# A Reconsideration of the Construction and Acoustics of the Viola

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## 1 Introduction : motivation

I have a hobby interest in playing the viola and, occasionally, the violin to a very amateur standard. I own several inexpensive instruments and have been intrigued, and at times infuriated, by the differences in playability and sound of these. I have had most of them adjusted with the aim – but mainly just in the hope – that they could be improved. I guess than many other string players will have done the same. The usual adjustments are to move the sound post, fit a thicker or thinner sound post, change the strings, refit the bridge, try a different chin rest and/or shoulder rest. One can spend quite a lot of time and money in having professional violin technicians make these changes, so I have learned to do most myself.

In the course of this I have heard and read anecdotes about the benefits and the cause-and-effect of modifying this or that part of the violin. I feel there is still a lot of folklore about stringed instruments, and adjusting them is more a black art that a science. This has prompted me to look into the matter for myself. I have accordingly read several technical books (e.g. by Carleen Hutchins) and articles about violin construction and physical acoustics. This article is a set of notes on my first reactions.

To test some of these ideas and to gain some hands-on experience, I have constructed a rough model of a large non-standard viola. I chose the viola partly because it is my preferred instrument, and partly because it has inherent acoustic problems due to its small size in relation to its lowest notes. I deliberately did not copy traditional designs, but rather 're-thought' the shape and arrangement, hoping to achieve a decent tone from an instrument which can be played without undue effort. This note describes this first model of an instrument, made of 'scrap' materials and without attention to finish.

The experience gained in this brief study convinced me of the value of being able to model the vibrations of the instrument in a computer model. To that end I have looked into finite element analysis (FEA), and have been using the inexpensive Canadian software LISA 7. A companion article describes my subsequent efforts to model wood and plywood plates with LISA 7.

## 2 Preliminary Model of Asymmetric Large Viola

Four pictures of the model viola, fitted with Corelli strings, are given in Figures 1 to 4. It turned out to be too heavy and cumbersome to handle, but I was able to play it a little to sample the sounds. I found these remarkably loud, rich and resonant, considering the unoptimised design and

Figure 1: Model of an asymmetric viola with plywood plates - view 1

Figure 2: Model of an asymmetric viola with plywood plate -view 2

rough construction. The bow produced sounds readily, with the top (A) string particularly strong. The poorest note was F on the C string, but even that was acceptable.

**Materials :** The plates are 3.7 mm thick 3-ply 'Far Eastern' plywood. This has a thin birch veneer on each side of a thicker meranti central layer. In addition to the wooden blocks between the two plates at neck and tail, there are four internal supports of 1 cm section square balsa wood spaced round the perimeter. The ribs are 1.5 mm thick balsa, attached with hot melt adhesive from a hobby glue gun. The internal bass bar is soft white wood glued on with PVA. The sound post and neck/peg box are also soft white wood, possibly spruce. The bridge is also home made, from a hardwood, probably afrimosa. The fingerboard and pegs (ebony) and tail piece (rosewood) and chin rest were bought in. The nut and tail piece pin are made roughly from rosewood. Strings are Corelli Crystal viola strings tuned to the usual C-G-D-A.

There were three major considerations in the design: a) ergonomics, b) acoustics, c) static strength. All cosmetic frills such as the scroll were dispensed with.

Figure 3: Model of an asymmetric viola with plywood plates - view 1

Figure 4: Model of an asymmetric viola with plywood plate -view 2

## 2.1 Ergonomics

Traditional violas are known to be too small in comparison with a violin for their compass. In particular the C string on low price instruments can sound hoarse and be unresponsive to the bow, requiring the player to work at producing a decent note. However larger models such as the Tertis (almost 17 inch body) are too long and thick, front to back, to be played without strain. Discomfort is most in placing the 4th finger on the C string, since the stretch is large.

I made some measurements of myself playing a standard 16 inch viola, noting the angle through which the bow must rotate from the C to the A string; it is $\pm30^o$, or $60^o$ in aggregate. The average plane of the viola body, as the instrument is held on the shoulder, is about $45^o$ to the horizontal. However I rotate the body in playing so that for the A string this angle is only $42^o$ (more horizontal) whilst for the C string it is $50^o$ (more vertical). This rotation of the instrument about the fingerboard as axis is to lessen the need for the right arm to lift so high to bow the C string. In turn this allows the weight of the right arm under gravity to draw the bow, giving a less forced tone. In view of this I decided to set the finger board at about $10^o$ away from being parallel to the top plate, giving a fixed rotation towards the A string.

The length from the nut to the tail pin was chosen as 22 inches, this being about as long as my arm could reach.

The thickness at the tail where the chin rest goes is $1\frac{3}{4}$ inches. Any more and it becomes too high for comfort when the chin rest and shoulder rest are added. The chin rest is placed to the left side of the tailpiece because it would be too high if is straddled the tail piece. In any case, the commercial chin rests I have found do not expand much beyond 2 inches. (My neck is about 4 inches from collar bone to jaw.)

The standard viola neck length is about $4\frac{3}{4}$ inches. I have extended this to $5\frac{1}{4}$ inches and kept the width of the body quite small at the A string side of the fingerboard. Both these are to let the left hand move up the viola to higher positions without having to reach round the body, which again would cause strain.

The width of body on the A-string side, level with where the strings fit into the tail piece, is limited by the right hand needing to place the heel of the bow on the A-string. There are no such limitations on width on the C-string side. This gives scope to increase the width and thickness of the body here. Hence the large lobe on the upper part of the body which makes the overall length along the diagonal 22 inches. Essentially a 22 inch long top plate has been turned about $40^o$ away from the line of the strings.

The width across the section where the bow moves clearly must be narrow enough for the bow to play the C and A strings whilst staying clear of the wooden edge on the instrument. There is no reason for it to be narrower.

A further consideration is weight, which should be a low as possible. The weight of a traditional viola with chin rest is about 700 gm. The finger board in ebony is probably the single most weighty component, and in future I might consider a less dense material. However balsa wood sides limit weight, as does a thin plywood top.

## 2.2 Acoustic considerations

The compass spans these frequencies:

$$C = 131Hz, \quad G = 196Hz, \quad D = 294Hz, \quad A = 440Hz, \quad E = 659Hz, \quad \text{top } A = 880Hz.$$

When played, the *whole* structure vibrates and radiates sound. I suspect that most radiation is from the top plate, though this is merely a suspicion. The viola and other bowed stringed instruments are a complex coupled vibrating system in which energy is transferred as follows:

1. from the bow to a string by a slip-stick mechanism in which the rosin on the bow and string plays a crucial role. There is a large literature on the Helmholtz oscillations of a bowed string.
2. from the string to transverse (along bowing direction) in-plane vibrations of the bridge. The string has transverse oscillations mainly in the bowing direction but also smaller longitudinal, torsional and vertically transverse vibrations. Similarly the bridge has vertical in-plane and

out-of-plane displacements. But the main action of the bridge seems to be as a lever, pivoting about the foot near the top string, to transform the horizontal transverse motion caused by the string to vertical compression oscillations under the other foot. Thus the foot at the C string presses up and down on the top plate. If the top plate were rigid, this would indeed be the main action. However the top plate is capable of flexing, so in practice both feet are part fulcrum, part load . The two feet can move up and down, and will in general be out of phase due to the rocking motion.

3. since the bridge is a lever, its mass should be minimised by cutting away all but structurally essential wood. Too much mass is known to act as a mute. The cut-out in the bridge have been reported to act as mechanical filters, preventing twisting and other non-compressive modes of vibration from transferring to the top plate.

4. from the bridge to the top plate. Wood has low internal damping so is naturally resonant. Plates are traditionally made of slow-grown northern spruce with grain running from nut to tail, the slow growth producing a fine grain and so a harder material.

5. The *f*-holes seem to have two purposes : i) principally to increase the compliance of the top plate near the bridge so that the vertical flexure of the top plate (supposing it to radiate most sound) is maximised. ii) to act as the opening of a Helmholtz resonator and so enable an air resonance from the enclosed cavity, akin to blowing across the neck of a bottle. The air cavity may act in part as a soft elastic cushion between the plates. A large volume of air may be necessary.

6. from the top plate to the back plate. This is via the ribs and end blocks, and also via the sound post. I suspect that the stiffness of the top plate around its edges has a crucial effect on the tone. The traditional thinning of the plates towards the edge increases compliance there, allowing the plate to move somewhat is a diaphragm.

7. the main action of the sound post seems not to transmit sound to the back plate (as is often said), but to establish a node at one foot of the bridge. This imports an asymmetry to the motion of the top and bottom plates which seems crucial to the effective radiation of sound. It is reported that an acoustically symmetric violin/viola would radiate little sound because the left and right halves of each plates would move $180^o$ out of phase, meaning that at a few wavelengths distant from the instrument destructive interference would reduce the perceived intensity to a low level.

8. It seems that a fairly high static load on the viola is desirable to ensure that the two feet on the bridge and also the sound post stay in intimate contact with the top plate, from top and underside respectively. High static load is achieved by high tension in the strings combined with a large angle of bend in the string at the bridge.

To gain a full and even tone it seems that the instrument should have a dense number of resonances fairly evenly spread over the audio range. The difficulty seems to be in placing the lowest 3 or 4 resonances. Hutchins says the main wood resonance of a violin should be at about the open A string (440 Hz), with the air resonance near the open D. She adds that violas and 'cellos have these resonances shifted 3 or 4 semitones too high so they a) miss the open strings and b) are empty on the C string. Normally the air tone on a viola is from B to Bmusic—b on the G string, about 233 Hz, making it sound good in g minor.

## 2.3 Mechanical strength

Tension in the strings imposes a significant downwards forces on the top plate – perhaps about 60 to 70 N. This tends to bend, even indent the top plate and to cause the box structure of the belly to collapse. The wooden construction must withstand these loads, as well as the knocks of every day use, without being either too stiff or too heavy. It is therefore a great challenge in design, and I suspect that the traditional form arrived at by craftsmen in the 17th and 18th centuries is close to optimum.

The plates are shells, approximating to shallow caps of ellipsoids. This dish shape gives them considerable resistance to static bending since bending would require the material round the perimeter of the shell to stretch. Shells usually fail by indentation under the loading point rather than by bending, as would a straight beam. However, the dishing of the plates will affect their dynamic response through an increase in stiffness and this will increase the resonant frequencies, which in turn could weaken the tone of the instrument at low frequencies. Clamping the plate edges to the ribs adds further to the stiffness. To counteract this, the purfling grooves, which cut about half way through the plate thickness, add flexibility, making the boundary condition closer to a hinged (simply supported) joint. It has been conjectured that the combined effects of a) the purfling grooves and b) flatness of the plates at their edges together give compliance to the edges, making the plates act more like pistons – 'a hard hat with a flexible brim'.

The role of the bass bar inside the instrument seems mainly to add static strength. The bar is a beam, thicker in the direction normal to the top plate and so with a strength proportional to this thickness cubed, $h^3$. It is bound to affect the vibrational pattern, however, and increase the lowest resonant frequency through the increase in rigidity.

Another weak point of the instrument is where the neck joins the belly. Under the load from the strings, the neck will tend to tear away from the ribs

The need for strength and low internal friction without stiffness and weight has made wood the preferred material for three centuries. Nowadays there is scope to explore modern composites and indeed some companies do manufacture carbon fibre violins and violas, to traditional shape and dimensions.

## 2.4 Construction

I made the plates flat, out of 3-ply from a builders' yard. The flatness makes them more susceptible to bending than dished shells. However, shells are difficult to shape accurately and the dishing makes it more difficult to fit the bridge and sound post. I took the view that the main roles of a plate are to bear the static loads and to vibrate fairly freely. To increase the air cavity I made the plates non-parallel as shown in Figures 1 to 4.

The balsa ribs are fixed to the outside edges of the two plates, not the inside as is traditional. There is no purfling, nor much need for it since a) the edges of the plates are not exposed directly to knocks in use, b) the plywood is not so vulnerable to splitting as spruce. Moreover, one purpose of purfling may be that the groove in the plate cut to take the purfling makes the rim more flexible, more like a hinged joint rather than a rigid one. In my model the hot melt adhesive is quite flexible and rubbery.

The bass bar is quite substantial - about 1 inch deep and $\frac{1}{4}$ inch thick and runs diagonally under the top plate, passing under the C foot of the bridge. Its line is marked in pencil on the top plate (see photographs). The sound post is roughly cylindrical, about 8 mm diameter, and held only under pressure (no adhesive).

The *f*-hole on the C side has been moved out to the edge of the top plate. On the other side I have tried an alternative in which the rib stops short of the top plate to leave a gap about $\frac{1}{8}$ inch wide, 5 or 6 inches long. Both designs allow the top plate to flex near the bridge. The slots are narrow at this stage, partly because there is no requirement to insert a sound post through them, and partly because I am not convinced that the Helmholtz resonator function is important compared with allowing the upper plate to flex.

There is a $\frac{1}{2}$ inch diameter hole cut in the rib at the extremity of the large upper C-string lobe. I cut this when the body was otherwise a completely closed box in the hope of being able to blow across the hole to excite the air resonance (as one blows across a bottle's lip). I have not been able to get the air resonance note to sound, but the hole remains. In later experiments I covered this up to see what effect it has on the acoustics of the instrument.

The instrument was made by hand with little attention to quality of finish or precision of measurement. It was built from the back plate upwards, without a jig or former. The stock of the neck is glued directly to the upper and lower plates rather than to a separate interior end block. In addition to the stock of the neck and a cuboid of white wood at the end button, four pillars of 10 mm square section balsa support the top plate at positions round the rim. The ribs where added in short sections, glued to each other and to the upper and lower plates. The string length from nut to bridge is $14\frac{3}{4}$.

The body is thinnest at the chin rest and thickest at the upper C-string lobe (6 cm = 2.4 inches external). The average internal separation of the plates is about 50mm (2 inches) and the area of each plate, judged by weighing, about 162 sq inches = 0.1045 $\mathrm{m}^2$, making the enclosed volume $V = 0.005226 = 1/190\ \mathrm{m}^3$

The weight of the completed instrument, with chin rest, is 1,000 gm, compared with a standard 16 inch viola which is 650 gm (without chin rest). So the instrument is about 300 gm too heavy. My immediate impression is that the D and A strings sound rich and full, the G is quite good, and even the C is acceptable, though I would like it better.

## 3 Modifications and rebuilding

The biggest problem with the instruments as described in §2 was that it was too heavy to play for more than a few minutes. Apart from being a strain on my left arm, it was difficult to change positions up the finger board. Clearly it needed to be lighter. I therefore reduced the weight to 800g without chin rest by

- thinning the top and bottom plates in non-structural places with a small plane and sander,
- replacing the ebony finger board with a pine one of my own making, this also being shorter and thinner than the ebony.

Of course, the thinner plate was much weaker, since deflection of a beam varies as $h^3$ where $h$ is the plate thickness. To reduce the static load on the plates I decreased the inclination of the finger board and reduced the height of the bridge by about 5 mm ($< \frac{1}{4}$ inch).

Other modifications were to cut a deeper bout at the C-string since the bow occasionally would catch there, and to thin the neck to make it less of a stretch to hold. The *f*-hole on the C side was replaced by a gap at the edge between top plate and balsa rib. On the C side the nominal *f*-hole is 13 cm long and about 7 mm wide; on the A side it is 15 cm long and 2 to 3 mm wide.

The structural weakness of the thinned plates was now a major and terminal problem. While tuning up to pitch, I noticed that the gap between strings and fingerboard was increasing wityh every turn of the pegs, and I could hear the wood creaking. The whole instrument was bending under the tension of the strings! To counteract this I added an ugly strap on the underside (back plate) of the instrument. This was a length of 3 mm yellow nylon strimmer chord jointed into a loop at a small aluminum box section using small nuts screwed in a self-tapping fashion onto the chord. One end of the nylon went round the tail pin (which had to be pulled out by 2mm so that it could also take the tail piece chord). The other end went round a 5mm diameter machine bolt screwed into the underside of the neck stock. This ugly temporary addition did at least stabilise the instrument and allow me to bring it up to pitch.

My initial subjective impression was that, when fitted up, it was a bit easier to manage but it sounded thin and weak, and had lost the loudness and brightness of the original instrument. I have recorded fairly comprehensively the sounds in tapping and bowing.

After testing the instrument with its thinned down plates, I assessed it by bending in my hands to see exactly where it was most weak and flexible. The weakest places were where the neck stock joined the two plates, flexing extensively at both. This meant that the instrument was close to collapsing through the two plates moving in opposite directions as the rectangular cross section sheared into a parallelogram by rotations at both these joints. As expected, the top plate was very stiff under the bass bar. I therefore think I was an error to place this bass bar diagonally – it should have gone in line with the strings so as to withstand the bending moment they apply.

I carried out various other modifications, tests and acoustic recordings on this thinned model, but will not describe them here. The tone remained disappointing compared with the first instrument with un-thinned plywood plates. It seems that this first instrument was a happy piece of serendipity.

## 4 Air resonance from *f*-holes

This section reports on the supposed role of the resonance of the air cavity and *f*-hole openings.

Carleen Hutchins, who dedicated much of her life to studying the acoustics of the violin family, suggests that the *f*-hole air resonance is important in supporting the low notes of the instrument. On a normal 2 inch deep viola the air resonance is at about A on G string (220 Hz). She reports one viola with only $\frac{1}{2}$ inch separation of plates, which gave a rich sound because the air subresonance (at half the *f*-hole resonance) was supporting the low notes. Its air resonance was at D♯ (300 Hz), making the subresonance about 150 Hz.

The simplest classical theory is for a Helmholtz resonator which has a rigid cavity enclosing a ‘spring’ cushion of air, and a cylindrical neck in which a well-defined plug of air of oscillates against the air spring. The resonant frequency is

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{VL}} \tag{1}$$

where $c$ is the velocity of sound ≈ 343 m/sec, $A$ and $L$ are the sectional area and length of the air plug, and $V$ is the volume of the cavity. I tested this using a 0.75L wine bottle with neck inner diameter 1.88 cm and length about 7.5 cm. The formula gives $f$ = 121 Hz (B♮) compared with B♭ as heard. I found the effective value of $A/L$ by adding water to the bottle to change the air volume. The relationship between frequency and volume (to the bottom of the neck) was close to $f^2V = 9.7$ SI units, making $A/L = 0.00325$, compared with 0.00370 from nominal dimensions. Then the effective length is 8.5 cm, 1 cm longer than assumed. This can be attributed to an open end correction, or to ambiguity in the length of the air plug at the shoulder of the bottle. A theoretical correction in the literature for circular holes (both inner and outer end corrections included) is

$$L_{eff} = L + 0.8\sqrt{A} \qquad \text{SI units.} \tag{2}$$

For the wine bottle example, this adds $0.8\sqrt{0.0002775}$ or 1.33 cm to the effective length, compared with the 1.0 experimentally. Overall, therefore, theory and experiment agree quite well for this the simple glass bottle.

I have tried to investigate the effect of changing the shape of the neck from circular to an elliptical slot but with limited success. I observed that it is difficult to excite the air resonance by blowing if the bottle is very flexible (plastic milk bottle) or the neck is far from circular.

If the plate is very thin, the end correction accounts for the total length and the relation for a circular hole becomes

$$f = \frac{1.11c}{2\pi}\frac{A^{1/4}}{V^{1/2}}.$$

The effective plug length for non-circular holes is

$$L_{eff} = L + \frac{1.7A^{3/4}}{\sqrt{s}} \qquad \text{SI units}$$

where $s$ is the perimeter of the opening. For the plywood viola the added air plug length at the C hole is about 17 mm, making $L_{eff} \approx 20$ mm, whilst on the A side it adds only 8 mm, making $L_{eff} \approx 10$ mm there. Applying these to the plywood viola, the air resonance at the C hole would be about 161 Hz (bottom E♭ to E), and 146 Hz (bottom D) at the A string. An alternative calculation is to combine the two holes into one with total area and total perimeter. This predicts the air resonance at 185 Hz (F♯) if the wood thickness is 6 mm, and 206 Hz (G♯) is it is only 2 mm thick at the edge of the hole. In principle any of these values indicates a useful boost to the sound on the C string. However, it may be that they do not sound well, the holes being far from circular, perhaps making the Q factor small.

I did the experiment of blocking one and then both holes with plasticine while bowing the viola to detect a change in sound, and particularly through a loudness test over the chromatic scale. Another experiment might be to add a slot-shaped cardboard tube to the *f*-hole to increase $L_{eff}$. One should hear an increase in resonant frequency. This might be a way of tuning the *f*-holes.

Overall I remain unconvinced of the importance of the air cavity bass resonance to the tone of an instrument. I hope to continue from this preliminary study to investigate the acoustics of the violin family by more experiments and by finite element computer modelling.