Vibrational characteristics of Balinese gamelan metallophones

Molly E. Jones[a)]
Department of Physics, University of Michigan, 450 Church Street, Ann Arbor, Michigan 48109
jonesmo@umich.edu

Kent L. Gee
Department of Physics and Astronomy, Brigham Young University, N283 ESC, Provo, Utah 84602
kentgee@byu.edu

Jeremy Grimshaw
School of Music, Brigham Young University, Provo, Utah 84602
jeremy.grimshaw@byu.edu

Abstract: A study of the eight metallophone pairs from a Balinese gamelan semara dana has been conducted. Acoustical recordings of metallophone bars being struck were used to examine ratios of overtone frequencies to the fundamental. Results showed large variability in the number and ratios of overtones present. Scanning laser Doppler vibrometry measurements made on several bars also revealed great variability in mode shapes present. The distribution of prominent overtones and their modal shapes do not appear to match those of Western metallophones. Notably, the overall gamelan metallophone characteristics are quite dissimilar to the glockenspiel, which disagrees with previous studies.

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1. Introduction

A gamelan is an Indonesian percussion orchestra composed of bronze metallophones, gongs, flutes, and sometimes stringed instruments or voices.[1] This study focuses on the metallophones of Brigham Young University's recently acquired gamelan semara dana, called gamelan Bintang Wahyu. ("Bintang Wahyu" is Balinese for "star of vision" and its name is meant to evoke the initials BYU.) The metallophones fall into two broad categories: gangsa and gender. Gangsa consist of 12 bronze bars spanning 2 octaves suspended over polyvinyl chloride (PVC) pipe resonators. (PVC was used, rather than the more traditional bamboo, because of Utah's arid climate.) Gangsa metallophones are struck with hard wood mallets. Gender metallophones are similar in construction, but they have seven bars within one octave and are struck with softer, padded mallets.

The complete ensemble of metallophones covers an approximate four octave range. As in all Balinese gamelan, the metallophones are created in pairs, with the female member of each pair tuned a few hertz lower than the other to generate a shimmery acoustic beating called "ombak," which is Indonesian for "wave."[1] Mm. 1 provides an example of the paired tuning.

Mm. 1. Ombak produced by a pair of metallophones called jublag. This is a file of type "wav" (2.7 kbytes).

The metallophone bars are trapezoidal in cross-section and are slightly curved along the length. (The Javanese bars studied by Carterette and Kendall[2] are similarly curved along the length, but their cross-section is airfoil-shaped rather than trapezoidal.[3]) Their lengths range

[a)]Author to whom correspondence should be addressed.

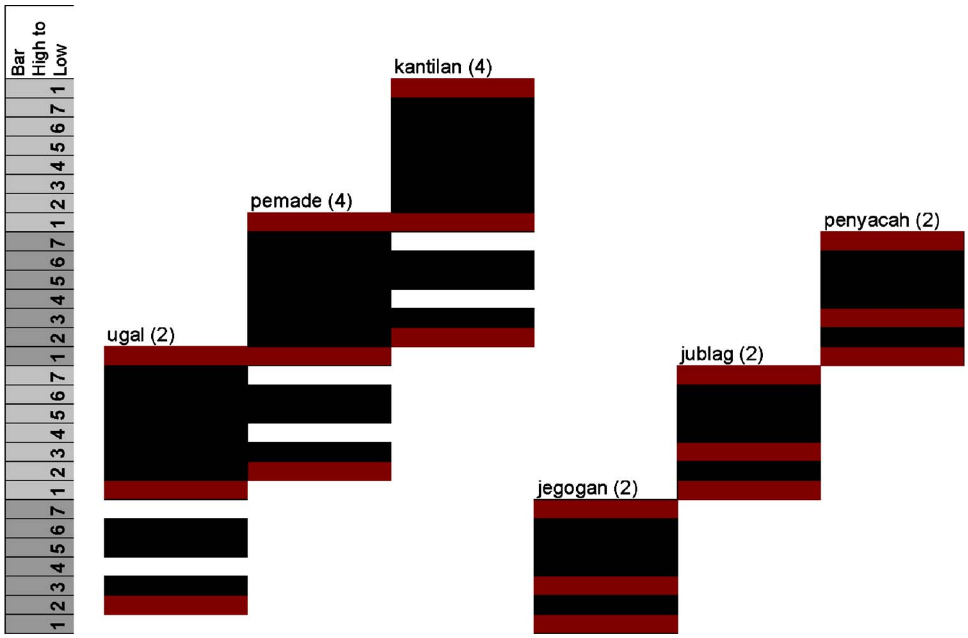

Fig. 1. (Color online) Chart of the six types of metallophones found in Bintang Wahyu and their ranges relative to the total four octave range of the ensemble. Numbers in parentheses refer to the number of each instrument type in the ensemble. The highlighted bars are those that were examined using the SLDV.

from 17 to 39.8 cm, and their widths (including the top three faces of the trapezoid) range from 6.4 to 9.3 cm. The thicknesses of the lowest bars are on the order of a few mm, and the thicknesses of the highest bars are around 2 cm. Many of the bars were undercut slightly in the process of tuning and so are thinner in the center.

Some studies have been performed previously on the vibrational characteristics of the Balinese gamelan. Most notably, Rossing and Shepherd[4] performed a study of a jegogan and concluded that the modal characteristics were comparable to those of the glockenspiel, which had been investigated previously by Rossing.[5] (This same comparison has since been repeated elsewhere.[6]) Other researchers have made some observations of the vibrational characteristics of gamelan metallophones, but most of these address either the properties of Javanese instruments, which do not have trapezoidal bars, or some aspect of the sound other than the vibrations of the bars themselves.[3,7–9] In this Letter, we describe the vibrational characteristics of the Balinese gamelan metallophones and compare them to those of the glockenspiel.

2. Measurements

Two types of measurements were made on the bars. First, acoustical measurements were made on all bars across the gamelan. Second, scanning laser Doppler vibrometry (SLDV) measurements were made on several bars to study the mode shapes produced. These measurements were repeated on five representative bars of a glockenspiel.

Figure 1 lists the metallophones of gamelan Bintang Wahyu and shows their ranges. An acoustic recording was made of each of the 162 bars using a type-1 12.7-mm (0.5-in.) prepolarized microphone and a National Instruments USB-9233 24-bit data acquisition module attached to a laptop running LABVIEW. Data were acquired at a sampling frequency of 50 kHz. Because spectral analysis of the recordings showed the struck bars produced very stable, high-quality-factor resonances, the data were treated as stationary for the purposes of determining frequency. The relatively long time window permitted the frequencies to be resolved using Fourier analysis to within 0.2 Hz. Trials were made with different percussionists and striking tech-

Table 1. The overtones of the fourth bar of a jublag and the eighth bar of an ugal. These represent the same note, but the partials present are quite different.

Overtone frequencies of jublag, fourth bar (Hz)	Ratio to fundamental	Overtone frequencies of ugal, eighth bar (Hz)	Ratio to fundamental
393.5	1	393.3	1
1090	2.77	1028	2.61
2037	5.18	1888	4.80
2096	5.33	1941	4.94
		2486	6.32

niques, and strike-to-strike differences were not significant for this particular study. All overtones with a sound pressure level ~35 dB or higher were listed as prominent. The ratio of each prominent overtone frequency to the fundamental frequency was then calculated for all bars.

For the SLDV measurements, a Polytec PSV-400 was used to scan 150–180 points per bar. One ugal, one jublag, one penyacah, and one pair each of jegogan, pemade, and kantilan (27 bars total) were examined with SLDV; the bars that were scanned are highlighted in Fig. 1. Each bar was excited with a pseudorandom signal from a Mackie HR-824 studio monitor, and the PSV was used to determine the prominent transverse modes of vibration. (In-plane bending and stretching modes were not taken into account.) In several cases, overtones that appeared prominently in the acoustical measurements were not present in the initial SLDV scans, probably because there was insufficient energy in the broadband acoustic signal to excite that mode. In these cases, and in cases where the SLDV indicated an overtone but showed no clear modal shape, the bars were excited again with a sine wave at the expected frequency of the overtone. This usually yielded a clear modal shape, and it allowed compilation of a final list of the prominent overtones of each bar.

3. Sample results

Table 1 lists the overtones of two bars from two different types of gamelan instruments that sound the same note. Their fundamental frequencies are slightly different because of the unusual tuning required to produce ombak,[2] but the partials that appear are totally distinct. This is one example of the marked inconsistency among metallophone bars. It is difficult to find a pattern in the prominent overtones of bars within one instrument or across the ensemble. The spectrum of partials from one bar gives little indication of the partials that its neighbors will exhibit. This seems to confirm Rossing and Shepherd's assertion that gamelan makers do not tune the overtones of metallophones.[4]

The gamelan metallophones' unique timbre is at least partially a result of their unusual overtones. Rossing and Shepherd[4] pointed out from their study that most of the gamelan's overtones die out within 1 s. However, many of Bintang Wahyu's overtones are present for as long as 4 s. Because much of Balinese gamelan repertoire requires that players strike a note and damp it very quickly, these overtones would sound for the duration of the note and are therefore important for timbre.

The variability of the bars extends to the modal shapes of the bars. Figure 2 shows the prominent vibrational modes of the lowest bar of a jegogan. Of the 19 prominent overtones, only 3 have ratios to the fundamental less than 15, and the highest 2 overtones have ratios greater than 40. The highest prominent frequency of this particular bar occurs at around 5.6 kHz. Although rectangular bar theory predicts some of the observed mode shapes up to a ratio of 14 times the fundamental,[4,10] many predicted shapes do not appear, and many shapes appear that are not predicted. The complex shapes of the higher modes are unique and do not occur in any other bars of the ensemble.

A number of bars in the lowest three octaves of the ensemble, particularly in the jegogan, have prominent harmonic overtones as well as the usual inharmonic ones. This suggests

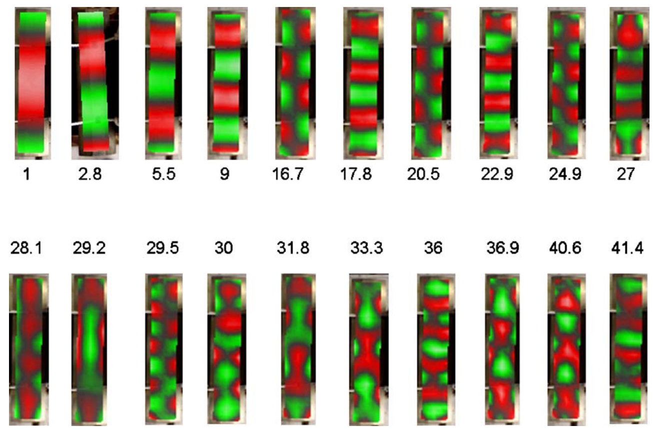

Fig. 2. (Color online) Prominent modes of the lowest bar of a jegogan, along with the ratios of their frequency to the fundamental frequency. Of the 19 prominent overtones, only 3 have ratios to the fundamental less than 15. The complex shapes of the highest modes are unique and do not appear in the other 26 bars examined with SLDV. Note that the lower torsional modes do not appear in this bar, but they do in other low bars in the ensemble.

that some bars behave nonlinearly when struck with typical playing force, a characteristic that would differentiate gamelan metallophones from Western metallophones like the glockenspiel and marimba.[5]

4. Analysis and discussion

The primary purpose of this study was to determine the important overtone ratios and modal shapes of gamelan metallophone bars and investigate their consistency across the ensemble. Although there is little consistency from bar to bar, there are general trends that can be found across the range of the ensemble. The lowest bars, those that fall within about the first octave of the gamelan, display the highest total number of prominent overtones (between 16 and 26 per bar). In this low range, most of the prominent overtones have ratios to the fundamental greater than 15 (see Fig. 2). In the second octave of the ensemble, the number of overtones present with frequency ratios greater than 15 drops dramatically, as does the total number of prominent overtones. In the highest two octaves of the ensemble, the bars have fewer total overtones (between 3 and 11), and none of these have ratios to the fundamental greater than 15. This is likely because of the increased thickness of the higher bars relative to their length. Some bars, particularly the highest bars, have only a few very closely spaced overtones close to the fundamental. There can be as many as five overtones with ratios less than 5. Figure 3 offers examples of common and uncommon mode shapes.

The second purpose of this study was to compare the overtones and mode shapes of Bintang Wahyu's metallophones to those of the glockenspiel. The prominent modes of the glockenspiel found by SLDV are those predicted by rectangular bar theory, and both mode shapes and overtone ratios are in accord with Rossing and co-worker's findings.[4,5] This is predictable given the emphasis Western instrument makers place on consistency across different instruments. The first five glockenspiel mode shapes, and their average ratio to the fundamental, are shown in Fig. 4(a). All five predicted modes were found in all five glockenspiel bars measured; the error bars show the range of ratios across which these modes were found.

Figure 4(b) provides the same information for the gamelan bars. The percentage beside each mode shape represents the percent of gamelan bars measured which actually displayed that particular mode. Only one or two bars displayed all five of the predicted mode shapes. Note that the first torsional mode always has a lower frequency than the second transverse mode; the order of these two modes is reversed from the glockenspiel. Both torsional modes have much lower frequencies relative to the transverse modes than they do in the glockenspiel, and they are less universal in the gamelan than in the glockenspiel, perhaps because of the curvature and shape of

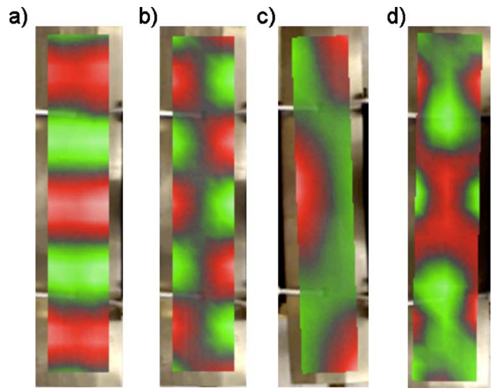

Fig. 3. (Color online) (a) A typical transverse mode as predicted by the theory of rectangular bars. (b) A typical high-frequency torsional mode as predicted by the theory of rectangular bars. (c) An unusual mode shape not predicted by the theory of rectangular bars. This shape appears in 9 of the 27 SLDV-measured bars, with a typical frequency ratio to the fundamental around 4.5. Although it resembles the second torsional mode shown in Fig. 4, it is distinct and has no nodal line down the center of the bar. It often appears in the same bar as the second torsional mode but at a higher or lower frequency. (d) An unusual mode shape that occurs once in the ensemble and nowhere else. It is the 15th prominent transverse mode of a jegogan (shown previously in Fig. 2).

the bars. Although the second transverse mode seems (impossibly) to sometimes have a higher frequency than the third transverse mode, it should be noted that those bars which had such a high second transverse mode did not show a prominent third transverse mode at all. It seems that the assertion that the overtones of the gamelan are comparable to those of the glockenspiel is not completely accurate, though it may be true for certain bars. Despite the inconsistency, the average ratios of the transverse modes are similar in both glockenspiel and gamelan.

5. Conclusion

The previous observation that the modes of Balinese gamelan metallophones are comparable to those of the glockenspiel is not accurate for the instruments studied. This is not entirely surprising, since gamelan instruments are created without any expectation of consistency between ensembles; the metallophone measured by Rossing and Shepherd[4] may have been more like a glockenspiel than those of Bintang Wahyu. Although there are similarities in some of the mode shapes and in the average ratio of the transverse modes to the fundamental, the inconsistency in

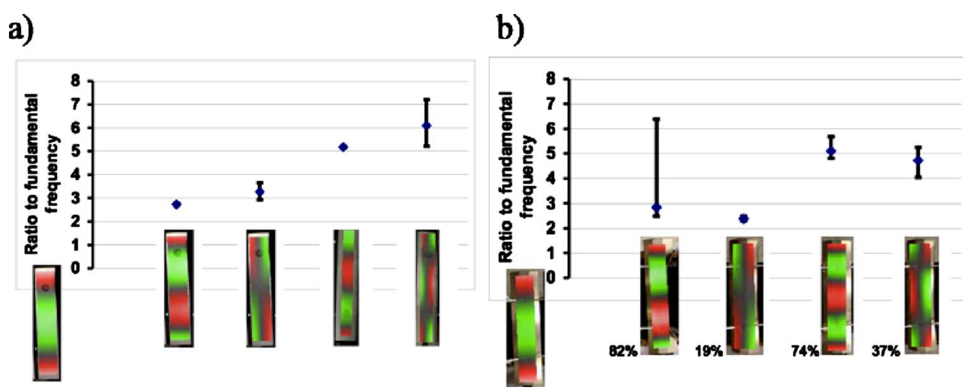

Fig. 4. (Color online) (a) First five modes predicted by rectangular bar theory and found in the glockenspiel, along with each mode's average frequency ratio relative to the fundamental. Error bars indicate the range of ratios found. (b) Same as (a), but for the gamelan metallophones. The percentages indicate the frequency of the mode shape occurrence in the 27 bars measured.

the presence and order of various modes and the additional unusual mode shapes and overtones make it difficult to predict the behavior of a gamelan bar, even if the spectra and modes of its neighbors are known. These differences serve to make Balinese gamelan metallophones rich and unique instruments with quite different properties from Western metallophones, including the glockenspiel. Further research could involve comparing the vibrational qualities of Bintang Wahyu's metallophones to gamelan made by other instrument makers or to other gamelan produced by the same artisan.

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