AN INVESTIGATION IN TONE CHARACTERISTICS OF 3D PRINTED UKULELE CHAMBERS

A Thesis

by

JOSHUA RIEFER

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Bruce Tai
Co-Chair of Committee,	Jyhwen Wang
Committee Members,	Vinayak
	Adolfo Delgado
Head of Department,	Andreas A. Polycarpou

August 2018

Major Subject: Mechanical Engineering

ABSTRACT

Perceptive vocabulary for musical instrument sounds often lacks structure and standardization. Descriptors often convey qualitative appreciations, varying from listener to listener. Defining tone in terms of quantitative metrics enables baseline testing of traditional instruments and comparisons with developing materials and technologies. As 3D printing enters the scene of musical instrument design, relatively unexplored sound possibilities accompany its wake. This fabrication approach introduces layer-by-layer build control and simultaneously adds the complexity of anisotropic material properties. Understanding 3D printed instruments' acoustical characteristics seems the first step toward wielding the technology to design for specific sound qualities.

In this endeavor, three metrics of tone were defined in light of existing studies and consideration for feasible frequency and time response analytics. Three different soprano style ukulele chambers were printed on a TAZ 6 printer using ABS, PLA and HIPS plastic and assembled with standardized components. Sounds were recorded and run through MATLAB using FFT and spectrogram functionality. Comparisons were made with traditional wood ukulele chamber fabrication. Metric use showed three different aspects of analyzed signal data that pertained to qualitative tone descriptions. Number of Harmonics showed promise as a meaningful gage of Fullness, decay time suggested that Sustain differentiates between ukulele sounds, and lastly, comparing fundamental frequency relative amplitude to other harmonics at decay time provided insight into pitch Strength.

CONTRIBUTORS AND FUNDING SOURCES

Special thanks to Chair Dr. Bruce Tai of Mechanical Engineering and Co-Chair Dr. Jyhwen Wang of Emerging Technology and Interdisciplinary Engineering for coaching and feedback along with Committee Members Dr. Vinayak of Mechanical Engineering and Dr. Adolfo Delgado of Mechanical Engineering.

No direct funding supported this endeavor.

NOMENCLATURE

ABS	Acrylonitrile Butadiene Styrene
HIPS	High Impact Polystyrene
PLA	Polylactic Acid
FFF	Fused Filament Fabrication

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CHAPTER I

INTRODUCTION

Musical sounds often lack accurate definition or consistent distinction in perceptive listening vocabulary. Beyond the structure of notes, key signatures, and musical arrangement, there still remains uniqueness among actual sounds. No violin renders the same quality as a Stradivarius and no musician replicates Vivaldi's exact performance of the Four Seasons. This very notion adds to the distinction of craft and skill that go into fine pieces of music; however, luthiers and manufacturers alike try to blend aspects of the artistic originality with scientific repeatability for sounds that resonate with people's perceptive preferences. To effectively achieve this, it becomes extremely important to understand what causes sound subtleties in the first place and how to design for them. This currently poses somewhat of a multifaceted problem, as many of the words used to describe characteristics and methodologies employed to investigate them lack standardization and structure. "Tone" shows up quite frequently in literature as a rather loosely used or undefined term for relaying qualitative measures of sound perception. Merriam-Webster Dictionary defines tone as "vocal or musical sound of a specific quality [1]." Establishing this overarching definition practically with accompanying quantitative metrics could enhance its meaning in the realm of sound characterization and provide a means for comparing different instruments.

Šali and Kopač proposed a 'rule of consonance-dissonance,' looking to define 'good' and 'bad' guitar tones based on pleasant or unpleasant interval combinations of frequency amplitudes [2]. This definition is based around music theory structure, yet hinges on agreed preference in guitar sound which still lends itself to some degree of interpretation by the listener. This introduces the matter of perceived sound quality and simply measurable differences in sound. A more objective use may not convey sound preference, but metric identification and comparison with existing baselines could shed light on causes of preferred sounds. Fohl, Turkalkj, and Meisel showed metric use in their endeavor to identify guitar sounds based on partial tones [3]. Results evidenced large dependency on guitar and player. Desired traits or attributes in instrument tone can vary from listener to listener; however, using metrics to simply deduce relative levels or intensities could provide insightful means for comparing sounds. Various frequency response tools are common for examining string instrument sounds [4]. FFT (Fast Fourier Transform) and spectral analysis techniques allow visualization and relative comparisons of the fundamental frequency and harmonic overtones contained in an overall signal. A simple count of the number of harmonics contributing toward sound quality has been used as an indication of timbre or perceived brightness of instrument sound [5, 6]. This metric seems analogous to qualitative fullness or presence of sub-sounds in a signal beyond the primary tuning frequency. Ramsey and Pomian further investigated the overtones' interrelation by considering each harmonic's relative percentage with respect to overall intensity [6]. This metric seems telling of the relative strength of each harmonic and, more specifically, the fundamental frequency's dominance or deficiency among harmonic tone contributors. Besides frequency domain attributes, some aspect of time response is also critical in studying tone characteristics. These two pieces really go hand in hand, as identifying what frequencies are present in the signal would paint an incomplete picture without also considering how they behave with time. In the time domain, a simple pluck of the guitar shows as variations in air pressure. The signal builds (attacks) to some peak amplitude and then wanes (decays) presumably exponentially with time. Having some metric that considers the rate of signal change is important, as sound after all exhibits dynamic behavior. French proposed attack and decay percentages based upon linear and exponential curve fits of filtered signal data in the time domain to determine transient points of interest [7]. This approach appears useful in studying overall signal response. Decomposing transient behavior even further, recall that within the overarching signal exist various frequency components, each decaying with time. The fundamental, each of the harmonics, and any noise in the signal (unless filtered) contribute to projected sound from guitars. Soon visualized this interplay of frequency and time behaviors through use of spectral analysis by plotting identified harmonics over time [8]. Isolating frequencies, the fundamental and harmonics specifically, allows already identified tone contributors to get targeted in the signal's time response.

Once meaningful tone metrics have been identified, they can be used to interpret sound changes caused by differences in the material or structure of musical instruments. Aspects of design such as material type, geometry, fabrication processes, and component placement all contribute toward the overall vibration and sound projection. On the side of geometric investigation, Ramsey and Pomian organized bluegrass genre instruments such as banjo, mandolin, and mountain dulcimer into overall shape categories and analyzed sound recording frequency responses and vibration Chladni patters to interpret tone behaviors [6]. With regard to feature contribution, Bader recorded modern renditions of two vihuelas and a classical guitar with an array of microphones to interpret effects of sound hole size and position on frequency radiation [8]. As far as the main chamber itself, Haines recognized significance of wood selection for the top and back plates in sound of the guitar [9]. Each variety of tree includes its own material properties and indigenous climate. What is more, each tree used in guitar making has its own unique ring pattern and thickness based on growing seasons. These can have an effect on vibration characteristics and, in turn, resulting instrument sound. To investigate this, Idrobo-Ávila and Vargas-Cañas recorded and explored frequency behaviors for both sound and vibration responses of Spanish guitar top plates to investigate influences of Canadian cedar and German spruce on sound characteristics [5]. Beyond material selection, nuances of fabrication techniques and manufacturing processes can have an effect on sound characteristics. Soon applied sound testing methodologies to members of the guitar family by recording and analyzing frequency responses of three ukuleles from different manufacturers, spanning wood and injection molded polycarbonate construction [10]. Šali and Kopač focused in even more specifically on subtractive manufacturing processes and explored influences of various machining operations such as cutting, planing, and sanding on resonant board properties [11]. Cutting and finishing processes showed signs of contributing toward average Young's modulus; however, more work remained for these implications to find root in guitar structure.

As instrument making materials, fabrication techniques, and geometric capabilities develop, so does the need for quality tools for analyzing their sound behavior. 3D printing has emerged as technology with relatively uncharted material properties and fabrication effects. Programmatic material deposition, laser hardening, powder binding, or ink jetting movements promote consistency and repeatability in building geometry layer-by-layer. Currently, string instrument construction involves many different treatment steps, machining processes, and finishing operations. As ink, polymers, powders, and filaments trend with advancing printer technology, fabrication materials should rapidly approach designable performance to fit specific applications. This begs the question of tailorable sound qualities in musical instrument design. Could the sound of a wooden 1700's Stradivarius find replication or close approximation in 21st century 3D printing technology? What about the originality of 3D printed instrument sounds themselves? As this manufacturing approach enters the arena of musical instrument development, there exists a need for methodology to evaluate its sound characteristics in light of conventional instrument sounds. While tone could imply level or degree of quality in certain contexts, for the scope of this research it will be limited to three subset attributes consisting of Fullness, Sustain, and Strength. Each of these descriptors will get discussed and interpreted in terms of comparative sound metrics obtained through Fast Fourier Transform and Spectrogram signal analyses. Correlations will be made between 3D printed ABS (Acrylonitrile Butadiene Styrene), PLA (Polylactic Acid), and HIPS (High Impact Polystyrene) acoustic resonating chambers and manufactured wood soprano ukuleles in regards to notes produced by G4, C4, E4, and A4 open string plucks.

CHAPTER II

SPECIMEN AND TESTING

Traditional Wood Specimens

Three wood manufactured instruments were analyzed with tone metrics – two of the same make and model and one from another brand. The two 21 inch Makanu soprano ukulele chambers (front, back and side wall) were made of sapele wood, while the Luna 21 inch Honu model chamber consisted of mahogany, providing industry baseline for comparison. Hardware and mounting components such as neck, headstock, fretboard, tuning keys, bridge, and saddle each have their own traditional material and fabrication approach with nuances across manufacturers; however, for the scope of this study, the major focus of instrument sound investigation was on differences in acoustic resonating chamber material and fabrication technique. All ukuleles followed soprano body style and were strung with Aquila® New Nylgut® strings. Figure 1 below shows the three wood ukuleles recorded for analysis. One was taken apart after recording in order to measure and produce CAD (Computer Aided Design) models for printing FFF (Fused Filament Fabrication) specimens. From left to right, the order is Makanu #1 (scrapped ukulele), Makanu #2, and lastly Luna.

Figure 1: Manufactured Wood Ukuleles (Makanu1, Makanu2, Luna)

3D Printed Plastic Specimens

Before producing and testing instruments with 3D printed acoustical chambers, an investigation of existing ukulele construction and layout had to first take place. A standardized CAD layout was modeled and assembled in SolidWorks based on caliper measurements and general construction of the manufactured Makanu ukuleles. An outline trace along the sidewall on both the front and back plates enabled approximation of basic upper and lower bout curvatures. For the sake of practical CAD spline fitting and symmetric idealization, only one template from the border trace was used for final matchup between top and back pieces. Once imported into SolidWorks, the template scan was scaled and one side of the outer boundary approximated with connecting spline points. This allowed reflection operation over an axis to idealize the ukulele bout shape for consistent fit between assembly pieces. While not necessarily mandatory geometry for 3D printing fabrication approaches, models included details such as internal tone bars, artificial kerfs, and back and neck blocks. Figure 2 shows basic scrap pieces from taking apart an existing wood ukulele to learn about instrument structure.

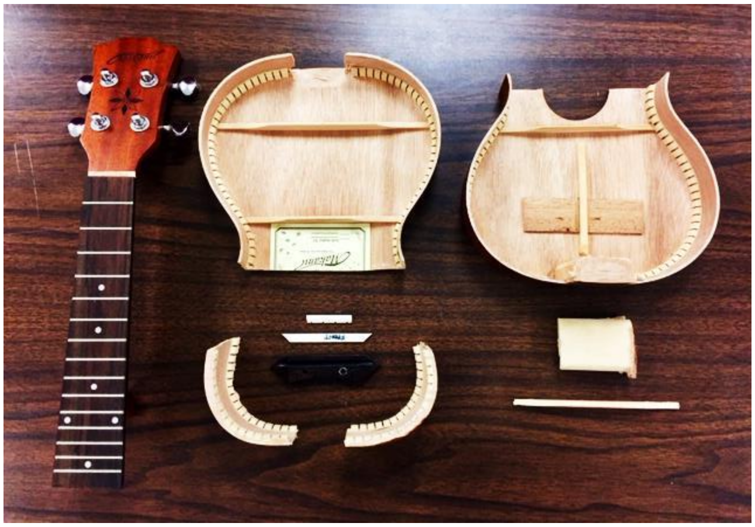

Figure 2: Makanu Ukulele Pieces Used in Measurements

Wood necks and tuning key kits were existing products used in mounting strings. Figure 3 below displays how back and front chamber pieces fit together along with nut, saddle, and bridge components from left to right, respectively.

Figure 3: 3D Print CAD Assembly Components

Cura open source slicing software was used to orient STL files and adjust print settings for GCODE machine movement. All main chambers were printed at 100% fill density using GizmoDorks filament extruded with 90% flow. This should equate to roughly 90% infill, as 100% would cause overflow and geometric fit issues. A build environment enclosure helped ensure quality prints for some of the more temperature sensitive filaments, such as ABS and HIPS. Printing pictures with the TAZ 6 machine are shown below. Figure 4 displays mid-print examples of back and sidewall and front pieces. The acrylic enclosure is featured in use with the picture on the right.

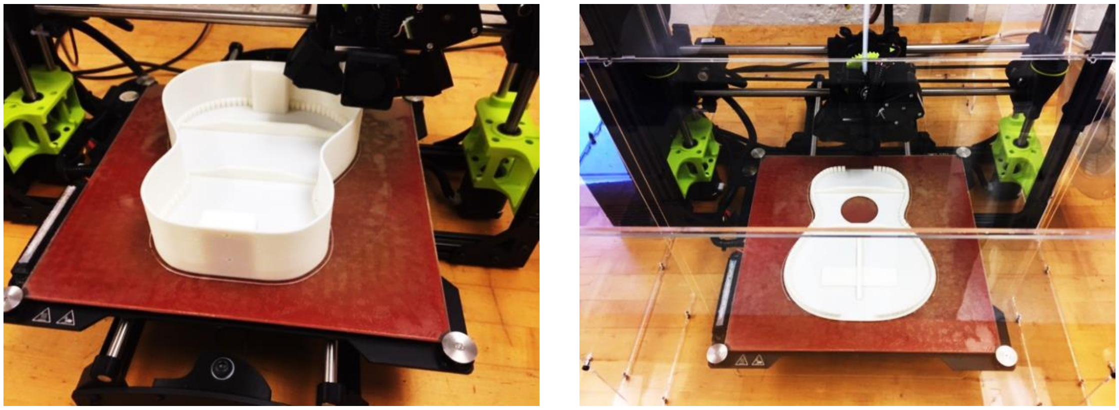

Figure 4: 3D Printing Back (left) and Front (right) Pieces of Acoustic Chambers

Extrusion temperature, bed temperature, and cooling rates were extremely important for maintaining adequate build plate adhesion. Insufficient parameter adjustment often resulted in warpage or shrinkage of the part. This became especially critical for achieving tight fit tolerances and flush assembly interfaces. See Table 1 for summary of nozzle and bed temperature print settings.

Table 1: Filament Printing Temperatures

Printing Material	Back and Sidewall Piece		Front Piece	
	Extruder Temperature (°C)	Bed Temperature (°C)	Extruder Temperature (°C)	Bed Temperature (°C)
Acrylonitrile Butadiene Styrene (ABS)	230	115	230	115
Polylactic Acid (PLA)	220	70	220	70
High Impact Styrene (HIPS)	230	120	240	110

It should be noted that there was 10 °C difference between both the extruder and bed temperature settings of HIPS assembly piece prints. This was largely due to heating adjustments to help ensure proper adhesion to build plate during printing. Two of the final chamber sidewalls also printed with slight splits along the sidewall. This was likely due to the large build plate surface area contact and high z-height layering. Cooling rates often affect how printed parts settle. To remedy splits, super glue was applied along the seamline of effected back sidewall pieces and clamped for drying. An ABS example of this is shown below in Figure 5.

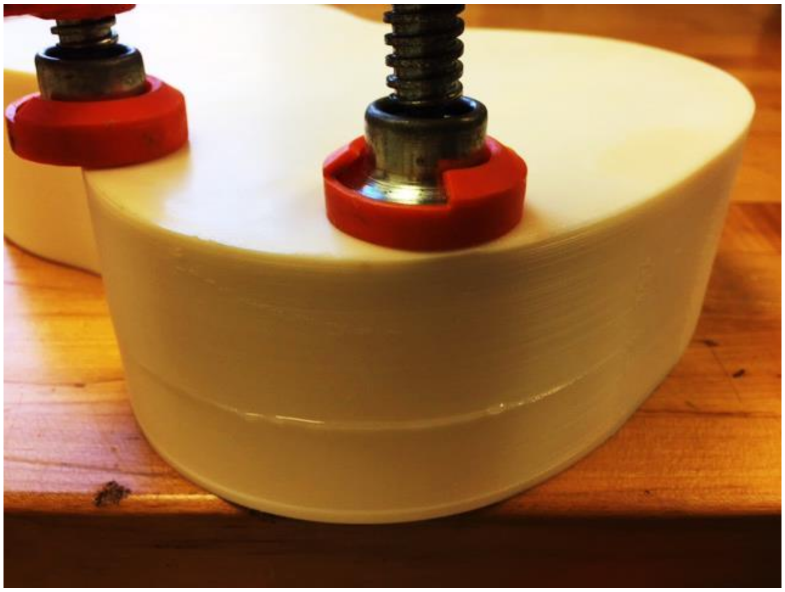

Figure 5: Ukulele Back Piece Split Repair

To standardize component material design, nut, bridge, and saddle component pieces were printed in the same orientation with HIPS material at 230 °C nozzle temperature and 120 °C bed temperature. Print fill density was 100% with 90% flow. This standardization of filament and print settings allowed focus to be on material and manufacturing process of the main acoustical resonating chamber. Picture of basic assembly plan layout is shown in Figure 6.

Figure 6: Assembly Component Layout

Predrill hole placeholders for hardware were integrated into neck block CAD design; however, hands on trials revealed practically that screw size and coarseness often split printed layers. For the final design, epoxy was used as an adhesive to mount wood neck to back chamber piece and screws were avoided altogether. Super glue was applied to tops of neck block, back block, and outer perimeter of sidewall interfacing front sound board seating. Superglue was also applied to nut, bridge, and tuning peg covers when positioning on top surfaces. Figure 7 depicts final assemblies each, strung with Aquila® New Nylgut® strings. Printed acoustical chambers are ABS, PLA, and HIPS from left to right, respectively.

Figure 7: Printed Plastic Chamber Ukulele Specimens (ABS, PLA, HIPS)

Recording Setup

Several configuration steps precluded sound testing. Figure 8 below overviews the general sound recording setup. A sturdy specimen fixture was constructed to hold each ukulele in place during testing. Stabilizing feet and interfacing points were cushioned with adhesive felt padding and an adjustable slide frame allowed the fixture mounts to fit to snuggly against the test specimen.

Figure 8: Sound Recording Setup

The microphone was suspended over the general sound hole region through use of an adjustable desk arm. Ukulele strings were marked approximately 8.6 cm away from leading edge of the saddle to denote a common pick strike location, as represented by dimension “a” and the apparatus was angled such that mic pad placement brushed roughly 8.6 cm away from the string plane, as illustrated by dimension “b.”

While not strictly hemi-anechoic, the test room did have considerable wall padding to assist with noise reduction in the environment. All recordings for the two groups were made on two separate recording days – manufactured wood ukuleles on one and 3D printed plastic specimens on the other. No filtering was done to original signals; however, individual note recording sections were normalized in Audacity® open source audio software before MATLAB analysis was conducted on samples. This was largely to adjust for the fact that manual string plucks would not result in repeatable excitation intensity, even if operator and pluck methodology were consistent across ukuleles.

The Rode Podcaster microphone was used for recordings with 18-bit capability and up to 48 kHz sampling rate. Audacity’s track management platform and normalization effect, as previously mentioned, were used to acquire signal data, prepare individual note samples, and export normalized .wav files.

Methodology

Ukuleles were tuned for standard G4, C4, E4, and A4 equal tempered scale compliance using an Intelli IMT-500 clip-on tuner. Strings were plucked with 0.73 mm Chromacast pick using an outward motion at Figure 8 point b. Each string was plucked open to avoid intonation issues. Recordings were made on mono tracks with at least five plucks per note contained in a given track.

CHAPTER III

TESTING AND ANALYSIS

Tone Metrics

As briefly described in the Introduction, efforts have used variants of frequency and time response metrics to interpret instrument sound. Three metrics will be used in this endeavor to constitute tone for the discussion of sound characteristics. Each one is further explained in the following paragraphs.

Fullness

Qualitatively, sounds tend to possess depth of noise or presence of multiple contributing sub-sounds that comprise the overall wave that propagates to the listener. While different listeners may have more or less detection or acumen to distinguishing subtleties in component sounds, relating this idea to signal analysis techniques can provide insightful comparisons for characterizing sounds produced by different musical instruments. At a basic level, tuning an ukulele involves tightened or loosening until sting tension matches pitch with a predefined note. A note, as referred to here, indicates a categorical letter designation that corresponds to a predefined fundamental frequency in its spectrum [7]. This is oftentimes also the most dominant frequency in the spectrum; however, relative dominance of this frequency will be coved more in detail when the “Strength” aspect of tone is discussed. There exists an order to frequencies such that multiples of the fundamental comprise significant amounts of the overall soundwave’s energy. These energy spikes can be identified through the use of Fast Fourier analysis. The Fast

Fourier Transform (FFT) decomposes recorded sound into constituent sinusoids via sum of sine wave mathematical approximations. From there, relative amplitudes of constituent sinusoids can be used to distinguish contributing harmonics from background recording noise. A simple count of these harmonics, including fundamental frequency, will constitute tonal “Fullness” for the scope of this research.

Sustain

While running FFT over an entire signal provides insight into what harmonic frequency components are present, plotting several frequency domain windows over time enables investigation of signal behavior as the harmonic amplitudes change. Unlike constant, continuous sinusoids, recorded ukulele sound amplitudes build, peak and wane or decay over time. This introduces an important aspect of signal analysis – transient behavior. Without consideration for time, frequency metrics simply lack full meaning in sound characterization.

Since the lowest harmonic is ultimately the frequency benchmark tuning objective, its behavior over time seems essential to interpreting how long an instrument sustains desired pitch. The time an exponential curve fit of the fundamental frequency decay data takes to reach 1/e of the peak value will constitute “Sustain” for the scope of this paper. Equation 1 below shows exponential curve fitting relationship, where f(t) represents the function with respect to time, a and b are fit coefficients, and t represents time. Equations 2 and 3 further demonstrate how this relationship is used to find decay time properties, where Ap indicates peak amplitude and td denotes decay time.

$$f(t) = ae^{bt} \tag{1}$$

$$A_p = f(0) = a \tag{2}$$

$$t_d = \frac{l\,n\left(\frac{A_p}{ae}\right)}{b} = -\frac{1}{b} \tag{3}$$

Strength

As already alluded to, multiple harmonic frequencies can simultaneously exist, all contributing toward the overall sound produced by a musical instrument. The sound energy is therefore spread across different frequencies and the exact distribution can vary from instrument to instrument. While the relative magnitudes of harmonic multiples could indicate some degree of the constituent makeup of sound, the fundamental frequency is considered the primary pitch parameter of interest, continuing logic from definition of Sustain. The ratio between the fundamental amplitude and overall contributing harmonic amplitudes should therefore provide insight into relative strength of each note's pitch at a critical time value. Since Ap/e has already been established as the decay point, the instant in time represents not only a benchmark for fundamental decay, but also a logical checkpoint for relative amplitude comparison. As mentioned earlier, Ramsey and Pomian have already used the tactic of comparing relative harmonic intensities as overall percentages. Applying this notion to respective curve fits at a specific point in time allows component contributions to be realized in light of decay characteristics.

Analysis

As stated earlier, recordings were made for each open string tuned for G4, C4, E4, and A4. Recordings consisted of multiple string plucks at various intervals on separate mono tracks for each string; however, signals were divided and normalized in Audacity, resulting in at least five .wav note pluck sound samples for each ukulele string. These samples could then be imported and analyzed separately.

MATLAB R2016b was used for signal analysis. Before visualizing sound features, though, individual samples were inspected for a basic noise level. This consisted of using Fast Fourier analysis over some 1 s portion of 48 kHz sampling rate signal (either before transient attack or after visual decay) to find a general room noise level for when the recording was made. The maximum amplitude was stored for later use in identifying significant contributing harmonic frequencies. Figure 9 below depicts example normalized signal.

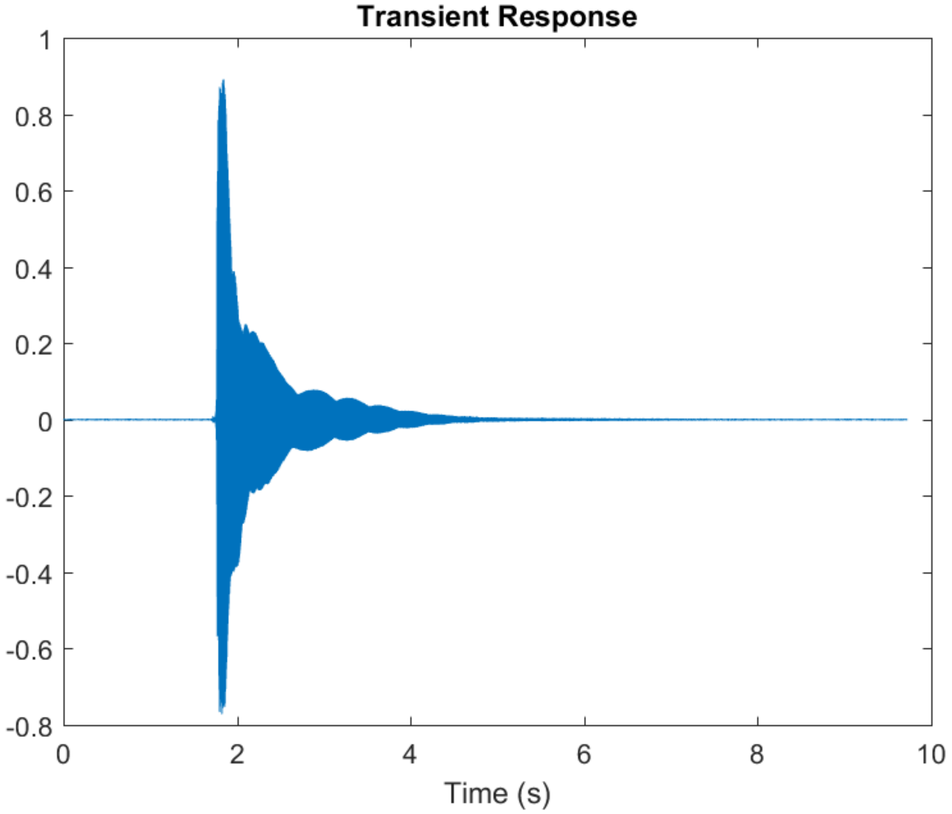

Figure 9: Normalized Signal of Makanu1 C4 String

Once a noise level was determined, the signal was further trimmed to 5 s. Figure 10 shows example processed 5 s .wav signal window of recording.

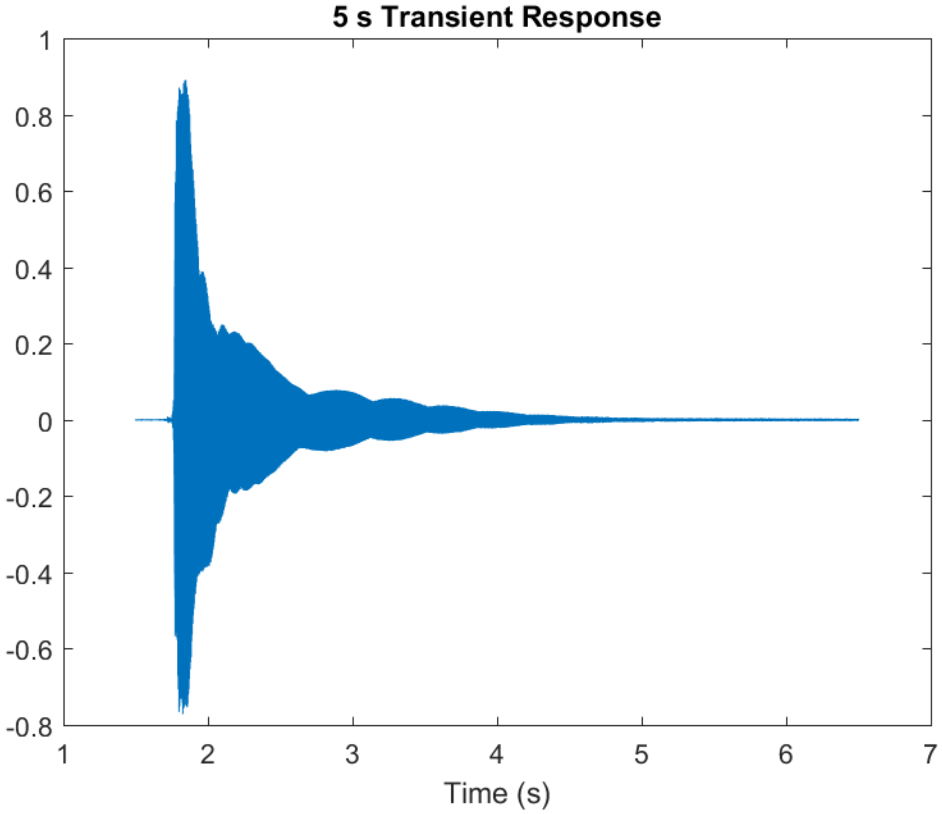

Figure 10: Trimmed 5 s Time Response Sample of Makanu1 C4 String

From there, the MATLAB FFT functionality was used yet again. This time, it was run over the entire 5 s signal to identify fundamental and harmonic frequency peaks. In order to locate fundamental frequency, MATLAB was coded to prompt for an ideal note pitch and search positive FFT coefficients (hereafter referred to as relative amplitudes) for a maximum within ±50 Hz of the user-defined value. These user-defined frequencies corresponded to equal tempered scale pitch values of 392.00 Hz, 261.63 Hz, 329.00 Hz and 440.00 Hz for G4, C4, E4, and A4 notes, respectively. Once the fundamental was identified, the code progressively checked integer multiples of fundamental frequency for significantly contributing harmonics (indicated by dashed red lines in Figure 11). Actual maximum relative amplitudes within ±50 Hz of anticipated frequencies were identified as harmonics, as denoted by blue circles. A simple count of these identified frequencies (including fundamental) was outputted as number of harmonics for a given sample.

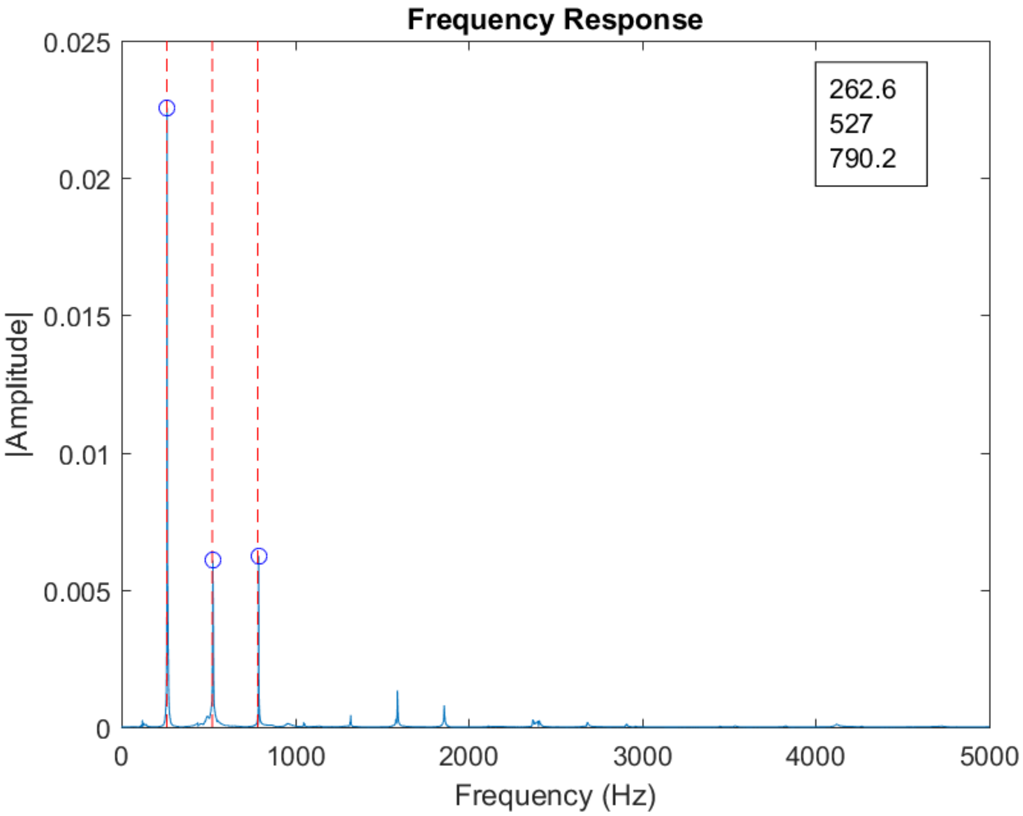

Figure 11: Example FFT Analysis Identifying Harmonic Peaks

Notice from plotting frequencies that only three harmonics are identified, while several substantially tall peaks exist. This is due to small peak value occurring at the third harmonic from fundamental frequency. Figure **12** below shows relative amplitude near anticipated harmonic frequency.

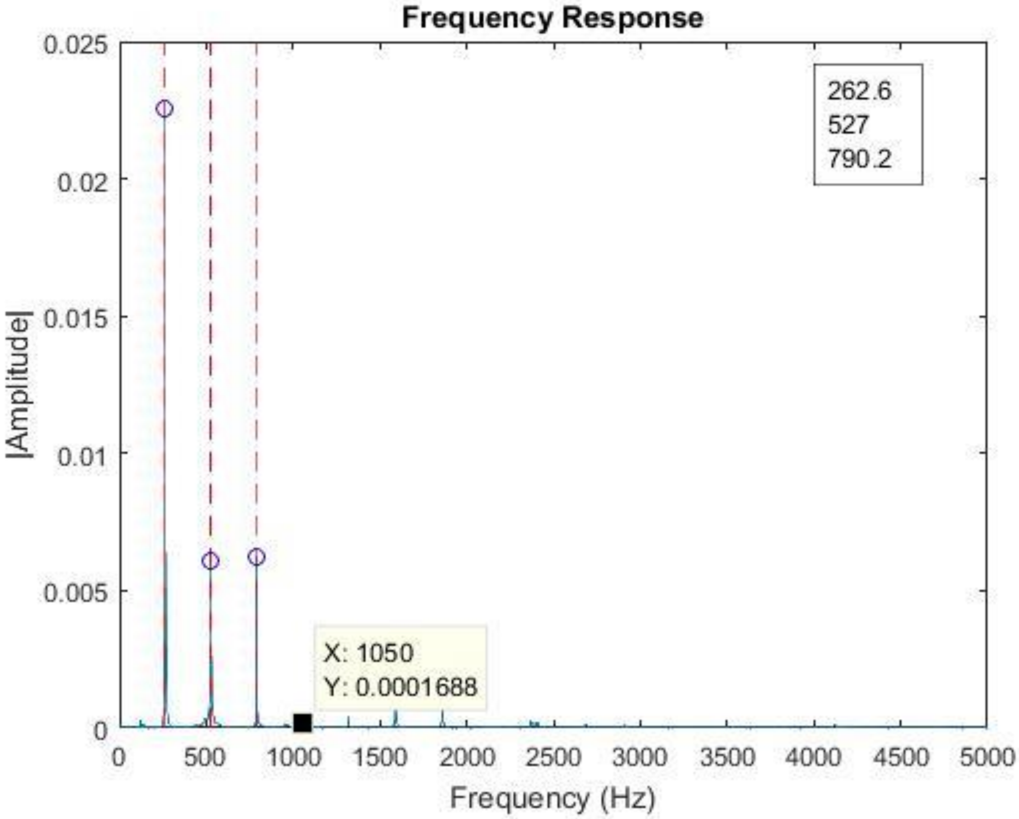

Figure 12: Harmonic Frequency of Makanu1 C4 String - Low Intermediary Value

For this particular code run, FFT over the first 1 s of normalized transient data resulted in a noise floor of approximately 0.000275. The third harmonic following fundamental frequency (ideally, 4 x 262.6 Hz = 1050.4 Hz) showed peak value well under threshold relative amplitude. This halted further looping for significantly contributing harmonics. Figure **13** shows another note case (Makanu1 A4) where harmonic frequency scanning continued past the third harmonic.

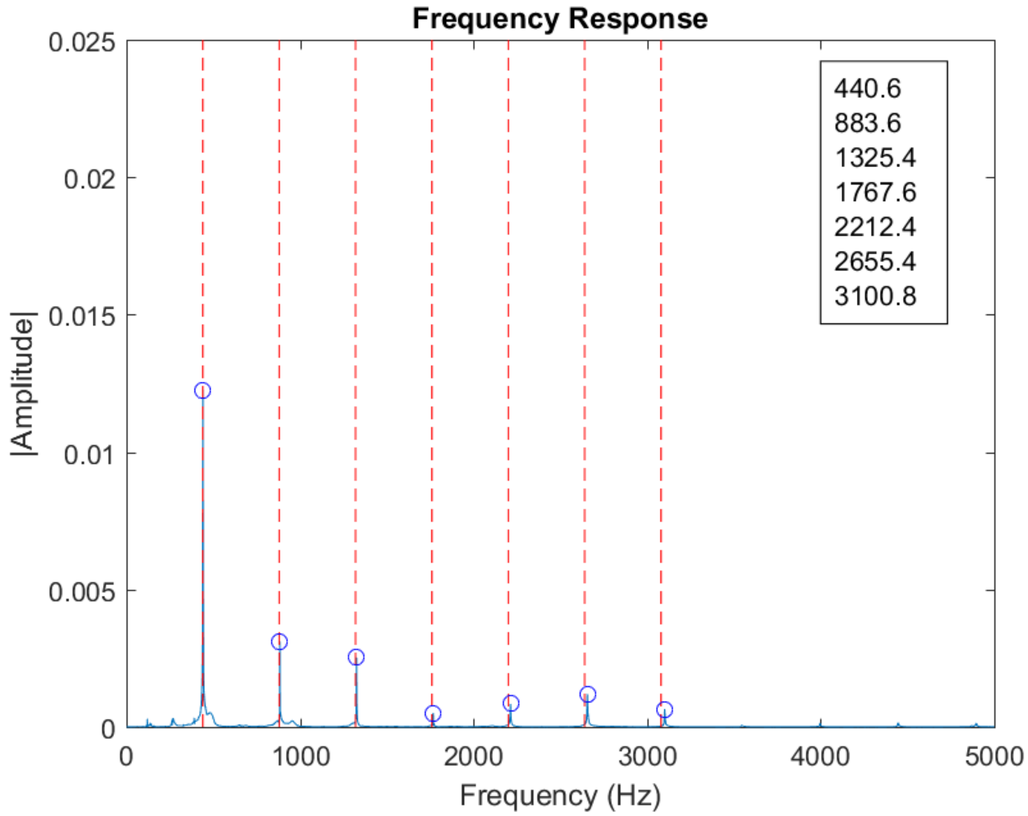

Figure 13: Single Sided FFT of Makanu1 A4 String - Large Intermediary Values

Modification for such cases in future endeavors could allow scanning of harmonics up to human hearing extent (approximately 20 kHz) regardless of low relative amplitudes in the middle; nonetheless, existing results still demonstrate use of number of harmonics as a metric of Fullness and further examine frequency contributions within signal behavior.

Once fundamental and harmonic frequencies were identified, spectrogram functionality was introduced to window the data and visualize relative amplitude decays over time (see Figure 14). The MATLAB spectrogram function was used with overlapping Hamming windows to realize data overall frequency band decay.

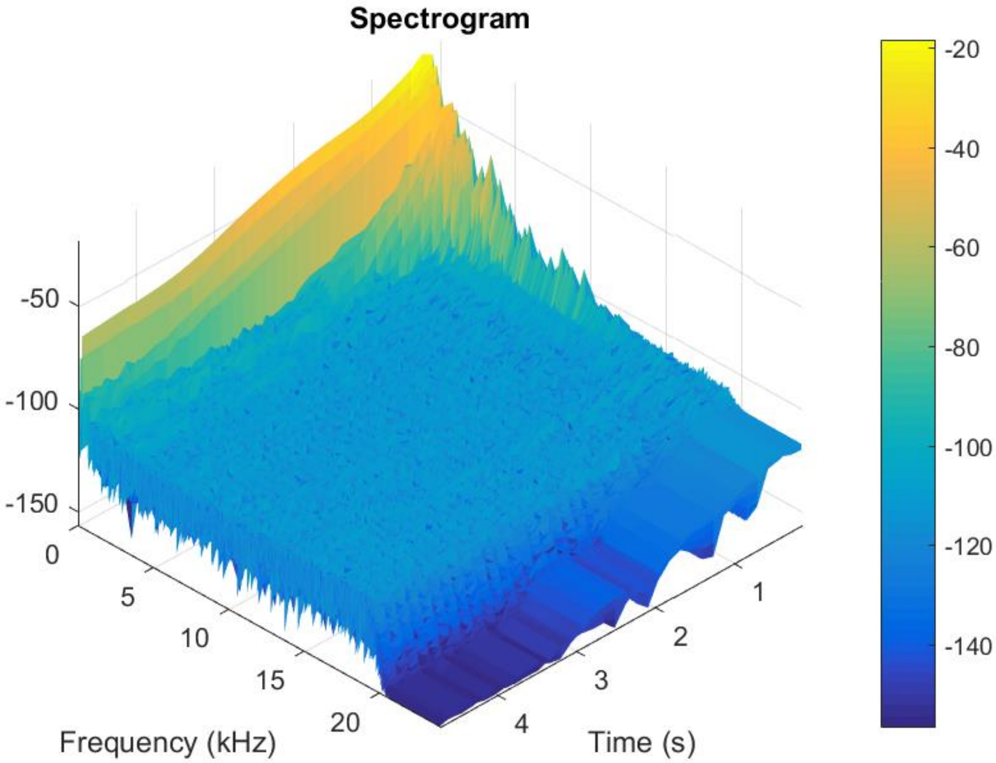

Figure 14: Spectrogram of Makanu1 C4 String

From there, fundamental and harmonics frequencies were extracted specifically and plotted in 2D for exponential curve fitting. First, the fundamental frequency was curve fitted over time using MATLAB exponential functionality with 95% confidence bounds and solved for both Ap and td from Equations 2-3 (indicated by blue circle in

Figure 15). The time corresponding to td was outputted as decay time for a given signal.

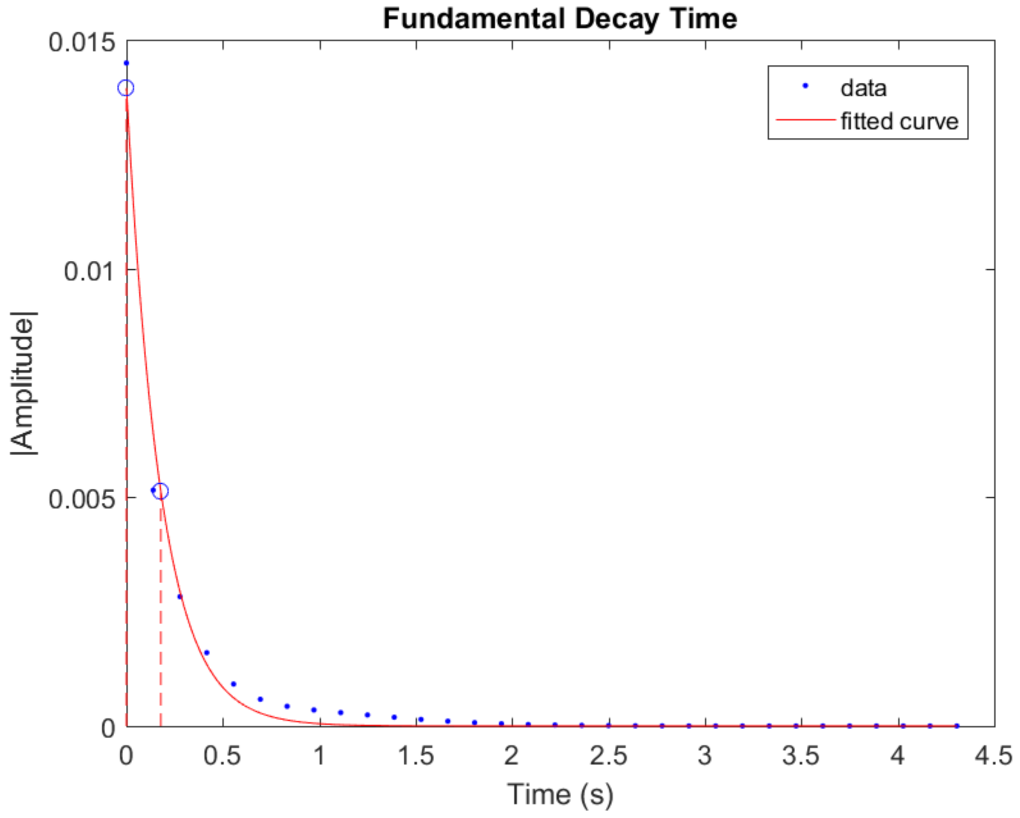

Figure 15: Fundamental Frequency Curve Fit Decay Time

Once decay time was determined (denoted by dashed red line), the other contributing harmonics could also be plotted, curve fitted, and solved for their respective values (indicated by blue asterisks) at that same transient time of interest. Figure 16 below displays identified harmonic frequency curve fits and points with respect to fundamental decay time.

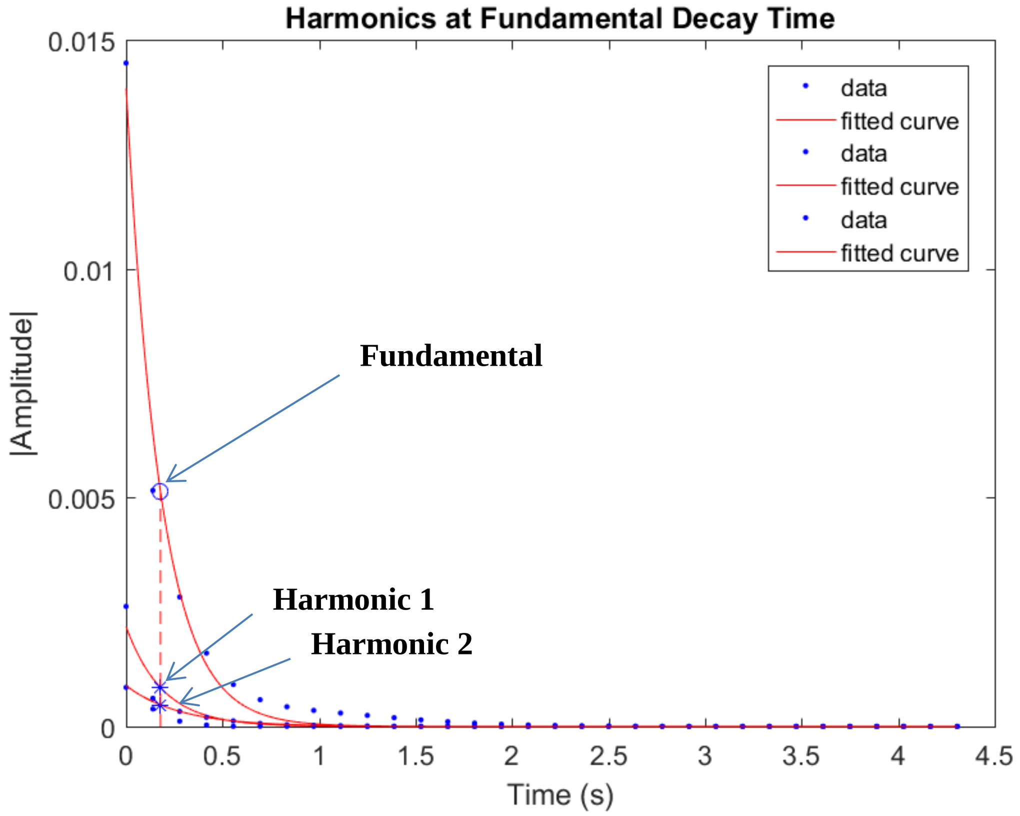

Figure 16: Harmonic Frequency Curve Fits at Decay time

Fundamental and harmonic relative amplitudes at decay time were compared as a measure of strength for a given signal. Each relative amplitude was divided by sum of constituent relative amplitudes and their percentages were visualized through pie chart slices. Figure 17 shows overall pie chart slices between members. The fundamental frequency’s pie chart ratio was outputted as percent fundamental for a given signal.

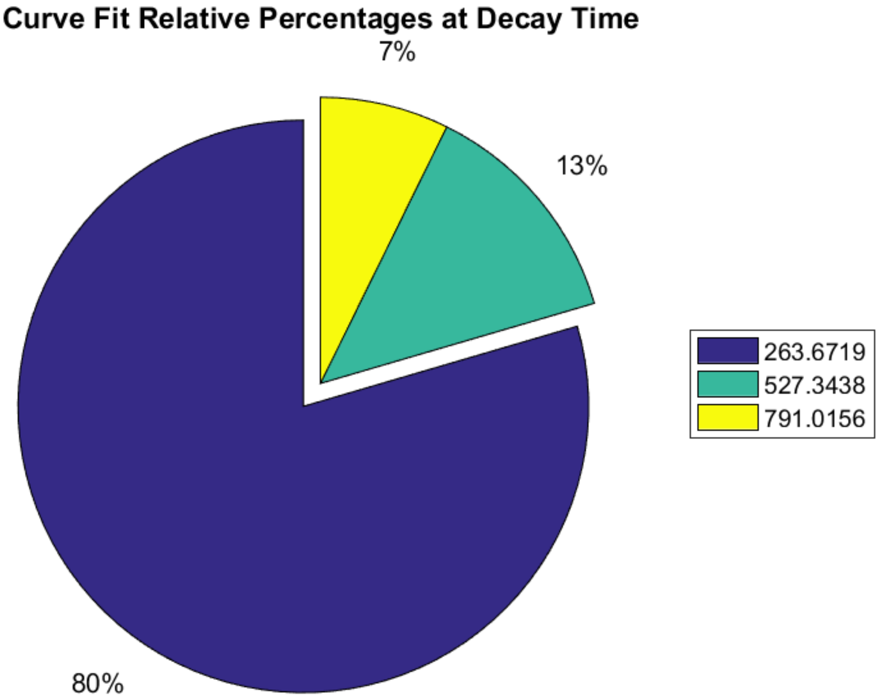

Figure 17: Harmonic Relative Amplitude Comparison at Decay Time

CHAPTER IV

RESULTS AND DISCUSSION

After running the sounds through the series of before mentioned MATLAB code analytics, the following results were obtained pertaining to each of the three described tone metrics. In order to more thoroughly investigate 3D printed plastic chambers sounds with consideration for machined wood ukuleles', traditional wood tone metric results will be discussed first, followed by printed filament performance, and lastly an inter-group comparison. Bar charts are shown with standard deviations. The order is arranged such that note tuning frequency increases from left to right. Bar chart error bars represent individual standard deviation.

Traditional Wood Results

Fullness

Recall that fullness, as a metric, refers to a count of harmonics contributing toward the overall sound. Upon running MATLAB analysis, it was found that considerable variance existed among sample readings. See standard deviation bars on average number of harmonics in Figure 18 below.

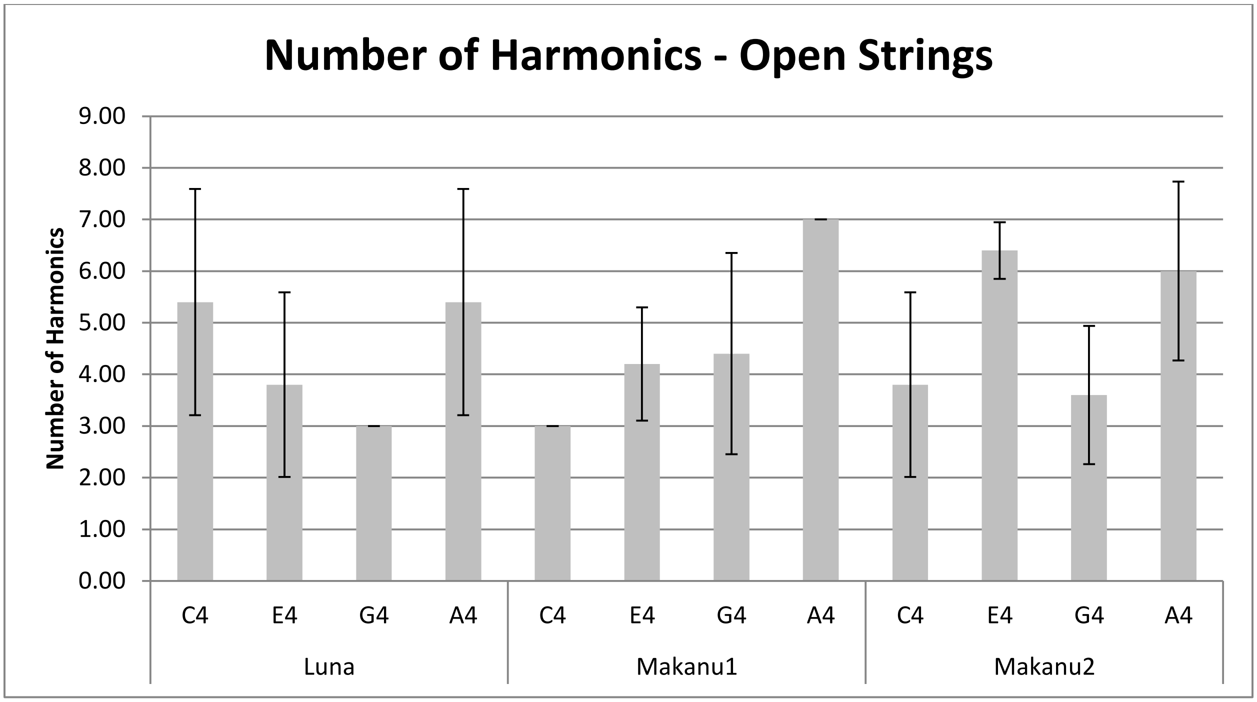

Figure 18: Traditional Wood Fullness Metric - Overall Comparison

This makes definitive differences rather difficult to infer, at least among traditional wood ukulele sound sample averages. There are several potential reasons for this relatively large spread among data points collected, but the foremost is likely the nature of the approach used to identify harmonics in the signal. Recall from earlier discussion that harmonic frequencies are found with respect to an individual noise floor for each sample. This means that if the room was particularly noisy, or outside disturbances besides pick strikes occurred during recording, they could have raised the noise floor. This could lessen the distinction of harmonic peak heights above the threshold and, in some cases, potentially even cause the code to gloss over a contributing harmonic. If an intermediate harmonic displayed relative amplitude below threshold identification, the code would stop scanning at the non-qualifying frequency multiple; only prior harmonics would get considered in Fullness count. Practical ways to potentially improve use of this metric in future endeavors would be adjustment so that scanning continues past . Ways to assist with identification could include quieter recording environment, cautious filtering, or a larger sample base to try and improve consistency in readings and ultimately reduce standard deviation among average values. On the opposite side of things, note categories with no standard deviation (i.e. Luna G4 and Makanu1 C4) make running 2-sided t-tests neither feasible nor practical overall for this metric data.

Sustain

Sustain is tied closely to understanding behavior of the fundamental frequency. This metric focuses in specifically on its decay with time. Average decay time values across the four ukulele strings are displayed in chart form in Figure 19.

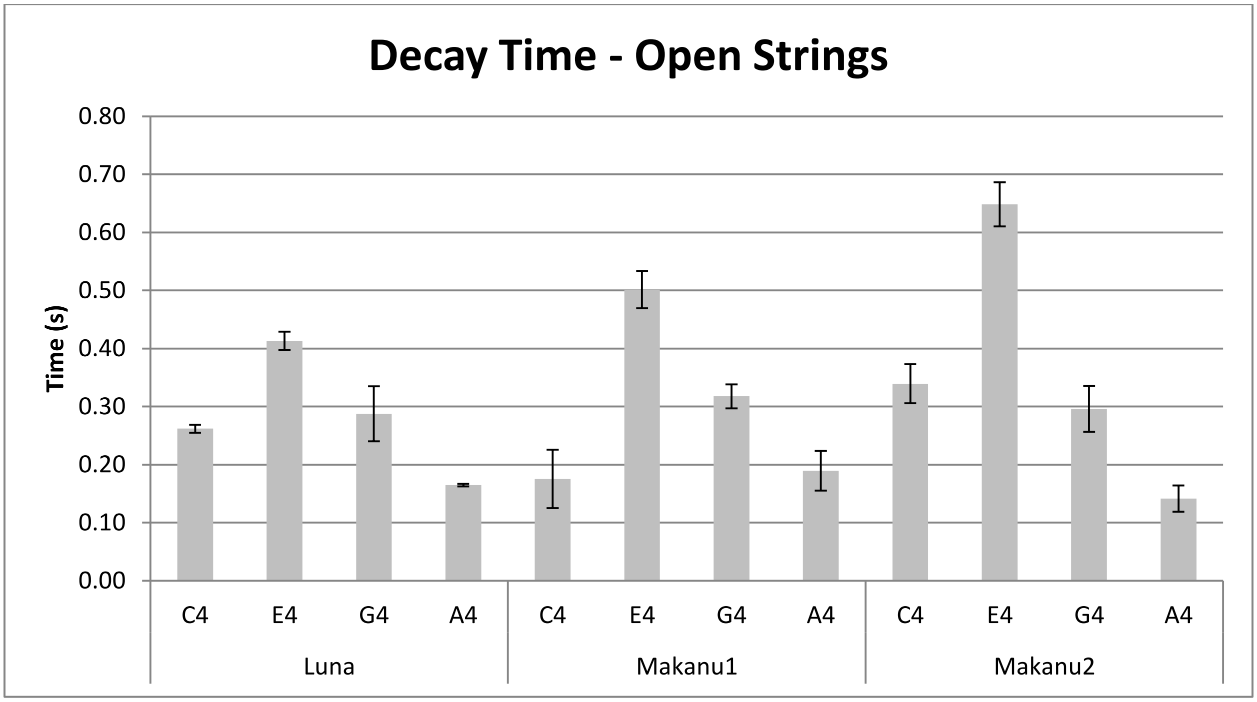

Figure 19: Traditional Wood Sustain Metric - Overall Comparison

Beyond visual inspection, statistics are shown below to better appreciate individual note comparisons between ukuleles. Two-sided t-tests were run in Minitab 7 at 95% confidence interval, not assuming equal variance. Results are summarized in Table 2. Running different combinations of this sample mean comparison technique allowed each pair of ukulele note data sets to be compared with methodology for interpreting results.

Table 2: Traditional Wood Decay Time Statistic (t-test p-values)

Note	Decay Time (p-value)		
	Luna vs. Makanu1	Luna vs. Makanu2	Makanu1 vs. Makanu2
C4	0.021	0.007	0.001
E4	0.691	0.452	0.310
G4	0.249	0.787	0.337
A4	0.776	0.034	0.103

The primary benefit of using this approach is that p-values under 0.05 at the 95% confidence interval imply significant difference between compared sample groups. Interestingly, each combination shows significant difference in the C4 string category. What is more, Makanu2 shows further sign of distinction from Luna with a p-value of 0.034 in the A4 string category.

Besides individual note comparisons, there is potential for somewhat of an apparent pattern in increment and decrement shifts among traditional wood ukulele string decay times. The Luna and each of the Makanu specimens increased noticeably from C4 to E4 and then stair stepped down to A4. In considering possible reasons for this, the influence of string size was explored. Ukulele strings come in assorted gages, depending on the tuning frequency, and sizing differences could contribute toward individual string sustain. To further investigate this, string measurements were taken with micrometers. A summary of results for five string sets is shown in Table 3.

Table 3: Ukulele String Diameters

String	AVG Diameter (mm)	STDEV Diameter (mm)
A4	0.588	0.0053
G4	0.636	0.0116
E4	0.773	0.0137
C4	0.941	0.0108

Figure 20 shows a rearranged version of decay time bar chart data. This represents both the order of decreasing tuning frequency and increasing string diameter.

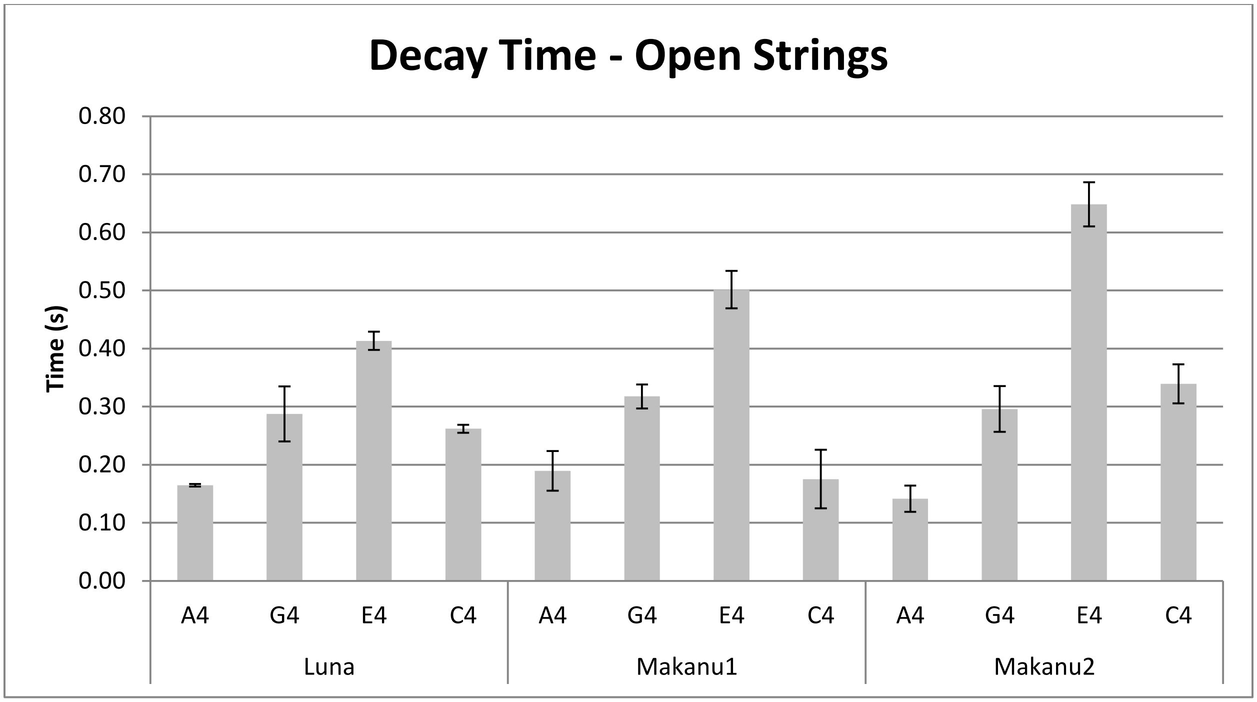

Figure 20: Traditional Wood Sustain Metric - Overall Comparison (String Size Order)

This reordering only mirrored the trend and did not completely answer pattern particularities such as the prominent peak at E4 and lower value at C4. It makes intuitive sense, however, that thicker and looser tensioned strings should generally vibrate longer with less amplitude and projection than high pitch frequencies. Aspects of instrument design such as string-structure interplay, soundboard resonant frequencies, and material properties could all affect these characteristics.

Strength

Strength, as an analytical tone metric, refers to relative deficit or dominance of fundamental when compared to identified harmonics in a signal. This should convey relative intensity of the objective tuning pitch. Figure 21 below summarizes percent fundamental for each of the strings.

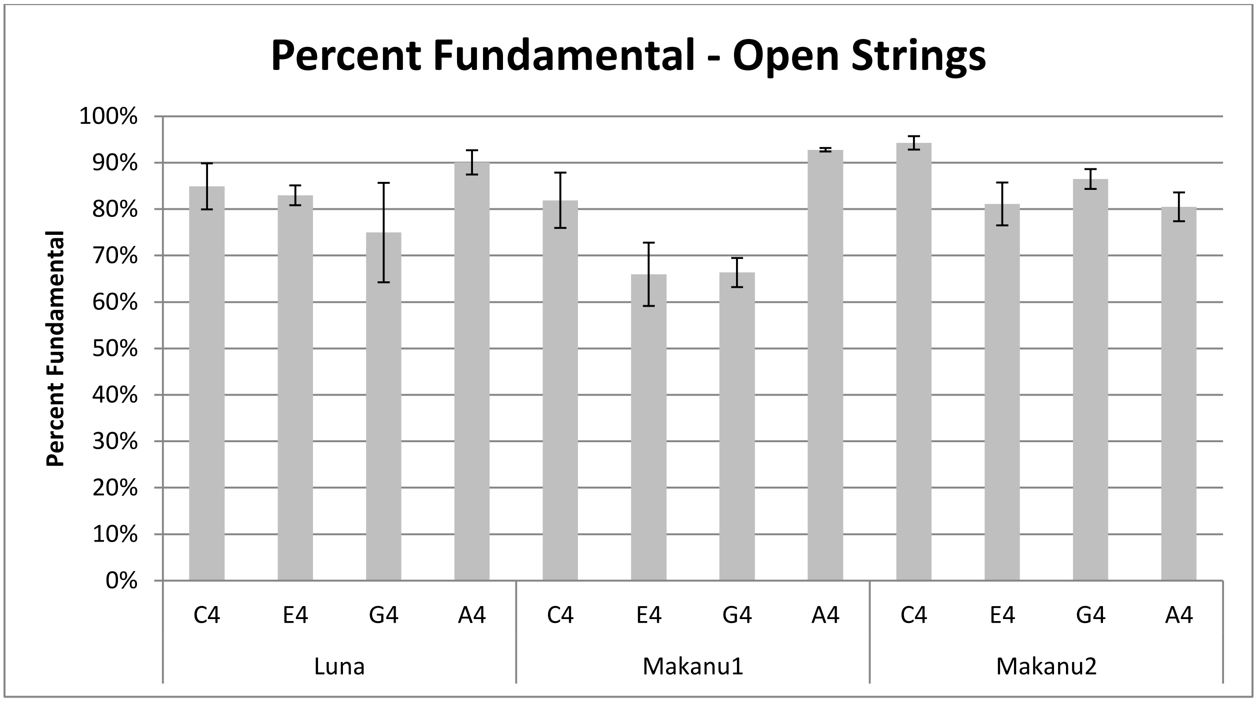

Figure 21: Traditional Wood Strength Metric - Overall Comparison

At first look, there does not seem to exist a standard pattern for relative levels, even among ukuleles of the same make and model. Ironically, the two Makanu ukuleles actually showed more note categories of statistical difference than Luna comparisons. Table 4 below displays p-values corresponding to each ukulele combination.

Table 4: Traditional Wood Percent Fundamental Statistic (t-test p-values)

Note	Percent Fundamental (p-value)		
	Luna vs. Makanu1	Luna vs. Makanu2	Makanu1 vs. Makanu2
C4	0.413	0.013	0.010

E4	0.452	0.177	0.056
G4	0.168	0.075	0.000
A4	0.005	0.019	0.000

Makanu1-Makanu2 comparison resulted in C4, G4, and A4 all under the 0.05 threshold with p-values of 0.010, 0.000, and 0.000, respectively. Both Luna comparisons rendered p-values under 0.05 for A4 strings and an additional C4 category when contrasted with Makanu2.

3D Printed Plastic Results

Directing attention toward printed plastic chamber sound comparisons, code for each of the previously mentioned tone metrics was also run for 3D printed specimens.

Fullness

An overview of the fullness metric performance is shown below in Figure 22.

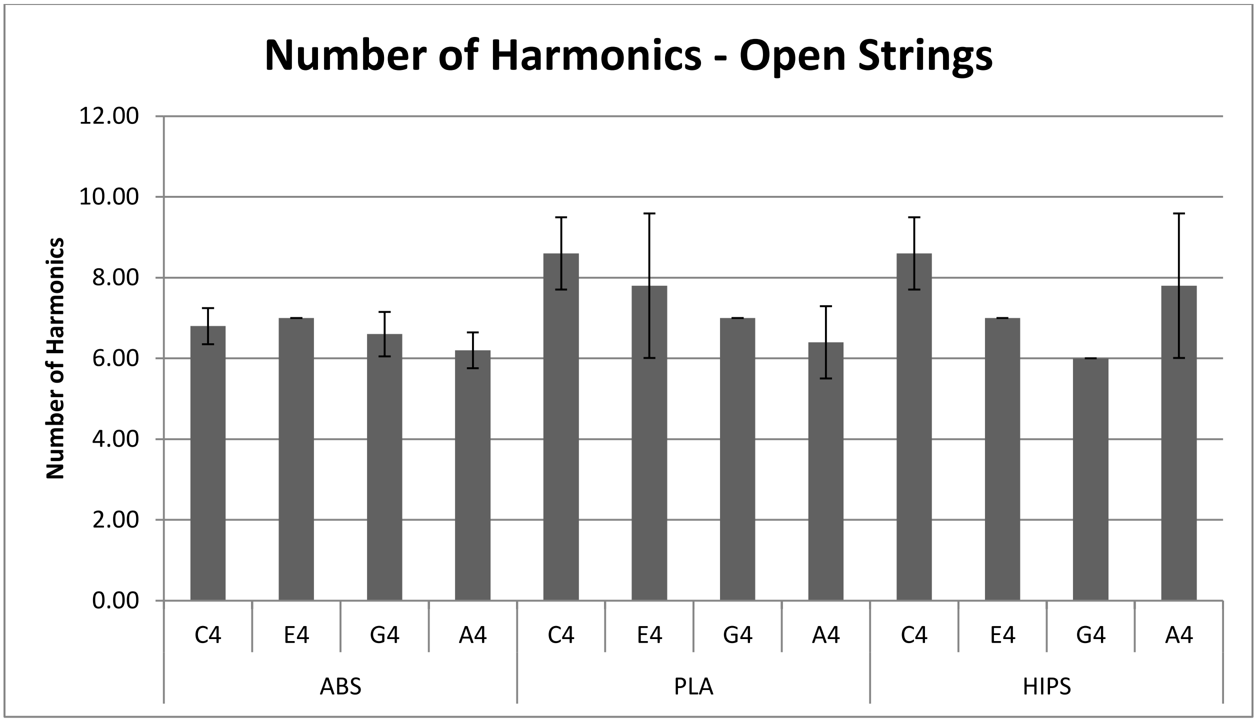

Figure 22: 3D Printed Plastic Fullness Metric - Overall Comparison

Considering standard deviation overlaps and general spread from 6-8 harmonics, additional specimen or sample reference seems important for inferring strong tone implications. Further conclusions will be drawn in later comparison with traditional wood counts. Note categories with no standard deviation (i.e. ABS E4 and HIPS G4) make running 2-sided t-tests simply not feasible for the metric.

Sustain

The sustain metric produced several interesting results. An overview chart is shown below in Figure 23.

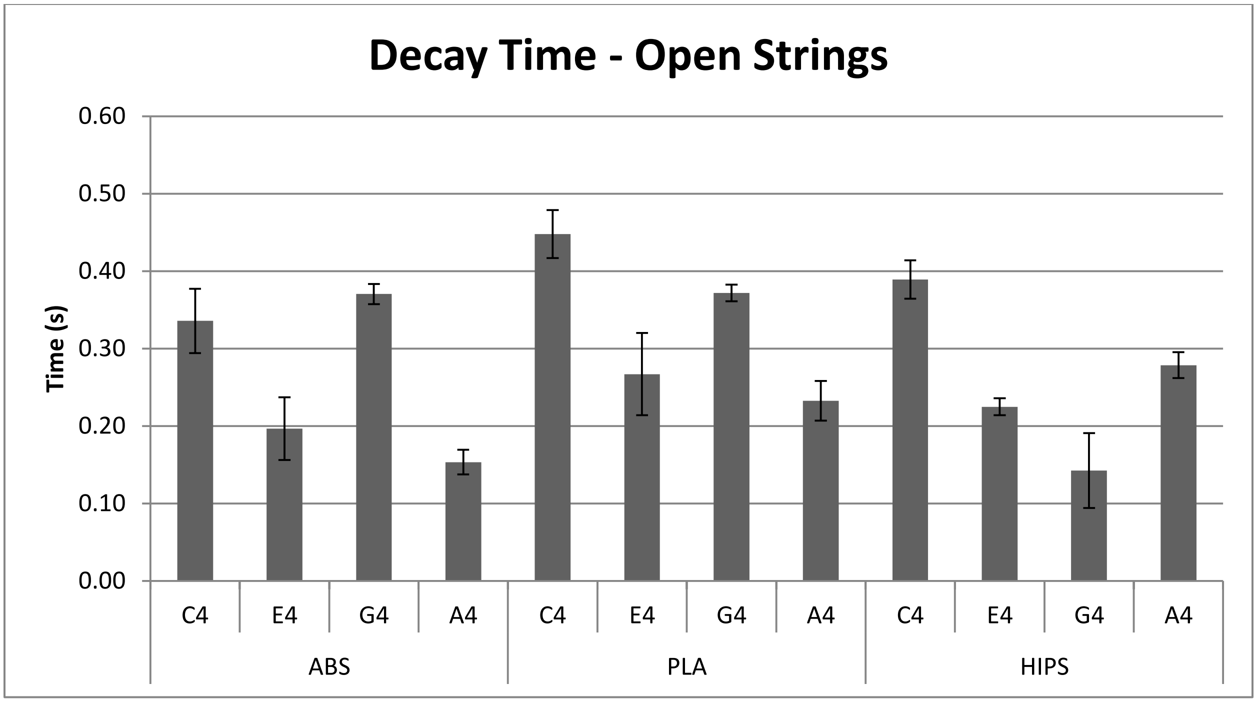

Figure 23: 3D Printed Plastic Sustain Metric - Overall Comparison

Though not the same tendency as traditional wood instrument sounds, another potential pattern is apparent from ABS and PLA increments and decrements. Both of them drop from C4 to E4 and then increase and drop again from G4 to A4. HIPS, however, does not continue with this, but rather bookends the frequency range with longer sustains at C4 and A4. Statistical p-value results also resulted in multiple note categories of significant difference, especially comparisons with HIPS (see Table 5 below).

Table 5: 3D Printed Plastic Decay Time Statistic (t-test p-values)

Note	Decay Time (p-value)		
	ABS vs. PLA	ABS vs. HIPS	PLA vs. HIPS

C4	0.002	0.048	0.013
E4	0.051	0.206	0.158
G4	0.857	0.001	0.000
A4	0.001	0.000	0.015

Both ABS-HIPS and PLA-HIPS t-tests revealed p-values under 0.05 in C4, G4, and A4 notes. Furthermore, ABS-PLA interactions resulted in p-values under 0.05 in C4 and A4 string categories.

Strength

Alluding to relative amplitude comparison of the fundamental frequency to harmonics at decay time, the Strength tone metric represents not only frequency components present in the signal, but also some degree of their longevity with time. 3D printed plastic chamber results are shown below in Figure 24.

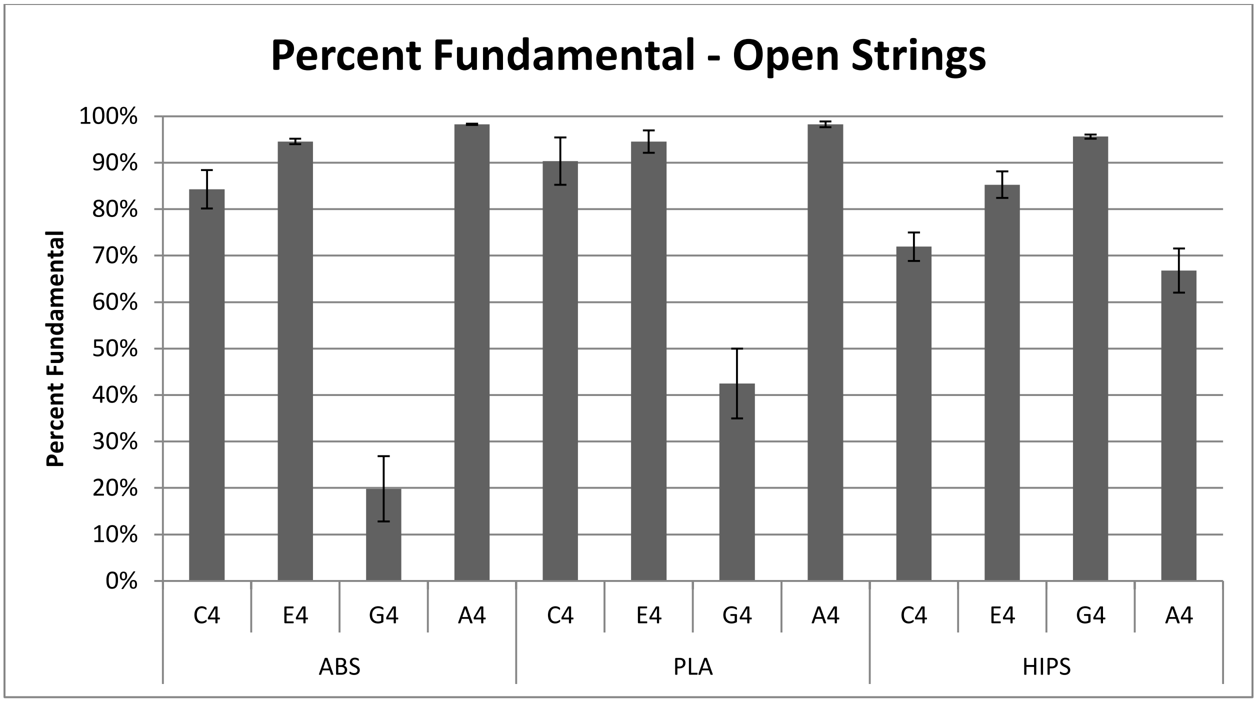

Figure 24: 3D Printed Plastic Strength Metric - Overall Comparison

Right away, an obvious deficit occurs at the G4 note for both ABS and PLA. A closer look at individual diagnostics reveals that all samples used for the above chart averages demonstrated higher overall percentage of the first harmonic following the fundamental frequency. Figure 25 demonstrates the nature of this anomaly.

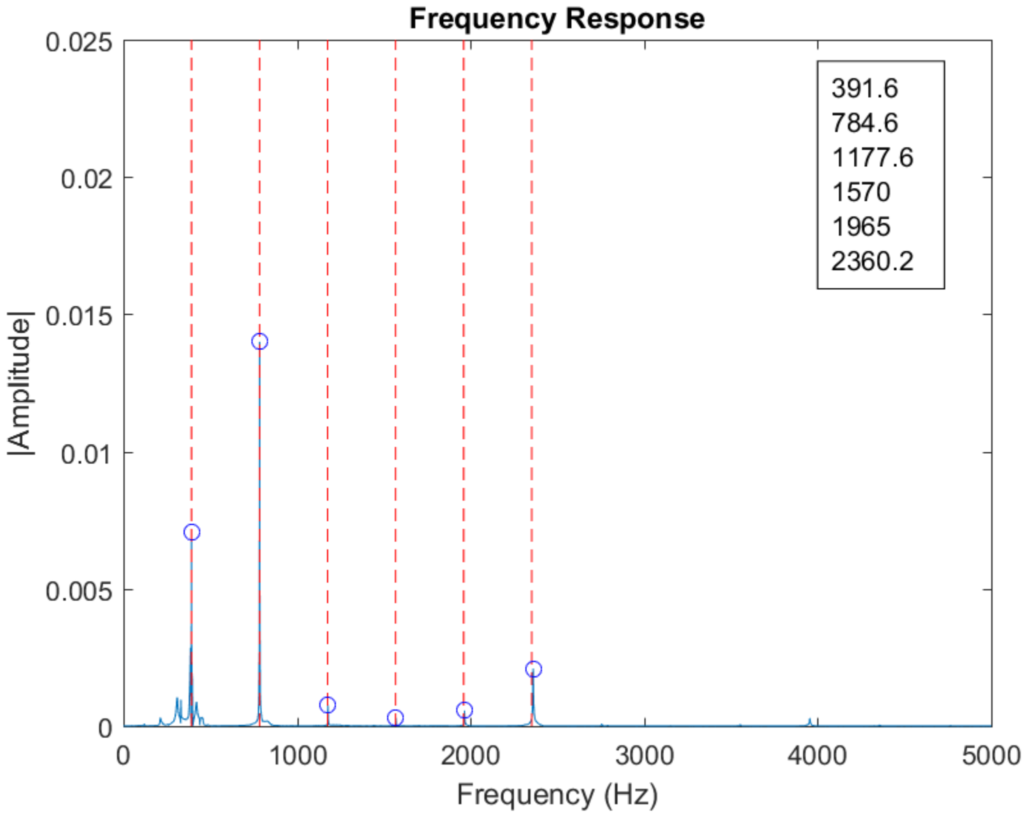

Figure 25: Example G4 Harmonic Relative Amplitude Anomaly (ABS)

Interestingly, a similar tendency occurred in Ramsey and Pomian’s instrument investigation – also with the G4 string [6]. This might have something to do with instrument vibration characteristic’s interplay with string vibration. Somewhat of a coupling effect occurs between the two, resulting in an overall amplified sound. Future work with Chaldni patterns or other such resonance recognition methodology might assist with examining root causes. Statistical note comparisons are shown below in Table 6.

Table 6: 3D Printed Plastic Percent Fundamental Statistic (t-test p-values)

Note	Percent Fundamental (p-value)		
	ABS vs. PLA	ABS vs. HIPS	PLA vs. HIPS
C4	0.076	0.001	0.000
E4	0.999	0.002	0.001
G4	0.002	0.000	0.000
A4	0.961	0.000	0.000

Most notably, HIPS shows reinforced difference from the other two filaments using Strength as a tone metric. For both ABS and PLA comparisons with HIPS, every note category resulted in p-value under 0.05. While not as widespread apparent across the tested frequency range, ABS-PLA t-testing still resulted in a p-value of 0.002 for the G4 note.

Comparison Results

Now, considering results from both traditional wood and 3D printed specimens, an inter-group comparison should reveal subtleties with context for the two. Recall from CHAPTER II SPECIMEN AND TESTING that 3D printed CAD design was inferred from the two Makanu ukuleles – Makanu1 especially, as it was taken apart for internal caliper measurements. Makanu1 will therefore serve as statistical baseline for t-testing; however, Makanu2 will appear additionally in bar charts to visual reinforce any potential manufactured wood patterns.

Fullness

Figure 26 below shows analytical averages for the tone fullness metric.

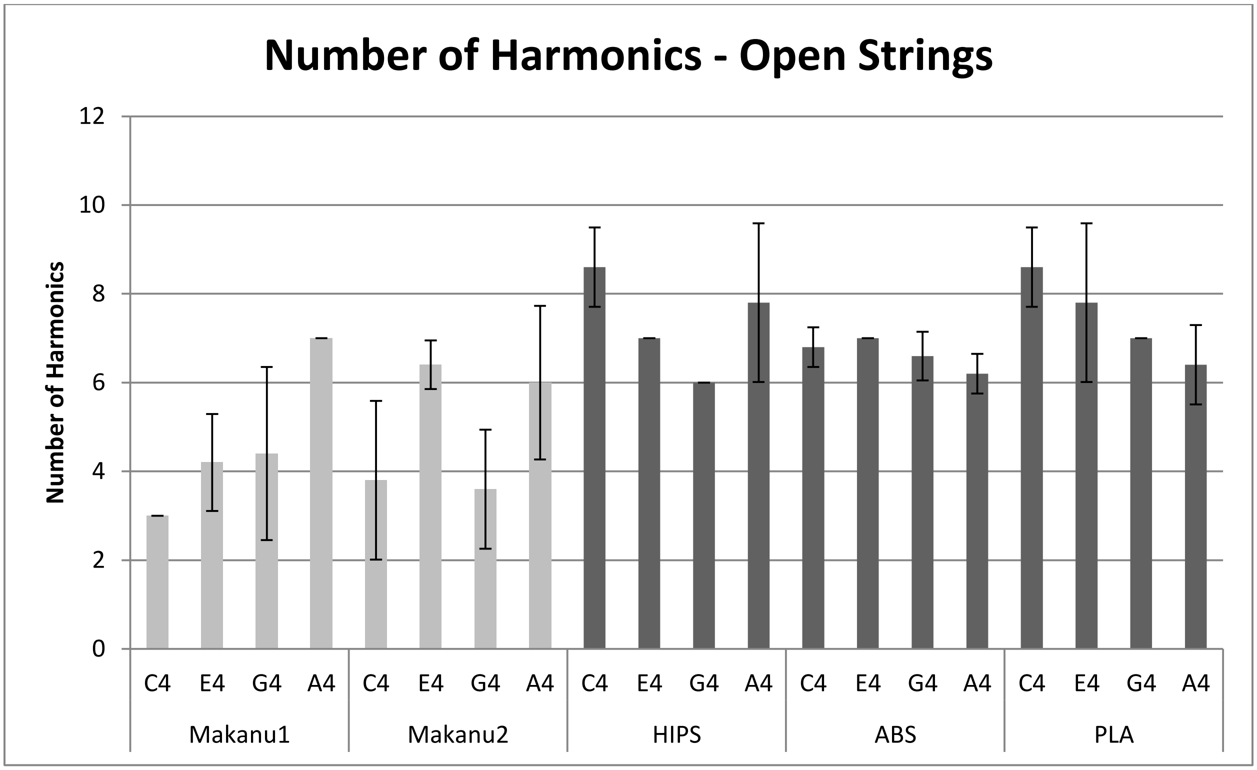

Figure 26: Baseline Comparison Fullness Metric - Overall Comparison

At first glance, standard deviations appear relatively large for the manufactured wood group with potential overlap between notes of wood and printed plastic ukulele sounds; however, even with relatively large variation in means, the wood group appears somewhat lower overall. Generally, numbers range from 3-7 for Makanu ukuleles and 6-9 for 3D printed filament specimens. Furthermore, the C4 note shows especially visual difference between the two groups (Figure 27) with average number of harmonics down as low as 3 for Makanu1 contrasted by printed plastic sound averages all over 6.

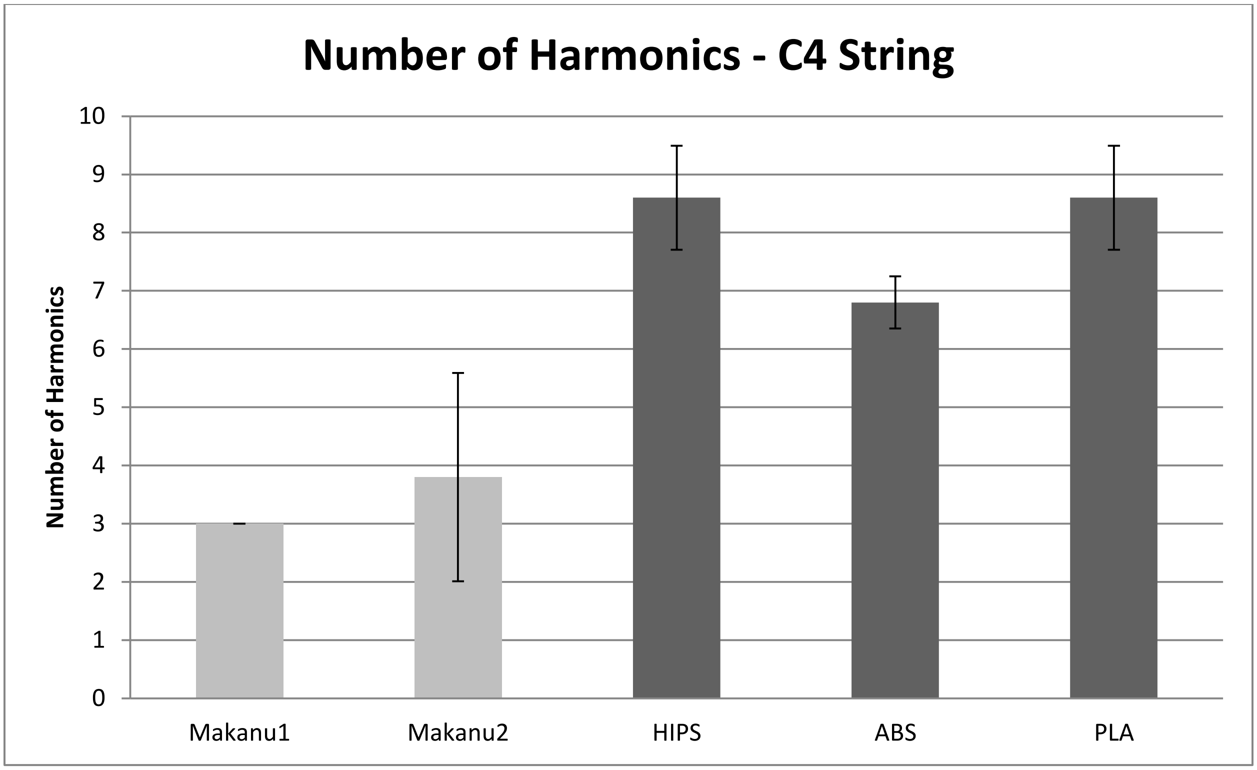

Figure 27: Baseline Comparison Fullness Metric - Extreme Case

Sustain

Looking at decay times of each note separately among specimens, there are apparent visual differences between the manufactured wood group and 3D printed plastic group. Figure 28 below displays note categories for each of the 3D printed plastic chambers side-by-side with Makanu manufactured wood averages.

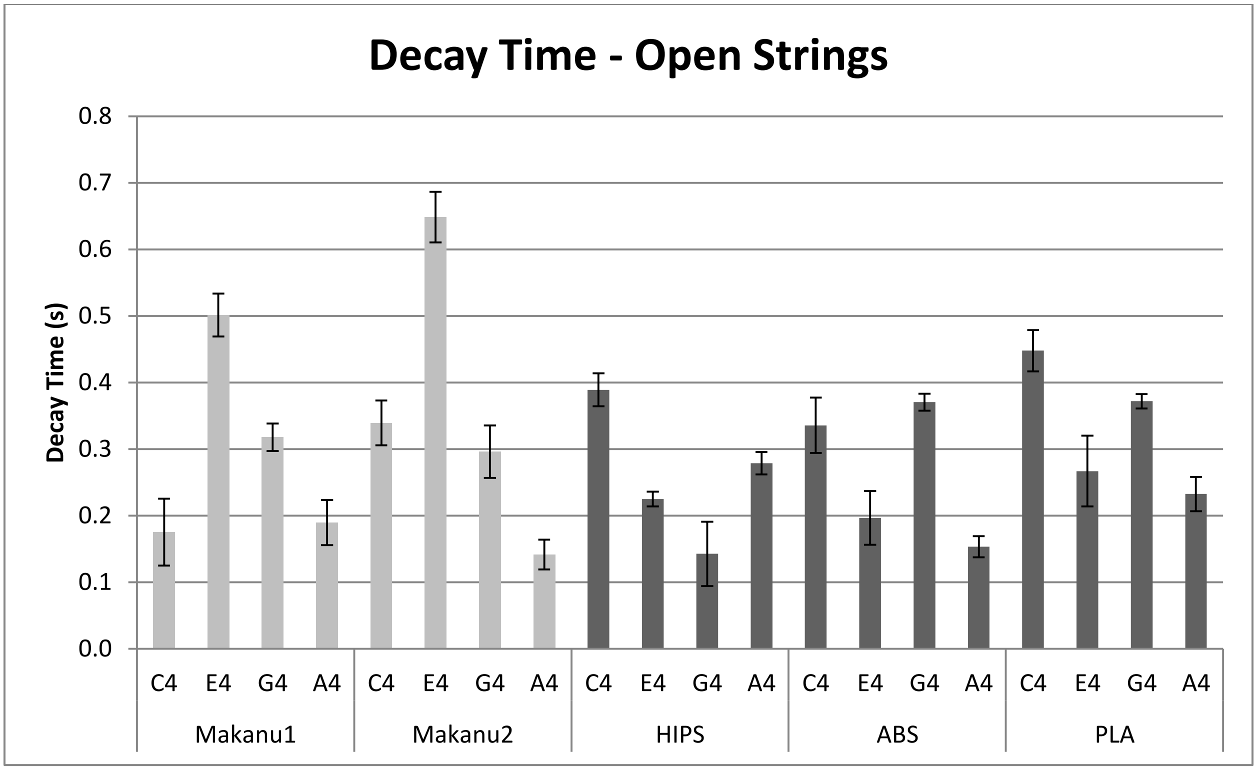

Figure 28: Baseline Comparison Sustain Metric - Overall Comparison

Indeed, two-sided t-tests conducted at 95% confidence interval (not assuming equal variance) comparing Makanu1 to ABS and PLA resulted in C4 through G4 note category p-values all under 0.05. Furthermore, statistical comparisons with HIPS were less than 0.05 for every single interaction. Table 7 overviews this information for the Decay Time analysis.

Table 7: Baseline Comparison Decay Time Statistic (t-test p-values)

Note	Decay Time (p-value)		
	Makanu1 vs. HIPS	Makanu1 vs. ABS	Makanu1 vs. PLA
C4	0.000	0.001	0.000

E4	0.000	0.000	0.000
G4	0.001	0.003	0.002
A4	0.003	0.084	0.059

This suggests statistical difference between manufactured wood sounds and printed plastic sounds. Figure 29 displays an especially contrasting case of this phenomenon.

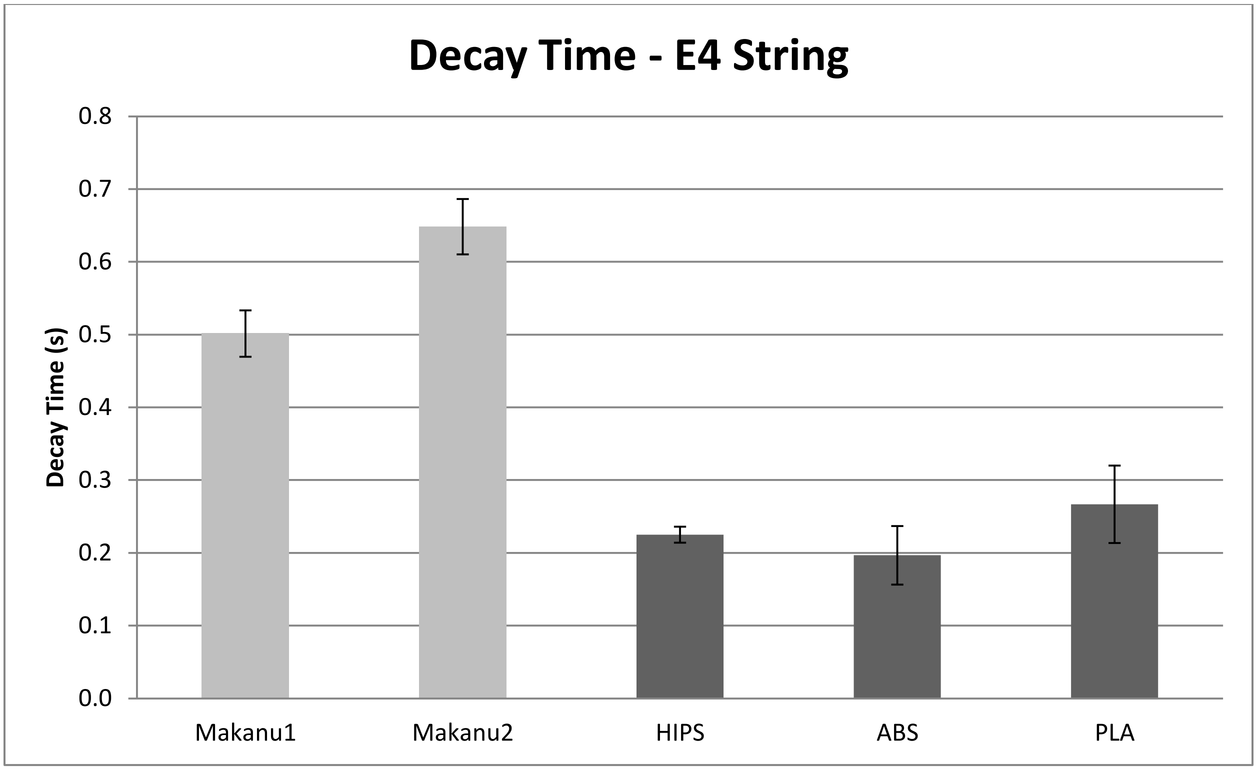

Figure 29: Baseline Comparison Sustain Metric - Extreme Case

While an obvious quick observation of this chart is that manufactured wood ukulele sustains are drastically longer (roughly double or more) than general printed filament specimen times, this impression should not carry to conclusions about overall instrument behavior. The above chart is based solely on one note's time response. Realize the context of E4 string behavior – from Figure 20, E4 exhibited the longest decay time among strings. Other visual inspections reveal that C4 or G4 even tip the other way with longer printed filament sustain times. Regardless of potential trends, individual note comparisons resulted in multiple categories of statistical difference and Figure 29 shows clear visual example of significant difference between the two groups.

Strength

Figure 30 below shows bar chart averages of percent fundamental, representing the Strength tone metric for each note category.

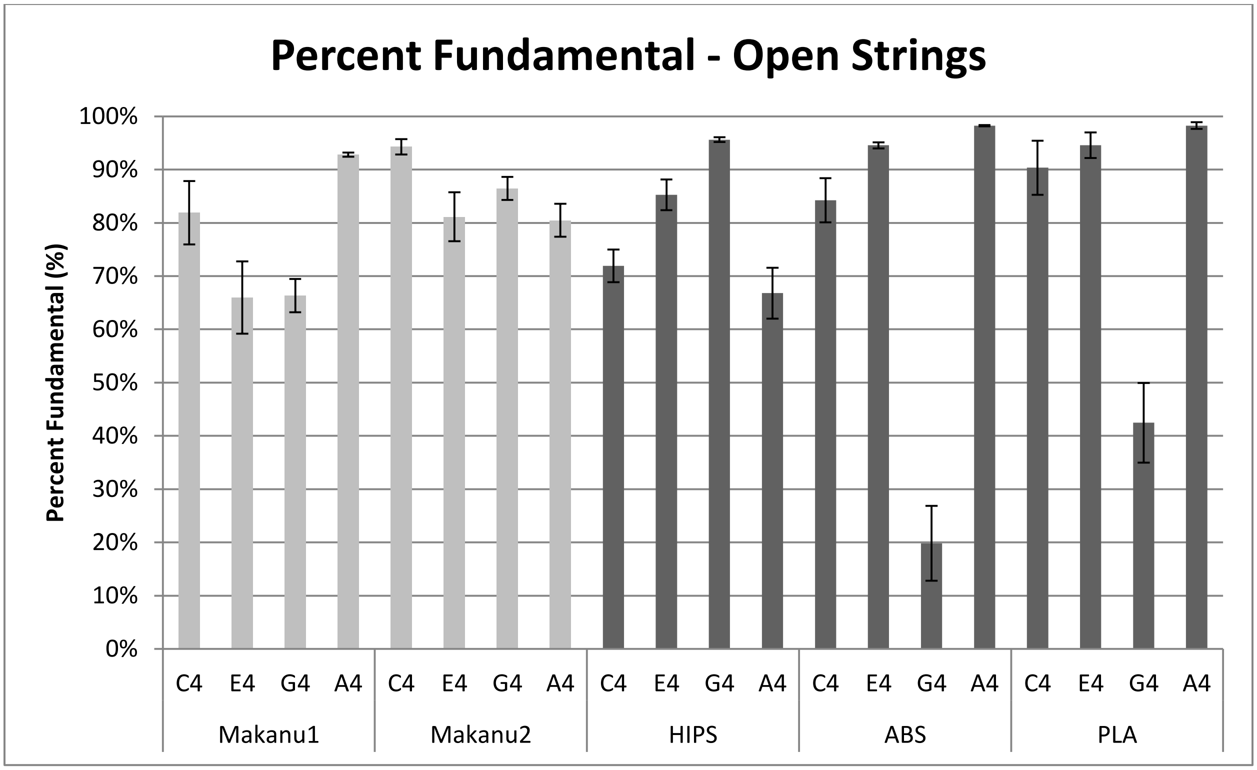

Figure 30: Baseline Comparison Strength Metric - Overall Comparison

Considering two-sided t-test statistics, this metric showed multiple reinforcements of difference between manufactured wood and 3D printed ukulele sounds, as every note category produced p-value under 0.05 (see Table 8 below).

Table 8: Baseline Comparison Percent Fundamental Statistic (t-test p-values)

	Percent Fundamental (p-value)		
Note	Makanu1 vs. HIPS	Makanu1 vs. ABS	Makanu1 vs. PLA
C4	0.021	0.491	0.047
E4	0.002	0.001	0.001
G4	0.000	0.000	0.001
A4	0.000	0.000	0.000

Aside from the before mentioned case of PLA and ABS G4 note levels, results generally faired over 60%. As a general takeaway, this suggests that fundamental frequency dominates harmonic contributions for most note comparisons.

Discussion

Surprisingly, the two ukuleles of the same make (Makanu) and model not only showed cases of distinction in traditional wood comparisons, but in some circumstances even more cases than Luna comparisons.

Number of Harmonics showed signs of difference, contrasting manufactured wood sounds with printed plastic sounds; however, there were considerable overlaps among standard deviations. Deviations in this particular parameter could have to do with differences in noise level, pluck angle, and strike intensity. Addressing the first of these, the method of identifying harmonics involved finding peaks in relative frequency amplitudes above an individually determined noise floor. A loud recording room environment could raise the noise floor and make harmonic peaks less distinguishable. Similarly, a less intense string strike could result in quieter instrument noise, and in turn reduce disparity between peak and floor. Differences in how the string is struck might also have implications with the number of harmonics present in vibration of the overall instrument. Ramsey and Pomian found differing results when a bow, pick, or thumb was used for string excitation [6]. If harmonic frequency amplitudes dip below threshold value for a particular sample, MATLAB code will stop scanning for peaks near anticipated multiples. This means that some qualifying (above noise threshold) harmonics could exist in a signal that simply miss identification due to coming after low value. Even considering these possible affecting contributors, Number of Harmonics shows promise as an insightful metric for investigating Fullness of string instrument tones and provides a frequency domain tool for analyzing musical signals.

Decay Time shows several note categories of statistical difference between manufactured wood sounds and 3D printed plastic sounds. This suggests that Decay Time provides sufficient distinction to benefit tone metric comparison. This aspect of sound consideration represents transient behavior, particularly fundamental frequency's, of the signal and adds an important piece to the tone metric puzzle.

There were several insightful aspects of the Strength metric that stood out in their relation to tone discussion. Overall, it resulted in multiple note categories of statistical difference for each printed filament comparison with Makanu1. This means that plucking any one of several (in some cases all) strings relayed difference between ukulele sounds. A somewhat unusual phenomenon was that ABS and PLA exhibited especially low percentages (20% and 42%, respectively) for the G4 note. Generally, instruments showed above 60% and in some cases even as high as 95% for the fundamental frequency ratio; however, these cases showed higher percentages for the first harmonic frequency following the fundamental. Regardless of cause, one interpretation of this dominance or deficiency in Strength is that relative level of fundamental frequency amplitude relates to note clarity. After all, each string gets tuned with respect to a defined pitch. That pitch corresponds to fundamental frequency, so a particularly strong fundamental relative amplitude could mean an especially dedicated tone. Contrariwise, particularly strong harmonic relative amplitudes could detract from or muffle the primary tuning frequency’s strength in the tone.

CHAPTER V

CONCLUSIONS

Qualitative terms used to describe musical instrument sounds often lack consistent meaning and definitive category among listeners. What one person perceives as warm or bright could be labeled mellow or brassy by another. Quite practically, there exists a need for standardized vocabulary backed by quantitative sound metrics for real scientific meaning to be drawn from musical discussions. In this investigation, three metrics were defined based on frequency and time response. Elements of Fullness were inferred from harmonic counts in the frequency domain and fundamental Strength and Sustain were determined via spectrogram functionality. Number of Harmonics showed promise as a meaningful Fullness metric; however, results rendered considerable standard deviation among samples. Primary source of variation is likely due to intermediate harmonic relative amplitudes dropping below threshold values of individual sound samples, causing scanning sequence to discontinue. Future endeavors could improve upon this approach with enhanced scanning techniques; nonetheless, its use provided key insight into sound interpretation and continued use and refinement is recommended for future endeavors. Sound recording samples revealed that Percent Fundamental and Sustain provided excellent distinction, especially comparing printed plastic sounds to manufactured wood ones. These are each based on curve fitted values which adds built-in versatility for various decay patterns.

Modern manufacturing processes and material properties pose relatively uncharted effects to sound characteristics of up and coming musical instruments. 3D printing specifically introduces heating, cooling, layering, and build optionality that simultaneously enable geometric flexibility and promote anisotropic material behavior. With so much customizability comes parametric control complexity. There is a need for systematic testing methodology and repeatable tone metrics for comparing these changes with respect to traditional manufacturing processes and materials. The three tone metrics presented in this paper provided ample means for comparing recorded sounds from traditional and 3D printed soprano style ukulele chambers. Distinctions were drawn between manufactured wood and 3D printed plastic samples with insights as to their relation to common qualitative descriptions of tone perception. The methodology for understanding tone shows promise for other string instruments as well and provides groundwork for further investigations in the sound quality of 3D printed instruments. Additional metric refinement, further instrument testing, and larger sample bases could all assist with continued investigation and better understanding of instrument design in the future.

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