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An investigation of directional and vibrational characteristics of a nonlinear harmonic of a Balinese gamelan gong

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Balinese gamelan gongs are instruments of special interest because of their unique geometry and sound. Unlike a Chinese tam-tam, the gongs are quite thick, with a protruding dome in the center and long edges that sharply wrap around the circumference of the gong. When struck in the center, the larger gongs are designed to produce strong, audible beating. Previous studies have shown the cause of this beating phenomenon to be the proximity of the harmonic of the first axisymmetric mode to the frequency of the second axisymmetric mode [Krueger et al, J. Acoust. Soc. Am. 128(1), 2010]. Previous work has not defined this first harmonic in terms of its modal deflection shape or directivity pattern, either isolated or coupled with the rest of the system to produce the beating. The results of this study characterized the harmonic as having the same behavior as the second axisymmetric mode. This was true whether the second mode was, or was not present in a given measurement. This paper will present measurements studying the vibrational and directional characteristics of the gong's first harmonic and a discussion with possible explanations as to why it appears to behave as the second axisymmetric mode.

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1. INTRODUCTION

Balinese gongs are uncommon in western orchestras, yet they form a key part of Indonesian culture, both musically and spiritually. This introduction details some of the characteristics of a Balinese gamelan, presents several related studies and introduces the current work.

A. CULTURAL BACKGROUND

Bali is an island province of Indonesia near Java. Its culture is full of intricacies, including many calendars and extreme attention to detail in clothing, architecture, and music. The Balinese gamelan is at the heart of music in Bali. The gamelan, meaning ensemble, contains anywhere from a few to as many as over seventy percussion instruments, including metallophones, drums, and gongs. Metallophones often provide the melody in this music, while the drums create more syncopated rhythms, and the gongs establish strong and weak beats in the meter and are left to ring out at the end of musical phrases. A different definition of tuning in Bali gives the gamelan music a shimmering effect due to pitches that sound out of tune to the Western trained ear. This acoustic beating phenomenon is known as "ombak," literally meaning "wave."[1] The large gongs (or gong ageng) of the gamelan are particularly interesting because they produce beating independently when struck in the center. These gongs have a unique geometry with a thickness up to 5 mm, a long rim at that wraps around the circumference, and a raised polished dome in the center called the "boss." This is quite different from a Chinese tam-tam, especially because the gongs are hand-crafted (usually from bronze) and do not have a uniform thickness.

B. PREVIOUS STUDIES

The directivity and vibrational behavior of musical instruments are among their most important attributes. Directivity studies have been performed on many instruments in the Western orchestra.[2] Other studies have focused on the vibrational characteristics of percussion instruments such as gongs and Chinese tam-tams[3,4] and even gamelan instruments.[5,6,7] A particularly relevant study by Krueger et al. investigated the cause of ombak in the large Balinese gongs.[8] They observed a nonlinearly generated harmonic of the first axisymmetric mode that occurs near the resonance frequency of the second axisymmetric mode, causing the perceived beating. This beating was reproduced by driving the gong at the first two axisymmetric mode resonances simultaneously.

In 2022, a study by Bellows et al. measured the directivity patterns of a large and small gamelan gong.[9] A comparison was made between the directivity and modal characteristics of these gongs, which revealed significant differences. The vibration and radiation patterns of the two gongs are similar, but not always the same, even for the same mode shape. The ordering of the modes is also different between the gongs; one gong cannot predict the other's behavior. Dipolar behavior is notable in the lower frequency radiation of both gongs, and a model has since been created using spherical harmonic and multipole expansions to predict directivity patterns.[10] An important observation of the directivity study was that the operating mode shape of a resonance can inform the resulting directivity pattern at higher frequencies. Placement and quantity of directivity lobes often correspond to antinodal sections of the mode shape. Another successful model has been developed that imposes mode shapes on a rigid sphere to preserve their effect on the resulting directivity.[11]

There was a notable exception to the tendency of directional behavior relating to mode shapes. A frequency band contained several resonances that appeared more omnidirectional than could be predicted from the mode shape. However, a third model, consisting of a vibrating cap on a hollow rigid sphere, also showed more omnidirectional behavior for these resonances.[11] This model includes a circular aperture opposite the cap, and thus a Helmholtz resonance of the gong cavity could account for the change in directivity in the gong and the model. The author adjusted parameters of the model to better match the geometry of the gong and took physical measurements with a microphone in various locations in line with the back rim of the gong. Both experimental and computational results supported the conclusion that a resonance of the back air cavity of the gong occurs within the omnidirectional region seen.[12]

C. CURRENT STUDY

Although there is some understanding of the beating, directivity, and modal behavior of the gongs, little has been done in terms of characterizing the nonlinear harmonic responsible for the beating. This paper will present a study that focused on defining the directivity and vibrational behavior of this harmonic. The harmonic is present when the gong is struck or driven at its fundamental frequency. Directivity and scanning laser measurements were taken while the gong was driven at only its first resonance to isolate the harmonic from other nearby resonances, and while the gong was driven at the first two axisymmetric mode resonances simultaneously so as to recreate the more natural beating effect of the gong. These data could be compared with each other and with past directivity data for a better understanding of the nonlinear harmonic behavior.

2. METHODS

In the nonlinear regime, a harmonic of the first mode of the gong wadon will form near the second mode and create audible beating. If the gong is driven sufficiently at the first mode, the harmonic will form an octave above it, and if the gong is driven at both modes, the frequency spacing between the harmonic and the second mode should cause acoustic beating. Testing these two conditions will allow for characterization of the harmonic both isolated, and interacting with the second axisymmetric mode resonance.

A. DIRECTIVITY MEASUREMENT

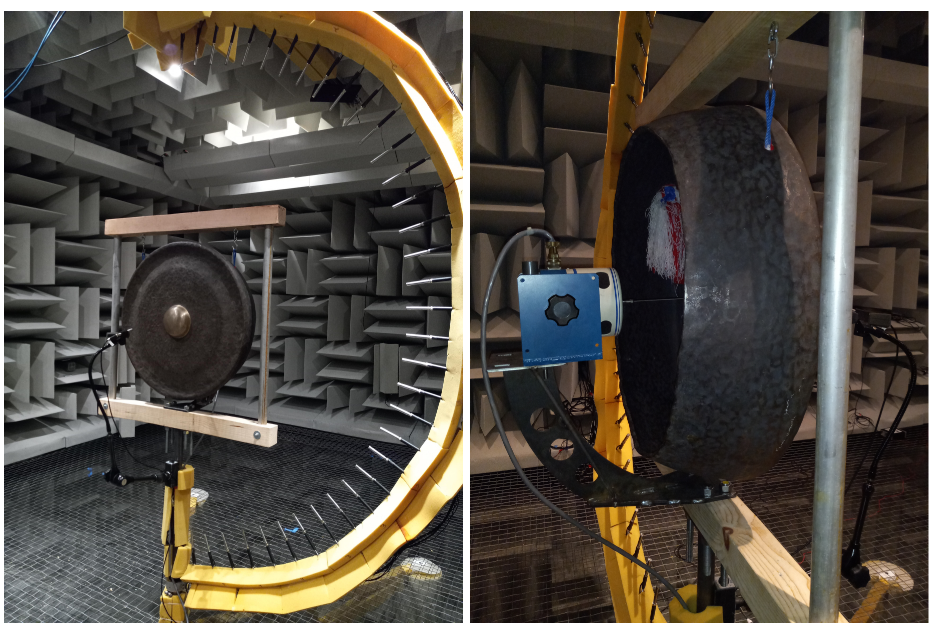

Figure 1: The gong wadon mounted in the directivity measurement system. A customized frame allowed for centering of the gong in the array. The rotational microphone array is seen in the 0 degree position. A shaker is set in the back and attached to the center of the gong.

The gong wadon was placed in a directivity measurement system (DMS) at Brigham Young University (see Figure 1). The DMS consists of a hemispherical array of 36 microphones within an anechoic chamber.

The array is connected to a turn table in order to rotate around the sound source.The top microphone remains fixed to give a total of 2521 unique sampling positions. A 37th microphone seen in front of the gong in Figure 1 serves as a reference and provides normalization in post-processing. A live musician was initially recorded striking the gong with its traditional mallet. Another measurement of the gong was taken with the instrument being excited with a low-amplitude shaker sweep in order to compare with the results of Bellows et al.[9] The sweep duration was 3 seconds, ranged from 20-5000 Hz, and was repeated 3 times per array position to include averaging.

The power spectral density (PSD) plots resulting from these measurements are shown in Figure 2. The PSD of the struck gong on the left is notable for the two clear resonances from the second mode and the harmonic. The resonance frequencies 121.5 Hz and 124.5 Hz cause the 3 Hz beating heard when the gong is struck in performance conditions. The PSD on the right shows the sweep data and the two axisymmetric mode resonance frequencies. Note that the resonances in the sweep data are slightly lower in frequency than those from the struck gong. This is due to the increased effective mass of the gong when the shaker is glued to the back. The resonances from the sweep data were chosen as the sine inputs for the harmonic study.

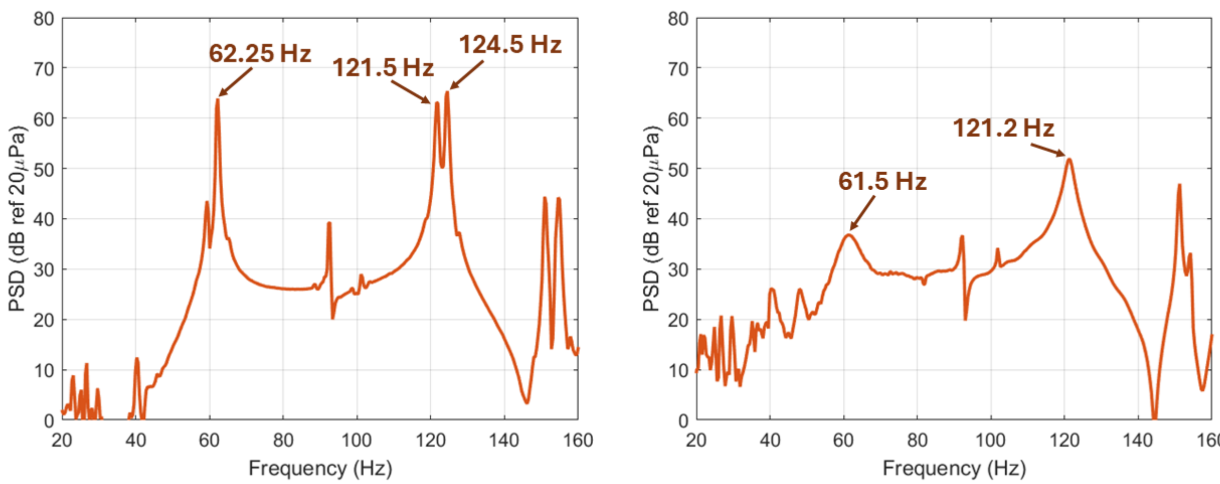

Figure 2: Power spectral density plots of the gong wadon. The plot on the left shows the gong's response when struck. The nonlinear affects are present and the proximity of the second mode at 121.5 Hz and the harmonic at 124.5 Hz is apparent. Sweep data on the right shows the first two axisymmetric modes with slight frequency variations due to the attached shaker mass.

To investigate the nonlinear harmonic, the gong was first driven at the (0,1) resonance to isolate the harmonic. Then, in repetition of the methods used by Krueger et al., the gong was driven at its first two axisymmetric resonances simultaneously.[8] The gong's response to the two sine wave input is shown in Figure 3. The distance in frequency between the second mode and the harmonic is slightly smaller than before because of the resonance change with the shaker attached. This causes the beating waveform shown on the right to have a slower pulse than the typical 3 Hz beating. A Siglent function generator (SDG2042X) was used to output both the (0,1) and (0,2) resonance frequencies into an operational amplifier, which then transmitted the combined signal to another amplifier and then the shaker. The amplitude of the first mode frequency was chosen to be 4 times that of the second to achieve the most natural sound. A larger shaker (Ling Electronics) was used to drive the gong at sufficient amplitudes to introduce nonlinearity. It was centered on the boss to more efficiently excite the (0,1) and (0,2) modes.

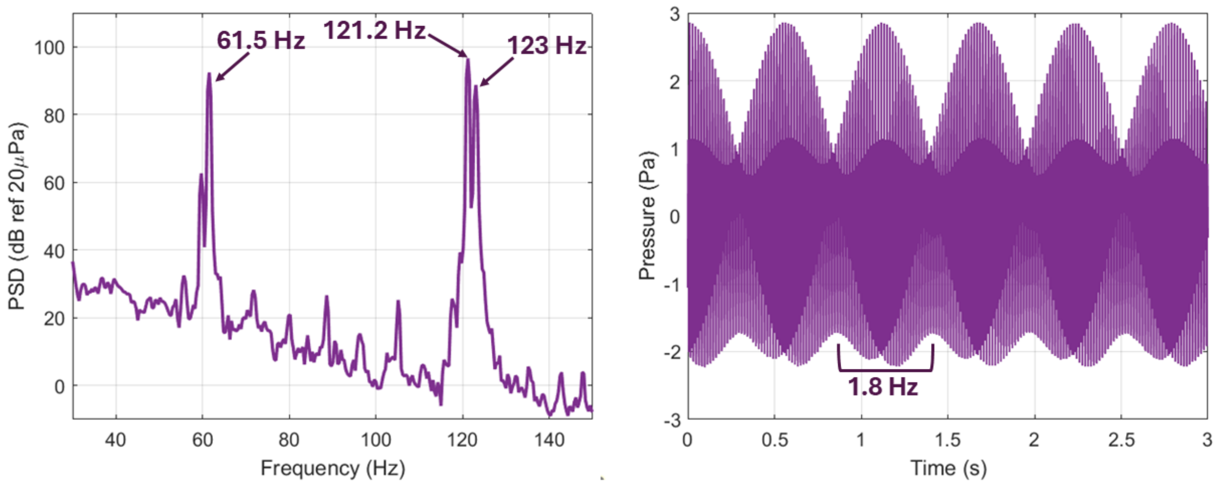

Figure 3: Power spectral density plot and beating waveform for the driven gong wadon. The PSD on the left shows the gong's response when driven at the 61.5 and 121.2 Hz resonances simultaneously. The nonlinear affects are present and the proximity of the second mode at 121.2 Hz and the harmonic at 123 Hz is apparent. The resulting 1.8 Hz beating is seen on the right. The frequency is slightly lower than the typical 3 Hz due to the shift in resonance frequency with the shaker attached behind the gong.

B. SCANNING LASER MEASUREMENT

A scanning laser Doppler vibrometer (SLDV) scan of the gong was also taken with a low-amplitude sweep, single sine wave, and combined sine wave inputs. Each measurement consisted of a square data grid of 437 equally spaced points covering the front face of the gong. The first scan was a 1 second sweep input from 20 to 1000 Hz and showed the expected mode shapes of the gong. Additional scans with the 61.5 Hz input and then combined 61.5 and 121.2 Hz input allowed for the structural presence of the harmonic both isolated and in combination with the (0,2) mode. The vibrational behavior was then recorded at the harmonic frequency and compared with that of the (0,2) mode shape and the directional behavior of the harmonic.

C. HARMONIC DISTORTION

It was noted early on that the harmonic of interest was present in the signal that was used to excite the gong. This was not desirable because the purpose of the study was to observe the harmonic as generated by the gong, and not the gong's response to being driven at the harmonic's frequency. Harmonic distortion from amplifiers constitutes a universal problem, and some studies have focused on removing distortion from the amplification process.[13] Figure 4 shows the microphone and signal spectra from a 61.5 Hz input, and from a combined input of 61.5 and 121.2 Hz.

The signal spectra in gray have multiple peaks resulting from distortion rather than the desired single or double sine input. Removing the amplifier from the system did not improve the results. Distortion can also occur from the AC current frequency in American outlets (60 Hz) being near the amplifier input of 61.5 Hz. However, improving the grounding also did not affect the signal spectrum. As there is no way to complete a measurement without the signal generator itself, the op amp signal combiner, or the shaker, the distorted signal had to be tolerated. Comparison of electric and acoustic signals ensured that the measured harmonic was not purely a result of harmonic distortion from the amplifier. Figure 4 shows that nonlinearity from the gong itself contributes to the harmonic amplitude. In both cases, the signal experiences a 30 dB decrease between 61.5 Hz and its harmonic at 123 Hz while the microphone plots drop less than 10 dB

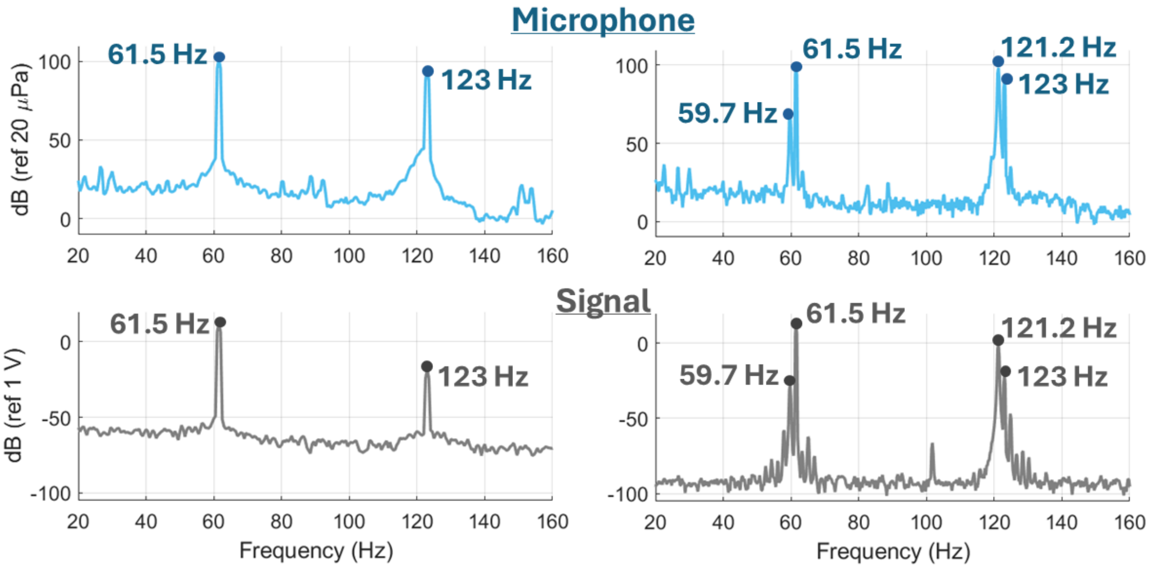

Figure 4: Frequency response of the amplifier-gong system. On the left are the spectra for a 61.5 Hz input and on the right are the specta for the combined 61.5 and 121.2 Hz input. The microphone plots in blue show the expected resonances, but unwanted harmonics are present in the signal that could not be eliminated. However, the harmonic of interest at 123 Hz is stronger in the microphone measurement than in the signal. This implies nonlinearity in the gong is contributing to the amplitude of the harmonic, thus validating the data set.

from 61.5 to 123 Hz. A linear scale from the signal to the sound produced by the gong does not hold. This implies a significant portion of the harmonic's amplitude as recorded by the microphone is contributed by the nonlinear effects of the gong which suggests that the desired phenomenon is present in the measurement.

3. RESULTS

The directivity of the first two axisymmetric modes and the harmonic of the first mode were taken and compared with the operating mode shape data from the SLDV, similar to what was done by Bellows et al. The behavior of the first two axisymmetric modes was comparable to that seen in previous studies.[9] The directivity of the harmonic from the struck gong data is shown in Figure 5. In this case, the 0 degree marks represent the top and the right side of the gong. The array position in Figure 1 shows 0 degrees in the azimuthal direction. The axial, median, and frontal plane behaviors are colored green, magenta, and blue, respectively. Immediately it was apparent that the directional behavior of the harmonic matches that of the second axisymmetric mode. There is a faint nodal line that can be seen in the green axial plane outline, and the majority of the radiation tends towards the front and back of the gong.

The directivity plot of the struck gong in Figure 5 shows how the harmonic resembles the (0,2) mode behavior. This was not only true for the struck measurement, but when the gong was excited by a 61.5 Hz signal and then a combination of 61.5 and 121.2 Hz, the behavior of the harmonic was identical. Although the measurement conditions differed and the resonance frequencies shifted, the harmonic and second mode from all tests appeared as seen in Figure 5.

Data from the laser scan showed similar results. Figure 6 shows the vibrational behavior of the gong at its fundamental and harmonic resonances. This scan was taken while the gong was driven at 61.5 Hz. The operating mode shape of the fundamental is shown in Figure 6a and demonstrates (0,1) mode behavior as expected while the harmonic at 123 Hz in Figure 6b vibrates like the (0,2) mode. The scan in which

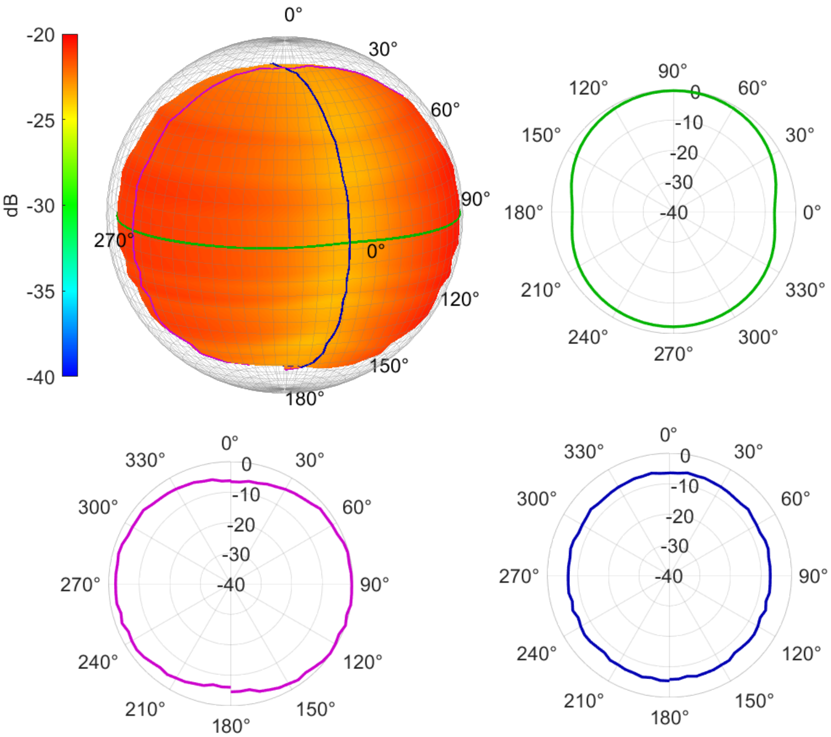

Figure 5: Directivity plot of the harmonic. This data was taken as the gong was struck with the traditional mallet. The directivity is shown in the upper left, where 0 degrees marks exactly above and to the right of the gong. Red regions are areas of higher pressure, with less level drop relative to the reference microphone. The behavior of the axial plane is shown in green, the median plane in magenta, and the frontal plane is outlined in blue.

the gong was driven at both resonances simultaneously was not as clear (possibly because the laser scanner had difficulty with the acoustic beating constantly changing the vibration amplitude) but showed the same results, where the (0,1) resonance behaved as expected and both the harmonic and second axisymmetric mode vibrated in the (0,2) pattern.

4. DISCUSSION

It was not anticipated to see the directional behavior of the harmonic match so closely with that of the second axisymmetric mode. They each have resonances at different frequencies which are visibly and distinctly separate in the PSD plots. Modal degeneracies studied previously were close in frequency and shared similar directivity plots due to their common mode, but were always distinct, often with lobes being shifted by some angle. Proximity in frequency has not caused identical directivity behavior before.

The plots could be identical because the harmonic distortion causes the shaker to simply drive the gong near the (0,2) mode, which results in (0,2) mode directivity. This is unlikely because the amplitude of the harmonic is much higher when measured from the gong than from the signal as seen in Figure 4. There is nonlinearity present, causing the harmonic to influence the nearby mode, which should be seen if the harmonic were to truly behave differently. Additionally, the directivity of the harmonic was the same for both struck and driven measurements. Distortion had no effect on the strike measurement, and the far-field behavior is very closely tied to the operating mode shape. If the harmonic has the same directivity across

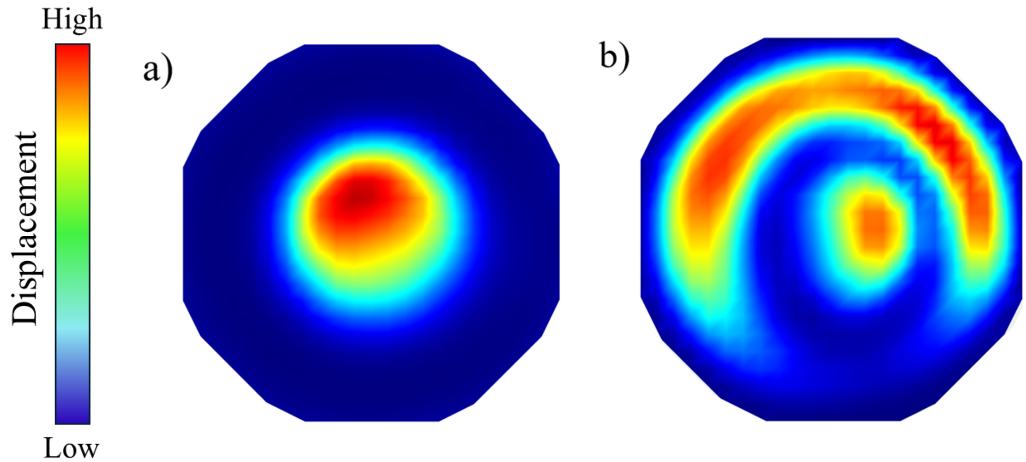

***Figure 6:** Vibrational behavior of the (0,1) mode and its harmonic. Here, red regions represent areas of maximum displacement where blue shows minimum displacement. This data was taken while driving the gong at 61.5 Hz. The fundamental mode behavior is seen in a), with (0,2) behavior seen in b), the harmonic at 123 Hz. The asymmetry in the plots could result from slight shaker misalignment or non-uniform thickness of the gong.*

all measurements, it is reasonable to assume the vibrational data are also the same (although it would be impractical to take a laser scan of a player measurement). With these considerations, it is not valid to assume that the vibrational data are identical due to distortion when the directivity data without distortion are also identical.

There are two other proposed explanations for the behavior of the harmonic. Nonlinearity produces the harmonic at $2f_0$, displacing the gong and creating tension forces there. Energy from the system is now being applied at that frequency and could be considered a force that drives the gong near the (0,2) mode resonance, causing the observed (0,2) behavior at both the harmonic and second mode frequencies. This is similar to the distortion argument above, with the important distinction that the gong creates this force naturally. Another possibility is a nonlinear superposition of modes.[14] Nonlinear normal modes (NNMs) can be quite complicated, where different energy levels or displacement amplitudes can cause one mode to behave as a linear combination of one or more higher-order modes.[15] Indonesian gong-making tradition could have found a way to unknowingly take advantage of NNMs and encourage the harmonic of the fundamental to behave as the second axisymmetric mode. The nonlinearity could produce a fundamental with minimal contributions from other modes while producing a harmonic that both vibrates with exactly the same pattern of the second axisymmetric mode and occurs within just a few hertz of it, enhancing the characteristic beating effect of the gong.

5. CONCLUSION

The Balinese gamelan is at the heart of music in Bali. The instruments in the gamelan have not received as much attention as Western instruments, but have been the subject of some studies that observed their vibrational behavior.[5,6,3] Studying these instruments helps keep their culture alive by increasing awareness of and interest in them. Research on the gamelan has also led to a better understanding of these instruments and motivated the development of several models that have demonstrated the application of theoretical principles to represent real instruments.

The directional behavior of the gong has been characterized in the linear regime, but the nonlinear harmonic responsible for the acoustic beating of the gong has not previously been studied.[8] Directivity and scanning laser measurements were taken of the gong driven at its fundamental mode and at a combination of its first two axisymmetric modes to observe the nonlinear harmonic both isolated and occurring next to the second mode.

Directivity measurements of the nonlinear harmonic matched those of the second mode in every instance. SLDV data further revealed the harmonic to behave the same as the second axisymmetric mode. Harmonic distortion was noted, but seems an unlikely culprit for the (0,2) mode behavior, as the radiation of a player measurement agreed with all other tests. Nonlinearity causes displacement and tension forces at the harmonic frequency, and these forces could simply drive the gong near the second axisymmetric mode to generate the observed behavior. Nonlinear normal modes (NNMs) offer another explanation for the behavior, as they can include a linear combination of higher-order modes. The gong may have been crafted so that the harmonic of the fundamental contains mostly nonlinear contributions from the (0,2) mode. This would likely enhance the observed beating as the two frequencies responsible for it share both vibrational and directional behavior. NNMs have complicated behavior, and their possible role in the vibration of the gong could be a topic of future investigation.

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