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Tuning the Nigerian Slit Gong

Ashley E. Cannaday
acannaday@rollins.edu

Brandon C. August
Rollins College, baugust@rollins.edu

Thomas R. Moore
Department of Physics, Rollins College, TMOORE@rollins.edu

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Ashley E. Cannaday, Brandon C. August, and Thomas R. Moore[a)]
Department of Physics, Rollins College, Winter Park, Florida 32789

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An experimental and theoretical investigation of the Nigerian slit gong is reported. It is shown that in tuning the gong the artisan ensures that the frequencies of the two lowest mechanical resonances are nearly coincident with the frequencies of two of the acoustic resonances of the internal cavity. Four possible tuning parameters are identified and the effects of changing these parameters are discussed. © *2012 Acoustical Society of America*. [DOI: 10.1121/1.3675940]

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I. INTRODUCTION

The slit gong is known to have existed for over a millennium in various regions across the world. It has numerous aliases, including the ekwe drum, slit log drum, lokole, mongo, and boungu, and is common to many cultures, including those in Africa, the Philippines, Mexico, and the South Pacific islands. The gongs range in size from less than 25 cm to several meters long.

A photograph of a typical Nigerian slit gong is shown in Fig. 1. Regardless of where in the world the gongs are found they have several common characteristics. The most notable characteristic is that it is formed from a single log and there is a slit carved into it, which separates two regions that produce different pitches when struck. However, slit gongs can have multiple slits, a wide variation in slit dimensions, and the details of the interior cavity may vary considerably. The Nigerian slit gong, which was initially used by indigenous Africans as a means of communication, has two tabs that produce two different pitches when struck and is representative of this common idiophone. A small gong approximately 0.5 m long and 20 cm in diameter can transmit messages up to 3 miles, and larger gongs that are approximately 1.5 m long and 1 m in diameter can send signals up to 7 miles.

To convey messages using a slit gong the drummer takes advantage of the fact that most African languages are tonal, using two pitches in the pronunciation of words. Each syllable of a word must be assigned one of these pitches, and a change in the pitch can dramatically alter the meaning of a word. Slit gongs use this reliance on enunciation to send messages; a syllable with emphasis is conveyed with the higher pitch, whereas a syllable without emphasis is conveyed with the lower pitch. However, many words can have the same combination of high and low pitches; therefore, African drummers have used much longer unique phrases for many objects, actions, people, or places.[1] Today, however, slit gongs are used primarily as musical instruments.

The slit gong is made by carving two rectangular holes into the side of a log and then hollowing out a cavity between them. A section of the log is left above the cavity between the two holes, and a slit is carved down the middle of it. This arrangement creates the two tabs between the holes. By ensuring that the thickness of the interior wall of the log is different near the two tabs they are made to have different resonance frequencies. Typically the gong is constructed from logs of *Pterocarpus soyauxii,* commonly referred to as African padauk, camwood, or coral-wood.

Although detailed studies have been conducted concerning the acoustics of numerous idiophones, to our knowledge the slit gong has not been investigated. This may be due to the fact that it is a rare and expensive instrument that must be imported from Africa. It appears that few people outside of Africa know how to make the instrument, and from informal communication with artisans in the United States it appears that those who do simply perform the steps that were taught through a short apprenticeship.

We report here on an investigation into the acoustics of this unique instrument. Our investigation included determining how the Nigerian slit gong is tuned and if this method of tuning is the most efficient. To determine the acoustic properties of the gong, we investigated the gong as both a mechanical resonator (the tabs) and an acoustic resonator (the air cavity). We then determined the relationship between the mechanical resonances of the tabs and the acoustic resonances of the air cavity. Analytical or numerical models were then developed for each resonator to investigate how changing the physical parameters of the gong changed the resonance frequencies.

In the work reported here three slit gongs were investigated. The three instruments were purchased over a period of five years from different vendors. Although there were differences in the details of each of the gongs, some of which will be noted in the following, in general the three gongs had similar measurements and characteristics. One gong was chosen as representative and the measurements of this gong were used for the modeling efforts described below. The physical measurements of this gong are shown in Table I.

The mechanical resonator of the tabs was modeled using commercially available finite element modeling software, and the results were compared to the power spectrum of the tab motion when struck to ensure their validity. The acoustic resonator of the gong was modeled both as a Helmholtz resonator and as a pipe that is closed at both ends but perturbed by the two open holes. The analytical models of these resonators were validated by comparing the predictions to the

a)Author to whom correspondence should be addressed. Electronic mail: tmoore@rollins.edu

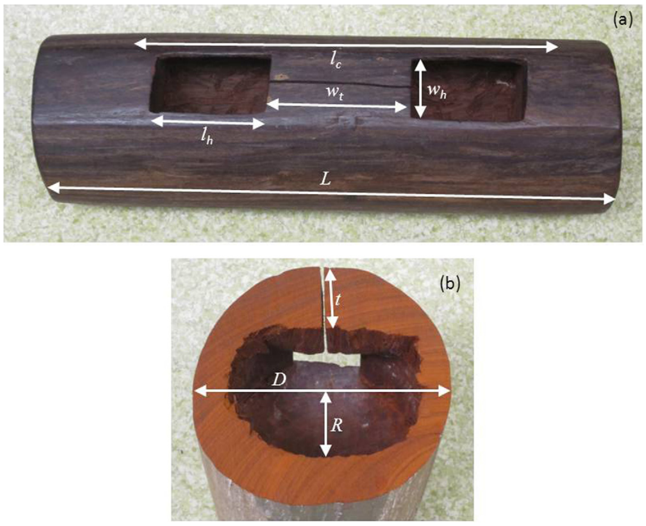

FIG. 1. (Color online) Photographs of (a) the Nigerian slit gong and (b) the cross section of the middle of the drum. The labels indicate the parameters used in modeling: Hole length l_h, hole width w_h, tab width w_t, tab thickness t, cavity radius R, cavity length l_c, length of the log L, and diameter of the log D.

power spectrum of sound within the interior cavity. We then used these models to determine how changing the tuning parameters affected the resonance frequencies of the tabs and the interior cavity.

II. ACOUSTIC AND MECHANICAL MEASUREMENTS

The power spectra of the motion of the tabs were obtained using a laser Doppler vibrometer (LDV), which recorded the velocity of the tab after it was struck with a rubber mallet. The air cavity power spectra were obtained by placing a speaker, driven with a linear sweep between 50 Hz and 2 kHz, inside the gongs and recording the amplitude of the sound using a microphone placed outside the gong. The power spectra for both tabs, as well as the air cavity power spectra for the three gongs, are shown in Fig. 2.

The coincidence between the frequencies of the tab resonances and those of the air cavity is of significant interest. For all three of the gongs, the frequencies of the lowest tab resonances are very close to the frequency of the lowest cavity resonance. Similarly, the second tab resonances have frequencies that are close to, or coincident with, the frequency of one of the higher cavity resonances. It can also be

TABLE I. The measured parameters of the slit gong used for the modeling.

Parameter	Symbol	Value (mm)
Gong length	L	476
Gong diameter	D	156
Cavity length	l_c	312
Cavity radius	R	48
Hole #1 length	l_{h1}	100
Hole #1 width	w_{h1}	50
Tab #1 thickness	t_1	44
Hole #2 length	l_{h2}	96
Hole #2 width	w_{h2}	52
Tab #2 thickness	t_2	42
Tab width	w_t	116

seen that for all of the gongs a local minimum in the air cavity spectrum occurs at the fundamental resonance frequencies of the tabs. Figure 2(d) is a detail of Fig. 2(a), where the interaction between the two resonances is more clearly seen in the acoustic power spectrum. These data suggest that at the tab resonance frequencies an exchange of power occurs between the tabs and the air cavity near the frequency of the lowest resonance, indicating strong coupling between the two. Interestingly, a cyclic exchange of energy between the tabs and air cavity of slit gongs has previously been posited by Sunohara *et al.*[2]

The theory that there is a cyclic exchange of energy between the tabs and the cavity is based on an investigation of the mokugyo, a Japanese round, wooden percussion instrument with a hollow interior and a narrow slit that appears qualitatively similar to the slit gong. In Ref. 2 the authors demonstrated that the mechanical resonator and the Helmholtz resonator of the mokugyo are strongly coupled, and that the energy from the vibration of the tabs is cyclically exchanged between the air cavity and the tabs. This led them to suggest that a similar effect occurs in slit gongs.

To determine the effects of this coupling on the slit gong, the sound of the gong with the power spectrum shown in Fig. 2(c) was recorded as one tab was struck with a mallet. The recording was made using a microphone placed ~30 cm from the gong. A graph of the sound pressure vs time is shown in Fig. 3(a) along with the power spectrum having a resolution of 12.1 Hz. It can be seen that there is a periodic modulation of the sound in addition to the expected exponential decay, similar to what is observed in the sound from a mokugyo. The period of the modulation is approximately 19.5 ms, resulting in a beat frequency of ~51 Hz. However, the power spectrum indicates that the modulation is attributable to the interference of two different frequency components that correspond to the resonance frequency of the tab and the resonance frequency of the air cavity. The lower resonance frequency of the tab is 501.5 Hz, and the lowest resonance frequency of the air cavity occurs at ~450 Hz, both of which are seen in the power spectrum. The difference in the two frequencies is equal to the observed beat frequency.

These data indicate that the modulation in the envelope of the sound is due to interference between the sound produced by the tab at its resonance frequency and the sound that is amplified by the resonance of the air cavity. This explanation is further supported by LDV measurements of the displacement of the tab after it is struck. The results of this measurement are shown in Fig. 3(b). In addition to the displacement, Fig. 3(b) also contains a plot of the exponentially decaying envelope function obtained through a least-squares fit of the peak values and a graph of the power spectrum. An examination of the displacement of the tab vs time reveals that there is no significant harmonic modulation of the motion beyond what is expected at the resonance frequency of the tab. Further, the power spectrum indicates that there is no significant power in the frequency range associated with the acoustical resonance at 450 Hz. This implies that there is not a significant cyclic energy exchange from the tabs to the air cavity, but rather that the tab motion is largely independent of the air cavity. That is, the tab resonance is driving the

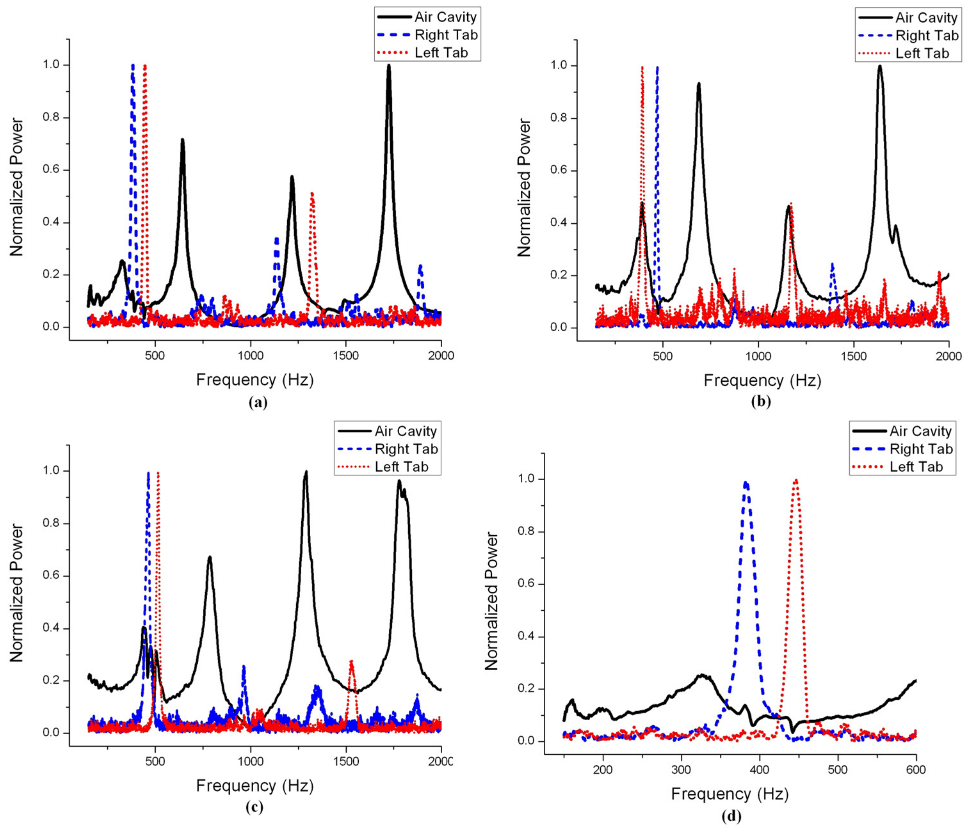

FIG. 2. (Color online) (a)-(c) Power spectra of the two tabs and air cavity for each of the three gongs that were investigated. (d) Detail of (a).

acoustic system with minimal feedback, and although some energy must be transferred back to the vibrating tabs, the effect of this is negligible.

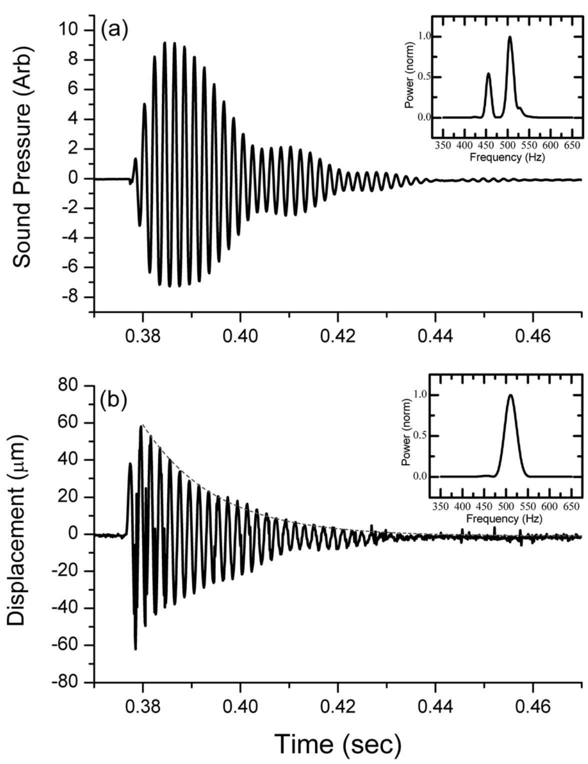

FIG. 3. (a) Plot of the sound pressure vs time when one tab of a gong is struck. (b) Plot of the displacement of the same tab of the gong vs time obtained using laser Doppler vibrometry. The dashed line is an exponential fit to the envelope. The power spectrum is shown as an inset in each case.

In addition to the overlapping lower tab resonance and lower resonance of the air cavity, the second tab resonance frequencies for each tab occur near the frequency of the third resonance of the air cavity. This suggests that the gongs are tuned so that the frequency of the lowest tab resonance occurs near the lowest resonance of the air cavity, and that the frequency of the second tab resonance occurs near the frequency of a higher resonance of the air cavity. The gong will therefore ideally have multiple coincident resonances, which is likely very difficult to achieve.

In the work reported here we sought to determine the most efficient methods of tuning the gong given the possible parameters the carver can alter. To tune the mechanical resonance the tab length, thickness, and width can be altered. To tune the air cavity resonances only the hole dimensions and air cavity radius can be altered once the length of the cavity has been chosen. However, changing the length and width of the holes subsequently alters the width and length of the tabs, and changing the radius of the cavity alters the thickness of the walls. Therefore, the artisan has only four independent parameters that can be used to adjust the sound of the slit gong: the thickness of the tabs (t), the radius of the internal cavity (R), and the length and width of the holes (l_h and w_h, respectively). In what follows we will show how changes in these physical parameters affect the mechanical and acoustic resonance frequencies.

III. MODELING THE MECHANICAL RESONANCES

Determining an analytical function that accurately predicts the mechanical resonances of the struck gong is a difficult problem due to the complex manner in which the gongs are carved. Although the tabs appear to be merely cantilever beams with one free end, the thickness of the tab varies with position. This situation has been modeled previously for the case of a beam with one end fixed,[3] but in the case of the slit gong the tabs are integrated into the wall of the drum and such a simple model does not produce meaningful results. Therefore, a finite element model was used to determine how the geometry of a tab affects its resonance frequency.

A finite element model of the slit gong that produced the power spectrum shown in Fig. 2(a) was created using commercially available finite element software. The modeling parameters are given in Table I, and the inner cylinder of the gong was offset slightly from the outer cylinder within the model so that the walls had different thicknesses that were similar to the measurements of the gong. Because the interior of the gong is hand carved, the walls are very rough and not of uniform thickness; however, the wall thickness used in the finite element model matches the mean wall thickness of the actual gong with an error of less than 3%. The density and Young's modulus can vary significantly among woods from the same species, therefore, these were used as fitting parameters for the model. A material density of 975 kg/m^3, Young's modulus of 8 GPa, and Poisson's ratio of 0.3 were chosen, which are consistent with the material properties of African padauk.[4,5] The material was assumed to be isotropic, and although wood is in fact not an isotropic material we find that the results of an isotropic model compare well to the experimental results. Therefore, the slight difference between the measured and predicted results did not justify the added complexity of including anisotropy in the model.

The finite element model analysis program FEMAP with NX Nastran was used to calculate the resonance frequencies of the model. The finite element model of the gong predicts the resonances of the two tabs to be 428 and 383 Hz. These values correspond well with the resonance frequencies of the tabs of 439 and 384 Hz, indicating that the simulation closely models the actual gong dynamics. The displacement of the gong predicted by the finite element model also closely matches interferograms of the motion of the first mode. The interferograms and predictions of the model are shown in Fig. 4.

Having validated the model with experimental data, the tuning parameters were changed within the model to determine what affect they have on the resonance frequencies of the tabs. These results will be addressed in Sec. V.

As discussed previously, the slit gong consists of a mechanical oscillator and an air cavity that acts as a resonator. The tab of the slit gong oscillates at one or more of the natural resonance frequencies and is not significantly influenced by the air cavity. Therefore, the air cavity inside the gong can be modeled independently from the tabs. This will be addressed in the next section.

IV. MODELING THE ACOUSTIC RESONANCES

As noted previously, the resonance of the air cavity inside the gong significantly affects the sound produced. The air cavity resonances are due to a Helmholtz resonator with two necks, as well as the fact that the cylindrical cavity of the gong is a pipe closed at both ends perturbed by the two holes of the gong. First, the network analog method is used to describe a Helmholtz resonator with two necks, and the predictions of the theory are compared to experimental results. Then this method is used to describe the closed-pipe resonance perturbed by the two open holes of the gong. After describing the models the results of changing the tuning parameters are presented.

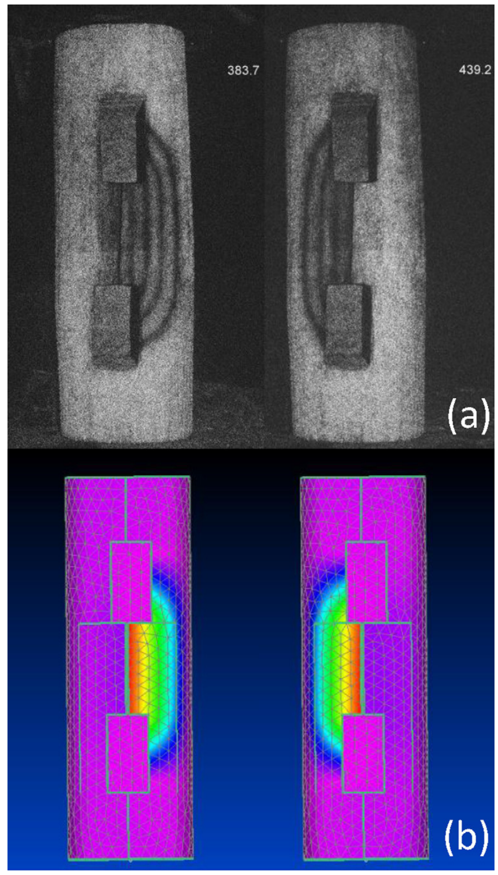

FIG. 4. (Color online) (a) Electronic speckle pattern interferograms of the slit gong being driven acoustically at the frequency of the first tab resonance for each tab. Harmonic motion is indicated by fringes of equal displacement. The resonant frequencies are 384 and 439 Hz. (b) FEA model of the displacement of the gong at the frequency of the first tab resonance. The predicted resonance frequencies are 383 and 428 Hz.

A. Helmholtz resonance

The frequencies of complex Helmholtz resonators can be found using the network analog method as described by Fletcher and Rossing.[6] The analog network describing the Helmholtz resonator with two necks is shown in Fig. 5.

The acoustic impedance of the holes of the gong, which are analogous to open pipes, is given by

$$Z_{p1,2} = j\omega\left(\frac{\rho_a t_{1,2}}{S_{h1,2}}\right), \qquad (1)$$

where ω is the angular frequency, $j = \sqrt{-1}$, ρ_a is the density of air, t is the thickness of the tab (which defines the length of the neck of the Helmholtz resonator), S_h is the surface area of the hole ($l_h \times w_h$), and the subscripts indicate the two

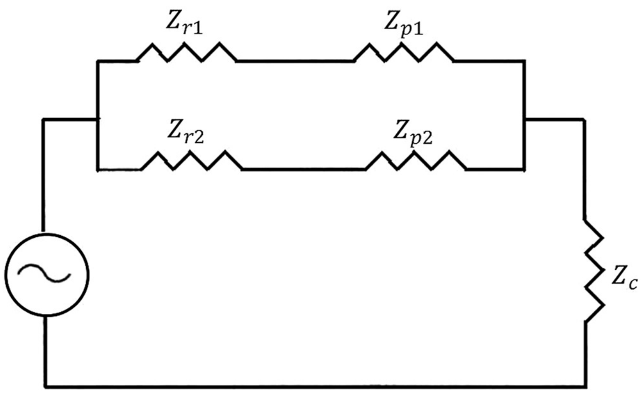

FIG. 5. The analog circuit of a Helmholtz resonator with two necks.

individual holes of the gong. The impedance of the cavity of air inside the gong is equal to

$$Z_c = \frac{-j\rho_a c^2}{V\omega}, \tag{2}$$

where c is the speed of sound in air, and V is the volume of the cavity. Finally, the impedance associated with radiation losses at the opening of the holes of the gong can be calculated from the equation for the open end of a flanged pipe of radius a and area S. The impedance is approximately given by

$$Z_{r1,2} \approx 0.16\frac{\rho_a \omega^2}{c} + 1.7j\omega\frac{\rho_a a_{1,2}}{S_{1,2}}, \tag{3}$$

where a is determined by assuming that the cross-sectional area of the rectangular hole S_h is equal to the cross-sectional area of the flanged pipe. That is,

$$a_{1,2} = \sqrt{\frac{S_{h1,2}}{\pi}}. \tag{4}$$

The effective impedance of the circuit is given by

$$Z_{\text{eff}} = Z_c + \frac{(Z_{p1}+Z_{r1})(Z_{p2}+Z_{r2})}{Z_{p1}+Z_{r1}+Z_{p2}+Z_{r2}}, \tag{5}$$

and at the Helmholtz resonance the impedance is transitioning from a phase of $\pi/2$ to $-\pi/2$. Therefore, the Helmholtz resonance occurs when the imaginary portion of Eq. (5) is equal to zero. The calculated Helmholtz resonance frequency for the gong is 349 Hz, which closely matches the frequency of the first peak in the air cavity power spectrum, which occurs at 335 Hz.

The dimensions of the two holes and the two tabs are approximately the same in all of the gongs that were studied. Therefore, for any particular gong Z_{p1} and Z_{p2} are approximately equal, as are Z_{r1} and Z_{r2}. Using this approximation we can write the equation for the Helmholtz resonance frequency as

$$f = \frac{c}{\sqrt{2}\pi}\sqrt{\frac{S_h}{\left(t+\frac{1}{2}\sqrt{S_h\pi}\right)V}}. \tag{6}$$

B. Perturbed closed-pipe resonance

The air cavity of the Nigerian slit gong can also be modeled as a pipe closed at both ends perturbed by two open holes in the side, but it is necessary to model this system separately from the Helmholtz resonator because the mode shapes differ significantly. Although the method for calculating the fundamental resonance frequency of a pipe closed at both ends is well known, in this case the perturbations cause the resonance frequency to be increased due to the fact that the holes effectively shorten the length of the pipe. Again, we use the network analog to determine the resonance frequency.

The network diagram for the closed pipe perturbed by two open holes is shown in Fig. 6(a). The compliance at each end of the cavity is given by[7]

$$C = \frac{4l_c S_c}{\pi^2 \rho_a c^2}, \tag{7}$$

where S_c is the cross sectional area of the cavity and l_c is the length of the cavity. L_{c1}, L_{c2}, and L_{c3} are the inertances in the cavity, which are dependent on the length of the first hole, length between the holes, and length of the second hole, respectively, and are given by[6]

$$L_{c1} = \frac{\rho_a l_{h1}}{S_c}, \tag{8}$$

$$L_{c2} = \frac{\rho_a (l_c - l_{h1} - l_{h2})}{S_c}, \tag{9}$$

and

$$L_{c3} = \frac{\rho_a l_{h2}}{S_c}. \tag{10}$$

Here l_{h1} and l_{h2} are the lengths of the first and second holes of the gong, respectively. L_{h1} and L_{h2} are the inertances of the holes, which are dependent on the thickness of the tabs and are given by

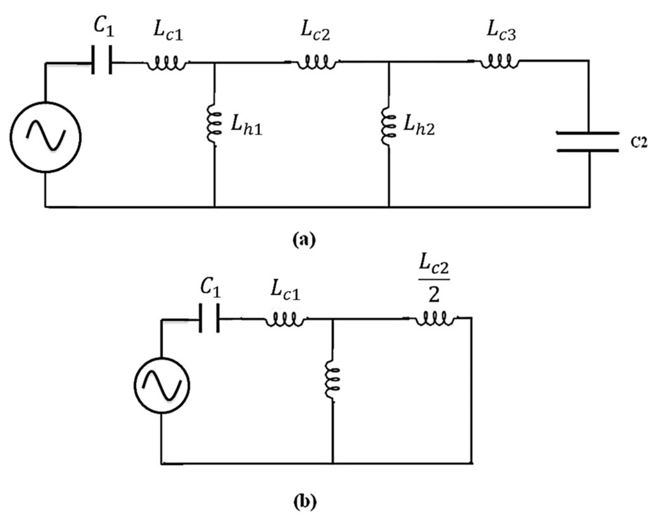

FIG. 6. (a) The analog circuit of a cylindrical pipe closed at both ends with two holes near the ends and (b) the circuit used to determine the resonance frequency of the second harmonic.

$$L_{h1} = \frac{\rho_a t_1}{S_{h1}} \quad (11)$$

and

$$L_{h2} = \frac{\rho_a t_2}{S_{h2}}. \quad (12)$$

The frequency of the resonance is calculated by finding the minimum of the effective impedance. Because the geometries of the holes and tabs of the gong are very similar, we assume that $L_{h1} = L_{h2}$ and $L_{c1} = L_{c3}$. The equation for the perturbed closed-pipe resonance frequency is then given by

$$f = \frac{1}{2\pi}\sqrt{\frac{L_{h1}L_{c2} + 4L_{c1}L_{h1} + 2L_{c1}L_{c2} + 2L_{h1}^2 + \sqrt{4L_{h1}^4 + 4L_{c2}L_{h1}^3 + L_{c2}^2L_{h1}^2}}{2CL_{c1}(L_{h1}L_{c2} + 2L_{c1}L_{h1} + L_{c1}L_{c2} + 2L_{h1}^2}}. \quad (13)$$

Using this equation, the calculated perturbed closed-pipe resonance for the gong is 692 Hz, which closely matches the frequency of the second peak in the air cavity power spectrum at 645 Hz. The difference between the predicted and measured frequencies is less than 10% and is most likely due to the fact that the interior cavity is not perfectly cylindrical.

Although Eq. (13) predicts the frequency of the pipe resonance well, when tuning the slit gong the goal of the carver is to closely align the higher order tab resonances with the second perturbed pipe resonance, rather than the fundamental pipe resonance. The second unperturbed closed-pipe resonance occurs when the wavelength of the pressure wave is equal to the length of the pipe; when this occurs there is an impedance minimum at the center of the cavity. Although the holes in the gong perturb the pipe resonance, due to the symmetry of the holes we assume that the impedance minimum still occurs at the center of the cavity. The network analog used to determine the impedance at the center of the gong is shown in Fig. 6(b). For this calculation, the length of the cavity is taken to be half of the original length and the second perturbed pipe resonance frequency is given by

$$f = \frac{c}{2\sqrt{2}}\sqrt{\frac{2tS_c + (l_c - l_{h1} - l_{h2})S_h}{l_c(t(l_c - l_{h1} - l_{h2})S_c + (l_c - l_{h1} - l_{h2})l_{h1}S_h + 2tl_{h1}S_c)}}. \quad (14)$$

The second resonance of the perturbed closed-pipe resonance is predicted to be 1148 Hz, which deviates from the measured frequency of 1219 Hz by less than 10%.

V. TUNING A SLIT GONG

To ensure that the resonance frequencies of the acoustic and mechanical resonators are nearly coincident, the carver can alter several parameters of the slit gong. However, most of these parameters are coupled, meaning that a change in any one parameter will change the Helmholtz resonance frequency, the closed-pipe resonance frequency, and the tab resonance frequency simultaneously. To determine how the carver can tune these important resonances one must understand how a change in one tuning parameter affects each of the important resonances. As noted previously, the independent parameters that can be changed are the tab thickness, radius of the cavity, hole width, and hole length. In what follows, the finite element model was used to determine the effects that changing these parameters have on the mechanical resonances of the tabs, and Eqs. (6) and (14) were used to determine the effects on the acoustic resonances. In each of the cases discussed here, the frequency is normalized to the actual frequency of the slit gong being modeled and the parameter of interest is normalized to the actual value of the carved gong.

A. Effect of changing the tab thickness

Altering the thickness of the free end of the tab of the slit gong changes the tab resonance, as well as neck length of the Helmholtz resonator and the inertance that perturbs the closed-pipe resonance. The dependence of the frequencies of the first two mechanical resonances of the tabs and the two important acoustic resonances on the tab thickness are shown in Fig. 7(a). Although the frequency of the Helmholtz resonance decreases monotonically as the tab thickness is increased, the fundamental tab resonance is well fit to a cubic polynomial. Therefore, whether the carver is increasing or decreasing the tab frequency depends on exactly how much of the tab is already carved away. Decreasing the tab thickness significantly increases the second closed-pipe resonance, simultaneously decreasing the second tab resonance. Changing the tab thickness could be used to tune the higher tab resonance and higher pipe resonance, but only by approximately 10% at most. Because of the uncertainty associated with this parameter, altering the tab thickness does not appear to be the best method of tuning either the

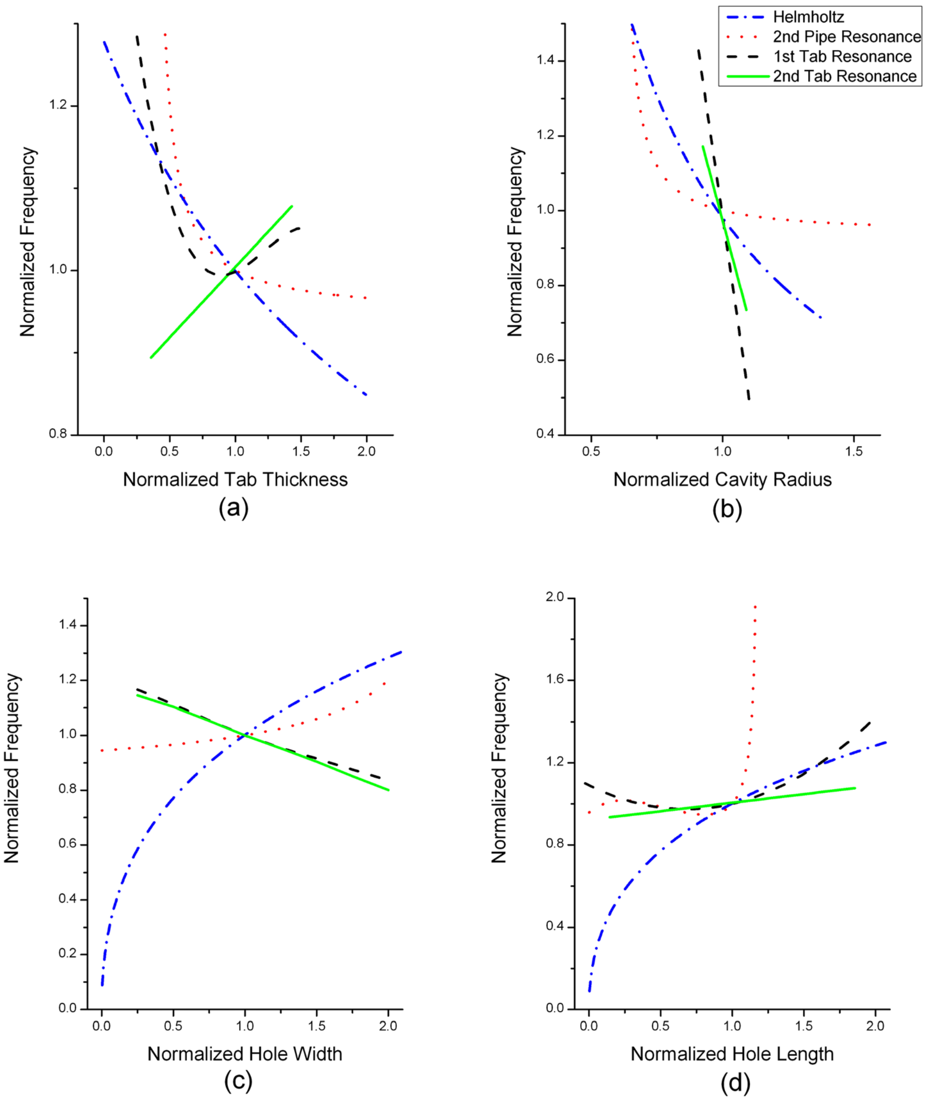

FIG. 7. (Color online) Plots of the important mechanical and acoustic resonance frequencies as a function of (a) tab thickness, (b) cavity radius, (c) hole width, and (d) hole length. The results are normalized to the measured parameters of the actual gong.

mechanical or acoustic resonances. Indeed, as the thickness of both tabs of all the slit gongs we have observed are very similar, it does not appear that the carver uses this parameter to do anything more than coarsely tune the gong.

B. Effect of changing the cavity radius

When the radius of the cavity is changed, the volume of the cavity changes as well as the thickness of the walls. The dependence of the acoustic and mechanical resonance frequencies on the radius of the cavity is shown in Fig. 7(b). As the radius of the cavity is increased, both resonance frequencies of the tabs decrease much more rapidly than the Helmholtz resonance frequency. Further, changing the radius of the cavity, which can only be increased, also leaves the second pipe resonance largely unchanged. Therefore, decreasing the wall thickness is an ideal method of tuning the tab resonances. It appears that the carvers of the Nigerian slit gongs take advantage of this as the cavity was offset from the center of the log in all of the gongs we examined, and the different resonance frequencies of the tabs was almost completely attributable to the differences in wall thickness.

C. Effect of changing the width of the holes

Changing the width of the holes of the slit gong changes both the surface area of the holes as well as the tab length. The dependence of the acoustic and tab resonance frequencies on this change is shown in Fig. 7(c). Changes to the Helmholtz frequency and the tab resonance are inversely related, and the Helmholtz resonance increases slightly more rapidly than the tab resonance decreases as the hole width is increased. Changing the width of the hole can be used to tune both the Helmholtz and tab resonances; however, it is much more useful as a tuning parameter for the Helmholtz resonance. It should also be noted that once carved, the original hole width cannot be significantly altered due to the geometry of the gong. Therefore, changing the width of the holes is most useful as a tuning parameter when the Helmholtz resonance needs to be increased by less than $\sim$10%.

A change in the hole width has approximately the same effect on the second tab resonance as it does on the fundamental tab resonance, with the tab resonance decreasing as the width increases. Conversely, the frequency of the second closed-pipe resonance increases as the width increases. The tab resonance decreases slightly more rapidly than the closed-pipe resonance increases, and therefore changing the hole width would be useful as a tuning parameter for the second tab resonance. However, the lower and upper tab resonances are shifted by the same amount, so altering the hole width is a useful tuning parameter only if both tab resonance frequencies need to be changed in the same direction.

D. Effect of changing the length of the holes

Finally, changing the hole length changes the surface area of the hole as well as the tab width. A plot of the acoustic and mechanical resonance frequencies vs hole length is shown in Fig. 7(d) and it can be seen that when the hole length is increased the second pipe resonance and the two tab resonances behave similarly, whereas the Helmholtz resonance increases significantly. Once the hole length has reached a length near unity the tab resonances and the Helmholtz resonance behave similarly, but the second tab resonance appears to change significantly as the hole length is increased. This rapid increase in resonance frequency with a small change in l_h is due to the fact that the tab width becomes smaller as the hole length is increased, and the situation approaches the case of having a completely open cavity. As the model assumes a single node located in the center of the cavity, it is likely that the behavior of the second pipe resonance is not well modeled as the tab width approaches zero. However, for a significant range from below unity to slightly above it one may assume that the model is valid.

Because the resonance frequencies of all four resonances change in a similar manner as the hole length is increased, this is not an ideal parameter for tuning the gong. The hole length must be approximately the correct size to ensure that the frequency of the Helmholtz resonance is correct, but since carving too much away from the hole will significantly change the second pipe resonance, the carver would be wise not to use this parameter for fine-tuning.

VI. CONCLUSION

Although it appears to be a simple instrument, the Nigerian slit gong is a complicated system of interacting resonators. From the power spectra of the air cavity and tabs of the three gongs that were studied, it appears that the artisans attempt to align the first tab resonances with the Helmholtz resonance of the cavity, some more successfully than others. Similarly, the second resonance of the tabs is aligned with the second closed-pipe resonance. However, these conclusions are true in detail only for the size of gong investigated here. The gongs that were investigated in this study were all $\sim$0.5 m long, but the slit gong can vary in size from 0.25 m to more than 3 m. As a result, although it appears that the artisan attempts to ensure that the frequencies of a mechanical and acoustical resonance are coincident, the actual acoustic resonances of interest change depending on the size of the gong. For example, an investigation of a gong approximately half the length of those discussed previously shows that the artisan tuned the higher tab resonance frequencies to fall near the fundamental closed-pipe resonance frequency, rather than the frequency of the second resonance. Despite the differences arising from size, the goal of the artisan still appears to be the overlap of both higher and lower tab resonance frequencies with one of the acoustic resonance frequencies. These coincident resonances result in a transfer of power from the tabs to the air cavity, which along with the highly damped motion of the tabs results in a loud, short sound when the gong is struck.

The results presented here indicate that tuning the slit gong is not a straightforward task. Altering most of the parameters of the gong results in simultaneous and significant changes to the acoustic and mechanical resonances. However, decreasing the wall thickness is most likely the best method for tuning the tab resonance, while increasing the width of the holes is the best method for tuning the Helmholtz resonance. Analyses of the slit gongs available for study indicate that indeed these are the two parameters the artisan uses most effectively, since in all of the examples studied the two tabs of a gong are of almost identical length, width, and thickness even though the resonance frequencies differ significantly. Although it is highly improbable that the carver is aware of the physics describing the gong, he has managed to perform a highly nonlinear optimization problem with surprising accuracy.

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