Modal analysis of an acoustic violin and a 3D printed electric violin

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Abstract
The F-F-Fiddle is an innovative, full size, 3D printed, electric violin. According to several sources, all violins, regardless of monetary value, have the same first five vibrational modes. This project is to determine whether or not the F-F-Fiddle has the same first five vibrational modes and whether or not it is comparable to an acoustic violin. In addition, the project explores how the equipment at the Cooper Union can be used to determine the modes of the violins.

Introduction
In recent years, 3D printing has grown in popularity. These days, makers have been experimenting with printing various things including violins. One such violin is the F-F-Fiddle which was designed by David Perry. More specifically, it is a 3D-printed electric violin. The purpose of this study is to quantify how similar the F-F-Fiddle is to acoustic violins by using modal analysis and comparing the modes.

According to Cheri Collins of Ovation Press String Visions, the first five vibrating modes of a violin are called Signature Modes and are the same in any violin regardless of monetary value. George Bissinger, as cited by Collins, is a physicist at East Carolina University and has done a lot of research on the Signature Modes of violins. According to him, the violins he has tested all have the same Signature Modes below 600 Hz. In addition, John E. McLennan, a researcher at the University of New South Wales in Australia has done impact tests on violins and also found that the first five modes tend to be 600 Hz or below. The frequency ranges for both Bissinger’s and McLennan’s violins’ first 5 modes are between 285 Hz and 600 Hz.

This study used an impact hammer to determine the modes of three violins. Two of the violins were acoustic violins and the third was the previously mentioned F-F-Fiddle. The two acoustic violins are made out of wood and the F-F-Fiddle is made out of carbon fiber. The violin was printed as three parts: body, neck, and bridge and assembled with various fasteners. One of the acoustic violins belongs to the Cooper Union while the other one belongs to Jackie Le. The owner’s name will be used to differentiate the two violins from here forward.

Experimental Methods
Acoustic Violin
Experimental Setup
First, a test stand was setup to support the violin vertically. Its design is based off the


test stand used by Douglas Cox, a violin based in Vermont. Douglas Cox uses impact hammer testing when building his violins; however, he uses a microphone instead of an accelerometer, which will be used in this study, to record the response of the violin. The test stand consisted of a box constructed out of PVC pipes and elastic tubing. As shown in Figure 1 and Figure 2, elastic tubing was stretched across one side of the PVC box and tucked under the violin’s scroll. On the other side, two elastic tubes were stretched across the box to support the bottom of the violin.

![Figure 1: Violin supported by test stand constructed out of PVC pipes and elastic tubing.](image1)

Second, the sampling rate and block size were set to 10000 Hz and 10000 samples respectively. While using different tips, the impact hammer was used to tap the violin. The Hammer power spectrum for each tip is shown in Figure 3, Figure 4, Figure 5, and Figure 6 and was used to see which frequencies were excited. Since the literature shows that the first five natural frequencies are within 0-600 Hz (citation here) and the 15 dB roll-off of the metal tip is 600 Hz, the metal tip was chosen for the tests. This process was repeated for both the acoustic violins and the 3D printed electric

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![Figure 2: Side view of test stand. Note that violin is only touching the elastic tubing which does not touch the ground.](image2)
violin (see Appendix 1: Hammer Power Spectrums for Various Tips for more details).

Third, a grid was taped onto both sides of the violin as shown in Figure 7 and Figure 8. The grids were coincident to each other. The intersection of the grid lines indicated the locations for the accelerometer and the impact hammer hits. A PCB U352C65 accelerometer was attached to the front of the violin at location 11 which corresponds to the row 1, column 1 on the back grid. See Appendix 2: Grid numbering to see how all of the points were numbered. A PCB Model 086C03 impact hammer tapped the front of the violin.
The impact hammer and accelerometer were attached to a NI USB4431 DAQ. LabView software collected the time domain data from the impact hammer and accelerometer and computed the magnitude, phase, real, and imaginary parts of the FRF were computed.

Since the metal tip excited frequencies up to 600 Hz, the sampling frequency, $f_s$, was set to $1500$ Hz so that it would be more than twice the maximum frequency of interest. The total sampling time, $T$, was 12 seconds because it took approximately 12 seconds for the vibrations within the violin to stop. Since $N = T \times f_s$, where $N$ is the number of samples, $N$ was 18000 samples.

Fourth, a paper towel was tucked between the strings and the finger board to dampen the strings. This is to ensure that the vibrations measured by the accelerometer are...
from the body of the violin and not the vibrating strings.

**Procedure**

Once the violin and test stand were set up, an impact hammer was used to tap each node of the grid on the back of the violin. Each node was tapped ten times and the data for each tap was averaged.

Two acoustic violins were tested in the same manner. The first violin belonged to Cooper Union and cost about $40. The second violin belonged to Jackie Le and cost about $700.

**3D Printed Electric Violin**

**Experimental Setup**

Similar to the acoustic violin setup, a PVC-elastic tubing test stand supported the 3D printed electric violin. Since the 3D printed electric violin did not have a scroll, two taught elastic tubes supported the neck of the violin as shown in Figure 9. In addition, two taught elastic tubes supported the base of the violin.

![Figure 9: 3D printed electric violin supported by a test stand made of elastic tubing and PVC pipe.](image)

A grid was taped on the backside of the violin as shown in Figure 10. Again, a PCB U352C65 accelerometer attached to the front side of the violin corresponding to location 11 on the back (row 1, column 1). A PCB Model 086C03 impact hammer tapped the front of the violin.

PCB U352C65 accelerometer and the PCB Model 086C03 impact hammer connected to a NI USB4431 DAQ. LabView software used the data from the accelerometer and impact hammer to calculated the magnitude, phase, real and imaginary parts of the system.
Procedure

The impact hammer tapped each node of the grid on the backside of the violin 10 times. Locations 32 and 41 were not tapped because the impact hammer could not contact the body of the violin because of tuners and internal wires respectively.

Results and Discussion

The magnitude and coherence data, shown in Appendix 3: Cooper Union’s Acoustic Violin Data, Appendix 4: Jackie Le’s Violin Data, and Appendix 5: F-F-Fiddle Data indicated what the natural frequencies were of the violins. The natural frequencies are summarized in Table 1.
Table 1: First 5 Natural Frequencies of the three violins tested.

<table>
<thead>
<tr>
<th></th>
<th>$\omega_1$</th>
<th>$\omega_2$</th>
<th>$\omega_3$</th>
<th>$\omega_4$</th>
<th>$\omega_5$</th>
<th>$\omega_6$</th>
<th>$\omega_7$</th>
<th>$\omega_8$</th>
<th>$\omega_9$</th>
<th>$\omega_{10}$</th>
<th>$\omega_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooper Union</td>
<td>5.5 Hz</td>
<td>8.75 Hz</td>
<td>73 Hz</td>
<td>189 Hz</td>
<td>228 Hz</td>
<td>264 Hz</td>
<td>390 Hz</td>
<td>440 Hz</td>
<td>514 Hz</td>
<td>610 Hz</td>
<td></td>
</tr>
<tr>
<td>Jackie Le</td>
<td>5.17 Hz</td>
<td>8.5 Hz</td>
<td>93.33 Hz</td>
<td>169.75 Hz</td>
<td>303.6 Hz</td>
<td>319.16 Hz</td>
<td>419 Hz</td>
<td>469 Hz</td>
<td>475 Hz</td>
<td>489 Hz</td>
<td>546 Hz</td>
</tr>
<tr>
<td>F-F Fiddle</td>
<td>6 Hz</td>
<td>8.5 Hz</td>
<td>142 Hz</td>
<td>285 Hz</td>
<td>308 Hz</td>
<td>418 Hz</td>
<td>486 Hz</td>
<td>613 Hz</td>
<td>625 Hz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The first two natural frequencies of all three violins were very close. Since they are so low, it is expected that they are due to rigid body motion. The other three natural frequencies are close between the two acoustic violins. This seems reasonable because the design and material (wood) of the two acoustic violins are quite similar. The natural frequencies for the F-F-Fiddle is quite different from the other two violins. This was expected because it is made out of carbon fiber which is very different from wood.

Below, in Figure 11, is a typical magnitude and coherence plot for the Cooper Union Violin. Figure 12 is a typical magnitude and coherence plot for Jackie Le’s violin.

![Figure 11: Typical magnitude and coherence plot for the Cooper Union Violin](image1)

![Figure 12: Typical magnitude and coherence plot for Jackie Le’s violin](image2)

For both violins, the first two peaks have a hump-like shape which suggests that there is leakage in the data. This may indicate that the total sampling time was not long enough or an exponential window should have been used. On the other hand, the coherence drops when there are drops at in the magnitude, at the anti-resonances. This is expected because at anti-resonances, the structure is not expected to move.

The first five natural frequencies are quite low compared to the literature. However, the literature used a microphone instead of an accelerometer to record the output from the violin. This may be why the first five frequencies found in this experiment were not close to the first five natural frequencies found in the literature. Some of the higher natural frequencies found in this experiment were close to the natural frequencies in the literature. In the future, the experiment should be redone with a microphone instead of an accelerometer.
to see if the lower natural frequencies are present. It is possible that the two violins tested happened to have much lower natural frequencies than the violins tested in literature.

On the other hand, the natural frequencies for the F-F-Fiddle is much different from the acoustic violins. Figure 13 shows a typical magnitude and coherence plot for the F-F-Fiddle. Looking closely, similar to the acoustic violins, the first two peaks have a hump-like shape. The first peak especially has a hump-like shape. This indicates that there is leakage. Again, this is attributed to the total sample time not being long enough. The experiment should be redone either with a longer sample time or an exponential window.

In addition, the magnitude plot has several areas that look almost like discontinuities. These areas are circled in Figure 13. It is unclear what these areas are however, since they are very sharp, they are most likely not a peak (i.e. natural frequency). They can probably be attributed to carbon fiber’s nonlinear material properties.

Moreover, the imaginary parts of the data, also shown in the appendices, revealed the mode shape of the violin. Using the natural frequencies and the imaginary parts, surface plots were created to visualize the mode shapes. A sample surface plot for 610 Hz for the Cooper Union Violin is shown in Figure 14: Surface plot of Cooper Union Violin at 610 Hz and the other surface plots can be found in Appendix 6: Surface plots of the Imaginary P.

Some of the surface plots from the Cooper Union violin and Jackie Le’s violin appear to have the same or similar shape, especially the surface plots between for the natural frequencies between 300 Hz and 600 Hz. For example, the 7th natural frequencies for the Cooper Union violin and Jackie Le’s violin are shown in Figure 15 and Figure 16 respectively. Although the magnitudes of the surface plots are not the same, the shape are quite similar. This indicates that these may in fact be the same mode for both violins.
Coincidentally, the 300 Hz to 600 Hz frequency range is very close to the frequency range for the natural frequencies found in the literature. More research should be done to see if the lower natural frequencies are simply not present when a microphone is used instead of an accelerometer or if the literature simply disregarded those frequencies. If they are not present when a microphone is used, more research should be done to explain why they are only present when an accelerometer is used.

For the F-F-Fiddle, the surface plots were not similar to the surface plots for the two acoustic violins. A typical surface plot is shown in Figure 17. The F-F-Fiddle was only tested with seven points. This is most likely not enough points to fully see what the F-F-Fiddle does when excited at various frequencies. The experiment with the F-F-Fiddle should be redone with additional points.

**Conclusion**

The experiments conducted revealed the natural frequencies of Cooper Union’s violin, Jackie Le’s violin, and the F-F-Fiddle. In addition, surface plots of the imaginary part of the frequency response of the violins gave a rough idea of the mode shape of the violins. However, the surface plots cannot truly be called the mode shapes of the violins for a number of reasons. First, the magnitude plots of the frequency response of the violins indicate that leakage occurred in the data. The experiments should be redone with a longer sampling size to avoid leakage or with an exponential window. Second, a limited number of locations on the violin were tested. More points would give a better picture of how the violins bend when excited by different frequencies. It is especially important to use more points if the F-F-Fiddle is retested because only 7 points were tested in this experiment.

After comparing the natural frequencies and surface plots, these initial tests suggest that the frequency response for the two acoustic violins appear to be similar. The frequency response for the F-F-Fiddle does not appear to be similar.

In addition to redoing the tests with a longer total sampling time, additional experiments using other experimental methods should be employed. These other experimental
methods include using sand and a shaker. Unfortunately, that would require a hole be drilled into the violins to create an adequate connection between the violin and the shaker. By using a shaker and sand, it would be very easy to determine the natural frequencies and visualize the mode shapes without too much other equipment. This would be a great way to verify the natural frequencies found via the impact hammer method.

Works Cited


Appendices

Appendix 1: Hammer Power Spectrums for Various Tips

Cooper Union’s Acoustic Violin

Figure 18: Hammer Power spectrum when impact hammer taps CU’s violin with an orange tip.

Figure 19: Hammer Power spectrum when impact hammer taps CU’s violin with black tip.

Figure 20: Hammer Power spectrum when impact hammer taps CU’s violin with white tip.

Figure 21: Hammer Power spectrum when impact hammer taps CU’s violin with a metal tip.

From the hammer power spectrum above, it can be seen that the metal tip has the flattest response up to 600 Hz. This tip was used because the frequency range of interest was 0 to 600 Hz.

Jackie Le’s Violin

Figure 22: Hammer power spectrum when impact hammer taps Jackie Le’s violin with an orange tip.

Figure 23: Hammer power spectrum when impact hammer taps Jackie Le’s violin with a black tip.
From the hammer power spectrum above, it can be seen that the metal tip has the flattest response up to 600 Hz. This tip was used because the frequency range of interest was 0 to 600 Hz.

F-F-Fiddle

From the hammer power spectrum above, it can be seen that the metal tip has the flattest response up to 600 Hz. This tip was used because the frequency range of interest was 0 to 600 Hz.
Appendix 2: Grid numbering

Acoustic violins
Appendix 3: Cooper Union’s Acoustic Violin Data

Magnitude

Row 1
Real Part

Row 1

Accelerometer Real Part - Pos 45

Accelerometer Real Part - Pos 11

Accelerometer Real Part - Pos 12

Frequency (Hz)
Imaginary Part

Row 1
Appendix 4: Jackie Le’s Violin Data

Magnitude and Coherence

*Note that orange lines are coherence and blue lines are magnitude.

Row 1
Phase

Row 1

Accelerometer Phase - Pos 11

Accelerometer Phase - Pos 12

Accelerometer Phase - Pos 13

Accelerometer Phase - Pos 14
Real Part

Row 1
Imaginary Part

Row 1
Appendix 5: F-F-Fiddle Data

Magnitude and Coherence

*Note that orange lines are coherence and blue lines are magnitude.

Row 1
Appendix 6: Surface plots of the Imaginary Parts
Cooper Union Violin

$\omega_1$

![Surface plot for $\omega_1$ at 5.5 Hz]

$\omega_2$

![Surface plot for $\omega_2$ at 8.75 Hz]
Jackie Le’s Violin

$\omega_1$

![Graph 1](image1)

$\omega_2$

![Graph 2](image2)
F-F-Fiddle Violin
Note: the imaginary parts of the first and second natural frequencies were not plotted because they are thought to be due to rigid body motion.