TONGUE DRUM

ME 492 – Project
Final Report

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ABSTRACT

The project aims to design a tongue drum by using a scientific approach. At first, various tongue drum designs are investigated and according to these investigations, finite element models are simulated to tune the different tongue shapes. Different materials, different shapes and dimensions are modeled as uncoupled acoustic analysis, uncoupled structural analysis of both the tongues and the body, and coupled acoustic analysis of the whole body. It is decided to design a hybrid tongue drum with a wooden body and a metal top surface with tongues. Several iterations and analyses are conducted and it is found that global modes interfere with tongues' modes. Since it creates chaotic mode shapes that would lead to unpleasant sounds, a wooden top plate is decided to be used in the final design. Sol major pentatonic scale is chosen and it is manufactured with mulberry wood top plate and MDF body. The material properties of the wood are found experimentally. After manufacturing, the measured fundamental frequencies are found 43.2% higher than the simulation results on average with an 11.2% standard deviation. Some tongues have an ambiguous pitch, which is investigated further to determine why there is an error between simulation and real results. As a final step, a new model is conducted according to the results coming from the manufactured tongue drum.

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INTRODUCTION

Tongue drum, also called “tank drum” or “hank drum” is a percussion instrument invented by Dennis Hevlana in 2007. It gets its name from the slits cut into the material that produces the notes, which are called "tongues". It is classified as an idiophone in the Hornbostel-Sachs classification system for musical instruments. Idiophones produce sound by the vibration of the instrument body. Gong, cymbal, kalimba and xylophone are other instruments in the idiophone family [1].

Hevlana’s tank drum was inspired by several instruments, primarily whale drum, Hang drum and tambiro, which can be seen in Figure 1. The tank drum has tongues cut onto a propane tank like a tambiro, but the positioning of the tongues is like the Hang drum. The original tank drum is produced from a 20 lb propane tank. First, the valve and foot stands of the tank are cut off. A circular hole remains where the valve is cut, this side is the bottom of the instrument. Then the tank is flipped over and eight tongues are radially placed on the bottom surface of the tank. Tongues are cut with a hand-held cutting tool. Later versions make the drum shorter and more compact by cutting out the bottom and top dome of the tank and welding them together [2].

Figure 1. Whale drum, Hang drum and tambiro [3] [4] [5].

Fine-tuning of the tongues is made by hand after cutting them in approximate sizes. The tongues are like cantilever beams and there are simple principles in tuning the fundamental frequency of a tongue. The frequency of the tongue can be lowered by increasing the mass at the tip of the tongue, where there is a lot of motion, or decreasing the rigidity of the base [6]. Many people make tongue drums at home following Havlena’s instructions. There are also mass-manufactured versions of the tank drum. These drums are not made from propane tanks but are usually formed from sheet metal. The tongues are cut with laser cutting. However, expensive tank drums are usually fine-tuned by hand after the initial manufacturing process.

A musical sound has some physical properties that depend on both the musical instrument producing them and the air which the sound propagates. When the musical instrument is excited, it starts vibrating and creating a pressure wave in surrounding air particles. The human ear detects the vibrating air particles and human beings hear that vibrating air as a sound [7].

The acoustic cavity, tongue shapes and material are important design parameters of the tongue drum. In the remainder of the report, the effect of these parameters is investigated and discussed.

OVERVIEW OF POSSIBLE SOLUTIONS

Fundamentals of Music

What makes the musical sound different from other sounds is the perception of the physical properties of the sound. One of them is the frequency of a sound, it is the number of cycles per second. The human ear can only detect 20 to 16000-20000 cycles per second which is represented as Hertz (Hz). Lower frequencies create low/bass sounds as higher frequencies create high/treble sounds. When the sound vibrates at a specific frequency, the human ear can understand it as a recognizable note, which is called pitch. Pitch is how the brain interprets the steady frequency of sound. Human beings can recognize different steady frequency values easily without any training when the value of the one frequency is 1% different than others [6].

The vibration of percussion instruments creates complex sounds comprised of various frequencies. However, the brain recognizes this complex sound like a single pitch having a characteristic timbre or a tone color. The brain focuses on one frequency which is the steady recognizable frequency of the sound. In some sounds, there is no specific pattern so the brain could not recognize the pitch of the sound. This group of different frequencies results in a pitchless sound which is considered noise.

The sounds of different musical instruments are perceived differently even though they have the same pitches. This behavior of the sound depends on the spectral envelope of the sound. The characteristic property of many simultaneous frequencies results in the particular timbre of the sound. The blend of the different frequencies is the fundamental factor in having tone quality [8].

When multiple frequencies present, the lowest one is called the fundamental frequency and the others are called overtones. There could be harmonic or inharmonic overtones. Harmonic overtones are integer multiples of the fundamental frequency. Many musical instruments, such as violin, piano and flute create sounds with harmonic overtones. On the other hand, inharmonic overtones whose frequencies are not equal to multiples of the fundamental frequency, give the feeling of multiples tones. If the vibration has highly complex waveforms, it can even be perceived as noise. In tongue drums like many percussion instruments, it is described as having ambiguous pitch. With a trained ear, one can easily pick out more than one pitch at the same time [6]. Also, how the sound changes through time is important for tone quality. This is called the sound's time envelope, which depends on the sound's specific rise and fall in volume. In a wooden tongue drum, the period of decay depends on the characteristic of the chosen wood and this highly affects the tongue drum's timbre too.

Materials

Materials used in acoustic applications, such as making musical instruments, must have certain elastic properties: low Young’s modulus and high yield strength. Bell bronze, a material historically used in making bells and cymbals, satisfies this criterion. In most materials, high Young’s modulus comes with high yield strength, so there is a trade-off between the two conditions. Steel, while having a higher Young's modulus than bronze also has higher yield strength. Because of that steel also has good acoustic properties. Another acoustic property of materials is acoustic brightness. This property measures how much the material damps vibration. Metals usually have high acoustic brightness.

Tongue drums can be made from wood or different metals. Before Hevlana’s tank drum, there were wooden tongue drums that originated from slit drums, an old African percussive instrument. They are usually shaped like a rectangular box as seen in Figure 2. Hardwoods such as African padouk, hard maple, mahogany and chestnut are frequently used in wooden tongue drums because they are rigid enough to sustain the vibration. Wood has high internal damping and produces a dull sound that decays quickly.

Figure 2. A wooden tongue drum with four tongues.

Tank drums are usually made from carbon steel. Steel produces a bright sound and it resonates for a long time. This resonance is an important factor in the unique sound of tank drums. High availability and ease of manufacture of steel are also factors in its frequent use in tongue drums.

There are examples of tongue drums made of other alloys or metals. Tongue drums made of a titanium alloy and bronze can be seen in Figure 3. Bronze has high resilience and a clear sound. However, too much resonance becomes a problem in tongue drums. Notes overlap with each other and build up in the background. Titanium has similar properties to steel and produces a unique, tinny sound. However, it is more expensive and harder to procure than steel. The advantages and disadvantages of these materials are summarized in Table 1.

Figure 3. Tongue drums made of bronze and a titanium alloy.

Table 1. Comparison of different materials for tongue drums.

	Wood	Steel	Bronze	Titanium Alloy
Brightness	+	+++	+++	++
Price	+	+	++	+++
Resonance	+	++	+++	++
Resilience	+	+++	++	++

Benchmarking

The tongue drum made by a French hobbyist from a 20-pound propane tank can be seen in Figure 4. The tongues are cut following the pattern on the right of Figure 4. The drum is in mi minor pentatonic scale and has a range from 164 Hz to 391 Hz.

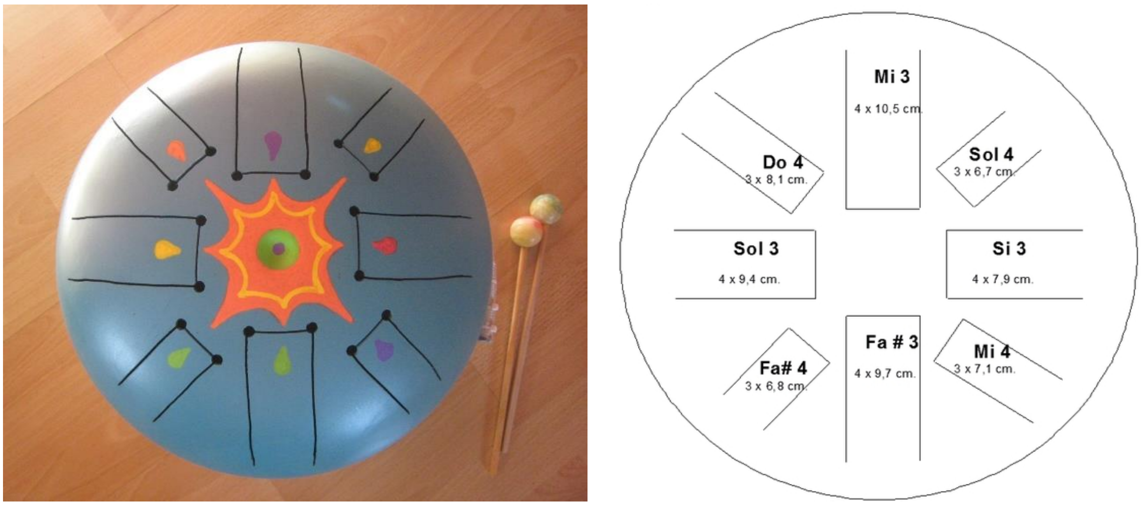

Figure 4. The tongue drum used in benchmarking with dimensions of the tongues.

This particular drum is chosen for benchmarking because of a couple of reasons. First of all, the dimensions of the drum and the tongues are known. In mass-manufactured tongue drums, the body of the instrument is produced not from a propane tank but by metal forming. Because of that, the curvature of the dome is unique for different brands and cannot be known without taking measurements on the actual drum. Propane tanks have standards so that they can be modeled more easily. Secondly, the maker provides a recording of all the notes played in order. They are not overlapping so that every note can be analyzed separately.

Audacity is an open-source program for editing and analyzing sound. It is used for the spectral analysis of the recording provided in. The tongues are modeled as beams with fixed-free end conditions in ANSYS Modal and their modes are analyzed. Results from the numerical model are compared with the spectral analysis.

The spectral plot of the sound from the Mi3 tongue can be seen in Figure 5. The first and biggest peak corresponds to its fundamental frequency, 163 Hz. The first six modes of the same tongue obtained from the numerical model are given in Table 2. As seen from the table, the actual fundamental frequency closely matches the model. The first overtone is not present in the spectrum, but there is a peak near the second overtone at 961 Hz. The rest of the overtones are at higher frequencies and have either very small peaks or do not have distinct peaks at all. The first overtone is a torsional mode, therefore a centered strike to the tongue should not excite it strongly, which is consistent with the spectral plot. It is also important to note that there is a 30 dB difference between the sound intensity of the fundamental and the second overtone at 961 Hz. This shows that fundamental frequency is dominant in the sound of tongue drums.

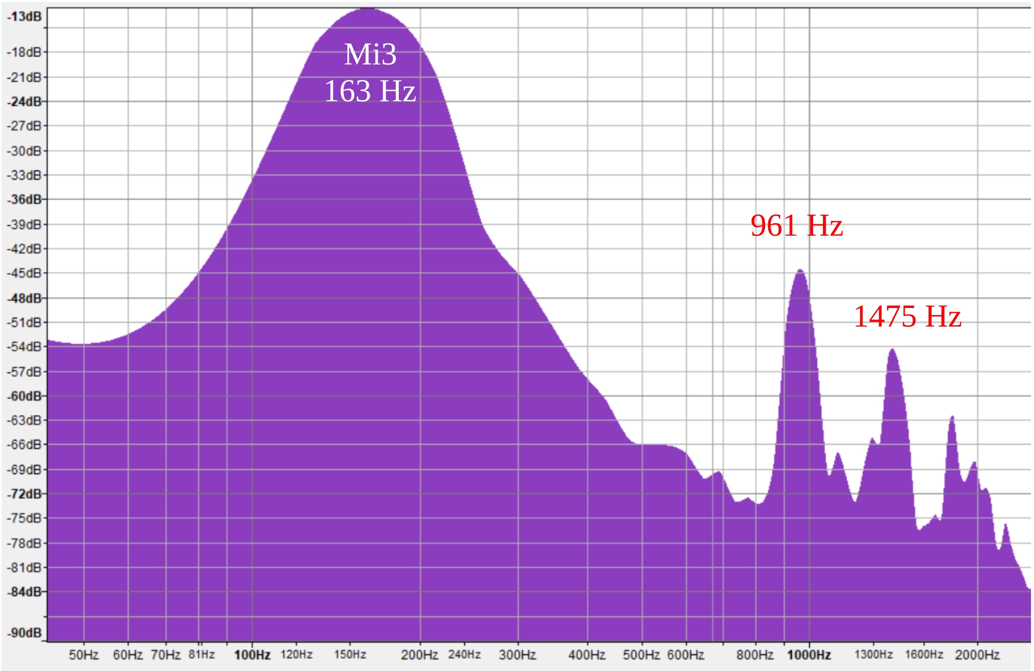

Figure 5. The spectrum of the sound produced by Mi3 tongue.

Table 2. Structural modes of Mi3 tongue when modeled as a cantilever beam.

Mode	Frequency (Hz)
1	162.03
2	803.43
3	982.91
4	2067.5
5	2765.1
6	3465.9

A CAD model of the whole drum is made, which is used to make structural and acoustic modal analyses in ANSYS. Distinct modes corresponding to all of the tongues show up in the structural analysis. Two of these modes corresponding to Mi3 and Fa#3 tongues can be seen in Figure 6. They are called “local modes” in this report.

170.76 Hz 192.62 Hz 507.78 Hz

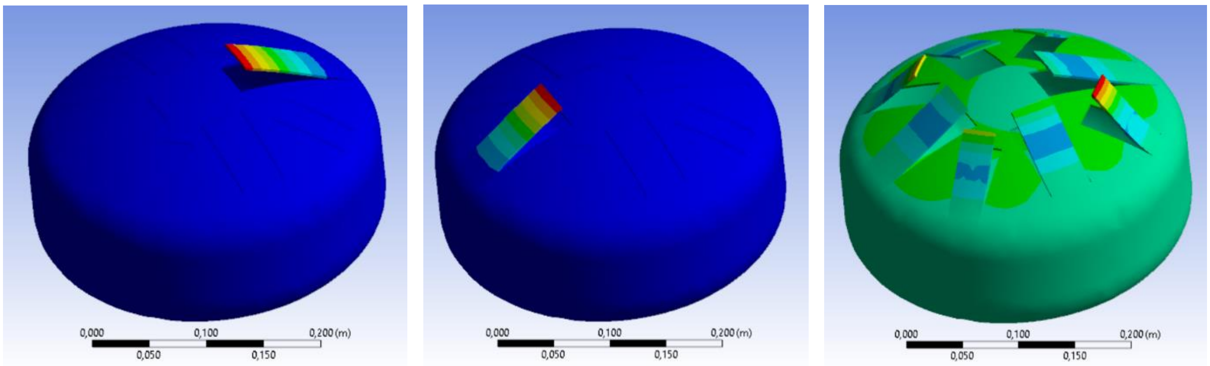

Figure 6. Local modes corresponding to the Mi3 and Fa#3 tongues, global mode at 507.78 Hz.

Local modes are compared with the spectral plot and the cantilever beam model in Table 3. As can be seen, local modes are slightly higher than fundamental frequencies found in spectral analysis. This is expected because the tongue drum is tuned by hand. The tongues are cut shorter than the template to be able to tune the note by gradually lowering it with a hand hacksaw. This means that the lengths of the tongues are not exact. Overall, local modes are consistent with sounds from the real drum and the drum can be tuned using this method of analysis.

Table 3. Comparison of frequencies for spectral analysis and different models.

Musical Note	Frequency of the Note (Hz)	Spectral Analysis (Hz)	Cantilever Beam (Hz)	Structural Analysis (Hz)
Mi3	164.8	163	162.03	170.76
Fa#3	185.0	184	187.69	192.62

At higher frequencies, there are mode shapes that affect more than one tongue or the whole body of the instrument. These are called “global modes” in this report. Global modes are chaotic and depend heavily on where the fixed support is defined in the analysis. The global mode shape in Figure 6 is obtained by fixing a small part of the bottom surface near the soundhole. In real life, this corresponds to how you are holding the drum, whether it is on your lap or a table. Because of that, the global mode shapes of the drum will not be tuned in this study.

The acoustic cavity of the drum is analyzed in ANSYS Modal Acoustics by assuming rigid walls. There is a peak at 1475 Hz that shows up in most of the spectral plots obtained from different tongues. It can also be seen in Figure 5. This peak does not match with an expected overtone but is close to an acoustic mode at 1478 Hz. It is possible that hitting the tongues excites this acoustic mode. Further coupled analysis is needed to determine how the tongues interact with the air in the cavity.

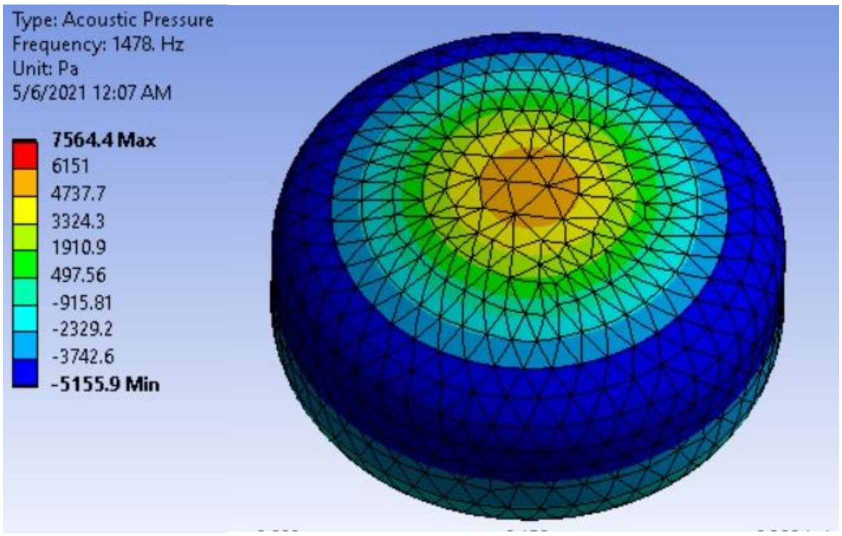

Figure 7. Acoustic pressure for the acoustic mode at 478 Hz.

Hybrid Tongue Drum

During the research of the tongue drums, various designs are investigated which are mainly wooden and metal tongue drums. As given before, metal ones can be made of carbon steel, titanium alloy and bronze. Wooden ones can be made of different types of wood, however, not all of them are qualified to have nice sounds. Wooden tongue drums are rectangular prisms consisting of a box and a top plate containing the tongues. On the other hand, metal tongue drums consist of curved top and bottom with a round shape.

An alternative idea came up, which was a combination of a wooden box and metal tongues. This way, the instrument would have an acoustic cavity similar to a wooden tongue drum but also have tongues that would produce bright sounds and resonate longer than the wooden ones. There are several advantages to this design. The dimensions of the acoustic cavity are more flexible, as it is no longer dependant on the size of the propane tank. Also, laser cutting on a flat surface is simpler than laser cutting on a dome shape. It can be done with an average laser cutting machine, which makes manufacturing less costly and easier.

The first step in the design process was determining the size of the soundboard. For that, acoustic modes of a closed rectangular box are investigated. These modes are described as "room modes". For a box with rigid walls, the walls act as sound pressure antinodes. Room modes are the superposition of standing waves in three dimensions. They can be calculated with the following formula, where L_x, L_y and L_z are the dimensions of the box. They are referred to as length, width and height respectively. c is the speed of sound in the air and n_x, n_y, n_z are the number of natural oscillations in each dimension. The fundamental frequency in each dimension corresponds to the lowest modes, which are (100), (010) and (001).

$$f_n = \frac{c}{2}\sqrt{\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2} \tag{1}$$

In a study of wooden tongue drums, the resonance of a tongue is maximized by changing the length of the sound board. Equation 1 simplifies to the following equation for the fundamental node (100), where L is the length.

$$f_{100} = \frac{c}{2L} \tag{2}$$

It is found that sound quality improves when the fundamental mode of the box matches the frequency of the tongue. This is one of the reasons most wooden tongue drums have a high aspect ratio. By increasing the length of the drum, the fundamental frequency is lowered. This enhances the quality of the notes with low frequencies. However, there is a practical reason to keep the soundboard small or the drum becomes too heavy and bulky.

The current design is planned with 8 tongues, therefore it is not possible to match all of the tongues with an acoustic mode. A musical scale is chosen to complement the (100) mode of the drum, with the tonic of the scale matching the fundamental frequency. Tonic is the first note of a scale. It gives its name to the scale. For example, a sol minor scale starts with the note sol. It is the harmonic focus and usually the final resolution tone in tonal music. Because of that, enhancing the tonic is beneficial for the overall sound of the drum.

An upper limit of 500 mm is determined for the length drum in the current design. With L_x = 441,6 mm, the first mode is at 391,9 Hz (Sol4). Therefore, sol major pentatonic scale is chosen for the drum. The width of the drum is chosen to be L_y = 294,8 mm, which introduces a resonant frequency at 587,3 Hz (Re5). This is the fifth note of the scale. A soundhole with a diameter of 75 mm is opened at the side of the soundboard facing the audience. This helps direct the vibrations to the listener. Furthermore, it introduces a Helmholtz resonant frequency, which is lower than all of the room modes of the box. A Helmholtz resonator is a rigid cavity with an open hole, also called a neck. The resonant frequency of a Helmholtz resonator is given in Equation 3, where A is the opening area, V_o is the volume of the cavity and L_{eq} is the corrected length of the opening.

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{V_0 L_{eq}}} \tag{3}$$

The acoustic cavity is modeled in ANSYS Modal Acoustics with rigid walls and a pressure boundary condition at the hole. The results show that Helmholtz frequency is around 150 Hz (Re3). The result of the simulation is checked against Equation 3 and they are found to be in agreement. This could enhance the bass sounds of the drum. The hole also affects the room modes and makes them a little higher. The acoustic pressure for the Helmholtz frequency is shown in Figure 8.

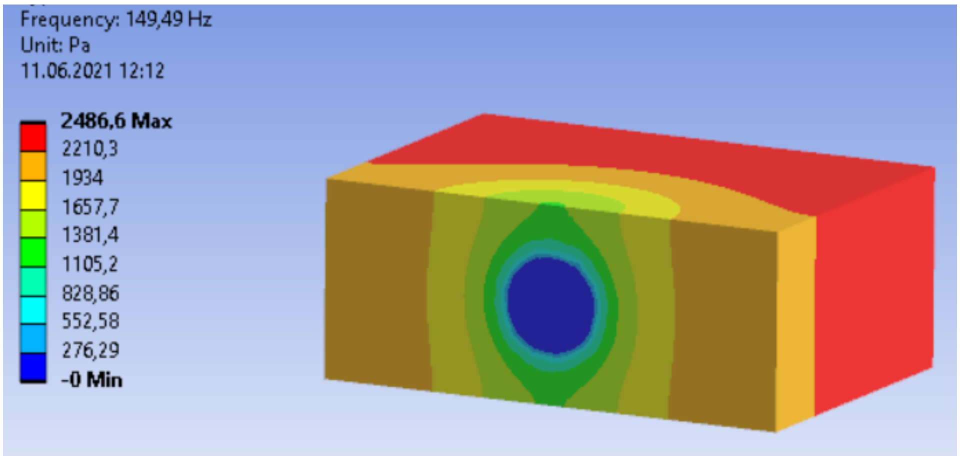

Figure 8. Helmholtz frequency of the box at 149,49 Hz.

Table 4. Acoustic modes of the box

Mode	Frequency [Hz]
Helmholtz	149,49
100	392,01
010	606,03
110	691,48
200	805,56
001	967,55

To see if the idea of a hybrid tongue drum is applicable, a great number of SolidWorks designs and ANSYS analyses are carried out. Since the concept is not experimented or found online, the process continued with trial and error. A 3mm thick steel sheet is chosen for the top plate. The tuning of the tongues is carried out in two steps. First, the tongue template seen in Figure 9 is made. By making a tongue shape with a narrow base and more mass towards the end, the fundamental becomes more prominent and sustain is increased [6]. As seen from the figure, the only free variable is the radius of the circle. This makes the tuning process easier.

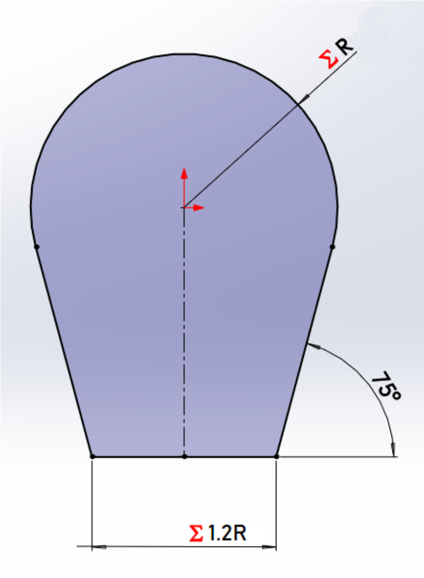

Figure 9. Tongue template.

Each tongue is modeled as a cantilever beam in ANSYS and an approximate radius is determined such that the fundamental frequency is close to the desired musical note. The fixed boundary condition is not accurate, because the top plate is elastic. Because of that, the position of the tongues, specifically their distance to the edge of the drum affects their frequency. However, it captures the general relation between the size of the tongue and its frequency and provides a starting point. In the second step, the tongues are positioned on the top plate and the whole system is modeled in ANSYS Modal. The tongues' lengths are tweaked until they are close to the frequency of the musical note.

The design of the top plate with tongues tuned in sol major pentatonic scale can be seen in Figure 10. The tongues consist of the following notes from the biggest tongue to the smallest: Re4, Mi4, Sol4, La4, Si4, Re5, Mi5, Sol5. It has a range from 293.7 Hz to 783.9 Hz. The tongues are positioned elliptically for comfortable playing, similar to the tank drum. The tongues fill only a small portion of the surface. This proves to be an issue because global modes exciting the empty spaces interfere with the tongues.

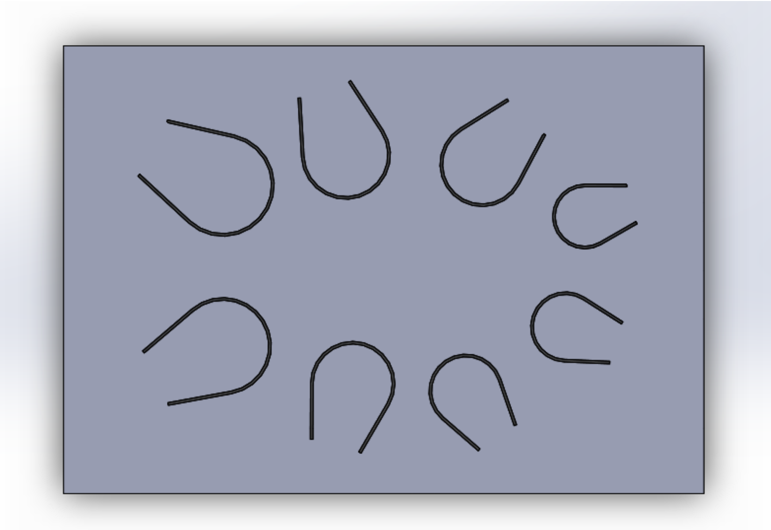

Figure 10. Top plate with elliptical tongue placement.

Analyses are continued with coupled analyses in ANSYS Modal Acoustics. During these Modal Acoustics analyses, an enclosure is created around the geometry which is a combination of the soundboard and the top plate. The parts are aligned, and the surfaces coinciding are shared in ANSYS SpaceClaim. In the modeling, the materials are assigned one by one. Structural steel is assigned to the top plate, oak wood is assigned to the box, and the air is assigned to the enclosure. Material properties are taken from the GRANTA MI database. The enclosure is defined as the acoustic region, the connected part is defined as the structural region. Later, the bottom of the box is defined as fixed support. Since it is a coupled analysis, fluid-solid interface is created. The mesh size is chosen small enough to be grid-independent.

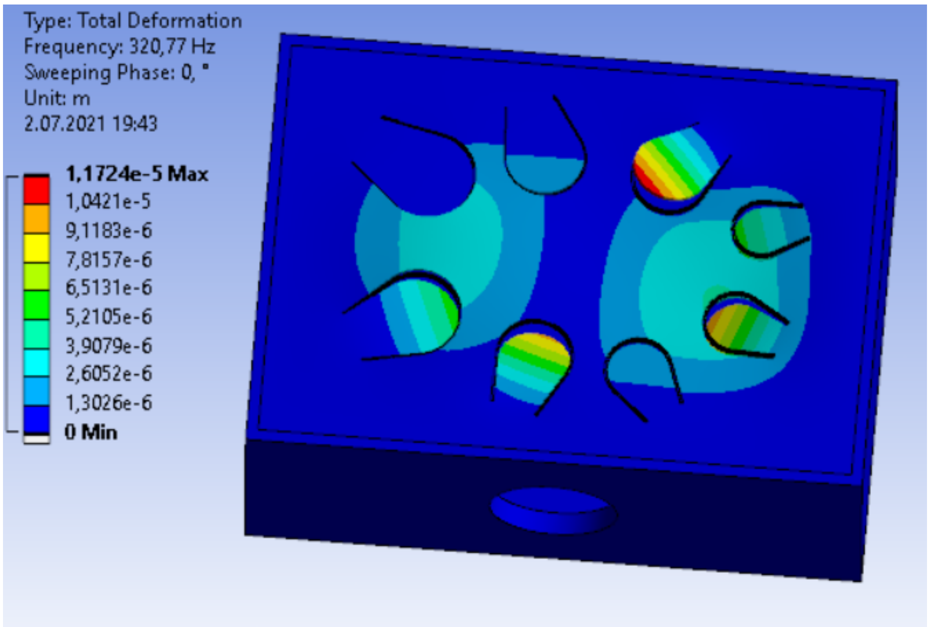

Figure 11. Global mode at 320 Hz in the coupled analysis of the elliptical drum.

In the solution, total deformations corresponding to the modes are inspected. It is observed that there are local modes that have similar mode shapes which are also close in frequency values. This makes it hard to know which mode is the fundamental mode and will be excited when struck by the mallet. Another observation was multiple tongues seemed to be excited at the same mode. There are two main reasons behind that. One is that the air within the body excites other tongues too and due to the acoustic pressure alterations tongues are excited. The other reason is global modes. When the metal surface was curved as in steel tongue drums, global modes were encountered at higher frequencies. However, when the board is flat, global modes come up in lower frequencies such that before local modes end at least one global mode is encountered. An example case is demonstrated in Figure 11.

To disable the effect of global modes, several methods were tried, which can be seen in Figure 12. The first effort was the insertion of wooden columns between the metal plate and the box. When the column is placed between upper and lower surfaces, volume-changing acoustic modes cause stress on the columns. Therefore, this method is abandoned. The second effort was inserting four crossbars from the middle of the top surface to the corners of the lower surface. This way, there would not be any force transfer to the bottom plate. It was partially successful yet manufacturing it would not be easy. The multiple tongue excitation problem was not solved by this method.

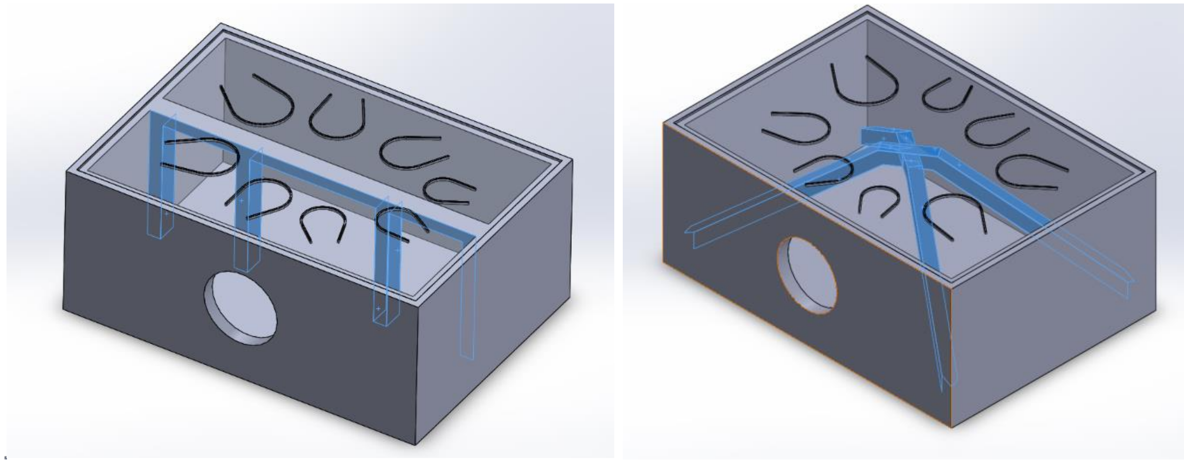

Figure 12. Hybrid tongue drum with columns and cross beams.

As another alternative, a narrow box is tried. Decreasing the width increases the frequencies of the global modes of the plate. This method was also not enough to eliminate the global mode effect. Before reaching the last tongue, a global mode was encountered. Two different global modes exciting the smallest tongue can be seen in Figure 13. Moreover, the air cavity should not be too small to not lose the advantage of the acoustic cavity. This approach was also abandoned.

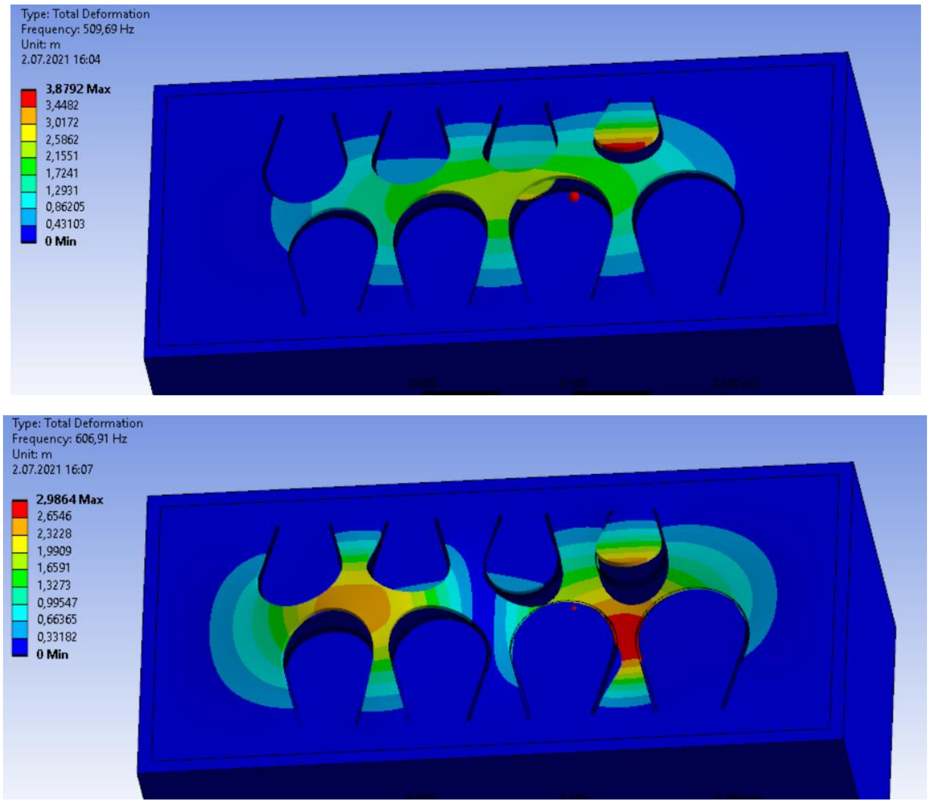

Figure 13. Two different global modes exciting the G5 tongue at 509 Hz and 606 Hz in the narrow drum.

DETAILED DESIGN AND ANALYSIS

Since the alternative approaches for the hybrid tongue drums are not successful, it is decided to use a wooden top plate in the final design.

The same soundboard as the hybrid tongue drum is used in the final design and the same scale, sol major, is chosen to complement the modes of the acoustic cavity. The wooden tongue drum is in sol major pentatonic scale and consists of the following notes: sol, la, si, re, mi. For a bigger range, sol, re and mi are repeated in the lower octave. The final design consists of 9 notes ranging from Sol2 to Sol4. Their arrangement on the top board of the drum can be seen in Figure 14, with lower notes on the left side of the drum and the higher notes on the right side.

The exact dimensions of the top plate are provided in the Appendix. The higher notes are narrower than the low notes to make their aspect ratio similar and get a better sound. To decrease the effect of global modes, the middle portion of the top plate has a hole. This way the tongues cover a big percentage of the top board with empty spaces only to the sides of the drum. They are also placed closer to the sides of the drum, which decreases the interference of neighboring notes. Because of the central hole, the rest of the soundboard is designed without air openings.

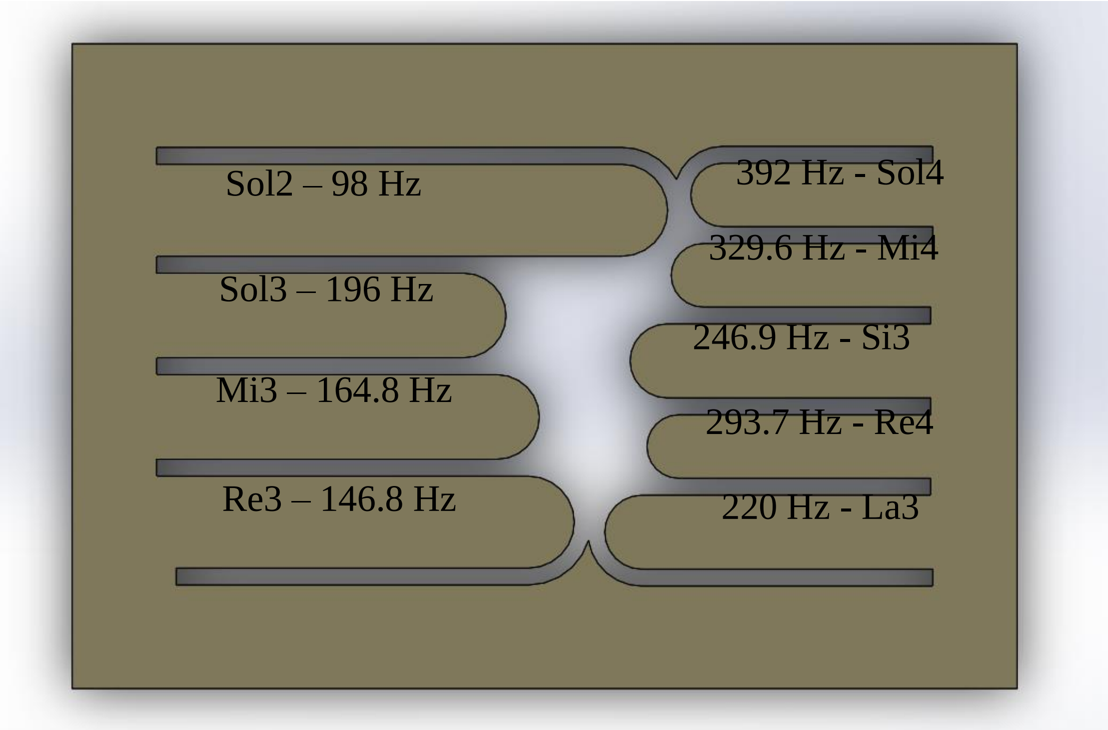

Figure 14. Arrangement of the tongues in the final design.

The central hole introduces a Helmholtz mode at low frequency. In these modes, there is a strong coupling between the air in the acoustic cavity and the soundboard. When the tongues are struck, the vibration is transmitted to the soundboard. The soundboard curves outwards in half of its cyclic motion and the box expands, causing low pressure inside the cavity. In the second part of the cycle, the opposite motion is carried out by the soundboard and the air is expelled from the cavity [6]. A similar mode is seen in the body of guitars, which is called the "breathing mode", where the bottom and top surface of the soundboard move out-of-phase to produce a similar motion.

Material

The aim of the product is to strike a tongue to produce a definite pitch. Tongues are fixed at one end to the upper surface of the drum and free at another end. The sound is produced by hitting the free end of the tongues, which produces the vibration. The fundamental frequency and the timbre of the sound depend on the mass of the tongue and the rigidity of the tongue. To obtain a steady and correct frequency pattern, the effective mass and the rigidity of the material used in tongues must be almost uniform along its length. Also, the fixed end of the tongues needs to be like a solid anchor. Therefore, the wood used on the surface of the tongue drum is the massive, single-piece mulberry wood to get these features.

Wood is not a standard material. Material properties of wood can change regionally and depend on many factors such as the manufacturing process of timbre. Because of that, the density and elastic modulus of the mulberry wood used in making the drum are found experimentally. The piece of wood used in making the drum is weighed using a sensitive weighing scale. The density of the wood is found to be 754 kg/m^3.

Wood is an orthotropic material, meaning that it has different elastic properties on three orthogonal axes. However, the tongues in the design are all aligned in the fiber direction of the wood so it has the same material properties in that direction for bending modes. Also, wood has very high internal damping so the overtones decay very fast, which means that the fundamental mode is very dominant. Because of that, knowing the elastic modulus on this axis is enough to tune the pitch of the tongues. The bending modes of a cantilever beam are calculated with the following formula.

$$\omega_n = \beta_n^2 \sqrt{\frac{EI}{\rho A}} \tag{4}$$

By inserting the crossectional area and moment of inertia for rectangular crosssection into this equation and isolating E, Equation 5 is obtained.

$$E = \frac{12\omega_n^2 \rho}{\beta_n^4 h^2} \tag{5}$$

β_n is calculated iteratively from the characteristic equation given in Equation 6. For the fundamental mode (n=1), $\beta_n L$ = 1,8751040687.

$$\cos(\beta_n L)\cosh(\beta_n L) = -1 \tag{6}$$

The experimental setup shown in Figure 15 is used to calculate the elastic modulus (E) of the mulberry wood used in the drum. A long piece of the wood is fixed to the setup. The fixed boundary condition is achieved by putting 5 heavy cinderblocks to the base of the wood. Cloth is used to increase friction between the wood and the surface and ensure the wood does not slip.

It also decreases rattling in the system. A mallet made from a rubber bouncy ball is used to strike the tongues. The frequency of the sound is recorded using a tuning app. Using this frequency, density and dimensions of the wood, E is found with Equation 5.

Figure 15. Experimental setup

Two pieces of wood with different cross-sections are tested at different beam lengths. Their dimensions, resulting frequencies and experimentally calculated E values are given in Table 5.

Table 5. Experimental results

Cross-section	Length (mm)	Frequency (Hz)	Elastic modulus (GPa)
10mm – 50 mm	200	91	3.8
	150	130	2.47
	100	233	1.57
10 mm - 39 mm	200	91	3.8
	150	140	2.87
	100	293	2.48

As seen from Table 5, different values are obtained for different cases. However, the measured frequency for two beams with L = 200 mm with different cross-sections is consistently 91 Hz. This result is supported by Equation 5, where the fundamental frequency is not affected by the width of the beam. Because of that, E is taken as 3.8 GPa. Finally, the Poisson’s ratio of the mulberry wood is taken as 0.3742 according to GRANTA MI material database.

The soundboard of the drum is made from MDF. The rigidity of the body of the tongue drum is significant for acoustic properties because a rigid and firm body would let tongues drive the air inside of the body. That means the body would work like a soundboard which helps tongues radiate their vibrations to the air inside of the room. However, the uniformity is not very important for this purpose as long as it is thick and rigid so MDF is used to produce the body of the drum because it is cheaper and easier to find. The density of the MDF board is 750 kg/m^3 and its elastic modulus is 4 GPa.

Tuning and Analyses

The tuning of the tongues is carried out similarly to the hybrid tongue drum in ANSYS Modal. In this case, approximate lengths are calculated using Equation 4. In the second step, the drum is modeled in ANSYS Modal and the tongues' lengths are tweaked until they are within ±1 Hz of the frequency of the musical note. The notes are not in ascending/descending order, because it is observed in Modal analysis that similar-sized tongues interfere with each other. To decrease interference, Sol2 and Re3 tongues are placed on two sides of their row apart from each other and Si3 tongue is placed between the Re4 and Mi4 tongues. In the end, the fundamental mode of each tongue is seen separately with minimal interference between them.

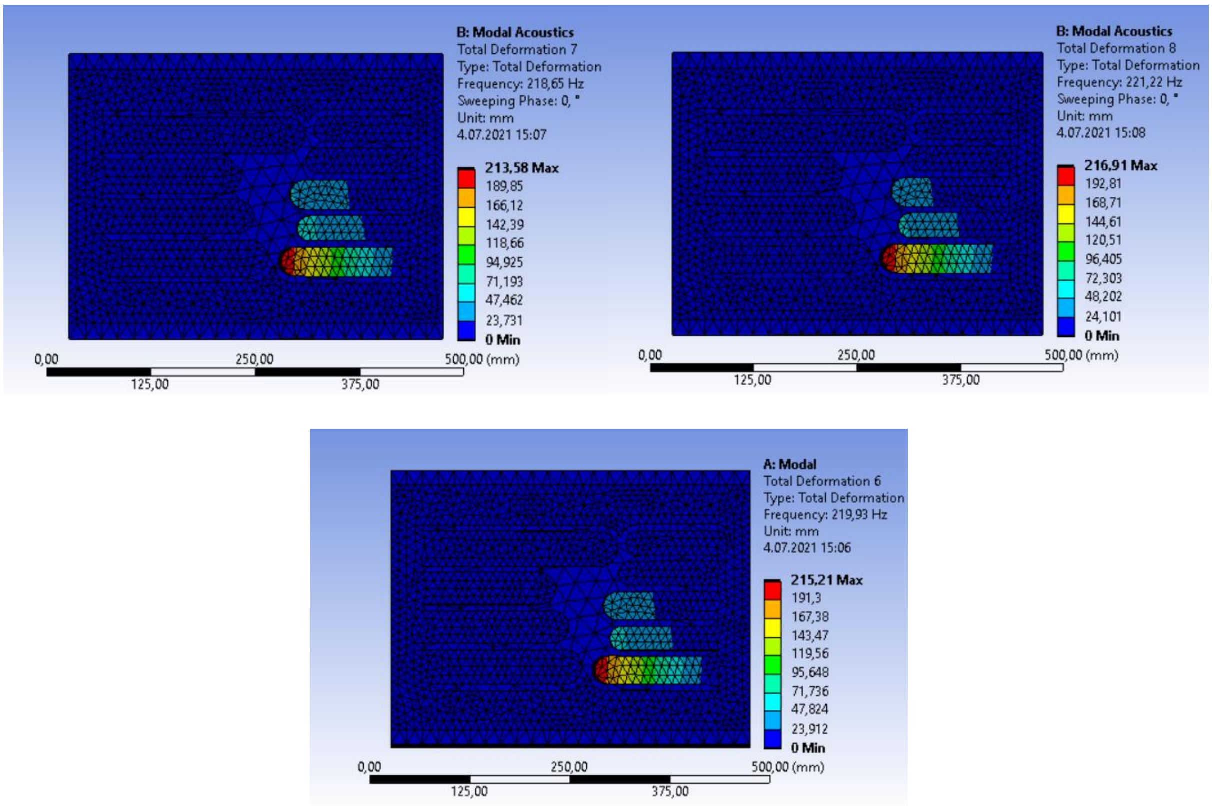

Figure 16. The mode shapes and deformations of La3 tongue for each frequency found in the analyses.

Analyses are continued with coupled acoustic analysis in ANSYS Acoustic Modal. The interactions between the acoustic cavity, soundboard and tongues are observed. The aim is to check the fundamental modes of the tongues to see if frequency values have changed with air in the system. In the analysis, the number of maximum modes to find is increased to obtain fundamental frequencies of all tongues. The reason is that in Modal Acoustics analyses extra modes emerge. These extra modes seemed to be formed close to the fundamental frequencies of some tongues for the smaller frequencies. An example is demonstrated in Figure 16. In the figure, the mode shape from both Modal and Modal Acoustic analyses that corresponds the fundamental frequency of La3 tongue is given. In the Modal Acoustic analysis, 2 mode shapes emerge at 218.64 Hz and 221.22 Hz while from the Modal Analysis the fundamental frequency of the same tongue was found to be at 219.93. Since this is a coupled analysis, being different from Modal analysis, air is present in the simulation. This means that in the solution, both structural modes and acoustic modes are found. Two different frequencies corresponding to La3 tongue can be explained with an acoustic mode measured in the vicinity of the structural mode of the tongue.

In **Hata! Başvuru kaynağı bulunamadı.**, the fundamental frequencies of each tongue from both analyses are represented. The frequencies are found to be consistent with the Modal Analysis. The biggest difference is found in Tongue 5 with a 0.586 % deviation.

Table 6. Comparison of frequency values between Modal and Modal Acoustics analysis

	Frequency (Hz)	
Tongue	Modal	Modal Acoustic
1	97.63	97.431
2	146.51	146.16
3	164.94	164.65
4	196.29	196.01
5	219.93	218.65 – 221.22
6	246.85	246.49
7	293.78	293.48
8	329.79	329.38
9	391.21	390.79

Manufacturing

Dimensions of tongues are the most significant property to get the wanted frequency so they need to be precise as possible. In order to get the precise tongue dimensions, wood CNC is used to cut the tongue shapes. CNC is working with 2D designs and blade depth is set by the technician as18mm which is the thickness of the wood plate. Thus, the surface of the tongue drum and tongues in the 3D design is converted to the 2D design in dxf. format. The blade width is 8mm so 8mm width is used between two consecutive tongues. Also, the interval between opposing tongues is designed longer than 8mm. After uploading the drawing in the CNC machine, the tongues are cut, which is shown in Figure 17. Also, how the blade cuts the tongues is shown in Figure 18. One of the most important considerations in this step is that the tongues should lie in the direction of the wood grain.

Figure 17. Wood CNC machine working on the surface of the tongue drum.

Figure 18. Wood CNC machine cutting the tongues.

Unfortunately, the flat mulberry wood plate is kept in a hot and humid atmosphere so it gets corrugated which is shown in Figure 19. As it is said the tree never dies even if it is cut. To make it flat again, it is kept under the sun wet. After that, with high pressure, it is fixed to the CNC machine flatly.

Figure 19. Corrugated mulberry plate.

The exact dimensions of the body of the tongue drum do not need to be as precise as the dimensions of the tongues so they are cut by using a jigsaw. The other five faces of the body are obtained by cutting the MDF plate with a jigsaw which is seen in Figure 20.

Assembly of the five faces and the surface of the tongue drum is also very important because of some fundamental reasons. One of them is that there would be not any air leakage to get the better acoustic properties so silicon is used along the line of the contact between two faces. Silicon fills the gaps in contact points. Another reason is that it will help the system be rattle-free because rattling changes the sound quality and the fundamental frequency of the sound. Also, silicon would decrease the unwanted noises and it would make the base of the tongues more firm so the steady frequency pattern would be obtained.

Figure 20. Cutting the MDF plates with a jigsaw.

In the assembly of the faces, quick wood glue is used. One of the reasons is that there were not any clamps during the assembly and it is wanted to test the product as soon as possible. The quick glue gives firm bonding between the plates, which facilitates better vibration transmission between the top plate and the soundboard. Screws are also not used in the product because of two reasons. The first one is that sound is created by the vibration which can loosen screws. Eventually, loose screws would create a rattling sound which will decrease the quality of the musical instrument. Also, screws would not be a problem for massive mulberry wood but it is not a good choice for MDF. Screws will not hold well to MDF without special techniques and special screws. MDF is made of wood fibers glued together with pressure but they are not as strong as it was. When the screw is used without any special equipment or technique, MDF might split around the screw.

The wood would sound better with moderately soft beaters so a bouncing ball mallet is produced to hit the tongues of the drum. It gives the most pleasant sound compared to other choices. It is also very easy to excite the vibration of the tongues with mallets. Bouncing balls are both soft and resilient in its surface so it does not create a lot of surface noise when it struck the tongues. Therefore, bouncing balls are glued end of a pencil to get the bouncing ball mallet.

Table 7. Cost analysis.

Material & Process	Part	Qty.	Price/ Area (TL/m^2)	Area(m^2)	Subtotal (TL)
MDF Plate	Soundboard	1	136.5	1.6	218.4
Mulberry Plate	Top Plate	1			0*
CNC	Tongue	-	-	-	50
Workplace expenses (Glue, Cutting Tools, Labor)	-	-	-	-	100
			Total Cost		368.4 TL

(*) It is provided by a local supplier for free, so the cost is unknown.

Testing

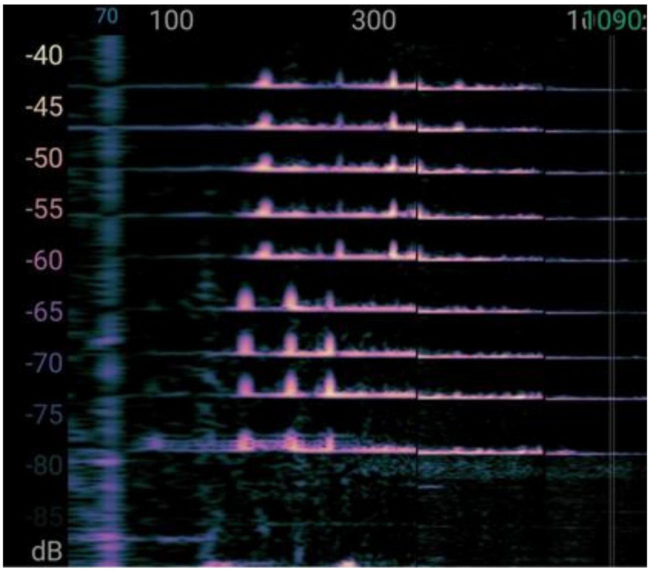

Figure 21. Waterfall view of the spectral envelopes of the nine tongues.

After manufacturing, the sound of each tongue is inspected by ear and analyzed using a spectral analysis application, Spectroid. The timbre is found to be pleasant. Mulberry wood provides a musical sound and the acoustic cavity helps to resonate the tongues which result in a deep, full tone. However, it is found that there are significant differences between the design values and measured values. The sound of the tongues can be categorized into three categories: tongues with a distinct pitch, tongues that have two audible tones and tongues without a distinct pitch.

Figure 21 shows the time history of the peaks when the tongues are struck from the lowest to the highest frequency in order. As seen from the figure, the first four and last five tongues have very similar spectral plots. These tongues are on the same side of the drum. The intensity of the peaks is different for each tongue but the peaks are at the same frequencies. This is verified with the naked ear, as the tongues on each side of the drum have a "common" sound.

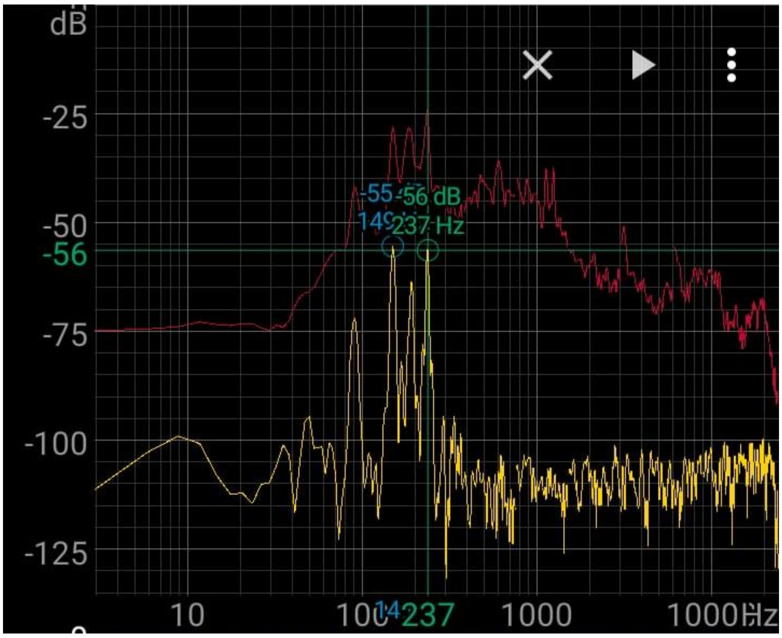

Figure 22. Spectral plot of the Re3 tongue.

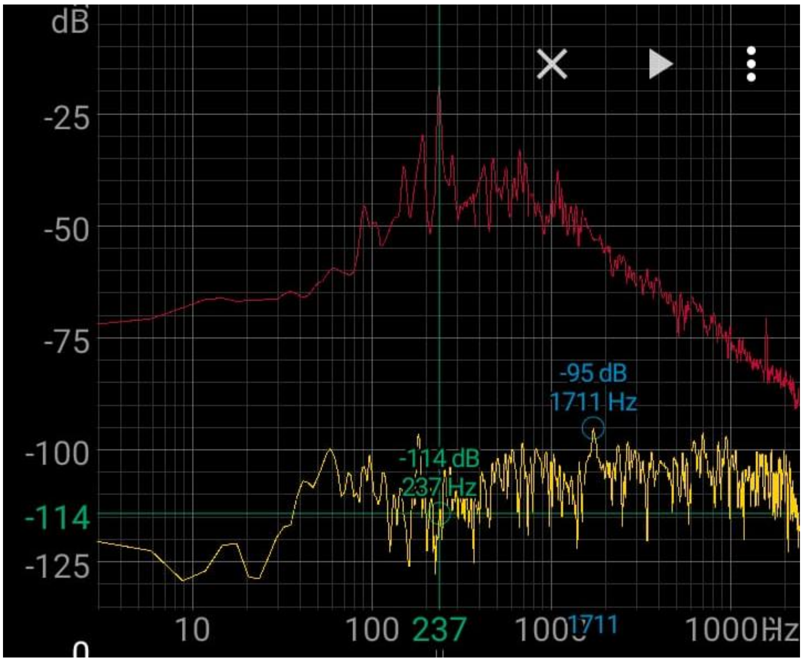

Figure 23. Spectral plot of the Mi3 tongue.

This phenomenon is further analyzed with the spectral plots of different tongues on the same side. Spectral plots for the second and third lowest tongues can be seen in Figure 23 and Figure 22. The red line shows the peaks recorded when the tongues were struck. Depending on the amplitude of the peaks, the pitch of the tongues is perceived as different. For example, the second tongue's sound is perceived as close to Sol3 at 193 Hz. The third tongue, on the other hand, is perceived as La#3 at 237 Hz. As seen from the figures, the peak at 149 Hz and 193 Hz are closer in amplitude to the peak at 237 Hz in the case of the second tongue. In the third tongue, the peak at 237 is more distinct.

As explained at the beginning of the report, timbre is the result of the multiple frequencies contained in the sound. In some of the tongues, such as the first and the second tongues, the difference is only in the tone color of the sound and a similar frequency is heard. This phenomenon is even more apparent in the smaller tongues on the right side of the drum, where the peaks at 167 Hz and 337 Hz show up in all of the spectral plots and only two distinct pitches can be heard. Overall, it can be said that tongues on one side of the drum significantly interfere with each other. This was not predicted by the coupled acoustic model of the drum.

It was not possible to distinguish the pitches of all of the tongues. However, in four of the tongues, a distinct musical note can be heard. These tongues are listed in Table 8 and their measured frequencies are compared with theoretical frequencies.

Table 8. Comparison of the theoretical frequency with measured frequency in tongues with a distinct pitch.

Musical Note	Theoretical Frequency (Hz)	Measured Frequency (Hz)	Difference (%)
Re3	146.8	193	31.5
Mi3	164.8	237	43.8
Si3	246.9	337	36.5
Re4	293.7	473	61.0

As seen from the table, measured frequencies are higher for all of the tongues with an average of 43.2% difference. The standard deviation of the values from the average is 11.2%. This difference can be caused by an error in the experimental calculation of the elastic modulus. As seen in Equation 4, frequency is related to the square root of E. Using this relation and the difference, a new value for E is calculated as follows.

$$E_{measured} = \left(\frac{f_{measured}}{f}\right)^2 E = (1 + |difference|)^2 E \tag{7}$$

Using average difference the $E_{measured}$ is calculated as 7.8 GPa, which is more than two times the initial elastic modulus. The coupled analysis is updated with this value. Since the standard deviation is not low, the frequencies of the individual tongues are not very accurate. However, some new phenomena are observed that explain the results better. The first 30 modes of the system are given in Appendix. Most of these modes can be considered global modes because they excite more than one tongue. However, they are usually focused on one particular tongue, which has the biggest deformation and is categorized as such.

A significant increase is seen in the number of global modes. In the previous simulation (with E = 3.8 GPa), fundamental modes of the tongues were distinct. As shown in the detailed analysis section, at most two tongues would be excited in these modes and interference was minimal. In the updated simulation this is no longer the case. There are modes where all the tongues in one side of the drum move together, such as in Figure 24. This explains the similar spectral plots obtained in testing from adjacent tongues on the sides of the drum.

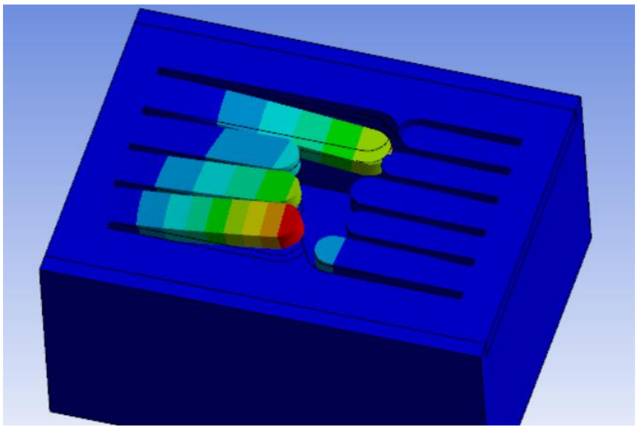

Figure 24. Second mode shape at 181.5 Hz.

Clusters can be seen around certain frequencies. An example case is a cluster focused on the Sol3 tongue around 270 Hz. Another cluster can be seen around 425 Hz that excites the Re4 tongue. As seen in Figure 25, the soundboard is deformed along with the tongues. These modes also excite several adjacent tongues, as well as some tongues across the board. The unexpected peak at 167 Hz observed in smaller tongues may be the result of such an interaction. With higher elastic modulus, tongues start moving jointly because they are more rigidly connected to the top plate. This causes interference between the tongues in the current design.

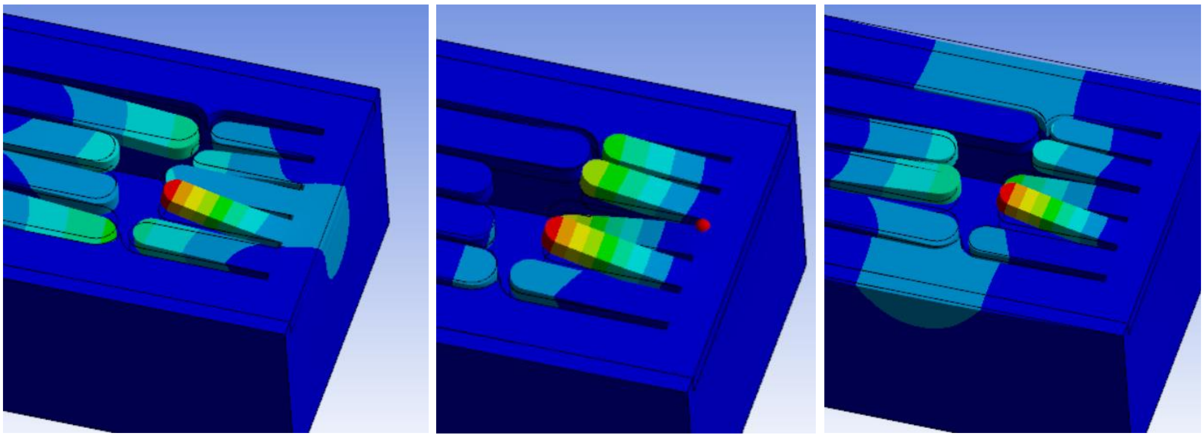

Figure 25. Modes exciting the Re4 tongue at 424.2 Hz, 424.8 Hz and 425.2 Hz.

The design can be improved by decreasing the rigidity in the base of the tongues. This can be achieved by different means. The shape of the tongues can be changed so that the width of the base is smaller, such as the tongues in hybrid tongue drum design. Another approach used by many wooden tongue drum makers is making the base thinner. A thin strip of material can be removed from the base of the tongues. This adds another step to the manufacturing process and the tongues should be tuned accordingly. Finally, the tongues can be brought closer to the edge of the drum. These measures were not considered, because there was an error in the calculation of the elastic modulus of mulberry wood. A better experimental setup is also necessary to calculate the elastic modulus of the wood.

CONCLUSION

In this project, tongue drums are analyzed in terms of materials and design to see how they affect the overall sound of the tongue drum. The aim is to form a finite element model of the tongue drum, which can be used in tuning them accurately. For this purpose, different materials used in tongue drums are investigated. Three types of models are constructed: structural models of individual tongues and the whole instrument, acoustic modes of the air cavity and coupled acoustic simulations, which are all solved in ANSYS Modal Acoustics. Benchmarking is carried out with an actual tank drum, where the spectral envelopes of the sound recordings are compared with the models.

Inspired by the acoustic cavity of conventional wooden tongue drums and the bright sound of the tank drums, a hybrid tongue drum design is conceived with a flat steel top plate and wooden soundboard. This design would be manufactured easily by laser cutting. Several iterations of this design are analyzed in ANSYS. However, flat surface proved to be a problem, as global modes of the plate interfered with the tongues to create chaotic mode shapes. The fundamental modes of the tongues were not as distinct as in the case of the tank drum, and this approach was abandoned.

Finally, a wooden tongue drum is designed using the accumulated knowledge about tongue drums. Sol major pentatonic scale is chosen, which complements the acoustic modes of the air cavity. The top plate is manufactured with a wood CNC machine from a one-piece mulberry wood. The elastic modulus of the wood is found experimentally. The soundboard is made from MDF and cut with a jigsaw. The pieces are assembled with quick wood glue and silicone is used to fill the small space between the top plate and the side of the box, which was caused by the corrugation in the wood. Then, the tongues are tested with a spectral analysis app using a smartphone. Only four tongues have a distinct pitch. These pitches are on average 43.2% higher than the design value with a standard deviation of 11.2%. The other tongues have a more ambiguous pitch, where it is possible to hear two tones in some tongues and a pitchless sound in the others. Overall, the row of tongues on each side of the drum seem to move together and cause interference between adjacent tongues. A new value for the elastic modulus is calculated from the average difference between the measured frequency values of the tongues and the theoretical value. The coupled analysis is updated with this new E value and a model that explains the interference between the tongues better is obtained. Finally, the methods that would improve the design are discussed.

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APPENDIX

Table A1. First 30 modes of the coupled simulation with E = 7.8 GPa.

Mode	Frequency (Hz)	Related Tongue
1	137,42	Sol2
2	181,51	Re3
3	205,12	
4	220,38	
5	231,53	Mi3
6	267,89	Sol3
7	270,43	
8	271,8	
9	276,44	
10	306,41	
11	319,22	
12	343,46	Si3
13	346,63	
14	348,56	
15	348,76	
16	349,03	
17	349,56	
18	416,03	Re4
19	416,6	
20	424,17	
21	424,82	Re4
22	424,84	
23	425,17	
24	425,19	
25	425,19	
26	425,47	
27	456,93	Mi4
28	461,49	
29	463,39	
30	464,45	

Top Board Technical Drawing