Solid Freeform Fabrication 2021: Proceedings of the 32nd Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

PITCH IMPERFECT: DESIGNING 3D PRINTED CLAVES TO MIMIC THE SOUNDS OF THEIR WOODEN COUNTERPARTS

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Abstract

Despite the benefits afforded students by music education, public schools operating on insufficient budgets often cut music programs to reduce expenses. Students deserve access to high quality instruments, regardless of socioeconomic status or district funding. Therefore, the goal of this research is to develop 3D printed, PLA claves that reproduce the sound of wooden claves. This study examined clave vibration by approximating claves as damped, simply supported, thin beams. The frequency predictions obtained from that model are compared to experimental results obtained by recording clave prototypes and analyzing the resulting frequency spectra. Results indicate that while it is technically feasible to 3D print a correctly pitched PLA clave, the design would not be suitable for an education instrument.

Introduction

Music education has been proven to benefit students in numerous ways, particularly students in kindergarten through 12th grade. For example, students who received music education have been found to demonstrate better spatial awareness and verbal memory skills than their peers [1,2]. However, many public-school music programs have been threatened by budget cuts in recent years, in large part due to lingering effects of the Great Recession and the widespread adoption of Common Core standards [3,4]. Instruments and other musical equipment can easily be very expensive, which further strains music programs [5–7]. Therefore, budget cuts only worsen persistent funding difficulties.

Recently, professionals and amateurs alike have begun designing and fabricating additively manufactured instruments. Researchers have successfully printed clarinet mouthpieces, flutes, and recorders, among other instruments [8,9]. Even professional musicians have begun to play instruments with additively manufactured components [10].

Music programs, therefore, may be able to alleviate their financial ails by leveraging their connections to 3D printing and STEM education as a whole. While music education is being underfunded, schools have devoted more resources to supporting STEM education. As part of efforts to encourage interest in engineering, public schools across the nation have begun purchasing 3D printers and incorporating their use into lesson plans and extracurricular activities [11,12]. Were music teachers and students able to use the newly introduced 3D printers to print instruments, they could not only provide instruments to students at a reduced cost, but also continue to promote interest in STEM fields and their interdisciplinary applications. In order to print quality instruments, students and teachers require access to quality designs. Websites such as Thingiverse have made model and file sharing very accessible, but it is still difficult to find designs that can produce printed instruments that are of sufficiently high quality to mimic their traditionally manufactured counterparts [13,14].

This work sought to analytically design 3D printed, polylactic acid (PLA) filament claves that closely mimic the sounds of traditional, wooden claves, which are shown in Figure 1. The remainder of this paper presents a literature review, the experimental methodology, the results, and a discussion, and concludes with an overview of the work done and future work and applications.

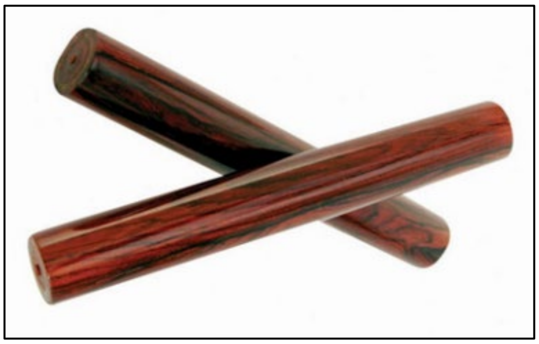

Figure 1 Rosewood claves [15]

Literature Review

Beyond exposure to music in the home or in school, dedicated music education has been proven to benefit students of all age groups in myriad ways. Students who are trained in singing or playing a musical instrument demonstrate superior verbal memory, better spelling abilities, enhanced spatial awareness, and higher-level reading ability [1,2,16]. Although research suggests that generally participating in extracurriculars benefits students [17], music has often been found to be unique in its academic benefits, even among other artistic activities such as drama or visual arts [18]. Yet, music programs are often some of the first to be cut from curricula when school districts are faced with budget cuts because music is excluded from Common Core standards, which only dictate standards for mathematics and English language arts [3]. Forty-one states and Washington, D.C. have adopted some form of Common Core standards, and many states require students to pass standardized tests based on the Common Core in order to graduate [3,19,20]. Thus, school districts have been pressured to divert resources toward mathematics and English language arts classes, often at the expense of extracurricular programs and elective courses. This diversion has only exacerbated the problems caused by budget cuts enacted during the Great Recession. As of 2015, there were still 29 states in which the total funding for music education per student was less than it had been in 2008 [4].

In recent years, researchers have begun studying 3D printing as a method for manufacturing musical instruments. Because 3D printing allows for increased customization without additional tooling cost, researchers and musicians alike have been particularly interested in 3D printing instruments and components that already have wide variability among styles and designs [8,21]. Wind instruments in general have been the focus of most 3D printed instrument research because they are expensive to manufacture traditionally [8,9,21]. The material of the instrument is also less critical to the sound produced than other factors, such as the key arrangement, mouthpiece shape, and choice of reed. For wind instruments, components such as key pads, valves, and springs can still be traditionally manufactured and then added to the 3D printed body. Additive manufacturing has also been investigated as a potential method for manufacturing novel instruments. Because an instrument with complex internal geometries would be difficult to traditionally manufacture, especially at a reasonable price point, 3D printing has become an appealing alternative [22].

Historically, instruments have been designed through trial-and-error methods; however, modern modelling software and novel, physics-based, mathematical modelling approaches now allow for more analytical design methods [23–27]. For mallet percussion instruments, modelling can be used to describe the vibration of each bar and find its modal frequencies, which determine the pitch produced. Inputs to that kind of dimension optimization include variables such as material, stiffness, reaction forces, and impact location [27]. The same variables are critical to the sound produced by claves, which can also be modeled as vibrating bars under different support conditions. Finite element analysis has also been proven to be a useful tool in predicting modal frequencies of different types of percussion instruments, such as xylophone bars, gongs, and metallophone plates [26]. Unlike with wind instruments, little research has been done into additively manufacturing percussion instruments, particularly wooden instruments, such as typical claves. Because percussion instrument sound relies so heavily on the materials used, typically varieties of wood and metals for professional grade instruments, there has yet been little interest in trying to additively manufacture percussion instruments from plastics. Additionally, although even simple, handheld percussion instruments can be expensive, they are not nearly as costly as brass and woodwind instruments, or keyboard percussion such as marimbas and vibraphones. Therefore, ventures in 3D printed percussion instruments have been largely left to hobbyists or undertaken only for the novelty [13,14,28].

Often, amateur designs are shared on websites such as Thingiverse, where users around the world can share models. Recently, middle and high schools across the United States have begun purchasing 3D printers for classroom use to encourage interest in STEM fields and supplement extracurriculars, such as robotics clubs. Even in school districts with limited funding, donations from manufacturers and the availability of grants from 3D printing organizations have made 3D printing more accessible [11,12]. Therefore, many music teachers across the country would be able to print instruments using 3D printers already in their schools, if high-quality designs were available online.

Claves were selected as the instrument to be modeled and tested in this study due to their simple geometry and ease of playing. Claves, which are played as a pair, are cylinders that are struck together to produce sound. An image is provided as Figure 1. Traditionally, claves are made of dense woods, such as grenadilla or rosewood, but metal and plastic claves are also widely available on the market today [29]. When playing the claves, an instrumentalist will lightly hold one clave between the tips of their fingers and the thick pad below their thumb, with their palm slightly cupped, which acts as a resonator. With the other hand, they hold the second clave with their thumb and first few fingers, and strike the first clave [30]. The sound of a clave is typically described as clear and penetrating; it can cut through even a dense brass ensemble

[30–32]. Claves are one of the most distinctive features of Cuban music, specifically of Afro-Cuban rhythms [30–33].

Methodology

Initially, three models were considered for the analytical prediction of the natural frequencies of the wooden and PLA claves: a cantilevered thin beam model [34], a cantilevered deep beam model using Timoshenko analysis [35], and a simply supported thin beam model [34]. The simply supported thin beam model best predicted the natural frequencies of the wooden traditional model and the PLA clave prototypes used in this study. The predicted natural frequencies obtained were compared to those experimentally determined by recording the claves and determining the natural frequencies.

Modeling the clave to predict natural frequency

The cantilevered models were examined based on the assumption that although the clave is struck at its center, the part of the instrument that vibrates is the length beyond the player's hand. However, it was reconsidered that the clave could be modeled as a simply supported, thin beam subject to damping, where the length is equal to the distance between the player's first and third fingers when holding the clave. Figure 2 is a photograph showing how the struck clave is held when played. Figure 3 represents the grip as a beam diagram.

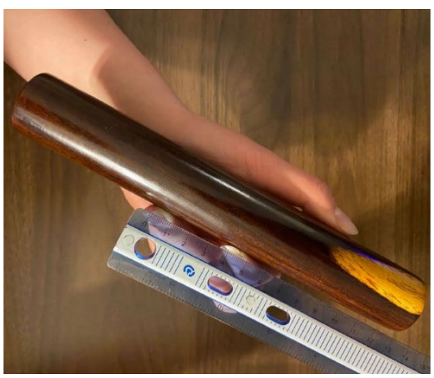

Figure 2 Photograph of the clave as held when played

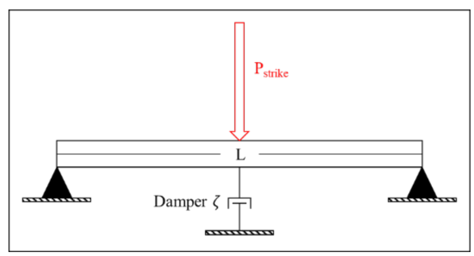

Figure 3 Diagram of clave modeled as a thin beam. L denotes the length of the beam, which is taken as the distance between the first and third fingers when played. P_{strike} denotes the force of the striking clave.

Damping was assumed to be due to the clave being in light contact with the rest of the player's hand and not only at the first and third fingers where it was tightly held. It was hypothesized that the damping effects would depend on the radius of the clave, because a player's grip would need to alter to accommodate different sizes of clave.

Additionally, two different moments of inertia needed to be considered for the wooden versus PLA claves. The wooden claves could be modeled as a circular cross section with a uniform density. However, the cross section of the plastic prototypes is better approximated as a circle of fractional but uniform density surrounded by a thin ring of 100% density. The area moment of inertia of a rod with a solid, circular cross section about its x-axis is

$$I_x = \frac{\pi}{4} r^4.$$

This is the moment of inertia used for the wooden clave. Area moments of inertia can be summed if they have the same centroid and are calculated about the same axis. Therefore, the area moment of inertia of the PLA claves can be calculated by summing the moment of inertia of the ring and of the center circle. The area moment of inertia of the thin ring is calculated by

$$I_x = \frac{\pi}{4}(r_{outer}{}^4 - r_{inner}{}^4).$$

The area moment of inertia of the inner circle is calculated by

$$I_x = (\%infill)\frac{\pi}{4}r_{inner}{}^4.$$

Regardless of the outer diameter of the PLA clave, the thin ring is 1 mm (0.001 m) thick. Therefore,

$$r_{inner} = r_{outer} - 0.001\,m.$$

Summing the two moment of inertia equations, substituting the above radius relation, and letting $r = r_{outer}$, the area moment of inertia of the PLA claves is equal to

$$I_x = \frac{\pi}{4}[r^4 - (1 - \%infill)(r - 0.001\,m)^4].$$

Figure 4 shows the assumed cross sections for the wooden and PLA claves and their respective second moment of inertia equations.

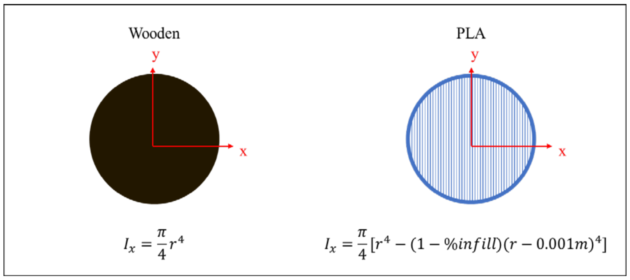

Figure 4 Cross sections and area moment of inertia equations for wooden and PLA claves

The calculations of predicted natural frequency and the MATLAB code used to perform them were again developed from those found in *Vibration of Mechanical Systems* [34]. The scripts and functions can be found in Appendix A. The first natural frequency of a simply supported beam is given by

$$f_n = \frac{\pi\beta}{2l}$$

where

$$\beta = \frac{EI}{\rho A}$$

and l is the length of the beam, E is the Young's Modulus, A is the cross-sectional area, I is the area moment of inertia, and ρ is density.

The damped natural frequency of a simply supported beam is given by

$$f_d = f_n\sqrt{1 - \zeta^2}$$

where ζ is the damping ratio.

To determine the value of the damping ratio, the predicted natural frequency value for each clave was calculated in MATLAB. Letting the predicted value be the undamped natural frequency and the experimentally determined value be the damped natural frequency, the ratio of experimental to predicted value, or damped to undamped value, was used to calculate the damping ratio

$$\zeta = \sqrt{1 - (f_d/f_n)^2}.$$

The damping ratio was averaged across claves of the same diameter. The averaged values for each size were then used as the damping ratios in a new calculation of the predicted natural frequency. These new predicted values were compared with the experimental values to judge the accuracy of the model. This analysis was used for both the wooden and PLA claves.

Experimental determination of natural frequency

In total, 25 PLA prototypes were printed and tested for this study. At each infill density, five claves with different diameters were printed. The five levels of infill density were 30%, 40%, 50%, 60%, and 70%, and the clave diameters were 1.5 cm, 2.0 cm, 2.5 cm, 3.0 cm, and 3.5 cm. Figure 5 shows a grid of the prototypes made, where each color represents a different infill density. The prototype claves were printed using Prusament PLA filament, which is widely used for both hobby and professional prints. Estimating the Young's Modulus of a printed part in the direction perpendicular to the direction of print layering was critical to developing a model of clave vibration. The average value provided by Prusa Polymers, which was used in this work, was 2.3 GPa [36]. The results from the PLA claves were compared to those obtained from a traditional pair of LE2368 Ludwig rosewood claves. The claves were each 20 cm long and 3.0 cm in diameter, and they each had a mass of 160 g. The Young's Modulus value determined in Green et al. for Brazilian rosewood at 12% moisture content, 13.0 MPa, was used in this study [37].

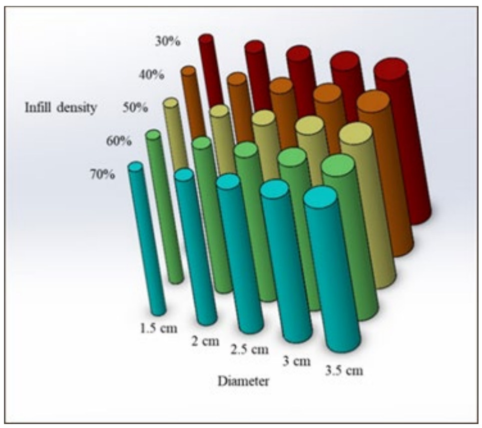

Figure 5 Grid of the 25 PLA prototype claves printed for this study

The wooden claves and PLA prototypes were recorded in studios at the Penn State University Park Pattee Library Media Commons. Claves were played as described in the literature review, but with a tight grip on the striking clave to damp its vibration and sound. Each clave was struck four times during recording. Including multiple "strikes" increases the intensity of the peaks at the frequencies produced by playing the claves, which allowed for the pitches of the natural frequencies to be better distinguished from the noise in most cases. The natural frequencies of the wooden and PLA claves were experimentally determined by analyzing recordings of the instruments in MATLAB and using the fast Fourier transform to determine the frequency spectra.

Results

The simply supported thin beam model with damped vibration predicted the natural frequencies of the PLA and wooden claves well, although it could only do so when the calculated damping ratio was very high.

Wooden claves

In order to determine the effect of playing technique, or varying grip, on the frequency spectra, recordings of the wooden claves played using varied grips were analyzed. From the resulting spectra, it was determined that grip variation did not significantly change the frequency of the sound produced. Plots comparing the frequency spectra when striking the clave closer to the far end (long grip), close to the hand, (short grip) and at the center (standard grip) is shown below in Figure 6. Table 1 also provides the locations (frequencies) of the four highest peaks for each recording, as well as the mean of each peak group, the standard deviation, and the standard deviation as a percentage of the mean. From the results of this analysis, it can be seen that the frequencies of the highest three peaks vary very little among the different grip recordings. Additionally, the frequencies of the highest three peaks for each grip are very similar. Therefore, for the purposes of the rest of the study, we defined natural frequencies obtained from the protypes as matching the wooden claves if they fall between 2540 and 2570 Hz, a slightly narrower range than provided by the varied grips.

As can be seen in Figure 6, all three frequency spectra showed a peak between 19 and 21 Hz. The range of human hearing only extends from about 20 Hz to 20 kHz, so these frequencies would be nearly or entirely imperceptible to any listener. Due to the consistent appearance of the approximately 20 Hz peaks, it can be concluded that these peaks are due to noise in the signal and not the sound of the claves. A prominent noise peak also exists in the recordings around 120 Hz.

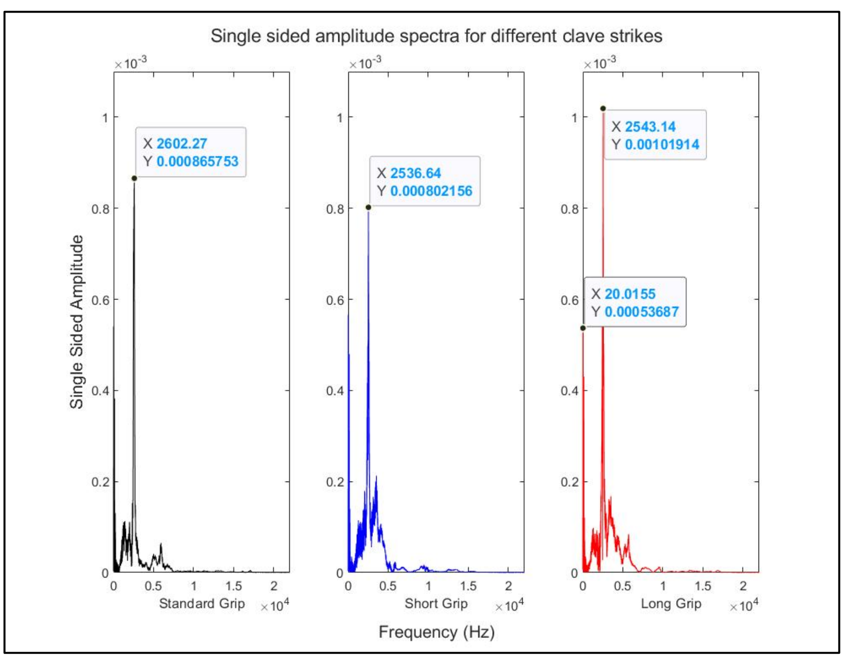

Figure 6 Frequency spectra for recordings of wooden claves held in three different grips

Table 1 gives the inputs for the wooden clave to the natural frequency calculation that yield a frequency within the acceptable range of 2540 to 2570 Hz. The mass and radius of the clave were measured quantities. The length, which in this model is the distance between the player's first and third fingers while holding the clave, was also a measured input. The Young's Modulus of rosewood was found in the literature [37]. Holding the other inputs constant, values of the damping coefficient that yielded acceptable predictions of the natural frequency were found iteratively. There exists a range of acceptable damping coefficient values, as indicated in the table. Using the low value in the table results in a predicted frequency of 2540, and using the high value results in a predicted frequency of 2570 Hz. The wooden claves would have to be subjected to near critical damping in the model in order for it to yield an acceptable theoretical natural frequency value. These results are examined further in the discussion section.

Table 1 Inputs to the natural frequency calculation for wooden claves

Input	Variable	Value
Length	l	0.04 m (4 cm)
Mass	m	0.16 kg (160 g)
Radius	r	0.015 cm (1.5 cm)
Damping ratio	ζ	$0.9948065 < \zeta < 0.9946829$
Young's Modulus	E	13 GPa

PLA claves

The natural frequencies of the prototype claves were determined in the same manner as the wooden prototypes. The frequency at which the highest peak in the frequency spectra was found was taken as the experimental natural frequency value for each clave. The same noise frequencies of 19-21 Hz and 120 Hz were also observed in the PLA prototype recording frequency spectra.

The PLA claves were each 20 cm long, which was the length of the wooden claves, but with varying masses, infill densities, and diameters. The value of the Young's Modulus used in the predicted frequency calculations was 2.3 GPa, which is an average value provided by Prusa Polymers in the data sheet for their Prusament PLA filament [36]. The simply supported length, which is the distance between the player's first and third fingers, was again equal to 0.04 m (4 cm). With the Young's Modulus, the simply supported length, diameter, and mass as inputs, the undamped natural frequencies were calculated.

The damping ratios necessary for each clave's predicted damped natural frequency to be equal to the experimental frequency were then calculated. The damping ratio was averaged across each diameter of clave. The calculated damping ratios for each diameter and infill are plotted versus the diameter of the clave in Figure 7.

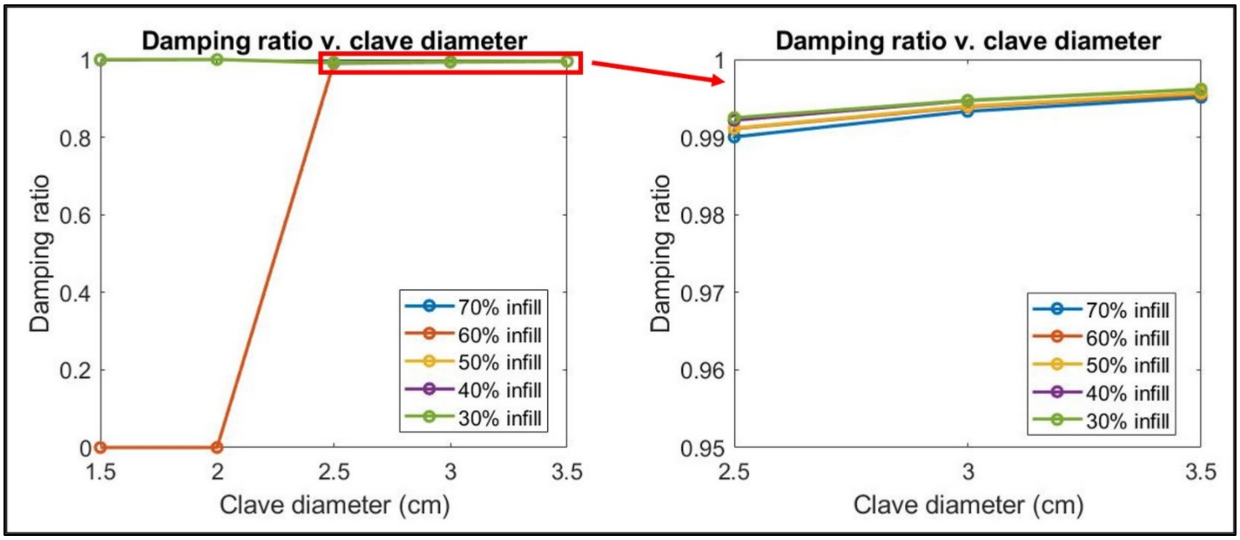

Figure 7 Damping ratio v. clave diameter for PLA prototypes. The image on the right shows a detailed view of the damping ratios plotted for the 2.5 cm, 3.0 cm, and 3.5 cm diameter claves. Note: for complex ratios, only the real component is plotted.

The theoretical damped natural frequencies were then calculated using the averaged damping ratio values. For several 1.5 cm and 2.0 cm diameter claves, the most prominent peak in their frequency spectra were noise peaks. Because of the prominence of the noise, all 1.5 cm and 2.0 cm diameter claves also had a frequency spectrum found for only one "strike" of the clave. This sectioning of the recording did not reduce the noisiness of the spectra. Because the actual experimental natural frequencies could not be identified for these claves with certainty, the noise frequencies were still used in the calculation of theoretical damped natural frequency to be consistent with the use of the tallest peak in calculating the other experimental natural frequencies. A more detailed examination of the frequency spectra for the 1.5 cm and 2.0 cm diameter claves is included in the discussion.

Figure 8 shows several contour plots illustrating the theoretically and experimentally determined values of the damped natural frequency for the claves, as well as the difference between the two values. The subplots in the left-hand column were created using only the data for the claves with the three largest diameters (2.5, 3.0, and 3.5 cm), while the subplots in the right-hand column present the data for all claves. The data for the three larger-diameter claves are presented separately as well as part of the whole set because noise frequencies dominated for the 1.5 and 2.0 cm diameter claves.

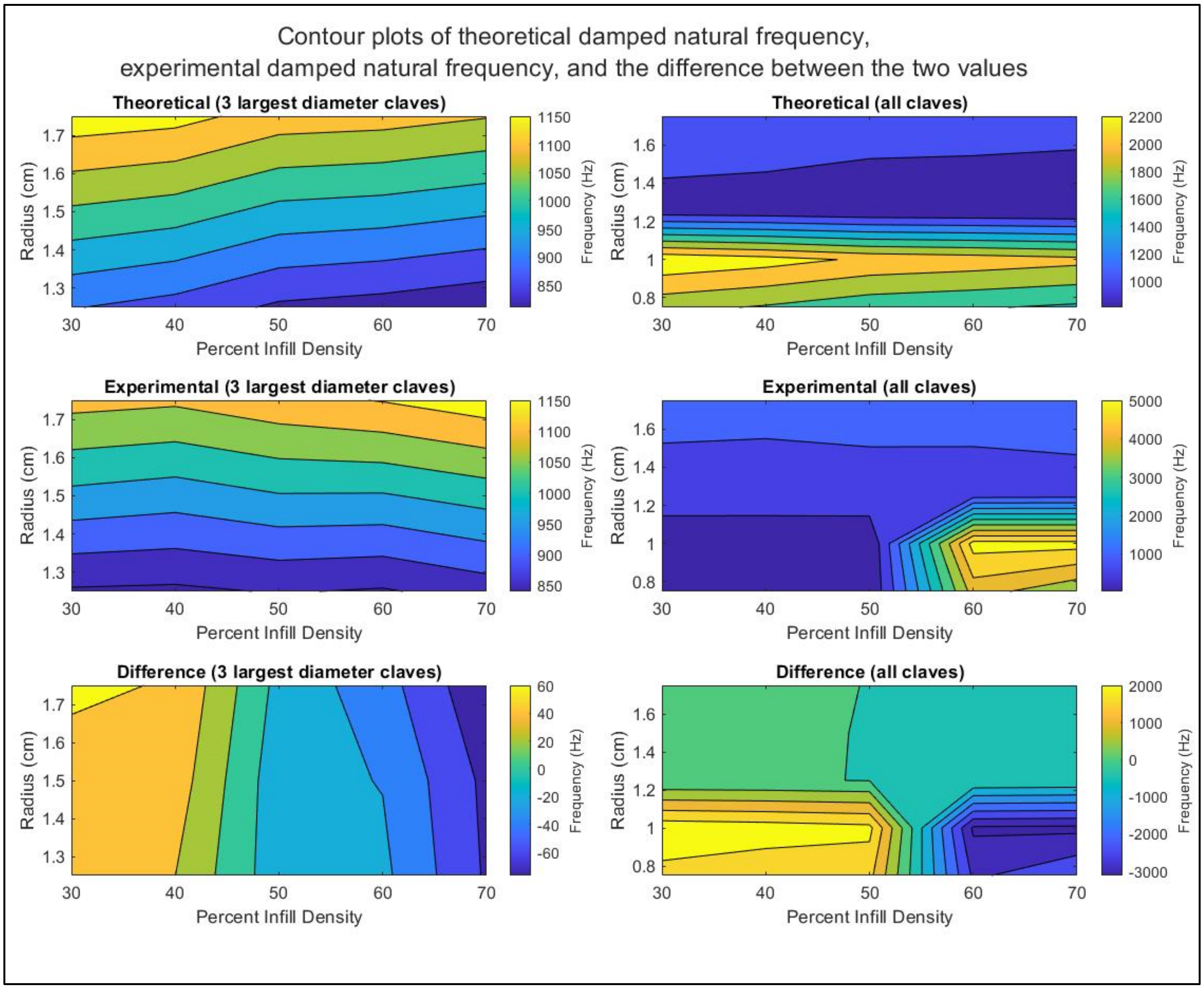

Figure 8 Contour plots showing the theoretical damped natural frequencies, experimental damped natural frequencies, and the difference between the two values for the three largest diameter claves (2.5, 3.0, and 3.5 cm) and for all claves

The necessary radius at each infill density for a clave that would produce the same natural frequency as the wooden claves was then calculated. At each infill density, the predicted and experimental values of damped natural frequency follow an approximately linear trend upwards. Therefore, the equations of lines of best fit were calculated using the theoretical damped natural frequency values corresponding to the higher three radii at each infill density. The results of these calculations are given in Table 2.

Table 2 Required diameters at each infill density to produce frequencies in the acceptable range of approximating wooden claves

Predicted damped natural frequency (Hz)	**Diameter (cm) necessary at 70% infill density**	**Diameter (cm) necessary at 60% infill density**	**Diameter (cm) necessary at 50% infill density**	**Diameter (cm) necessary at 40% infill density**	**Diameter (cm) necessary at 30% infill density**
2540	8.4075	8.3601	8.4285	8.2762	8.3985
2550	8.4416	8.3944	8.4634	8.3111	8.4345
2560	8.4758	8.4287	8.4982	8.3469	8.4706
2570	8.5099	8.4629	8.5331	8.3807	8.5066

Discussion

As seen in the Results section, the frequency of the PLA claves could be predicted using the model of a simply supported thin beam with damping. However, in order to predict the frequency of the PLA claves, the input damping ratio would have to be very close to 1, which would represent critical damping. The same would be true of the damping ratio necessary to match the frequency of the wooden claves.

With regard to both the wooden claves and the PLA claves, there are a number of possible explanations for this discrepancy, the first of which being uncertainty about the composition of the claves and variations in the mechanical properties of wood and PLA printed objects. Wood is an anisotropic material, and there are often large variations, such as knots, even along a single axis. Although rosewood, like other varieties of wood commonly chosen for instrument making, is more dense than other varieties and is less prone to variation, it is still not a uniform material. Printed objects are also anisotropic. The PLA data sheet provided by Prusa for the Prusament filament reported average values of the Young's Modulus along different axes of a printed object, but those values are still approximations. A number of factors, such as part geometry and layer height, determine the mechanical properties of a printed part, so it is difficult to estimate properties accurately.

Additionally, it is likely that although the model can accurately predict outcomes for the PLA claves, it is not accurately describing the true boundary conditions and response when struck. The end conditions, where the clave is held tightly, are modeled as fixed-point supports. Because human hands are in reality soft, and there is no way to only contact an object with a single point on the hand, the end conditions of the beam are also greatly simplified. This model takes the input length to the simply supported beam calculation to be the distance between the player's first and third fingers, which ignores the length of the clave that overhangs on either end. The distance between the player's hand is only 4.0 cm, and therefore the overhang distance in total accounts for 80% of the length of the clave. When the input length in the theoretical frequency calculations is increased, the damping ratios necessary to match the experimental pitches decrease. Figure 9 plots the necessary damping ratios for each clave when the input length is increased from 4.0 cm to 10.0 cm. Following the trend seen in Figure 7, the necessary damping ratios increase with clave diameter for the larger diameter claves. However, all damping ratios are below 0.9, which is more physically plausible. Therefore, a more accurately descriptive model would likely consider more of the full length of the clave. This model also fails when the undamped, theoretical natural frequency is less than the experimental value, because the damping ratio necessary to match the frequencies becomes a complex number. Ultimately, although modelling the claves as simply supported thin beams with damping yields accurate predictions for the purposes of this study, it is likely not an accurate representation of the actual vibration response of the claves.

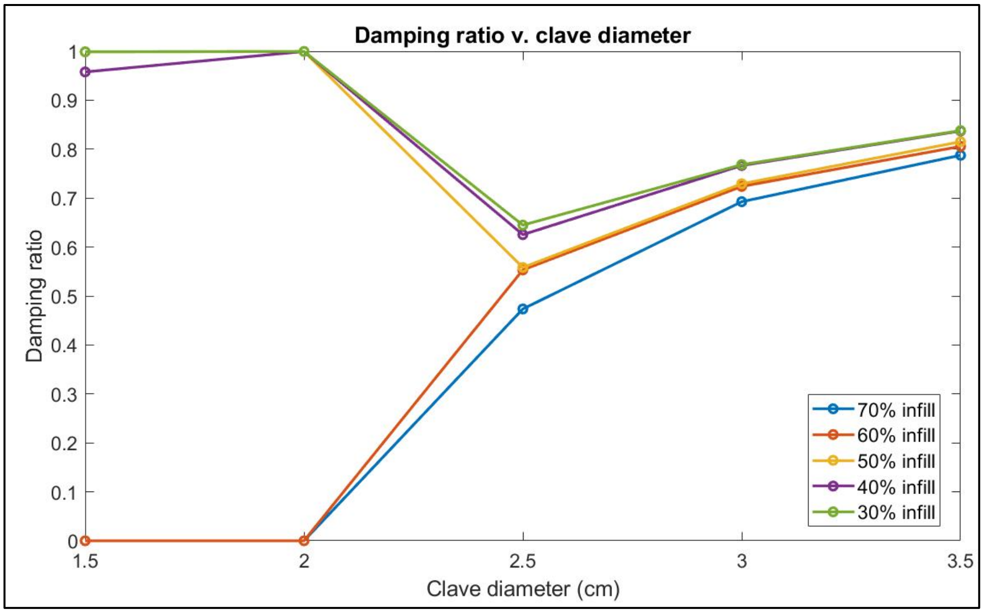

Figure 9 Damping ratios for each clave necessary to match the experimentally determined frequency when the input length is taken to be 10 cm. Note: for complex ratios, only the real component is plotted.

While the claves with 2.5 cm, 3.0 cm, and 3.5 cm diameters tended to produce frequency spectra with one well-defined peak and some smaller peaks, usually including at least one noise peak, the 1.5 cm and 2.0 cm diameter claves produced much denser frequency spectra with a greater number of less defined peaks. The comparatively dense and ill-defined spectra for 1.5 and 2.0 cm diameter claves are likely due to the difficulty of holding and playing a clave with such a small diameter. Because they are so thin, it is nearly impossible to hold the "struck" clave in the correct position for playing. The players palm cannot be cupped as a resonator, and the clave will be in tight contact with all of the player's fingers and the pad of their hand below the thumb. It is therefore difficult to play without also striking one's own fingers or fingernails.

Because the thickness of the outer ring of the print remained a consistent 1 mm for all claves, the 1.5 cm and 2.0 cm diameter claves were also relatively denser than the larger diameter prototypes, even when printed with the same infill density setting. This likely negatively affected the resonance of the claves and the timbre. "Timbre" is an imprecisely defined term used to describe the quality of a sound that is not its pitch or intensity. When musicians describe a sound as "bright," "dark," "warm," or "round," or in similar terms, they are describing timbre. Researchers have been attempting to quantitatively describe and analyze the timbre of a sound using various methods for the better part of a century [38,39]. Although the enhanced computing power of the 21st century and the advent of sound processing and analyzing software have allowed for better understanding of the frequency patterns and fluctuations that contribute to timbre, many subtleties of timbre are still better detected by the human hear than by a computer [39]. Therefore, qualitatively the 1.5 cm and 2.0 cm diameter clave prototypes were less resonant and produced duller, thinner sounds than the other prototypes. The comparatively dense frequency spectra likely reflect the inconsistent damping due to grip variations as well as the indistinct timbre of the instruments.

Using the results of modelling the claves as simply supported beams subject to damping, any PLA clave with an infill density between 30% and 70% would have to be over 8.0 cm in diameter to produce the same pitch as the wooden claves, if the length were held constant at 20 cm. A clave of that size has several potential problems, the first of which being printing challenges. Any clave at 20 cm tall could already present an issue, as it may exceed the height limit for certain types of hobby printers that would be common in schools. Hobby printers that are also prone to failing during long prints may not be able to print such a large clave, and the wasted filament and time may be more expensive than simply purchasing a pair of claves. Claves that are 8 cm in diameter could also be difficult for children to play. Although high school students, who may already be adult-size or are nearing adult-size, may be able to effectively hold and play such a large instrument, the same cannot be said for elementary or middle school students. However, it is possible that the instrument could instead be mounted on a small stand and then struck with a small mallet in order to produce the same sound. However, this would detract from the student's playing experience. Such a large clave played in that manner would essentially become a wood block. The goal of this research was to investigate a way to develop a lower cost, 3D printed version of a particular instrument, not just to develop a pitch equivalent. The task of designing new, handheld percussion instruments could be a fantastic creative opportunity in a music or engineering class, but student musicians still need to be exposed to and to play traditional instruments.

Conclusion

Claves can be modeled as simply supported thin beams subject to damping. Although the model does not truly accurately describe the system, it does produce accurate results, as verified by the experimental recordings and analysis. In the model, the cross section of a solid wooden clave is most accurately represented as a solid circle. The cross section of a PLA 3D printed clave, however, is best modeled as a 100% dense thin ring surrounding a circle of the chosen infill density. The correct identification of the cross-sectional shape is critical to accurate modelling because it determines the area moment of inertia, which is necessary for the natural frequency calculation.

Damping is dependent on the diameter of the clave. Because the damping is due to the shape of the player's hand while holding the clave and the amount of contact between the player's hand and the clave, the damping varies with diameter. The amount of damping is consistent across infill densities at a given diameter. If the length of a clave is held at 20 cm, any PLA clave with a density between 30% and 70% is predicted to need over an 8.0 cm diameter in order to produce a pitch in the accepted range for the wooden claves, or between 2540 and 2570 Hz. A clave of that size could be difficult to print correctly on a hobby printer and would also be difficult to play, especially for children.

Further investigation could be done into printing at infill densities between 70% and 100%. Additionally, varying the internal geometry of a clave would change the pitch produced. A clave with a nonuniform internal cross section may be more difficult to model and may require a finite elements approach.

This work could also be used to inform the development of new, handheld percussion instruments, such as in a middle or high school level music or technology course. The aim of this study was to lower the cost barrier to accessing a traditional instrument, although made of a nontraditional material, but the ability to aid in any improvement in a music education program justifies the research efforts made.

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