Analyzing Wood: An Exploratory Study of the Speed of Sound in Maple and Spruce

Quinn Batten, Noah Carson, Andrew Keene and Nyla Worker

300 North College St., Northfield, MN 55057

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I. INTRODUCTION

In the world-famous Fiemme Valley in Italy, an artisan confidently selects a piece of tonewood and exclaims, "Yes, this piece is the right piece. I can tell just by flicking it" [9]. Such stories of deep craftsmanship and intuitive knowledge of wood may play well with a particular audience, but often the reality of violin-making is more complicated. The artisans that make the world's finest violas, violins, cellos and basses have incredible intuition; they also continuously seek to improve their process, doggedly uncovering and testing new techniques to assess wood blanks. Luthiers place great importance on selecting the "right" piece of wood; a single blank can cost $3000 dollars.

What can luthiers learn about a piece of wood before they commit to turning it into a violin? What measurement techniques provide the most valuable information at the least cost? In this paper, we approach this question from a scientific perspective. The organic nature of wood complicates this task; acoustic qualities (density, resonant frequency, etc.) are far more difficult to measure and model in wood than they are in more uniform materials like steel. The density and structure of wood fluctuates throughout, and depends on minute details of the growing conditions that the tree experienced throughout its life cycle. We explore the techniques luthiers use to assess tonewoods, share the results of two experiments, and make preliminary recommendations about optimizing measurement technique. By improving the reliability of these measurements and exploring new computational uses for the resulting values, we hope to help luthiers bring what they know about a piece of wood into sharper focus and possibly aid in the critical process of tonewood selection. Throughout this study, we have worked closely with David Folland, a well-respected luthier based in Northfield, Minnesota.

II. BACKGROUND

It is believed that the violin has been in production for at least 500 years [1]. As technology has advanced since the inception of this well-known instrument, so has knowledge of what factors create excellent violins. Studies have analyzed string quality, bow design, and various parameters of the wood used to build a violin [3]. In this paper, we present new data on this third topic: assessing the quality of wood used to build a violin. We focus, in particular, on the speed of sound through the wood.

Most published studies investigating the speed of sound in wood use one of several closely related techniques. These techniques share a general format: a device sends a stress wave (or multiple stress waves, later referred to as vibrations) through the wood, and a microphone or sensor picks up those vibrations once theyve traveled through the wood sample. One of these techniques is the Schmidt method, which is described in detail in Appendix A. The Schmidt method is easy, fast, and cheap; it is therefore used by many luthiers. Its accessibility and broad usage make it a particularly interesting leverage point— any improvements to this technique could have broad and powerful effects; luthiers who use the improved technique will be empowered to select better wood, thereby reducing costs and increasing product quality. Because of this unique positive potential, we investigate the Schmidt method and offer some tentative recommendations for refining and improving it. Although this technique is widely used, there are other, more expensive tools to measure the speed of sound that some luthiers find useful.

Many established luthiers today use the Lucchi meter, invented by Giovanni Lucchi in 1983. This machine sends ultrasonic vibrations through a wood sample to a receiving sensor and estimates the speed at which the sound has traveled through the sample [4]. Lucchi Meter measurements are sensitive to variations in the force applied to the sensors; to such a degree that it may cause substantial error in recorded measurements. Our study aims to help luthiers reduce error in Lucchi Meter measurements by recommending a procedure that incorporates several error-reduction strategies. We also provide recommendations for procedures to use when taking measurements using the Schmidt method, and perform some exploratory statistics with the goal of describing patterns of error for these methods and better-understanding the relationship between these two strategies of measurement.

While previous studies have certainly been performed with precision and accuracy, they generally do not effectively translate their findings into practical and accessible advice for luthiers. This study is an attempt to bridge the mathematical and experimental world with the world of violin making. We hope to provide luthiers with further information about analysis of tonewood and practical advice that will help them refine their own measurement procedures.

III. METHODS

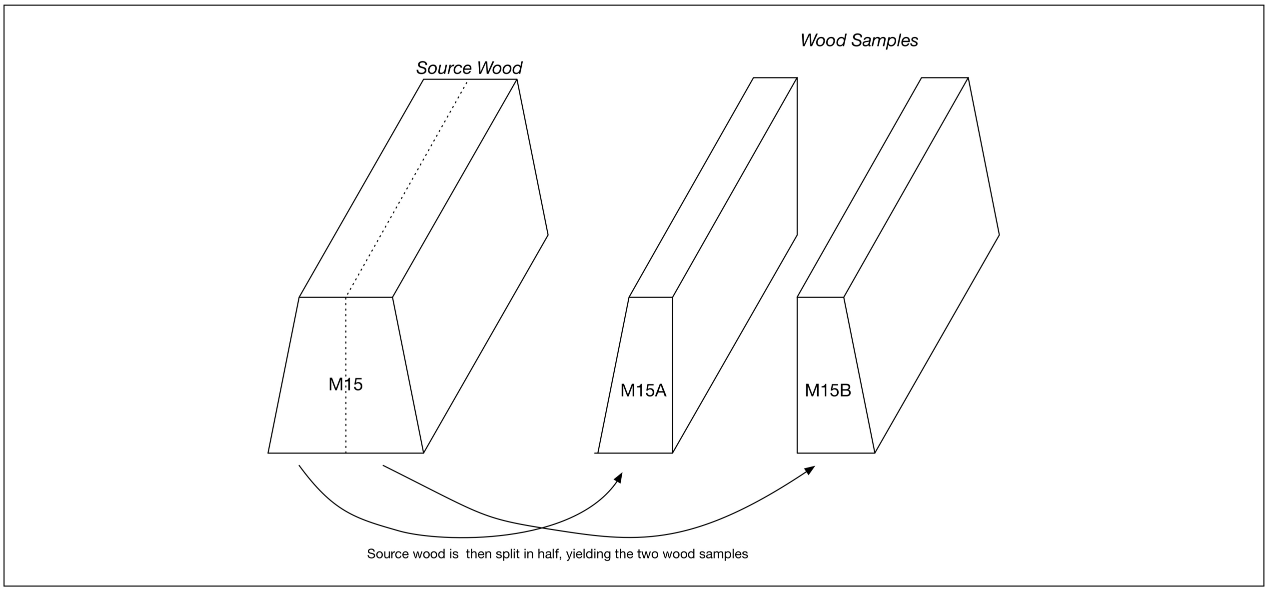

Figure 1. Illustration of nomenclature for wood samples. M15 source wood is used as an example."M" indicates that the wood is maple; 15 is an arbitrary ID number; "A" and "B" are arbitrary identifiers for the wood samples, which are the two split halves of the source wood M15.

For this paper, we performed two studies to measure the speed of sound in wood: one using the Lucchi meter and one using the Schmidt method. David Folland provided us with wood samples from his stock of wood blanks for violin tops. A violin top blank arrives as a quartersawn wedge of wood, which we will refer to as the "source wood." The next step in the process is to split the source wood in half. We will refer to the resulting halves as "wood samples." See Figure 1 for an illustration of this process. The eight samples we tested come from four pieces of source wood. Each piece of source wood is labeled with a letter, representing the wood species, and an arbitrary two-digit ID number to differentiate the pieces of wood from that species. Then, once the source wood is split in half, an additional letter, A or B, is added to the end of that name, in order to differentiate the two wood samples coming from that piece of source wood. Our wood samples are made from maple, signified by an "M," and spruce, signified by an "S." The eight wood samples we use are named: M15A, M15B, M47A, M47B, S67A, S67B, S68A, and S68B.

A. Schmidt Method

Our first study consisted of performing several trials of Schmidt measurements on our eight wood samples. We performed ten trials on each wood sample using an adaptation of the Schmidt method. Our procedure is described in detail in Appendix A; hereon, our new, adapted Schmidt procedure will be referred to as the modified Schmidt, and the Schmidt procedure as laid out in the original source document will be referred to as the original Schmidt method. Two important refinements that we made to the original Schmidt procedure were resting the wood on painter's pyramids and using a pendulum to create a stress wave in the wood; the classic Schmidt procedure uses a small hammer. Resting the wood sample on painter's pyramids minimizes damping due to contact with the surface the wood rests on. The pendulum allows us to ensure that the force applied remains constant for every "tap".

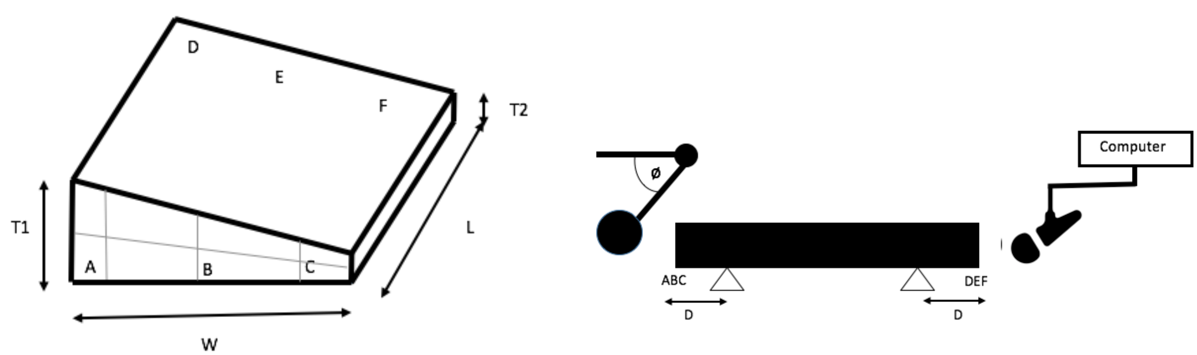

Figure 2. The left image is a side view of a wood sample, with several points labeled. A and D are in the same spot in terms of horizontal placement but are on opposite sides of the wood. A, B, and C represent the tapping spots and D, E, and F the places where the microphones are placed. The painting pyramids holding the wood are located at a distance of 5 inches (D) from the ends. On the right side we can see our experimental setup with the pendulum at $\phi = 75° \pm 5°$

B. Lucchi meter

The Lucchi meter manual warns users that, in order to ensure that measurements remain consistent, the same force must be applied to the sensors for each measurement [8]. In our second study, we explore how Lucchi meter measurements vary depending on the amount of force applied to the sensors. Figure 3 shows the experimental setup. The wood sample rests on three painters pyramids, in order to minimize any damping effect due to contact with other surfaces. The Lucchi sensors are attached to two newton meters, to measure the force with which each sensor is being pressed into the wood sample. We apply a predetermined amount of force to the sensors and then record the Lucchi measurement, repeating several trials for each force-level and each wood sample. The force-levels we test are (in newtons): 2, 5, 8, 12, and 25.

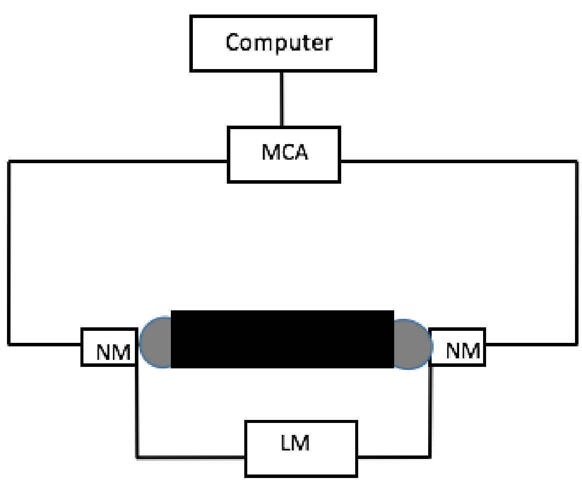

Figure 3. The Wood is the plank in the middle. On the sides we see both ends of the Lucchi sensors that are connected to Lucchi meter (LM). The Lucchi sensors are next to newton meters (NM) that are connected to a multichannel analyzer (MCA), which connects to the computer, where we are able to see the force applied to the sensors and control it.

IV. RESULTS

A. Schmidt Method: Improving the Algorithm and Analysis of Error

The results of the Schmidt method are highly dependent on the algorithm used to choose which peak represents the resonant frequency of the wood sample. We assess and improve upon the original algorithm (i.e. the algorithm used in the original Schmidt method). Further, we discuss the precision of the Schmidt method using each algorithm.

The initial step in the original Schmidt method algorithm is to select the "peak" in the frequency spectrum which will represent the resonant frequency of the wood sample; the original Schmidt method uses one trial and selects the maximum of the frequency spectrum. In other words, the wood sample is tapped once, one frequency spectrum plot is produced, and, from that plot, the frequency with the highest decibel measure is chosen as the resonant frequency. In our trials, the frequency spectra are limited to a range of 3000 Hz to 22,000 Hz, so any maxima at frequencies outside of this range are rejected. For our initial analysis, we used the original algorithm to find the speed of sound for each trial. Table I shows the standard deviation in speed of sound for each wood sample using the original algorithm; the last row shows the average of the standard deviation for all wood samples. Note that there are three clusters of standard deviations, at 0, 225, and 800 Hz, and that the standard deviation doesn't seem to be strongly related to which original wood piece the sample was drawn from. It appears that these measurements aren't coming from a normal distribution around an actual resonant frequency.

We turn to the original frequency spectra to investigate the mechanism behind this error pattern. See Figure 5 for graphs of all frequency spectra, with the maximum labeled on each graph. Note that, because of our chosen range and the way Audacity formats its output, there are 220 possible frequencies per frequency spectrum. When creating frequency spectra, Audacity uses 255 discrete frequency values for which to output the volume, and our chosen range of frequencies further narrows that set of frequencies down to 220 total frequencies. It appears that, for each wood sample, there is a particular set of peaks that appear at identical (or almost identical) frequencies across almost all trials for a single wood sample. It seems that each wood sample has specific features that result in a unique set of frequencies resonating more loudly when the wood is tapped; these appear as peaks in

TABLE I. Standard deviation of speed of sound, as measured by Schmidt Method, for all wood samples. Schmidt method used for this study is as described in Appendix A. N=10 for each wood sample.

Sample	St. Dev
M15A	252.22
M15B	199.45
M47A	0
M47B	0
S67A	772.19
S67B	0
S68A	0
S68B	840.53
Avg.	258.05

the frequency spectra. The frequencies of these peaks are very consistent across trials for a given wood sample, but their volume does vary slightly. So, there is a particular set of peaks that "compete" for the position of overall maximum, with some peaks winning out more or less often than others. With this mechanism in mind, the pattern of error shown in Table **??**tab:sdspeed is less surprising. The frequency spectra across trials for a given sample are highly similar; a wood sample may have one, two, or three peaks that compete for the position of maximum. The distance between competing peaks in a given sample's spectra is a major determinant of the standard deviation of Schmidt results. However, theory indicates that one of those peaks is the "true" resonant frequency while the other is located according to some set of unknown parameters and is likely to be completely uncorrelated with the value we seek. In other words, one of these peaks is a direct result of a particular feature of the wood (the speed of sound through the sample) that we are seeking to measure, while the other peaks occur because of some other, unrelated, unknown feature(s) of the wood sample. We believe it makes sense to conceptualize frequencies of these other competing peaks as "mistakes" and to discard them, rather than to include those values as a factor in calculating our measurement. On the other hand, the rate at which each frequency appears per trial does seem to be a relevant piece of information.

We suggest a new algorithm, based on these results and our knowledge of average speeds for spruce and maple wood samples for violins:

1. Run ten trials of the experimental section of the Schmidt procedure. Use Audacity to create a frequency spectrum for each trial (or "tap"). Return the frequency spectra that are output from Audacity.

2. Select the maximum of each spectra. Return a list of maximum frequency for each spectrum.

3. From this list, remove any frequency that occurs less than twice (less than 20%of the time).

4. Select the frequency that is "highest" (i.e. the frequency with the greatest hertz out of all frequencies on the latest list). This is our expected peak resonant frequency for that wood sample.

5. Plug this frequency, along with the length of the wood sample, into the given equation, $c = 2lf$. This yields the measured speed of sound through that wood sample.

This algorithm is based on our interpretation of the data we've gathered along with our background knowledge regarding this problem. Our data shows that, for every sample, this algorithm returns a value that is consistent with our expectations.

Based on our data and our conversations with David Folland, we believe that the speed of sound through maple is usually roughly between 4000 and 5000m/s, while the speed of sound through spruce is roughly between 5000 and 6000m/s. Figure 4, is a histogram of the measured speed of sound from all ten trials for each wood sample, excluding those wood samples for which all trials found the same maximum frequency and therefore the same measured speed. For three of the four samples, the speed which appears most frequently closely matches our expectations. For example, the trial for M15A gave three speeds, two of which are below 3500m/s, and the third of which is near 4000m/s; the latter appears in seven trials, versus the lower cluster, which was measured in three total trials. Again, we expect maple samples to generally have a speed that is above or around 4000m/s, so the higher-frequency measurement of 4000m/s is generally consistent with our expectations for this wood sample.

It's difficult to compare the error rate between the two algorithms in our study; the difference in error rates would be an interesting topic for future study. The new algorithm uses ten trials to select a single measurement value, while the old value uses a single trial; we only took ten trials per wood sample, so we are unable to find the variation in results for the new algorithm.

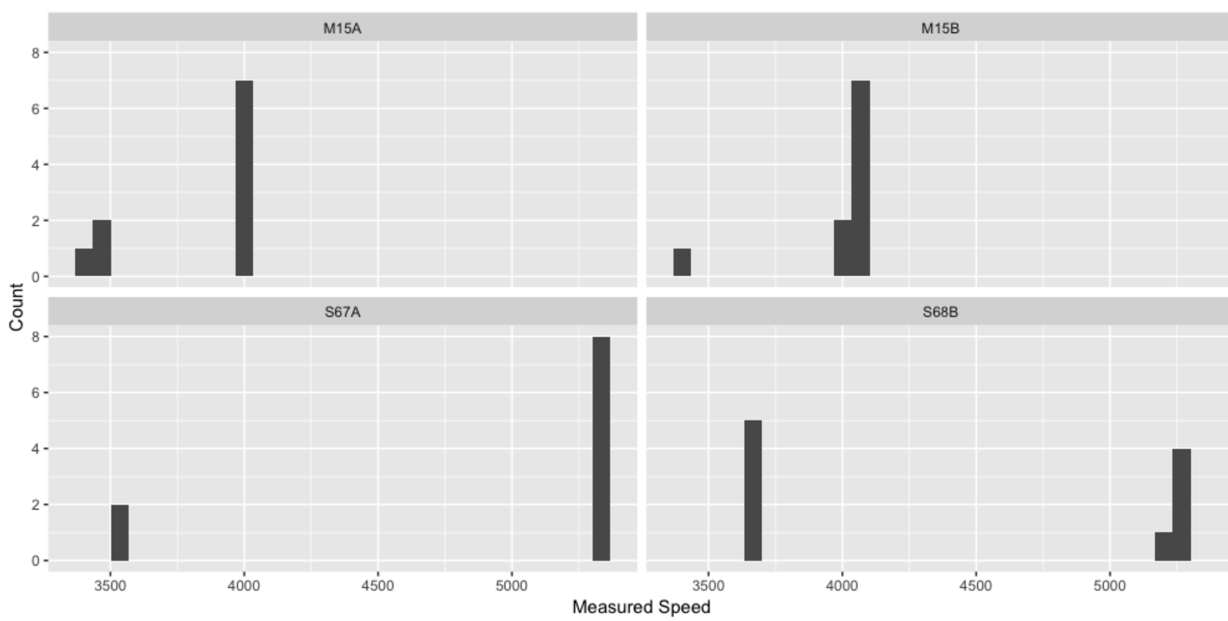

Figure 4. Speed of sound, as measured by Schmidt, for all trials. (Samples with only one peak frequency across all trials are excluded)

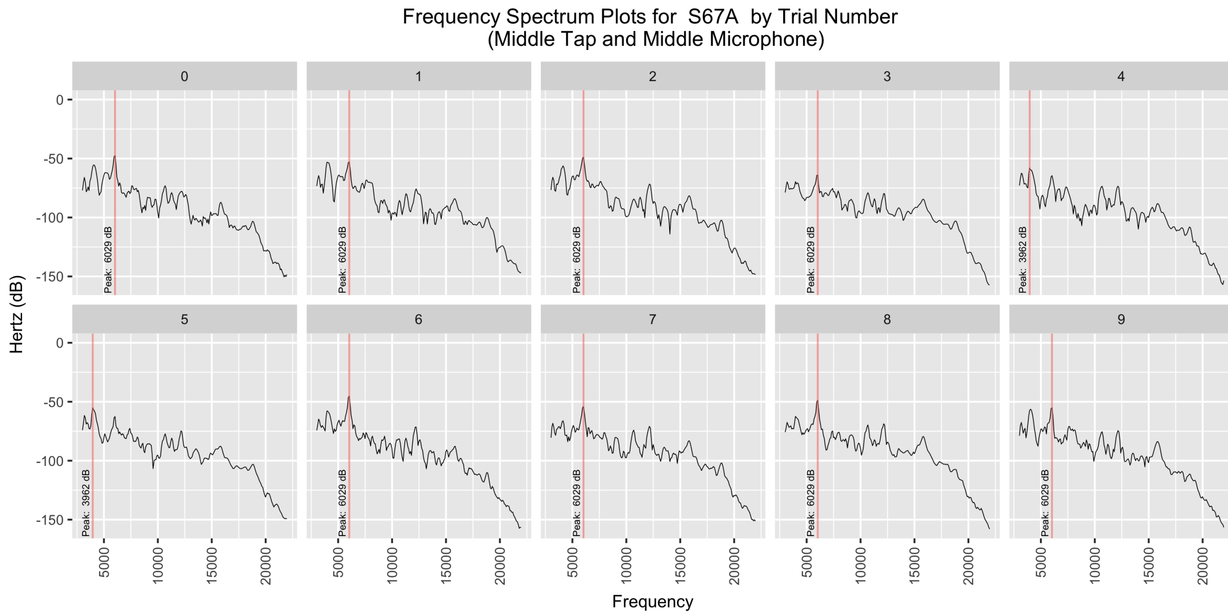

Figure 5. Example of frequency spectrum output, with maximum labelled. This set of frequency spectra is from wood sample S67A.

B. Lucchimeter: Force Applied as a Source of Error

The Lucchi meter manual warns users that they must apply a constant force to the sensors in order to ensure accurate and consistent measurements. We investigate the responses of Lucchi meter measurements to variations in the force applied to the sensors. Figure 6 shows the distribution of standard error in Lucchi measurements across different levels of force-applied. One data point used to create a boxplot in Figure 6 represents the standard error for all trials with a given force-applied for a given wood sample. So, Figure 6 shows the distribution of the standard errors for all trials and all wood samples for each level of force applied.

Figure 6 shows clearly that, on average, within our tested range of force, increasing the force applied to the sensors decreases between-trial variation. Looking to Figure 7, it does not appear that wood species interacts with this relationship, nor do there seem to be any samples which deviate from the previously discussed pattern; at least not to any practically significant degree.

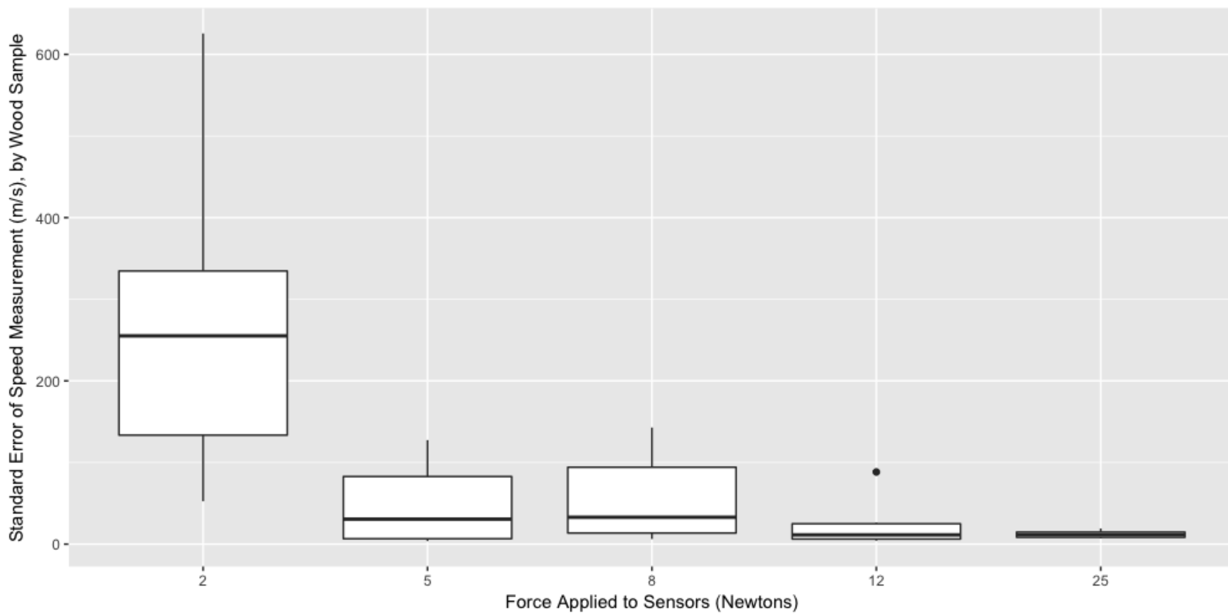

Figure 6. Distribution of sample standard errors for each wood sample.

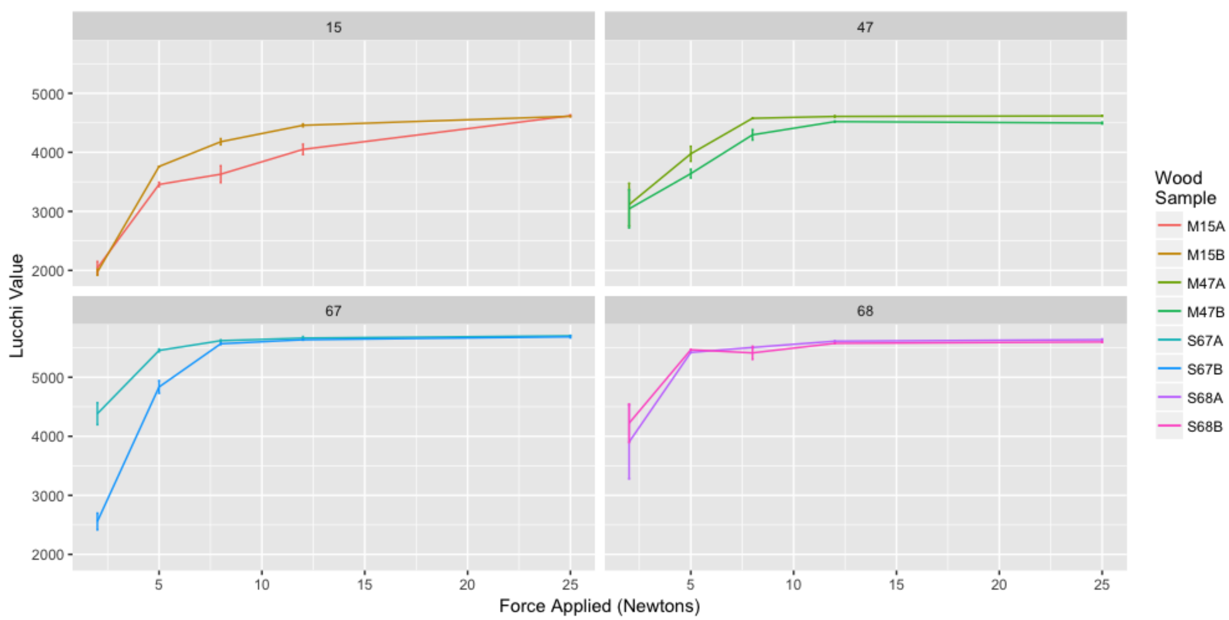

Figure 7. Speed of sound, as measured by Lucchi, for each wood sample.

C. Comparison of Lucchi Meter to Schmidt Method

Figure 8 shows the distribution of measures using all variations of the Schmidt and Lucchi methods. In other words, it includes all tested levels of applied force for the Lucchi measurements, and all variations of microphone placement and tapping position for Schmidt measurements. For Schmidt measurements, we use the original algorithm and includes all ten trials as separate data points. Figure 9 shows a subset of the results from Figure 8, the best available parameters for each measurement type. For Schmidt, that means that only middle tap location to middle microphone measurements are included, with all trials. For Lucchi measurements, we include only trials with a force-applied of 25 newtons are included. In Figure 8, the Lucchi measurements seem to be strongly left-skewed, while the Schmidt measurements, if not normal, seem to be fairly centered. Turning to Figure 9, the Schmidt method original algorithm clearly results in a wide and discretely-distributed variation in measured values. The competing peaks are quite far apart, so the range of Schmidt methods is either zero or quite large. S68B, especially, is a sample where the Schmidt method using the original algorithm utterly fails to provide a useful measurement. It's clear that improvements need to be made to the Schmidt algorithm in order for it to compete with the Lucchi meter as a measurement method.

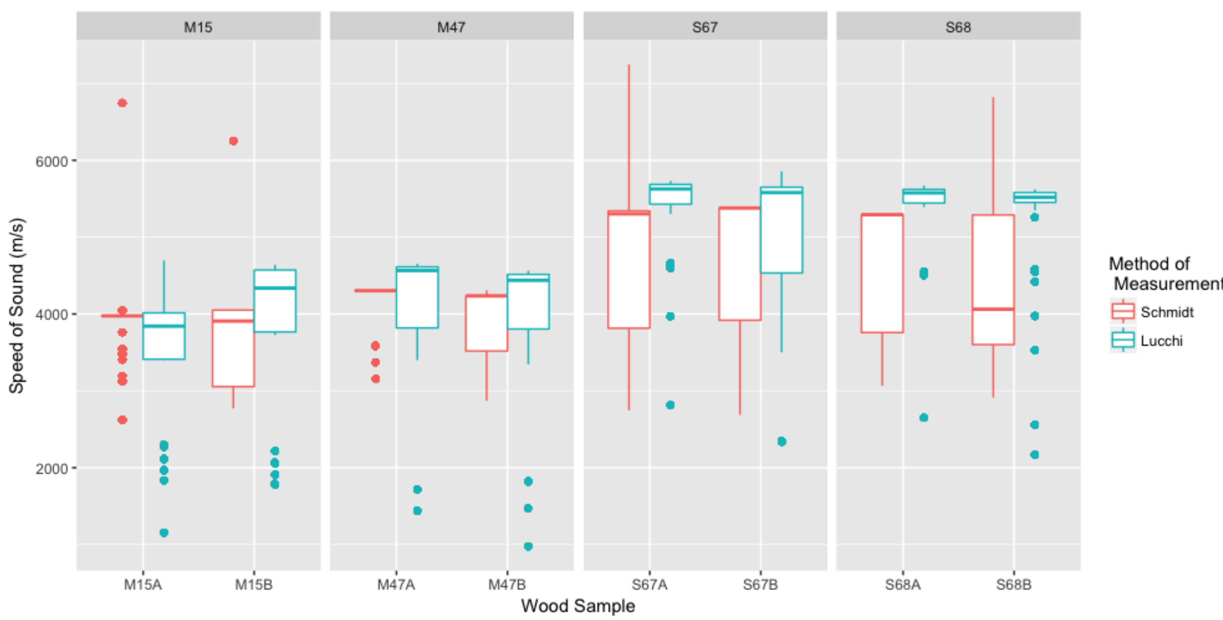

Figure 8. Speed of sound, for all trials and both measurement techniques.

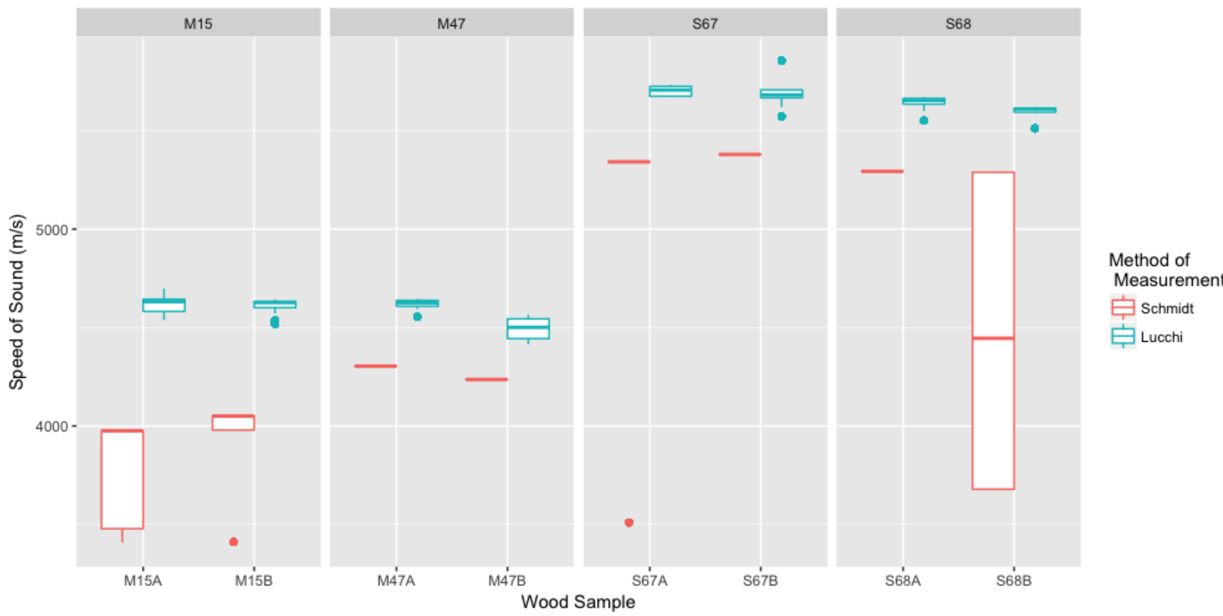

Figure 9. Speed of sound, for specific trials and both measurement techniques. Schmidt measures include only the middle tapping point and the middle microphone. Lucchi measures include only those with a force applied of 25 newtons.

V. DISCUSSION

A. Lucchi Meter Response to Variation in Force-Applied

The Lucchi meter results present two key observations upon which this study can expand. First, there is a positive correlation between the force applied with the Lucchi sensors and the speed of sound recorded from the wood. In other words, pressing harder onto the sensors increases the speed shown by the meter, although at a diminishing rate. This effect raises some issues regarding our confidence with this measurement tool, which can give vastly different readings for the same piece of wood over a range of sensor forces. In Figure 4, the recorded speeds are clustered in groups. Each of these groups is associated with a particular force applied to the wood. As the data suggests, higher forces (> 15 N) result in similar speed measurements (lower error), consistent enough to embody a high-speed median in the graph. It is clear that the speeds can vary tremendously, ranging from well below 2000 m/s to nearly 5000 m/s for this particular piece of maple.

To complicate matters, the relationship between applied sensor force with the Lucchi sensors and speed of sound reported is not a simple linear function. In fact, the behavior of the data presented in this study closely resembles that of a logarithmic function, namely $-e^{-x}$ (Figure 7). This study did not take extensive efforts to validate this functional model, and the model may not hold for other experimental situations. Nevertheless, we mention this observation for the benefit of those concerned with the practical implementation of this method. The data clearly shows that there is a certain threshold (loosely, an asymptote) for each piece of wood in which the speed of sound reported by the Lucchi meter will not likely cross. Whether or not this threshold truly exists, the significance of this fact is that variation in speed measurements decreases significantly at higher sensor forces. The standard deviation is smaller, thus the confidence of the values increases. While there is no definitive way to know the true speed of sound of wood from the Lucchi meter, one can theoretically obtain consistent values by applying consistent sensor force. Without the aid of force meters like those used in this experiment, consistent force may be difficult to achieve.

B. Schmidt Method: Accuracy and Algorithm

Data found using the Schmidt method proved reproducible and consistent, which verifies the reliability of this method for practical measurement of the speed of sound in wood. However, the method is not without its issues. Peak frequency measurements ranged widely for some samples, and the ideal acoustic environment for the procedure may not be easily reproduced. But despite the aberrant peaks in some instances, the Schmidt measurements did converge to frequency peaks within the expected range for all woods tested. This convergence suggests that the speed of sound derived from the Schmidt method represents a measurable characteristic of each piece of wood. As expected, spruce samples had higher peak frequencies than the maple samples tested, and bookmatched samples showed similar spectral peaks (Figure 7).

A purely algorithmic approach to selecting the correct peak may be the cause of some erroneous readings. The frequency peak selection process used in this experiment is aided by a pre-existing understanding of where peaks should be located in the spectra. For instrument-grade maple and spruce, one expects to see peaks between 4000-6000 Hz. Peaks outside of this range are likely the result of other phenomena, particularly the acoustic effect of the physical tapping and general ambient noise of the room. This experiment focused on achieving clear frequency peaks in the expected range, and did not deeply explore the significance of information across the wider spectral plot.

One of the issues arose from the apparatus used to tap the wood sample ends. For thinner tapping locations (approximately one inch or less), we had difficulty striking the wood cleanly and consistently. Occasionally the metal head of the hammer would miss the edge of the sample and the wooden shaft would strike the wood instead. In these instances, the clear resonating of the sample was replaced with a clunk sound. These instances can also be identified by their spectral plots, which exhibit dramatically different peaks and overall greater excitation across the frequency range. Other causes of the variation in peak frequency are less obvious. In some samples, the peak frequency varies significantly despite little audible difference in between the taps. Four of these samples exhibited this behavior. (Figure 4). We have some hypotheses to explain this variation, which could be explored further in future experiments. Slight changes in the angle of the hammer tap could cause different frequencies to be excited, perhaps sending the compression wave of the tap at an oblique angle through the wood sample. Imperceptible movement of the sample towards the microphone element may create an airborne wave that skews the readings from the closely placed microphone. But overall, the effect of these variations can be reduced by taking multiple tap measurements and disregarding those without a clear peak.

C. Comparison of Lucchi Meter and Schmidt Method

D. Conclusion

While both have their drawbacks, the Lucchi meter and Schmidt method have shown themselves to be relatively practical and reliable ways of measuring the speed of sound in wood. The Lucchi meter is an costly tool that can report wide-ranging values, but consistent results can be obtained with careful procedure. Keeping the applied force consistent, along with replicating aspects of this studys experimental setup, can help provide more confident measurements. Interestingly, we found that the lower-cost Schmidt method rivals the Lucchi meter for measuring the speed of sound. This method can be improved by using the same hammer for tapping the wood, as well as measuring the same peak frequency values in the spectrum analysis for final calculations. More on this is detailed in the appendix.

It is difficult for this study to conclude a true speed of sound in a given sample of wood. This is partly due to experimental shortcomings; there are more accurate ways to measure the speed of sound in wood (some are described in the background). A reason these experiments were not feasible concerns the dimension of the wood that is being measured. While some experiments required the wood to be cut in a dowel configuration, this study worked with samples for violins. Thus, there is plenty of room for waves to deviate from their path from sensor to sensor (Lucchi meter), or hammer to microphone (Schmidt method). The dimensions of a sample of wood also may have direct impact at the speed of sound in the given sample. Future studies could explore this directional sound wave influence, as well as attempt to develop a conversion for speed in a dowel to speed in other shapes. Finally, wood is a very heterogeneous material. It is an organic composition of cellulose fibers enveloped in a matrix of lignin. Despite the hefty prices paid for wood used in high-quality violin making (and instrument making, for that matter), it is impossible to generate a piece of wood that is uniform throughout its body, not to mention identical in structure to another piece of wood. Future studies could look into modeling the composition of a given sample of wood (or wood in general), and applying sound waves through it to see how these waves behave.

In conclusion, this study hopes to be of some use to luthiers around the world. The content analyzed, experiments carried out, results discussed, and recommendations made in this paper aim to provide luthiers with the added expertise they need to improve their craft.

Here we will compare with other papers and talk about how this is meaningful for different luthiers. The side C of the wood is the thinnest, which made it difficult to apply a constant tapping.

VI. REFERENCES

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Appendix A: Schmidt Method Experimental Procedure

Supplies:

1. Three painter's triangles, with rubber grips on all corners to prevent sliding.

2. Three microphones with stands.

3. One pendulum. Solid arm, hinged joint, and small metal point for wood contact. Our device consisted of two small dowels (one for the user to hold, and the other which will act as the pendulum) connected by a hinged joint, with a small nail driven partially through the pendulum dowel. The head of the nail acts as the contact point and weight.

4. A computer with Audacity (a free audio program)

Procedure:

1. Mark the short sides of the wood with four lines each as shown in Figure 2.
2. Rest wood sample on three painter's pyramids, lying with the short side facing you, and the thicker edge of the wedge facing left.
3. Set up three microphones on the far side of the wood sample. The center of the microphone is centered one of the intersections of the lines drawn (see Figure 2).
4. Begin recording audio.
5. Using the pendulum device, strike the wood sample at the intersection of the lines. We start the pendulum for each measurement at the same angle (75°± 5°), as shown in Fig. 2 . Repeat ten times at each intersection.
6. End audio recording. Open audio file in Audacity.
7. In Audacity, highlight one tap in the track from the central microphone. Click Analyze > Plot Spectrum.
8. Export spectrum to a text file. Repeat for all spectra. Apply algorithm to select frequency.
9. Plug length of wood and chosen frequency into equation: $c = 2lf$, where "l" is the length of the wood sample from tapping point to microphone (in meters), and "f" is the chosen resonant frequency (in hertz). Solve for "c"; "c" is the speed of sound through the wood sample in meters per second.

Appendix B: Procedure Recommendations for Luthiers

1. Schmidt Method

In addition to taking the standard Schmidt measurement, which prescribes tapping and measuring along the longitudinal center of the sample, this experiment placed two additional microphones near the outside edges of the wood and recorded taps at the corresponding additional locations. While the standard tap and microphone locations yielded usable results, this experiment found tapping and measuring at the thicker end of the sample returned more consistently clear peaks than the standard method. Importantly, the thick-side peaks did not differ significantly from the peaks measured using the standard middle-to-middle method. Thus, consistent values were retained.

One plausible explanation for this difference in performance is that the microphone element did not overlap at the thick end of the sample, as it did in both the middle and thin ends. We hypothesize that the wider area of the thick end blocked more extraneous acoustic information from reaching the microphone, thus resulting in a clearer reading.

To help create a successful Schmidt measurement, one must remember that the ultimate goal is to capture acoustic information from within the wood being tested, while recording as little information from the air around it as possible. Choosing a microphone with a narrower pickup pattern (e.g., hypercardioid or supercardioid) can help reject unwanted acoustic information. A contact microphone adhered directly to the wood might also produce desirable results.

However, microphone placement seems to make a larger difference than pickup pattern. A hypercardioid microphone was used for the middle pickup location, and wide-cardioid microphones were used at the outer edges. Despite the ostensibly poorer room rejection characteristics of the wide-cardioid microphones, the thick-end measurement produced clearer peaks. One additional recommendation: one must take care to not overload the microphone input, as the resulting distortion will create inaccurate spectral readings. Lowering the microphone gain, whether within Audacity or on the equipment being used, will help reduce this possibility and yield clearer, more precise results.

2. Lucchi Meter

While impossible to obtain a true speed of sound in wood using the Lucchi Meter, there are ways in which the precision of this measurement can be controlled. The manual of the Lucchi Meter calls for a luthier to apply as much force as possible before reading the instrument, and in general, this study concludes this to be a good recommendation. However, to improve both consistency and accuracy, this study recommends a luthier to apply a force of 25 newtons using the Lucchi sensors. Simple newton-meters can be purchased and attached to the Lucchi sensors as indicated in the methods section; replicating this experiment will provide the most consistent results.

We wanted to avoid disturbing the wave travelling through the wood as little as possible. Therefore, we used the painter pyramids to have the least contact possible between the wood and any surface. The simple way of understanding why we need the painter pyramids is by using the example of a longitudinal wave travelling through. A string of a guitar. Here when someone holds the string the wave is not able to travel and gets reflected. When it gets reflected it causes different patterns that change the wave. The other option is that the wave travels through the material that is holding it. This is why when you hold the string it tingles; in this point the wave is changing to a new medium, the hand. All of these disturb the wave and end up changing the frequency.

Appendix C: Technical Reference: Schmidt Method

Using Newtons second law, we know $F = ma$. Therefore, we know that the acceleration with which the stress wave propagates through the wood depends on the force. Using wave mechanics and the wave properties we find:

$$F = \rho A dx \frac{\partial^2 u}{\partial t^2}, \tag{C1}$$

where A is the area, rho is the density, and u is the displacement of the shock wave. We then derive from the previous equation the wave equation:

$$\frac{\partial^2 u}{\partial x^2} = \frac{E}{\rho} \frac{\partial^2 u}{\partial t^2}. \tag{C2}$$

We can solve this differential equation and get a simple harmonic oscillator. Solving this differential equation we find that the speed of sound is:

$$C_0 = \sqrt{\frac{E}{\rho}}, \tag{C3}$$

where E is the modulus of elasticity and C_0 is the speed of sound the beginning. For material, such as metal that is isotropic we find a specific modulus of elasticity. However, wood is anisotropic [6], so we encounter different values that depends of each unique piece of wood. Additionally, while we are able to find the approximate density of the whole piece of wood; wood has different densities in different places of the wood. Given these irregularities, in the Schmidt experiment, we try to keep the force constant. Specially, since the modulus depends on the force from the derivation of the wave equation. In the equation

$$E = \frac{FL_0}{A\Delta x} \tag{C4}$$

we see this dependence. In Eq.C4 delta x is the distance traveled by the wave and L_0 is the length of the wood. Since the wave travels more than one oscillation, delta x changes and that depends en the density and damping. However, keeping the force constant allows us to minimize this error and have a more precise value for the modulus of elasticity, which affects the wave.

In this calculation, we do not account for damping, which reduces Δx as well. Therefore, we are not able to get a very precise result.