VIOLIN TAILPIECE DYNAMICS: RESONANCE EFFECTS FROM SET UP

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Abstract (Executive Summary)

This report investigates the resonance of the violin tailpiece subject to changes in set up. An individual resonance was characterized by use of modal analysis. The identified mode was then tracked as changes were made to the set up of the tailpiece. The mode frequency was found to vary from 365 to 875 Hz in the range of set ups tested. A sensitivity analysis was used to examine which set up parameters are most effective at changing this frequency. The length of chord from the bottom of the tailpiece to the violin body was shown to be the most effective parameter in affecting the resonance observed. Ansys finite element software was then used to compare results from the experimental data on the change in the characterized mode. The use of linear trends to describe patterns seen in the data from both the Ansys tests and the experimental tests were discussed. The ability of set up to affect strong resonances in the tailpiece was confirmed.

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1. INTRODUCTION

The violin tailpiece has been known by instrument makers for hundreds of years to effect the sound of the instrument. The reason for this, it is postulated here, is that the tailpiece acts as a sprung mass damper absorbing the driving force (the force imparted on the instrument by the bow) at its resonant frequencies. The tailpiece then, if tuned, can be used to effect unwanted audible resonant frequencies of the violin by tuning a strong resonance of the tailpiece to that frequency. The most notable case in the instrument world where an unwanted frequency interaction occurs is the "wolf note" (described by [1]) whereby a strongly emitting resonance of the violin body interacts with a note that the musician is trying to play. The result is a beat frequency that moves around the desired note but does not allow it to be played. A study of the effects that tailpiece set up (how the tailpiece is mounted on the violin) has on the resonant frequencies of the tailpiece, to the author's knowledge, has had little or no attention in the literature. The question posed here is whether or not the set up of the tailpiece will change the position of any of the strong resonant frequencies of the tailpiece. An understanding of how the tailpiece responds to adjustment could improve its role as a tool for makers to affect the sound quality of the violin. Modal analysis (of the kind performed in [2]) will be used to identify the modal shapes that correspond to resonant frequencies of interest. Due to the strong reactivity of the violin a purpose designed and built rig ("dead rig") made to copy the geometry[Appendix] of the violin will be used in the measurements. To help confirm trends as well as provide a tool for further studies the program Ansys will be used to perform finite element modeling (FEM) and analysis (FEA) on CAD models of the tailpiece geometry allowing for the calculation of modal frequencies and shapes. The FEA will be compared with the measured to determine the usefulness of the model for further inquiries.

2. GLOSSARIES

- *Violin family instrument*- includes cello's, violins, bases, and viola
- *Violin anatomy* – (see figure 1 below)

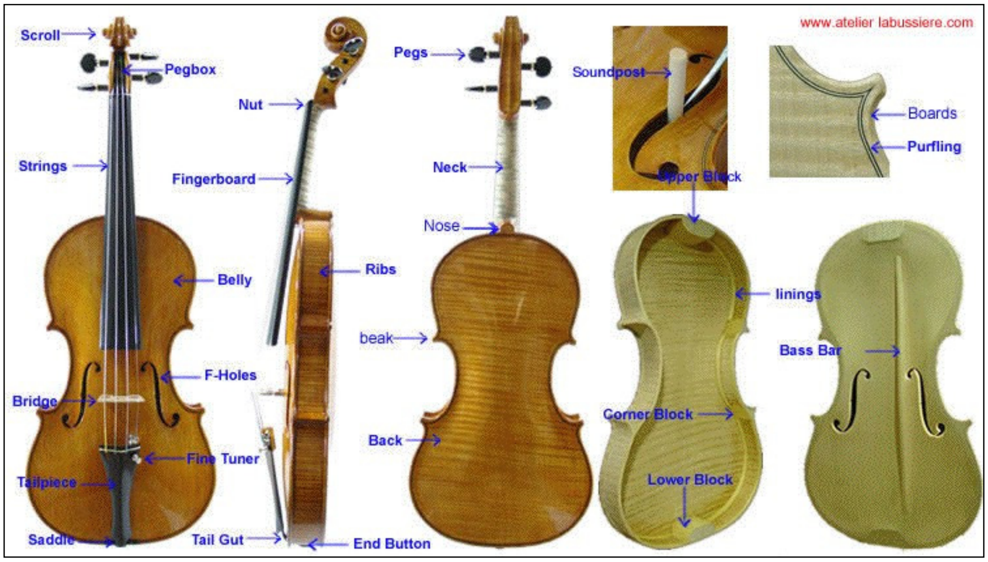

Figure 1 diagram of violin anatomy

- *French pattern tailpiece* –Rounded body (fig 2)

Figure 2 french pattern tailpiece http://www.harmonie.net/us/catalogue/a-cordier.html

- *Tail chord* – Chord that runs from the bottom of the tailpiece to the end button.
- *After-length* – Length of string between the bridge and the break point on the tailpiece.
- *Node* – Location of zero displacement in a vibrating body.
- *Saddle* – Location where the tail chord terminates over the violin body.
- *Rt*- Resonance identified in the tailpiece design tested here between 500 and 800 Hz exhibiting a characteristic rocking motion see 4.1.
- *Keyhole*- The holes that the bottom end of the string enters to secure it to the tailpiece. Located just behind the fret.
- *Fret*- Metal insert at the front end of the tailpiece created as a break point for the strings.
- *Coherence*- A measure of consistency in a single measurement taken multiple times. Flat coherence means that each measurement at the same location is more or less identical.

3. Materials and Methods

3.1. Tailpiece Design

The tailpiece design used in this study was created by Ted White of Arbutus fittings. The design shown in figure 3 is an example of a French style tailpiece with a channel cut in the underside to allow the sliding of a weight which has the effect of changing its mass distribution about the axis drawn in figures 3, 5, and 6. The use of the channel is not the focus of this report though it is important to mention that this feature is not standard on most tailpieces. The use of this particular tailpiece design is primarily done for proprietary reasons and secondly the geometry of this design exists in a computer aided design (CAD) model document in close tolerances (within 1/10 mm) to the fabricated tailpiece which is vital for the FEA.

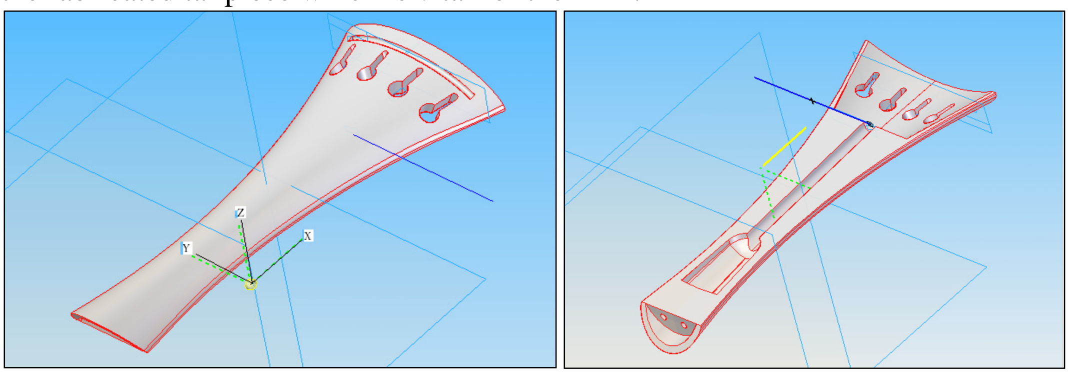

Figure 3 Tailpiece top (left) and underside (right) showing axis of rotation in blue

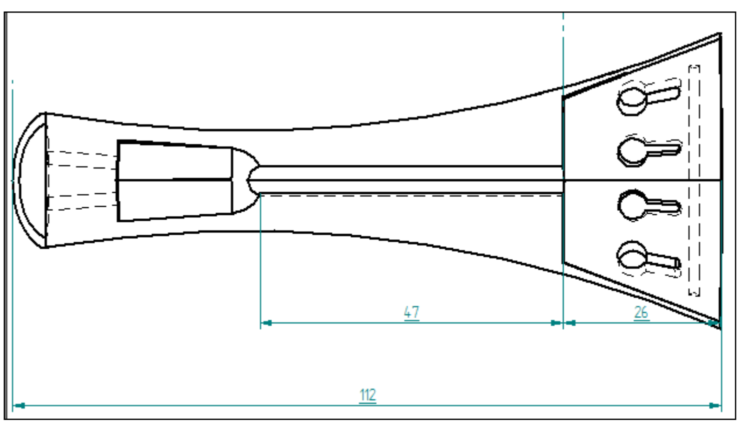

Figure 4 112 mm tailpiece design

3.2. Modal Analysis

3.2.1. Testing

The procedure for modal analysis is done by;

- Laying out the geometry of the tailpiece and specifying measurement locations using the “mode shape” software (fig. 8).

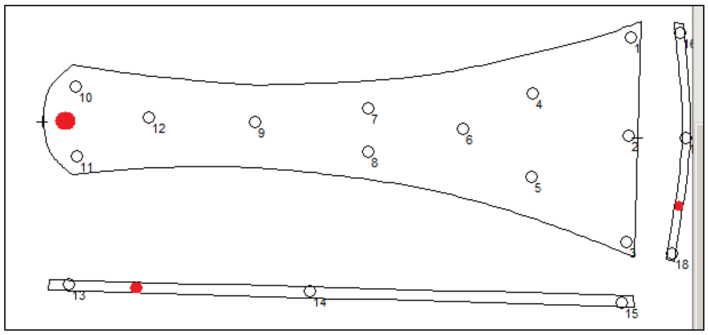

Figure 5 hammer and accelerometer locations for test tailpiece

- Mounting the accelerometer (red dots in fig. 8) in the appropriate plane. The accelerometer was mounted using wax provided by the manufacturer of the device.
- Recording the complex (magnitude and phase) acceleration response of the objects to applied impulse signals in the form of hammer strikes at the measurement locations and converting them to frequency response functions (FRF’s) for analysis. Each FRF is taken as the average of 5 hammer strikes in order to reduce errors in measurement as well as to confirm a good coherence between measurements.

In order to remove the tailpiece from the effects of the instrument a “dead rig” (fig 7) mimicking the instrument geometry (see appendix for geometry) was built from laminated birch plywood. The material was chosen to provide a structure with dimensional stability and increased mass relative to the instrument. The dead rig is mounted on marine engine compartment insulation to isolate the rig from the table during testing.

Figure 6 Violin "dead rig" set up

The modal hammer used in these experiments was a PCB 4.8 g hammer, model 086E80, and the vibrations were recorded using a Dytran uniaxial 0.6 g piezoelectric accelerometer model 3225E.

In order to standardize the hammer strikes a hammer rig (fig. 9) was constructed providing a 6 degree of freedom tool for orienting the hammer head to the 3 principle directions of the tailpiece. The software for acquisition and post processing of this data has been created and donated free of charge by George Stoppani.

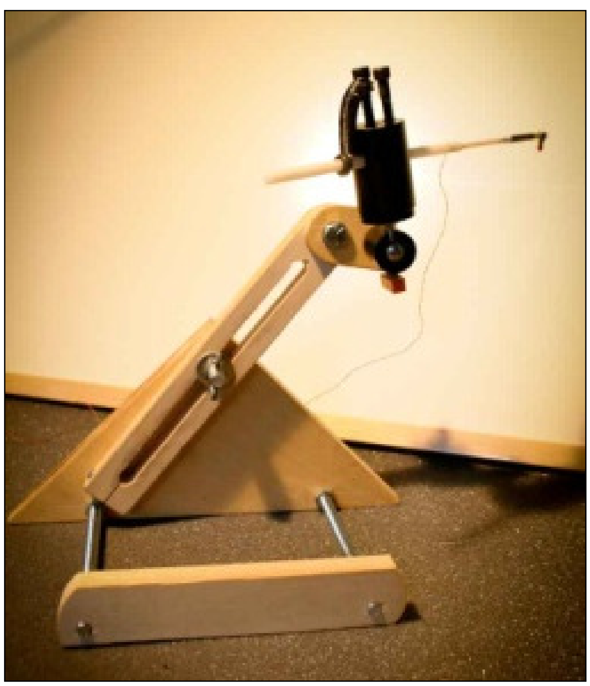

Figure 7 Hammer rig

3.2.2. Post processing

In order to determine the resonant peaks of the object being analyzed, the program "mode fit" provides a way in which to locate probable resonances and to fit curves to the acceleration response for each point. The fits are then saved and visualized in "mode shape" to view the patterns of movement at a particular frequency. Figure 10 shows an example of a fitted resonant peak. The black lines are the raw data and the red lines are fitted polynomial functions (in this case of order 13) describing the behavior of the FRF's within the specified window.

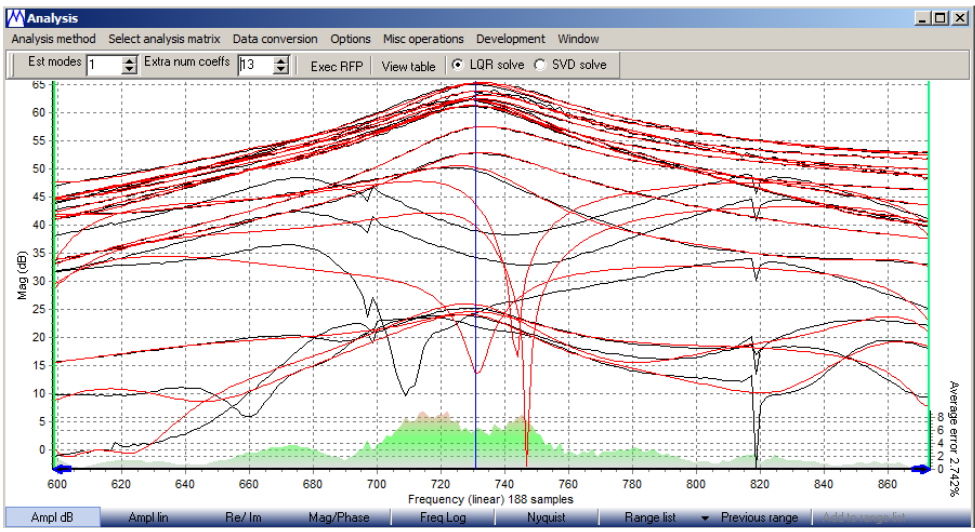

Figure 8 Mode fitting at around 730 Hz (each line is one measurement location)

The program "Mode Shape" was used to allow the motion at resonant frequencies to be visualized. Modal images presented in this paper will be given as normalized two dimensional color plots. Figure 9 can be interpreted by noticing that the black line is a position of zero displacement, the blue color is into the page and the purple color is out of the page. In the right hand side of figure 9 one can see an oblique angle to view the departure from the equilibrium position shown as an outline. Top measurements are defined as those in the XY plane. Side measurements are defined as the acceleration in the ZX plane, visually displayed as a side profile beside the tailpiece in the color plot. The front measurements are defined as those in the ZY plane displayed as the front profile above the tailpiece in the color plot. Due to the amount of information the focus of this study will be on the modal behavior of the top of the tailpiece at frequencies below 1000 hz.

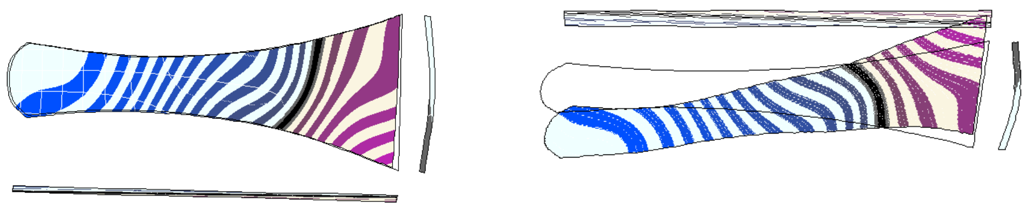

Figure 9 2D color plot of 112 tailpiece at 731 Hz

Fourier transforms representing the frequency domain of the recorded time functions displayed in this report will be graphed using the dB amplitude of the signal Z vs. the frequency at which the amplitude occurs. Phase information is useful for coordinating the motion of points in the modal visualizations but for the purposes of comparing individual FRF's this information is neglected. For real component data Re and imaginary data Im the dB amplitude of the acceleration Z is given by,

$$Z = 20\, log(Re^2 + Im^2)^{.5}$$

3.3. Set up and adjustments

String type - D'ddario Helicore 4/4 medium tension strings. String tension was standardized by tuning to standard violin string notes (figure 10) which correspond to the tensions shown in table 1.

Tail chord type - Vectran (trade name) chord

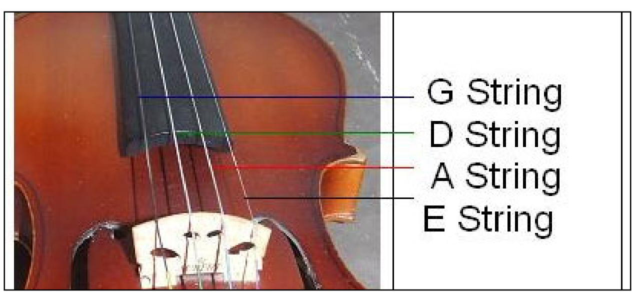

Figure 10 Notes of the violin strings

Table 1 String tensions

E	A	D	G
80.5 N	56.5 N	51 N	45 N

The tailpiece set up, afterlenghts, tailgut lengths, and overall length between the bridge and the saddle, will be specified for each test. Tracking changes in resonance peaks will be done by taking a single measurement point at a location on the tailpiece chosen to avoid any nodes identified in the modal analysis.

3.4. Finite element Model (FEM)

3.4.1. Model import

The Ansys workbench software was used to simulate the suspension and boundary conditions that mimic those of the actual tailpiece suspension. The tailpiece geometry was created in Rhino computer aided design (CAD) software and was then imported into the geometry component of the Ansys workbench system as an assembly of the tailpiece solid model, 2 tail gut segments, and a bridge component (geometry specifies the spatial location of string contact at the bridge). The set up parameters for each test was pre specified in the assembly by orienting the components (tail chord length and bridge location) to the correct positions for each test.

3.4.2. Model set up

The String elements of circular cross section with a .7mm diameter were applied to the imported model with the string tensions as specified by the D'Adarrio website for their medium tension 4/4 Helicore violin strings (table 1) . Connections between elements are as follows:
Tail chord to ground- Fixed supports to ground.
Tail chord to tailpiece- Fixed body-body connection where the tail chord enters the end of the tailpiece.
Taipiece to strings - Spherical body-body joints at the tailpiece fret where the strings break after exiting the keyholes on the tailpiece.
Strings to bridge - Displacement constraints which allow tension to be applied along the length of the string but inhibit motion in all other directions.

The material assignment to all parts in the model was structural steel. The use of structural steel was chosen because of its ability to give a close initial approximation to the observed data. Attempts to approximate the constituent material properties led to unrealistic results therefore the choice was made to make the material uniform throughout the model.

Table 2 Structural steel properties

Density	7850
Youngs modulus	200 GPa
Poisson's ratio	0.3

3.4.3. Issues and Assumptions

Assumptions were made in order to simplify the tailpiece model and also to address some of the set up issues in the FEA of such a complicated system. Table 3 shows some of the issues addressed and the assumptions that were made.

Table 3 Issues and Assumptions with FEM

Issue	Assumption
Anisotropy of wood	Single isotropic material used
Complexity of chord and string geometry (wound and woven material)	Approximated as a circular cross section string element with isotropic properties.
Vibrations of support	Approximated as a rigid ground connection at saddle and bridge.
Varying string tension on strings w/ vibration	Constant string tension assumed.

It is important to note that due to these assumptions it is likely that the model will not show identical behavior though its potential use as an analogous system will be examined.

3.4.4. Finite element analysis (FEA)

Analysis was done using the Ansys workbench solutions tool which provides automatic meshing that optimize the number of nodes and elements in the system to provide sufficient refinement while not sacrificing speed in analysis. For the current investigation modal response was obtained from the pre-stressed model. Results are presented in Ansys as graphical animations of mode shapes. This report will provide images and frequency values to convey the data obtained.

4. Results/Discussion

4.1. Identifying mode shapes on "dead rig"

The Mode shapes associated with the strong resonances of the tailpiece were first identified to characterize the type of motion responsible for the resonant peaks of the tailpiece. The coordinate system can be seen in figure 3. The set up for the mode identification is done with a standard set up for violins shown in table 4.

Table 4 set up for mode identification

tail gut length (mm)	after length (mm)	Overall length (mm)
8.2	49	161

4.1.1. Top Resonance and Mode Identification

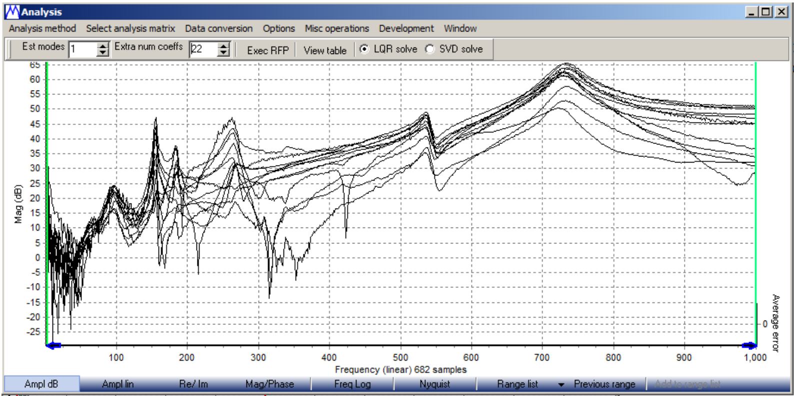

Figure 11 Resonant frequency at around 750 Hz

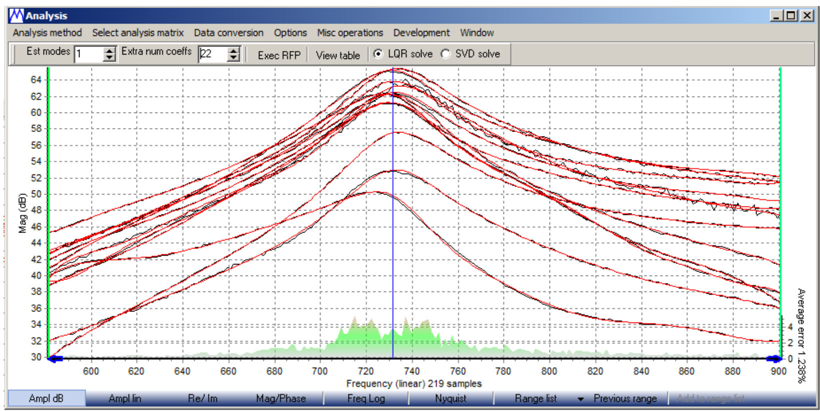

Figure 12 Mode fit for 731.58 Hz

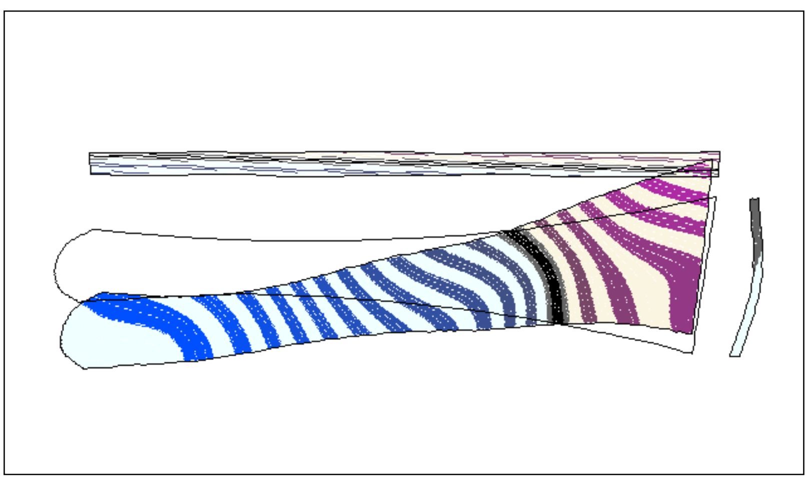

Figure 13 Mode shape for 112 tailpiece xy plane at 731 Hz

Figure 14 shows the mode shape for the resonance peak identified in figure 12.
The mode shown here is the highest amplitude resonance for the tailpiece below 1000 hz. Many low frequency peaks below 200 Hz are observed but the low coherence shown in measurements as well as their relatively low amplitude, with the highest peak at 20dB below the peak at 731 Hz, are not presumed to be of acoustical consequence at this point. The high peak at 731 Hz corresponding to the mode shape shown in figure 13 will henceforth be referred to as Rt (Tailpeice resonance). Rt is a good candidate for investigation in part because of its high amplitude but also because of its proximity to a strongly emitting body mode of the violin (B1 + see terminology) which ranges typically around 500 Hz. Being able to tune the tailpiece around this frequency could provide a tool for the maker to adjust the tailpiece to effect this body mode and other body modes close by.

4.2. Variations in Mode due to changes in set up

From the mode identification in 4.1 the movement of the resonance peak will be tracked as changes are made to the tailpiece set up.

Table 5 Test parameters for 161 overall length

Test #	After length	Tail chord length	Over all length	Frequency
0	20	37	161	365
1	30	27.5	161	405
2	36	20	161	460
3	41	16	161	540
4	45	12	161	620
5	49	8.2	161	740
6	52	5.5	161	875

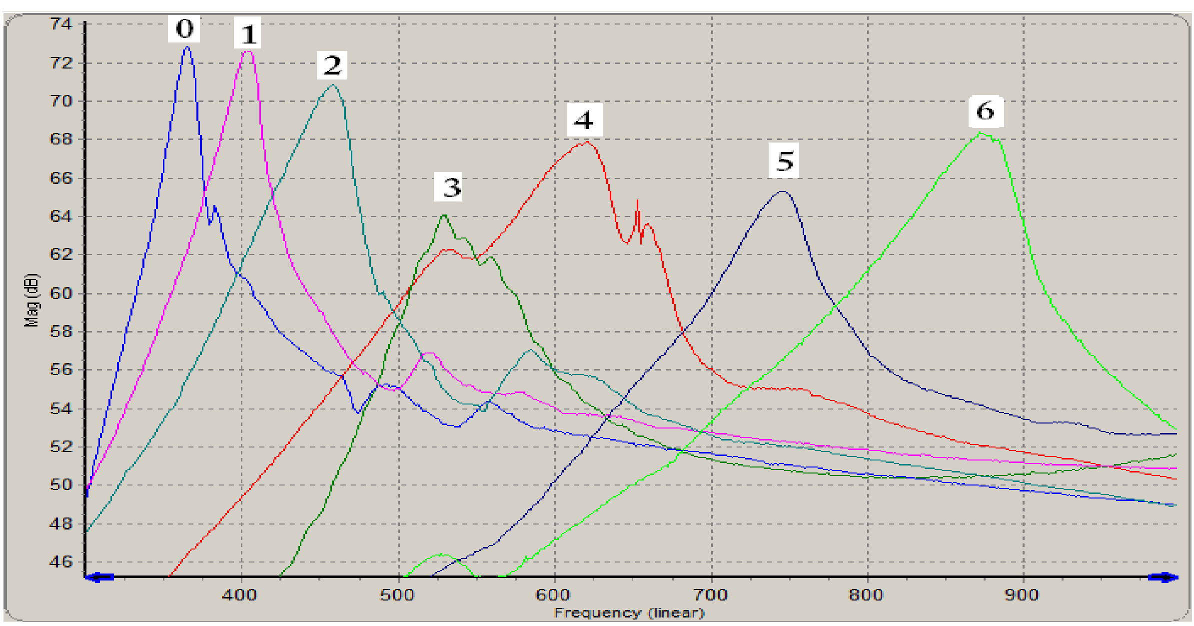

Figure 14 Frequency vs. dB amplitude for the tests in table 4

From the frequency response functions shown in figure 14 changes in the location of the resonant frequency of the mode found in 4.1 can be observed. The band width of adjustment for the set up values found in Table 4 is measured as 365-875 Hz .

4.3. SENSITIVITY TO SET UP PARAMETERS

The sensitivity of the resonance in 4.1 to changes in afterlenght vs. changes in tail chord length is important with regard to tailpiece design therefore adjustments were made to the overall length in order to maintain a constant tail chord length for varying afterlength and also to investigate constant afterlength for varying tailgut length. Table 6 shows the results from the sensitivity analysis.

Table 6 Set up values for sensitivity analysis

Test #	After length	Tail chord length	Over all length	Frequency
7	49	8.2	161	740
8	57	8.2	169	750
9	49	16	169	530
10	41	16	161	540

The data shown here shows that for a decrease in afterlength of 8 mm there is a corresponding increase of Rt of approximately 10 Hz for both the 16 mm and the 8.2 mm tail chord length cases. For a 7.7 mm change in tail chord length at an afterlenght of 49mm a change of approximately 210 hz is observed. This large change coupled with the possibility that the 10 hz change could be accounted for by measurement error implies that between the two parameters the tail chord is, at least in the range tested here, a more significant factor in the frequency magnitude of Rt.

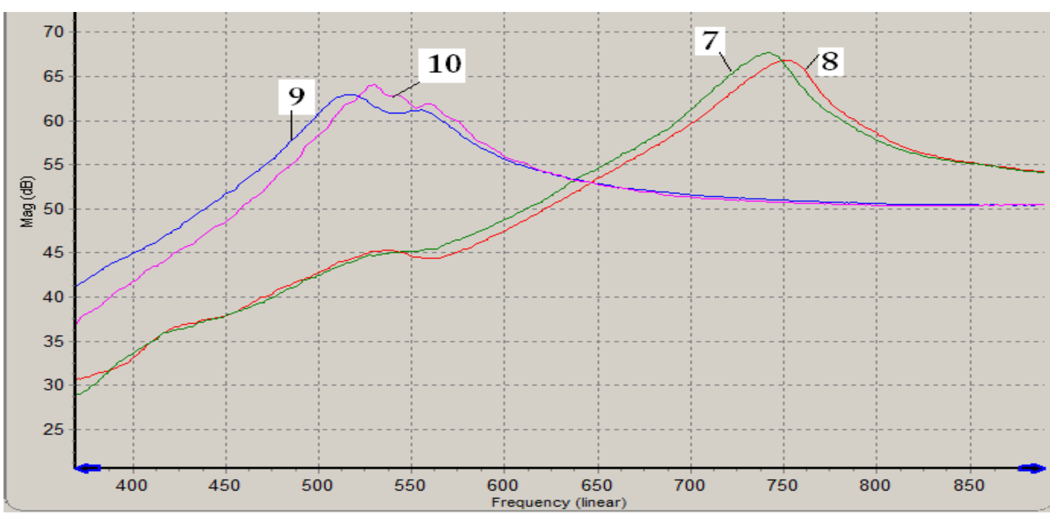

Figure 15 FRFs for sensitivity analysis

4.4. FEA RESULTS

FEA was performed on 6 different set ups. The modal shape determined in 4.1 was observed in all tests and its frequency location was noted. Figure 16 shows a screen shot of the mode found in 4.1 compared to the mode shape observed in the FEA. The two mode shapes are similar in the location of the node below the keyholes and the articulation of motion.

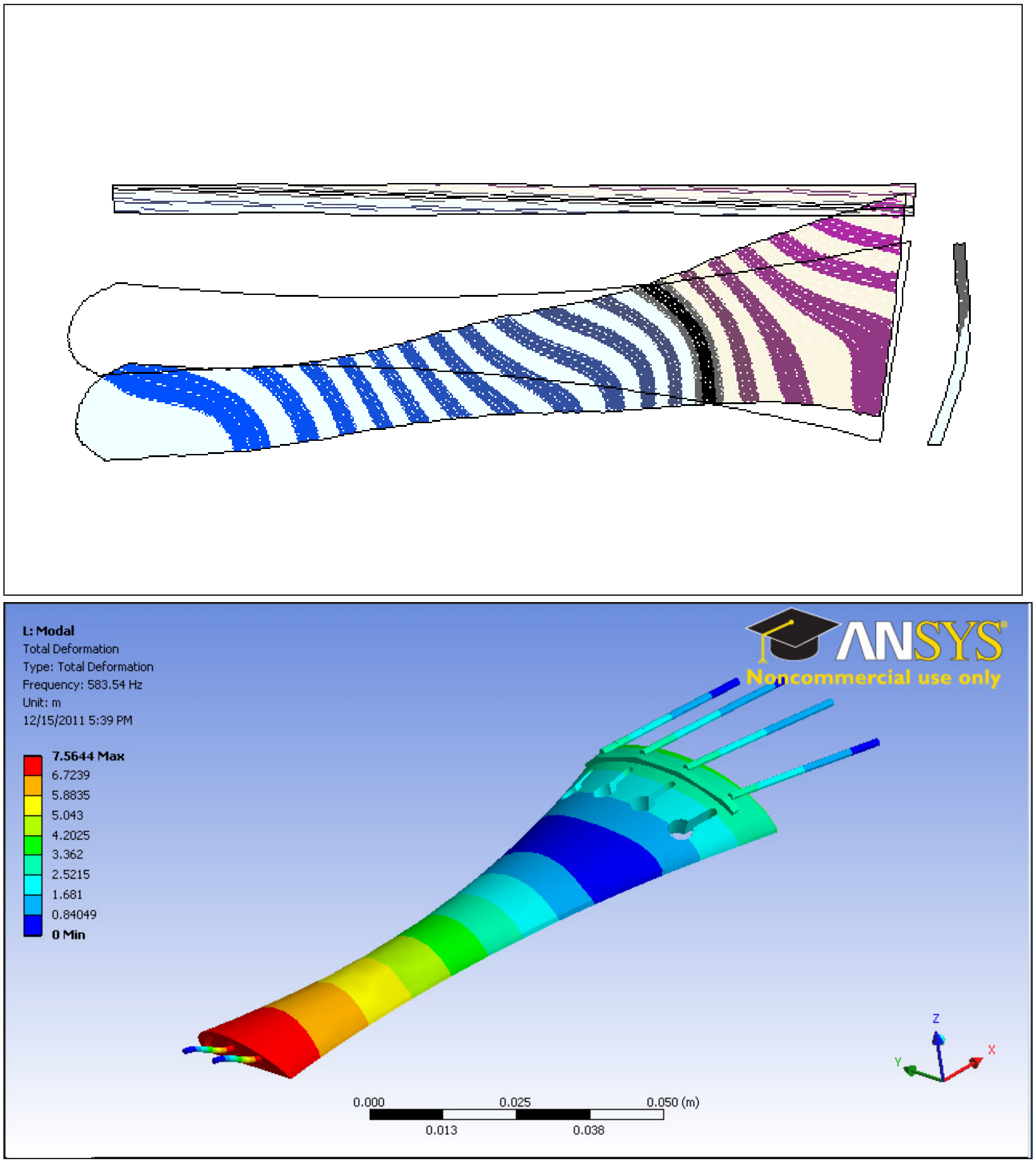

Figure 16 Comparison of Mode shapes for Rt, above: measured data visualization and below: Ansys modal visualization

The frequency of the mode shape in figure 17 was tracked as changes were made to the Finite element model, tests 11-16. Table 7 shows the changes to the set up between tests and the corresponding Rt frequency. The changes to the set up on the FEA were designed to match the measurements done on the "dead rig" in order to have a comparable data set.

Table 7 Data for tests done using FEA

Test #	Tail chord length	FEA Rt Frquency	Over All length
11	8.2	804	161
12	12	583	161
13	16	378	161
14	20	294	161
15	27.5	252	161
16	37.5	190	161

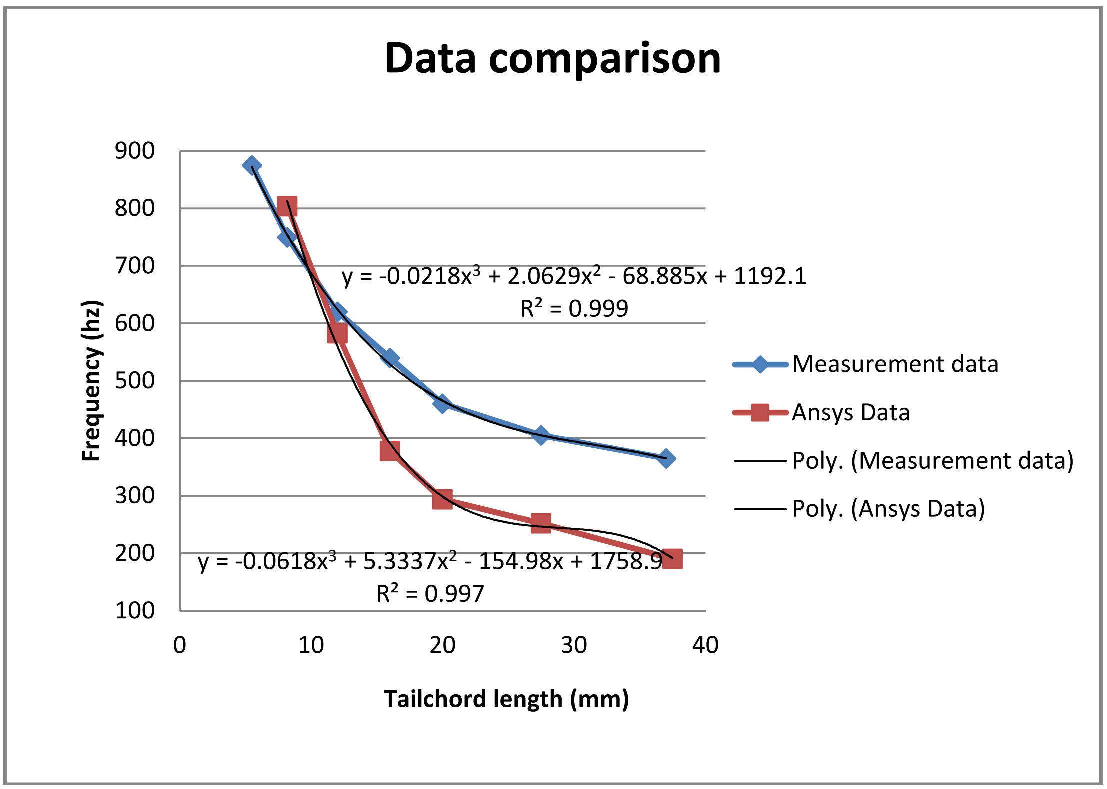

Figure 17 Comparison between FEA data and measured data.

The data gathered from the FEA analysis shows strong linear regions of frequency dependence on tail chord length above 20 mm and below 16. The more complicated fit shown in figure 17 of $y = -0.0218x^3 + 2.0629x^2 - 68.885x + 1192.1$ Hz for the experimental data provides a better R squared value of .999 though the use of a cubic leads to erroneous results in fitting the Ansys data. Also for the limited experimental data set it is easier for the computer algorithm to match a cubic polynomial than a straight line to fit the data.

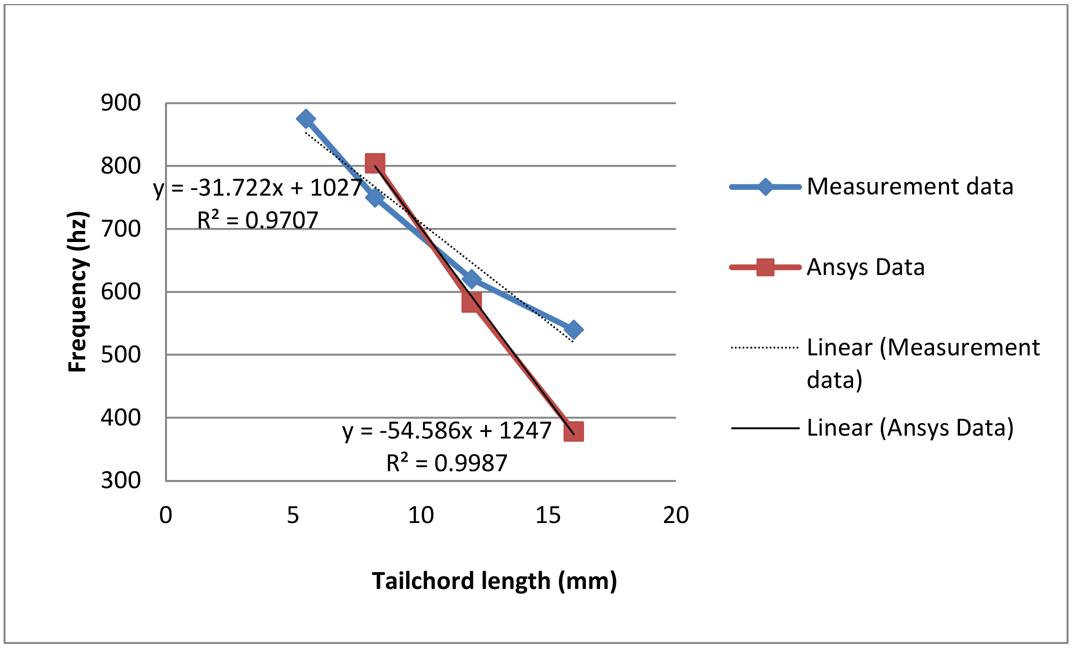

Figure 18 Frequency dependence on tail chord length below 16 mm

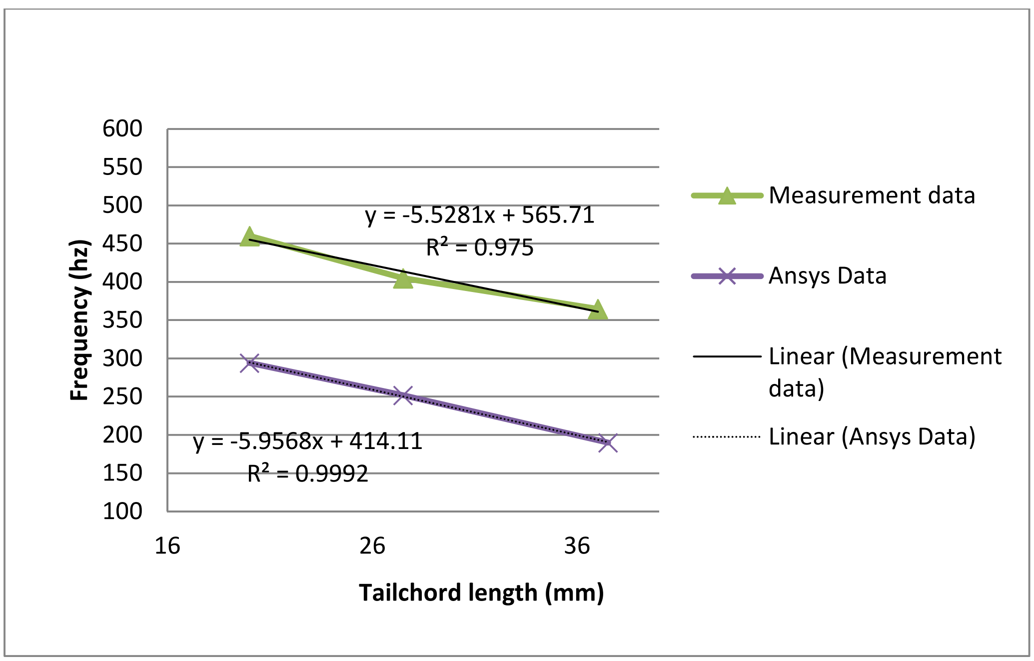

Figure 19 Frequency dependence on tail chord length above 20 mm

Table 8 Linear fit data above 20mm and below 16 mm

Below 16 mm			
Data Source	Slope Hz/mm	Y-intercept Hz	R squared value
Experimental	-32	1030	.971
Ansys	-55	1250	.999
Above 20 mm			
Data Source	Slope Hz/mm	Y-intercept	R squared value
Experimental	-5.8	565	.975
Ansys	-6	414.11	.999

The linear dependence of the Ansys data above 20 mm and below 16 mm has an R squared value of .999 (Table 8) indicating an accurate fit. This high R squared value also implies that perhaps there is a theoretical basis for this discontinuity between 16 and 20 mm because it is unlikely that errors would cause such a coincidence of correlation in the data. The fact that a similar trend was observed in the experimental data is intriguing though it is difficult to validate until more tests are done. It would be beneficial to run the same experiment on different tailpieces and search for a similar trend.

The similarities between the slopes of the linear fits of the Ansys and experimental data (above 20mm), -5.8 and -6 respectively, differing by 1.7%, shows an unexpected correlation. This could imply a property of the system that is independent of the differences in materials between the two systems, though again testing multiple tailpieces and adjusting the material properties of the Ansys model would help to confirm this hypothesis.

Treating different regions of tail chord adjustment as a linear section would allow a simple method for makers to set up models for their tailpiece adjustment. Four measurements, two within each of the linear sections described here would be enough for them to characterize the tailpiece and get two linear equations with which to predict how adjustments would effect Rt.

5. Conclusions/ Recommendations

The question of whether or not adjustments of the tailpiece setup would effect large resonances of the tailpiece below 1000 Hz was answered here. Varying the tail chord between 5.5 and 37.5 mm with a set overall length of 161 mm resulted in a change in the frequency of the identified mode shape Rt from 875 Hz at the 5.5 mm adjustment to 365 Hz at the 37.5 mm adjustment. A corollary to this result is that from studies of the violin body several strong body resonances, B1-,B1+, and A0 (see Glossary) fall within the range of adjustment. This fact could allow makers to tune the mode found here to match and possibly effect the output of one of these modes. Tests should be done to examine how the tailpiece effects the sound output of the violin when this mode is moved to interact with the strong body modes. This will confirm the ability of the tailpiece to be used as an acoustic filter.

A sensitivity analysis was performed in 4.3 to observe the sensitivity of Rt to changes in set up parameters. The results showed that Rt is 20 times more sensitive (in the region tested) to changes in tail chord relative to changes in afterlength. The sensitivity test is not able to say how the overall length change is effecting the frequency change, it can only show that tail chord length effects Rt more strongly (within the range) than afterlength.

The FEA program Ansys was then used as a comparison tool modeling the same parameters that were used in the set up of the tests done on the "dead rig". Linear trends intersecting between 16 and 20 mm tailgut lengths (on a frequency vs. tailgut length graph) were observed in the Ansys data with high R squared values of .999 for both linear regions below 16 mm and above 20 mm. The graph formed by the experimental data was also examined for linear behaviour in the same regions as the Ansys. R squared values of .97 were obtained for both regions. A much stronger fit (R squared .999) for the full experimental data set was found when considering a cubic polynomial though this curve fit was erroneous for the Ansys data, showing inflection changes (fits shown on fig 17) so the linear method was chosen to examine the similarities. The slopes for the linear fits for both data sets above 20 mm found similar slopes of 5.8 and 6 Hz/mm for the experimental and Ansys data respectively. This unexpected trend should be investigated as being possibly independent of material properties in the system.

It should be noted that the adjustments made in this experiment have gone well outside the range that makers typically use. Perhaps that in light of these observations makers will be persuaded to go outside of their usual routines when considering tailpiece set up. Also using the method of linear approximation for frequency changes in Rt vs tail chord length in the region below 16 mm and above 20 mm could provide a simple tool for makers to characterize their tailpiece and predict changes to Rt. A recommendation to the Arbutus fittings company is to include the two linear fits with each tailpiece model sold for use by the customer.

6. References

[1] O. Ina´cio, J. Antunes, M.C.M. Wright (2008). "Computational modeling of string–body interaction for the violin family and simulation of wolf notes" *Journal of Sound and Vibration* (N° 310): 260–286

[2] *1. Stough, B.* (1996), "The lower tailpiece resonances". *CASJ Catgut Acoustical Society Journal* 3 (N°1 series II): 17-25.

[3] Henry A. Strobel, "Useful Measurements For Violin Makers, a reference for shop use" *Has Oregon* (July 1988)

[4] http://www.jdaddario.com/resources/JDCBOW/BOPK_Tension_Charts_Violin.pdf

7. APENDIX

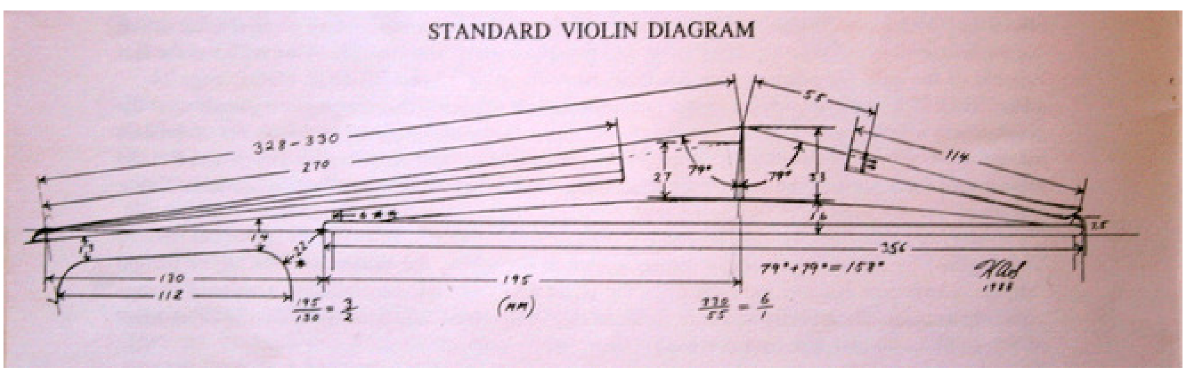

Figure 20 Dimensions used in Violin "dead rig" From "*Useful Measurements for Violin Makers*", Henry A. Strobel

Material properties for ebony- http://www.ukuleles.com/Technology/woodprop.html

Violin string tensions-