are more dents on the outer part of the plate, it is expected that the outer part will be thinner than the inner part. In order to find out the thickness variation of the Jing, the plate's thickness was measured at 25 grid points in which the distance between the neighboring grid points were 2.5cm (see Fig. 3). In Fig. 3, note that the thickness varies from 1 mm to about 3mm with a general tendency of decrease in thickness as one moves outward from the



(a) The front of Jing

(b) The back of Jing

Fig. 1 Photos of Jing. Note the irregular dents on the main plate due to the hammering process

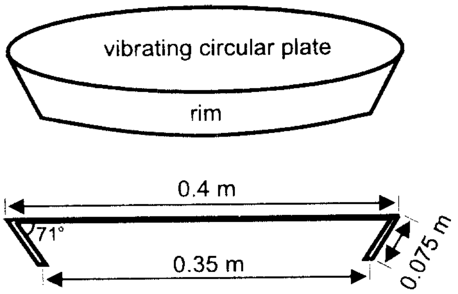


Fig. 2 Basic geometric configuration of Jing.

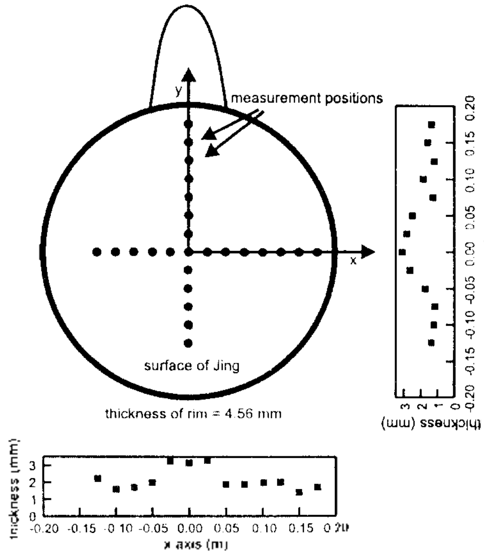


Fig. 3 Thickness variation of the main plate. Thickness was measured at 25 different position along the two designated axes

center of the plate. This variation in thickness is what shifts the inharmonic partials toward harmonicity. It is a commom knowledge that a flat circular plate cannot produce harmonic sound because of its inherently inharmonic vibro-acoustic characteristics[3, 4].

III. Experiments

3.1 Implementing planar acoustic holography[5-8]

The experimental set-up is illustrated in Fig. 4. Instead of using a large number of microphones, we applied scanning technique[7] which only requires a 16 channel microphone array system. The reference microphone was located as shown in Fig. 4 and the other 15 microphones were arrayed horizontally on a thin bar. The space between the microphones were chosen to be 0.1m and the whole array was designed to allow vertical movements for scanning. The total number of measurement points was 30 x 30 which involved a 15 microphone array to be located at 60 different positions. Pressures were measured at the corresponding positions for the complete scan. Both the vertical and the horizontal sampling space was 5 cm. The only horizontal movement involved was shifting the whole array system sideways by 5 cm. The Jing was struck at each new scanning positions, so that the experiment involved 60 strokes with measurements corresponding to each stroke. At this point you may be wondering if this kind of experimental procudure would give a valid result,since the sound field is nonstationary. But, we found out that even though the field is nonstationary, the only variable that's changing is the magnitude of sound pressure which decays at a very slow rate. Fig. 6 shows the nonstationarity of the field. It shows a very slow decay of SPL along the time axis and such a slow decay validates the use of the scanning technique described above. Thus, the sound field can be viewed as a quasistationary field and this justifies the use of the scanning method which can only be applied to stationary fields[7].

The Jing was struck on the back so that the rubber pendulum swing, used to simulate the mallet, wouldn't obstruct the pressure measurements in the front of the Jing. (See Fig. 5) It was verified by experiments that striking the Jing on the back, instead of the front didn't affect the basic modal behavior of the Jing as expected of a linear system. (See Fig. 6 and 7) Thus, striking the back of the Jing is justified. The rubber pendulum weighed 0.27 kg and was released from a designated height to produce a momentum of 0.33 kgm/s at the point of impact. The momentum of 0.33kgm/s was chosen so that a linear response of the Jing can be attained

The acoustic pressures were measured at a sampling rate of 2048 Hz and a 512 points-FFT was performed, so that the Nyquist frequency was determined to be 1012 Hz and the spectral resolution 4 Hz. The frequency responses are shown in Fig. 8. The peaks at the frequency of multiples of 60 Hz are due to the electrical noise. Note that the dominant frequency components occur below 500 Hz and that the levels decay at a very slow rate. This explains the extraordinarily long lasting low tones that the Jing produces. Also note that the high frequency components die out rapidly, which is why the Jing is low-tone-dominated.

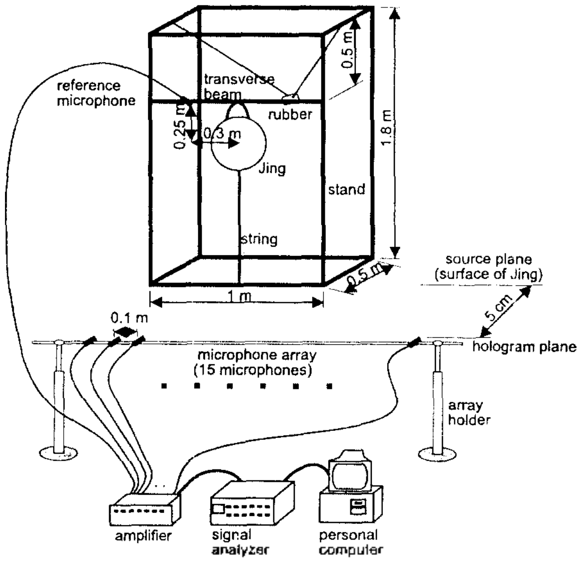


Fig. 4 Experimental set-up for the pressure measurements.

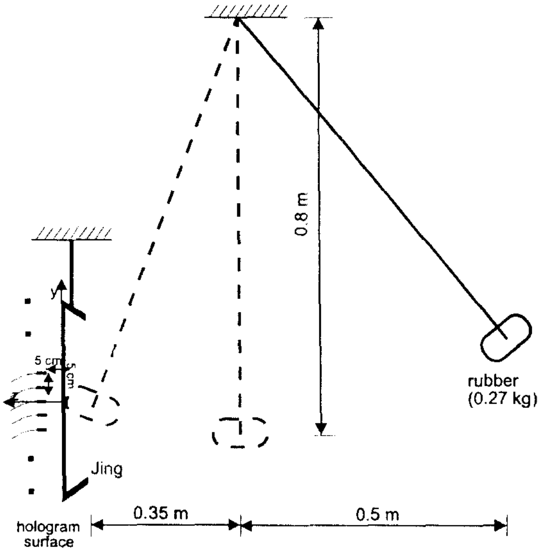
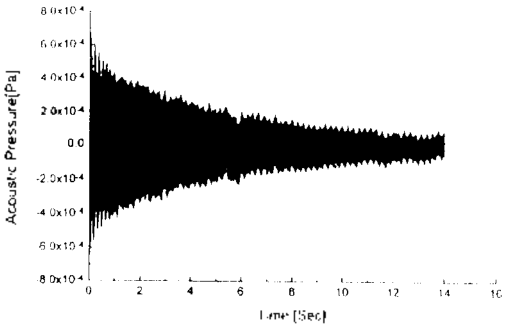
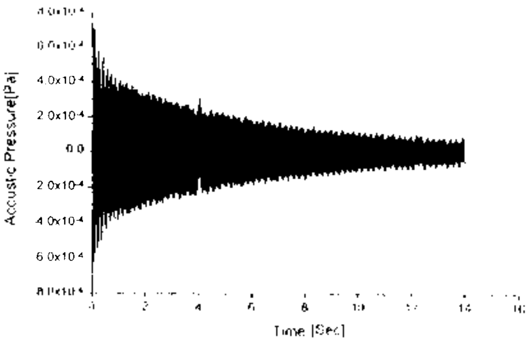


Fig. 5 Excitation of the Jing by the rubber pendulum. The location of the hologram surface is also indicated.

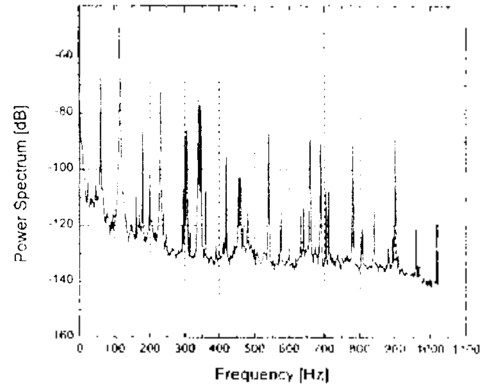


(a) Response of the Jing when struck on the front

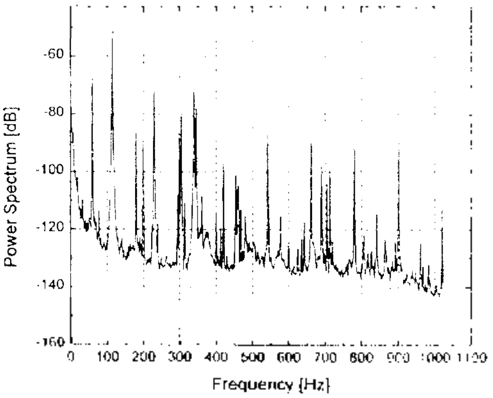


(b) Response of the Jing when struck on the back

Fig. 6 The time histories of the acoustic pressure for two different striking locations: the front and the back of the Jing. Note the slow rate of decay.

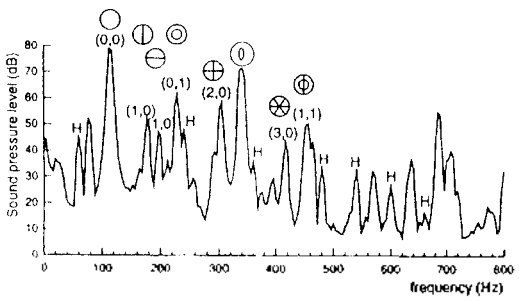


(a) Frequency response of the Jing when struck on the front

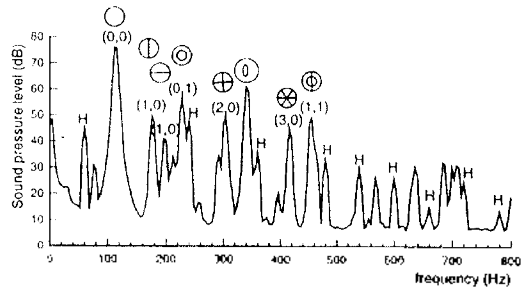


(b) Frequency response of the Jing when struck on the back.

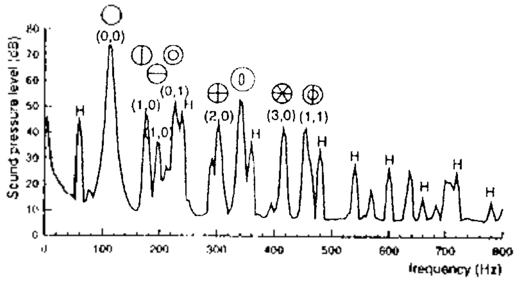
Fig. 7 The frequency responses corresponding to two different striking locations: the front and the back of the Jing. Note that (a) and (b) show almost the same behavior



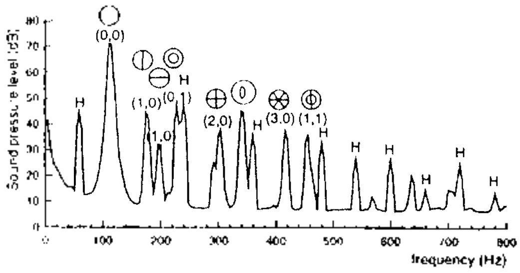
(a) 0-2 seconds



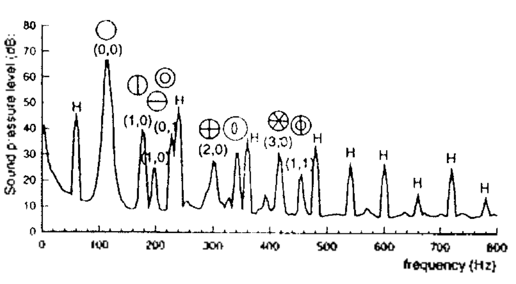
(b) 2-4 seconds



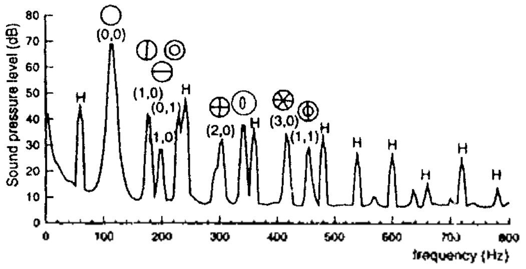
(c) 4-6 seconds



(d) 6-8 seconds



(e) 8-10 seconds



(f) 10-12 seconds

Fig. 8 SPL's measured at the reference microphone for each time intervals of 2 seconds after striking the Jing. Mode shapes corresponding to the fundamental and its overtones are shown in the small circles. H denotes the multiple of 60Hz which are due to the electrical noise. Note the different decay rates of each frequency components.

3.2 Measuring the mode shapes using accelerometers[2, 9]

The planar acoustic holography inherently renders prediction errors due to finite number of measurement points, even though it usually gives satisfactory results as long as adequate number of measurement points are used[6, 8]. To find out if the holographic reconstruction of the vibration modes was good enough, the mode shape of the Jing was measured using accelerometers. Such a direct measurement was performed in order to compare its results with those predicted by the holographic method and ensure that the holographic data we have obtained are reliable.

The basic experimental set-up is similar to that of the holographic method. The only difference is that in this case, the microphone array was removed and accelerometers were glued on the Jing. An impact hammer was used as the striking tool instead of the rubber pendulum swing. In measuring the mode shapes, the principle of reciprocity had been applied so that instead of using a large number of accelerometers, we only needed one. Actually four accelerometers were used to ensure that the acceleration can be measured as long as any one of the four accelerometers is not located on a nodal line; in fact two accelerometers would have been enough to ensure data acquisition. The accelerometers weighed 5g each, thus the mass loading effect was insignificant. They were positioned near the edge of the main plate to avoid having them located on nodal lines as much as possible as in Fig. 9. Fortunately, the results from the four accelerometers turned out to have the same relative magnitudes in the frequency domain, which means that none of them were located on nodal lines. As shown in Fig. 11, the relative magnitudes are the same, thus the same mode shape would be obtained. The number of measurement points or in this case the striking points were 70, 49 of which were positioned on the same locations corresponding to the holographic scanning positions on the main plate, i.e. with the same grids, and the remaining 31 points on the rim to investigate the vibro-acoustic behavior of the Jing.

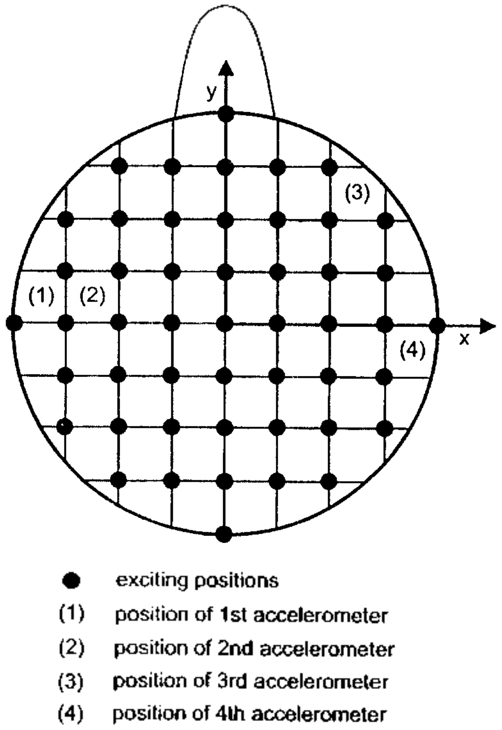


Fig. 9 The specific locations of the accelerometers.

Since the signals we had obtained from the four accelerometers virtually gave the same mode shape, we processed the signals from just one of those and the signals from the force transducer. We performed FFT to see the frequency reponses and the mobility(acceleration/force) was obtained.

Ⅳ. Results and Discussions

4.1 Frequency characteristics

In Fig. 8 which shows the SPLs measured by the reference microphone, sharp peaks at 112, 196, 228, 304, 340, 416, and 456 Hz are observed, which are the dominant frequency components of the Jing. These tones also have slow decay rates as shown in Fig. 10, and it is these low frequency components that make the Jing's low tones last for so long. Note that in Fig. 8, the three most dominant

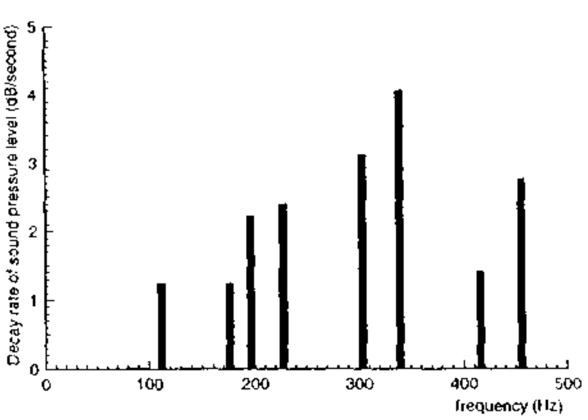
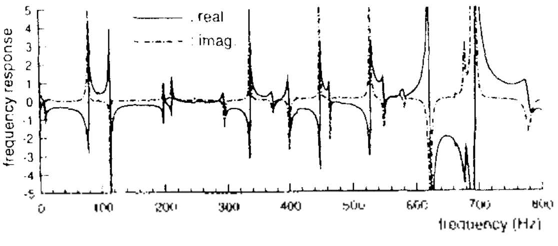
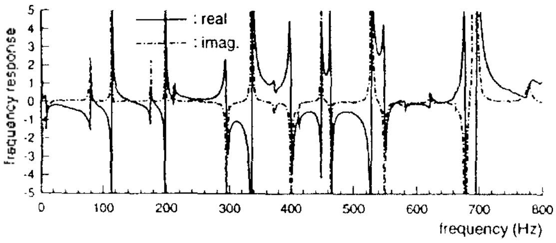


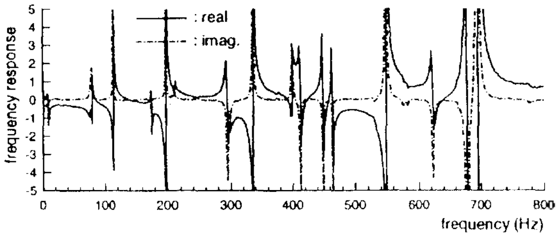
Fig. 10 Decay rates of the dominant low tones. Especially, note the decay rates of the fundamental(112Hz) and its overtones(228 and 340Hz)



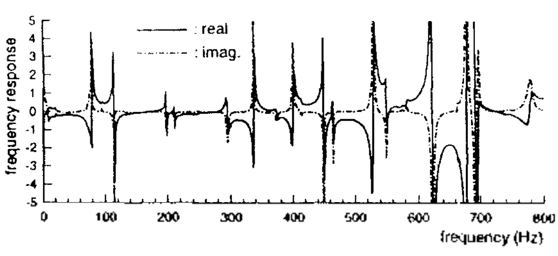
(a) Frequency response from the 1st accelerometer.



(b) Frequency response from the 2nd accelerometer.



(c) Frequency response from the 3rd accelerometer.



(d) Frequency response from the 4th accelerometer.

Fig. 11 Frequency responses(vibration velocity/force) obtained from each of the four accelerometers.

frequency components 112, 228, and 340Hz have ratio of 1:2.04:3.04 which means that they are almost perfectly harmonic. In fact, such harmonicity is not encountered in ordinary percussion instruments in which the tones show inharmonicity[3, 4]. These tones were found to be the natural frequencies of the Jing as illustrated in Fig. 11. Note the sharp peaks of the imaginary parts and the zero-crossings of the real parts at these frequencies which clearly demonstrates that they are the natural frequencies.

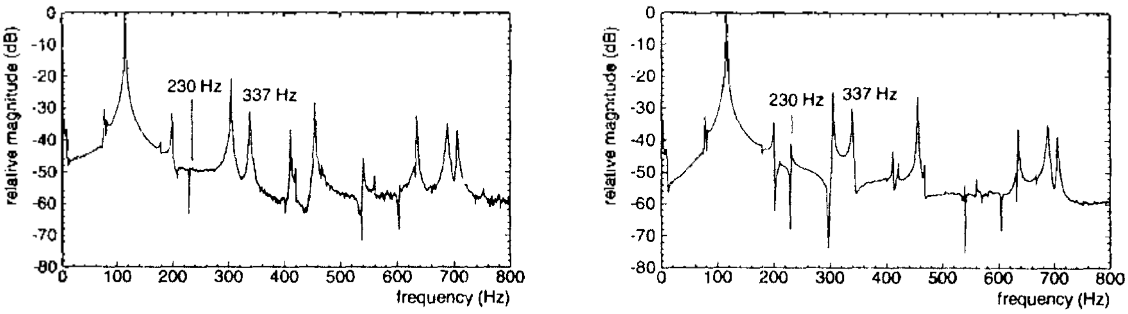
After careful comparisons of the SPL measurements at the reference microphone (Fig. 8) and the frequency response from the direct measurement (Fig. 11), it can be noticed that two of the major frequency components(228 Hz and 340 Hz) that appeared in the SPL data are missing in the direct measurement data. This phenomenon can be understood if you consider the mobilities(velocity/force) at these two frequencies.

Recall that in the SPL measurement, the Jing was excited by the rubber pendulum swing whereas in the direct measurement the excitation was carried out using the impact hammer. This difference in the magnitudes of the excitation is probably responsible for the two missing frequency components in the direct measurement data. In Fig. 12, note that the relative magnitudes at 230 and 345 Hz show strong dependence on the magnitude of the input force, while other peaks show some constancy. Also note that the peaks at 230 and 345 Hz become more pronounced as the magnitude of the input force is increased.

4.2 Spatial characteristics of the tones

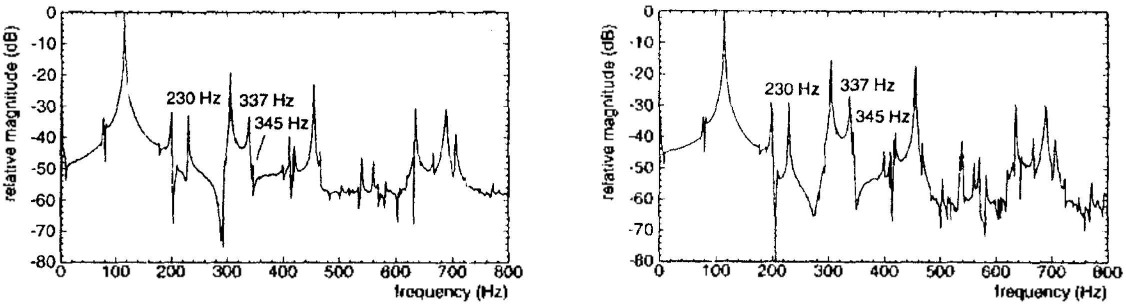
Investigating the spatial distributions and behavior of the radiated sounds from the Jing is one of the most important factors that is required in order to completely characterize the unique acoustic properties of the Jing. To do this, we visualized the sound fields using the planar acoustic holography.

Fig. 13 shows the mode shapes reconstructed from the holographic data and those from the direct measurements. Note that the mode shapes at 228 Hz and 340 Hz by the direct mearsurements are omitted since these two components didn't appear in the frequney response data due to weak excitation by the impact hammer. At other major frequeneies, it is clear that the reconstructed images are in good agreement with the the direct measurements. This demonstrates that the planar acoustic holography gives valid results. The vibration of the rim was also visualized with the vibration amplitude magnified by 10 times, but it turned out that its vibration is almost negligible as is clear in the graphs.



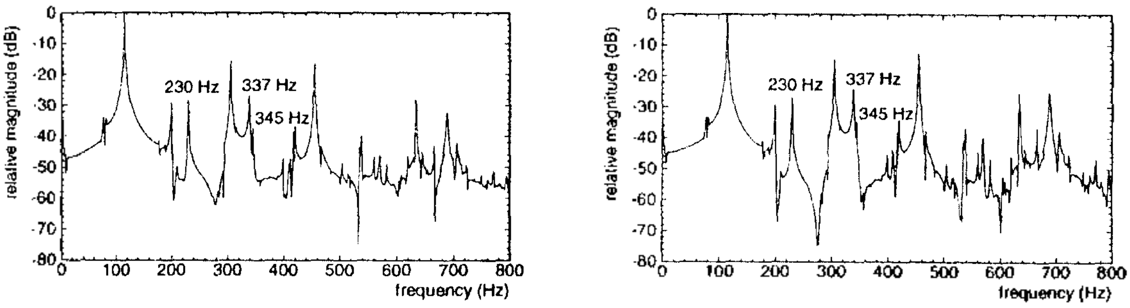
(a) mv = 0.05 kgm/s

(b) mv = 0.08 kgm/s



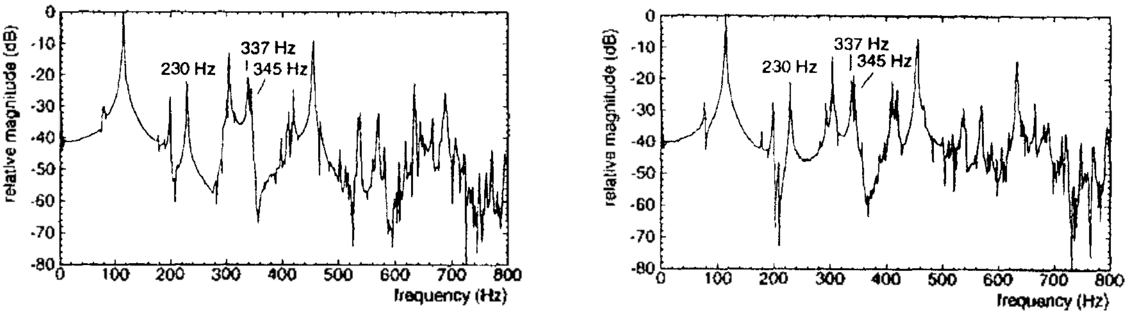
(c) mv = 0.11 kgm/s

(d) mv = 0.14 kgm/s



(e) mv = 0.16 kgm/s

(f) mv = 0.18 kgm/s



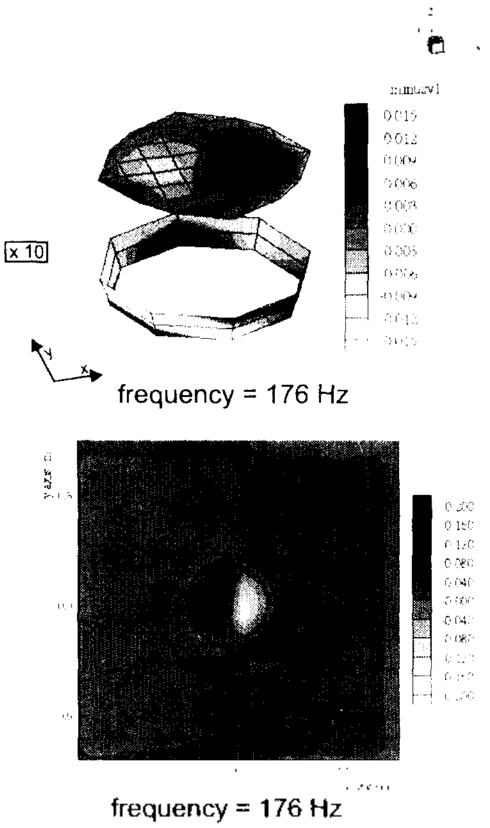
(g) mv = 0.26 kgm/s

(h) mv = 0.33 kgm/s

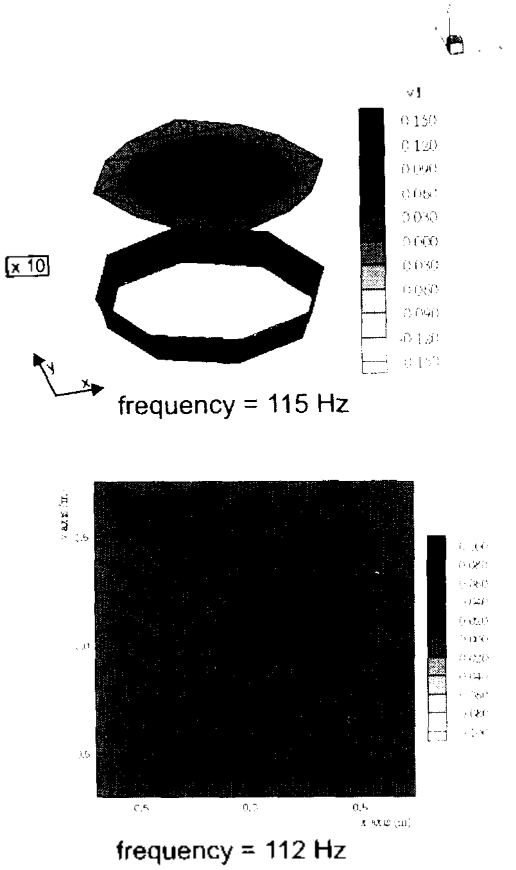
Fig. 12 Frequency responses of the Jing for various input forces. The spectra were calculated by taking the logarithm of each frequency components normalized by the fundamental tone; 115Hz. Note that the relative magnitudes at 230 and 345Hz increases as the input force is increased.

The spatial characteristics of the sound fields were studied by the acoustic intensity map. (See Fig. 14 and 15) The acoustic intensity vectors were reconstructed on four planes along the z axis, where the z axis is normal to the holographic plane. The active intensity vectors, of which the time averaged values are non-zero, correspond to net local transport of energy; whereas the reactive intesity vectors, of which the time-averaged values are zero, correspond to locally reacting energy that does not propagate. By looking at the mean active intensity, the details of how sound is radiated from the Jing can be clearly seen. Especially, note the intensity map for 416 Hz where rotating energy flow associated with a circulating mode can be observed.

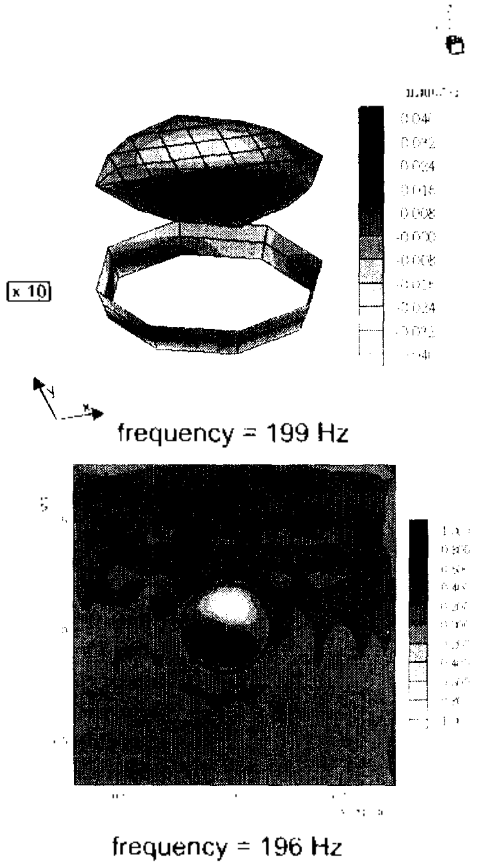
In the holographic reconstruction of the mode shapes, the dominance of the harmonic tones: 112, 228, and 340 Hz, can be observed. After a careful observation of the mode shapes in Fig. 13(a), (d) and (f) at the mentioned frequencies, the anti-nodes located in the center of the Jing can be noticed. This means that a typical stroke right in the center of the Jing will give rise to these domint modes.



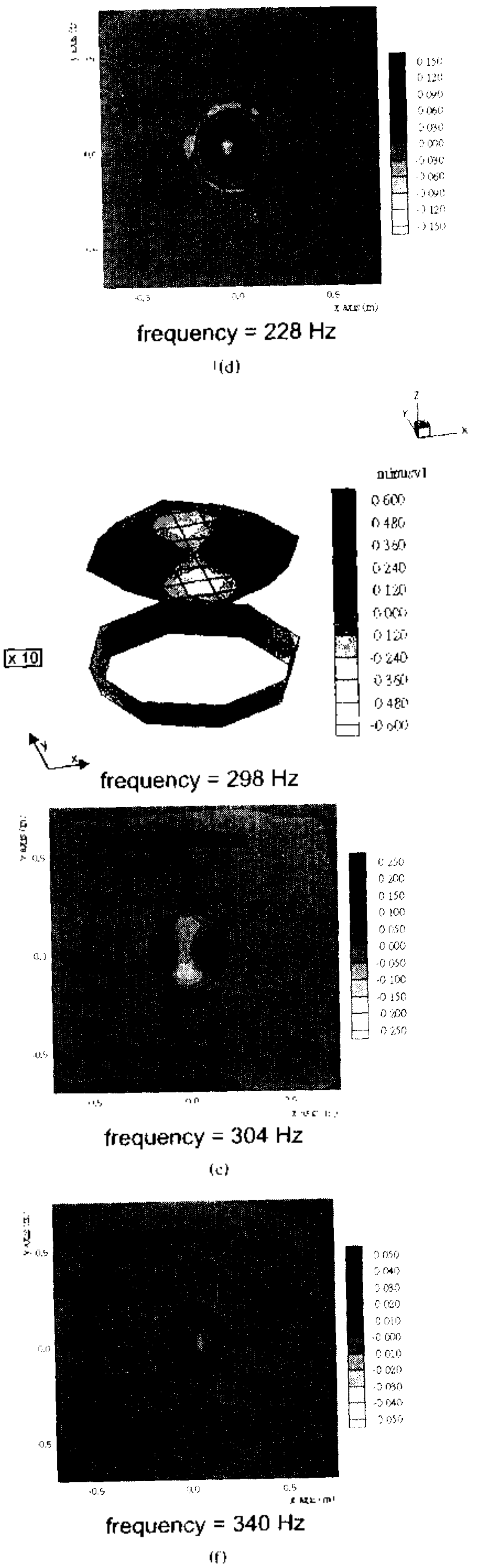
(b)



(a)



(c)



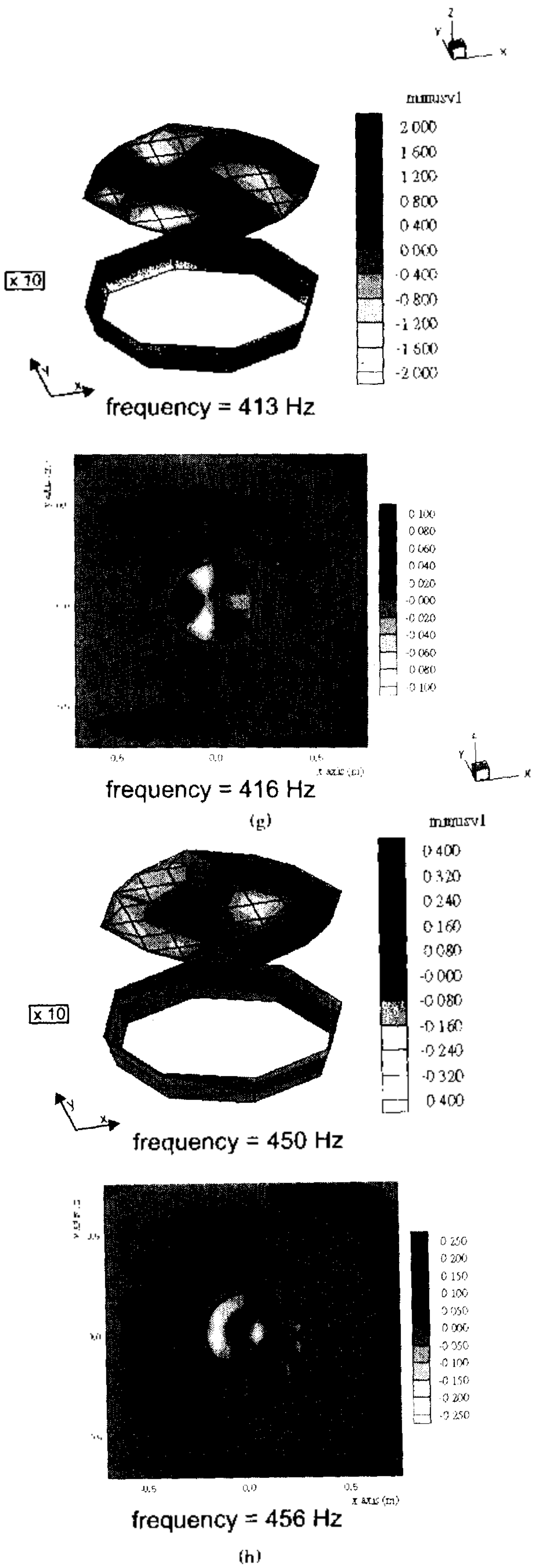
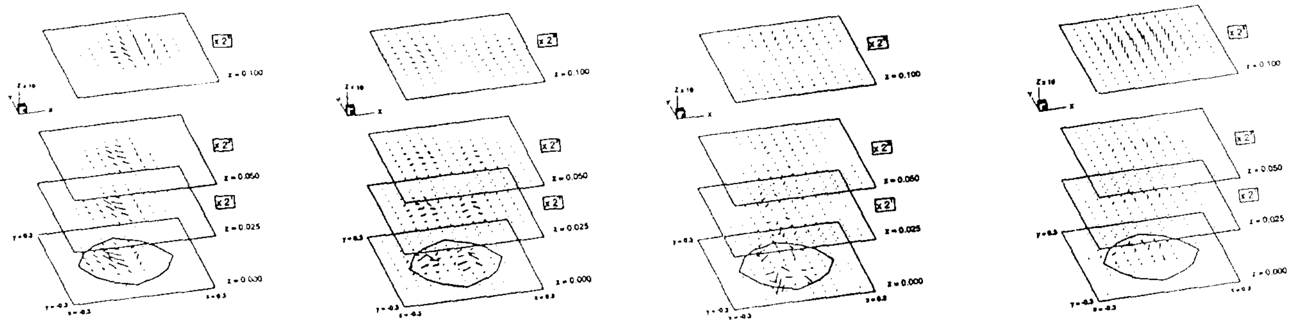
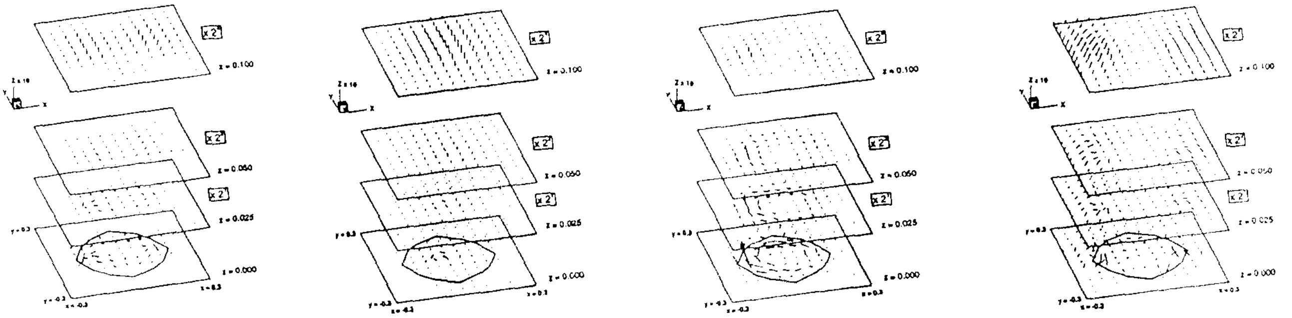


Fig. 13 Comparisons of the measured mode shapes and the reconstructed normal velocity image of the main plate by planar acoustic holography.

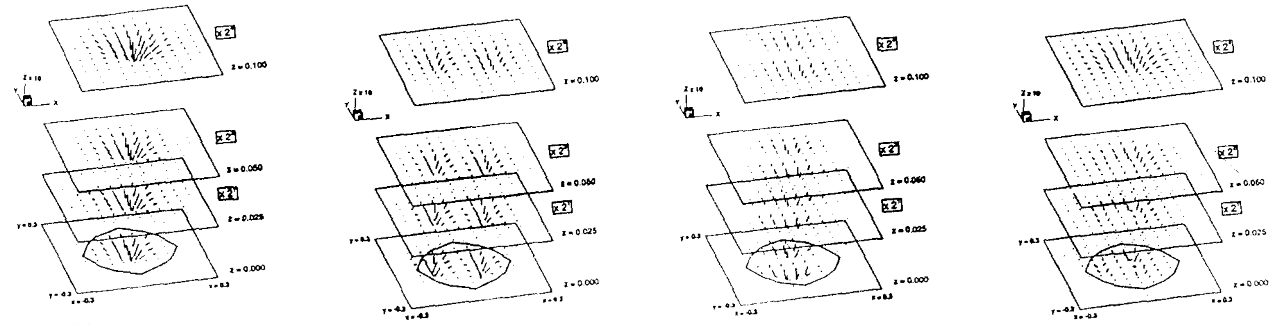


(a) 112 Hz (b) 176 Hz (c) 196 Hz (d) 228 Hz

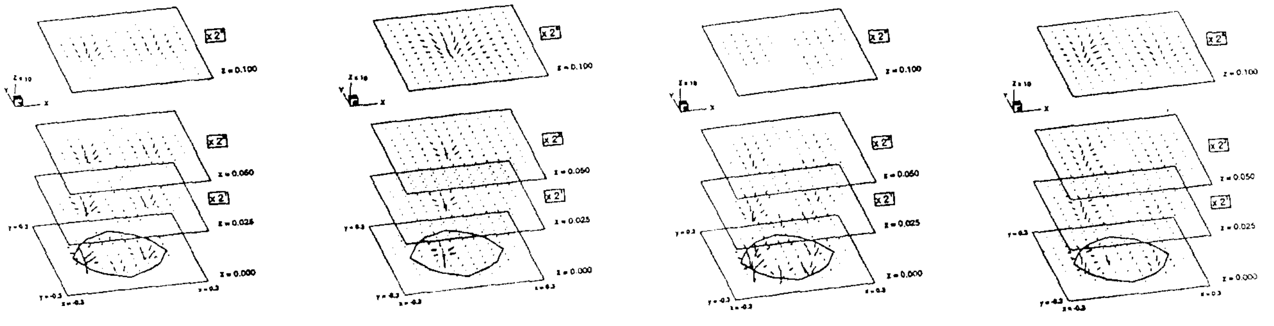


(e) 304 Hz (f) 340 Hz (g) 416 Hz (h) 456 Hz

Fig. 14 Reconstructed mean active intensity vectors. The magnitudes of the intensity vectors on $z=0.025$, 0.05, 0.1m were multiplied by factors of 2, 4, and 16 respectively.



(a) 112 Hz (b) 176 Hz (c) 196 Hz (d) 228 Hz



(e) 304 Hz (f) 340 Hz (g) 416 Hz (h) 456 Hz

Fig. 15 Reconstructed reactive intensity vectors. The magnitudes of the intensity vectors on $z=0.025$, 0.05, 0.1m were multiplied by factors of 2, 4, and 16 respectively.

V. Conclusions

It turned out that the harmonic overtones of the fundamental have higher sound presure levels than the other tones, and these overtones seem to be the major contributor to the Jing's peculiar timbre, especially the long lasting tones which give a clear sense of pitch. The antinodes at the dominant harmonic frequencies were found to be located in the center of the Jing just like you would expect from any other percussion instruments. The comparison of the holographic data and the direct measurements with accelerometers showed good agreement, which justifies the assumption of quasistationary sound fields.

The intensity map was constructed to visualize the actual energy flow in the sound field of interest. The rotating energy flow corresponding to the rotating mode at 416 Hz was especially interesting.

The harmonicity of the tones in the Jing is attained through a unique tuning process which involves hammering the main plate of the Jing. This hammering process gives rise to thickness variation, surface inhomogeneity, and changes in the material property and these factors are responsible for shifting the inharmonic partials to harmonicity. Such an ingenuity in the tuning process is what makes the Jing stand out from other ordinary percussion instruments.

Acknowledgment

We would like to thank Mr. Dong-Hyoun Kim for his help throughout the experiments. Also, we thank Duk-In company for the kind help in measuring the thickness of the Jing.

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