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Analysis of vibrational modes of chemically modified tone wood

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ANALYSIS OF VIBRATIONAL MODES OF CHEMICALLY MODIFIED TONE WOOD

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Introduction

It is generally accepted that every violin has different tone quality in terms of intonation and the depth of the harmonics produced. The best violins are made by experienced luthiers that craft each with precision to produce the best possible tonal quality. The quality of the finished violin is dependent upon both the specific shape and the vibrational response of the wood used in its construction. Because the hard wood used in violin construction is inhomogeneous, the composition and structure of material used is critical to the final product.[1] Luthiers would initially rely on their experience to feel the vibrations and intuition as to the quality of wood used, which is an extremely subjective method of analysis. Then, as they progressed in their skills, it became much easier to make violins of similar sound and sound quality when they were made from the same kind of wood. Today, most violins are made from spruce, maple, and artificial materials.[2]

Luthiers craft each violin by hand, carving the wood so that the assembled violin generates a pleasing sound. In the construction process of many wooden instruments such as guitars or violins, tone wood is used. The selection criteria for tone wood is broad and can vary depending on the type of instrument being constructed, along with personal preference of the crafter. Several common criteria include the species of the tree, lack of structural defects in the wood, stiffness, and properly dried wood.[2] No matter how many selection criteria are kept constant when selecting tone wood, the innate structural makeup of wood prevents the construction of two identical violins. While there is a variety of tone wood available, pernambuco has remained a popular yet elusive choice of wood for string instrument bows. Pernambuco is so heavily sought after due to its reputation as the only material in the world, natural or synthetic, that provides the highest quality of performance bows.[3] However, due to the excessive use of pernambuco in past centuries coupled with its slow growth rate and sometimes-poor quality, this decline in the wood has forced a search for alternative wood materials such as spruce and maple.[3] Today violins and other string instruments are most often made with the hardwoods spruce and maple due to their abundance and general consistency in quality.[4] With the inability to produce identical violins and the introduction of new tone wood materials, the importance of analytical methods to analyze the quality of violins from an objective standpoint continues to grow. The creation of a method to perform this objective analysis with reliable accuracy using two-dimensional vibrational modal analysis is explored further here.

Literature Review

Many modern luthiers today still rely on their ability to tap the body of a violin, listen and judge the quality of the violin. For centuries this was the only way to evaluate the quality of a violin.[5] Modern technology has made it possible to accurately determine the quality of a violin through a variety of methods. Carleen Hutchins has conducted experiments using laser hologram interferometry.[6] This method highlights areas on violin plates where there is little vibration or nodes. The evaluation of violin plates was done over a range of frequencies and was able to illustrate how in tune a plate was, as well as help judge the quality of violin plates. This method is limited to just evaluating plates, preventing the evaluation of a fully constructed violin. Throughout the construction process, the violin's response frequencies can change drastically. In addition, it is unknown if this method would work well in analyzing different materials used for violin plates, such as plastic or carbon fiber. Because this method focuses on areas of the violin plates with little vibration, any differences in resonance frequencies based on different materials may not be seen or properly analyzed using laser interferometry. Hutchins' method is a starting point for analyzing full violins for their quality.

There is also a need to determine how varnishes and other wood treatments affect the quality of violins. Skrodzka et al. discusses the differences in tonal quality of violins based upon whether or not the varnish used on the violin was oil or spirit based.[7] They determined that there were few differences in vibrational frequencies, but the oil-varnished violin subjectively performed better than the spirit-varnished violin. The relevance of this study comes in with the fact that varnishing the violin only creates a very thin surface layer on the wood of the instrument rather than impregnating the entire thickness of the wood. It raises the question of how chemical modification and surface layer treatment affects the physical qualities of tone wood, and whether or not a thin surface layer is enough to change the major vibrational frequencies of the tone wood.

With today's technology, violins and other string instruments are made out of many kinds of materials other than wood such as carbon fiber and plastic.[8] One group of scientists at Pacific Northwest National Laboratory is studying the process of wood petrification.[9] Their method to create this "petrified" wood has it soak in strong acid for several days, with a rinse and then subsequent soaking in silica solution, air dry, and then is put into an argon-filled oven at 1400°C to bake for a few hours, leaving behind something very similar to true petrified wood.[9] In this method, the acid soak removes all material within the wood, leaving behind the cellulose base, of which the silicon fills in the gaps and binds with that carbo-based backbone structure. After baking, this forms a ceramic of sorts, leading to the similarity between it and petrified wood. If this method could be easily reproducible in other laboratory settings, further research could be completed on its potential use in violins and other string instruments. The advent of these new materials for instrument use introduces a new element to the analysis of violin quality because they are not wood; therefore, the method of analysis must be able to encompass these materials.

Varnishing the wood also changes the surface structure of the wood, but the comparison of varnished, silicated, and other forms of treated tone wood regarding the physical characteristics and major vibrational frequencies has yet to be completed within the same study or with the same method of analysis.

The vibrational characteristics of the violin components are unique and therefore optimized for each individual violin, necessitating a quantitative and objective study of violin quality. Although measuring how the material affects the resonance frequencies of the unattached front and back plates of violins has been done for many years, the results have been difficult to quantify. These previous studies are stepping stones to determining the overall quality of violins and other string instruments based upon their tone wood and the chemical treatment or modification of that wood. Hutchins's laser interferometry study provides a good basis for quantitative analysis of plate quality focused on resonating frequencies in one dimension. Adapting this type of analysis for two dimensions may allow for a more quantitative and method of analysis that can be applied to more materials than just wood that are used in violin construction. Luthiers and others continue their search for the best wood and methods to recreate the beautiful-sounding violins of old, so creating a two-dimensional method for analyzing violin quality may assist them on that journey.

Methodology

Vibrational spectroscopy is the study of electromagnetic radiation and its application, with analysis tools available for both absorption and emission spectroscopy. The relevant analogous technique for this study is the absorption spectroscopy of Infrared (IR) spectroscopy.[10] IR spectroscopy provides information on molecular symmetry, bond vibrations, bond distances, and bond angles of a chemical compound. This is done through the analysis of an IR spectrum, which is the graphical output of the aforementioned information. IR can be sensitive enough to also recognize overtone bands or couple frequencies, which show up as peaks in various places along the spectrum that hold specific meaning for each compound. This type of two-dimensional analysis can be applied to string instrument resonance frequencies. The vibrational analysis in this situation looks at the resonance frequencies of the wood rather than bond vibrations and can also determine coupled and harmonic frequencies.

This study looked at those vibrations within an unattached violin front plate and tone wood strips. The vibrational analysis was performed in the soundproof chamber depicted in the block diagram below in Figure 1. This soundproof chamber and analysis method were devised previously in Dr. Hanson's laboratory using unattached violin plates.[11] The chamber consisted of a large speaker on the back wall to send frequencies from an oscilloscope at the violin plate at a loud volume, with soundproofing in place to minimize outside noise interference.

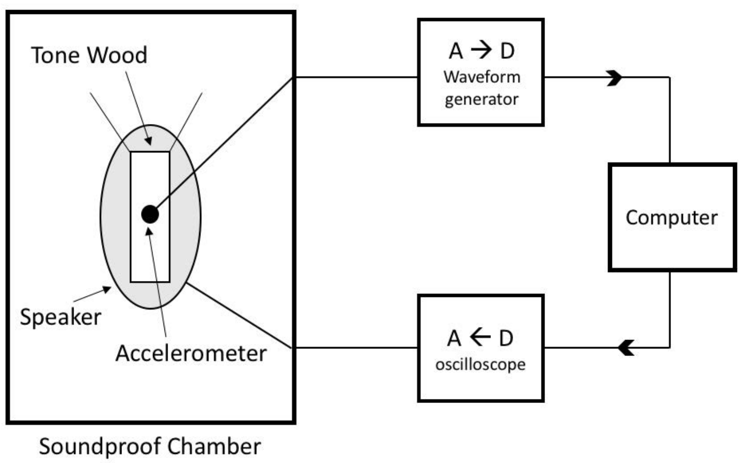

Figure 1. Block diagram of the soundproof chamber and computer setup for vibrational analysis.

The program Measurement and Automation Explorer was used to manage the analysis through three different computer parts. National Instrument 5102 is the PCI digital oscilloscope card, which is depicted as the digital to analog converter in the diagram and sends signals to the speaker so that it sends out frequencies in 10 Hz intervals in the range of 10 Hz to 5000 Hz.

National Instrument 5411 is the PCI arbitrary waveform generator, shown as the analog to digital converter, which transforms the raw data output collected from the piezoelectric micro-accelerometer into a one-dimensional waveform graph. Lastly, PCI 6711 is the analog digital output card that controls the pulse generator sequences. LabView was the program used to control the system and interpret the data collected from the oscilloscope and the piezoelectric micro-accelerometer directly affixed to the unattached front violin plates and tone wood strips.

Inside the soundproof chamber, the unattached violin plates and tone wood strips were hung parallel to the speaker on the back wall. Fishing line was strung between two hooks secured to the top of the chamber. These hooks were modified to have to sections of fishing line with loops at the end to hang the unattached plate by the upper bout corners as seen in Figure 2. Light pencil marks indicated the three-centimeter by three-centimeter coordinate system devised to measure how the amplitudes of various frequencies changed over the plate while maintaining symmetry. The center of the plate served as the origin and the top- and bottom-most points served as the most positive and negative coordinates, respectively, allowing for cataloging and graphing of all points systematically. This grid system was replicated on another unattached front plate that had been carved into a very flat shape, which subjectively indicates poor violin quality.

Figure 2. Spruce wood unattached violin front plate hung in the soundproof chamber with the micro-accelerometer attached for vibrational analysis.

The same loops the plate hung by were used to hang the pieces of tone wood from two clips on the top corners of the strip, shown in Figure 3. Notches originally were going to be carved near the top of the tone wood strips, but after completing the first acid treatment for one, it was determined the wood weakened significantly and therefore the notches would not last through additional treatments. For analysis of the tone wood strips, two points located at the bottom and the middle of the strip were used to measure the major vibrational frequencies. Only two points were selected for analysis because the wood pieces were all simple, flat rectangular shapes, so symmetrical responses were expected between the top and bottom halves of the pieces of wood, even after treatment. The wood pieces were fully submerged or evenly coated during the treatment process, so variation was determined to be unlikely and therefore not looked at.

Figure 3. Spruce tone wood strip hung in the soundproof chamber with the micro-accelerometer attached for vibrational analysis.

In this study, tone wood strips of equal size and shape were treated with various chemicals to determine their effects on the composition and resonance frequencies of the tone wood. All of the tone wood used was spruce. Treatments such as 6M and 12M sulfuric acid (H_2SO_4), polymer, sodium silicate solution ($(Na_2SiO_2)_nO$), and brown acrylic paint were used. Physical attributes such as color and flexibility were analyzed as well. The free induction decay, or the length of time the wood vibrates and rings, of each treatment were measured and compared to the untreated control and other treatments.

The vibrational analysis occurs through the measurement of response frequencies produced in the violin plate wood, as captured by the accelerometer. Shown in Figure 4 is a side view diagram of the wood in the chamber for analysis. This diagram illustrates a simplified version of how the analysis method works. From the speaker, a frequency is applied to the wood, at V_1 and then the accelerometer measures the amplitude of the response of the wood at V_1.

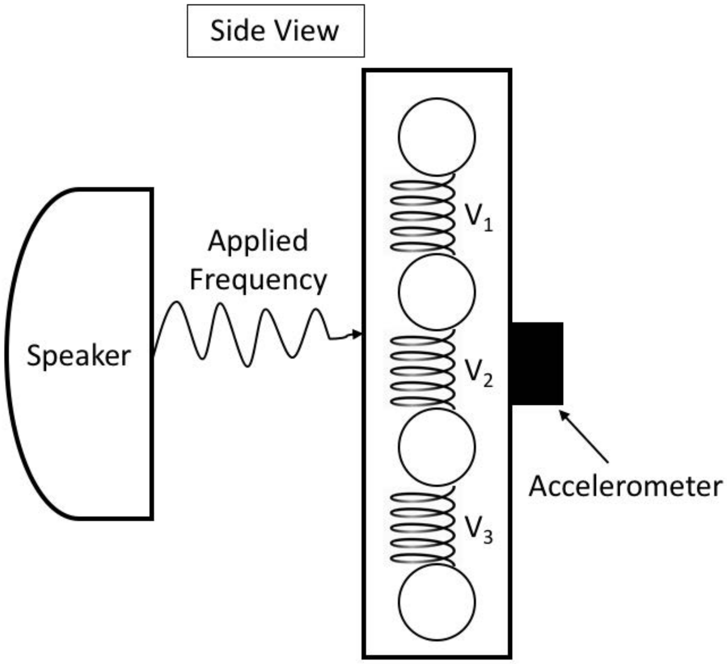

Figure 4. Side view diagram of the soundproof chamber setup for vibrational analysis.

This application of a frequency and the subsequent response is illustrated graphically in Figure 5. The graph in Figure 5(a) is the intensity of the frequency being applied, while (b) is the waveform graph showing the progression of the frequencies being applied. Figure 5(c) is a one-dimensional plot of the response frequencies and their amplitudes of the wood at a given coordinate. This one-dimensional analysis is important, but the method in this study takes this one step further, into two-dimensional analysis.

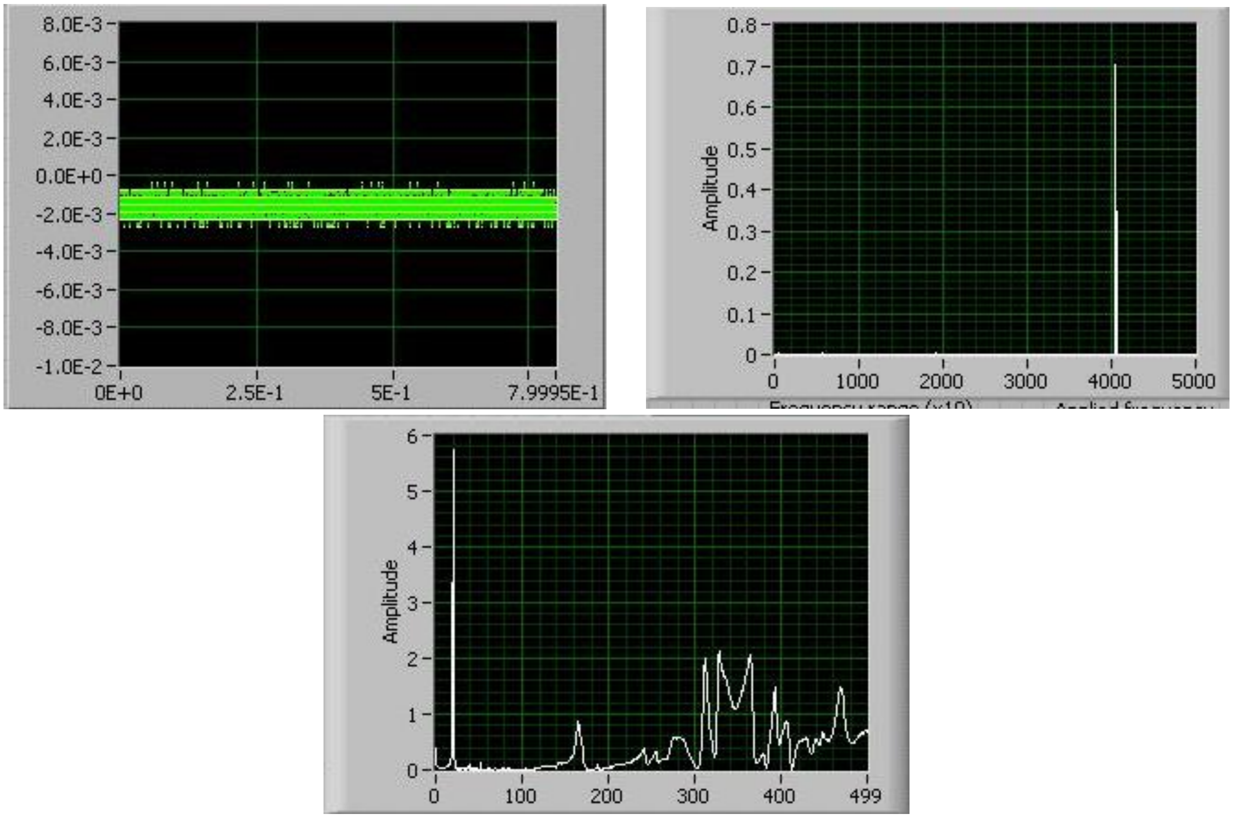

Figure 5. (a) Intensity of frequency being applied. (b) Waveform graph showing progression of applied frequencies and amplitudes. (c) One-dimensional plot of the response frequencies and their amplitudes.

Two-dimensional vibrational analysis is important because it allows for data analysis of more than just the major response frequencies of the unattached violin plates and tone wood strips. This type of analysis looks at frequencies that are coupled with the major response frequency. The best way to visualize it is with four circles attached in a line with springs in between each one, as depicted in the cartoon of Figure 6. The three vibrational modes are represented by V_1, V_2, and V_3, respectively. When a specific frequency is applied at, for example, V_1, the goal is to analyze all frequencies produced. In this situation when V_1 is applied, the response frequencies would be V_1 and V_2 because the frequency put in is always put back out, but V_1 is coupled only to V_2, so it has a lower amplitude but is seen by the detector. When V_2 is applied, all three frequencies are detected, because V_2 is coupled to both V_1 and V_3, so all three have amplitude and respond to the applied frequency. Lastly, if V_3 is applied, then V_3 and V_2 will be detected due to their coupling.

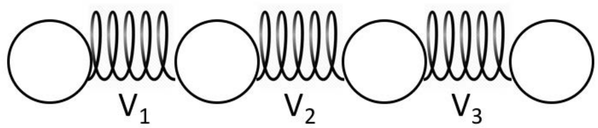

Figure 6. Cartoon depiction of vibrational modes in a system.

This shows how modes are coupled and how big the harmonics and depth of the frequencies created are. Using this method of analysis, a more complete picture of the major response frequencies and their coupled, harmonic counterparts could be drawn, and conclusions made about the effects of chemical modification on tone wood and its quality within violins.

Results

The unattached violin front plates had similar major response frequencies, but they differed in their amplitudes and contour plot shapes. The two-dimensional plots revealed multiple coupled frequencies with the major response frequencies, along with some frequencies that appeared to be present as background all of the time. These plots are illustrated in Figure 7, where the darker the color, the higher the amplitude. The graph on the left is the one-dimensional plot with all of the response frequencies at that coordinate without showing any coupling. These are the major response frequencies over the range of applied frequencies, with the highest amplitudes occurring at approximately 250 and 430 Hz at this coordinate. Figure 7(b) shows the principal response frequencies as the large diagonal line down the center with amplitude shown in the negative direction. The fainter diagonal lines are the coupled frequencies, or harmonics, that were detected along with the major response frequencies. These have significantly lower amplitudes, which is expected from a coupled frequency, but their presence indicates coupling is occurring within the wood. The vertical lines represent background noise, frequencies that were present in all of the samples taken and do not play a role in determination of the major response frequencies.

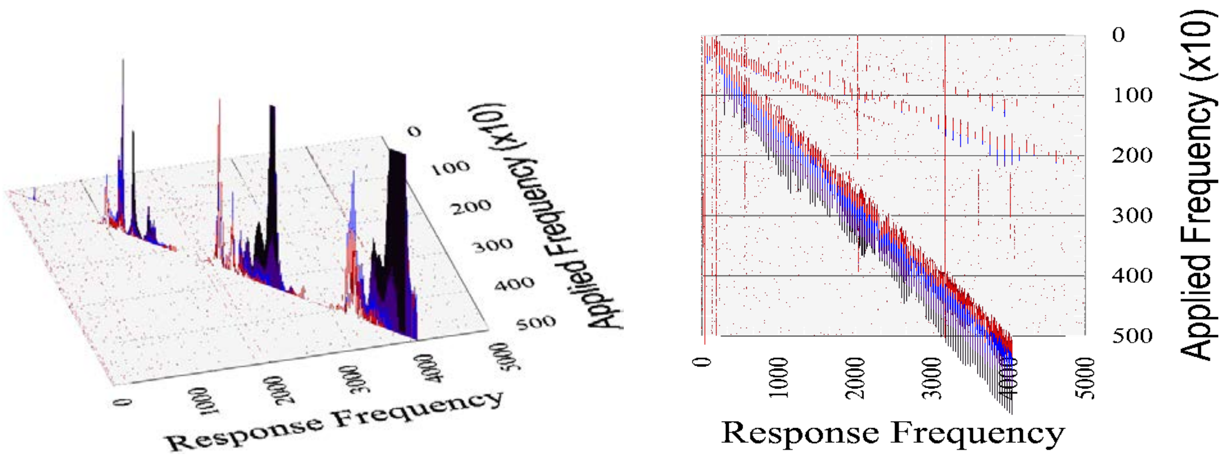

Figure 7. (a) One-dimensional plot of response frequency versus applied frequency on the normally carved unattached violin front plate at coordinate (3, -6). (b) Two-dimensional plot illustrating the secondary harmonics with frequency for the normally carved unattached violin front plate at coordinate (3, -6).

Once this was completed for the normally carved plate and the flat-carved violin plate, analysis was done to determine the most common response frequencies throughout both plates; these would be considered the major response frequencies. For the normally carved plate, the four major response frequencies were 110, 250, 330, and 420 Hertz (Hz). Surface contour plots of the violin plate at these four frequencies were created to provide a visual of the response pattern over the entire plate. Figure 8 shows these plots for the normally carved unattached front plate, where the color blue indicates higher amplitude and red indicates lower amplitude. Violins tend to resonate best at lower frequencies, which matches the values gathered from this analysis. There also appears to be some slight symmetry between the top half and bottom half of the plate for most of the frequencies, which shows that the wood was carved well in a symmetric manner. The bass bar and f-holes also show higher amplitudes, as the bass bar is on the right-hand side of the plate in the plots, and the f-holes are just inside the lower bout corners towards the center of the plate in the surface contour plots.

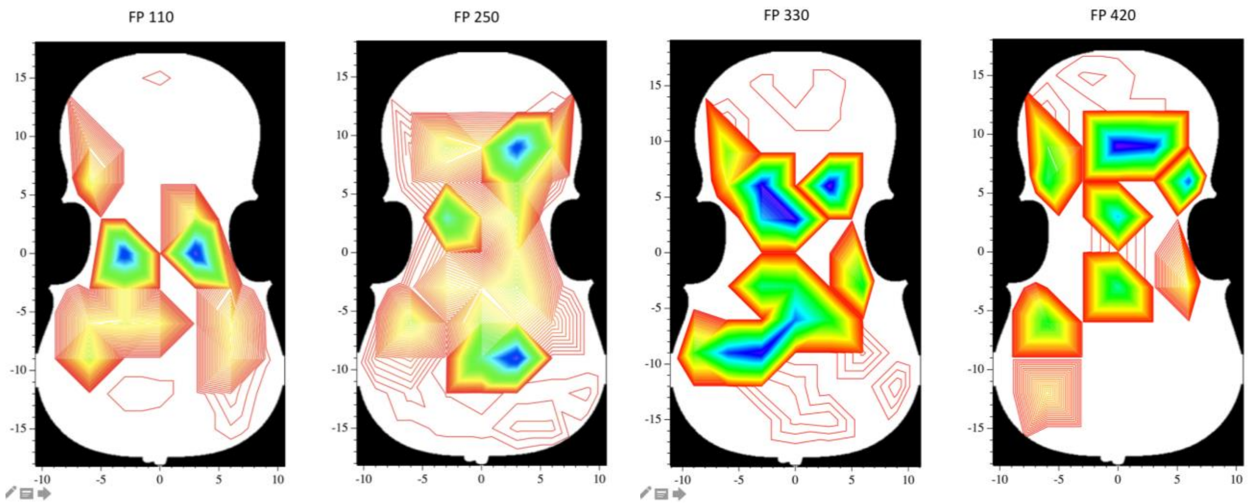

Figure 8. Surface contour plots of the normally carved unattached violin front plate from left to right at 110, 250, 330, and 420 Hz.

These major response frequencies were tested with another method of analysis for determining the vibrational modes of a violin plate called Chladni lines. This was done to confirm that the values determined from the accelerometer were similar to the true modes of the violin plate and were accurately determined. Chladni lines form when sand, or a similar grainy material, moves from an even, scattered distribution across the plate and forms into a distinct line pattern at the node of the plate for that specific frequency being applied. This process is shown in Figure 9. The first image shows the initial scattered sand, with images two and three representing the Chladni lines at 230 Hz and 340 Hz, respectively. These two nodes are similar to the two major response frequencies of 250 Hz and 330 Hz found electronically on the plate.

Figure 9. Images of the normally-carved unattached violin front plate with Chladni lines. From left to right, the initial sand scattering, 230 Hz Chladni line, and 340 Hz Chladni line.

This experiment was important to perform as it indicates that the two-dimensional method devised in this study recognizes the major response frequencies in the same locations as the traditional method of acoustic analysis. Ernst Chladni developed this method in the late 18th century to reveal the complex patterns of vibration in a rigid surface.[6] This method moves the sand to areas of little to no vibrational motion when a frequency is applied to the plate, which are called the nodal lines. These lines, when looked for in the accelerometer data, show up as low amplitudes in the surface contour plots. While the grid system used may be too large to clearly see the line pattern, there are similarities in the absence of sand in the center of the plate where the plots show high vibrational motion. Performing the Chladni experiment supports the method created here and acts as proof of concept that technology can do the same thing that sand and a speaker can in terms of determining vibrational motion.

After analysis of the normally-carved front plate was completed, the second, flat-carved plate was analyzed using the same accelerometer-based method. The four major response frequencies for the flat plate were at 120, 250, 320, and 420 Hz, which are very similar to the normally-carved front plate. The surface contour plots at these frequencies are illustrated in Figure 10, where blue color indicates higher amplitude and red indicates lower amplitude at that coordinate on the plate. Across the entire plate, amplitudes were significantly lower than the normally-carved front plate.

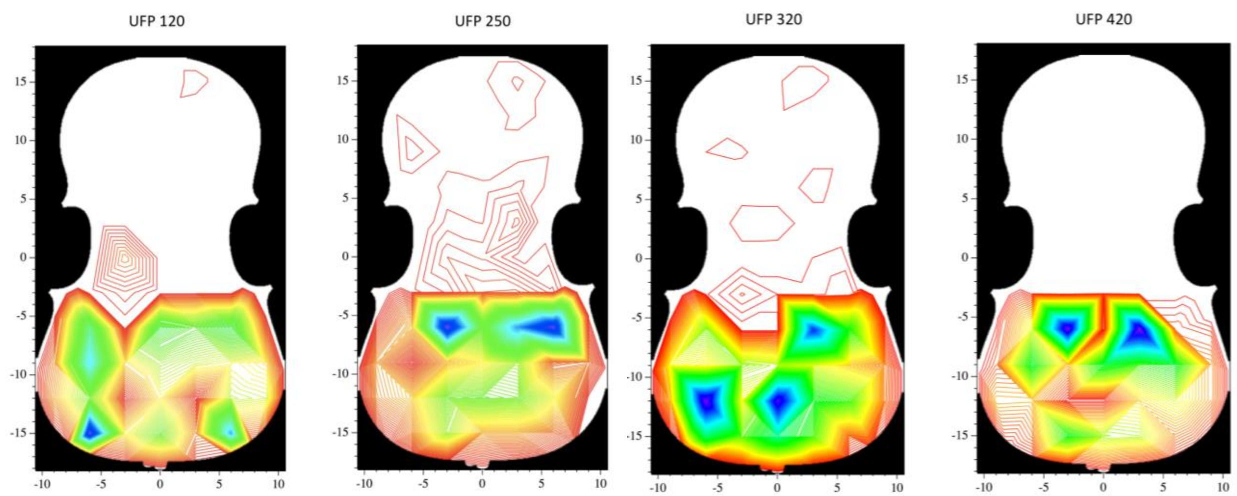

Figure 10. Surface contour plots of the flat-carved unattached violin front plate at the major resonance frequencies from left to right at 120, 250, 320, and 420 Hz.

The flat plate showed significantly lower amplitudes and lower symmetry across the entire surface. This indicates a poor carving as the resonant frequencies do not appear much in the top half of the plate, like they do in the normally-carved plate. The lack of symmetry is expected as the plate was intentionally carved in a flat manner on the lower half to determine if there were differences in the vibrational response patterns. Around the f-holes the amplitudes did increase slightly, as expected from the normal plate, but the amplitudes are still much lower than any seen on the normal plate. The resonance pattern of the flat plate appears to be primarily in the lower half of the plate with only the f-holes giving a clear reason for increases in amplitudes.

With the preliminary study of the unattached violin front plates completed, chemical modification of tone wood was performed. Strips of spruce tone wood of similar size, shape, and mass were treated with various chemicals, as pictured in Figure 11. The treatments included a polymer solution, 12 Molar (M) and 6M sulfuric acid, sodium silicate solution, and brown acrylic paint. For all treatments except the untreated control, acrylic paint, and 12M sulfuric acid, the wood was first soaked in 6M sulfuric acid for three days, water for three days, acetone for two days, and finally baked in an oven at 50°C overnight to drive out any remaining acetone within the wood matrix. This soaking was done to leave as much of the cellulose base behind while getting rid of the other organic matter within the wood matrix to allow for easier penetration of the polymer and sodium silicate treatment solutions. The 6M sulfuric acid is a moderately strong concentration of the strong acid, rendering it more useful for this process over other strong acid options for acid treatment.

Figure 11. From left to right, the various treated tone wood strips: polymer solution, 12M H_2SO_4, untreated, sodium silicate solution, 6M H_2SO_4, brown acrylic paint.

The flexibility of the treated tone wood strips varied. The 12M sulfuric acid soak disintegrated the outer half of the wood strip, leaving behind a very thin, brittle strip with dark marks from the acid all over it, which is shown in the second from the left position in the figure. Even though the strip lost a large portion of its mass and became extremely fragile, it was still viable for vibrational analysis. The least flexible of the treated woods was the sodium silicate-treated strip, as once the silicate hardened, it was essentially glass-coated wood. The polymer-treated wood was less flexible than the untreated wood, but still had some bend to it. The 6M sulfuric acid and acrylic paint wood strips were similar in flexibility to the untreated wood.

The sodium silicate treatment was explored further in an attempt to replicate the work done at Pacific Northwest National Laboratory with their quick petrification method mentioned previously. Figure 12 is an image of the result of a piece of tone wood that had been soaked in the sodium silicate solution under vacuum for approximately a week after baking in an oven at 700°C for several hours and cooling gradually. The image shows that the sodium silicate was unable to fully penetrate the full thickness of the wood, resulting in the disintegration of the interior of the strip from the high temperature. This showed an inefficiency with the soaking method for the sodium silicate solution, and this path was taken no further.

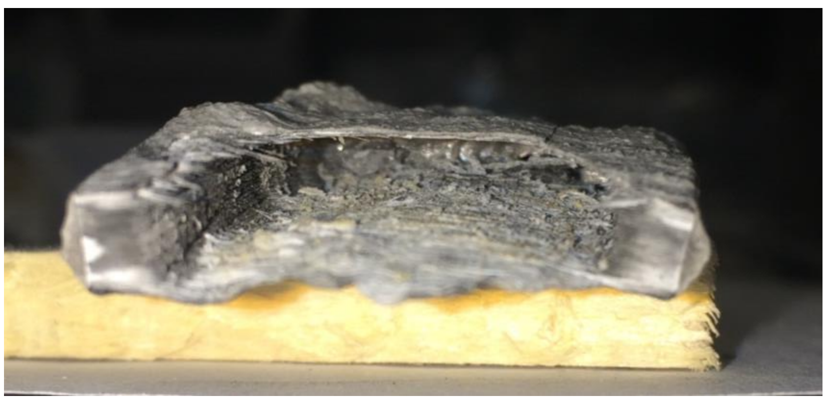

Figure 12. Image of the sodium silicate treated tone wood strip after baking, exhibiting the absence of the interior of the wood strip.

A purely silicate-carbon strip was also tested in the oven, to determine if the organic matter from the wood was the issue in the first attempt, or if it was something else. The strip was made using a mold and filling it with a mixture of one part carbon to five parts sodium silicate solution and allowing it to dry completely before heating. Once dried, the strip was analyzed in the chamber to look at its vibrational response before and after heating. However, after baking in the oven, the strip deformed and curled significantly, rendering it useless for vibrational analysis post-heating, but the data collected before was still applicable. This strip provides insights into how non-wood materials compare to untreated and chemically modified tone wood. The major response frequencies for the tone wood strips were similar to the unattached violin front plates, as seen in Figure 13.

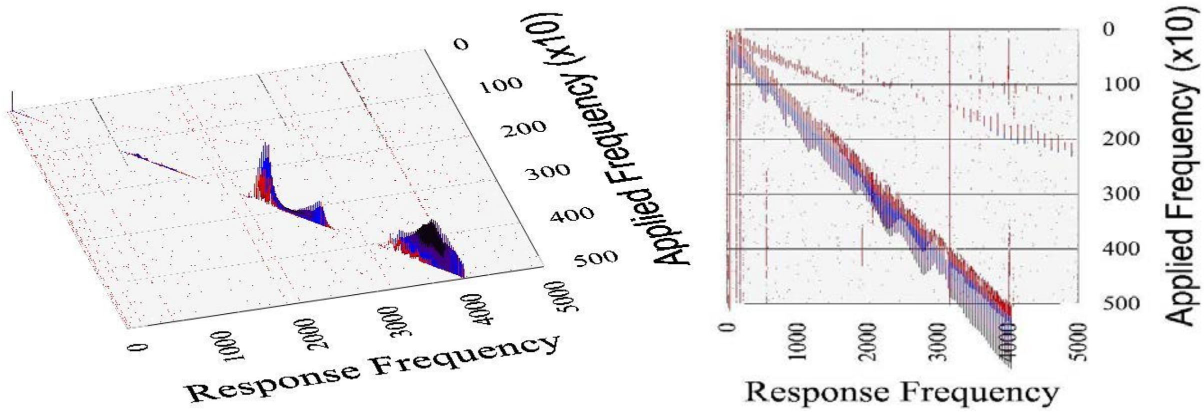

Figure 13. (a) One-dimensional plot of response frequency versus applied frequency at the midpoint on the untreated tone wood strip. (b) Two-dimensional plot illustrating the secondary harmonics with frequency at the midpoint on the untreated tone wood strip.

The two-dimensional analysis plot on the right shows frequencies coupled with the major response frequencies distinctly, along with some new background frequencies. In this instance, the one-dimensional plot shows the major response frequencies to be at 250, 360, and 400 Hz, which are close to the unattached violin plate major response frequencies detailed earlier in this study. The resonance pattern over the strip appears to be similar to that of the unattached violin plates, with the center vibrating and resonating the most, and the endpoints resonating the least. This is illustrated in the surface contour plot in Figure 14, which shows the pattern at 290 Hz. The axis on the left indicates the height of the strip, and the right axis indicates the width of the strip. The strip was approximately eight millimeters thick. The purple color means higher amplitude while red means lower amplitude at that location. All points were measured at the center of the strip.

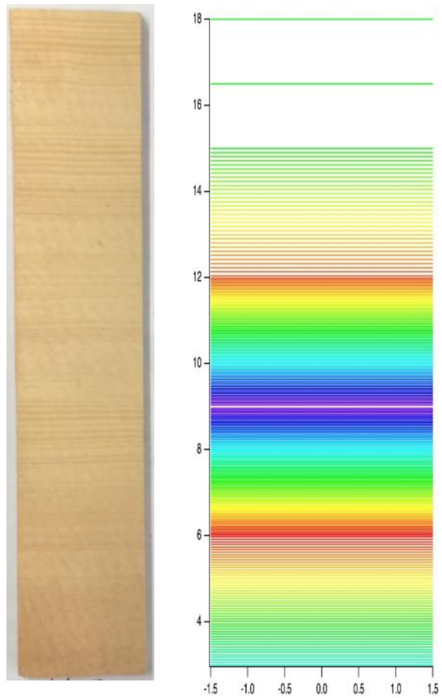

Figure 14. Surface contour plot of the carbon-sodium silicate tone wood strip at a major resonance frequency of 290 Hz, with the untreated tone wood strip as reference.

This is indicative of the tone wood strips acting as a pseudo-miniature version of the violin plates with the middle providing the most response and the outer ends providing a minimal response. The significantly low response at six and twelve centimeters on the strip may indicate a more complicated resonance pattern within the strip, but it is unclear at this time what it may mean. The symmetry within the strip is reflective of the unattached violin plates between the top and bottom halves, further strengthening the argument for the wood strips modeling the plates. A diagram of this resonance pattern is illustrated below in Figure 15. The wood is moving such that the most movement occurs directly in the center, with less movement occurring just outside the center, and moderate outer edge movement. This movement of the tone wood strip mimics that of the violin plate, supporting the wood strips acting as models for the plates.

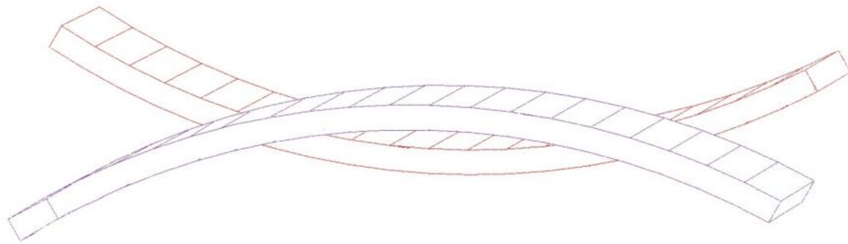

Figure 15. Diagram of tone wood strip vibrational movement pattern.

The major response frequencies and amplitudes at both the midpoint and endpoint for all of the tone wood treatments are shown in Table 1. The untreated frequencies and amplitudes are underlined for clarity purposes in determining how the treatments deviated from these responses. The middle and end were selected based on a hypothesis that they would be similar in response amplitudes and frequency to the full violin plates, so a full nodal analysis was not completed on all of the treatments because of that. The untreated response frequencies were very similar to the unattached violin front plate.

Table 1. Major response frequencies and their corresponding amplitudes for all tone wood treatments at the midpoint and endpoint of the wood strip.

	Major Response Frequencies					
Treatment	*Middle Point: Frequency/Amplitude*			*Bottom Point: Frequency/Amplitude*		
Untreated	240/10	360/75	400/25	10/13	240/4	360/13
Polymer	250/65	385/68	400/90	20/12	300/11.5	390/18
6M H_2SO_4	320/30	350/40	400/26	10/25	260/7.5	380/24
12M H_2SO_4	280/140	340/100	420/60	5/93	290/18	370/38
Acrylic Paint	270/125	360/50	420/30	15/5	290/16	370/7.5
Sodium Silicate	310/12	360/10.5	410/19	20/4	160/1	330/2

Clear differences in response frequencies and amplitudes appeared between the midpoint and endpoint for all of the treatments. The midpoint consistently had much higher amplitudes than the endpoint for each strip. All of the treated woods aside from the acrylic paint showed shifts in the response frequencies in comparison to the untreated tone wood. Overall, the differences in response frequencies on the plates and strips illustrate that the two-dimensional analysis is effective in comparing different materials and shapes to each other that can be applied to determining the quality of material or plate being studied.

Discussion

The two-dimensional vibrational analysis of both the unattached violin front plates and the chemically modified tone wood provides great insights into how violin modes change with applied frequency. Between the two unattached front plates, the four major response frequencies were analogous. The normally-carved plate resonated most at 110, 250, 330, and 420 Hz, while the flat-carved plate resonated most at 120, 250, 320, and 420 Hz. This indicates that the shape of the violin likely does not play a major role in which frequencies resonate most throughout the entire plate. However, the symmetry of the plate is considerably changed, and this was reflected in the surface contour plots; the flat plate primarily resonated in the lower half, while the normal plate had good top and bottom symmetry for frequency and amplitudes. Furthermore, the amplitudes of the flat plate were consistently much lower than the normal plate, meaning the coupled frequencies were also present in a much smaller capacity, and the sound produced would be lesser in quality than a normal violin. The method used here detected these differences, and it can be applied in determining violin quality based on the front plate curvature; the flatter the plate, the lower the volume and quality of sound and resonance the violin will have in comparison to a nicely curved violin plate.

Performing the Chladni lines experiment was important because it supports this method as a proof of concept that the computer program can find the same vibrational nodes that the sand does for the Chladni lines. While the nodal lines in the sand form based on sending a single specific frequency at the violin plate, the method using the accelerometer at various locations over a range of frequencies maps out these nodal areas at each coordinate. This experiment also shows why amplitudes at a given coordinate changes with the frequency applied because different parts of the plate resonate more in different locations than others at any given frequency. It allows for the violin nodes to be mapped and then analyzed for the quality of sound the violin will produce based on those nodes.

The chemical modification of the tone wood strips illustrates the need for quality materials when constructing a violin in order to produce the desired sound. The response frequencies shifted in one direction or the other for all of the treatments aside from the acrylic paint when compared to the untreated wood. The paint did not shift due to the paint being an extremely thin surface layer on top of the wood, rather than a full soak in the paint that penetrated the wood fully. The polymer treated wood had an approximate mass of one-and a half that of the untreated control, and it shifted frequencies about 10 Hz with comparable amplitudes at both points. The sodium silicate treatment weighed twice that of the untreated control and shifted frequencies lower by approximately 20 Hz with amplitudes lower by over a factor of two, indicating that the silicate affects the amount of vibration that occurs the in the wood due to its glass-like nature after hardening. Using this type of material would likely pose issues for violins as it would require much more effort to get sound out of the violin because it would resonate less. For the two sulfuric acid treatments, the 12M treated wood had half the mass of the untreated wood and shifted at least 20 Hz to higher frequencies with approximately one-and-a-half times the amplitude. The amplitudes were likely due to the thinness of the wood allowing for the vibrational response to be more amplified. The 6M acid treatment had similar mass to the untreated control, with slightly higher peak shifts of roughly 20 Hz but amplitudes close to the untreated wood's amplitudes. These results from the two acid treatments indicates that mass may play a larger role than previously expected in violin resonance and sound quality. Lastly, the one to five ratio of carbon to sodium silicate solution strip produced major response frequencies and amplitudes to the untreated control wood with one-and-a-half times more mass. However, because it did not contain wood, the relationship between mass and frequency response cannot be applied. This "synthetic" strip shows that fully non-wood materials can be analyzed with this method and the response directly compared to other materials and treatments.

Through this study, the tone wood showed a relationship between mass and amplitude of the major response frequencies. The larger the mass, the lower the vibrational amplitude, which is caused by a greater absorbance of the sound by the wood. For the lighter masses, the amplitudes were higher, and a higher response frequency was achieved due to less sound absorption by the wood. As was discovered with one test of the sodium silicate treatment, the inability for this treatment, and potentially others, to fully penetrate the wood may have impacted the results as the interior of the wood strip was untouched. This instead makes the treatment more of a surface layer over top of the wood strip, with a minimal amount actually settling into the tone wood. This two-dimensional vibrational analysis method can also be applied to synthetic materials with reasonable accuracy as seen with the carbon and sodium silicate mixture strip. Overall, the treatments affected the vibrational response of the tone wood strips in both directions for amplitude and response frequencies produced, indicating the method works and the treatments did alter the structural makeup of the wood for those differences to be detectable.

Conclusions

Chemical treatment and the impact of coating such as varnish on instrument quality have been a topic of study for centuries. Firstly, the quality of the carving and curvature of the unattached violin front plates changed which part of the plate had the highest amplitudes for the major response frequencies. The normally-carved front plate showed a clearer pattern of vibrational nodes at two of the major response frequencies, 250 and 330 Hz. The bass bar and f-holes also showed larger amplitudes on this plate due to less sound absorbance occurring near those locations. This plate also showed good symmetry between the top and bottom halves, with similar amplitudes occurring at opposing coordinates. On the other hand, the flat plate had low amplitudes across the whole plate, indicating high sound absorbance, with most of the response occurring in the lower half of the plate. These two plates illustrate the effectiveness of this two-dimensional analysis method for detecting differences in sound quality based on the curvature and carving of an unattached front plate.

Using strips of tone wood as a model for violin plates, these studies show the relative impact of surface treatment of tone wood to the vibrational response from applied frequencies. Although greatly simplified, a single strip of tone wood mimics the nodal characteristics of a full violin plate. This is shown by the large differences in amplitudes from the end to the center of the strip, with the middle of the strip resonating with the highest amplitudes and a significant drop in amplitudes at the ends of the strip. This suggests that the ends of the tone wood strip act as nodal points with the center of the strip acting as the active mode, or the part where sound resonates and is produced.

These studies suggest that surface treatment of the tone wood is largely negligible in terms of vibrational response compared to the mass of the material used. In the experiments detailed previously, the larger mass of the sodium silicate treated tone wood resulted in a significant drop in amplitude and shifting of major resonance frequencies to lower values; the smaller mass of the 12M sulfuric increased in response amplitude and resonated at slightly higher response frequencies compared to the untreated tone wood strip. Therefore, it is reasonable to predict that the lighter and thinner the material used in construction, the higher the vibrational response and greater the sound produced from the violin.

The data gathered in this study provides the starting point to having a fully quantitative method of analysis for judging the quality of violins and other string instruments. Two-dimensional analysis of the vibrational modes of both unattached violin plates and chemically modified tone wood strips revealed important information about both things. Firstly, that this method allows for mapping out of violin plates based on major response frequencies and amplitudes to find the nodal patterns that each violin plate has, which can be corroborated with the Chladni lines experiment. Secondly, differences in the carving and shape of the plates were detected by the accelerometer and were seen to be significant based on amplitudes and regions of resonance in both plates. The chemical modification revealed that thin surface layers do not play a large role in determining response frequencies, but if the applied material penetrates the interior and leaves an outer coating, then the response frequencies and amplitudes may change. It did show a relationship between mass and response frequency amplitudes, though, leading to the conclusion that thinner, less massive materials will produce more sound than thick, heavy materials will in instruments. All of this information is helpful in creating a solid method of analysis for instrument quality that is objective and quantitative, which has been lacking in the field for a long time because subjective judging has been the only realistic method until recently.

Future Work

Future work will concentrate on multiple avenues with synthetic materials using the two-dimensional vibrational modal analysis method to quantitatively determine violin and other string instrument quality. The reason for this is to expand the reaches of this method and reduce the current limitations of the study. This study was limited by only looking at unattached violin front plates and chemically modifying only tone wood strips. Analysis of a complete violin and chemically treated unattached plates and full violins also should be done to fully determine how response frequencies can change throughout the construction process. More work will be completed on studying the effects on vibrational response of a very thinly-carved violin front plate to compare it to the previously studied unattached front plates. For chemical modification, studying synthetic materials to replace wood, such as a combination of carbon, bismuth, and sodium silicate, will also be done to see how various mixtures of non-wood materials compares to wood and to each other in terms of vibrational response.

A violin front plate, full violin, and strip of “tone wood” will be 3-D printed to determine if plastic can be analyzed with this method. All three of these would then be comparable to the wood analyzed in this study. Analysis of carbon fiber in some manner would also be a good idea, as it is becoming more prevalent for those who can afford an instrument made of that material, because they have comparable sound quality to classic violins. Luthiers and musicians could then directly compare carbon fiber, plastic, and classic wooden violins quantitatively with results from this analysis method in conjunction with their subjective feelings towards the different materials and sound production of each violin. Overall, more study on the effects of various materials, varnishes, and other applicable treatments used on violins and other string instruments needs to be done in order to generate enough applicable, reliable data to have a fully objective, quantitative view on the quality of an instrument.

References

1. Nagyvary, J. *J. of the Violin Soc. Of Am*. **1981**, 2: 57.
2. Wegst, U. G. K. *Am. J. of Botany*, **2006**, 93(10): 1439-1448.
3. Rymer, Russ. "Saving the Music Tree." *Smithsonian Magazine*, **2004**.
4. Dunlop, J. I. *Australian Acoustical Society*. **1989**, 17: 36.
5. Nagyvary, J. *Chem. Eng. News*. **1988**, 24.
6. Hutchins, C. M. *Scientific American*, **1981**, 245(4): 170-186.
7. Skrodzka, E. B., et al. *Archives of Acoustics*, **2013**, 38(1): 75-81.
8. Ono, T., and Isomura, D. *Acoust. Sci. & Tech*. **2004**, 25(6): 475-477.
9. Pacific Northwest National Laboratory. *Want to petrify wood without waiting a few million years? Try this.* **2005**. http://www.pnnl.gov/news/release.aspx?id=76
10. Noda, I. *Appl. Spectrosc*. **1993**, 47: 1329.
11. Martin, C. J. *Vibrational Analysis of Chemically Modified Wood*. Masters' Thesis. University of Northern Iowa, Cedar Falls, IA, **2005**.