

**STRUCTURAL PROPERTIES AND PERCEIVED
ACOUSTIC QUALITY OF MODERN VIOLINS**

A THESIS

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ABSTRACT

What does a good violin sound like? Violin dealers exploit the uncertainty of this question by massively inflating a violin's price, as there has not been a set method to visually distinguish an acoustically ideal violin from a random set of violins. A beginning violinist without proper ear training would likely make the mistake of selecting a poor-sounding violin intentionally made to attract the eye, potentially wasting hundreds of dollars on an inferior violin-shaped object. Subjective descriptions such as warmth and brightness have been thrown around to describe a violin's ideal sound, but a truly optimal violin would have a perfectly balanced combination of all tonal descriptions with every harmonic perceived at the same loudness corresponding to the equal-loudness contour, as well as boasting increased overall projection and resonance.

Two violins—one arbitrarily “good” and one “bad” sounding violin—were subject to vibroacoustic testing with a combination of accelerometers and microphones measuring the frequency response of the violins' top plate, spatially averaging 67 carefully chosen points. Heavy use of the fast Fourier transform was applied to analyze the magnitudes of harmonics generated by a string or bridge excitation method to confirm the improved tonal balance and resonance in the better-sounding violin, which was also expected to be more expensive. Great effort was made to remove inconsistencies between the two violins caused by differing parts, such as strings and other accessories, isolating the vibroacoustic effects of the violin's wooden body and its structural properties.

TABLE OF CONTENTS

ABSTRACT	ii
LIST OF TABLES	iv
LIST OF FIGURES	v
1. INTRODUCTION	1
2. VIOLIN TEST SAMPLES	22
3. STRUCTURAL-ACOUSTIC INTERACTION	35
4. SIGNAL PROCESSING METHODS	45
5. VIBRATION ANALYSIS	52
6. ACOUSTIC ANALYSIS	74
7. RESULTS	80
8. CONCLUSION	97
APPENDICES	99
A. SENSOR DRAWINGS	100
B. CALIBRATION CERTIFICATES	104
REFERENCES	108

LIST OF TABLES

5.1. Hammer Sensitivity for Various Tip-Extender Combinations [31].....	59
7.1. Frequency Response at the 2 nd and 8 th G-String Harmonic.....	95
7.2. Frequency response at the 2 nd and 8 th E-String Harmonic.	95

LIST OF FIGURES

1.1. \$8,614 Buffet Crampon clarinet (top) and \$192 Apollo Clarinet (bottom) [1,2].....	2
1.2. \$50,000 violin (left), \$8,000 violin (center), \$225 violin (right) [3-5].....	3
1.3. Front and side view drawing of a violin [7].....	6
1.4. Violin string tension for various violin string materials.	8
1.5. Hill style tailpiece made from Pernambuco wood (left) and Harp style tailpiece made from boxwood (right) [15].	11
1.6. Violin bridge on the 1721 Stradivarius “Lady Blunt” violin [16].....	12
1.7. Net forces on bridge from various string materials.	13
1.8. Standard bridge positioning relative to the sound post and bass bar before any adjustments [18].	14
1.9. Top plate thickness mapping of a variety of antique and contemporary violins from reputable makers [19].	16
1.10. Graduating caliper used to check the thickness of a violin top plate [20].	17
1.11. Bass bar being fitted on violin (left), sound post viewed through f-hole (right) [21,22].....	18
1.12. Equal-loudness contour [23].	20
2.1. Front view of 2019 William Bagnato violin, \$4,250 (left) and 2021 Franz Hoffman Vienna violin, \$269 (right).....	25
2.2. Labels for the \$4,250 William Bagnato violin and the \$269 Vienna violin.	26
2.3. F-hole overall dimensions on the expensive violin.	28
2.4. F-hole overall dimensions on the cheap violin.....	28
2.5. Overall thicknesses of both expensive violin (left) and cheap violin (right).	29
2.6. Width of expensive violin (left) and cheap violin (right) at the narrowest point.....	30
2.7. Plastic Wittner tailpiece (left) and ebony Hill tailpiece (right) [25,26].....	32
2.8. Bridge on expensive violin (left) and modified bridge on cheap violin (right).	33
2.9. Brandt style chinrest (left) and Guarneri style chinrest (right).	33

3.1. Longitudinal wave propagating through a plate or beam.	36
3.2. Shear wave propagating through a plate or beam.	38
3.3. Flexural wave propagating through a plate or beam.	40
3.4. Measured wave speeds in a plate that is 10 centimeters thick.	41
3.5. A simplified circular violin vibrating sound waves into an anechoic tube.....	42
4.1. LabVIEW block diagram.	50
5.1. PCB 352A24 Accelerometer [29].	53
5.2. Amplitude Response of the PCB 352A24 Accelerometer [29].....	54
5.3. Phase Response of the PCB 352A24 Accelerometer [29].	55
5.4. Typical test accelerometer response [29].....	55
5.5. Petrowax used for accelerometer adhesive on the violins [30].	56
5.6. PCB 086E80 Impulse Modal Hammer [31].....	57
5.7. Response curves for the PCB 086E80 Impulse Modal Hammer [31].	58
5.8. NI USB-9234 module (left) and NI USB-9171 chassis (right).	60
5.9. A foam pad was used to mitigate stray vibrations during vibrations and acoustic testing.	61
5.10. 67 accelerometer test points.	63
5.11. Accelerometer placed at various locations on the expensive violin: point 1 (top left), point 31 (top right), point 40 (bottom left), and point 67 (bottom right).	64
5.12. Placement of an accelerometer at point 21, under the fingerboard.	65
5.13. World-class violinist Hilary Hahn performing Brahm’s violin concerto with her bow at the midpoint between the fingerboard edge and the bridge [33].	67
5.14. Violinist Hilary Hahn shifts the contact point of the bow towards the bridge when playing a high note [34].	67
5.15. Sample trials of string excitation measured by attaching an accelerometer to the tip of a guitar pick.....	69
5.16. Four locations selected for the bridge excitation method.	71

5.17. Bridge excitation location on expensive violin (left) and cheap violin (right).	71
5.18. Sample trials of bridge excitation via the PCB 086E80 impulse hammer.....	72
6.1. PCB 130F20 Array Microphone [35].	75
6.2. Response plot of the PCB 130F20 Array Microphone [35].....	76
6.3. Anechoic chamber designed by Industrial Acoustics Company, Inc. for the Acoustics Lab at CSULB.	77
6.4. Violin ready for acoustic measurements inside the anechoic chamber (left).	78
6.5. The tripod, holding the microphone, is carefully wedged into the anechoic wedges.....	79
7.1. Frequency spectra from accelerometer spatial averages of all points when excited by the string.....	81
7.2. Grouping for three subsections: top, middle, and bottom.....	83
7.3. Frequency spectra using accelerometer spatial averages of top, middle, and bottom subsections when the G-string is excited.	84
7.4. Frequency spectra using accelerometer spatial averages of top, middle, and bottom subsections when the E-string is excited.	86
7.5. G String performance at the 1 st harmonic.	87
7.6. E String performance at the 1 st harmonic.	87
7.7. Frequency spectra using averages of all points along the edges of the violins.....	88
7.8. Frequency spectra using averages of the four points surrounding the bridge (points 34 to 37).....	90
7.9. Frequency spectra at each of the four points surrounding the bridge (points 34 to 37). 91	
7.10. Frequency spectra using microphone measurements of the violins when excited at the strings.....	94

CHAPTER 1

INTRODUCTION

There is a delicate bond between a musician and their instrument, which is expected—a musician will be interacting with their instrument for thousands of hours during both of their lifetimes. However, a musician starts with no musical experience accumulated and therefore has no idea of what qualities to look for in an instrument. With no guidance, the most obvious idea would be to go for the most affordable, yet playable instrument that will be just “good enough” for the aspiring musician to develop their fundamental skills. Of course, this idea of a good-enough instrument will be highly subjective and skewed by the musician’s lack of auditory skill and knowledge of an instrument’s capabilities. Nonetheless, an instrument must be chosen, and this process repeats as the musician progresses in their instrumental studies, with the overall average trend being that with higher skill, a more expensive instrument is required. This more expensive instrument ideally would be an “upgrade” from the previous instrument, whether it be in the playability or the sound based on the musician’s new idea of a quality instrument, budget considered. In some cases, the higher price may not even be attributed to any obvious functional use—perhaps a more expensive material was used, or the instrument was once owned by a famous musician. In either case, the musician will always pick an instrument with at least some bias towards one that would benefit their overall experience of being a musician given their budget.

With regularly manufactured instruments such as brass and woodwind instruments, the correlation between price and quality is quite straightforward. The manufacturer can undergo years of development focused on the direct improvement of sound and playability while still retaining the core clarinet sound. For example, the BCXXI B-flat professional-level clarinet designed and manufactured by Buffet Crampon, comes at an \$8,614 price tag, which is one of

the most expensive clarinets readily available for consumers. This amount is easily justifiable: while the Buffet Crampon brand sticker is enough to bump up the price, much work has been done towards sound-improvement measures in the clarinet. The poly-cylindrical bore, for example, is a recent innovation by the company, which allows for improved tuning between notes. Other developments by Buffet Crampon include the extension of the lower joint allowing for the placement of a resonance vent, a shorter bell that boosts the resonance of the entire clarinet rather than the fundamental notes E/B and F/C, ergonomic positioning of the clarinet keys, and a revised third fingering that improves overall resonance [1]. In addition to these design modifications, carbon fiber rings have been implemented to retain the weight of a traditional clarinet. This contrasts with a beginner-level clarinet that could be found on Amazon for less than \$200 with none of the sound-improvement strategies developed by Buffet Crampon [2].



FIGURE 1.1. \$8,614 Buffet Crampon clarinet (top) and \$192 Apollo Clarinet (bottom) [1,2]. The Buffet Crampon clarinet is made with high-quality material and has sound-improvement features.

For wooden string instruments such as violins and cellos, it is much more difficult to correlate the quality of the instrument with the purchase price. In the Shar Collection, owned by Shar Music, one of the biggest violin retailers in the world, there is a listing for a “French Violin labeled Lupot, Mid-19th Century” for \$50,000. The description for this instrument, however,



FIGURE 1.2. \$50,000 violin (left), \$8,000 violin (center), \$225 violin (right) [3-5]. The \$50,000 violin is the most expensive despite having cosmetic defects due to natural wear.

comments mainly on its sound qualities, describing “tonal balance,” and an ability to “speak more loudly and with less effort.” Surprisingly, the only comments on the violin’s build quality refer to its flaws, describing an “organic, asymmetrical outline” [3]. Looking at a less expensive \$8,000 violin labeled “Matthias Weineisen Violin, Germany, 1916,” also from the Shar Collection, there is nothing remarkable about the construction of the violin in the description. Also, like the \$50,000 violin, there are comments regarding a “well balanced” sound [4]. Looking at even cheaper violins in the \$200 range, the beginner-level violins from Shar music also note a “pleasing tone” and a “balanced response,” while also using the same advertised

materials its more expensive counterparts [5]. These descriptions of the violins are basically identical, so why should a violinist in the Los Angeles Philharmonic spend more than \$200 for a violin if it will provide the same sound as a \$50,000 violin?

The purpose of this thesis is to tackle the issue regarding the ambiguity of violin sound quality across several price ranges—there should be some hidden structural aspects of high-priced instruments that are responsible for their favorable sound. The highest-priced instruments are Stradivarius violins, built by Antonio Stradivari during the 17th and 18th centuries. These Italian violins are still widely praised for their acoustic quality and craftsmanship; despite the current availability of modern technologies to potentially improve on the violin design, they are still used as an acoustic and structural model for violin makers. Unfortunately, these violins are incredibly expensive, as much as \$16 million, so naturally, efforts have been started to replicate the sound qualities of Stradivarius violins in modern violins. In 2014, renowned soloists were presented with six newly made instruments and five Stradivarius violins and one 18th-century Italian violin of similar reputation. Each soloist was asked to blindly rank four of their favorite instruments, with four points being awarded to their top choice and a point deducted from the other rejected 8 instruments. Two modern instruments ended up being the highest ranked, with a Stradivarius violin surprisingly having the lowest ranking [6].

The study clearly showed that it was possible to create a close replica of Stradivarius violins at the fraction of the cost. Assuming the cost of a Stradivarius violin is mainly due to its antique history, it could be also inferred that much of the cost of the modern violins could also be due to the good reputation of the skilled modern violin maker as well as the high demand for instruments that can replicate fine Italian violins. Additionally, although the modern violin makers were able to successfully replicate the sound qualities of the antique Stradivarius violins,

there has not been much engineering research into the actual definition of good sound—it should not take a team of expert violin soloists to laboriously rank violins. Knowing what “good sound” is will allow for the creation of a violin that directly aims for that sound without having to blindly follow the rules of a Stradivarius model violin.

To know what “good sound” is, it is also necessary to analyze the acoustics of violin that has a “bad sound.” This violin is expected to be incredibly cheap while having the same overall dimensions and setup as a more expensive violin with a good sound. After performing vibrations and acoustics analyses on both cheap and expensive violins, we will be able to identify common patterns and traits from both violins via FFT and define good sound as having less of the cheap violin’s traits and more of the expensive violin’s traits. Then, we can confirm the FFT results by analyzing the structural components of both violins. There should be some obvious acoustic differences between the cheapest violin on the market and the most expensive violin. Ideally, the sound qualities in expensive violins will be attributed to structural differences which could be implemented on cheaper violins to improve their sound.

1.1 Violin Construction

A violin is filled with several distinct parts that all have some sort of contribution to the resultant sound. Therefore, there exists a concern that, for example, a \$100 violin with some high-quality parts might sound “better” than a \$4,000 violin with cheap parts or will sound different because there were some positional adjustments on either violin that were unaccounted for. Therefore, it is useful to fully understand all the components of the violin necessary for sound production, considering the mechanics of the violin. Doing so will allow for a controlled, consistent experimental design between a cheap and expensive violin without any unwanted contributions from the violin fittings.

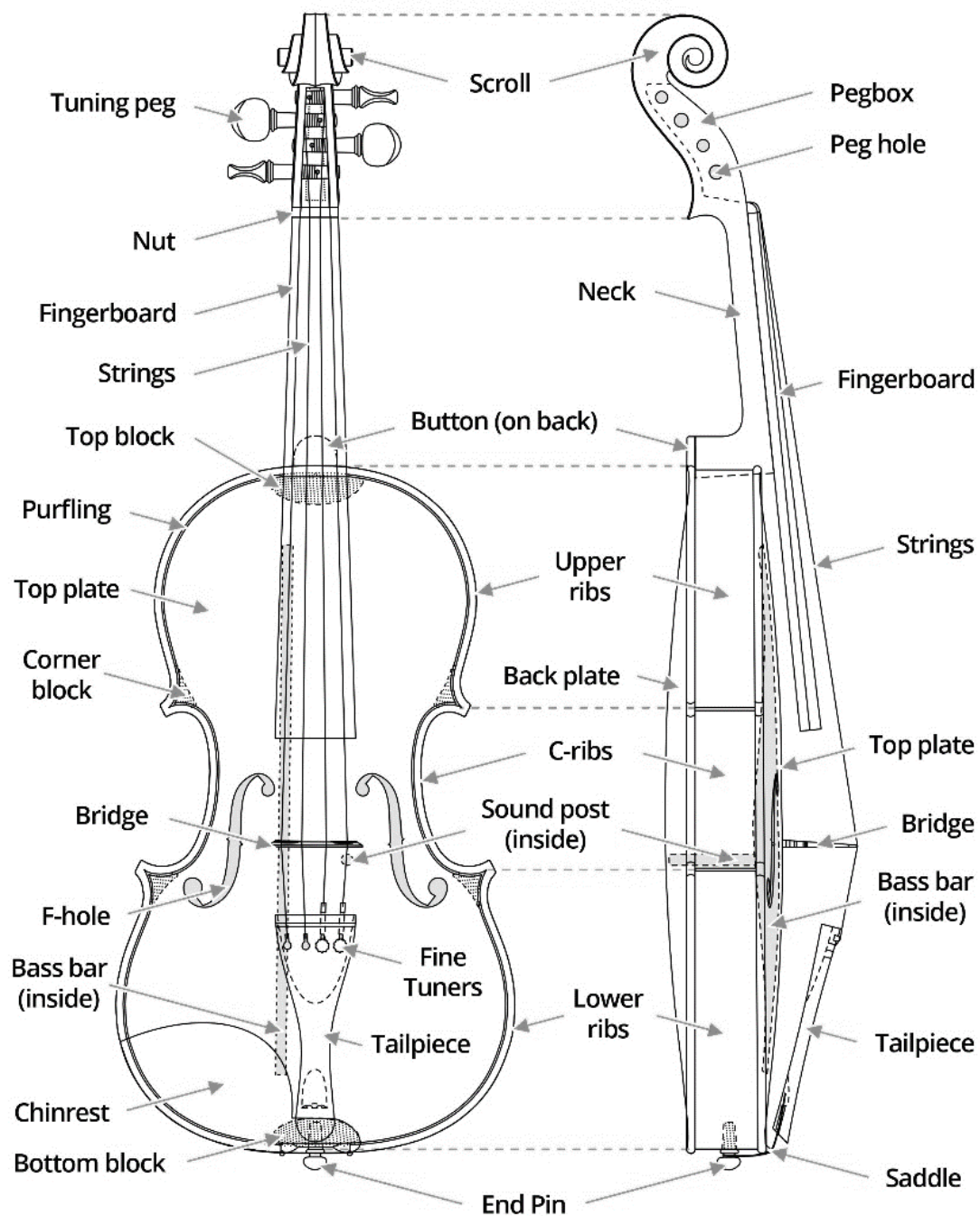


FIGURE 1.3. Front and side view drawing of a violin [7].

1.1.1 Violin Strings

In a typical violin performance, the violinist uses a violin bow to excite the violin strings. The violin bow is simply a bundle of horsehair tensioned along the wooden stick, powdered with sticky rosin. The spiky cuticles in the hair synergize with the rosin to grip the string, pulling it back and releasing it. This process happens thousands of times along the bow length, producing the violin sound. This is very akin to manually plucking the string thousands of times with minimal force. The effects of a string excitation can have varying results in the quality of sound depending on the construction of the violin string, so it is helpful to understand several types of strings to purposefully control the experimental design.

The material and tension of the strings are secondary to the string tuning and string manufacturers must account for the varying tension across the strings. The tuning for violin strings follows a simple pattern of equally spaced perfect fifths. This means that there are exactly five notes from a string to its adjacent string. This makes for convenient playability: in a performance setting, a fingering pattern done between the lowest two strings can be also done between any other two adjacent strings. From lowest pitch to highest, the strings and their standard tunings are G (196.0 hertz), D (293.7 hertz), A (440.0 hertz) and E (659.3 hertz) [9]. The E string frequency is very clearly more than three times higher than the G string frequency, so there already exists a challenge for string designers and manufacturers.

$$f = \frac{\sqrt{\frac{T}{\left(\frac{m}{L}\right)}}}{2L}$$

From the Mersenne-Taylor equation, to triple the output frequency f , the tension T of the string needs to be increased by a factor of 9, mass and length held constant. This is impractical,

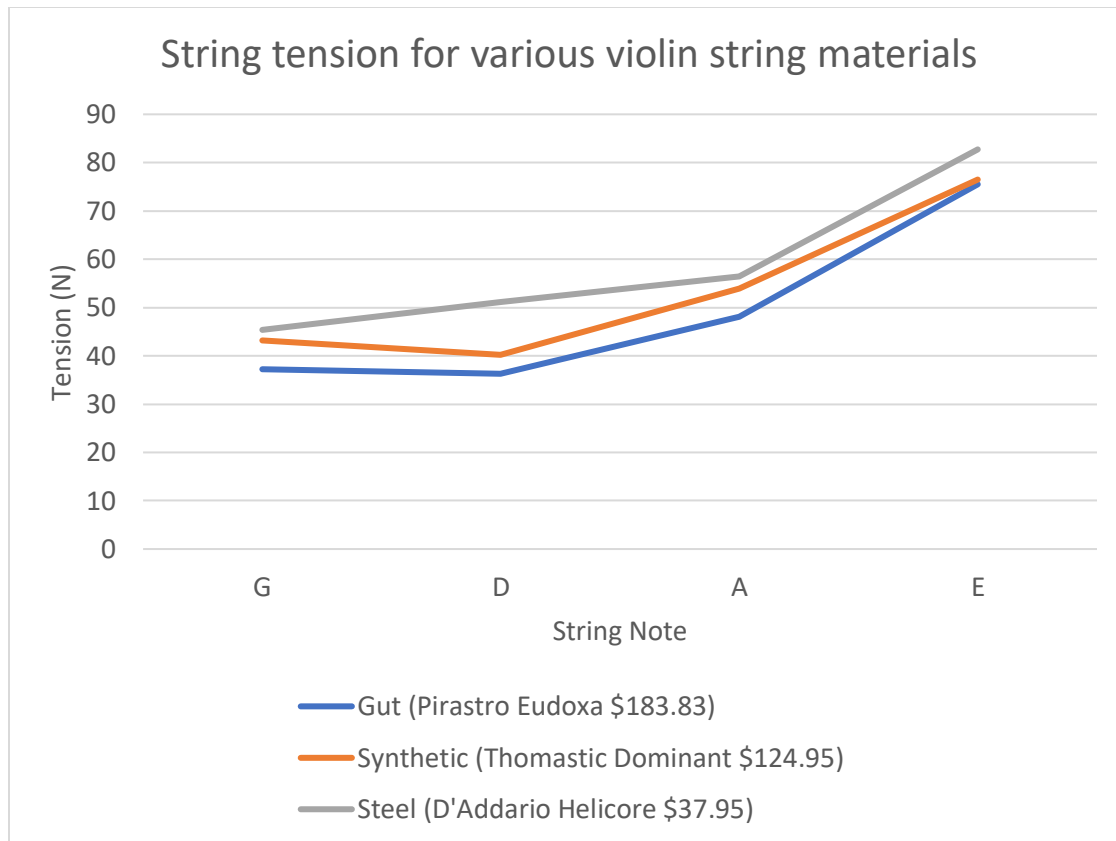


FIGURE 1.4. Violin string tension for various violin string materials. With higher price comes lower tension, more flexible materials, and warmer harmonic-rich sound [10-12].

so string designers have opted to make the E string as thin as possible (often only using a simple steel wire) and filling the G, D, and A strings up with different composite materials until there was a realistic balance between the string tensions. The selection of these materials varies in price and sound quality.

Violin strings have developed over time to be more favorable to musicians with different budgets, the most expensive type of violin string being made of sheep and cow intestines. In general, these “gut” strings are prized for their warm, harmonic-rich sound, as well as the lowest tension strings, and therefore comfortable under the fingers. However, since it is made of organic material, it is very sensitive to humidity and temperature changes resulting in pitch instability. Additionally, since it is very low in tension, the volume of the sound may not be enough in

specific performance cases. Over time, violin string manufacturers developed strings made of synthetic material, which replace the organic material with usually a multi-strand nylon or perlon core wrapped in aluminum. This effectively improves on the warping issue seen in gut strings, as well as being higher in tension. The cheapest violin strings on the market are steel strings—although they can easily retain their pitch over great temperature transitions and are long lasting, they are only selected by beginning musicians on a budget. Steel strings are wound at a high tension and are the least flexible strings. Seemingly opposite of how gut strings are described, steel strings have a very notable thin and bright sound, with very few harmonics [8]. Figure 1.4 shows the string tensions for the most popular brand for each type of strings.

1.1.2 Tailpiece Assembly

The violin string is connected to the violin through the workings of several parts all working together. The violin string first fastens to pegs inside the violin pegbox, is held in place at the nut, runs along the fingerboard, is held in place by the bridge, and ends at the tailpiece, whether it be directly fixated to the tailpiece or to a fine tuner, which is then mounted on the tailpiece. This establishes the vibrating length between the nut and the bridge. Already there are a few mentioned factors that could affect the sound outside of the permanent structure of the violin: the bridge, fine tuners, and tailpiece. First, we will talk about the tailpiece and the optional fine tuners as it is most relevant to the tensioning of the strings.

The primary function of the tailpiece is to secure the string to the end of the violin—although seemingly straightforward, simply changing a few physical factors can make a huge difference in the sound. Like violin strings, tailpieces are also made in different materials with Pernambuco wood being the densest, followed by ebony, rosewood, and boxwood [13]. In

addition to the tailpiece material, violinists have the option to commonly install mechanical fine tuners into the tailpiece, increasing the overall mass.

Although the tailpiece may not directly interfere with the string vibration, it is additional mass added that could lower the natural frequencies of the violin, which is very simply represented as

$$w_n = \sqrt{\frac{k}{m}}$$

We could suggest that increasing the tailpiece mass will therefore reduce the tendency to vibrate at higher frequencies or harmonics. Subjective approximations of the sound quality with this adjustment could be described as dark, muddy, warm, and deep. In the contrary, decreasing the tailpiece mass by removing the fine tuners or using less dense woods could result in more vibrations at higher harmonics, resulting in sound that could be described as brighter, focused, intense, and hard-edged [14]. Depending on the needs of the musician, either direction, to some degree, is equally beneficial in terms of playability and sound production.

Violinists also have the option to opt for more interesting tailpiece styles, such as the Harp style tailpiece shown in Figure 1.5. On the Harp style tailpiece, there is more mass on the E string side and less mass on the G string side, so we might be able to assume that the G string side will have higher harmonics and the E string side will have lower harmonics. Subjectively speaking, users have noticed improved projection, balance, a stronger bass, improved resonance, and significant reduction of unwanted resonant frequencies, or wolf tones [15]. The tailpiece selection for this thesis must also be taken seriously to ensure that there are no unwanted acoustic effects from tailpieces of different natures.



FIGURE 1.5. Hill style tailpiece made from Pernambuco wood (left) and Harp style tailpiece made from boxwood (right) [15].

1.1.3 Violin Bridge

So far, we have examined the importance of the violin strings and the tailpiece with regard to acoustic performance. Although they are quite effective at solely tensioning the strings, not much sound would be produced from a string-tailpiece assembly without the use of a bridge. The bridge is believed to be the main contributor of the transmission of the string's energy to the violin body and is tightly wedged between the tensioned strings and the top plate of the violin without any use of glue. Fundamentally, it is just a thin slab of maple wood with holes cut through for mass reduction and the top convexly curved for playability—a violinist must be able to selectively excite individual strings with the bow, and this is accomplished by simply tilting the bow to be tangential to the convex curve of the bridge at the desired string.



FIGURE 1.6. Violin bridge on the 1721 Stradivarius “Lady Blunt” violin [16].

Simply referring to Newton’s second law, a thicker bridge will require more force to accelerate and vibrate. This begs the question: why not just make the bridge as thin as possible to make the violin resonate as much as possible? The answer to this is that the bridge needs to have enough structural rigidity to support the downforce of the strings. The approximate net forces acting on the bridge can be calculated by taking bridge angle measurements from reliable violin maker sources and calculating the y-component force using the previous tension data of the three strings. For the violin, the angle between the string and the bridge on both sides of the bridge is 79 degrees [17]. The net string downward force F on the violin resulting from the individual G, D, A, and E string tensions could be approximated as

$$F = 2(G + D + A + E)\sin(79)$$

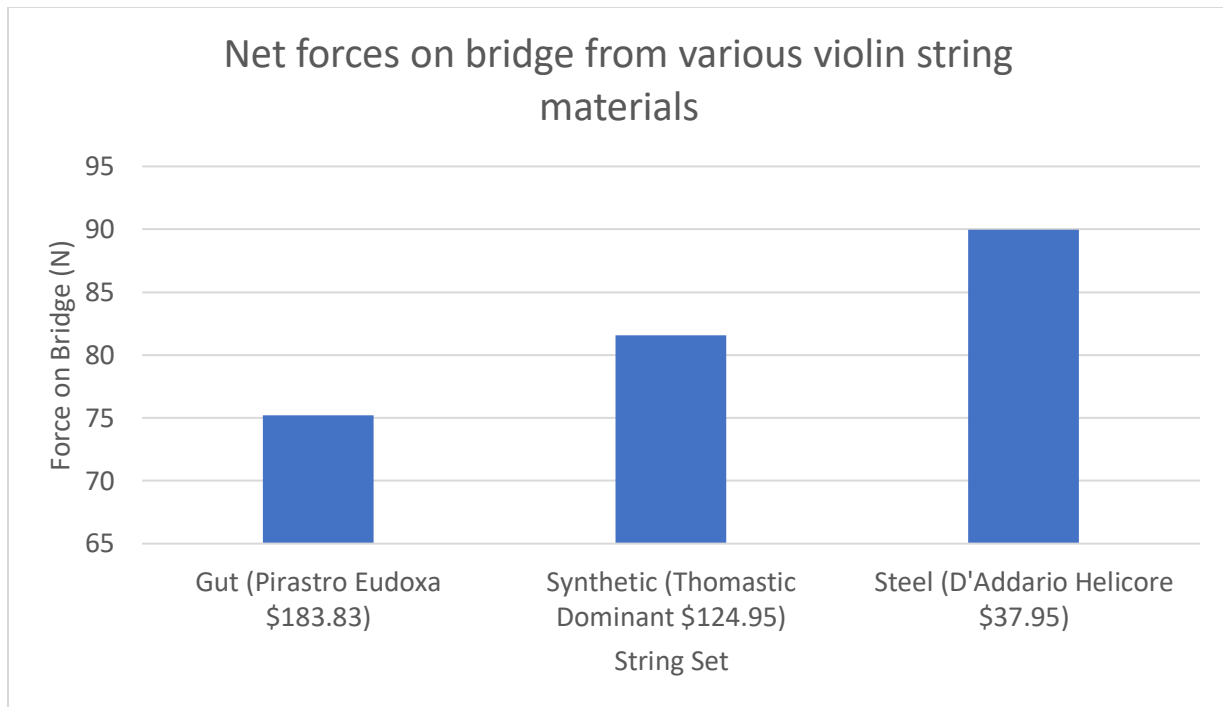


FIGURE 1.7. Net forces on bridge from various string materials.

While it might already be obvious that a change in string tension will result in a change in force acting on the bridge, this merely highlights the forces a bridge must withstand if there were any ideas towards thinning the bridge for increased resonance, as well as the existence of a significant force change on the violin front between the string types. If left uncontrolled, the different string types could present skewing, seemingly unexplainable results in the sound quality of the violins.

The general rule is to place the bridge directly between the notches of the f-holes. Regardless, it is important to also understand the effects of offsetting the bridge—since the bridge is only held in place only by the downforce of the strings, the violinist has the option to make fine adjustments in the violin’s sound by moving the bridge forward or backwards in small increments. This generates another changeable factor that must be considered to accurately compare violins of different price ranges.

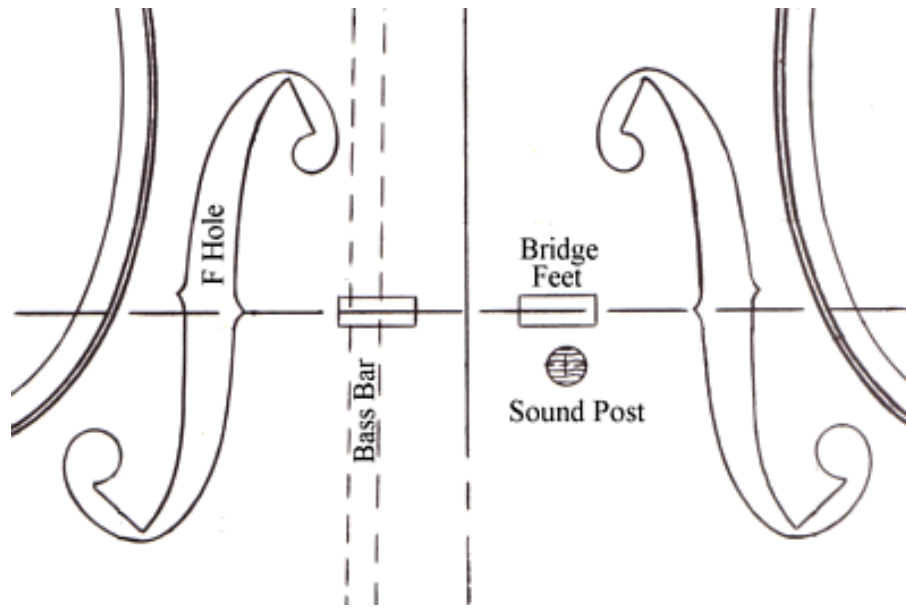


FIGURE 1.8. Standard bridge positioning relative to the sound post and bass bar before any adjustments [18].

Going back to the Mersenne-Taylor equation, we can make sense of one of the things that happen if we move the bridge, string frequency held constant. Moving the bridge towards the scroll reduces the vibrating string length L , reducing the amount of tensile force needed to produce the note, reducing the force acting on the bridge and reducing the bending force on the violin. In addition, the vibrating string has less mass when shortened so the resonant frequency is also increased for the string, theoretically producing harmonics at higher frequencies. One might be able to compare shortening the vibrating length to playing on a smaller sized violin—on a smaller violin, the sound is “bright,” with very high overtones and harmonics. A smaller sized violin preserves the proportions of a full-size violin, but solely moving the bridge changes other factors such as the distance between the bridge and the soundpost, and the bridge and the center of the C-bout. Perhaps there should be a study to directly investigate the bridge-soundpost distance with regard to sound production. There are many factors at play when moving the bridge around; regardless, it has been generally observed within the violin community that

shortening the vibrating string length by moving the bridge a couple millimeters will generally result in a “brighter” sound with higher harmonics.

1.1.4 Top Plate

Unlike the strings, tailpiece and bridge, the top plate cannot be easily adjusted or swapped out after the violin is made—the top plate is such a huge part of the violin that changing the top plate would be akin to changing the character of the violin and its resulting sound quality and price. Therefore, it can be considered as one of the non-adjustable components in this thesis, and the overall violin price will likely be mainly proportional to the quality of the top plate, all other factors constant.

The top plate is made by first tracing a pattern on spruce wood that is in the shape of typical violins made by Antonio Stradivarius or Bartolomeo Giuseppe “del Gesù” Guarneri. These two profiles are very similar, but violinists have observed a deeper, darker tone from violins made from Guarneri patterns and a silky, brighter tone from Stradivarius violins (perhaps this is attributed to the violin’s response to low and high frequencies). After the pattern is traced, the outline is carefully cut out and the wood planed and carved to match an average thickness of about 2.5 mm. This is the step that determines most of the quality of the top plate—violin makers typically try to match the plate thicknesses of violins that have been already known for their great sound quality, particularly antique Italian violins, which have a thickness that varies greatly throughout the top plate. These known violins are likely a product of trial and error, refining the plate thickness to achieve a certain level of acoustic quality. Finally, once the violin has been formed to the violin maker’s idea of perfection, it is time for the cutting of the f-holes, a violin design aspect that is also a product of trial and error. Like the plate thickness, there have been centuries of refining and tonal improvement to optimize the acoustic effects of these f-holes.

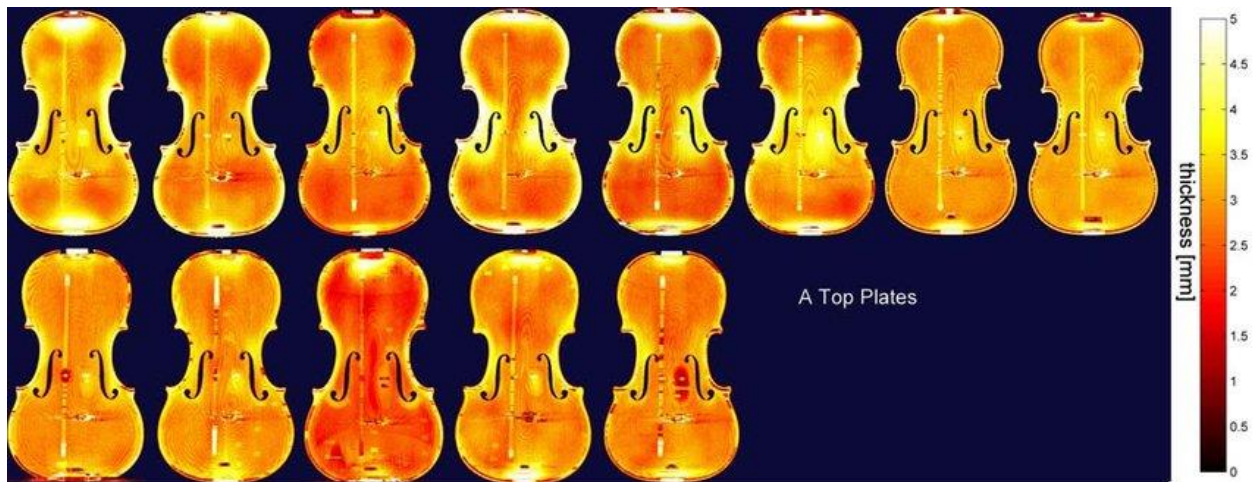


FIGURE 1.9. Top plate thickness mapping of a variety of antique and contemporary violins from reputable makers [19].

Modern violin makers have the option to base their design on any profile they desire. If a violin maker wanted to make a copy of the famous 1742 “Lord Wilton” Guarneri de Gesu, they would be able to do so using CT scans of the instrument and would likely end up with a violin more like a \$6 million dollar instrument than a cheap \$100 factory-made violin.

If there are plenty of resources for violin makers to easily replicate million-dollar legendary instruments, then why do cheap \$100 factory-made violins exist in the first place? The process of graduating a violin to an exact textbook thickness is incredibly laborious and time consuming, considering all the hundreds of thickness variations at different points on the plate. In addition, this process requires specialized precision tools that require proper training to use effectively. It is much easier to just vaguely carve the top plate to an estimated “thin enough” thickness—after all, nobody will see the underside of the top plate and if the violin looks like a violin, people might buy it. It is also much easier to quickly copy-paste some f-hole-looking shapes onto the violin without much thought into its effects on sound production. Of course, any deviations from the “tried and true” thickness map of the top plate can likely lead to unwanted



FIGURE 1.10. Graduating caliper used to check the thickness of a violin top plate [20].

drops in the violin's acoustic quality and price.

1.1.5 Internal Components

While the inside specifications of a violin may not be easily acquired without use of a CT scan or destructively ungluing and opening the violin, it is still useful to explore the purposes of various internal elements to make an informed guess on its acoustic effects. Conveniently, there are only a couple of things inside the violin that are known to be responsible for the quality of sound, and their names also suggest that: the sound post and the bass bar, both made from a piece of spruce wood.



FIGURE 1.11. Bass bar being fitted on a violin (left), sound post viewed through the f-hole (right) [21,22].

The sound post is friction fitted between the front and backplate, directly under the E string and on the tailpiece-side of the bridge, typically about five millimeters away from the bridge. The bass bar is glued to the underside of the top plate, under the G string. The positioning of the sound post and the bass bar can suggest that they work together to strategically amplify vibrations from both bass and treble registers. Because the sound post is located asymmetrically under the E-string side of the bridge, it resembles a pivot point for the G-string side to freely vibrate. Any low-frequency vibrations from the G-string side will easily be transmitted to the rest of the top plate since the bass bar is conveniently located directly under the G-string. In addition, the sound post being on the E-string side and contacting the backplate allows for high-frequency vibrations to be amplified via the back plate. This concept allows us to make some acoustic predictions regarding the effects of changing any parameter related to the bridge, sound post and bass bar.

If the sound post is moved away from the bridge, the sound post will be excited with less energy from the E-string side, so there will be less high-frequency transfer to the back plate. This will lead to a warmer, bass-rich sound. Conversely, moving the sound post closer to the bridge will allow the violin to transmit more vibrations to the backplate, resulting in a bright, treble-rich

sound. The fit and quality of the bass bar also plays a role in acoustic performance: if the bass bar is not properly contacting the inner face of the top plate, any low-frequency vibrations may not be communicated well throughout the top plate, resulting in a brighter-than-intended sound. This may also cause the top plate to warp and cave in as the bass bar would no longer be providing structural support along the top plate. At the same time, for example, if the bass bar is fitted well but abnormally big, much of the bass vibrations will be delegated to mainly vibrating the bass bar rather than being transmitted across the top plate. Therefore, this brings a requirement for an incredible amount of craftsmanship and attention to detail to be able to effectively balance the violin's construction to optimize the sound, and an expensive violin's tone can likely also be explained by proper control and usage of these elements.

1.2 Human Perception of Violin Sound

While violin makers are constantly exploring ways to improve a violin's sound, it is also important to realize that the quality of the sound is dependent on how humans perceive sound. For example, in a parallel universe, there might be a version of us that loves hearing babies scream and cars honk –it can be assumed that if that were the case, more purposeful effort would be put into making babies scream and cars honk. Likewise, there will be always some general acoustic footprint that is universally acceptable for a violin's sound.

Violins are unique in that minute adjustments to its setup can result in vast changes in the amplification of different frequencies, resulting in vast changes in the sound signature of the violin. These adjustments will be made incrementally until there is no more improvement in the sound. Therefore, it could be said that the ideal sound of a violin depends on our sensitivity to sound at different frequencies. There have been previous studies regarding the sensitivity of the

ear and its perception of sound at different frequencies, which could be represented by the equal loudness contour.

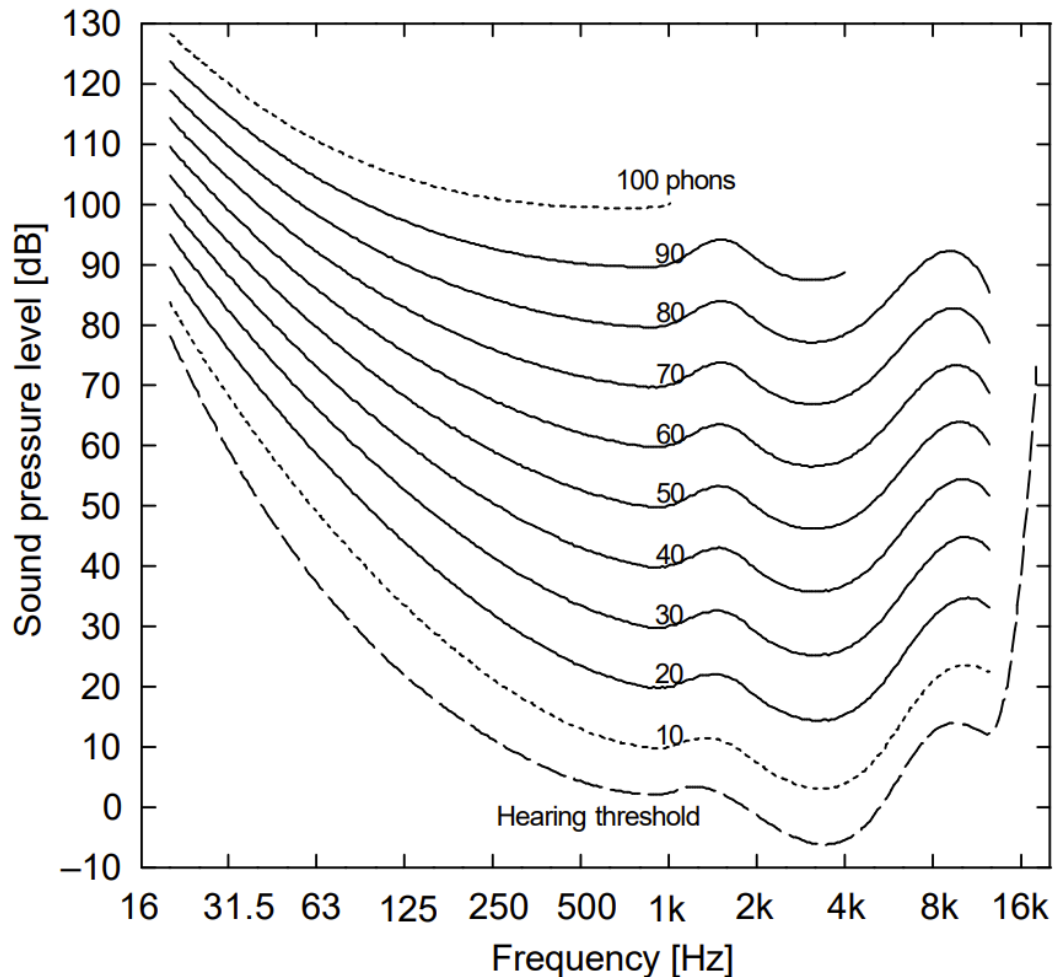


FIGURE 1.12. Equal-loudness contour [23].

The equal-loudness contour demonstrates the perception of “loudness” at various sound levels and frequencies. There is a general trend that at low and high frequencies, the sound level needs to be increased to be heard and interpreted at the same level. At 0 decibels, there is not much sound heard except some frequencies between 2,000 and 4,000 hertz. To combat this, it is logical to generate sound that has a strong presence in the low and high frequencies so that frequencies across the entire audible range could be heard equally. This does make sense: a full symphony orchestra playing a chord sounds better than a generated sine wave from a computer.

All instruments heard equally, it could also be assumed that the piccolos and double basses are outputting more decibels than the violins. Of course, it is impossible to audibly hear this decibel increase as it would be interpreted as sounding as balanced as the other parts in the orchestra.

This concept could be applied to understand how a good violin sound should behave with regard to the amplitude of the various frequencies displayed. A violin is not a symphony orchestra by any means, but a note played from a violin can easily have an abundance of harmonics and overtones like all the instruments in an orchestra in charge of a certain register. Likewise, the quality of a violin's sound could be directly proportional to the relative decibel level of the highs and lows. For example, a violin with equally high decibel output in both the 3,000 hertz and 2,000 hertz frequency areas will likely sound worse than a violin that has slightly more decibel output in the 2,000 hertz range.

CHAPTER 2

VIOLIN TEST SAMPLES

The idea of an acoustically good violin has already been established, and there is some direction in how to improve a violin using its existing adjustable parts. However, it is unrealistic to eliminate a violin if, for example, the sound produced does not mirror the equal-loudness contour, or if the violin uses steel strings. When comparing two similar violins of similar price ranges, there will be very small changes in the frequency response. In most cases, the violinist testing the violins will notice some difference in “warmth” or “brightness,” and either case would be fine depending on the preference of the violinist. If made by a violin maker that knows exactly what they are doing, these violins might both show the same general balance according to the equal-loudness contour (although not very perfect), but any minor differences might contradict the price. On the other hand, looking at two violins of completely different price points should be an easier comparison, and any acoustic differences can be explained by the price, making sure that all adjustable elements (tailpiece, string type, bridge position, etc.) are held constant between the two violins.

2.1 Instrument Selection

Selecting two violins for use in this thesis was quite challenging. Any “expensive” and “cheap” violin could be used, and violins come in a variety of colors as well. How expensive is expensive enough? If a random expensive violin of a certain price is selected, what cheaper violin would be a viable candidate for a comparison, and what physical traits should be held constant? What steps could we take to avoid accidentally picking a “cheap” violin that happens to sound “better” than the expensive violin? Once two violins are selected, how would we control the acoustics-improving effects of the accessories (tailpiece, strings, bridge) to ensure

that the resultant sound is correctly proportional to the price? All these questions must be properly addressed to ensure a complete and optimized comparison.

2.1.1 Expensive Violin Selection Process

With all these concerns (and budget) in mind, it was decided that the most logical procedure would be to first visit music stores, try out several fairly expensive fine violins above the \$4,000 range, and subjectively select the best acoustically sounding violin. Expensive violins \$4,000 and up seemed to be a decent price range because it was the most that could be allotted not only for this thesis, but for long term possession outside of the thesis. To avoid any kind of bias regards to the physical appearance of the violin, audio recordings of potential candidates would be sent to random accessible people (family, friends, and colleagues), and the violin that accumulated the most votes would be selected as the expensive violin. With regard to the retailer's decision on the violin's selling price, a slight concern was that a portion of the violin's price would be attributed to non-acoustic aspects, such as the violin's history, maker, or the year made (older violins with a known maker are usually more expensive). While this would lead to a possibility of encountering poorly sounding violins that sound like they should not be at the \$4,000 range, this could also lead to good-sounding violins that were made by anonymous makers, or unintentionally ignoring good-sounding violins at lower price points. To address this, violins strictly above \$4,000 were considered only, and selected purely by its acoustic performance.

2.1.2 Cheap Violin Selection Process

After the expensive violin is selected, the next step would be to match a cheap violin to it. Contrary to the selection method of the expensive violin, the ideal cheap violin would be the lowest priced violin that most closely matches the physical appearance of the expensive violin.

This refers to the varnish style and color. Although possibly insignificant to the violin's sound, matching the varnish adds to the level of consistency across the violins and reduces a variable. The sound quality of the cheap violin is neglected because there is a thin line between a cheap legitimate violin that has a poor sound, and a violin that has a poor sound because it is so cheap that it no longer qualifies as a violin, often referred to as a VSO (violin-shaped object). In addition, all violins will sound generally the same at such a low price range. To maintain consistency and ensure that a qualifiable cheap violin is picked, reputable violin retailers will be contacted with an image of the expensive violin and a low budget range (less than \$500), and they would do their best to match the varnish style and color.

2.2 Selected Violins

The two violins chosen were a \$4,250 William Bagnato violin made in 2019, and a \$269 Franz Hoffman violin made in 2021. The top plate of the expensive violin simply looks shinier and has a slightly more pronounced wood grain, and the back plate has a much more pronounced flaming pattern in the maple wood.

2.2.1 Historical Differences

Now that we have two violins of different price levels, we can start to piece together clues on why there is such a huge price difference. First, we can examine the violins' labels. While the more expensive violin's label does look more decorative than the cheap violin, it also indicates that the violin was made in Chicago for William Harris Lee and Company. The cheap violin's label indicates that the violin was made in Romania for Shar Music. This alone may already be highly influencing the price, as the cost of living in Chicago is double the cost in Romania [24]. Additionally, William Harris Lee and Company specializes only in expensive fine violins, and Shar Music covers all string instruments at all price levels, primarily online. A rough



FIGURE 2.1. Front view of 2019 William Bagnato Violin, \$4,250 (left) and 2021 Franz Hoffman Vienna Violin, \$269 (right).

analogy can be made that Shar Music is the “Ross” and William Harris Lee is the “Louis Vuitton” of music stores, so everything, regardless of what is sold, will be more expensive because of the branding. However, it is hard to believe that William Harris Lee would make and sell a violin resembling the quality of the cheap \$269 violin (although if they did, the selling price would be increased to probably around \$500, but nowhere near \$4,250).



FIGURE 2.2. Labels for the \$4,250 William Bagnato violin and the \$269 Vienna violin.

2.2.2 Physical Differences

Now that we have gotten the historical price bias out of the way, we can assume from this point that the expensive violin is guaranteed to be better sounding than the cheap violin. These acoustic differences could be explained by the violin’s structure, so this next part pertains largely to physical differences between the two violins.

Firstly, the mass of the expensive violin was 419 grams, and the cheap violin was 430 grams, which was a mass difference of 2.5913%. This may seem like a small percentage, but as discussed before, objects with more mass would require more force to excite, which could lead to a hypothesis that the cheap violin is more muffled and resonates less than the expensive violin.

However, this mass weight pertains to the overall mass, so there might be a chance that, on the cheap violin, little mass is around the vibrating body and the scroll is a lot heavier than usual. From a performance standpoint, less mass is preferred as less effort from the performer would be required to hold up the violin, contributing to the violin's playability.

In earlier sections, there was quite a bit of discussion on the vibrating string length, so it was decided to measure this length on both violins with a Mitutoyo ABSOLUTE Digital Caliper: it was 327 millimeters on the cheap violin and 324 millimeters on the expensive violin. This was measured when the bridge was at its standard position between the two f-hole notches. While it could be said that that this shorter length on the expensive violin would reduce the vibrating string mass, increasing the natural frequency of the violin strings, this may not necessarily increase the natural frequency of the violin, as there are other modes in the violin body to consider when moving the bridge around. However, it could be said that less string mass would result in a stronger response in the string's individual vibration with excitation force remaining constant.

It was believed that the shape of the f-hole might also have some effect on the sound, so measurements were taken on these little beauties. This was done by measuring the longest point-to-point length, and the widest width at the middle of an f-hole, taking care to not damage the internal rim of the f-holes with the sharp measuring surfaces of the digital caliper during each measurement. Perhaps a fuller investigation of the f-hole geometry, examining contours and style tendencies across violin price points for example, could be done in future studies.

It appeared that the f-hole on the more expensive violin was both narrower and longer than the cheap violin. This was the case for both f-holes on the expensive violin—the f-holes were longitudinally longer in the direction of the wood grain. If the f-holes were even longer and



FIGURE 2.3. F-hole overall dimensions on the expensive violin.



FIGURE 2.4. F-hole overall dimensions on the cheap violin.

skinnier, would the result sound equate a more expensive violin? Perhaps a future study could be done to address the effects of f-hole shape on sound. Since the expensive violin seemed to favor longer and narrower traits, further measurements on the bodies were done to confirm this pattern.



FIGURE 2.5. Overall thicknesses of both expensive violin (left) and cheap violin (right).

For the overall thicknesses of both violins, the expensive violin was 2.25% narrower than the cheap violin, measured at 39.55 millimeters versus 40.45 millimeters for the cheap violin. This follows the overall theme of the expensive violin being narrower. This thickness can be attributed to a thicker top plate and a wider rib around the cheap violin: the expensive violin's top plate is 4.05 millimeters thick and the cheap violin's top plate is 4.56 millimeters thick.

Cheap violins often have a thicker plate because carefully honing the thickness to a smaller thickness would take more time and money, considering that the thinner wood would be more prone to breakage. As previously discussed, this would affect the sound quality, as the plates are the biggest vibrating components on the violin. A thicker plate would require more excitation force to vibrate at the same amplitude.

Not to anyone's surprise, the vibrating body of the expensive violin measured 112.04 millimeters wide at its narrowest point, and the cheaper violin measured 113.33 millimeters—the expensive violin was 1.15% narrower. Longitudinal measurements were also taken, and the expensive violin measured 138 millimeters long and the cheap violin measured 136 millimeters



FIGURE 2.6. Width of expensive violin (left) and cheap violin (right) at the narrowest point.

long—the expensive violin was about 1.46% longer. Although it is not confirmed whether this has a direct impact on improving the violin sound, there is clearly a pattern here in that the expensive violin is overall narrower and longer than the cheap violin. Perhaps this was a design choice in the same way thin smart phones are more “premium” than their thicker counterparts (the expensive violin does in fact feel more premium). We might be able to explain the acoustic effects of this (if any) in later sections. The shiny flamed maple back of the expensive violin, also shown in this figure, added additional weight with violin polish material, but still resulted in an overall lighter build than the cheap violin.

2.2.3 Adjustments for Consistency

The goal of the comparison was to realize the effects of the differing violin bodies on acoustic performance. Therefore, anything except for the wooden body had to be controlled and held consistent between the two violins so that the effects of the body are isolated. This was done by performing modifications and swapping parts on the cheap violin so that it would be virtually

identical to the expensive violin, body out of the picture. The expensive violin was not modified to match the cheap violin because doing so might accidentally, for example, destroy the violin or result in unintended irreversible damage to the structure of the violin that would result in a higher repair fee than the cheaper violin.

2.2.3.1 Strings. Performing a string change on the cheap violin was the first task done towards consistency. The cheap violin came with Overture Ultra synthetic strings, which are made with a synthelon core. This was switched to match the Thomastik Dominant strings on the expensive violin, which use a perlon core. Curiously, the Overture Ultra strings were listed online for only \$25.74, which was quite small compared to the \$124.95 price on the Thomastik Dominant strings. Reviews online indicate that the Overture Ultra strings were less durable and snapped more frequently, which could be the case. Perhaps in the future there will be a study to compare the acoustic differences of synthetic strings. After the Thomastik Dominant strings were installed and tensioned on the cheap violin, the strings exhibited somewhat of a metallic sound. This was resolved by allowing the strings to “break in,” playing on the strings and waiting a few days until the sound became as unmetallic as the expensive violin.

2.2.3.2 Tailpiece. The tailpiece is another part of the violin that needs to be consistent for a body comparison. The cheap violin came pre-installed with a plastic Wittner-style tailpiece with four fine tuners and was swapped out for an ebony Hill-model tailpiece with one fine tuner on the E-string. The fine tuners alone would contribute to a substantial portion of the mass difference as well as the difference in the center of gravities. Beginner violins typically come with a fine tuner on each string as they improve the ease of tuning. As a violinist progresses, the necessity for a better-sounding violin overcomes the difficulty of tuning the violin, so violinists eventually opt to use the stiffer violin pegs situated in the scroll of the violin, optionally keeping

a fine tuner on the E-string to assist with the highest-tensioned string.



FIGURE 2.7. Plastic Wittner tailpiece (left) and ebony Hill tailpiece (right) [25,26].

2.2.3.3 Bridge. The last adjustment was that of the bridge. It was noticed that the cheap violin's original bridge was thicker than the expensive violin by about 80%, and taller by about 20%. The thicker bridge would dampen the vibrations from the strings, requiring more force to excite at the same magnitude. The tallness would increase the downforce of the strings, subjecting the violin to increased force. Both would result in a change in acoustic performance. Additionally, the tallness would degrade the playability of the violin—the strings would be harder to press down onto the fingerboard and more work from the violinist would be required to play the violin. After using sandpaper to carefully adjust the height and width of the bridge, these issues were addressed as cost-efficiently as possible. Although the cheap and expensive bridges have some uncontrollable differences in material due to the random nature of wood growth, best effort has been done to make the two bridges geometrically more similar.

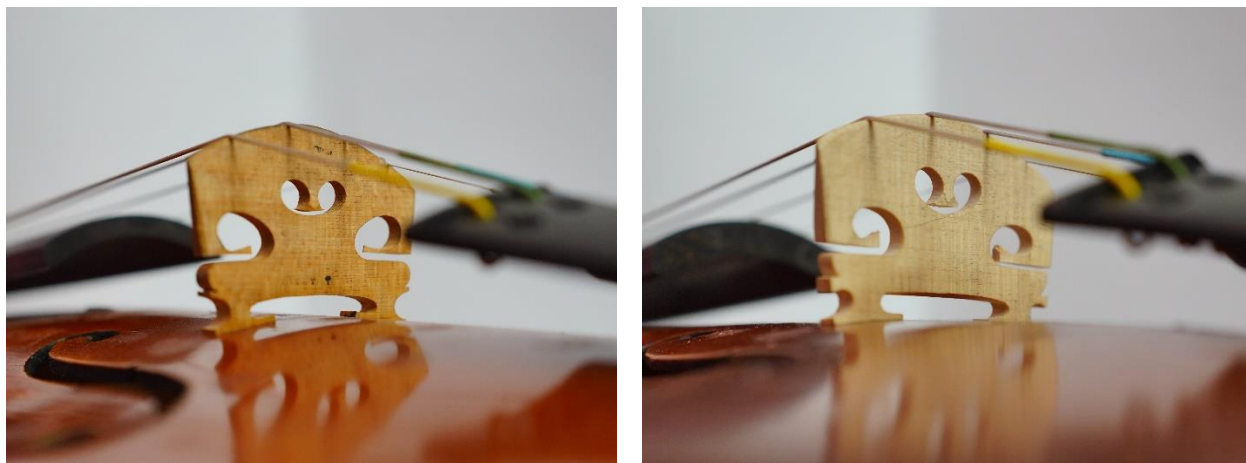


FIGURE 2.8. Bridge on expensive violin (left) and modified bridge on cheap violin (right). Both bridges are similar in overall geometry.

2.2.3.4 Chinrest. Although not exactly a swap nor a part modification, this last step concerned the physical differences in the violin chinrest. The expensive violin was fitted with the Brandt chinrest, which was made of ebony. This chinrest is one of the smallest and lightest chinrests made for the violin and provides the bare minimum amount of wood to allow a violinist's chin to secure a violin on the neck. The cheap violin was fitted with a Guarneri style chinrest made of plastic, which was very much taller than the Brandt chin rest and attaches to the violin on either side of the tailpiece.



FIGURE 2.9. Brandt style chinrest (left) and Guarneri style chinrest (right). The Guarneri style chinrest was much taller and heavier than the Brandt style chinrest.

It was decided that a chinrest is not required for a comparison of the two violins as sound could be produced without the use of a chinrest. A chinrest merely helps the violinist secure the violin to their neck, allowing for the left hand to be freed and able to press the strings. There are also huge differences in the geometry and material between the two chinrests that would easily affect the violin's sound. The clamping force from the chinrest's two lead screws is also highly variable, and it has been generally noted that a tightly installed chinrest has some muffling effects on the sound. Given all these reasons, the chinrests from both violins were removed for the acoustic comparison.

CHAPTER 3

STRUCTURAL-ACOUSTIC INTERACTION

3.1 Structural Vibrations

Now that we have noticed some physical differences between the cheap and expensive violin, we can target these traits and analytically investigate whether the differences might have anything to do with the quality of sound. With some basic knowledge of the equal-loudness contour, we can simply say that “good” sound consists of weaker vibrations in the 4,000 hertz area as compared to everywhere else, or strong vibrations in the lower-frequency range as opposed to the higher 4,000 hertz range, considering that the fundamental frequencies of the violin strings are all below 1,000 hertz. We can start by having a basic understanding of several types of sound-producing vibrations that might be present during a violin’s excitation, referring largely to work listed by Stephen A. Hambric et al. [27].

The vibrations that occur on a violin are fundamentally made up of three different kinds of waves: longitudinal waves, shear waves, and flexural waves. For a wave longitudinally traveling in the x direction of a simple plate, the wave equation and sound speed equations are:

$$\frac{\partial^2 w}{\partial x^2} = \frac{1}{c_l^2} \frac{\partial^2 w}{\partial t^2}$$

$$c_l = \sqrt{\frac{B}{\rho}}$$

where w is the x direction deformation, ρ is the volumetric mass density of the vibrating structure, and B is the elastic bulk modulus. The elastic bulk modulus is a ratio between volumetric contraction of the vibrating plate:

$$B_0 = \frac{-p}{dv/v}$$

ν being the kinematic viscosity of the fluid around the vibrating structure, which is air in this case. A fast longitudinal wave therefore is produced by a stiffer structure and the higher a frequency is, the faster the wave. Additionally, the geometry of longitudinal waves imply that they do not directly vibrate normal to the surface so there may not be as much resonance compared to the other wave types. From this, we can infer that if longitudinal vibrations were to occur in a violin, they would most easily and quickly resonate the entire top plate regardless of excitation frequency.

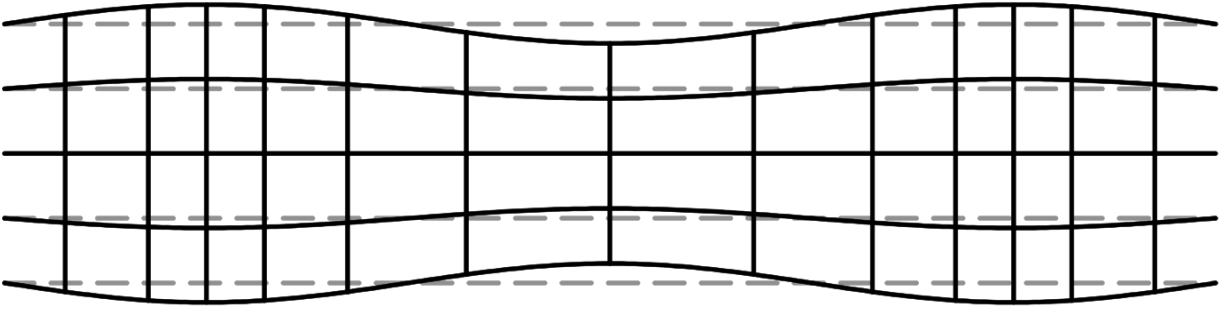


FIGURE 3.1. Longitudinal wave propagating through a plate or beam.

Additionally, there exists a difference in longitudinal speeds for plates versus beams in an air-fluid environment, with the plate speed being about $1.0952 \times 10^{-8}\%$ faster, all things constant:

$$c_1(\text{beams}) = \sqrt{\frac{E}{\rho}}$$

$$c_1(\text{plates}) = \sqrt{\frac{E}{\rho(1 - \nu^2)}}$$

Where E is the Young's modulus which is an indicator of a material's ability to stretch and deform. For air with a kinematic viscosity of $1.48 \times 10^{-5} \text{ m}^2/\text{s}$, the Young's modulus is calculated to be $4.0 \times 10^{-8}\%$ smaller than the elastic bulk modulus.

$$E = \frac{B(1 + \nu)(1 - 2\nu)}{1 - \nu} (E < B)$$

This means, in simplest terms, that for low-frequency vibrations to be stronger than high-frequency vibrations, a violin must be shaped more like a beam than a plate while also being stiffer. Coincidentally, the expensive violin is narrower and longer than the cheap violin. The bass bar for the expensive violin might also be more intentionally crafted than on the cheap violin, acting more like a beam and boosting the lower bass frequencies as its name suggests. Considering these traits, it could be said that the expensive violin may perform better at lower frequencies than the cheap violin.

For shear waves, the wave equation is the same used for the longitudinal waves. The equation for speed, however, indicates that shear waves are slower than longitudinal waves. Both are represented as

$$\frac{\partial^2 w}{\partial x^2} = \frac{1}{c_s^2} \frac{\partial^2 w}{\partial t^2}$$

$$c_s = \sqrt{\frac{G}{\rho}}$$

where G is the shear modulus. For air, it is calculated to be 66.67% smaller than the Young's modulus.

$$G = \frac{E}{2(1 + \nu)} (G < E)$$

The speed equations for shear and longitudinal waves are similar, except longitudinal wave speed is dependent on the elastic bulk modulus B and shear wave speed uses the shear modulus G . Since $G < E < B$, shear waves are much slower than longitudinal waves. Because the bridge of the violin transmits vibrations perpendicular to the top plate, shear waves may be more common than longitudinal waves.

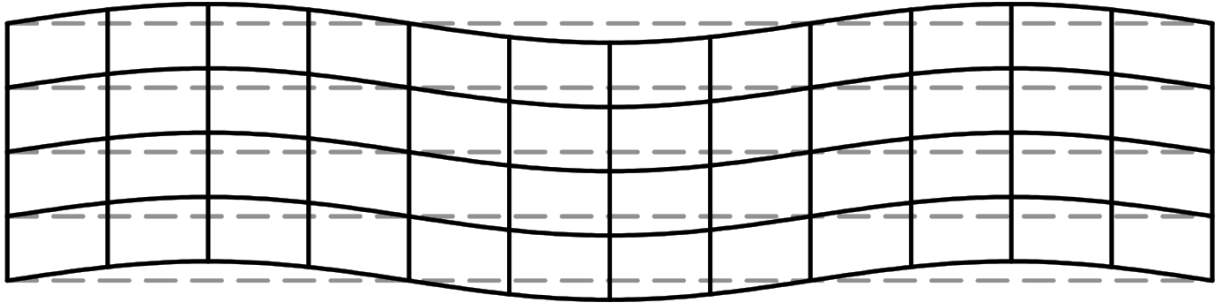


FIGURE 3.2. Shear wave propagating through a plate or beam.

Flexural waves are more complicated than longitudinal waves and shear waves because it now incorporates traits specific to the geometry of the vibrating structure, such as the resistance to deformation from shear and the mass inertia of the cross section. Equations for this can be split up between waves in beams versus plates. The wave and wave speed equations corresponding to beams are:

$$\frac{EI}{\rho A} \frac{\partial^4 W}{\partial x^4} - \left(\frac{I}{A} + \frac{EI}{KAG} \right) \frac{\partial^4 w}{\partial x^2 \partial t^2} = - \frac{\partial^2 w}{\partial t^2} - \frac{I\rho}{KAG} \frac{\partial^4 w}{\partial t^4}$$

$$c_B = \sqrt{\frac{\left(\frac{EI}{KAG} - \frac{I}{A} \right)^2 \omega^4 + 4 \frac{EI}{\rho A} \omega^2 - \omega^2 \left(\frac{EI}{KAG} + \frac{I}{A} \right)}{2 \left(1 - \omega^2 \frac{I\rho}{KAG} \right)}}$$

where ω is the frequency of vibration, A is the cross-sectional area, K is the correction factor, which is the cross-sectional fraction that resists shear, and I/A , which is the cross-section's inertia during rotation. For plates, where the waves can propagate in two dimensions, the wave and wave speed equations become:

$$\frac{D}{\rho h} \nabla^4 w - \left(\frac{I'}{h} + \frac{D}{khG} \right) \nabla^2 \left(\frac{\partial^2 w}{\partial t^2} \right) = - \frac{\partial^2 w}{\partial t^2} - \frac{I' \rho}{khG} \frac{\partial^4 w}{\partial t^4}$$

$$c_B = \sqrt{\frac{\left(\left(\frac{D}{KhG} - \frac{I}{h} \right)^2 \omega^4 + 4 \frac{D}{\rho h} \omega^2 - \omega^2 \left(\frac{EI}{KhG} + \frac{I}{h} \right) \right)}{2 \left(1 - \omega^2 \frac{I \rho}{KhG} \right)}}$$

where D is the flexural rigidity, combining the elastic modulus and moment of inertia, ∇ is the gradient operator differentiating across all x , y , and z unit vectors, and h is the thickness of the plate. Considering that at high frequency vibrations the shear modulus and shear correction factor is most active to resist shear, we can simplify the wave speed equations for high frequency vibrations,

$$c_B = \sqrt{\frac{KG}{\rho}}$$

and low frequency vibrations where shear resistance becomes less apparent, and the dimensional characteristics of the vibrating component fall into place:

$$c_B = \sqrt[4]{\frac{D}{\rho h}} \omega^2$$

Because the frequency term disappears from the high-frequency equation, any slight change in vibrating frequency may be negligible to the resultant wave speed. In terms of a violin

performance, this could imply that there might not be a difference in volume between any two high notes directly resulting from flexural vibrations. This could detract from the musicality of a piece when some dynamic contrast between notes is needed for musical effect—the musician would have to do more work to produce the intended effect. The $\frac{1}{4}$ root in the square root also shows that the low frequency vibrations travel at a slower speed, forcing the correlation between frequency and wavespeed.

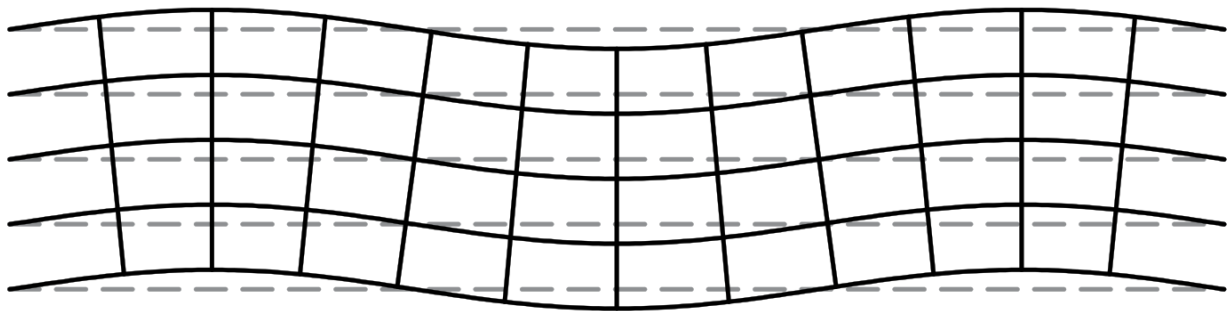


FIGURE 3.3. Flexural wave propagating through a plate or beam.

While shear and longitudinal vibrations do not depend on the frequency of the vibrations, flexural vibrations do. As flexural vibrations increase to extremely high frequencies, the wavespeeds asymptotically approach that of shear vibrations. Additionally, from the wavespeed equations, thin plates with bigger h values can be observed to have a faster relative wavespeed than thicker plates. From the previous chapter, the expensive violin's top plate was measured to be 4.05 millimeters thick and the cheap violin's top plate was 4.56 millimeters thick, so all vibrations amplified in the expensive violin will propagate a bit faster than in the cheap violin. This could subjectively translate to a better response of the violin during normal playing—any note played will easily excite the entire top plate of the violin relatively quicker and will seem easier to play.

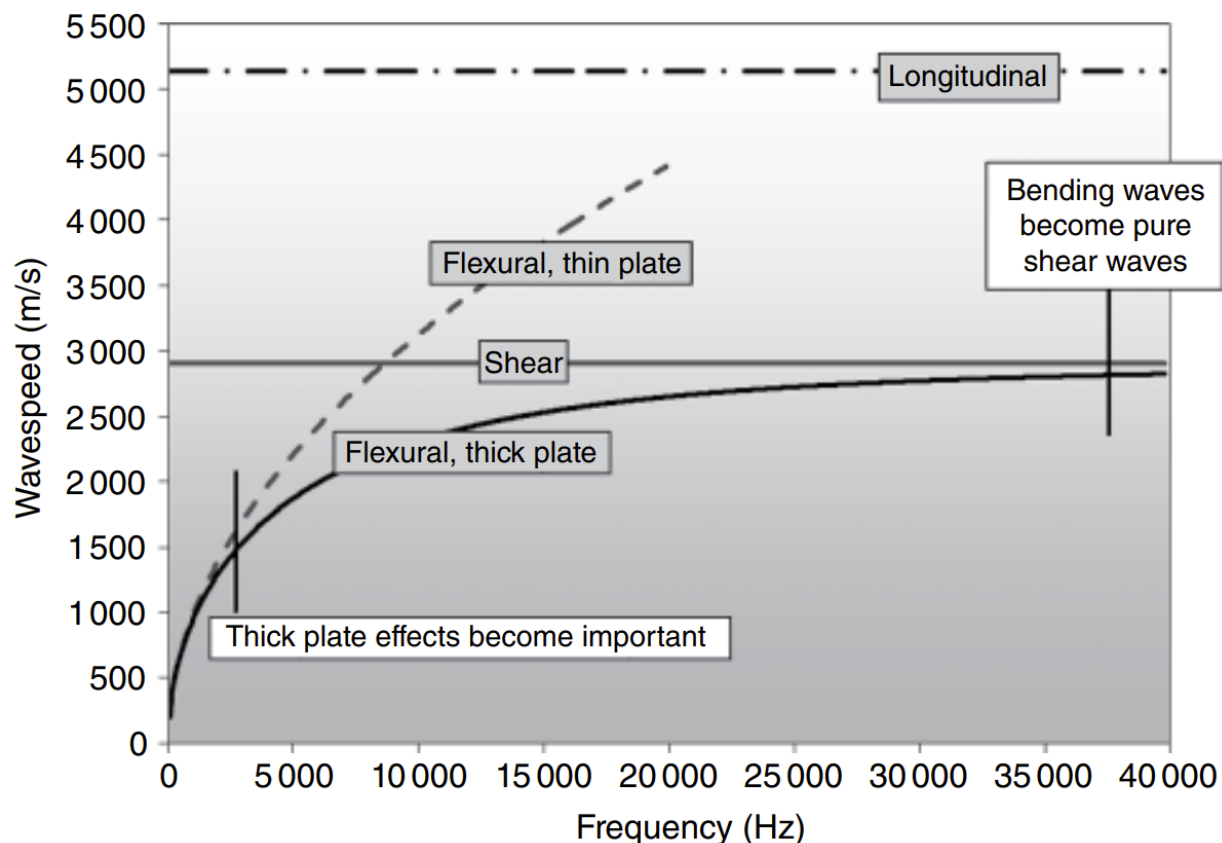


FIGURE 3.4. Measured wave speeds in a plate that is 10 centimeters thick.

3.2 Sound Radiation

We have discussed the types of vibrations that might occur on the violin's top plate and how specific types would be more prone to occur, as well as the potential frequency ranges we might come across between the expensive and cheap violin. This information could be correlated with the acoustic side of the story, exploring how these vibrations could be interpreted as sound radiating from the violin, propagating through the fluidic air at a distance away from the violin. This investigation will refer from works listed by Shung H. Sung and Donald J. Nefske [27]. At the most basic level, an ideal violin most efficiently amplifies vibrational frequencies to its surrounding fluid medium with as little energy loss as possible, excitation force held constant.

A straightforward way to represent a violin's sound is to picture sound as coming from only one x direction, with no stray sound waves bouncing around off walls. Given the round nature of the violin, it is appropriate to simplify its geometry as a circle with surface area A at $x = 0$, vibrating with velocity $\hat{u}_{p\exp(i\omega t)}$, radiating sound through an anechoic tube of the same diameter:

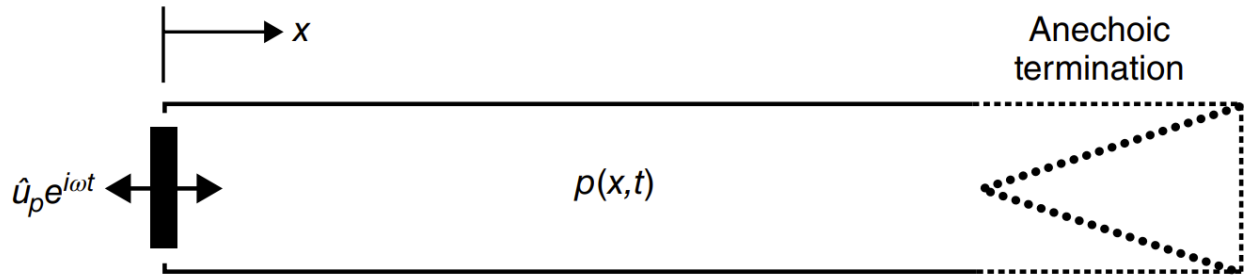


FIGURE 3.5. A simplified circular violin vibrating sound waves into an anechoic tube.

We can start with the acoustic wave equation, which is given by

$$\frac{1}{c_o^2} \frac{\partial^2 p}{\partial t^2} - \nabla^2 p = p_o \frac{\partial q}{\partial t}$$

where p is the sound pressure, p_o is the sound pressure at equilibrium, q is the interior acoustic volume flow of a cavity, and c_o is the speed of sound at equilibrium. Since we are only dealing with external sound waves in one direction, we could edit the gradient operator ∇ to be only in terms of x and remove the interior acoustic volume flow q :

$$\frac{1}{c_o^2} \frac{\partial^2 p}{\partial t^2} - \frac{\partial^2 p}{\partial x^2} = 0 \quad (1)$$

The idea is to find equations for sound pressure and air particle velocity at any point in front of the violin in terms of the air particle velocity $\hat{u}_{p\exp(i\omega t)}$ at the violin. The sound pressure anywhere in terms of the speed of sound is

$$p(x, t) = f(x - c_o t) \quad (2)$$

where f is the forcing frequency of vibration. We are given the linearized continuity equation of mass flow:

$$\rho_o \frac{\partial u}{\partial t} + \nabla p = 0 \quad (3)$$

where u is the air particle velocity at a distance x and ρ_o is the density of air at equilibrium.

Combining equation (1), (2), and (3), we have an equation for air particle velocity in terms of the speed of sound:

$$u(x, t) = -\frac{1}{\rho_o} \int \frac{\partial p}{\partial x} dt = \frac{1}{\rho_o c_o} f(x - c_o t) = \frac{p(x, t)}{\rho_o c_o} \quad (4)$$

Solving for sound pressure by rearranging equation (4),

$$p(x, t) = \rho_o c_o u(x, t) \quad (5)$$

For harmonic excitations, which might be the case of the violin's sound, equations (2) and (4) are combined and represented as

$$p(x, t) = \hat{p} e^{-ik(x - c_o t)} \quad (6)$$

$$u(x, t) = \frac{\hat{p}}{\rho_o c_o} e^{-ik(x - c_o t)} \quad (7)$$

where $\hat{p}$ is the maximum sound pressure, and $k = \frac{\omega}{c_o}$ is the wavenumber. We can solve for this

maximum sound pressure in terms of the violin's velocity by equating equation (7) to the air

velocity at the violin $\hat{u}_{p \exp(i\omega t)}$ when $x = 0$:

$$u(0, t) = \frac{\hat{p}}{\rho_o c_o} e^{i\omega t} = \hat{u}_p e^{i\omega t} \rightarrow \hat{p} = \rho_o c_o \hat{u}_p \quad (8)$$

Substituting equation (8) into equations (6) and (7),

$$p(x, t) = \rho_o c_o \hat{u}_p e^{-ik(x-c_o t)}$$

$$u(x, t) = \hat{u}_p e^{-ik(x-c_o t)}$$

These two equations indicate a large initial air pressure and speed at the surface of the violin, which both drop immediately as the distance away from the violin increases, asymptotically approaching a zero magnitude. The air pressure and speed measurements at a distance from the violin are both directly dependent on the initial velocity of the sound wave. Additionally, extremely high frequencies will not be able to travel as far as lower frequencies—naturally, this will benefit the presence of the lower frequencies as they become more apparent as distance increases. While this sounds like a promising idea according to the equal-loudness contour, this could provide some misleading results as a cheap, ear-piercing, high-frequency violin listened from afar could have a better sound than an expensive violin listened up-close.

CHAPTER 4

SIGNAL PROCESSING METHODS

4.1 Fast Fourier Transform

The fast Fourier Transform is a powerful tool for signal analysis, converting a set of data from a time domain to a frequency domain. This will be especially useful in analyzing the frequency response of a violin by indicating the amplitudes of various frequencies amplified by the violin, which is already known to produce vibrations and sounds of frequencies of interest. Any correlations or patterns in the frequency spectrum can be used to make an educated judgement on the violin's quality.

Before we can comfortably press the FFT button in the LabVIEW program, it helps to understand the basic workings behind FFT analyses, starting with the Fourier integral. The Fourier series is used for period functions, so is therefore not used in this case because while the individual vibrations of the violin might seem periodic, the vibrations immediately begin to fade away in amplitude after excitation and does not repeat at the same magnitude automatically in a periodic manner. A non-periodic signal can be represented by the Fourier integral as a combination of sines and cosines canceling each other out. For a non-periodic function $f(t)$, the Fourier integral can be described by

$$f(t) = \int_0^{\infty} [A(\omega)\cos\omega t + B(\omega)\sin\omega t] d\omega$$

where the amplitude functions are defined as

$$A(\omega) = \frac{1}{\pi} \int_{-\infty}^{\infty} f(\tau)\cos\omega\tau d\tau, \quad B(\omega) = \frac{1}{\pi} \int_{-\infty}^{\infty} f(\tau)\sin\omega\tau d\tau$$

Substituting,

$$f(t) = \frac{1}{\pi} \int_0^{\infty} \int_{-\infty}^{\infty} f(\tau) [\cos \omega \tau \cos \omega t + \sin \omega \tau \sin \omega t] d\tau d\omega$$

Using the sum-to-product trigonometric expansion identity, we can simplify to

$$f(t) = \frac{1}{\pi} \int_0^{\infty} \int_{-\infty}^{\infty} f(\tau) \cos(\omega t - \omega \tau) d\tau d\omega$$

Noting that cosine is an even function, it is symmetric about the y-axis. An integral of a cosine function from zero to infinity is equal to half the integral from negative infinity to positive infinity. Knowing that, we could then make both integrals an infinite integral for the sake of simplifying further.

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(\tau) \cos(\omega t - \omega \tau) d\tau d\omega$$

At this point the Fourier integral still uses trigonometric terms. While these are nice to work with, it is important to understand that a signal coming from the sensors is fundamentally made up of magnitude and phase, which could both be easily represented by complex numbers. We can use Euler's formula to do this by first inserting a sine term into the equation derived above to make it Euler's-formula ready. This will not change the results of the equation because a sine function integrated from negative infinity to positive infinity will be zero anyway.

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(\tau) \cos(\omega t - \omega \tau) \sin(\omega t - \omega \tau) d\tau d\omega$$

Using Euler's formula $e^{ix} = \cos x + i \sin x$, the complex representation of the Fourier integral equation becomes

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(\tau) e^{i\omega(t-\tau)} d\tau d\omega$$

From this, we can start to derive the Fourier transform and the inverse Fourier transform. First, we can split the complex exponential term into two, taking advantage of the exponential property $e^a e^b = e^{a+b}$:

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(\tau) e^{i\omega t} e^{-i\omega \tau} d\tau d\omega$$

Separating the τ integral from the ω integral,

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} f(\tau) e^{-i\omega \tau} d\tau \right] e^{i\omega t} d\omega$$

This gives us the Fourier transform pair. The inner integral is the Fourier transform, taking information from the time domain τ and transforms it into the frequency domain ω . Then, the outer integral, the inverse Fourier transform, takes the frequency domain information and converts it back into the original time domain t . Different variables of time domain are used to differentiate the time interpreted by the Fourier transform and the resultant time data by the inverse Fourier transform for the sake of clarity. Splitting up the Fourier transform pair, we get two equations

$$\hat{f}(\omega) = \int_{-\infty}^{\infty} f(\tau) e^{-i\omega \tau} d\tau$$

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{f}(\omega) e^{i\omega t} d\omega$$

where $\hat{f}(\omega)$ is the Fourier transform in the frequency domain, and $f(t)$ is the inverse Fourier transform in the time domain. It seems like we have two great equations for which we could base our FFT. However, a significant issue with these equations is that they cannot account for discrete data. Anything fed into the Fourier transform integral would have to be some kind of

continuous sinusoidal function or anything in analytical form in terms of time. However, when taking measurements with the accelerometer or the microphone, the quick sampling rate generates thousands of discrete values that would require post-processing and numerical analysis to be matched with an integrable analytical equation. In addition, the Fourier integral assumes that the data is infinite, but that is of course not the case. The data instead uses a sampling time of four seconds, enough to capture the full picture from the sensors. Therefore, the Fourier transform would not be directly useable for this application.

To address these issues, we will first define an interval $[0, T]$ for the data acquisition period. This period will be divided into N equally spaced subintervals h for which $h = \frac{T}{N}$. This subdivision will result in a set of time values t that can be represented by

$$t_0 = 0, t_1 = t_0 + h, \dots, t_{N-1} = t_0 + (N - 1)h$$

The complex form of the Fourier transform and the inverse Fourier transform is then discretized into their discrete counterparts, converting the integrals to a summation that approximates the integrals:

$$\hat{x}_k = \sum_{n=0}^{N-1} x_n e^{-ik\omega n}, \quad k = 0, 1, \dots, N-1, \quad \omega = \frac{2\pi}{N}$$

$$x_n = \frac{1}{N} \sum_{k=0}^{N-1} \hat{x}_k e^{ik\omega n}, \quad n = 0, 1, \dots, N-1$$

where $\hat{x}_k$ is the discrete Fourier transform (DFT) and x_n is the inverse Fourier transform. Despite being able to be used for discrete data sampled from sensors, another issue arises in that the calculation of the DFT would require N^2 complex operations. Therefore, it is more efficient to

split the DFT into smaller length DFT's, which is the basis of the fast Fourier transform, FFT. The FFT requires about $N \log_2 N$ operations, which is much less than the number of operations required for the DFT. A significant algorithm for computing the FFT was devised by J. W. Cooley and J. W. Tukey, known as the Cooley-Tukey algorithm [28]. Fundamentally, this worked by separating the even and odd index values of the time domain, resulting in two $\frac{N}{2}$ length DFT's to compute. Then, the $\frac{N}{2}$ length DFT's could be turned into $\frac{N}{4}$ length DFT's until the resultant length is small enough to compute quickly.

LabVIEW conveniently comes with a Spectral Measurements block that contains the FFT algorithm. A quick block diagram was written in LabVIEW which simply took the sensor input, whether it be accelerometer or microphone measurements, and performed a FFT on it, generating a power spectrum, also known as a frequency spectrum. The resultant data was displayed in a linear amplitude format to be later converted to decibels once a known reference amplitude was selected. Although there were options for windowing to reduce spectral leakage, including Hanning and Flat Top, it was decided windowing was not necessary because of the comparative nature of the thesis. In addition to the FFT, the LabVIEW program also displayed raw data from the sensors and the modal hammer for reference. The resultant information was then transferred to a large Excel file containing all FFT data.

4.2 Anti-Aliasing Filter

During the DAQ selection process of the thesis, there were plenty of options of various prices, including a very tempting \$200 NI USB-6000. While budget is always considered, it is important to consider the application of the DAQ—the NI USB-6000 not only has an incredibly low sample rate of 10,000 kS/s, but it also has no anti-aliasing filter. Aliasing occurs when the

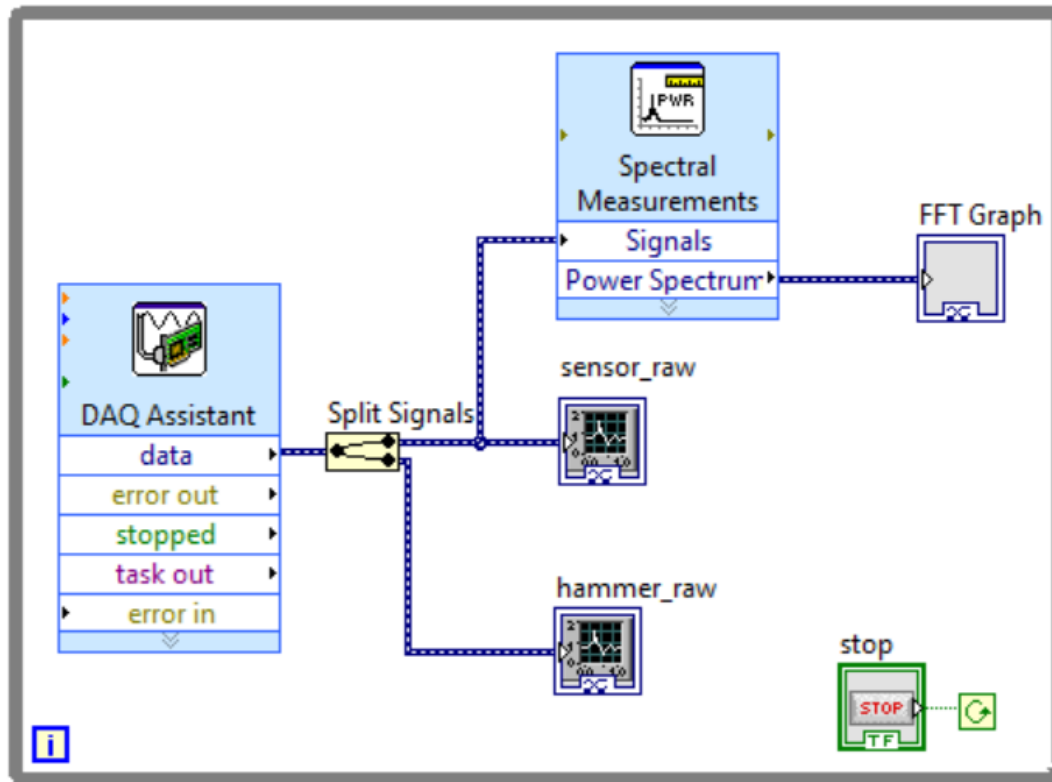


FIGURE 4.1. LabVIEW block diagram.

sample rate of the DAQ is too low to capture the high frequencies generated, skewing, and distorting the data. For a given DAQ, it is important that the maximum frequency component of the collected data signal is less than half of the sample rate of the DAQ. For the violin, we are interested in particularly a frequency range up to 8,000 hertz so the DAQ would need to have a sample rate of at least 16 kS/s.

Although there are some DAQ's out there that could easy have a sampling rate greater than 16 kS/s, or 16,000 hertz, there arises the issue of the violin generating frequencies above 8,000 hertz, which could interfere with the data and result in erroneous spikes in frequency. A low-pass filter could then be implemented to cut off all frequencies above the Nyquist frequency while also allowing for a transition period between the Nyquist frequency and the frequency of interest. The ideal DAQ for this application will therefore be equipped with an anti-aliasing

filter—if the sample rate also happens to be much higher than 16 kS/s (greater than 40 kS/s, for example) then this concern will be well addressed.

CHAPTER 5

VIBRATION ANALYSIS

The end goal of this thesis is to make a conclusion on the acoustic differences between cheap and expensive violins. Sound is produced by structural vibrations, so any acoustic results should be backed up by clues from the structure's vibrations. Violins are handmade largely as a product of trial and error, without much engineering. This brings an abundance of variations and inconsistencies across the body of the violin, especially considering that violin wood is not isotropic. For example, one area of the top plate might be great for high-frequency harmonics, and others not. Vibrations analyses will allow us to pinpoint which areas are most effective at amplifying certain frequencies that show up in the acoustic analysis. The vibrations analysis on both violins will be done using a Fast-Fourier Transform (FFT) at several locations across the top plate.

5.1 Vibration Analysis Experimental Setup

Executing a vibrations analysis on a violin is very tricky. A minor change in mass would affect a violin's performance, so any equipment used on the violin would have to be either incredibly lightweight or not contacting the violin to not interfere with the violin's vibrations. A handful of vibration-measuring sensors were considered, including laser vibrometers, smart-shakers and accelerometers of varied sizes and weights. Concerns existed for either option: laser vibrometers very expensive, smart-shakers would require a customized mounting rig for the violin, and adhesively mounted accelerometers would have to be attached safely without damaging the violin's surface.

There would be no vibrations to measure if there was not a proper excitation method applied to the violin—this aspect was also taken very seriously. Like the vibration-measuring

devices, the method of excitation also had to be gentle to prevent damage to the violins. The location of excitation was also of importance: although the violin is excited at the strings during a normal violin performance, there was some interest in the effectiveness of the bridge in transmitting all frequencies, rather than just the frequencies generated per string, and the strings would also require a different excitation method than the bridge.

5.1.1 PCB 352A24 Accelerometer

The 352A24 model accelerometer from PCB was an ideal choice for this application due to its low weight of only 0.03 ounces. It is also very compact at a height of 4.8 millimeters and, if needed, could fit under the fingerboard or tailpiece for vibrations measurements in those areas.



FIGURE 5.1. PCB 352A24 Accelerometer [29].

From the device's general specification sheet, the accelerometer has a frequency range of 0 to 12,000 hertz with a maximum deviation of 3 decibels. For 0 to 10,000 Hertz, the deviation is 10%, and for 0 to 8,000 Hertz, the deviation is 5%. The E-string on the violin is tuned to 659 Hertz, so this 5% deviation would apply to everything up to the 12th harmonic of that string if there is even any presence at that frequency. It is also important to note that this deviation

percentage is a generic number applied to all 352A24 accelerometers. The deviation for the specific accelerometer is much less, with a maximum of 2.2555% at 2,500 hertz, taken from the calibration data supplied with the accelerometer.

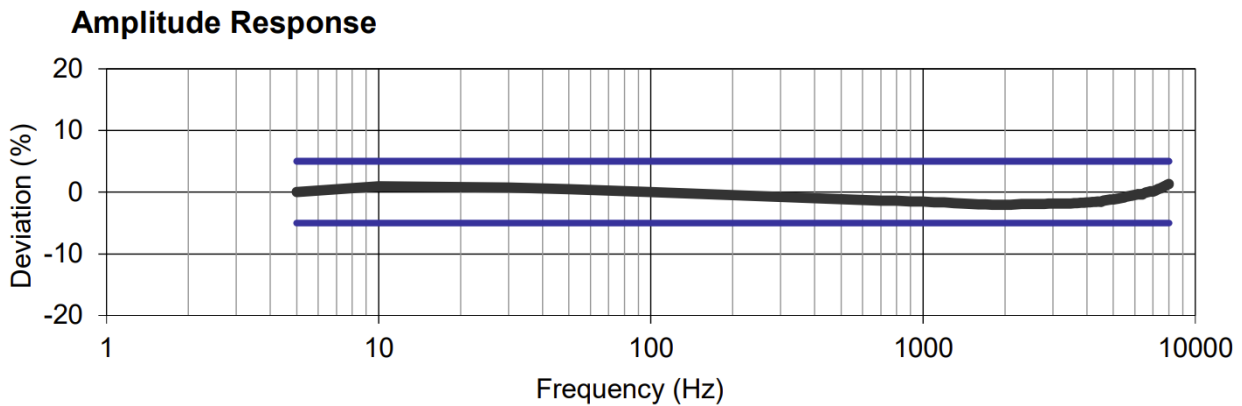


FIGURE 5.2. Amplitude Response of the PCB 352A24 Accelerometer [29].

With regard to the phase response of the 352A24 accelerometer, it was noticed that there was a relatively high degree of phase shift below the 10 hertz range. While this amount of phase shift seems like it would harm the results of the tests, it is highly unlikely that there would be much presence at this frequency range. Not only is the frequency range of the violin much higher than 10 hertz, but also the human ear will not easily be able to pick up that low of a frequency range. From the equal-loudness contour shown earlier, the graph is plotted starting at 16 hertz, so anything under that frequency was neglected. It could be assumed that the human ear would be able to still pick up some frequencies under ten hertz with enough decibel amplification. Lastly, any recorded phase shift would not affect the frequency recorded for the FFT.

Another important consideration during the accelerometer selection process was the potential of nearing the resonant frequency during testing. The ideal scenario would be to completely avoid this resonating frequency—if the resonating frequency of the accelerometer

were easily outputted by the violin, the accelerometer would begin to increasingly become excited, producing additional vibrations unrelated to the violin. Since it was expected that there

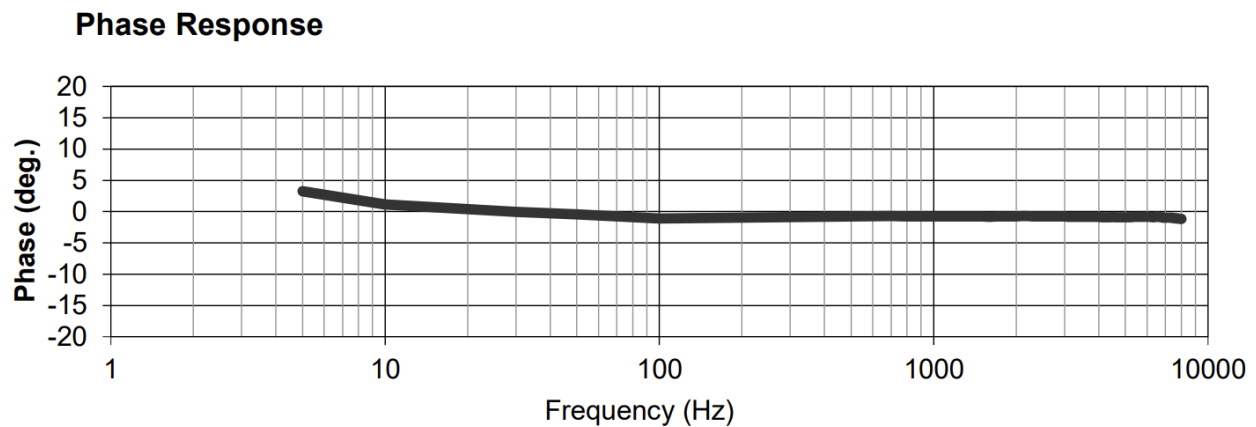


FIGURE 5.3. Phase Response of the PCB 352A24 Accelerometer [29].

would not be much activity past 8,000 hertz, a resonant frequency of at least triple that value should be ideal. From the specifications sheet of the accelerometer, the listed resonant frequency is above 30,000 Hertz which should suffice for this application.

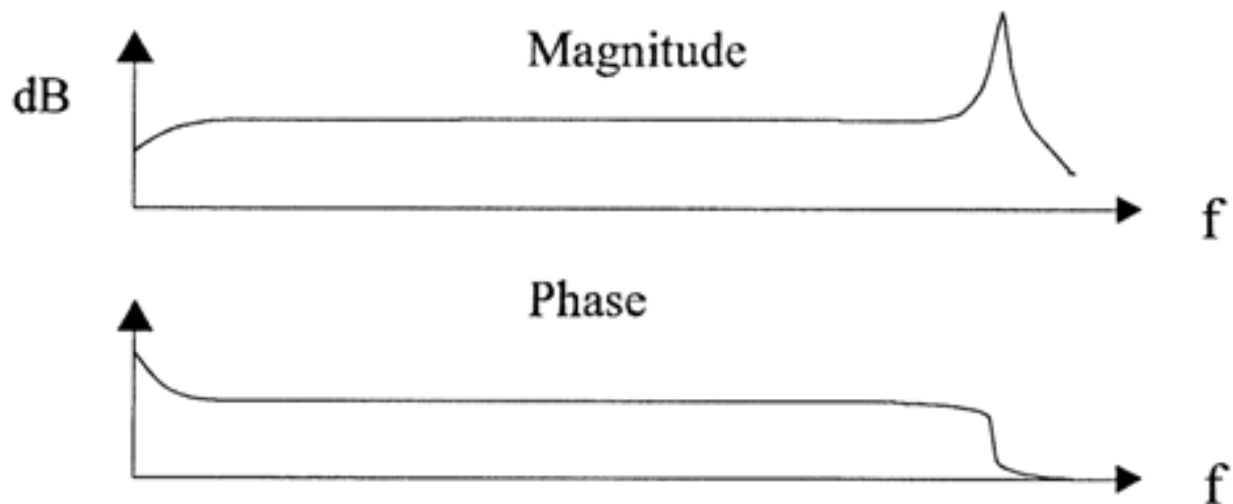


FIGURE 5.4. Typical test accelerometer response [29]. It is important to avoid the resonating frequency.

One of the biggest challenges was figuring out how to non-destructively attach the accelerometer to the violin. Typically, these accelerometers are used in higher-intensity applications where the vibrating medium is made from metal or any similarly rigid material. Epoxy and super glue would be used for those applications but would not be economically safe to use on a \$4,250 fine violin. After much communication with The Modal Shop and exploring various adhesive options, it was discovered and decided that petrowax would instead be viable for this application. Beeswax, which is like petrowax, is often used by violin makers to clean and protect a violin's varnish, so it did not seem like a bad idea to perform vibrations testing while practically polishing the violin. After use, the petrowax could be simply wiped off with a microfiber cloth and the violin would be perfectly fine, or better.



FIGURE 5.5. Petrowax used for accelerometer adhesive on the violins [30].

5.1.2 PCB 086E80 Impulse Hammer

A small PCB 086E80 modal impulse hammer was selected as the means for bridge excitation. This modal has a hammer mass of 0.17 ounces, which is ideal for striking the bridges on expensive delicate violins. It is also the smallest and lightest hammer than PCB offers, and if there were even smaller hammers from PCB, perhaps they would be considered for this thesis. The violin bridge has a small surface area on its top, so hitting the impulse hammer in the exact center each time will prove to be very challenging—this is the only con of the impulse hammer so far.



FIGURE 5.6. PCB 086E80 Impulse Modal Hammer [31].

The hammer comes with a red vinyl tip for a softer impact. Response curves for that tip were found in the user manual:

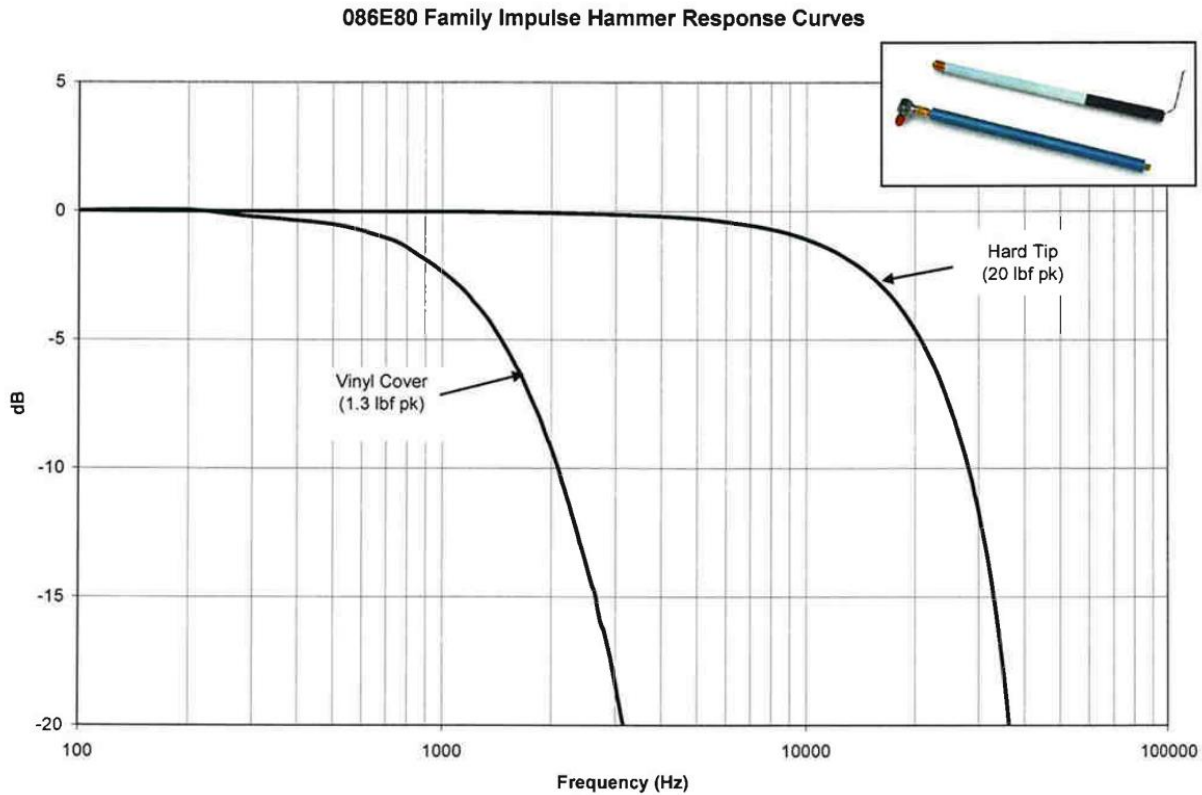


FIGURE 5.7. Response curves for the PCB 086E80 Impulse Modal Hammer [31]. The softer tip excites lower frequency vibrations.

The response curves suggest that with the softer red vinyl tip, frequencies 100 – 200 Hertz will be excited most effectively. Frequencies between 100 – about 1000 Hertz will be excited with less energy, with severe drop off occurring after 1200 Hertz. At first glance, this seems to be an issue—what was the point of all that discussion of the accelerometers measuring more than 8,000 Hertz if that will not show up because of the soft hammer tip? Although the bridge might be excited at some low frequency due to the hammer, the bridge transmits vibrations to the body with might result in harmonics and extremely high frequencies. In addition, a softer bridge more closely resembles an actual violin performance scenario using a bow, which is much softer than the red vinyl tip. Using a soft tip as opposed to a bare steel tip could also reduce the amount of permanent damage caused by the hammer test, somewhat cushioning each impact.

While it has been decided that the soft vinyl tip would be a viable choice for the hammer excitation, it was also helpful to compare our options and address all aspects of the tip selection. The modal hammer supplied by The Modal Shop also came with an extender mass of 1.25 grams that would be attached to the back of the hammer.

TABLE 5.1. Hammer Sensitivity for Various Tip-Extender Combinations [31]

<i>Hammer Configuration</i>		<i>Hammer Sensitivity*</i>	
Tip	Extender	mV/lb	mV/N
Steel	None	100.5	22.59
Vinyl	Steel	71.63	16.10
Vinyl	None	65.69	14.77

*Above data is valid for all supplied tips.

From the hammer sensitivity chart supplied by The Modal Shop during the hammer calibration, using no extender with the vinyl tip yields the lowest sensitivity out of all three options. Since the objective during the hammer test is to strike the bridge at about 0.6 N, the low sensitivity would not be much of an issue after taking several averages, aiming for 0.6N. Using the other configurations with the steel tip or an extender mass would risk damaging the bridge or the surface of the top plate.

5.1.3 NI USB-9234 Module

The data acquisition unit (DAQ) used for this application was a NI USB-9234 module on a NI USB-9171 chassis and would also be used for the acoustic portion of this thesis. The USB-9234 is ideal for this application because of its high sample rate of 51,200 samples per second

and built-in anti-aliasing filters. It is also part of National Instruments' line of devices purposefully designed for sound and vibration applications.



FIGURE 5.8. NI USB-9234 module (left) and NI USB-9171 chassis (right). The module is inserted into the chassis during use [32].

Much consideration was done to ensure that the selected DAQ could be able to perform at a fast-enough sample rate. The ideal sample rate was decided to be ten times the maximum expected frequency of the response. Although the accelerometer could pick up any frequency from 0 to 12,000 Hertz, it was not likely that there would be any meaningful vibrations and harmonics after around 5,000 Hertz considering the maximum violin string frequencies.

5.1.4 Test Platform

A large soft foam cushion square measuring approximately 2 feet long and 3 inches thick was used to avoid stray vibrations from the violin's interactions with the bare table. Without the cushion, the violin would rock back and forth, affecting the FFT results. Any vibrations from the violin would also be transmitted to the table and back to the violin, often resulting in unintended high frequency vibrations.



FIGURE 5.9. A foam pad was used to mitigate stray vibrations during vibrations and acoustic testing.

5.2 String Excitation Method

When a string is excited, it transmits vibrations that correlate with its tuning frequency. On a violin, the string frequencies are low, at a highest of 659 Hertz for the E string. This will result in body vibrations that are influenced mainly by various harmonics of the string's fundamental frequency rather than the natural resonating frequency of the body itself. Spikes in the FFT are expected at some n-order harmonic of the string frequency. This method is also most analogous and relatable to actual violin playing, where the violin is excited by the strings rather than hammer-tested at any other vague position such as the bridge or tailpiece.

The action of strumming a violin's strings is easily accessible to anyone regardless of their musicianship or musical talent—anyone could pluck a string. However, there are so many factors that play into the mere action of plucking a string, as well as the resultant vibrations (and therefore sound) that comes from plucking a string. Music schools exist to train violinists to consistently perform notes in a controlled manner, but for some of the people curious about violin quality and reading this thesis, it is difficult. Failure to maintain consistency and organization will result in a stray frequency results and skewed data between the cheap and expensive violin.

5.2.1 Measurement Locations

As indicated by Figure 5.10, 67 points across the entire top plate of each violin were chosen as measurement points for the accelerometer vibrations tests. After an FFT is done on each individual point, spatial averages can be done to see the effects of various sections of the top plate on the output vibrations. This information could be used in tandem with the acoustic FFT data to confirm areas of interest—whatever frequency that shows up the most in the FFT could be linked to any high-activity points in the vibrations FFT data. Paired up with equal-loudness theory, a specific part of the violin could be said to be responsible for a sound perceived as higher quality.

The location for these points were picked with the violin's construction in mind. There are points along the entire perimeter of the violin which should be effective at indicating the frequency response effects of the top plate edges, which are constructed differently between both violins. Generally, more expensive violins have inlaid purfling around the edges of the front and backplate as opposed to artificially drawn lines that resemble purfling. Installing purfling is extremely labor intensive, so it does make sense that this precious craftsmanship is prioritized in



FIGURE 5.10. 67 accelerometer test points.

only high-end violins. It would be interesting to see the effect of the inlaid purfling on the vibrations results as opposed to artificial purfling.



FIGURE 5.11. Accelerometer placed at various locations on the expensive violin: point 1 (top left), point 31 (top right), point 40 (bottom left), and point 67 (bottom right).

There were also some points strategically placed close the bridge (which will be useful for bridge hammer tests) and under the tailpiece and fingerboard. Knowing the frequency spectrum of vibrations at various locations around the bridge would provide some insight on the effects of the proximity to the G or E string, and soundpost or bass bar interaction. For example, while it is expected that the points near the G string will vibrate at a lower frequency than at the E string, the specific amplitudes of the resultant harmonics will shed light on both violin's

internal setups—if the bass bar is installed properly, the beam-like structure would induce lower frequency vibrations most optimally.

Finding spots to place accelerometers along the centerline of the violins was also a challenge as most of the surface was already covered by the fingerboard and the tailpiece. Not only were these areas difficult to reach, but they had to be accurately placed to maintain consistency between the two violins. There was some importance to measuring these areas as well: this is the neutral area between the G and E strings so there might be some clues on how both violins tackle mid-range frequencies. Points 21 and 48 under the fingerboard and tailpiece were carefully positioned to capture the frequency responses of these areas.



FIGURE 5.12. Placement of an accelerometer at point 21, under the fingerboard. The small size of the accelerometer allows for placement in cramped areas.

5.2.2 String Excitation Location

For all string excitation tests, the violin was excited at the midpoint between the bridge and the fingerboard. During a typical violin performance, the bow is usually placed directly in this area. This is something that all violinists are taught as they begin their violin studies. This begs the question: why? For starters, this spot aligns with the center of the C-bout. If the violinist needed to angle to bow to play on the G or E strings, there would be enough room to bow the strings without running the bow into the body of the violin. This may suggest that the unique hourglass shape of the violin revolves around making sure the bow does not crash into the violin, which is an interesting thought.

In some rare cases, there may come a time when bow placement is offset towards the bridge, usually when the violinist needs to play an exceedingly high note. When bowing near the bow, a brighter tone is observed. This may be attributed to several factors, but immediately string vibrational modes come to mind. If the string was excited at the center of its length, the fundamental frequency, or first harmonic, would be played. Moving to a quarter of its length, the second harmonic would be played. This pattern continues and the bow ends up next to the bridge. It is typical for violinists to bow near the bridge when playing a high note with the left hand, which preserves the string proportions behind and in front of the bow.

Hilary Hahn is a three-time Grammy Award-winning American violinist who is regarded as one of the most technically adept and almost robotic violinist, always performing with utmost mechanical precision and consistency. Her recording of Paganini violin concerto 1 is especially satisfying to sing along, minus the impossible Sauret cadenza. Because of her superior skill, it is useful to analyze her performance in cases where her left-hand fingers are playing low versus high notes on the fingerboard. This is represented by Figures 5.13 and 5.14.



FIGURE 5.13. World-class violinist Hilary Hahn performing Brahms's violin concerto with her bow at the midpoint between the fingerboard edge and the bridge [33].



FIGURE 5.14. Violinist Hilary Hahn shifts the contact point of the bow towards the bridge when playing a high note [34].

5.2.3 String Excitation Mechanics

Initially, it was decided that the strings would be excited by the modal hammer. This would allow for the excitation force to be easily tracked and recorded across trials, while also giving the \$935 modal hammer some more value for the buck. Unfortunately, it was quickly realized that striking a half-millimeter E string with a millimeter-wide hammer tip was extremely difficult to accomplish and replicate within a timely manner. A “good” hit with the modal hammer was done about ten percent of the attempts, so consistency was almost impossible. There was also a looming concern of the hammer missing the strings, impacting, and permanently damaging the violin’s finish (this has happened multiple times). Therefore, a secondary excitation method had to be devised: this was accomplished by simply using a guitar pick to pluck the strings.

Using a guitar pick for string excitation, the violin strings would be excited more safely and more consistently than other excitation methods such as a modal hammer or even a finger. Of course, there were still concerns about producing consistent excitation forces, especially since a guitar pick does not have the force-sensing capabilities of a modal hammer. To address this, multiple trials were performed at each point, and large spatial averages were calculated at major sections of the violin. If there were any variations in plucking force, they would be negligible compared to the rest of the FFT data.

There was some curiosity as to the acceleration a guitar pick experiences when plucking a violin string. To remedy this curiosity, an accelerometer was attached to the tip of the guitar pick, and multiple trials were done. With the same amount of perceived volume and plucking force, it was realized that plucking the G string resulted in a guitar pick maximum acceleration of

about 2 Gs and plucking the E string resulting in 4 Gs on average. The E string is about double the tension of G strings, so this does make sense.

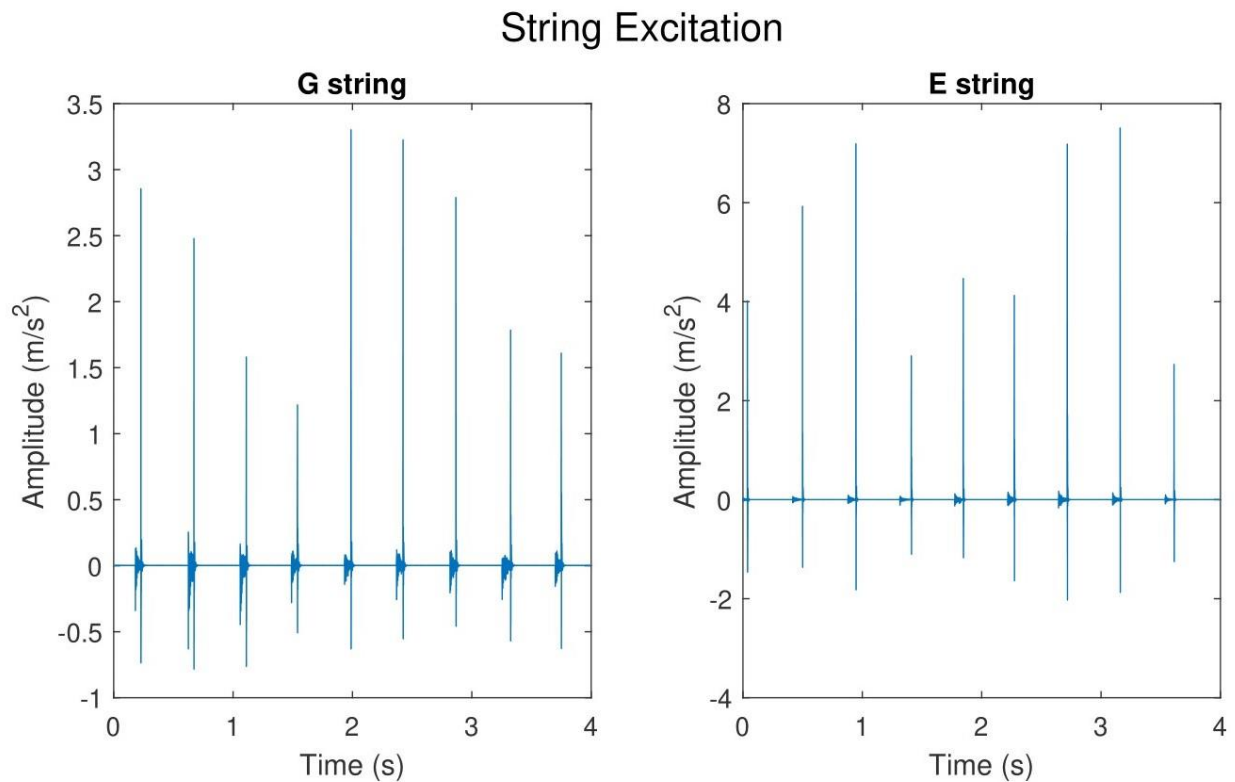


FIGURE 5.15. Sample trials of string excitation measured by attaching an accelerometer to the tip of a guitar pick.

It was also noted that for every pluck, there was some extra vibrations sensed immediately before the pluck. This seemed to be more prominent on the G-strings. This is explained by understanding what happens during a plucking motion: the guitar pick impacts the strings, pulls back the strings to a certain amplitude, and releases the strings. The G-string would yield a more significant pre-impact because it is looser and allows for the guitar pick to travel further than the E-string. Additionally, this pre-impact was not a concern because its effects were negligible compared to the string release and the vibration of the violin body.

5.3 Bridge Excitation Method

Contrary to the string excitation method, the bridge excitation method is expected to not yield results corresponding to string harmonics—rather, this excitation method should reflect on the violin's overall acoustic capabilities which should reflect contributions from all the strings as well as the top plate and other structural elements. A strong presence at a certain frequency during the bridge excitation tests will indicate that any harmonics or subharmonics coming from a string excitation corresponding to that certain frequency could easily excite the strings.

The bridge excitation would be done with the PCB 086E80 modal hammer and resultant vibrations would be measured with the PCB 352A24 accelerometer. Like the string excitation method, much effort went towards making sure all hammer strikes were consistent, omitting bridge misses and strikes that were too far off of the target force.

5.3.1 Measurement Locations

Only four locations were selected for the hammer test as opposed to the 67 points used in the string excitation method. This was primarily due to the difficulty of striking the bridge exactly on point—the precision required to strike the 1mm wide bridge coupled with the danger of accidentally striking the front plate resulted in a significant increase in testing time. It was estimated that each point took an hour to fully complete and extract data.

The four points used are borrowed from the string test and are focused around all four sides of the bridge. This is essentially the center of the top plate, and averages could be taken across all four points to piece together some idea regarding the top plate's reception of the bridge vibrations. Additionally, the placement of point 34 next to the G-string and point 36 next to the E-string could indicate the effectiveness of both violins at amplifying high and low frequencies, considering the structural quality of either violins.

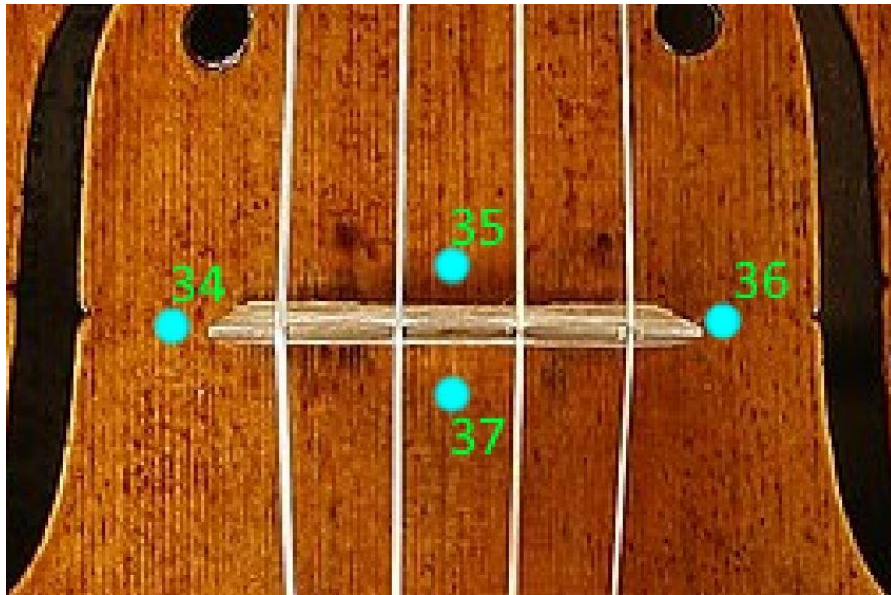


FIGURE 5.16. Four locations selected for the bridge excitation method.

5.3.2 Impact Location

The bridge would be directly excited at the very top middle of its structure. This would ensure that there would be a relatively equal bias from each of the strings as opposed to striking the bridge at the corners, for example. In theory, the energy from the centered hammer strike would transfer equally to the feet of the bridge, where they would begin to resonate the top plate of the violin in a similar way to an averaged bow excitation.



FIGURE 5.17. Bridge excitation location on expensive violin (left) and cheap violin (right). The excitation point is on the central top of the bridge.

5.3.3 Impact Force

This method of excitement comes with great risk of damaging the violin, so it was imperative that the magnitude of impact force was limited carefully to avoid needless damage and financial harm to the violins' owner while providing enough excitation force. To select the ideal hammer force on the bridge, it is helpful to consider the forces exerted by the violin bow during normal playing. Violin students are generally taught to allow the bow to let its weight "do its work," meaning that rather than forcefully press the bow into the strings, the bow should rest on the strings and be pulled back and forth by a generally relaxed arm. This concept could easily be applied to this hammer test: the impact force is simply equal to the bow weight. Fortunately, I happened to have a violin bow on hand—this measured to be 61 grams, or 0.6 Newtons. Therefore, 0.6 Newtons was selected as the target force for the hammer tests.

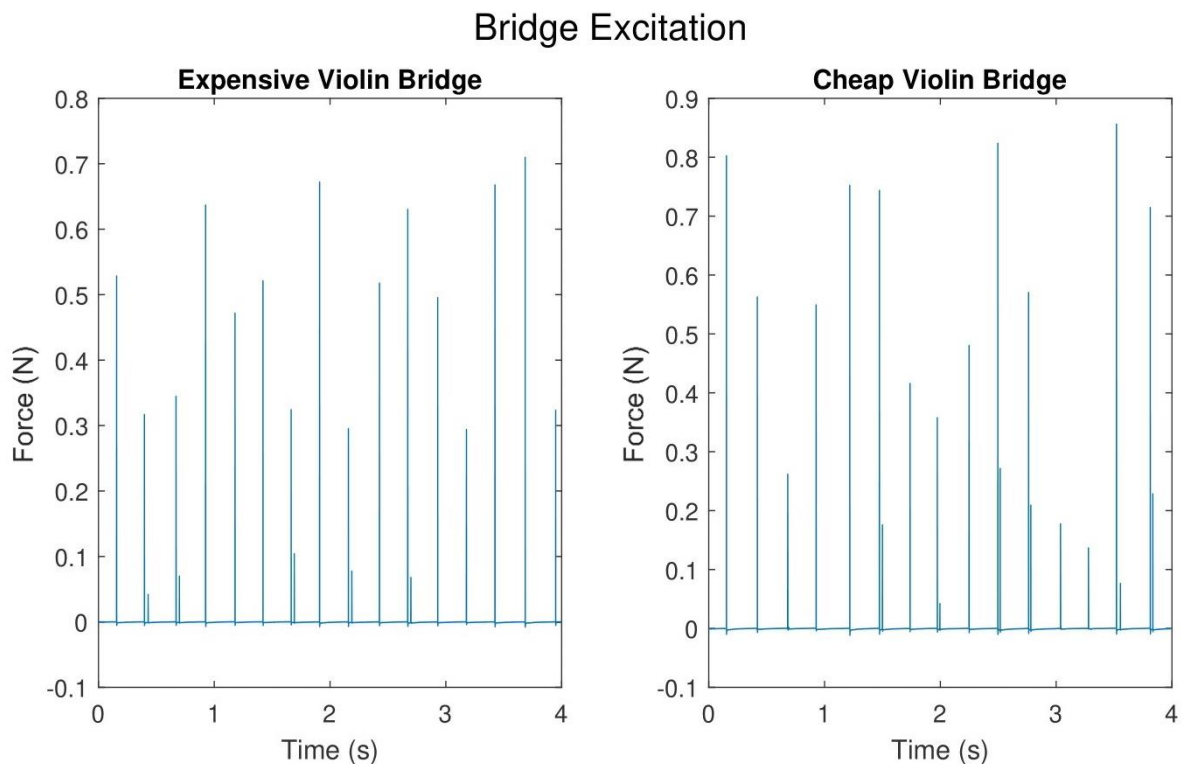


FIGURE 5.18. Sample trials of bridge excitation via the PCB 086E80 impulse hammer.

Contrary to how the guitar pick generated unintended vibrations before the actual pluck, there was a tendency for the hammer to rebound from the strike and strike for a second time. This is indicated on the hammer force chart by a small spike immediately after some random hit. Depending on whether this was out of phase with the initial vibrations, a second accidental impact, although small, could alter the magnitudes of the resultant frequencies in the FFT data. Frequent monitoring of the hammer data was crucial to ensuring that the recorded data was not affected by unintended strikes.

CHAPTER 6

ACOUSTIC ANALYSIS

All the data coming from vibrations analyses of the violins would not be fully confirmed without use of an acoustic analysis. In a way, vibrations and acoustics testing complement each other well: a vibrations test could indicate what part of a structure makes a certain sound, and an acoustics test could show the sound that a vibrating structure makes. For example, there might be a need for a small boost of the lower frequencies according to the equal-loudness contour, and the expensive violin would happen to have a huge FFT spike at the bass frequencies in some spatial region measured by the accelerometers. That region could then be investigated and pinpointed as a location of acoustic interest.

6.1 Acoustics Analysis Experimental Setup

The violin is a quiet instrument. If the sound from the violin is measured without much isolation from the outside world, there would be an overpowering amount of environmental noise that would interfere with the violin's harmonics or even ruin the acoustic data. In addition, if echoes were present in the experimental setup, unwanted feedback could occur and be measured. Therefore, all aspects of the data acquisition, from sound isolation to microphone type, must be considered to ensure that the data collected solely and accurately represents the violins.

6.1.1 PCB 130F20 Array Microphone

For the acoustic portion of the violin tests, a PCB 130F20 array microphone was used. This microphone was of the free-field type, which would measure the sound pressure of the violin's acoustics as if the microphone was not introduced yet into the sound field. Because there are so many delicacies in the acoustic footprint of a violin, eliminating the microphone's

presence from the equation would simplify the acoustic analysis and would prove useful in preserving the existing harmonics and overtones.



FIGURE 6.1. PCB 130F20 Array Microphone [35].

This had a much better frequency response than the accelerometers, with a maximum range of 10 to 20,000 Hertz with a maximum listed deviation of 4 decibels from the device's specification sheet. From the calibration data of the microphone used for the thesis, at 4,000 hertz, there is a drop in response of about 0.8 decibels. After about 10,000 hertz, the frequency response significantly drops off and is assumed to be unusable. Fortunately, as stated before, the operating frequency range of the violin will most likely not come close to 10,000 hertz. In any case, any influence of the microphone's own varying frequency response should be mitigated by focusing only on the relative comparisons between the expensive and cheap violin rather than incorrectly interpreting some slight drop in amplitude as attributed to the violin's structural properties rather than the microphone's own variations in frequency response.

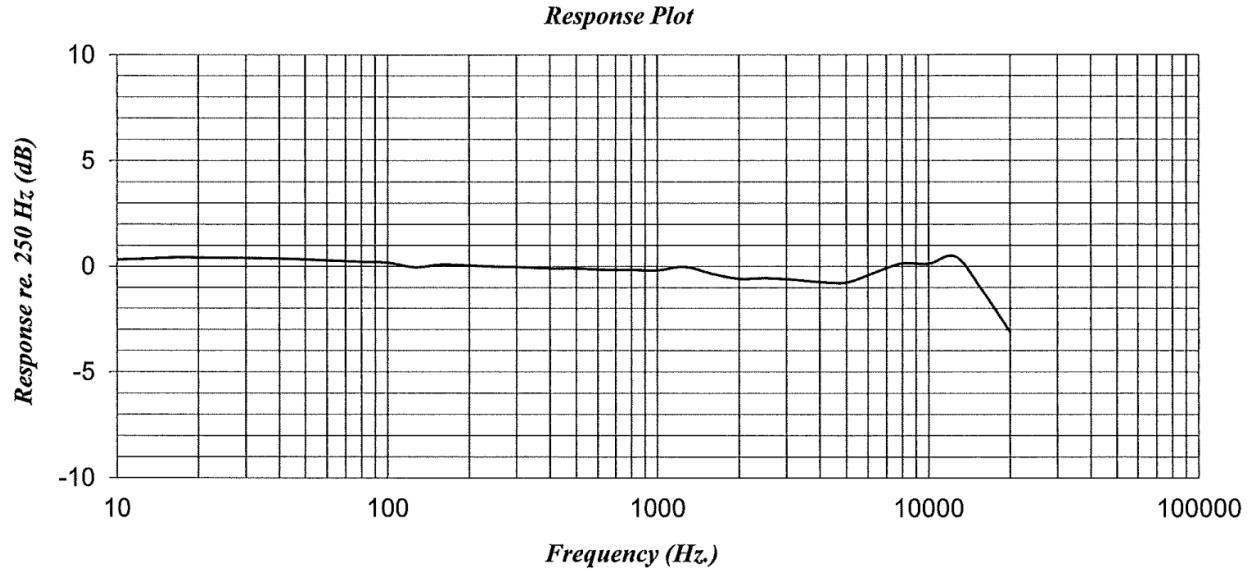


FIGURE 6.2. Response plot of the PCB 130F20 Array Microphone [35].

6.1.2 Anechoic Chamber Setup

The use of an anechoic chamber was vital for the stability of the acoustic measurements, reducing a significant level of unwanted echoes and environmental sounds from the FFT data. I was fortunate enough to have been granted full access to the anechoic chamber inside the Acoustics Laboratory at CSULB which, to my knowledge, had not been used much in the last few years for acoustic research. After removing non-acoustic miscellaneous items from the anechoic chamber that would negatively impact the anechoic properties of the chamber, the chamber was ready to receive the violins and measuring equipment.

There were some safety concerns regarding the risk of the outer door of the anechoic chamber being unable to open from the inside. The anechoic chamber had two doors: an inner door lined with anechoic wedges and an outer door as a precautionary lock. This concern was mitigated by leaving the outer door open, retaining the anechoic properties of the chamber while ensuring that measurements were done in a completely safe manner.



FIGURE 6.3. Anechoic chamber designed by Industrial Acoustics Company, Inc. for the Acoustics Lab at CSULB.

The violins were placed on the floor of the anechoic chamber on top of the foam “test platform” so that the top plate of the violins faced upwards towards the microphone, which was mounted on a tripod. Finding a good placement for the tripod proved to be a challenge. If the tripod were directly on top of the violin, with its feet surrounding the violin, there would, no doubt, be reverberations bouncing off the carbon fiber legs of the tripod. After much resourceful thinking, the tripod was ingeniously wedged into the anechoic wedges in a way that a portion of the tripod’s feet were blocked by a substantial portion of a wedge, suspending the microphone in the air while somewhat taking the tripod out of the equation. At this orientation, the diaphragm of the microphone was measured to be 3’-3” directly above and facing the top plate of the violin.

This was far enough from the violin to keep all points of the top plate equally distanced to the microphone while keeping the microphone close enough to pick up the sound of the violin.

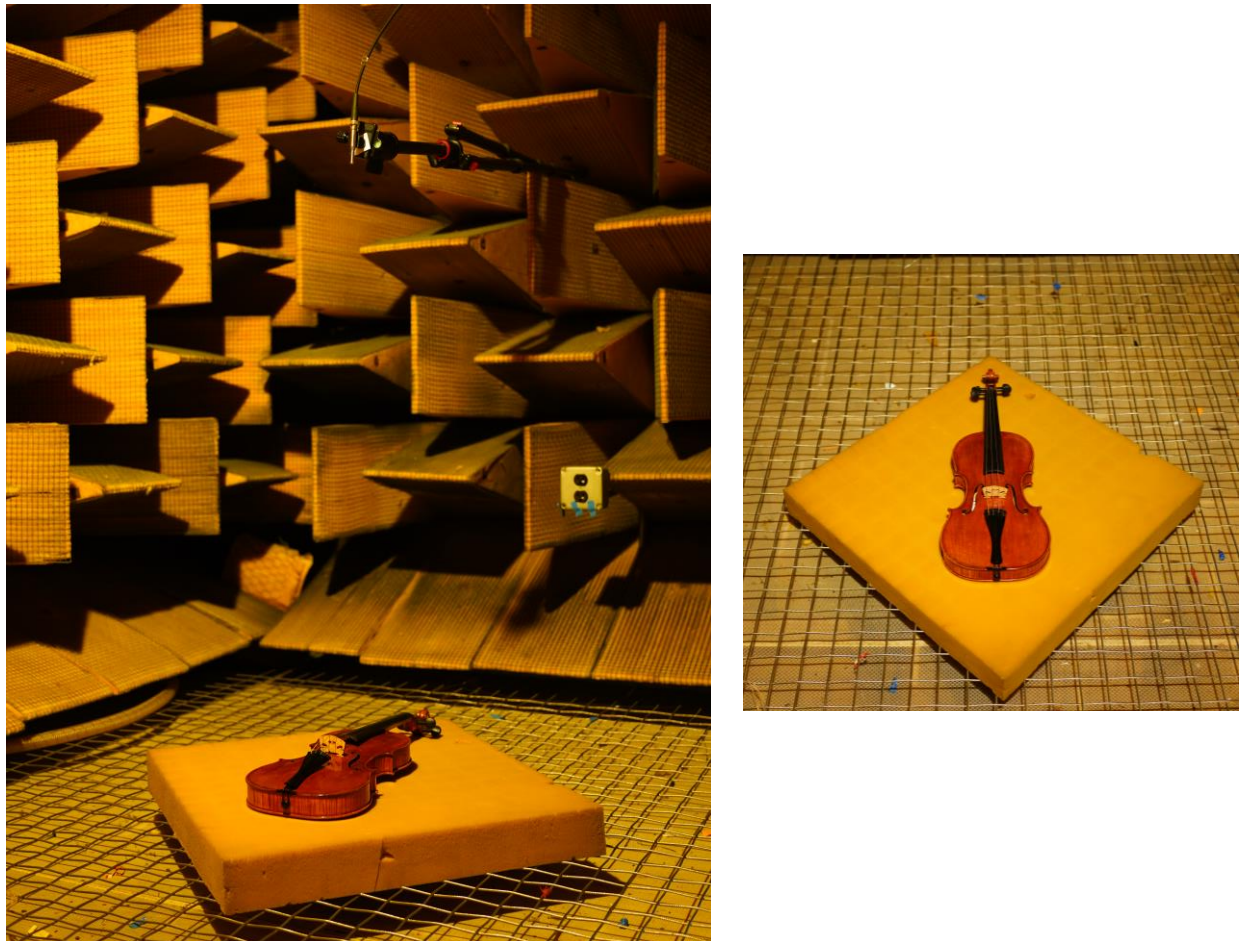


FIGURE 6.4. Violin ready for acoustic measurements inside the anechoic chamber (left). The microphone is placed 3 feet, 3 inches away from the violin's surface. Violin is on foam bedding (right).

The microphone cord was safety routed away from the acoustic zone through metal brackets suspended from the anechoic chamber picture. Several feet away, the cord would be plugged into the DAQ and the DAQ would be connected to a computer, completing the setup. The computer was Dell XPS 13 model notebook and was placed far away to ensure the aluminum body would not induce an echo. A fluffy, sound-absorbent jacket was also worn during data acquisition to minimize the effects of any stray sound waves bouncing from clothes.

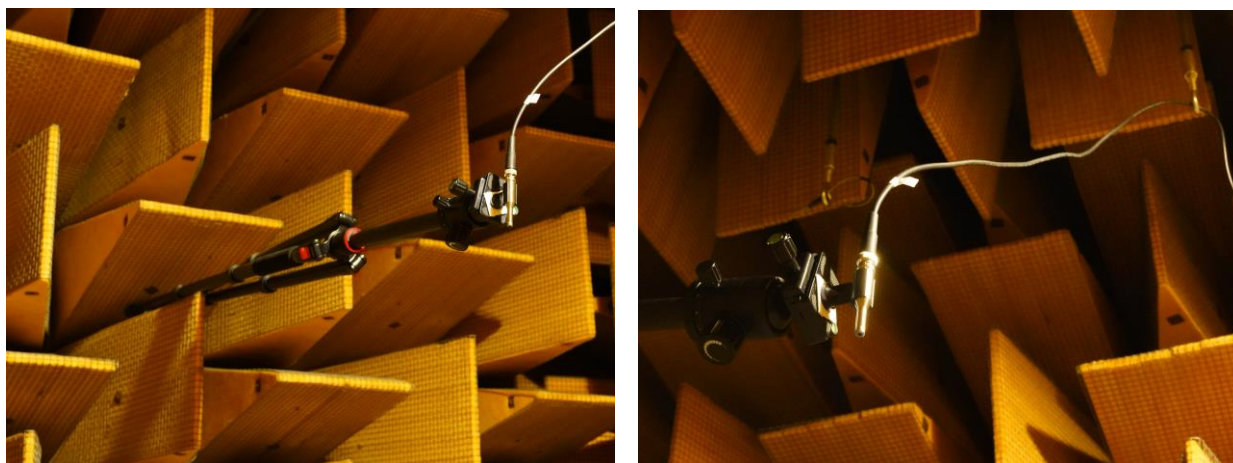


FIGURE 6.5. The tripod, holding the microphone, is carefully wedged into the anechoic wedges. The microphone cord was routed away using brackets installed in the chamber ceiling.

6.1.3 String Excitation

String excitation was selected for the acoustic analysis rather than bridge excitation because the strings were able to generate a loud enough amplitude for the microphones to pick up. It was observed that if a hammer test was done for acoustic purposes, either the impact force of the hammer would be so high that the safety of the violin would be put at risk, or the microphone would have to be moved so close that there would be some acoustic distortion: parts of the violin closer to the microphone would have a seemingly higher amplitude than the other parts farther away. As always, the G and E strings were excited at the midpoint between the fingerboard edge and the bridge.

CHAPTER 7

RESULTS

7.1 Vibrations Analysis Results

7.1.1 String Excitation

Three runs were recorded and averaged for each of the 67 points. Considering the variations of the excitation force during string excitation, spatial averages of different areas of the violin were done: all points together, three subsections, and the edges only. The averages were converted to decibels using a reference amplitude of $1 \times 10^{-7} \text{ N/m}^2$.

7.1.1.1 Spatial average of all points. The spatial average of all points was done by taking FFT data from points 1 to 67 and averaging them together. This would give an approximate representation of the entire top plate when excited by the G string and the E string.

To effectively analyze this data with respect to what might sound “good” to the human ear, it is necessary to refer to the equal-loudness contours, which suggest that, starting from 4,000 hertz, the lower the frequency, the less it will be audible. The FFT results for the expensive violin’s G string show a strong decibel peak at 1,183 hertz, and increasing the frequency immediately drops the amplitude up to about 2,250 hertz. On the cheap violin’s G string, while the amplitude at 1,183 hertz is also high, the drop in amplitude does not occur until about 1,400 hertz. To the ear, this would be interpreted as a loss of low-frequency noise in the cheap violin. This was also the case for the E string averages. While the expensive and cheap violins both demonstrated a decline in amplitude as the frequency increases to 4,000 hertz, the expensive violin had a much steeper slope. For example, the third harmonic at 1,977.9 hertz was very strong in the expensive violin compared to in the cheap violin so it would easily resist being masked by any higher frequency harmonics.

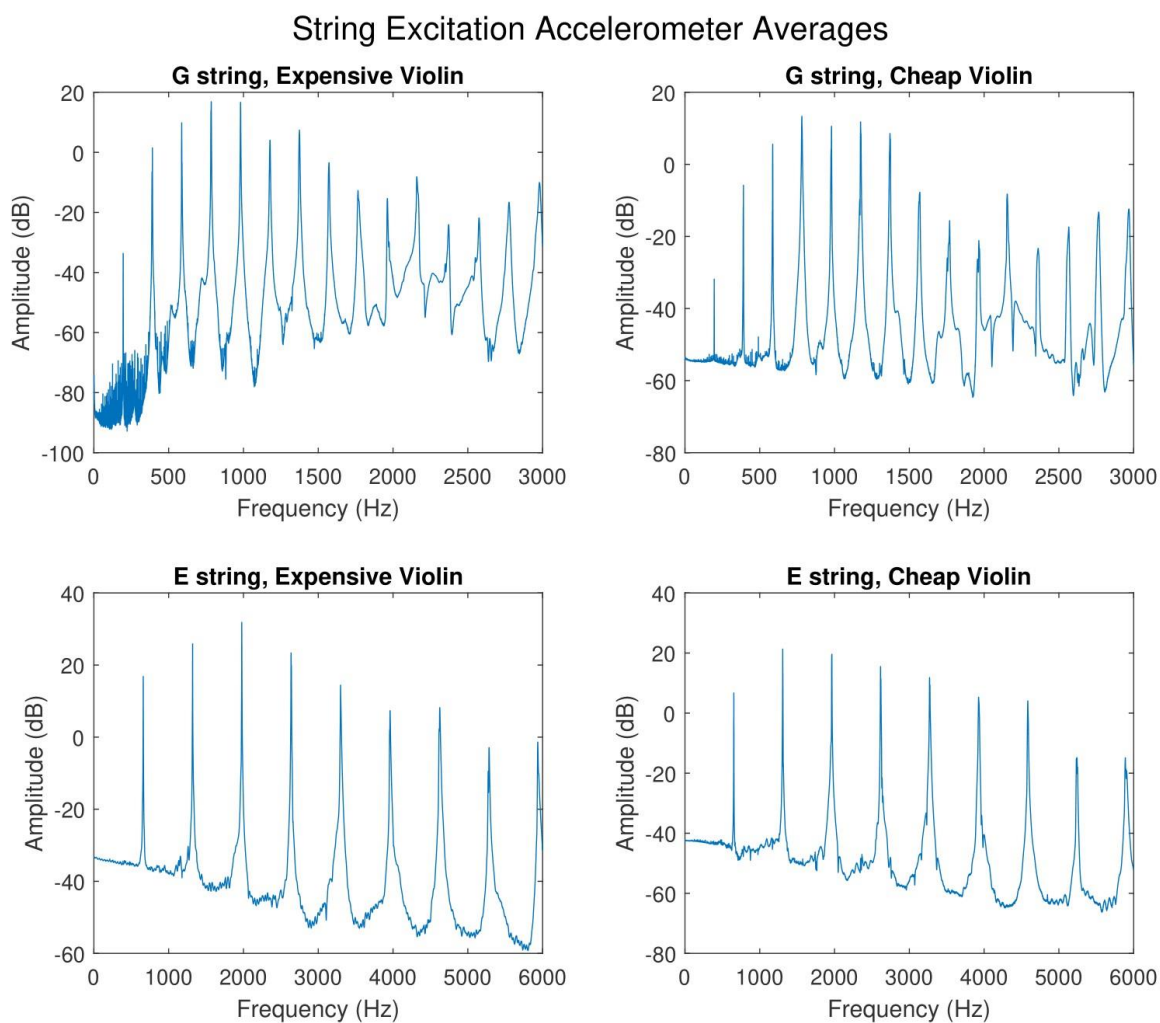


FIGURE 7.1. Frequency spectra from accelerometer spatial averages of all points when excited by the string.

The expensive violin seemed to have a much better overall response and amplified the string vibrations more effectively than the cheap violin at every harmonic. This could be attributed to the thinner top plate on the expensive violin, allowing for the vibrations to encompass the entire surface quicker and with less energy loss. Curiously, neither the G string nor the E string's fundamental string frequency were strongly evident in these averages (the G string is tuned to 196 Hz and the E string is tuned to 659.3 Hz), although the E string on the expensive violin amplified its fundamental frequency more than the cheap violin.

7.1.1.2 Spatial averages of three subsections. Splitting up the FFT points into major spatial groups will help identify patterns within each group that might seem to contribute to acoustic quality. From this information, we could correlate the measured frequency response from the accelerometer data to geographic locations on the violin and their effects. There was some curiosity as to the individual effects of the lower and upper bout of the violin and how their differing sizes would contribute to vibro-acoustic performance. In addition, the bridge area gathered interest as the bridge was the main excitation point from the strings. Therefore, three subsections carefully splitting up the lower bout, bridge area, and upper bout were selected, using the corner points corresponding to each bout as a separation line for the subsections. Figure 7.2 represents the grouping selected for these averages.

Looking at Figure 7.3, the expensive violin better addressed the equal-loudness contour. The cheap violin could be seen to exhibit some random resonant behavior at its 13th harmonic, around 2,197 hertz, in which the amplitude jumped up just for that harmonic. Although the amplitude of this spike was small compared to harmonics around 1,000 hertz, it would be heard as overpowering the lower frequencies. This might result in an overly bright sound with a lack of bass presence. The top section of the expensive violin also showed this jump at the 13th

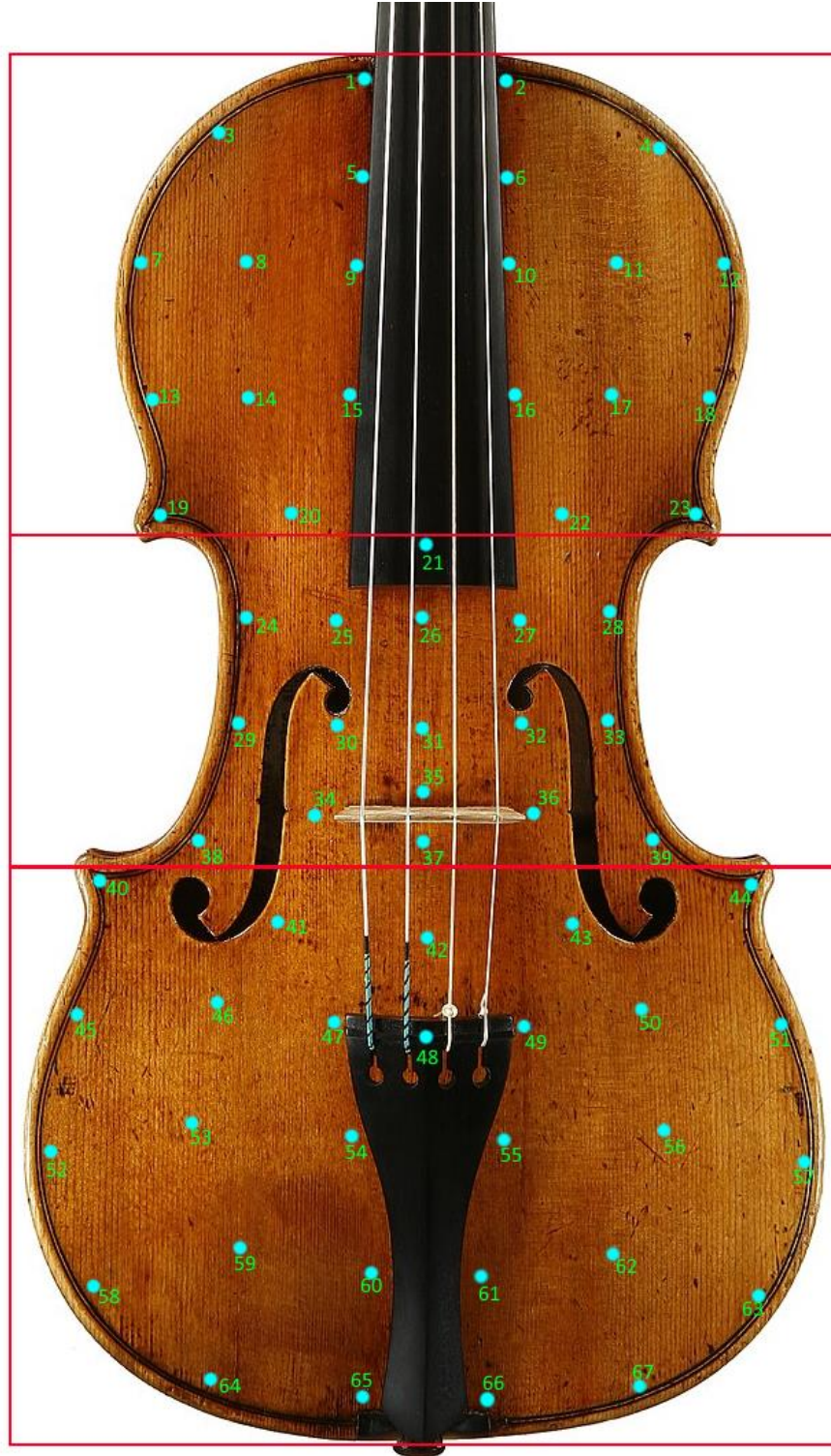


FIGURE 7.2. Grouping for three subsections: top, middle, and bottom.

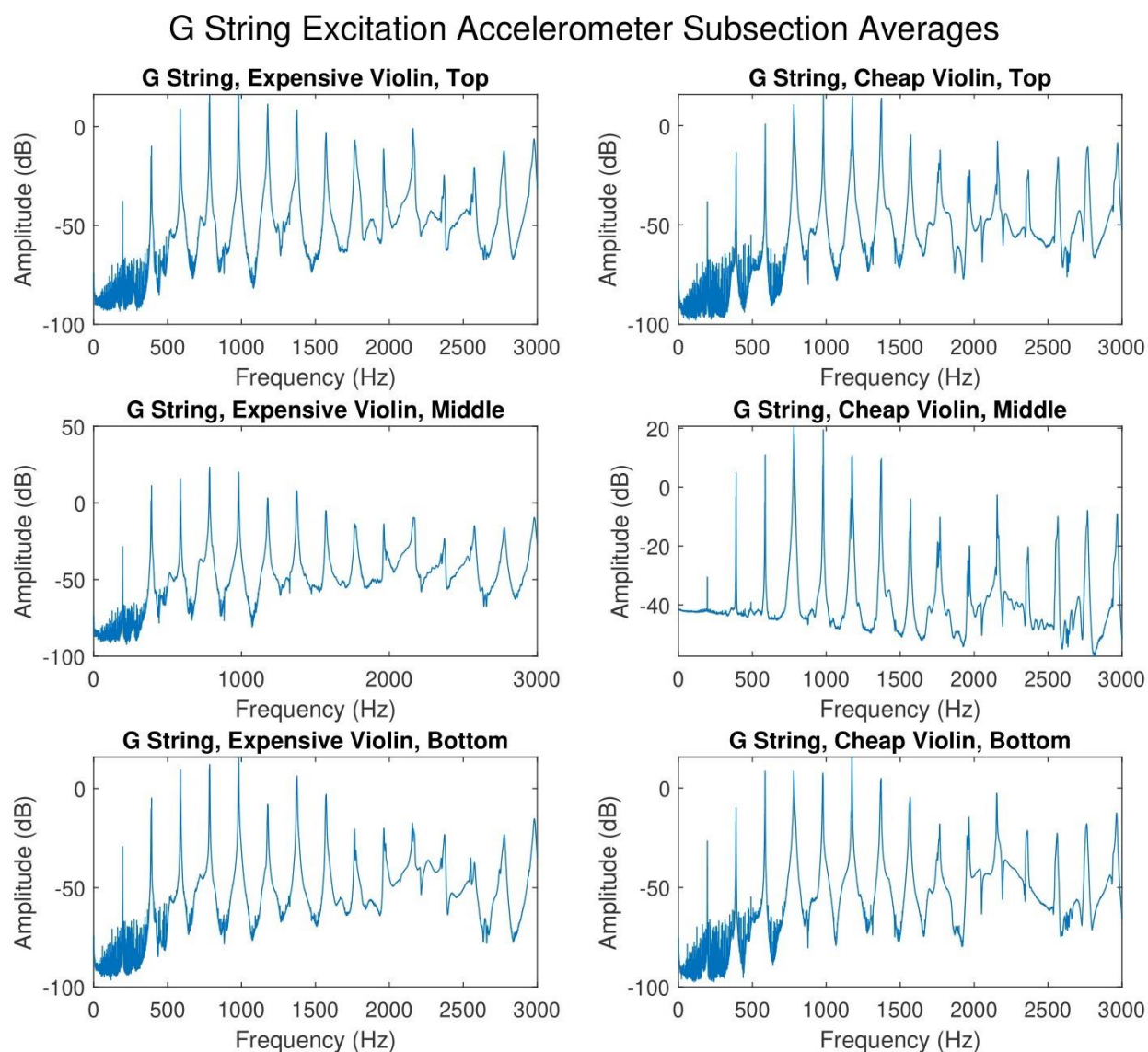


FIGURE 7.3. Frequency spectra using accelerometer spatial averages of top, middle, and bottom subsections when the G-string is excited.

harmonic, but this does not appear in the middle and bottom section. Typically, violins are much thicker in the top area, so this added thickness might increase the stiffness of the wood, making it more prone to high frequency vibrations.

The bottom subsection also had a stronger low-frequency performance than the top section. This could be explained by the wider cavity in the bottom subsection than in the top.

From the natural frequency equation $\omega_n = \sqrt{\frac{k}{m}}$ this would suggest that the added mass in the bottom section would result in a tendency for lower frequencies. Perhaps a brave violin maker could experiment on widening the bottom, or even the top subsection, to further boost the bass frequencies.

From Figure 7.4, the FFT data for the E string on the expensive violin displayed a steeper downward slope than the cheap violin, notably shown by the expensive violin having stronger presence at the third harmonic. Like the G-string results, the E-string also had a better response in the lower frequency harmonics in the bottom subsections for both violins due to the increased surface area and mass, confirming the acoustic relationship between the lower and upper bouts of the violin.

Comparing the cheap violin to the expensive violin at the 1st harmonic of both strings in Figure 7.5 and 7.6, there was a general trend of the bottom subsection being more prone to low-frequency vibrations than other subsections. For the E string on the cheap violin, however, the middle subsection was much weaker than the rest—the bass bar is also centralized in the middle subsection and may not have been properly installed as to promote lower frequency vibrations. Soundpost placement may have also contributed to this difference in low-frequency performance, but the exact causes cannot be fully confirmed until experimental tests are done specifically to realize soundpost and bass bar effects.

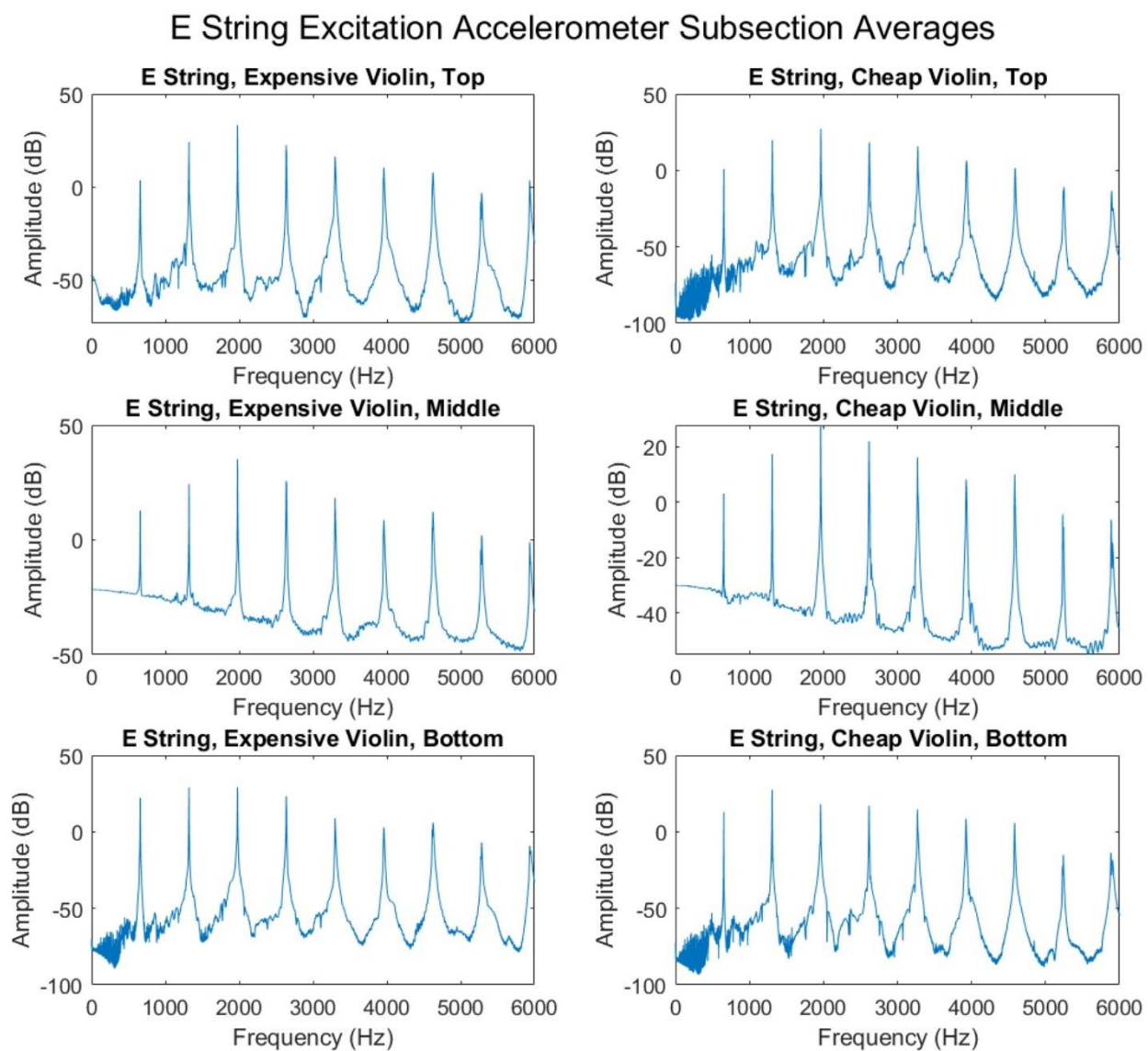


FIGURE 7.4. Frequency spectra using accelerometer spatial averages of top, middle, and bottom subsections when the E-string is excited.

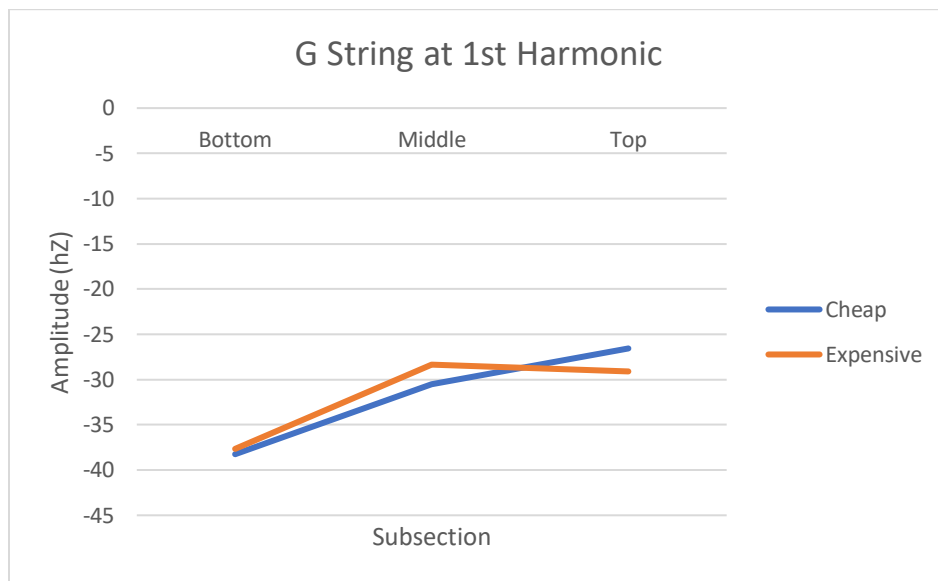


FIGURE 7.5. G String performance at the 1st harmonic.

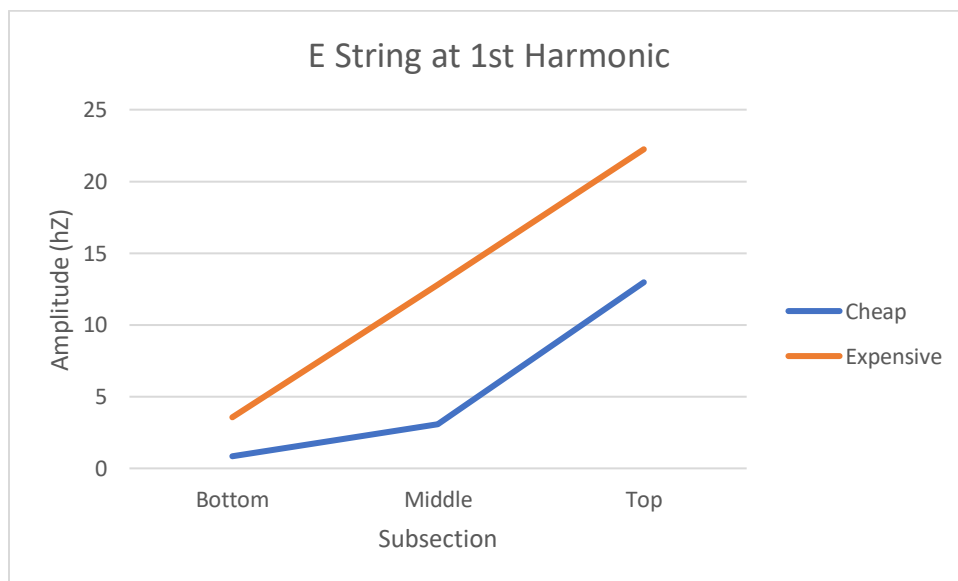


FIGURE 7.6. E String performance at the 1st harmonic.

7.1.1.3 Spatial average of edges. It was expected that the edge measurements would involve much higher vibrations because the edge is stiffened by structural parts of the violin, such as the blocking, ribs, and purfling. This was reflected by the strong E-string presence at 659.3 hertz. Besides that, there is not much new news: the expensive violin still showed a smoother inverse relationship between frequency and amplitude between 0 hertz and 4,000 hertz.

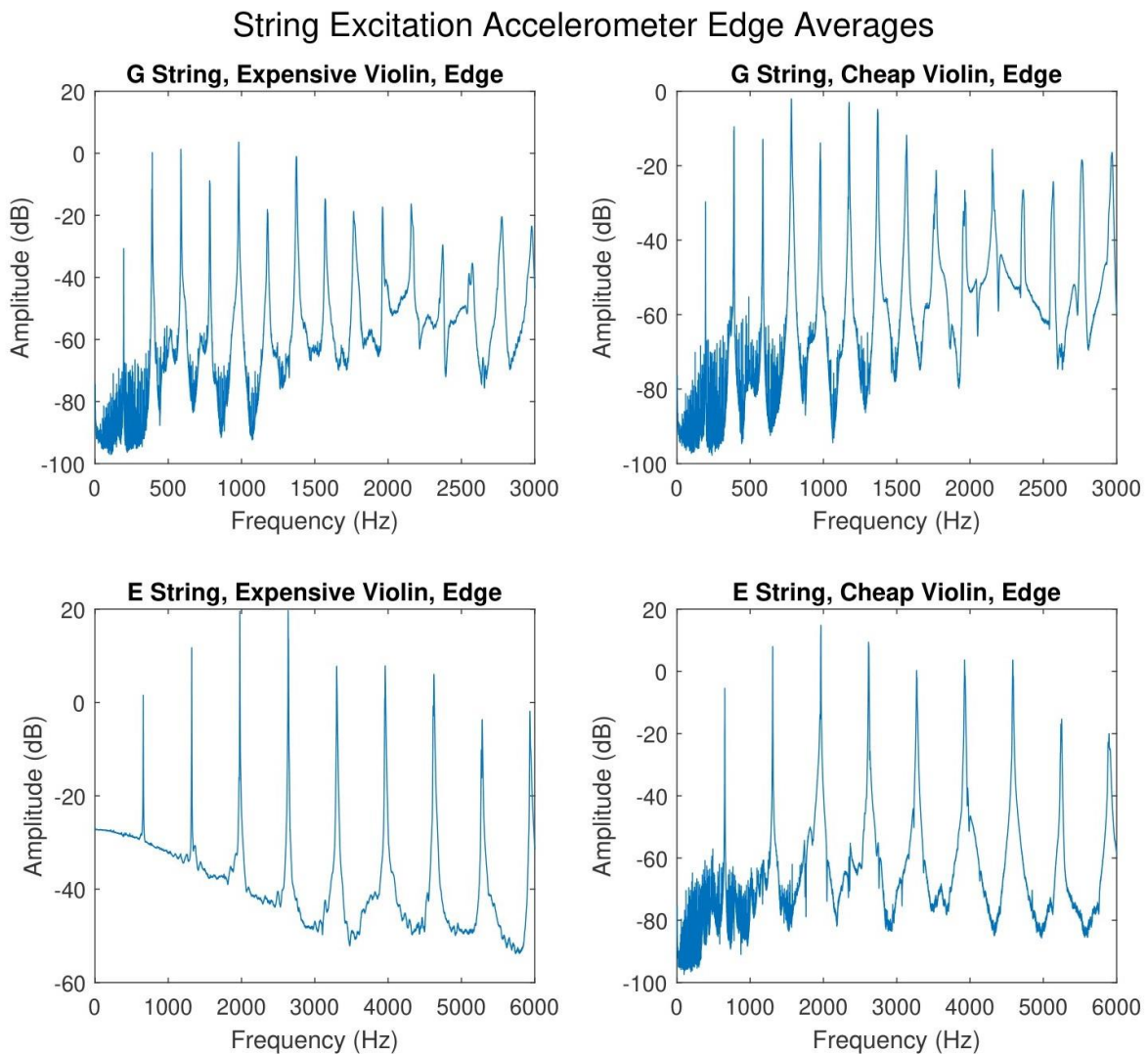


FIGURE 7.7. Frequency spectra using averages of all points along the edges of the violins.

7.1.2 Bridge Excitation

Excitation at the bridge removes the harmonic effects of the strings—whatever vibrations are produced during a hammer test are akin to the true natural frequencies of the bridge and the violin. Rather than showing how the violin would respond to different specific string frequencies, it will show the overall capabilities of the violin and its response to all frequencies.

7.1.2.1 Spatial average around the bridge. Before we dive into the details of the specific locations around the bridge, it is helpful to first establish a general idea of how either bridge from the cheap or expensive violin handles an excitation force from the hammer. This will be done by taking a spatial average of four selected standard points on the front, bottom, left, and right sides of the bridge, represented by points 34 to 37.

From Figure 7.8, it was immediately obvious that there was a generally downward trend for both the cheap violin and expensive violin, which agreed with the equal-loudness contour. Unlike the previous accelerometer cases that indicated that the expensive violin seemed to demonstrate a downward frequency-amplitude trend more evenly, both the expensive violin and cheap violin seemed to have a nice balance between all frequencies in this hammer test.

The expensive violin bridge seemed to be more selective of the frequencies that were transmitted to the top plate, and some frequencies clearly became more amplified than others. This contrasted with the cheap violin, which had a more stable downward trend with less oscillations than the expensive violin. Upon a closer look at some of the peak values in the expensive violin's FFT, we can see that the violin performed well at frequencies such as 953 hertz, 1,429 hertz, 1,898 hertz, and 3,103 hertz. Interestingly enough, these four frequencies correspond well to the fifth harmonic of each string. The fifth harmonic can be calculated by multiplying the fundamental frequency by five, resulting in 980 hertz, 1,468.5 hertz, 2,200 hertz,

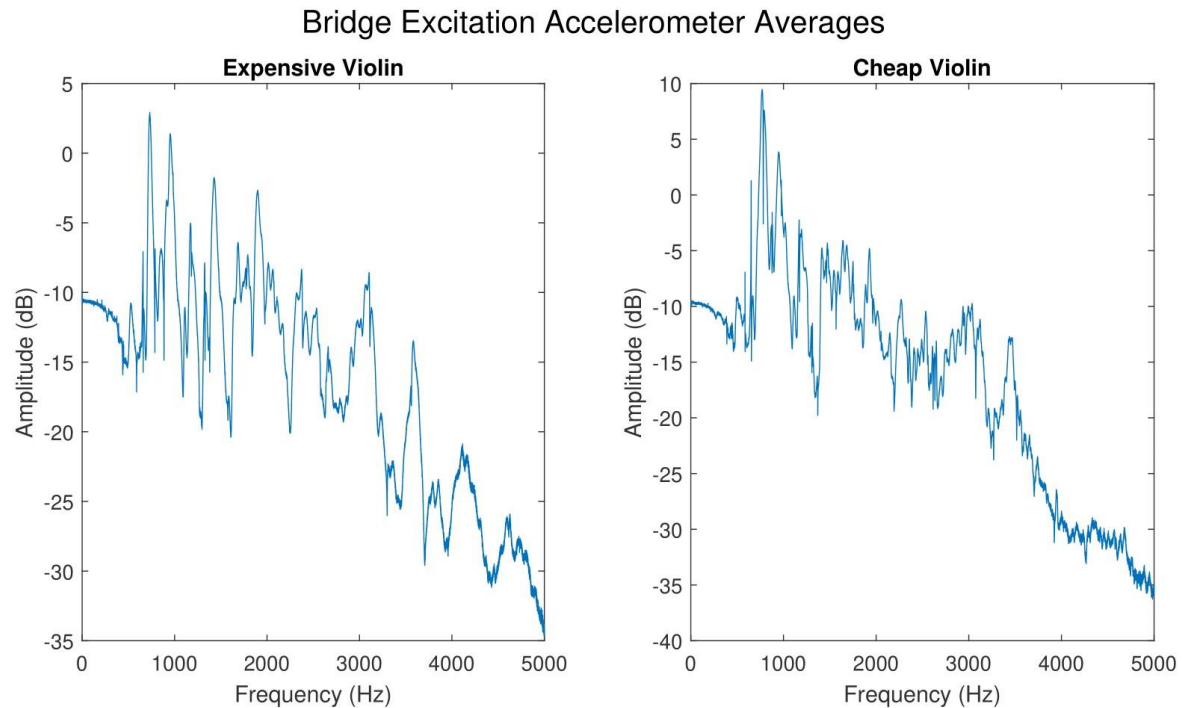


FIGURE 7.8. Frequency spectra using averages of the four points surrounding the bridge (points 34 to 37).

and 3,296.5 hertz for the G, D, A, and E strings. This was a much better match compared to the cheap violin, which had a spike at 947 hertz, 1,169 hertz and a couple vague spikes at 1,647 hertz and 3,026 hertz.

One possible explanation for this is that after years of playing, the violin becomes more responsive to frequencies it is most exposed to. The string notes (without any finger changing the note) vibrate with the most amplitude and cause the wood grain structure to shift around, possibly moving some mass towards the stationary nodes of the violin to allow for more vibrations at the harmonics. It is generally observed by violinists that violins sound better when they are played often, and the cheap violin has not been played much compared to the expensive violin.

7.1.2.2 Individual results around the bridge. The results of measurements taken around the bridge would reflect the string positioning and would give clues on how the violin would perform at different frequency levels. Point 34 is on the G-string side, 35 is in front of the bridge facing the fingerboard, 36 is on the E-string side, and 37 is behind the bridge towards the tailpiece.

From Figure 7.9, we can look at points 34 and 36 as indicators of the violin's performance at G-string and E-string frequencies and their corresponding harmonics. On the expensive violin, a neat downward trend was followed, balancing frequencies between 1,000 hertz and 4,000 hertz. On the other hand, the cheap violin exhibited some seemingly random dips at around 3,000 hertz and 4,000 hertz. Although it is good to have less presence at these high frequencies to bring out the lower frequencies, drastic dips at certain harmonics may lead to an uneven projection across notes in a violin performance.

On the expensive violin, for point 34 and 36, 4,000 to 5,000 hertz seemed to be the lowest amplitude frequency range, with about -75 decibels at point 34 and -50 decibels at point 36. On the cheap violin, the minimum amplitude range was from 3,000 to 4,000 hertz, with about -60 decibels on point 34 and -70 decibels at point 36. In other words, on the cheap violin, the E-string side of the bridge had a worse high-frequency response than the G-string side despite the E note being higher than G. This could lead to an overtone imbalance when using the lower versus higher strings: although the A and E strings were designed to utilize high frequencies more than the G and D strings, they would be limited by the violin's tendency to do the complete opposite. A seemingly easy fix for this would be to just reverse the order of the strings. However, this would also reverse the string tension and might just as well result in the same outcome.

Bridge Excitation Accelerometer Measurements

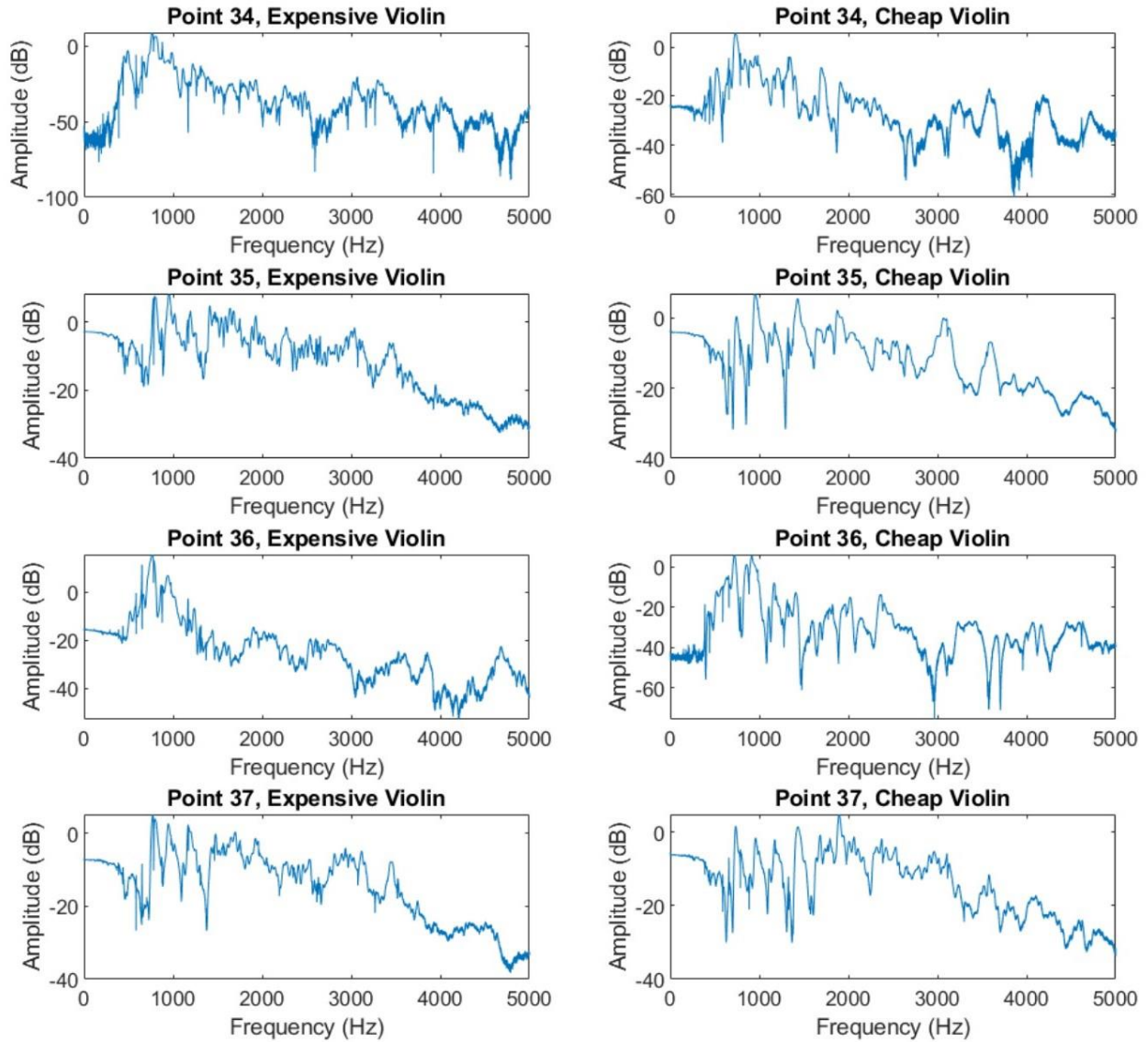


FIGURE 7.9. Frequency spectra at each of the four points surrounding the bridge (points 34 to 37).

7.2 Acoustic Analysis Results

The acoustic FFT results in Figure 7.10 indicate previously discussed correlations between the cheap and expensive violin with respect to the equal-loudness contour, but we can compare these acoustic results in Figure 7.10 to the overall averages for the accelerometer tests to realize any structural-acoustic correlations. From our theoretical analysis of sound pressure at different distances from the violin, we can infer that the difference in amplitude between the high frequency and lower frequency vibrations will be greater at a distance and even greater at a longer distance. Theoretically, this means that if the cheap violin has too much of the high-frequency harmonics when listened from a reasonable distance, it will sound exponentially better when the distance is increased. This is represented in Table 7.1 and Table 7.2, which is the frequency response at the 2nd and 8th string harmonics for the G and E strings.

In theory, greater differences between the 2nd and 8th harmonic are preferred. In all cases, the expensive violin performed better than the cheap violin, and all results showed a relatively stronger bass presence during microphone tests except for the E-string accelerometer test for the cheap violin. This might be due to the string being out of tune and therefore exciting different modes—the FFT data showed a spike at 653.5 hertz instead of the correct 659.5 hertz tuning for E. Additionally, the E-string for both violins seemed to retain relatively the same difference in amplitudes between the 2nd and 8th harmonics at both microphone and accelerometer tests when compared to the G-string. This could infer that while high notes on the violin might sound the same up close and afar, the listener should take a few steps back to have the low notes come into relative balance, with generally better sound coming from a more expensive violin in all cases.

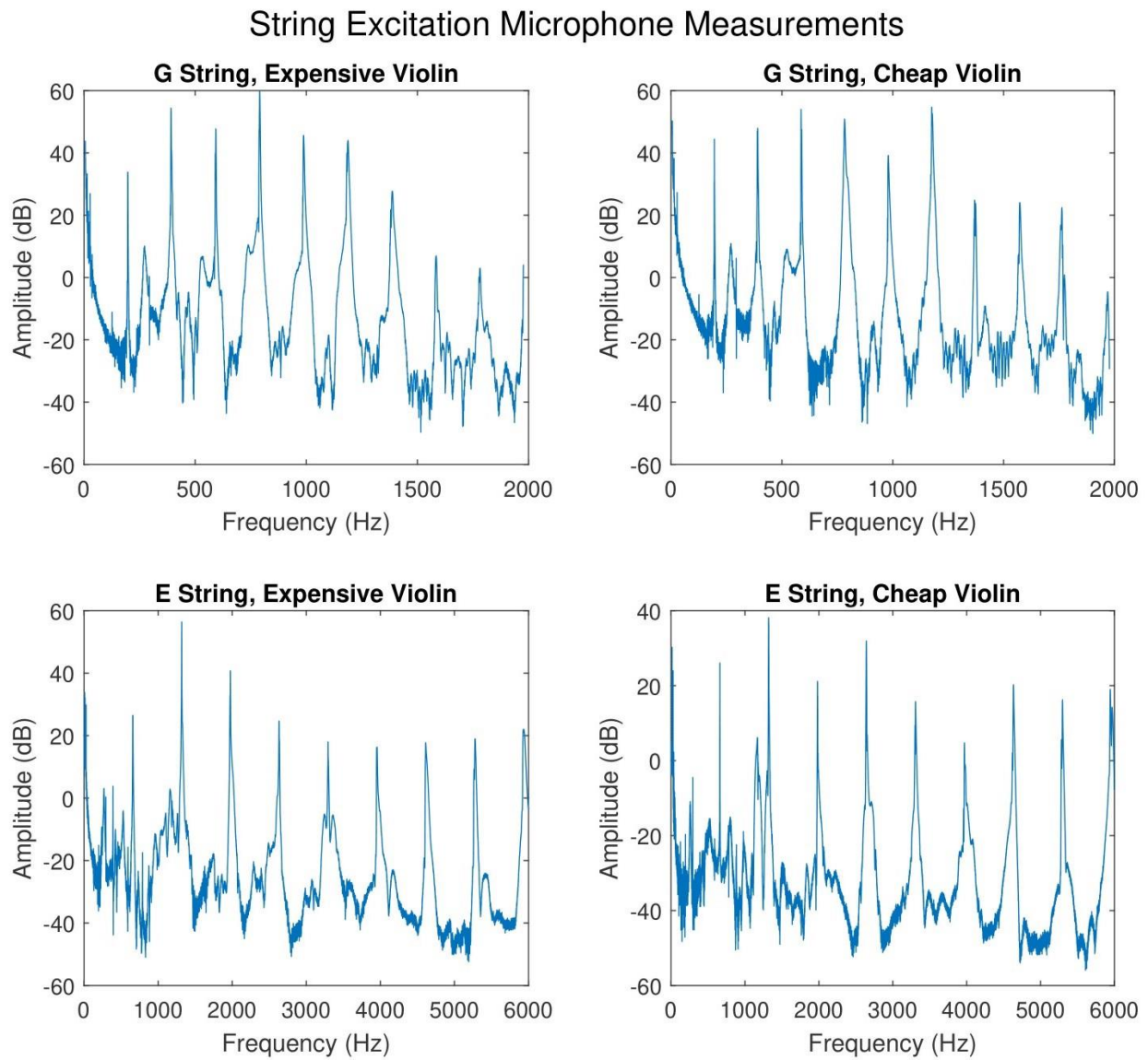


FIGURE 7.10. Frequency spectra using microphone measurements of the violins when excited at the strings.

TABLE 7.1. Frequency Response at the 2nd and 8th G-String Harmonic

G-string	Microphone Tests		Accelerometer Tests	
	Expensive	Cheap	Expensive	Cheap
2 nd harmonic (dB)	53.0	47.9	1.5	-5.8
8 th harmonic (dB)	6.9	23.7	-3.4	-7.8
2 nd harmonic – 8 th harmonic (dB)	46.1	24.2	4.9	2.0

TABLE 7.2. Frequency response at the 2nd and 8th E-String Harmonic

E-string	Microphone Tests		Accelerometer Tests	
	Expensive	Cheap	Expensive	Cheap
2 nd harmonic (dB)	55.9	38.0	25.9	21.4
8 th harmonic (dB)	18.6	16.1	-3.0	-15.2
2 nd harmonic – 8 th harmonic (dB)	37.3	21.9	28	36.6

The acoustic data easily confirms all the already-discussed trends on how the expensive violin more accurately addresses the equal-loudness contour. The G string on the expensive violin reached its max around a very low 750 hertz, then dropped down significantly past that frequency. On the contrary, the G string on the cheap violin remained somewhat constant at a high until around 1,250 hertz, then slightly dropped down around 1,400 hertz. On the E string of the expensive violin, a similar case is observed. There was a huge spike at the second harmonic, and when the frequency increased, the amplitude gradually decreased and did not increase much after. The E string of the cheap violin was more volatile: even though there was a drop starting at about 3,000 hertz, higher frequencies around 5,000 hertz were easily excited with high amplitude. This would of course lead to an overabundance of high frequency sound, resulting in a bright, narrow tone indicative of a cheaper violin.

CHAPTER 8

CONCLUSION

A \$4,250 William Bagnato violin made in 2019 and a \$269 Franz Hoffman violin made in 2021 were both subjected to vibro-acoustic tests to investigate their frequency response when excited either by the strings or the bridge. From accelerometer tests, the expensive violin performed much better at across all frequencies, with especially more emphasis in the lower frequency harmonics at the middle subsection. This may be due to a thinner top plate and a more effective bass bar. The high preference for lower frequency harmonics makes the expensive violin more balanced to the human ear, which is not as sensitive to those lower frequencies. From hammer tests, the expensive violin showed a frequency response that seemed to favor string frequency harmonics; because it was played on significantly more, the structure of the violin may have become attuned to amplify string frequencies more easily. In both violins, low-frequency vibrations were more apparent in the bottom subsection due to the wider area. Regarding acoustic tests by string excitation, while it was noticed that low-frequency harmonics would relatively become stronger with increased distance, the frequency response of the expensive violin would better mirror the equal-loudness curve when compared at the same distance.

So far, this thesis successfully confirmed general trends regarding the difference between two violins of different prices. The radiation efficiency and power flows of either violins could be analyzed in future studies using an intensity probe. Future studies could also be made to individually focus on factors such as the bridge position, string type, and f-hole shape and their effects on the violin's vibro-acoustic properties. Because the wood structure of violins is highly variable being an organic material, improved consistency could be achieved by designing a

simplified violin model from scratch using isotropic materials of known properties to fully monitor and isolate the effects of various accessorial changes. This would eliminate any variability resulting from the seemingly random top plate thickness, curvature, and wood grain as well as any subjective design choices by violin makers.

With all this evidence pointing that the more expensive William Bagnato violin is analytically and experimentally better sounding than the less expensive Franz Hoffman, a question arises regarding whether it is financially efficient to spend additional money for its noted improvements. For an experienced violinist, these acoustic differences are more easily detectable with the trained ear, and a beginner violinist would be more focused on their fundamental technique rather than nitpick on the “brightness” of a violin—if an object resembles a violin, it could technically be played. Nonetheless, an expensive violin’s balanced acoustics combined with a crafted physical appearance and exclusive origin makes it a fine choice for those with the budget. With enough practice and effort, any violinist will be able to bring out a violin’s acoustic potential and perform all the Paganini violin concertos and other great works by Beethoven, Teddy Park, Mickey, and Lin-Manuel Miranda.

APPENDICES

APPENDIX A
SENSOR DRAWINGS

APPLICATION			REVISIONS				
NEXT ASS'Y	USED ON	VAR	REV	DESCRIPTION	ECN	DATE	APP'D
			B	CHANGE REMOVAL TOOL	16343	3/26/03	pmj/03

12331

PCB Piezotronics Inc. claims proprietary rights in the information disclosed hereon. Neither it nor any reproduction thereof will be disclosed to others without written consent of PCB Piezotronics Inc.

3D VIEW

SCALE: 3=1

CABLE 030A10
MINI COAXIAL TO
10-32 COAXIAL PLUG

6 BE CAREFUL TO NOT APPLY "QUICK BONDING GEL" TO CONNECTOR THREADS, IMPROPER CONNECTOR MATING WILL RESULT.

5.) SEE SHEET 2 OF 2 FOR CABLE STRAIN RELIEF AND REMOVAL INFORMATION.

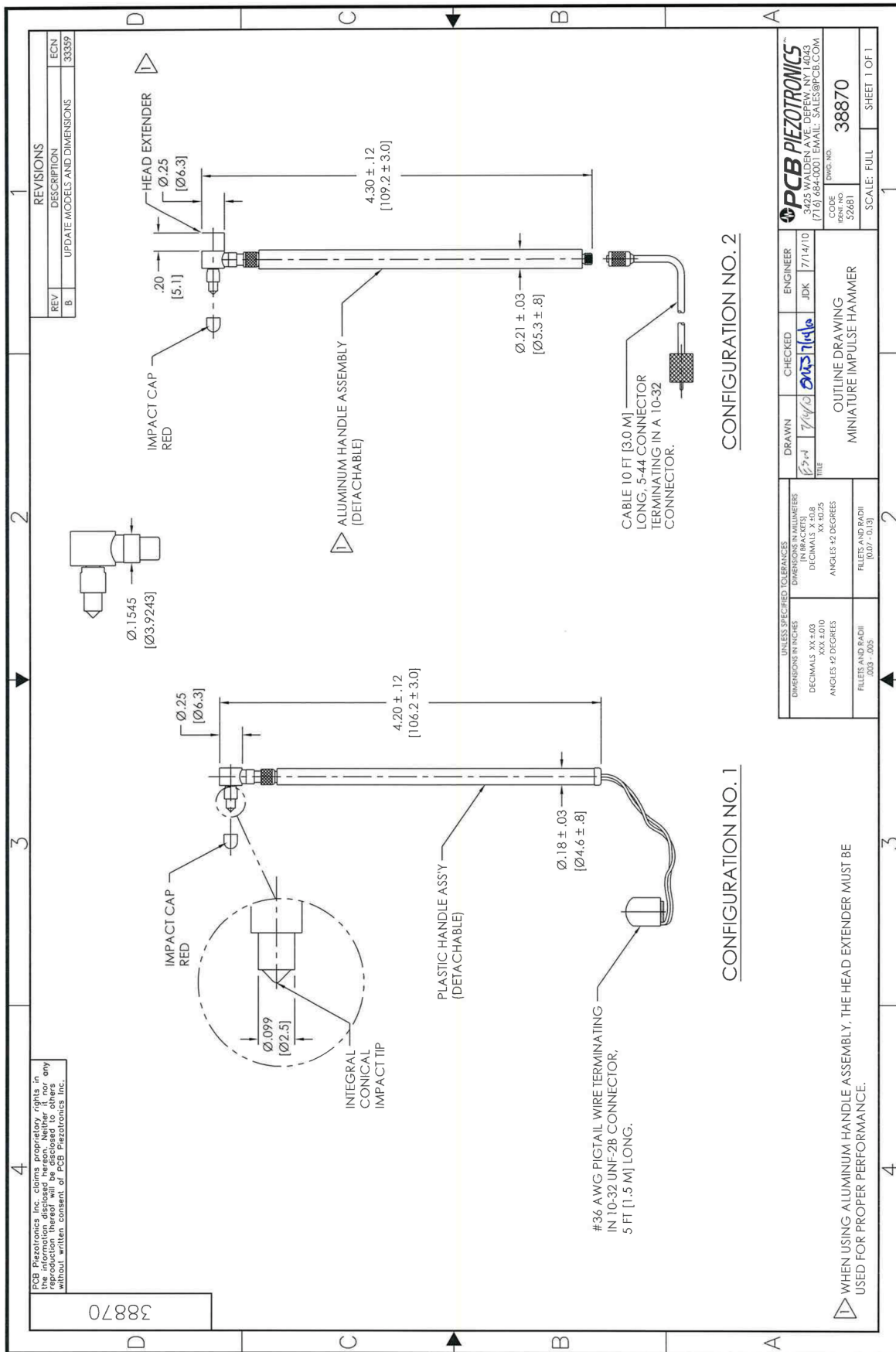
4 DO NOT MOUNT ON THIS SURFACE.

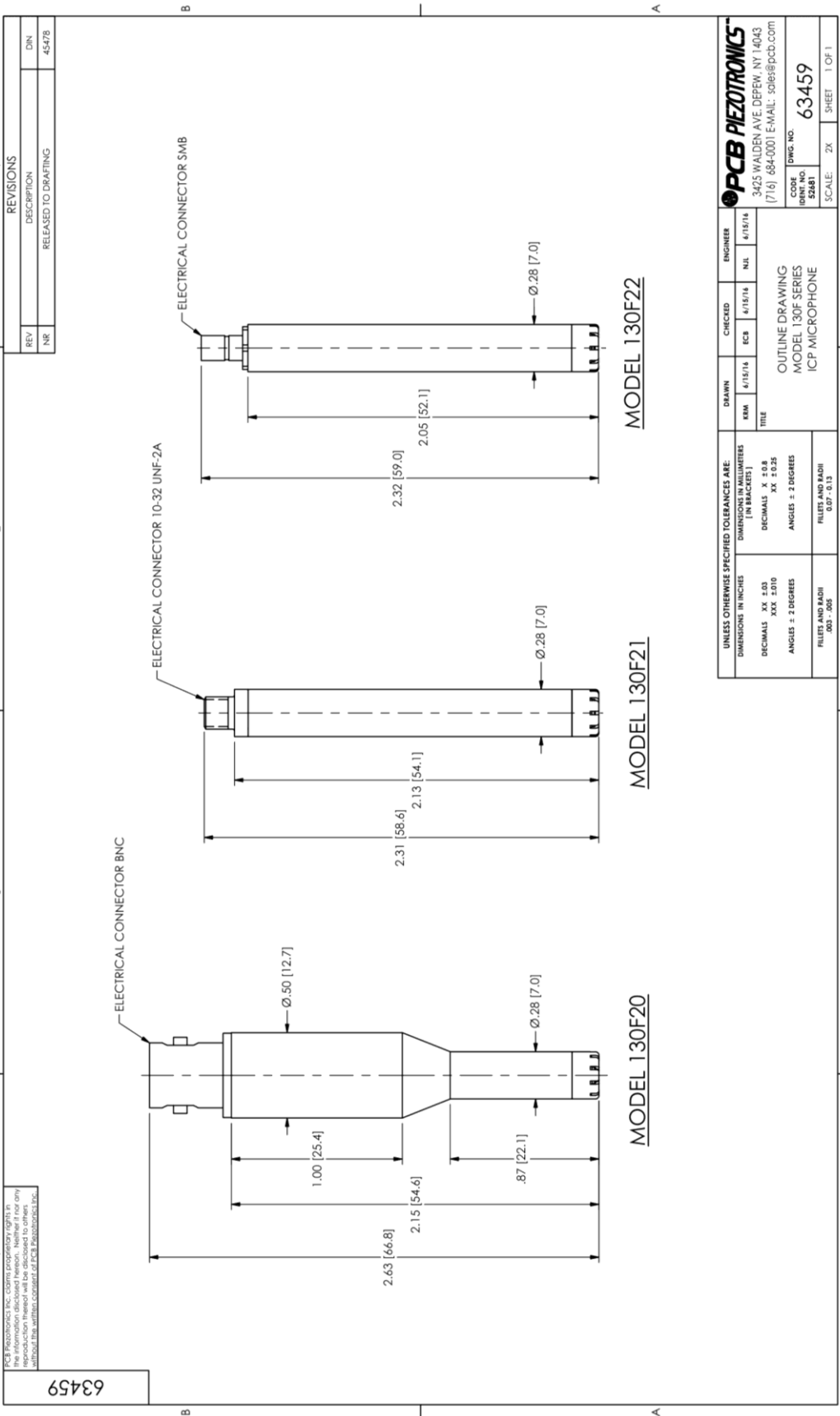
3 FOR SEMI-PERMANENT MOUNTING USE MODEL 080A90 "QUICK BONDING GEL" OR EQUIVALENT.

2 FOR TEMPORARY MOUNTING APPLICATIONS, USE PETRO WAX (MODEL 080A109). APPLY APPROXIMATELY 5 POUNDS(22 NEWTONS) OF FORCE TO TOP OF ACCELEROMETER CREATING A THIN BUT HOMOGENEOUS LAYER OF WAX.

1 RECOMMENDED MOUNTING SURFACE SHOULD BE FLAT TO WITHIN .003(.08) TIR OVER $\phi.375(\phi9.52)$ WITH A 32/ (0.8/) FINISH FOR BEST RESULTS.

UNLESS SPECIFIED: TOLERANCES		DRAWN		MFG		PCB PIEZOTRONICS™	
DIMENSIONS IN INCHES	DIMENSIONS IN MILLIMETERS [IN BRACKETS]	CHK'D	3/3/03	ENGR	JMO	3425 WALDEN AVE. DEPEW, NY 14043 (716) 684-0001 EMAIL: SALES@PCB.COM	
DECIMALS XX ±.01	DECIMALS X ±0.3	APP'D	4/2/03	SALES	NR	CODE IDENT. NO. 52681	
XXX ±.005	XX ±0.13	TITLE INSTALLATION DRAWING MODEL 352A24 ACCELEROMETER				DWG. NO. 12331	
ANGLES ±2 DEGREES	ANGLES ±2 DEGREES					SCALE: 6X	
FILLET AND RADII .003 - .005	FILLET AND RADII [0.07 - 0.13]					SHEET 1 OF 2	
DD011 REV. C 01/21/03							





UNLESS OTHERWISE SPECIFIED TOLERANCES ARE:		DRAWN		CHECKED		ENGINEER	
DIMENSIONS IN INCHES		KMA		4/15/14		4/15/14	
DIMENSIONS IN MILLIMETERS		TITLE		ECB		NIL	
DECIMALS XX .03 XXX .010 ANGLES ± 2 DEGREES		OUTLINE DRAWING MODEL 130F SERIES ICP MICROPHONE					
FILLET AND RADI .0017 .005							
FILLET AND RADI 0.07 0.13							
PCB PIEZOTRONICS		3425 WALDEN AVE. DEFEW, NY 14043 (716) 684-0001 E-MAIL: s066@pcb.com		CODE IDENT NO. 52481		DWG. NO. 63459	
SCALE		2X		SHEET		1 OF 1	

APPENDIX B

CALIBRATION CERTIFICATES

~Calibration Certificate~

Sensor Information

Model Number: 352A24
Serial Number: LW201487
Manufacturer: PCB
ID Number: 56855
Description: ICP® Accelerometer

Calibration Data

Sensitivity @ 100 Hz: 104.9 mV/g
10.70 mV/m/s²
Phase @ 100 Hz: -1.09 deg.
Test Level: 1.00 g

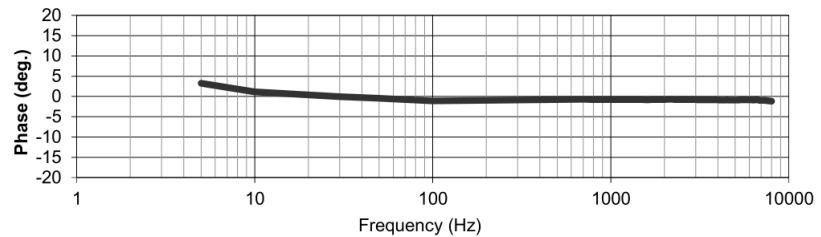
Transducer Specifications

Amp. Range: ± 50 g
Resolution: 0.0002 g
Resonant Freq: ≥ 30000 Hz
Temp. Range: -54 to 121 °C
-65 to 250 °F
Axis: Uni-Axial

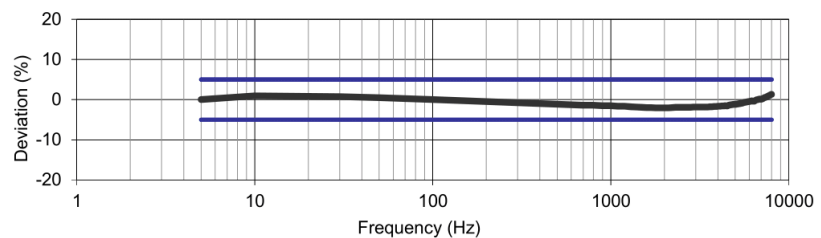
Data Table

Freq. (Hz)	Deviation (%)	Phase (deg)
5	0.0346	3.2659
10	0.9604	1.1719
100	0.0000	-1.0933
1000	-1.5008	-0.7913
1500	-1.8817	-0.7546
2000	-2.0654	-0.7516
2500	-1.9064	-0.7745
3000	-1.8187	-0.7598
3500	-1.8600	-0.8046
4000	-1.6424	-0.8351
4500	-1.5665	-0.8365
5000	-1.1697	-0.9009
5500	-0.8120	-0.8245
6000	-0.4379	-0.8070
6500	-0.1830	-0.7903
7000	0.0916	-0.9714
7500	0.6984	-1.0178
8000	1.3127	-1.1684

Phase Response



Amplitude Response



Notes

Results relate only to the items calibrated.
This certificate may not be reproduced except in full, without written permission.
Method: Back-to-Back Comparison Calibration per ISO 16063 Part 21.
This calibration was performed with TMS 9155 Calibration Workstation 1 version 7.0.2.
Proficiency in calibration traceable to PTB (17014/17004) and NIST (683/287323).
Back-to-Back Comparison Calibration per ISO 16063-21
Procedure Used: PRD-P220 or PRD-P239
Measurement uncertainty (95% confidence level with coverage factor 2) for frequency ranges tested during calibration are as follows: 5-9 Hz; ± 1.7%, 10-99 Hz; ± 1.2%, 100 Hz; ± 0.75%, 101-920 Hz; ± 1.0%, 921-5000 Hz; ± 1.4%, 5001-10,000 Hz; ± 1.9%, 10,001-15,000 Hz; ± 2.2%, 15,001-20,000 Hz; ± 2.8%.

Unit Condition

As Found: In Tolerance
As Left: In Tolerance

Lab Conditions

Temperature: 72 (22) °F (°C)
Humidity: 56 %

Customer

TMS Rental

Cal Date: 19-Jul-21

Due Date:

Technician Notes

Approval Information

Technician: William Kellner

Approval: *William Kellner*

10310 Aerohub Boulevard
Cincinnati, OH 45215
Ph: 513.351.9919
www.modalshop.com



2649.01
Calibration Laboratory

Cal ID: 49618

~ Calibration Certificate ~

Model Number: 086E80 Customer: _____
Serial Number: 46710 _____
Description: Impulse Force Hammer P.O. Number: _____
Manufacturer: PCB Method: Impulse (AT-303-1)

Calibration Data

Output Bias: 10.6 VDC
Temperature: 71 °F = 22 °C
Relative Humidity: 57 %

Hammer Configuration

Hammer Sensitivity*

Tip	Extender	mV/lb	mV/N
Steel	None	100.5	22.59
Vinyl	Steel	71.63	16.10
Vinyl	None	65.69	14.77

*Above data is valid for all supplied tips.

Condition of Unit

As Found: N/A
As Left: New Unit, In Tolerance

Notes:

1. Calibration is N.I.S.T. Traceable thru Project 684/O-0000000851 and PTB Traceable thru Project 17016.
2. This certificate may not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.
3. Calibration is performed in compliance with ISO 10012-1, ANSI/NCSL Z540.3.
4. See Manufacturer's specification sheet for a detailed listing of performance specifications.
5. Measurement uncertainty (95% confidence level with a coverage factor of 2) is +/-3.8%.

Technician: Mary Warren *mw*

Date: 7/12/2021



~ Calibration Certificate ~

Model Number: 130F20

Serial Number: 62439

Description: ICP® Microphone

Manufacturer: PCB

Calibration Data

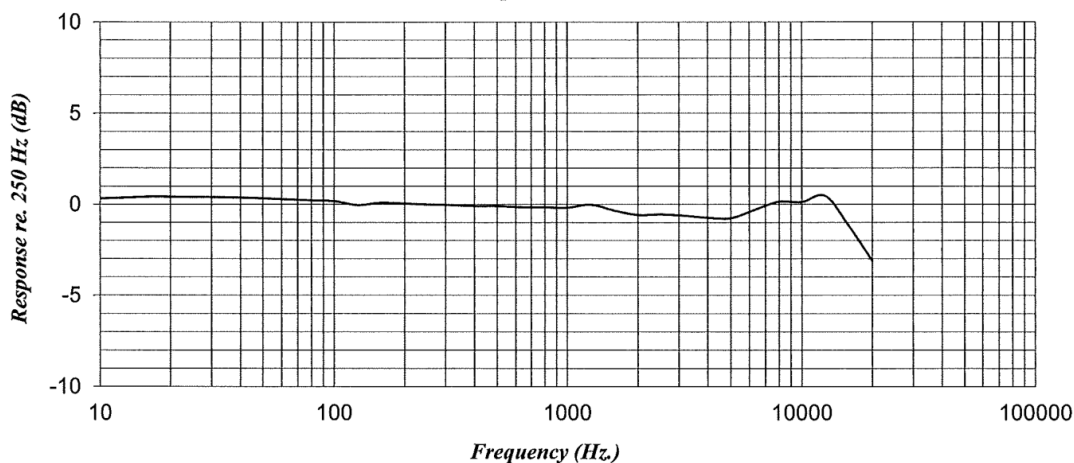
Sensitivity: 39.5 mV/Pa
-28.1 dB re 1V/Pa

Reference Freq.: 250 Hz.
Output Bias: 9.3 VDC

Temperature: 75 °F 24 °C

Relative Humidity: 52 %

Response Plot



Condition of Unit

As Found: n/a

As Left: New Unit, In Tolerance

Notes

1. Frequency response determined by IEC 61094-5: Methods for pressure calibration of working standard microphones by comparison.
2. Calibration of reference equipment is traceable to one or more of the following National Labs: NIST, PTB or DFM.
3. Calibration is performed in compliance with ISO 10012-1 and ANSI/NC SL Z540.3.
4. Due to state-of-the-art limitations, 4:1 calibration ratios are not possible on pressure measurement standards, microphones and acoustic calibrators. Calibration ratios for these types of devices are limited to 1:1.
5. See Manufacturer's Specification Sheet for a detailed listing of performance specifications.
6. This certificate shall not be reproduced, except in full, without written approval from PCB Piezotronics, Inc
7. Calibrated per ACS-21.

Technician: Tiffany Brinkley *TB*

Date: August 26, 2021



Headquarters: 3425 Walden Avenue, Depew, NY 14043

Calibration performed at: 10869 Highway 903, Halifax, NC 27839

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