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Design, Analysis, and Fabrication of A 3D Printed Violin for the Public

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Professor John Sullivan joined WPI in 1987. He has had continuous external research funding from 1988 thru 2013. He has graduated (and supported) more than 100 MS and PhD graduate students. He has served as the ME Department Head and in 2012 was elected Secretary of the Faculty through 2015. Prof. Sullivan has always maintained a full teaching load. He strongly supports the WPI project-based undergraduate philosophy.

Design, Analysis, and 3D Printing of a Musical Instrument

Introduction

The violin is the third most played instrument in the United States, behind the piano and the guitar. However, quality violins usually start at around $500, but can cost significantly more depending on the violin brand you choose [1]. For a family looking to buy a decent student violin, $500 might be a significant expense. For children who want to learn music outside of school, private lessons and community orchestras are additional expenses. For children growing up in a family where money is tight, being able to purchase a less expensive 3D printed violin might provide them with opportunities to learn music.

A 3D printed violin was designed as a cost effective option for people looking to play an instrument. A major goal is to achieve a sound quality approaching that of a traditional student violin. This was done through testing materials as well as testing the acoustics of the printed violins. This paper will discuss previously produced 3D printed violins, a brief history and structure of a violin, the analysis of a 3D printed violin, and the materials used to create a cost effective 3D printed violin with a quality sound. It will also discuss the methods for creating this violin and the testing involved. This discussion includes the CAD modeling and the challenges to 3D print a full sized violin. Finally, an acoustic analysis on the violins will compare pitch, volume, and tonal quality as a function of print settings to that of a wooden violin. This paper will discuss the design ideations and print optimization.

Background

The components of a violin are designed to allow it to be played in both a practical and aesthetic way [2].

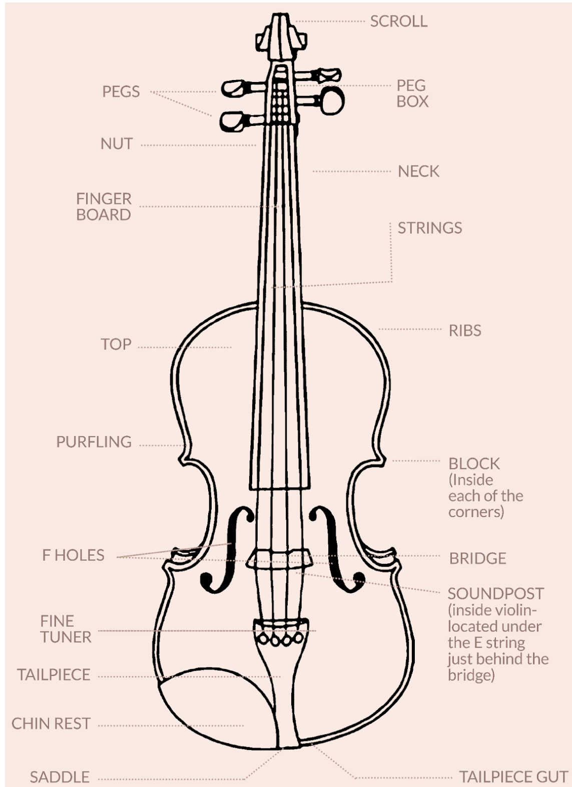

Figure 1: Violin Component Diagram [2].

The scroll of the violin is a decorative piece and does not affect the violin's sound production. The scroll is often a way for the craftsmen who built the violin to showcase their skill [3]. Four pegs located at the top of the violin are used to tune the instrument. Each string is wrapped around a peg. When the peg is turned it changes the string's tension. Tightening the string, it raises the pitch produced by that string whereas when the string is loosened, the pitch decreases. The pegs are located within the peg box which encloses the wound strings within the scroll. The fingerboard is the surface where the strings are pressed down in order to change the pitch of the note. The fingerboard is located on the neck of the violin. The tailpiece is located at the bottom end of the violin that holds the other end of the strings and it. The tailpiece is attached to the violin by the tailpiece gut, which is also located at the bottom end. The chin rest allows for the player to rest their chin on the violin while it is being played [2].

The sound post, located inside the body, is essential for transmitting the strings' vibrations throughout the body. The location of the sound post has a strong correlation with the quality of the tone and the volume produced by the violin. Running under the center of the top piece of the body, parallel to the strings, is a bass bar to strengthen the top piece against the forces applied to it by the bridge and to enhance the resonance of the instrument. Within the body there is also a saddle, which is a block that supports the tailgut and the tension of the strings. The soundpost also connects the top plate that has a level of flexibility and the bottom plate of the violin which is considerably stiffer [5].

On the front face of the violin are the two f-holes. The f-holes allow sound to emerge from the violin and promote resonance. The bridge is held to the front face of the violin solely by the force of the strings. The bridge balances under the stings and transmits the vibrations from the sting to the body of the violin. It works to transmit the vibrations from the strings into the body of the instrument. Violins produce sound through the vibrations of strings that are transmitted throughout the instrument. The strings' vibrations are transmitted by the violin's bridge which pushes down on the top plate as seen in Figure 2. [4].

The bridge of the violin transfers the vibrations to the violin's body. The bridge of the violin is located between the f-holes on the face of the top plate. The f-holes connect air outside the violin with air within and allows the top plate to move. The top vibrates up and down in order to produce sound.

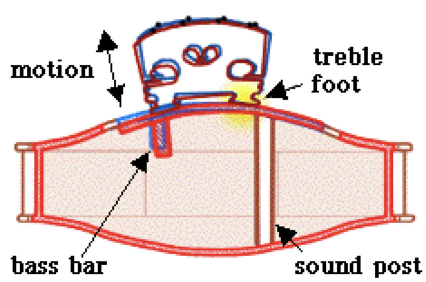

Figure 2: Violin Inside Schematic [5].

Governing Equations

The hyperbolic wave equation was used to describe the acoustic wave through space and time.[6] The one dimensional form of the wave equation was first published by Jean le Rond d'Alembert in 1747, with higher dimensional forms being discovered later. With this equation, it assumes that if a string was fixed at both ends, and an initial displacement was put somewhere in the middle, the string would vibrate. D'Alembert discovered that the correlation between the position and time of the wave is defined as: $\frac{\delta^2 u}{\delta t^2} = c^2 \frac{\delta^2 u}{\delta x^2}$ |Eq. 1| [6]

In Equation 1, *u* represents the position of the vibrating string as a function of time and space. Secondly, *x* is the physical location of the wave along the one spatial dimension inherent to the problem. The c is a constant set to the speed of sound in air. This 1D equation can be expanded to 3D, giving: $\frac{\delta^2 u(x,y,z,t)}{\delta t^2} = c^2 (\frac{\delta^2 u(x,y,z,t)}{\delta x^2} + \frac{\delta^2 u(x,y,z,t)}{\delta y^2} + \frac{\delta^2 u(x,y,z,t)}{\delta z^2})$ |Eq. 2| [7]

Unlike in the 1D scenario where *u* was displacement, *u* can be the acoustic pressure of a vibrating string which causes the sound to propagate. With the governing equations established, the next step in the mathematical modeling is to define the boundary conditions and initial conditions. The boundaries of the string are defined as its two end points (the top of the neck to the bridge). If the string is length *l*, then the boundary conditions would be applied at *0*, the start of the string, and *l*, the end of the string. The violin's boundary is represented with δΩ, which surrounds the inside of the violin of space Ω. In a physical sense, Ω would be the air inside of the violin, while δΩ would be where the violin body contacts the air. With the boundaries defined, boundary conditions can be defined. The string's boundary conditions are fixed such that *u* equals 0 at *0* and *l*. For the boundary conditions of Ω, the boundary conditions are less strict, as there is no point that is completely fixed, so the boundary conditions for Ω are established in relation to the vibration of the string.

The initial conditions along the violin string are in the form of the initial displacement of the string at a given point, which can change based on the initial position of the bow. If the violin is playing from rest, then the initial displacement is zero. The additional boundary condition (to satisfy the Cauchy requirements) depends on how the violin is played, essentially the displacement velocity as a function of the bow's position. A sawtooth wave, shown below in Figure 3, represents the motion of the bow along the string of the violin. This can be used as the boundary condition for the string's displacement.

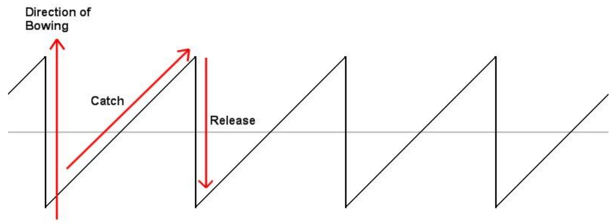

Figure 3: What equation B might look like [8]

Societal Impact

Music can bring people together and create a sense of community. Students from districts and lower income communities are less likely to have music offered at their school compared to students in wealthier communities [9]. By creating an economical 3D printed violin, an option exists for less wealthy communities or for people that want to play. It can enhance the sense of community without regard to wealth.

Methods and Procedure

Two initial approaches to modeling the instrument were taken: a mesh model and a vector based CAD model. Both were based on measurements of a traditional violin.

Mesh design prototype

A mesh model is a model consisting of vertices, connected to form polygons, which define a three-dimensional shape. The mesh model of the violin was constructed in Blender: a free, open source software with powerful mesh modeling capabilities [10]. The mesh model was constructed by taking measurements from the existing violin and using those measurements to define the positions of key points in 3D space. The details of the shape of the violin were created using the measurements as a basis and a photograph of the instrument for reference. This method allows for rapid modeling and easy adjustment of details of the instrument such as the shape of the curved faces, however this method is less precise than the vector based CAD approach.

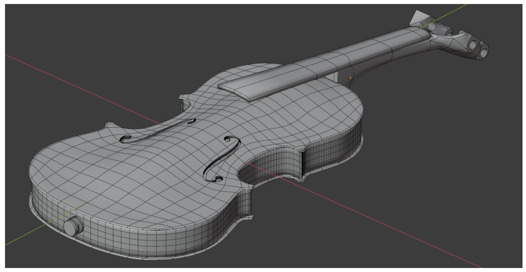

Figure. 4: The mesh model of the violin.

A vector based CAD model is a model where the surfaces and solid bodies are defined by mathematical functions rather than individual vertices and polygons.

Vector Design Prototype

The vector design approach constructed the CAD model using SolidWorks [11]. The violin was sized and shaped based off of a traditional wooden violin. After the violin's vector body was designed, SolidWorks features were used to insert features of a traditional violin into the model such as its curved faces, hollow body, bass bar and sound post.

The violin was then split into 6 different components to allow for successful 3D printing on readily available non-commercial printers: the end pin, lower body, upper body, neck, finger board and scroll. To ensure a smooth fit that minimizes acoustic effects or body design, the SolidWorks "Fastening features" were implemented. These features assign one section to have the lip and its adjoining section to have the grove. The grove removes a small section of material from the body, whereas the lip adds material to the body. This dispersion of the material allows the bodies to slide together seamlessly. To attach the bottom of the finger board to the top of the neck, SolidWorks "Mounting bosses" were implemented. The mounting bosses feature inserts either a pin or hole, that when aligning with each other, snaps into place. Additionally the end pin was given a thread feature that fits with the thread feature in the lower body's pin hole.

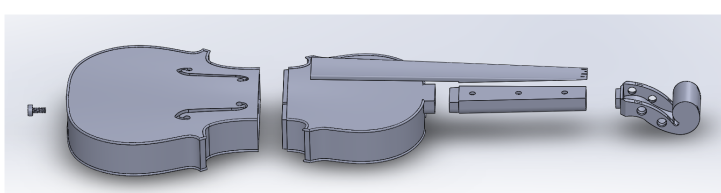

Figure. 5: Vector Violin Split Components.

Printing

The body of the violin was sliced at its thinnest point in order to reduce the amount of support material that needs to be printed. The other pieces, the fingerboard and the neck, could be printed in their entirety without having to divide them.

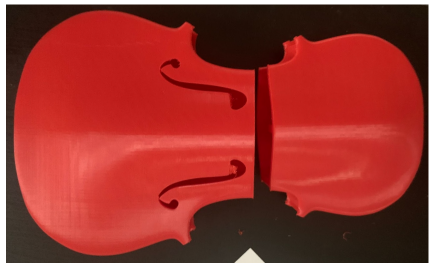

Figure 6: The two pieces of the violin before assembly.

Assembly

To assemble the instrument, cyanoacrylate adhesive was used on the edges and connected the two pieces together, keeping a firm amount of pressure on the pieces until the glue was set. The same method is used to connect the neck to the top of the body. The fingerboard is then attached to the neck using glue as well. The tuning pegs were then inserted into the violin and the chin rest, tailpiece, and strings were added to the instrument. Geared tuning pegs that were designed for use in guitars were selected for use in this instrument because traditional wooden tuning pegs are held in the instrument purely by friction and the friction between the plastic pieces of the 3D printed instrument would not be sufficient to hold up to the forces the string applies to it. The instrument is then tuned and tested for any physical problems so the design can be improved before the next iteration is printed.

To measure the rigidity of the violin when acted upon by the violin strings, measurements were taken throughout the course of three weeks. Measurements from the violin string to the fingerboard were taken at the fingerboard's beginning, middle and end, as well as the distance from the fingerboard to the base of the violin. These locations were chosen as it was believed the fingerboard would be the most vulnerable part when subject to the tension of the violin strings.

To do this, the violin was placed on its side, and a caliper was then used to measure the locations three times. This data was then collected and graphed over time in order to measure the deformation over time.

Figure 7: Traditional Violin Side View. [12]

A digital space was used to test physical properties as well. The sound of the violin was recorded, and put through a virtual oscilloscope in order to get a waveform. This waveform was then compared to the waveform from a traditional violin.

Results

Throughout the design phase, many different prototypes of the 3D printed violin were tested. Changes were made to the neck, fingerboard and pegs in the different prototypes to test the strength of the filament as well as test how the violin sounds compared to a traditional violin. Overall, a 3D printed violin that satisfied the requirements was able to be created.

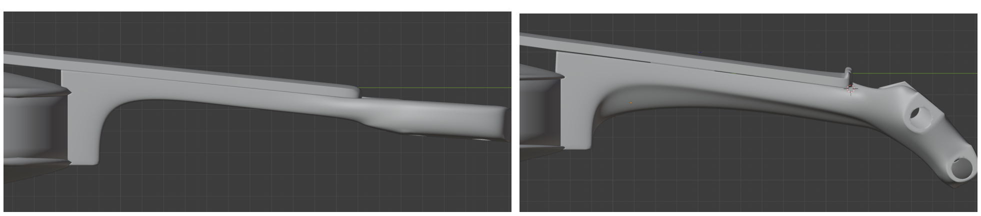

Figure 8: Original and improved designs of the violin neck and head showing strengthened neck and modified tuner mounting.

Physical Measurement Results

The results gathered from the first prototype in relation to its deformation proved inconclusive. Measurements were made mostly during the beginning and end of the three week span, as during the second week the researcher was unavailable to provide measurements, despite keeping the violin in tune.

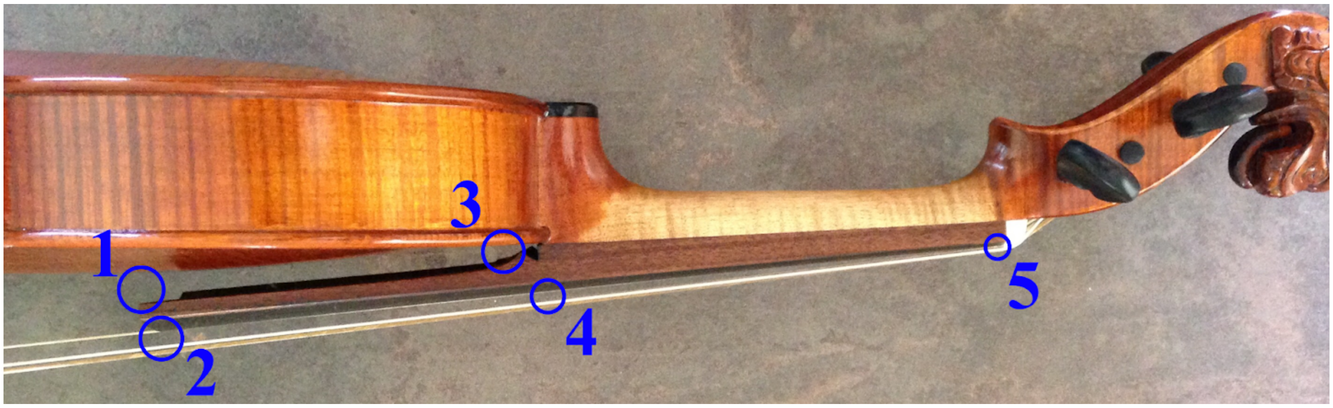

Figure 9: Violin Locations [12]

At location 1, the general trend was the distance between the stringboard and the body decreased by an average of 0.5333 mm over the course of the trial. At location 2, there was no significant trend - if a trend needed to be inferred, there was a very slight increase in the distance between string and the stringboard, at 0.3667 mm, though this was not deemed significant. At location 3, there was no significant change deformation trend amongst the data. At location 4, there was no significant deformation trend found. Finally, at location 5, there was also no significant deformation. From the limited data the team collected on the deformation, it seemed that there was only minor deformation due to the strings being centralized around the section of the violin's string board that lacks support..

After a 6-week trial with virtually daily tuning, the neck of the initial prototype snapped. Multiple subsequent neck designs were formulated and built to mitigate the structural inadequacies of the initial prototype.

Conclusion

After several iterations of violin designs, a 3D printed violin that had a similar sound quality to that of a traditional wooden violin was created. Multiple CAD systems such as SolidWorks and Blender were used to make the initial violin design and all of the prototype iterations. These iterations enhanced structural integrity, ease of construction of the instrument, sound volume and quality as well as aesthetic improvements. Multiple materials and different bonding agents were also tested to figure out the combination that worked best for the instrument. Efforts testing multiple print materials, wall thicknesses and print sequences are still continuing as well.

References

[1] J. Dais, "Best Violin for Beginners (2021): Top 15 Violin Brands," *TakeLessons Teachers*.
[2] MasterClass staff, "What Are the Different Parts of a Violin and How Do They Work? Learn About the Violin's 20 Key Components," Sep. 29, 2021.
[3] S. V. Dyck, "Violinmaking: Carving the Scroll," *Benning Violins*, 2021.
[4] Yamaha Corporation, "The Structure of the Violin How sound is produced," *Yamaha*.
[5] J. Wolfe *et al.*, "Violin Acoustics."
[6] J.-B. le R. d'Alembert, "Recherches sur la courbe que forme une corde tenduë mise en vibration," in *Histoire de l'Académie royale des sciences et des belles-lettres de Berlin*, vol. 3, Deutsche Akademie der Wissenschaften zu Berlin, 1749, pp. 214–219.
[7] L. Euler, "Supplément aux recherches sur la propagation du son," *Mémoires de l'académie des sciences de Berlin*, pp. 452–483, Jan. 1766, [Online].
[8] T. Liu, "Artificial Harmonics on the Violin – Young Scientists Journal," Aug. 30, 2017.
[9] L. Mongeau, "Low-income districts find ways to help students make music," *Hechinger Report*, Dec. 16, 2019. [Online].
[10] The Blender Foundation, "The Freedom to Create," *blender*.
[11] Dassault Systemes SolidWorks Corporation, "INTRODUCING SOLIDWORKS." [Online].
[12]D. Schou, *Français : Baroque violin Walter Mahr, 2010 - neck & lionhead*. 2016.[Online]