Acoustical and vibrometry analysis of a large Balinese gamelan gong

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Abstract: The Balinese gamelan gong ageng wadon produces distinct acoustic beating (called *ombak*) when struck. This phenomenon is explored using both acoustical and vibrometry measurements. The measurements have revealed the beating has two sources. First, there are four closely spaced modes that, given their asymmetric vibration patterns, might have been deliberately hammered into the response of the gong. Second, and more importantly, a nonlinear structural response of the gong causes the fundamental axisymmetric mode to produce harmonics. The second harmonic of the fundamental mode interacts with the second axisymmetric mode with relative amplitudes such that strong beating is produced.

PACS numbers: 43.75.Kk, 43.40.Ga [DC]
Date Received: November 13, 2009 **Date Accepted:** April 11, 2010

1. Introduction

In Indonesia, a gamelan, a generic term that means "orchestra," consists of a variety of percussive instruments such as metallophones, chimes, xylophones, drums, and gongs. The size of a gamelan can range from a few instruments to over 75. In Balinese gamelan, metallophones are manufactured in pairs, with the female instruments' bars tuned slightly lower in frequency than their male counterparts. This purposeful tuning of a pair to slightly different frequencies results in acoustic beating as they are struck in unison, which is referred to in Bali as *ombak* (meaning "wave"). The beating or *ombak* results in a shimmering quality to the music that is unique to Bali. For a general understanding of gamelan, the reader is referred to Ref. 1.

Some instruments in the ensemble do not need to be played in unison with another instrument for beating to occur. For example, the gong ageng wadon, which is the largest gong in the gamelan, produces a tonal sound with beating of about 2.5 Hz when struck with a padded mallet. The quality of the gong's *ombak* is an important factor in evaluating the overall gamelan sound.[1] An audio file of the gong being struck with a moderate performance-like blow is included as Mm. 1, and a picture of the gong is shown in Fig. 1(a). Rossing and Shepherd[2] found that the tonality of gamelan gongs can be attributed to the raised dome in the center (referred to as the boss), where the gong is struck. The mass and size of the boss relative to the rest of the gong causes a nearly 2:1 relationship of the two principal axisymmetric modes of vibration, giving the gong its tonality. Harshberger *et al.*[3] have indicated the frequencies of two close axisymmetric modes near the octave of the fundamental axisymmetric mode control the *ombak* rate. However, it appears counterintuitive that there would be two axisymmetric modes closely spaced in frequency, because of the circular geometry. Consequently, there is a need to better understand the vibrational characteristics of the gong and the resulting *ombak*.

Mm. 1. [Struck Gong Ageng Wadon audio file. This is a file of type "wav" (1.09 Mb).]

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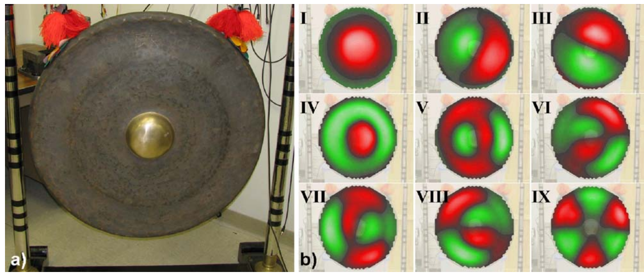

Fig. 1. (Color online) (a) The front of the gong, with the boss (the polished, raised dome at the center) visible. (b) SLDV plots of vibrational modes at (I–III): 61.75, 92.00, 101.75 Hz; (IV–VI): 121.25, 150.25, 153.25 Hz; (VII–IX): 160.00, 162.50, 236.00 Hz.

In this Letter, we describe essential features of the modal response of the gong ageng wadon and the origin of its *ombak*. In a sense, the Letter proceeds chronologically as we first describe initial structural and acoustical measurements that only partially revealed the origin of the *ombak*. These measurements motivated a deeper experimental investigation, during which we learned that the dominant perceived *ombak* is created by a nonlinear structural response of the gong's lowest axisymmetric mode interacting with the nearly harmonic second axisymmetric mode. Other *ombak* present is created by closely spaced structural modes that might be purposefully hammered into the gong's response.

2. Initial structural and acoustical measurements

To determine the frequencies present in the gong's response, structural and acoustical measurements were taken in a large room, roughly 74 m^2 (800 ft^2), with no sizeable obstructions within approximately 2.5 m (8 ft) of the gong. Three types of sensors were used for the tests. One was a 12.7-mm (0.5 in) GRAS Type-1 microphone placed behind the gong and within the cavity. In all tests, the microphone was placed in the same location relative to the gong. Another sensor was a PCB 352C68 accelerometer placed either on the front or back of the boss, depending on the gong excitation. The third sensor was a Polytec PSV-400 scanning laser Doppler vibrometer (SLDV) used to take noncontact measurements of the steady-state vibration of the gong with 0.25-Hz resolution. The microphone and accelerometer data were acquired with a National Instruments USB-9233 24-bit data acquisition module at a sampling rate of 50 kHz.

Initial SLDV measurements using 1277 points on the face of the gong were made while the gong was excited with white noise from a Mackie HR624 loudspeaker placed near the rear cavity of the gong. Figure 1(b) shows all of the modes measured by the SLDV below 240 Hz, among which are two axisymmetric modes (I and IV), that occur at 61.75 and 121.25 Hz. These two axisymmetric modes have the nearly 2:1 frequency ratio that, as explained by Rossing and Shepherd,[2] causes the gong to be tonal. Notice that both axisymmetric modes have an antinode on the boss, while the other modes do not, which produces greater average displacements and relatively efficient acoustic radiation. Note further that some shapes are characteristic of the circular geometry, exceptions being the pairs near 150 and 160 Hz, [V–VIII in Fig. 1(b)]. These latter modes' related shapes suggest that they are loosely phase-shifted versions of one another. This phenomenon appears to be related to the work of Chaigne *et al.*,[4] who studied vibrations of shallow spherical shells and gongs. They describe how asymmetric modes occur in pairs with slightly shifted frequencies and the same vibration pattern but with a quadrature spatial phase shift. Gong inhomogeneities break up the mathematical degeneracy that would normally be expected for these asymmetric modes. Modes V–VIII in Fig. 1(b), however, appear to have related—but not identical—shapes, which suggests more complex behavior than that studied by Chaigne *et al.* Note that Fig. 1(b) also shows a more straightforward quadrature spatial phase shift between the 92 and 101.75 Hz (II and III) modes.

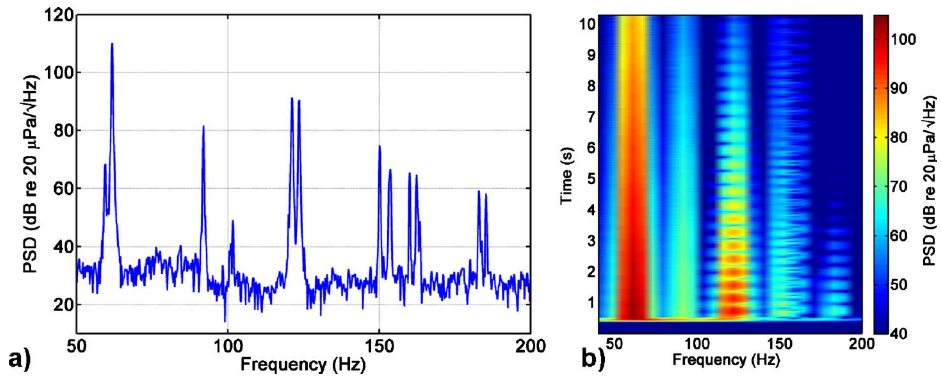

Fig. 2. (Color online) Spectra calculated from the struck gong microphone recording in Mm. 1. (a) Power spectral density (PSD), averaged over 10 s beginning with the gong strike. (b) Spectrogram of the recording.

Before proceeding to a discussion of the various modes' contributions to the *ombak* heard in Mm. 1, it is essential to consider the acoustic response of the gong. Figure 2(a) shows the power spectral density (PSD) in dB re 20 μPa/$\sqrt{\mathrm{Hz}}$ averaged over 10 s from the moment the gong was struck. Although averaging the transient signal in the PSD calculation produces amplitudes that are too low, this has been done in order to show the stability of the gong's natural frequencies over time and the very high quality factors of the modes. A PSD-based spectrogram of the struck gong's response, calculated using 2^{13}-sample blocks (6.1 Hz resolution) with 90% overlap, is shown in Fig. 2(b). Note that this coarser frequency resolution was required to clearly observe the important temporal features. In looking vertically along Fig. 2(b), *ombak* is visible at certain frequencies as significant fluctuations in level (represented by color) as a function of time. Near 120 and 180 Hz, the beat frequency is about 2.5 Hz. The spacing of the paired modes at about 150 and 160 Hz suggest multiple beat frequencies from 3–13 Hz, which when coupled with the 6.1-Hz frequency resolution in the spectrogram, yields a complicated temporal response. It is also noteworthy that the 120-Hz and 180-Hz *ombak* appear to be in phase, suggesting some form of deterministic relationship.

A comparison of Figs. 1 and 2 indicates that the structural results in Fig. 1(b) only represent a partial solution to the origin of the *ombak*. According to Fig. 1(b), the only modes that occur within a few hertz of each other are the pairs near 150 and 160 Hz. Their patterns (unpredicted given the circular geometry), their amplitudes, and frequencies suggest that these modes were possibly hammered deliberately into the response of the gong to produce *ombak*. However, as summarized in Table 1, there are more *ombak*-producing natural frequencies in the microphone PSD in Fig. 2(a) than were found in the initial structural measurements. For example, there is an acoustic response at 123.5 Hz as well as a pair of peaks near 180 Hz in Fig. 2(a) that do not appear structurally in Fig. 1(b).

The fact that the acoustic response of the struck gong has frequencies present that are not part of the structural response of the acoustically-excited gong suggests a nonlinear response of the gong not captured by the SLDV measurement. This hypothesis is strengthened when the peak displacements of the acoustically-excited (Fig. 1) and struck (Fig. 2) gong are

Table 1. Peak frequencies of the SLDV-measured structural and microphone-measured acoustic responses. The relationships between 61.75 and 121.25 Hz (called f_1 and f_2, respectively) and peaks present acoustically but not structurally are also shown.

SLDV (Hz)	⋯	61.75	92.0	101.0	121.25	⋯	150.25	153.25	160.0	162.5	⋯	⋯
Mic (Hz)	59.5	61.75	92.0	101.0	121.25	123.5	150.25	153.25	160.0	162.5	183.0	185.25
Relation	f_2-f_1	f_1			f_2	$2\times f_1$					f_1+f_2	$3\times f_1$

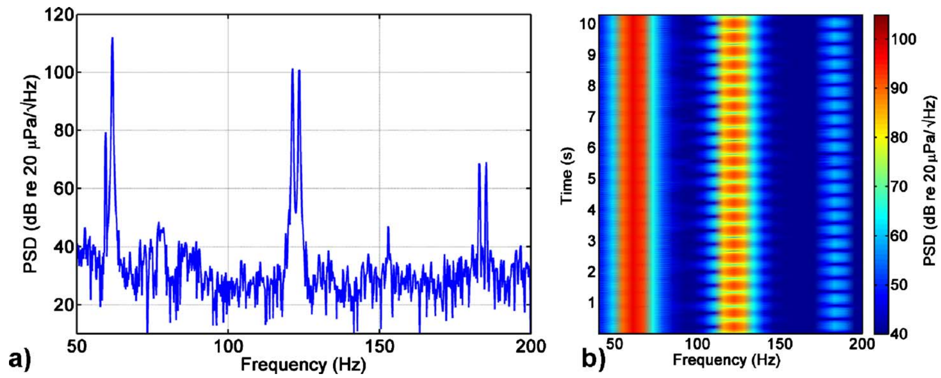

Fig. 3. (Color online) Spectra calculated from the microphone recording of simultaneous 61.75 and 121.25 Hz steady-state gong excitation. (a) Power spectral density. (b) Spectrogram of the recording.

considered. For the structural results in Fig. 1, white-noise acoustic excitation only yielded peak displacements on the order of 2 μm. On the other hand, the peak displacement of the boss when the gong was struck was approximately ±0.44 mm, a significant fraction of the gong thickness. (For reference, the gong thickness is 7 mm at the boss center and approximately 3 mm along the rest of the gong face.) The values of the additional frequencies present in the struck-gong spectrum also point toward nonlinear behavior, as there are exact mathematical relationships between the lowest two axisymmetric modes, 61.75 Hz [I in Fig. 1(b)] and 121.25 Hz [IV in Fig. 1(b)], and those peaks present in the acoustic data but not in the SLDV data. Shown in Table 1, these additional frequencies are required to produce the gong's *ombak* around 120 and 180 Hz. Additional measurements to characterize the nonlinear response of the gong are now described.

3. Investigation of gong's nonlinear response

To further investigate the modal frequencies absent from the SLDV measurement in Table 1, a Labworks ET-126B shaker was attached to the back of the boss. The shaker permitted steady-state gong excitation at much greater amplitudes than possible via acoustic excitation. The input to the shaker was a summation of 61.75 and 121.25 Hz sine waves. (Harmonic distortion in the amplified input signal was negligible for all amplitudes considered.) The boss-mounted accelerometer and the microphone were used to determine the structural and acoustic responses of the gong. It was quickly discovered that although the gong was being driven at only these two frequencies, additional frequencies, which corresponded to those missing from the original structural measurements, were present both structurally and acoustically.

The amplitudes of the two tones were adjusted so that the peak displacement at the boss was ±0.38 mm and the relative acoustic amplitudes of the two modes approximated those 2–3 s after the gong strike. This excitation caused distinctly audible beating. Figure 3, calculated in the same manner as Fig. 2, shows the averaged PSD and spectrogram from the steady-state excitation. Besides 61.75 and 121.25 Hz, the additional frequencies from Table 1 are clearly present in Fig. 3(a), which yields the in-phase *ombak* around 120 and 180 Hz in Fig. 3(b).

The results shown thus far demonstrate that the gong is responding structurally in a nonlinear fashion. Based on Table 1, the nonlinear response appears to be limited to the 61.75 Hz mode interacting with itself to produce harmonics and with the 121.25 Hz mode to produce sum and difference frequencies. Because *ombak* is ultimately an acoustically-perceived phenomenon, an additional experiment was carried out to confirm that acoustical nonlinearities (e.g., a nonlinear resonance of the gong cavity) do not contribute to the acoustical response of the gong at its fundamental mode. To examine this, the boss-mounted shaker was driven with a 61.75 Hz tone at root-mean-square (RMS) boss displacements from 1.4 μm to 0.4 mm. Figure 4 shows the microphone PSD (in dB re 20 μPa/$\sqrt{\text{Hz}}$) and the accelerometer PSD (in m^2/s^4 Hz) for

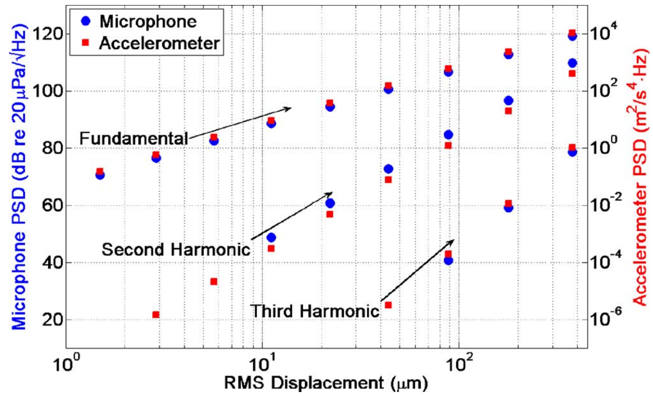

Fig. 4. (Color online) Comparison of the fundamental (61.75 Hz), second, and third harmonics' acceleration and pressure level amplitudes as a function of boss RMS displacement amplitude.

61.75 Hz and next two harmonics as a function of RMS boss displacement. Because pressure and acceleration levels for each frequency grow at the same rate as RMS displacement increases, (rather than the pressure levels growing more quickly), we conclude that the nonlinear oscillations are restricted to the structural domain.

Previous studies characterizing the nonlinear behavior of gongs have focused mainly on the Chinese tam-tam.[5–7] The nonlinearity is described in terms of nonlinear mode coupling, which produces new modes at harmonics of ordinary modes, a chaotic response, and drift of modal frequencies as a function of strike amplitude. We have shown that nonlinear mode coupling does exist in the gong ageng wadon, which is the dominant cause of its *ombak*, but the nonlinear response in this current study is different from the tam-tam in that (a) it is not chaotic for typical strike amplitudes and (b) the modal frequency does not appear to change with amplitude. A very hard strike (with peak boss displacement several millimeters) causes a chaotic response of the gong ageng wadon, but that point is well beyond normal performance conditions.

4. Conclusions

This investigation has revealed two sources of *ombak* in the gong ageng wadon. First, there appear to be structural modes that have been specifically created due to their asymmetric shapes not expected in the response of a circular gong face. These modes are part of the gong's linear response and contribute to the timbre and "shimmer" of the gong's response but are not the dominant source of *ombak* in the gong. The dominant *ombak* is caused by the nonlinearly-generated second harmonic of the fundamental axisymmetric mode interacting with the quasi-harmonic second axisymmetric mode. This phenomenon was not observed when exciting the gong acoustically but was readily observable when the gong was driven by a shaker at the frequencies of the first two axisymmetric modes at amplitudes comparable to those produced when the gong is struck. In conclusion, our study shows that the two principal axisymmetric modes that contribute to the gong tonality[2] are the same modes ultimately responsible for the dominant *ombak* produced by the gong.

The results of this investigation into the origin of *ombak* in the gong ageng wadon are particularly fascinating given the intuitive, artistic process that is the creation of these large bronze alloy gongs. For hundreds of years, the gong smiths have altered the shape and size of the boss to produce a very tonal sound that is unique among gongs. Furthermore, their possible adjustment of structural modes in the tuning process so that they are both close in frequency and amplitude is unexpected because of its circular geometry. Finally, it is remarkable that the dominant *ombak* relies on a nonlinear response of the gong with the additional requirement that the relative amplitudes of nonlinearly-generated second harmonic of the fundamental and the second axisymmetric modes must be approximately equal. Future studies of gamelan gongs may focus on the comparative behavior of the smaller gongs in the ensemble, some of which are designed to not produce *ombak*. In addition, the directivity of the gongs' acoustic radiation may be studied as well.

Acknowledgments

D.W.K. was supported in part by a BYU Mentoring Environment Grant. Molly E. Jones and Dorothy Manuel performed preliminary measurements on the gong, the results of which motivated this work. Daniel Manwill is thanked for his assistance with instrumentation. Finally, the reviewers are acknowledged for their helpful comments.

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