The violin
music acoustics from Baroque to Romantic

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A Baroque violin was initially made. It was then incrementally converted to a Romantic (modern) setup by replacing the short neck with a longer, more slender neck and adding a longer ebony fingerboard, a heavier bassbar and soundpost. This increased the total mass from 386 to 440 g. Several different Baroque and modern configurations, with baroque and modern style bows, were used for acoustical measurements and playing tests with professional violinists.

Chladni patterns were similar in both versions and also when the bridge was placed below the soundholes. The Baroque version gave higher body mode frequencies than the Romantic. Placing the bridge below the soundholes lowered the frequency of the 800 Hz resonance to 600 Hz.

Saunders Loudness Tests showed a response that varied strongly over the body resonances. For the transition from Baroque to Romantic setup, hand bowing showed an increase of 1 dB and machine bowing about 5 dB.

The compliance of the body added to the air lowered the main air resonance by 5 Hz, equivalent to adding about 130 cc to the 2000 cc air volume.

The top plate stiffness measured at the bridge feet was about 10 kN/m higher at the treble foot than at the bass foot, for all locations of the soundpost outside the treble foot. The stiffness at the bass foot remained constant. This was reversed when the soundpost was placed between the two feet: the stiffness at the treble foot was then lower than at the bass foot.

The rocking and bounce frequencies of the bridge were lowered from 3000 and 6000 Hz respectively to about 2.5 and 3 kHz when fitted to the violin. Thinning the bridge waist lowered the rocking frequency.

Recordings of performances on the violin were made for many combinations of physical state (baroque or romantic), type of string and bow, position of bridge, and others. Long-term average spectra for these recordings are compared here, and an online appendix includes these recordings in a way that allows them to be readily compared:

www.phys.unsw.edu.au/music/people/mclennanappendix.html

Frontispiece: **The violin of the study, from baroque to romantic.**

ORIGINALITY STATEMENT

'I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.'

Signed ....

Date ....

Acknowledgments

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CONTENTS

Chapter 1

INTRODUCTION

The violin is arguably the most important musical instrument. It takes the largest role in symphony orchestras. It is prominent in chamber music, and in a range of other genres (folk, jazz and music of various cultures). It has a very large range of dynamics, and a wide range of timbre. The violin is extremely portable and requires no ancillary equipment, apart from the bow.

The violin evolved from earlier bowed string instruments. Along the way, it lost frets from the fingerboard and acquired the deep C bouts that allow bowing of individual strings. By the 16th century the violin had acquired a body that resembles its modern form. However, the violins of today differ very substantially from those for whom Bach, Vivaldi, Mozart etc. wrote.

Early in the 19th century, the musical demands on the violin brought about changes to the setup. All violins, including virtually all of the Amati, Stradivari, Guarneri and Stainer violins, had their Baroque setup altered to the Romantic or modern setup. This improved the facility of the violin for modern concert music. The changes included (i) fitting a new longer, thinner neck morticed into the top block, (ii) slanting the neck back and fitting a slender ebony fingerboard. This allowed (iii) a taller bridge to become standard. The top was reinforced with a larger bassbar and soundpost to counter the effect of the increase in tension of the strings which were now longer. The steel E string came into use after 1940 and since then a variety of string designs appeared. Most were overwound with cores of nylon filaments, steel wire, steel cable as well as overwound gut.

Anyone who listens to an 'original instruments' concert will note that the sound is very different from that of the modern instrument. The differences in sound between a modern instrument and a Baroque violin come from several different sources (i) they are different violins, made from different pieces of wood, (ii) they have structural differences, as listed above, (iii) they have different bridges, tailpieces etc. (iv) they have different strings, (v) they are played with different bows, and (vi) they are played in a different style. Further differences might arise if one compares an unmodified, existing Baroque instrument with a modern one. I would consider the style of playing assisted by the bow chosen to be the main determinant in the different sound achieved by the player.

Early bows were made of Snakewood (*Piratinera guianensis*) a strong, dense wood. They were light with a slight convex camber, a pike's head and a loose frog that was held in place by the hair ribbon which was about 6 mm wide. The hair was tensioned mostly with the finger in addition to the initial effect of the frog. These bows were shorter at about 640 mm than the modern Tourte bow at 750 mm. The modern Tourte bow was introduced in about 1780 with a concave camber and a 10 mm wide hair ribbon attached to the frog, which was screw adjusted to tension the hair. The modern bow had a hatchet head to separate the hair ribbon further from the stick than with the pike's head. The force applied by the player through the stick caused the convex camber to increase on the early bows. With the reverse camber increasing the force on the string caused the bow stick to straighten enabling a more uniform force to be applied for the full stroke of the bow. This was more difficult with the early bows.

This thesis describes the results of an attempt to investigate these differences by converting a hand-made Baroque violin and studying the acoustic and playing response for both setups. This reduces the number of variables: the body in both versions comprises the same top, back and general design. The other changes are made, one at a time, in a controlled way.

Three different styles of bridge were examined but, to limit the number of cases to study and therefore the time taken, not all combinations were evaluated by the players. Bridges varied greatly in style and, like bows, were discarded when replaced. The three chosen were the Renaissance, Stradivari and Paris bridge. The bridge chosen for most of the work was the Renaissance. The effect of positioning the bridge in each of two positions, at the notches in the soundholes and below the soundholes, was studied. The bridge at the notches in the soundholes marks the "stop" or diapason but it is shown in many positions below this in early paintings. This can be accounted for by the player increasing the string tension on changing the string tuning or compensating for poor string quality. Another look at the main air resonance extended our understanding of it. The two lower in-plane resonances of the modern bridge have also been studied.

This thesis begins with a chapter on the history of the violin and some of its prominent makers (chapter 2). An account of the acoustics of the violin follows (chapter 3), setting out a summary of the principal features as they are now understood by the author. This sets the background to the construction of a Baroque violin (chapter 4) and the characterisation of its main parts and the assembled instrument.

Chapter 5 describes the testing procedures used throughout the study.

Playing test results follow with results for both hand and machine bowing (chapter 6). Player reaction, rated under a number of playing and sound qualities for both violin setups are presented. The subjective assessment of the sound quality of selected music on both versions by professional violinists using early and modern bows was made. Long Time Average Spectra were taken of the recordings, some of which appear in chapter 7.

A study of the effect of moving the bridge of a Baroque violin to a position below the soundholes, as shown in many early paintings, on the sound of the instrument appears in chapter 8.

Three additional studies were made during the work. Experiments were undertaken to determine the contribution of the body compliance to the main air resonance (chapter 9). Some observations on body resonance modes are made (chapter10). The bridge resonances that influence the response of the violin in the 2 to 4 kHz region, the so called Bridge Formant region, were investigated (chapter 11).

Suggested further work and extension of the studies in this thesis are also outlined.

A list of publications from earlier work by this author can be found on the website: www.phys.unsw.edu.au/music/people/mclennan.html

It is appropriate in a physics thesis about the violin to consider a simple physical model of the instrument. It consists of an assembly of resonances due to its construction that together with the full harmonic content of the force delivered by the bowed string to the bridge radiates a sound across its range that the listener finds fairly even.

Below about 1kHz the main resonances are sufficiently separated that each one can be approximated by a simple model of a mass moving against the stiffness of a spring. The response of a freely suspended violin to a tap to the body is to excite all the resonances present. The forces present must be balanced and sum to zero. The system is considered to be linear and at low frequency can be described by

$$m(dx/dt)^2 + sx = 0$$

and if viscous damping is included

$$m(dx/dt)^2 + c(dx/dt) + sx = 0.$$

If the damping is weak, these lead to an approximate equation for the resonance frequency

$$f = (1/2\pi)\sqrt{(s/m)}$$

from which the Schelleng equations used in this thesis are derived in §5.13.

Other forms of damping e.g. structural, which is frequency dependent may be present but has not been considered. However, Q values have been found from the bandwidth of prominent resonance peaks.

To extend this treatment from the single degree of freedom case above to a multi-degree of freedom covering the full response plot is outside the purpose of this work. Of the many references on this subject, two are quoted:

D.J.Ewins "Modal Testing: Theory and Practice" Research Studies Press, Letchworth, Hertfordshire, England, 1986. Distn. Jacaranda-Wiley Ltd. GPO Box 859, Brisbane, Qld. 4001.

Thureau P. and Lecler D. " Vibrations of Linear Systems" Stanley Thornes (Publisher) Ltd. 1981.

Marshall K.D. "Modal Analysis: A Primer on Theory and Practice" JCAS Newsletter #46, 1986, p7-17.

Chapter 2

THE VIOLIN: ITS ORIGINS, CONSTRUCTION AND ADJUSTMENT

Histories of violin making have been written many times and in great detail. This present history relies heavily on other reviews [1, 2, 3, 4, 5]. One has to rely on existing accounts and the latest offer the most reliable information. One of the earliest, devoted solely to the violin appeared in 1856 by F. J. Fetis although there had been two main treatises on playing the violin before this, by Francesco Geminiani (1751) and Leopold Mozart (1756). On the frontispiece of both, the bridge is shown below the soundholes, a matter that is discussed in chapters 6 and 7 of this thesis.

Researchers have studied the etymology of the name ‘violin’ linking it with the idea of a ‘bowed guitar’, the vihuela. It is possible the progression originated with the Moors in Spain and travelled with the Spanish to Italy ending up in the Lombardy, Piedmont, Venetia and Emilia districts in which several towns developed into centres of violin making.

Sol Babitz [6] studied the forms of the violin as it changed from the Renaissance to the modern setup. He also studied the transition in the bridges used. This is summarised in figure 2.1 taken from his paper.

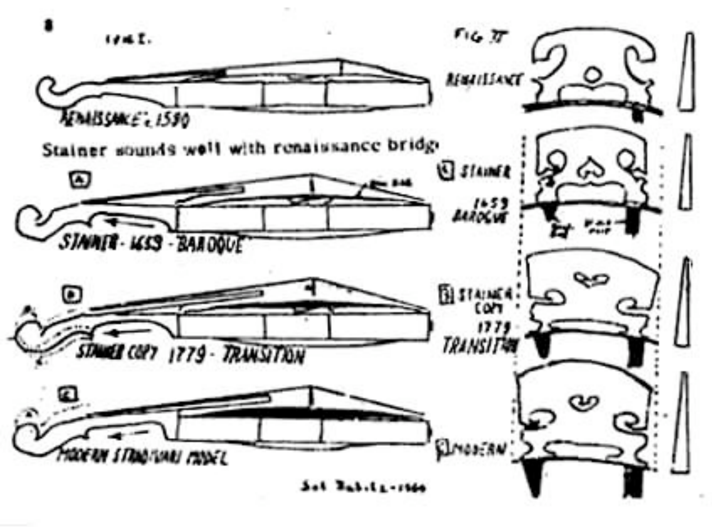

Figure 2.1 Changes in Neck/fingerboard, bassbar, bridge and bridge position from Renaissance to modern setup. From [6] page 8.

No changes are shown in the bodies as one goes through the progression. The body is given the same outline with the centre bouts established, the top and back arched and the f-shaped soundholes located in the same place throughout. A higher arching was in use compared to the lower arching that was used by later makers. The instrument body varied in size and shape during the Renaissance but was reasonably constant from the Baroque era on. An example of Renaissance instruments showing the placement of the bridge is shown in figure 2.2 from Andrew Dipper [7].

Figure 2.2 Early string instruments (not violins) showing the bridge positioned below the soundholes [7].

The main changes that took place concerned the 'working parts' rather than the sound producing parts i.e. the body. These 'working parts' were the neck/fingerboard, bridge, soundpost and bassbar. Babitz shows no bassbar in his Renaissance violin and the bridge is shown below the f-holes. This is not discussed in his paper. He points out that because they were not fixed, the bridges and soundposts from these times have largely disappeared. He does not show soundposts but shows the size increase in bassbars from the Baroque to the modern violin. Placing the bridge below the soundholes was a much earlier practice, as shown in figure 2.2 [7] and the top of figure 2.1.

The big change concerned the neck/fingerboard. While butting the neck to the body and nailing through the top block is thought to be the standard method of attachment as practiced in Cremona, it was not the only method [8]. Watchorn found other methods while examining instruments in European Museums. These were probably used outside Italy. The wedge between the neck and the fingerboard assisted holding the violin while most playing occurred in first position. The lengthening of the neck (and fingerboard) and its angling back to give a slimmer grip – made possible with the chinrest – allowed easier movement along the fingerboard. These changes, made necessary by the music being composed, were accompanied by changes in the bow. Thomas Georgi [9] describes the significance of the main bow advances to the music and the playing techniques in vogue at the time. He deals in turn with the short, light Corelli bow that required the player to adjust the tension with separate frogs which were loose, fitting in a notch under the hair. The Tartini bow was longer but had a screw operated frog. Both bows had pike heads and no camber. To quote Georgi regarding the Tartini bow 'rapid repeated notes on the string are wonderfully articulated, they sound as if they were off the string'.......the modern bow does not make this sound' (page 7). Bows were made of snake wood which is denser than pernambucco. A violinist trained on the modern setup with a classical repertoire, has to learn how to play with these early bows to be able to play Baroque music.

2.1 Early Development

We could say that the violin as we know it began in the Middle Ages and developed through the Renaissance, Baroque and Classical periods to the Romantic from which it is little changed today. Before the Renaissance, up to about 1400, musical instruments were rather primitive and used to accompany voices mainly associated with church music. There was a steady development of bowed instruments from what was essentially a bowed guitar, or bowed lute, to the violin as we know it at about 1500; it is thought its present day form was established around 1520, by Andrea Amati.

An extensive survey of early iconography by Christian Rault [10] suggests that before the 16th century and certainly overlapping in the 16th century with later developments in instrument construction, the ribs were sawn from a solid piece. The drive for lower pitches which meant larger instruments forced the use of bent and built-up ribs. This in turn became adopted for the smaller bowed instruments. It seems in the early instruments that had flat top plates or bent or carved "arched" plates, there was no soundpost or bassbar but tops were known to have a central spine. Top plates (presumably flat) were known to have transverse bracing. The lack of any internal structure encouraged the placing of the bridge lower on the instrument to lower the pitch (for the same string tension) that became popular. Mention is made of a centrally placed square soundpost found by studying museum specimens and offering an explanation for the central pin hole in the back plate where the soundpost had been fixed.

There was no mention of when the soundholes had changed from two face-to face “C” shapes to two “f” shaped soundholes by turning out the lower half of the “C”. There were rudimentary f-holes in instruments before Andrea Amati.

The violin is thought to have had a humble beginning (the fiddle/geige and Lira da Braccio being the early forms [2]), and could have been the instrument of itinerant musicians as it was very portable and easily adjusted to suit the purpose of the player. It took various forms, mostly guitar-like in shape; was played on the arm and was used by the Church to double voice parts as shown in many early paintings. It got its name from the Italian ‘violino’ (little viola) in 1538 and by the 1550s was finally established. It blossomed into the instrument we know today and its final form has been linked, as mentioned above, with Andrea Amati (1505 - 1577) who lived in Cremona in Lombardy, Northern Italy. It is understood that Andrea Amati learnt his craft in Brescia [4] settling in Cremona and establishing a dynasty. His grandson, the greatest maker of the family, was Nicolo (1596 - 1684). Nicolo’s son Jerome (1649 - 1740) was the last of the line.

Violins since the first half of the 16th century have all had the same basic design and differ only in minor details, characteristic of the particular maker and difficult to detect by the untrained eye. The violin was easy to make with simple hand tools but very difficult to optimise acoustically. A balance had to be reached where the body was strong enough to resist the tension of the strings and light enough to respond quickly to the bow.

The violin was distinct in that it was fretless. This enabled tuning to be adjusted easily and with a loose bridge it became very flexible in this respect. The changes to the early bowed instruments were indenting the sides to form a waist and also possibly arching the plates. The culmination of these changes was the violin body as we know it today. It was arrived at in the early part of the 16th Century. However the neck and pegbox were butted onto the outside of the body and secured by one to three nails through the top block into the shoulder of the neck. It appears that most violins, certainly those in Italy, were made this way, up to the end of the 18th Century.

When the Baroque period began around 1600, the violin was starting to be used in massed bands for large scale works and in bigger venues. Viols were developed at the same time, possibly from the lute, but the violin was louder and more suited for these purposes while the use of viols was preferred for 'Salon music' by the nobility. Viols were preferred in England long after they were replaced by violins on the Continent. Two examples of the increasing use of violins was an order in 1560 for 24 'violins' by Charles IX of France and their use by Monteverdi in 1607 for his opera 'Orfeo' [2].

Different styles of bow were used with the violin subject to the demands of the music being played. Corelli and Tartini, mentioned above, were influential in the changing the design of the bow. It began as a straight stick with a pike's head and was shorter than the modern bow. A loose frog was often used to keep the hair ribbon away from the stick. Horse hair was used for the hair ribbon. The bow stroke was mostly for single notes. The Tourte bow in 1780 with its reverse camber assisted the emerging new style with extended melodic lines favouring legato articulation and hence the longer bow. The frog was now firmly attached and moved with a screw. John Dodd, in England around the same time, is accredited with similar changes.

It turns out that we have a most remarkable product of human craftsmanship. A little wooden box of exquisite shape, weighing about 400 g, the parts glued together with animal hot water glue and able to withstand a combined string force of 230 N placing about 50 N on the top at each bridge foot. The 4 strings, tuned in fifths, give a range of over four octaves and it is capable of an output of more than 90 dB. Moreover, there are some violins 400 years old that can still be played.

To quote Carl Fo(a)rseth ("Annals of the Early Italian Violin Makers" The International Violin & Guitar Makers Journal, 1963? Pp 9-12):

‘The viol, lyra and violin entered the stage of history not so far apart. The first crude viol may have been assembled as early as 1450, but the fully developed instrument did not appear till 1550, at which date the violin form was fully developed. The lyra appeared in Venice towards the end of the 15th century. In 1499 in Venice, was pictured the first two-cornered lyra representing the true violin body. The maker was probably Francesco Linarol. Putting a viol head on this lyra body, and reducing the strings to four may have occurred around 1515.’

Venice, where there were international workers, was thought to be the melting pot for these activities. However, more recently David Rivinus [11] has traced the early history of the violin to Ferrara. Bologna was also a centre of violin making.

Carl Forseth again:
‘The history of musical instruments is the survival of the loudest. Early in the 1500’s someone contrived a small but noisy instrument that could outshout a passel of viols. It had the arched top of the rebec, viol and lyra, also their soundpost and the bassbar of the latter two. In particular it had the arched back of the lyra and the head of the viol. It was a small instrument, containing no more wood than necessary and that judiciously distributed; and the stresses were so well balanced that it awoke from a touch of the bow.’

The violin as we know it today evolved to meet the demands of music making at each change in the social life of the times [2]. Music was an essential part of the life of the church, the courts of the nobility and the lower classes. Most music employed wind and string instruments, either plucked of bowed. The pipe organ was present in many churches. Drums were common but other percussion instruments e.g. the forte-piano, came later. Bowed string instruments took many forms and were played either on the arm or at the knee. Instruments played on the arm often had three strings while those played at the knee had mostly five of six strings.

The rise in popularity of the violin was due to its loudness. It was used by ‘peasants’ for dances and outdoor ceremonies. Initially, the nobility preferred the viol, a flat backed, fretted, bowed instrument played at the knee. It is now thought that both types of string instrument were played by the nobility. The bow was held ‘underhand’ i.e. with the palm up when the ‘push’ or ‘in-stroke’ was the stronger. It was used to accent the first note in the bar. The violin bow is held with the palm down making the down-bow stronger and accenting the first note (and to a lesser extent) the third note in the bar as described in early treatises on violin playing [12]. This comes about from the manner of supporting the instrument [3]. Viols were of different sizes depending on the tuning, and supplied music for genteel dancing in small salons where loudness was not needed.

As the type of music changed, and with its increasing popularity and the introduction of opera requiring large bands, large venues were required to defray the costs. Large string bands were being employed for the first time. The church had been using fiddles (violins) for some time to double voice parts and four sizes of string instruments had come into general use for this purpose. Viols were displaced by the violin for public performance. The earliest recorded use of massed violins was their appearance in Monteverdí’s opera ‘Orfeo’ in 1607. One has to look at early paintings to see the variation in size and shape of the fiddles in use before the form of the violin, as we know it, came about by about 1550 although innovative combinations of body, neck and head had appeared earlier.

Tracing the evolution of the violin from a small primitive 3-string bowed instrument has proved very difficult. There are no survivors of these instruments and theories have to be based on early paintings and some manuscripts e.g. Prætorius [13]. Some doubt has been expressed about the authenticity of early paintings but it is thought the artists would have been very particular in the details as well as having very critical employers who were largely the nobility, the church or wealthy merchants.

2.2 Structural Changes

It is most likely that the violin from the latter part of the 18th century was thought to limit the freedom of violinists to express the music being composed. Bach, Haydn and W.A. Mozart were active and Beethoven was becoming known. Many violin virtuoso/composers at the time influenced violin playing, included Paganini, Kreutzer, Rode, Spohr, Viotti and others from the French and Belgian Schools.
J.B.Vuillaume, a maker in Paris, in the early 19th century was prominent in converting many violins to the modern setup. To make it easier to stop notes in higher positions, a

longer fingerboard was needed. The neck of the violin was reset to eliminate the wedge under the fingerboard, made longer and morticed into the top block to give a stronger attachment. The strings were therefore about 4.5 % longer and there was an 9 % increase in string tension for the same tuning pitch and strings. All these changes were aimed at raising the output of the violin that was being demanded by changes in musical practice.

To enhance the sound output of the fundamentals, a soundpost was installed early on in the Renaissance/Baroque period. Viols, it is thought, did not have a soundpost or bassbar [14] and were lightly strung, accounting for their soft sound. The five, six or even seven strings also limit the tension in each string and therefore the level of the output. The soundpost and bassbar in these instruments, came later due to the competition from the violin. The sound of viols emanated largely from the arched top. In the violin the soundpost was followed by the bassbar, which served to counter the loss of stiffness on cutting the f-shaped soundholes. The introduction of the soundpost, initially to support the top, must have added noticeably to the output of the violin in the region of the fundamentals. Corner blocks are thought to have been introduced by Paulo Maggini early in the 17th century. He succumbed to the plague in 1630.
With the Amati family, Cremona, a rich agricultural city on the river Po in Lombardy, became the centre of violin making for 200 years. In other centres of Northern Italy, notably Venice, Milan, Bologna and Turin, violin making also flourished. Linked with the Amati workshop were other makers especially Antonio Stradivari (1644 - 1737) and Andrea Guarneri (1626 - 1698). The latter's grandson, Guiseppi Guarneri del Gesu (1698 - 1744) has become, along with Stradivari, the most highly regarded of violin makers.

Besides the details depicted in paintings to show the changes in instrument design, a number of authors e.g. Bagatella, Beck, Otto, etc [15] beginning with the lute outlined empirical geometric methods of design, some of which invoke proportions discovered in architectural masterpieces. These methods employ simple ratios that were achieved with ruler and compass. They often used the Golden Section. The most recent attempt to explain the method used is by Francois Denis [16] using a ratio called the analogia, again derived from architecture.

The starting point for design has often been the vibrating length of the string. It so happens that for the Baroque violin made for this study the string length was 315 mm. This was equal to the inner length of the violin body. The stop i.e. the distance from the upper edge of the top plate to the notches in the soundholes, which was standard at 195 mm, was, 0.618 of the inner length of the violin body. This ratio, 0.618, was known as the Golden Section. The string length of 315 mm, also coincided with the "stop" plus the length of the neck, 120 mm.

2.3 The Classical Method of Construction

The method of construction used in violin making was well established when Cremona became the centre of excellence. The craft of violin making had a long apprenticeship and the secrets were passed on by word of mouth. The only documentation that remains is a collection of outline templates and inside moulds on which to construct ribs, some tools, and the violins that still exist.

Violin making today has not much altered from classical practice and is largely a hand craft [17], but uses some mechanical aids. It is described here briefly for convenience. The billets of tonewood must be free of defects and thoroughly air dried for dimensional stability. Spruce *Picea excelsis* for the top is best split on the quarter: from this the sound board is carved. The rest of the body is usually made from European maple *Acer platanoides*. Fittings e.g. bridges, pegs and tailpiece, used sycamore, rosewood and boxwood. The fingerboard on early violins was often a pine or willow core to reduce weight, veneered with maple or ebony. Today, these fittings are most often ebony or boxwood but not the fingerboard. For the fingerboard with the growing shortage of ebony, carbon fibre/epoxy veneer layers are being tried. A hard wearing surface is desirable to prevent grooving.

It is not known what design method was used. Half templates of the body outline were made from the design of the violin (as well as a template for the neck/head and soundhole) using stiff paper. An additional template of the body allowing for the overhang and rib thickness was made from which an inside mould was cut with recesses to take the top and bottom blocks together with those at the corners. The mould was usually about 13 mm thick. As the sides were 30 mm wide, the mould was supported on a flat surface on 8 mm spacers thus placing it at the middle of the sides. The sides, about 1 mm thick, were glued to blocks of willow which were temporarily glued to these recesses in the mould. It is not known how the sides were bent but it is thought this was done hot. To increase the gluing surface on the sides for attaching the top and back plates after carving, willow linings were glued to the inner edges to give a width of 3 mm. This arrangement helped to maintain the shape of the sides when taking them off the mould. The method of joining the parts throughout used hot water animal glue. This had the advantage that it was readily reversible and did not have to be removed when regluing. In Baroque times the neck was butted onto the body, and secured by gluing and nailing through the top block. These nails were the only metal fastenings used when constructing a Baroque violin.

The top plate of spruce, having been cut on the quarter, was glued along its length with the outside of the tree in the centre to form a 'book joint' (with the centre of the tree at the outer edges). This gave a block with a raised centre from which the outside arching could be carved. The back could be one piece or two pieces similar to the top. The neck, pegbox and scroll were likewise carved from a solid block. Once the outside arching was established, the top and back plates were thicknessed by removing wood from the inside to some predetermined recipe, using weight and/or thickness. Flexing the plates was probably the most common practice. No guideline has come down to us except that some plates undergoing repair have been studied by subsequent makers. There is no evidence to suggest from modern studies of top plates that plate tuning was in use [18]. Today the researcher can only deal with the finished plates of the classical makers. The top has two soundholes in the shape of a Baroque 'f' cut in the centre and a bassbar attached after the top is carved. The precise point at which the tap tone of the top was taken, if used in earlier making practice, is not known.

After carving, the top and back were glued to the sides. In one sequence, one edge of the sides was sanded flat and would become the surface to which the top would be glued. The neck would then be nailed through the top block with the sides resting on a spacer to allow for the edge thickness of the top plate. The fingerboard would not be fitted at this point. The top plate could be glued to the sides at this stage and the neck aligned with the soundholes. The exact detail of the method is uncertain because of some other features e.g. the 2-3 mm taper of the sides from the upper corners to the neck and/or a slight upward tilt of the neck from the body that have been noticed in some violins. If the purfling is present on the top under the fingerboard, it suggests that the edges had been finished before gluing.

It is possible that after the neck had been attached to the sides, instead of the top, the back was glued to them. This would have required that the other edge of the sides be levelled and the end of the neck trimmed at the shoulder. Alignment of the neck would then require a centreline to the endpin. Questions of this kind arise when trying to study the working methods from examining early violins [19].

2.4 The Location of the Bridge and Soundpost

There has been much discussion among violin makers in recent times about the validity of the iconography as to whether the depiction of the bridge below the f-holes is historically accurate. There is little evidence of footprints on existing early violins. This could be due to subsequent restoration. If repositioning of the bridge took place, it has been assumed by this author that it was due to the necessity to change the pitch to suit that of an accompanying organ or to lower the sound output when playing with viols. It has been suggested that the desire to move the bridge was the reason it was never glued in place. Moderate repositioning the bridge above the notches in the f-holes was to raise the pitch and below the notches to lower the pitch. This was done without altering the string tension so that moving the soundpost was not a consideration. To move the bridge below the f-holes, on the other hand, would have required a shorter tailpiece as well as a higher bridge and possibly repositioning the soundpost. The reason for such a drastic change must have been related to the musical effect required as the sound quality would have changed since the strings could not easily have been bowed near the bridge.

2.5 Comparison of the Baroque and Romantic Violin

A comparison of the Baroque violin with its conversion to a Romantic (modern) violin should consider the motive for the change and whether as a result there were significant differences in the behaviour of the instrument.

There was much emphasis on church music, e.g. doubling voice parts and in the community and courtly dance and street processions; all with the Baroque setup and the short light bow. Much experimentation in playing took place, at this time, with double stops, scordatura and artificial harmonics, etc.

It appears that the changes to the violin occurred late in the 18th and early 19th centuries. At this time the Tourte bow with its ‘hatchet’ head and change in balance and the standardisation in length to 29 inches (74 cm), became popular for legato playing which was required more by composers. The appearance of the chinrest in 1820 by Ludwig Spohr, freed the left hand for more virtuosic fingering. All this and the growth of larger string bands, together with the desire for more volume, encouraged makers to alter the necks of older instruments and make the other changes.

2.6 Scientific Violin Making

Quantitative scientific studies did not take place until about the 1820ís. Earlier there had been studies of string behaviour with Pythagoras and Mersenne and Galileo and Newton were working in the 17th century but they appear to have had no input to violin acoustics. Felix Savart [20] did some pitch tests on plates in association with J.B.Vuillaume in Paris at the time violins were being converted to the modern setup. Some experiments on the behaviour of the soundpost were carried out by Savart and Chladni patterns were known, but little was done until the 1930s in France and Germany. In the 1940s, F.A. Saunders at Harvard in America studied many Stradivari and Guarneri violins for their response, harmonic content and loudness. Modern innovations such as the use of carbon/fibre composites [21] and veneered balsa plates [22,23] are outside the scope of this study. Much of the modern research has been contributed by Jansson and colleagues at KTH in Stockholm, Sweden. Much of this work has been brought together in a work by Jansson [24]. Modern contributions to acoustic research will be taken up in the next chapter.

Modern violin making has the benefit of very sophisticated computer programs and engineering equipment to study vibrations of instruments to aid the maker achieve the goal of maximising the result of hand crafted violins. These aids are being slowly taken up but because of the many variables in both materials and design the artistic ability of the maker cannot be ignored in its contribution to the final result.

2.7 Violin Acoustics

There are many questions concerning the acoustics of the violin yet to be answered. The detailed behaviour of the bowed string has numerous subtleties, as does the behaviour of the body that is necessary to transform those vibrations into audible sound. Every part of the violin has some bearing on the quality of sound that is finally heard. The parts of the body that have the greatest influence on this are the top and back of the violin whose wood can be chosen with desirable physical properties and fashioned into plates of a specific arching and thickness.

What techniques might the makers of classical violins used in the 16th, 17th and 18th centuries? Perhaps they listened carefully to the tap response of the free plates. This response was the pitch and the length of the decay as the note died away. For determining the pitch, it is unknown where the plate was held and where it was tapped. It is thought the mode with the highest pitch was sought. Or perhaps they assessed their flexibility by bending in the hands. Modern methods have revealed a number of vibration modes for the free plates. Makers today would like some endpoint to indicate when to stop thinning. As it is, as plates are thinned, their mode frequencies are lowered as plate stiffness and mass decrease. In contrast the ‘activity’ of the plate increases. There seems to be no limit to this progression. A maker has to stop before the plates are too weak to withstand the forces due to string tension. Maybe the “end point” could be a load bearing test; measuring an optimum deflection at the top plate centre during graduation and before the soundholes are cut. This would be established after a number of trials.

Another question concerns the bridge; it is higher than bridges on plucked instruments and it is not permanently attached in one position as in the guitar and lute. Similarly, the soundpost is not glued in place. Why? The simple reason is so that they can be moved. The bridge is high so that the outer strings can be reached by the bow thanks to the indentations in the body called C-bouts. There may be two main reasons for wanting to move the bridge; one, to allow adjustment for playing with other instruments, and two, to enable players to compensate for variable string properties. A further reason, which may turn out to be the most important, is the loss of tone quality when it is glued in place. Even though the tension in the violin holds it together, for some modes of vibration the plates at the soundpost are not moving in the same direction [25]. This can also apply to the motion of the bridge and the top plate. The bassbar is another part of the violin that merits further study. It is essentially a strut but it does not have to resist the torsional forces met in plucked instruments like the guitar and lute where numerous struts are glued inside the top. The more general use of struts, with thinner tops, could also be studied.

2.8 Playing Considerations

Violins (and other bowed instruments) are the most important sections of modern orchestras. This is due to the wide range of tone colour and output with bowed strings. However, the violin today is different from that used by Bach and Mozart in that the setup they used was Baroque with gut strings that had to be carefully selected to be free from defects. With today's modern setup, the Tourte style bow and the high quality of steel and wound strings, together with the development of modern playing techniques advocated by e.g. Carl Flesch, Leopold Auer etc. the sound has moved away from that heard in Bach's day. Leopold Mozart in his 1756 monograph [12] on violin playing recommend the use of vibrato for long notes. The lighter early bow allowed playing notes with frequent lifting of the bow off the string.

In recent years there has been an attempt to go back to original autograph manuscripts to get the composer's markings. Some instruments have been returned to their Baroque setup and specialist makers of gut strings for early music have become established. Replicas of early bows are being made as well.

All this has been encouraged by an interest in returning to Historically Informed Performance Practice (HIPP) which aims to perform music according to the performing conventions of its time of origin..

2.9 Summary

The violin grew out of a variety of forms and sizes prevalent in the fifteenth century because of the demands of society for a louder virtuosic instrument that would suit the music being composed and be able to be assembled into string bands for large venues. Makers, until recently, have intuitively met these demands. The development of scientific acoustics has not yet enabled advances on the violins produced 250 years ago.

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Chapter 3
The ACOUSTICS of the VIOLIN

3.1 Introduction

The acoustics of the violin will be described by first setting out the circumstances surrounding its displacement of the viol in popularity. A brief account will be given of the behaviour of the bowed string followed by a discussion of the two plates, the body, the soundholes, the bridge, the soundpost and the bassbar.

The violin incorporates a range of acoustic principles in its function as an acoustic impedance matching device that enables the notes stopped on the string to become sounds in the air (analogous to the flare on a brass instrument). It was not until recent times that a more complete understanding of the acoustics of the violin has been realised. This has been brought about by the development of advanced experimental techniques [1, 2, 3].

The acoustics is, to some extent, determined by the purpose for which the violin was used. This meant that the use of the violin and the associated acoustics evolved together. Another bowed instrument, the viol, was in general use by the nobility in the 16th and 17th centuries, and took the lucrative making commissions. The viol, of which there were six sizes, played underhand at the knee, had an arched top, a flat back braced horizontally, a fretted fingerboard and six/seven strings. Later in the life of the viol a soundpost was fitted between the top and a central brace. It also had a bassbar.

By contrast, the violin was less elaborate, was used by travelling players and the general public indoors as well as outdoors, and was very portable. It was played (bowed overhand) at the shoulder, had an unfretted fingerboard and was loud because it had only three/four strings. It was fitted with a soundpost and either a bassbar or an increase in thickness of the top plate on the bass side. The loudness was raised by the top and back being coupled by the sides and enhanced by the soundpost making the instrument a "simple source". This allowed the violin to radiate almost equally in all directions for frequencies below about 1 kHz. The selection of four strings on the violin was a compromise as any additional string reduces the output of the instrument because of the restraint imposed by the other strings to the one on which the note was being played. The four strings are tuned in fifths giving the violin a range of three and a half octaves.

It would appear that an unfretted fingerboard and the variable position of the bridge allowed some freedom in the choice of tuning pitch for the violin. The life of the gut strings was probably a major consideration in setting the pitch. Because of its greater loudness, the violin displaced the viol for string bands and use in large venues.

Having set the stage on which the violin was launched, the acoustics can be described in some detail. The bow imparts energy to the string which is made to vibrate between a fixed point on the fingerboard and the bridge. The bridge transmits some of this energy to the central region of the top which is detached in part from the sides of the violin by the soundholes. This central area, about 45 cm^2, is connected to the back by the soundpost and to a minor extent to the rest of the top by the bassbar. The ligament at the upper end of the f-holes provides the greater link between the central area and the rest of the top plate. This places some importance on the flexibility of this region of the top. These two items maximise the vibration of the body as a whole providing a total area of about 1500 cm^2, that radiates the sound of the strings. Only part of this area is effective, depending on the nature of the mode of vibration.

There is now an extensive literature on the acoustics of the violin [4]. The present account can only outline what I think are the important basic findings. The component parts that make up the violin, each studied separately, have characteristic mechanical and vibrational properties. Assembled in the violin, these properties contribute to produce a different vibrational behaviour.

The violin body provides a means whereby the vibrations of a bowed string are converted efficiently into a high intensity sound which can approach 100 dB SPL in the near field. We shall first consider an ideal string.

3.2 The Bowed String

An ideal, one-dimensional homogeneous string, fixed rigidly at both ends generates overtones which are all harmonic. Generally, the amplitudes of harmonics decrease with the harmonic number. On a bowed violin, an ideal string would produce a sawtooth bridge force, modified by the width of the bow hair and an absent harmonic where the bowing point coincides with a node. Helmholtz [5] established this behaviour and a motion called a Helmholtz motion which he published in 1862 using a vibration microscope. This has been confirmed since by other workers, with improved detail [6, 7, 8, 9, 10, 11]. The bow, when placed at the usual position (up to one fifth of the vibrating string length from the bridge), travels first to the bridge from which it is reflected back to the bow when the string is picked up but the kink travels on to the "nut" or finger where the other end is anchored, and returns to the bow ready to slip again, figure 3.1.

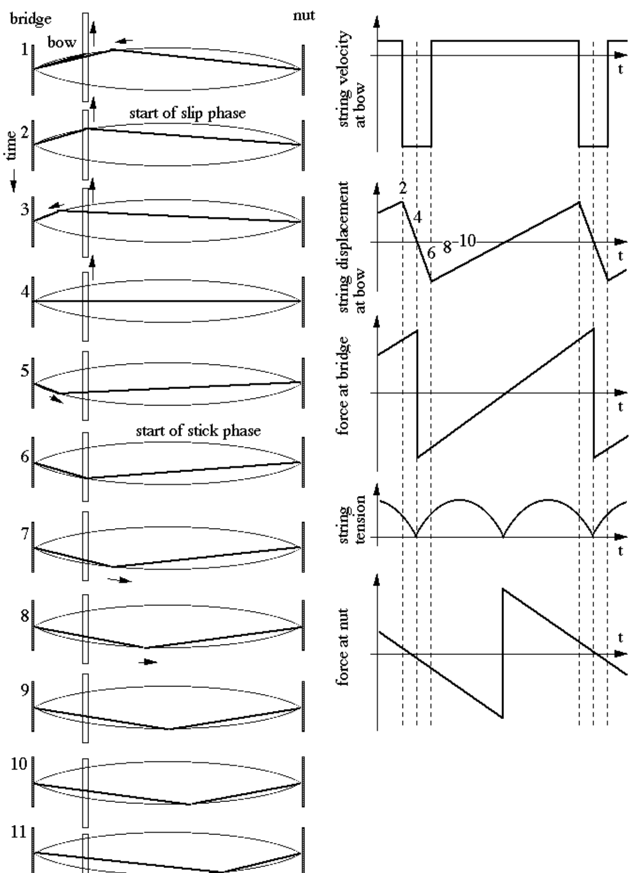

Figure 3.1 Idealised bowed string motion and associated effects

The kink follows two parabolic arcs in its cycle, which determines the pitch of the fundamental of the note being played [12]. The number of harmonics seen at the bridge depends on the sharpness of the kink which is governed by the stiffness of the string and the force exerted by the bow and is never ideally sharp. The manipulation of the bow i.e. the force and position of the bow hair on the string control the geometry of the kink and hence the harmonic content.

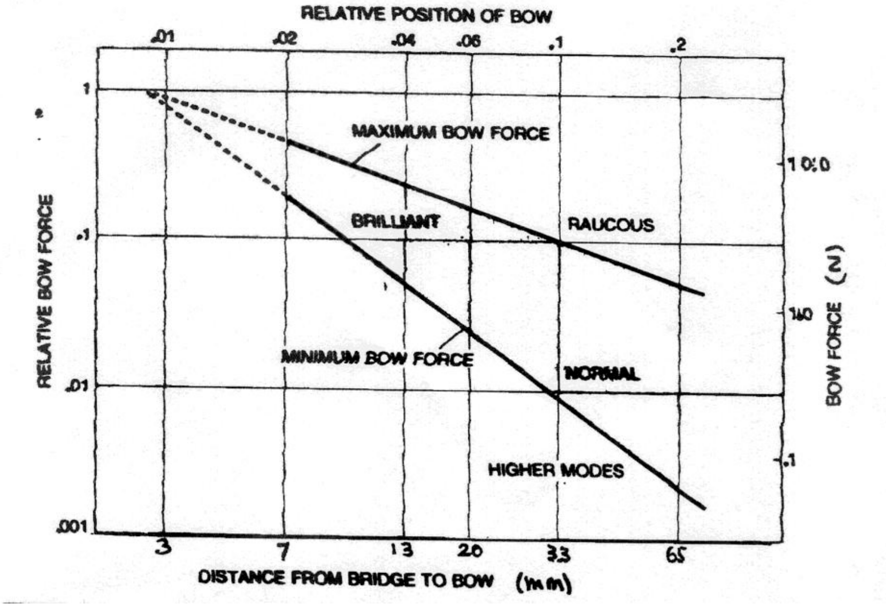

Figure 3.2 Playing parameters for the violin with the Schelleng diagram altered to give values of bow force in Newtons and bow distance from the bridge in mm. The useful range extends closer to the bridge for the violin. The numbers are approximate only. [after 13]

For an ideal string and an infinitely narrow bow hair, the bow force must be within certain limits for a uniform Helmholtz motion to be generated. For a distance, x, from the bridge of a vibrating string length, L, the limits are proportional to $1/(x/L)^2$ for the minimum and $1/(x/L)$ for the maximum bow force [13]. Above the upper limit an irregular, aperiodic, motion occurs with unpleasant low pitched sounds while below the lower limit the octave is generated sometimes, followed by the fundamental, see figure 3.2. This figure has been modified with numbers more suited to the violin. The slope of the lines is determined by the conditions of bowing at the time. These two limits are set by the frictional behaviour between the rosined hair of the bow and the string. In the full treatment of Schelleng [13], both limits are multiplied by the bow velocity, v, divided by the difference between the coefficients of static, μ_s, and dynamic, μ_d, friction and β

= x/L. At the minimum bow force, F_{min} and bow velocity, v, the resistance of the bridge, r, and the characteristic impedance of the string, Z, enter the equation,

$$F_{min} = \frac{Z^2}{2r} \frac{v}{(\mu_s - \mu_d)\beta^2} \qquad \text{as } \frac{Z^2}{2r}$$

whereas at the maximum safe bow force,

$$F_{max} = Z \frac{v}{\beta(\mu_s - \mu_d)}$$

Z is the only additional multiplier.

The violinist learns to match an appropriate bow force with the bow velocity to stay within the limits set by these two lines. Benade [14] has given the range between these two lines as:

$$F_{max} - F_{min} = \frac{2vZ_0}{\beta(\mu_s - \mu_d)}\left(1 - \frac{Z}{\beta r}\right)$$

A higher string impedance, Z, would raise the lines while a higher bridge resistance, r, would lower the bottom line thus widening the space between them. The real position however, is more complicated than this.

The frequency, f_n, of nth harmonic on the string is given by:

$$f_n = \frac{n}{2L}\sqrt{\frac{T}{\mu}}$$

where n is the harmonic order, L the string length, T the string tension and μ the linear mass density.

The vibration amplitude of the string is proportional to the velocity of the bow. The time taken for the kink to travel back to the bow is constant and depends on the frequency of the fundamental. If the bow moves with a higher velocity, the string will be in contact for the same time and will travel further thus increasing the amplitude, all else being equal. The energy stored in the string is proportional to the product of the amplitude at midpoint squared and the frequency squared, thus:

$$E = 2\pi^2 m A^2 f^2$$

where A is the amplitude of vibration and m is the mass of the vibrating length of the string.

The characteristic (or wave) impedance of a string with no terminations is

$$Z_0 = \sqrt{T\mu}$$

However, for a string of fixed length with ends that are not rigid the position is more complicated.

The sudden change in bridge force when the kink is reflected has been equated to -2vZ/(x/l) where, v, is the bow velocity. This force steadily builds at the rate Tv/x as the kink completes the return trip [15].

Guettler [16] has discussed the content of the Schelleng diagram which was designed to fit the circumstances of bowing the cello.

The string transfers energy to the bridge which acts at low frequencies as a lever, with a pivot point near the treble foot [17]. The bass foot exerts a vertical force on the top plate over the bassbar. For a given string, the lever action is approximately the ratio of the distance from the treble foot to the string slot on the bridge, and the distance between the bridge feet. This is approximate because the actual pivot point is not known. A low bridge would have a lower ratio and exert a lower force than a higher bridge. The motion of the bass foot will be governed by the stiffness of the top plate which in turn will limit the movement at the string slot. A highly arched top plate will usually be stiffer than a lower arched top and, together with a lower bridge, may account for some of the loudness differences among violins.

The impedance of the bridge/body as seen by the vibrating string is frequency dependent due to the many body resonances, but is about 1000 times higher than that of the string. Such a difference is necessary to avoid mechanical instability, such as wolf notes, and to ensure harmonic behaviour of the string. A wolf note occurs when the fundamental of the note being played coincides with a strong resonance. Exchange of energy between the string and the top plate produces an unstable note.

Gough [18, 19] has developed the study of string resonance coupling with body resonances using a highly sensitive technique with a further explanation of the Wolf note.

3.3 The Behaviour of the Bridge

The first important study of the violin bridge was that of Minnaert and Vlam [20] who recorded both the in-plane and out-of-plane motion. An important result was that the side cuts in the bridge prevented the out-of-plane torsion and rocking motion of the top half above the cuts from being transmitted to the violin top plate. This work was followed by a study of the two main in-plane resonances of the bridge by Reinecke [21] who measured the resonance frequencies of a bridge mounted on a rigid base. He found a rocking motion at 3 kHz and a bouncing motion at 6 kHz. These were confined to the top part of the bridge above the waist. He confirmed these motions with holographic images. Muller [22] investigated the effect of changes as the bridge moves from a blank to the finished piece. Hacklinger [23] studied the effects of modifying the stiffness on the low frequency vibration behaviour of the violin. Jansson [24] has described the effect of mass loading and the selective removal of wood on the first or rocking resonance of the bridge on a rigid base and the interaction with strings on a violin.

The bridge has two important resonances, an in-plane rocking of the top half at about 3000 Hz and a vertical in-plane motion at about 6000 Hz when tested on a solid base. When the bridge is installed on a violin, these resonances occur at lower frequencies. A downward force due to the change in string tension at twice the fundamental is transmitted.

Since the study of Reinecke [21] on the bridge resonances that revealed a rocking motion at 3 kHz and a bounce motion at 6 kHz for a bridge mounted on a rigid base, a body of work has appeared on the so called ‘Bridge Hill’ at 2.5 kHz on the violin. There is a corresponding reversal in phase at this frequency [25]. Not all violins exhibit the Bridge-Hill phenomenon. It is linked with brilliance and projection in the sound. It could better be called the Bridge Formant in line with the feature developed by singers to enable them to stand out against an orchestra. There is some uncertainty about the connection between the bridge and the top plate in producing the effect in the violin response [26].

The research on this topic has culminated in two papers of importance: one, a computer study by Woodhouse [27] exploring the effect of variation in bridge and top plate parameters and the other by Beldie [28] modelling the bridge behaviour.

3.4 The Behaviour of the Body

The modern violin is subject to a static longitudinal force of about 230 N due to the combined pull of the strings which has a tendency to fold the instrument up. This puts the top in compression and the back in tension. In old violins, as a consequence, the top is distorted with the upper bout raised and the bridge area depressed which may extend to the lower left bout [29]. This may be influenced by the bassbar. By contrast, the additional force applied by the string during playing rarely exceeds 2 N.

Mass is important; light violin plates are easy to excite but there is a lower limit to the plate thickness to prevent distortion. An optimum weight for a modern violin appears to be about 400 g. The acoustic behaviour of the body is quite complex, being made up of resonances generated in the body as a single entity; in addition, the plates and the air enclosed as well as the fingerboard and tailpiece also resonate as part of the overall behaviour. The neck takes part in some body resonances either in a bending or torsional mode, as do the fingerboard and tailpiece. Below about 1 kHz where most of the fundamental frequencies occur, the body has a monopole component or breathing action as part of the vibrational behaviour of its resonance modes. It is desirable that this component be prominent for a high output. This would be assisted by nodal lines close to the margins of the plates. Above 1 kHz the plates divide into smaller areas which radiate more directionally than the modes at lower frequencies.

The violin vibrates when free to do so, in such a manner that the phase and amplitude of each part in motion are balanced ensuring that the centre of mass remains stationary.

3.5 The Main Air Resonance

For the size of the violin, the height of the sides has been set at 30 mm to give an air volume of about 2 litres which, for the combined area of the soundholes, about 1200 mm^2, results in an air resonance of the Helmholtz type, A0, at about 275 Hz. This is discussed in more detail in chapter 9. A small area at the treble foot on the top plate and taking in the soundpost, is out of phase with the rest of the top, but in phase with the back. This establishes a "breathing" action and it is convenient to regard the two plates moving away from the centre of mass as being in phase and forming a "simple" source. The main air resonance combines with an adjacent higher body resonance of opposite polarity [30] to support the lower fundamentals. The main air resonance, A0, represents a major monopole radiator. For a high output in the range of the fundamentals, a high monopole component is desirable.

There are higher air resonances in the violin [31] that may interact with coincident body modes. The one that is readily identified, A1, with a pressure maximum at each end of the body, occurs at about 485 Hz and is primarily determined by the inner length of the body.

3.6 Free Plate Modes

Free plate vibration modes are used during thinning as a means of quality control. The labelling of vibration modes of plates counts the number of boundaries between regions of opposite phase, expressed horizontally and then vertically. For free plates this amounts to counting the nodal lines. Where edges are supported in rectangular plates, they may count as 1/2 or set to zero as in Fletcher and Rossing [32].

The most characteristic modes to monitor, in the present case, are 1,1; 2,0 and 0,2 which for an arched plate, are about an octave apart in the top, with the 1,1 mode set at 90 Hz as an optimum. These modes are labelled respectively 1, 2 and 5. The plate frequencies, 90, 180 and 360 Hz would give a top plate about 3 mm thick and a mass of 70 g. The back plate has an octave between 2,0 and 0,2 i.e. modes 2 and 5. Hutchins [33] suggests that the 2,0's are best matched between the top and back plates. Mode1,1 in the back is usually at about 110 Hz. Figure 3.3 shows a Finite Element determination of the free plate modes indicating the change from a flat top plate to an arched plate and the difference between spruce and maple in the nodal line positions [34].

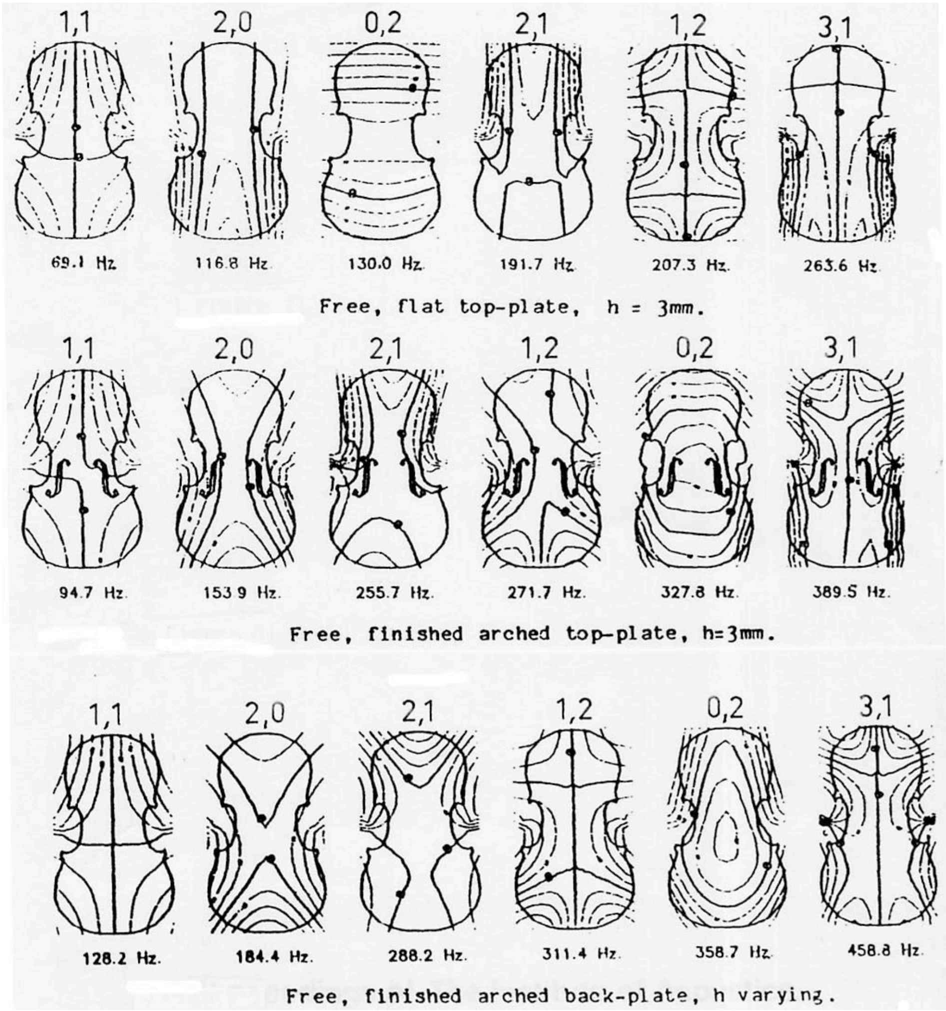

Figure 3.3 Predictions of the modal behaviour of violin plates by the finite element method [34]

When the soundholes are cut, the frequency of the 0,2 mode (mode 5) falls about 60 Hz. The bassbar is said to be tuned to restore the mode 5 frequency to its original value before the f-holes were cut. Early bassbars varied in size and it is not known whether tuning the plate was part of the installation besides strengthening the top. The possibilities for tuning mode 5 to other frequencies by this means have not yet been explored to my knowledge. It has been advocated that the bassbar should be sprung to counteract the down bearing of the bridge but it is not a general practice [35].

3.7 Chladni Patterns

The open spaces clear of contour lines in the Finite Element Patterns of figure 3.3 are nodal regions. A simpler method of depicting nodal lines, used in this study for free plate vibration modes as well as body modes, is the display of Chladni patterns. A low density powder such as sawdust or lycopodium powder could be used on a dark surface. In this case unused tea leaves were used against the light coloured wood. The plate or violin body is vibrated at the resonance frequency of the mode in question, as explained in chapter 5, and tea leaves scattered on the surface when they will migrate to the nodal regions. Well separated resonances will have a definitive pattern, and if clear, with narrow nodal lines. Adjacent vibration modes would interfere with the clarity of a pattern. Because the plates are arched, body modes show an accumulation of tea leaves at the margins which are rarely part of the Chladni pattern.

In practice, Chladni patterns on a violin are Operating Deflection Shapes, ODS, and represent the sum of contributions from all resonances active at that frequency whether strongly or weakly. As a result, the pattern may be distorted from that for the pure resonance, or independent normal mode, if it alone acted at the frequency chosen.

The nodal lines are regions where there is no motion normal to the plate surface. The motion of the plate on either side of it will be of opposite phase. Nodal lines have to be closed on the violin and will cross from the front to the back along the sides. Only on the free plates can they end at the edge.

3.8 Body Resonances

The violin vibrates in a number of ways when excited. Being a mechanical system, the modes of vibration are affected by the way it is supported and where it receives the excitation. For exploring modes, the violin is usually suspended at the corners and the scroll either by rubber bands or soft pads. The bands have low stiffness, so any support resonances fall at frequencies below the range of interest. In use, the violin is held at the neck and the bottom edge by a chinrest and shoulder pad so the behaviour will be different to that discussed above. It is expected that some modes will be mildly damped. This study is primarily interested in the modes associated with sound production. This means the way in which the body vibrates. Modes other than those producing sound may be felt by the player. The neck/fingerboard can vibrate in either torsion or bending. This can give two similar modes at different frequencies (see figure 3.5 and [36]). We are mainly interested in body modes above 200 Hz, the lower end of the range of the violin.

At frequencies below 200 Hz, the violin flexes as a simple beam in a way that is not connected directly with sound production. However, attachments may also vibrate in this low range. The tailpiece is known to have modes below 200 Hz as well as at higher frequencies [37]. The body modes that have a monopole component below 1 kHz enable the violin to radiate sound almost equally in all directions. It is desirable to maximise this feature by manipulating the nodal line positions. These body modes occur in the middle regions of the playing range, 200 to 1 kHz. At higher frequencies the plates are divided into smaller areas that radiate more directionally. For any note with harmonics, many vibration modes are excited at the same time.

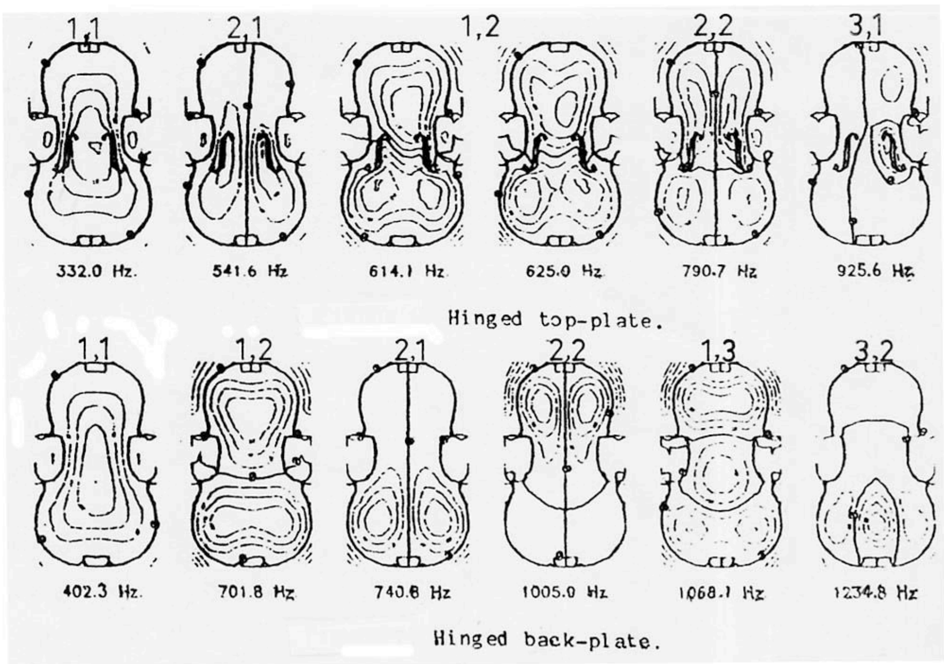

Figure 3.4 Effect of attaching sides to a top and back plate [34]

As an intermediate step to full body modes, the effect of loading and hinging the plate edges by attaching sides to them shows a dramatic change to the nodal patterns. Figure

3.4 shows the lowest mode with only one nodal line, at the boundary [34]. This is closer to the behaviour of the plates in the violin at its lowest frequency mode.

Body modes that can be identified and studied easily occur below 1 kHz. These modes are characterised by closed nodal patterns i.e. nodal lines, in simple cases, on the top and back being joined across the sides. Good violins have body modes approximately as follows: C2 at 385 Hz; B1- (T1) at 460 Hz; B1+ (C3) at 520 Hz; C4 at 600 Hz. There is also a first upper air mode, A1, at 485 Hz and sometimes other body modes at 700 and 800 Hz approximately. Chladni patterns can usually be obtained for these body modes by exciting the violin suspended over a speaker and irradiated with a sine wave of adjustable frequency. These body modes have been studied extensively [36]. Figure 3.5 shows typical mode shapes for resonances below 1 kHz [36]. The naming of body modes cannot use the nomenclature used for free plates and the labels adopted is that commonly employed by makers.

The notation (m,n) for describing the vibration patterns on plates cannot be applied to violin bodies. F. A. Saunders [38] detected the main air and body resonances by a bowing technique and labelled them “A” and “P” (principal peak). Jansson and co-workers [39] developed a general method of naming body modes in terms of their prominent element; A for air modes, C for body (corpus) modes and T for top plate and N for neck, allowing the possibility of additional names as required. Hutchins [40] reduced this nomenclature to simply A and B for body modes, adding a modifier to indicate a specific action. Table 3.1 summarises the equivalent mode names below 1 kHz.

Table 3.1 equivalent mode names for violin resonances

Hz	Jansson	Hutchins	Description
190	C1	B-1	“Beam” bending mode
280	A0	A0	Main air (Helmholtz) resonance
300	N	B0	Neck/fingerboard bending mode
385	C2		Vertical translation of C bouts
460	T1	B1-	Top bends transversely, back bends longitudinally
485	A1	A1	First upper air mode
530	C3	B1+	Top bends longitudinally, back bends transversely
650	C4		Dipole in lower bout, ring mode in back

The vibration of the body is quite complex, as investigated by Marshall [36] with a modern violin. A Baroque violin is not expected to be very different except for some perturbation of modes due to the nature of the neck/fingerboard. Body modes excited by the bridge will generally have a nodal line near the treble foot because of the presence of the soundpost. The bass foot will be associated with an anti-nodal region but may not be at the point of maximum amplitude. These body modes below 1kHz contain a monopole component that ensures near equal radiation at these frequencies. To maximise this component it is important that the out of phase anti-nodal regions be very different in size. This can be achieved if the nodal lines are near the margins of the plates. The height of the arching and the elimination of the scoop at the plate edges may favour this position of the nodal lines. Placing the soundholes closer to the C-bout edges may help this happen.

The two main body modes, B1- and B1+, have nodal lines similar to those of the free plates. B1- has mode 2 nodal lines in the top and mode 5 in the back and occurs at a lower frequency than B1+ with the nodal lines reversed. Since the top is more active than the back, its stiffnesses may determine the order of these nodal line patterns. The monopole radiativity of the violin used by Marshall [36] can be seen in Hutchins [3].

The breathing action or monopole behaviour, is necessary to prevent cancellation as the wavelength of sound at the low end of the range is about four times the length of the body of the violin. The critical frequency where the bending waves in the top equal those of the sound waves is about 1 kHz. As a result the violin radiates sound nearly omni-directionally up to about 1 kHz which includes most of the fundamentals of notes played. At higher frequencies vibration patterns become more complex and the violin radiates more directionally [41]. A note containing many harmonics is subject to all these interactions with a resulting complexity of sound.

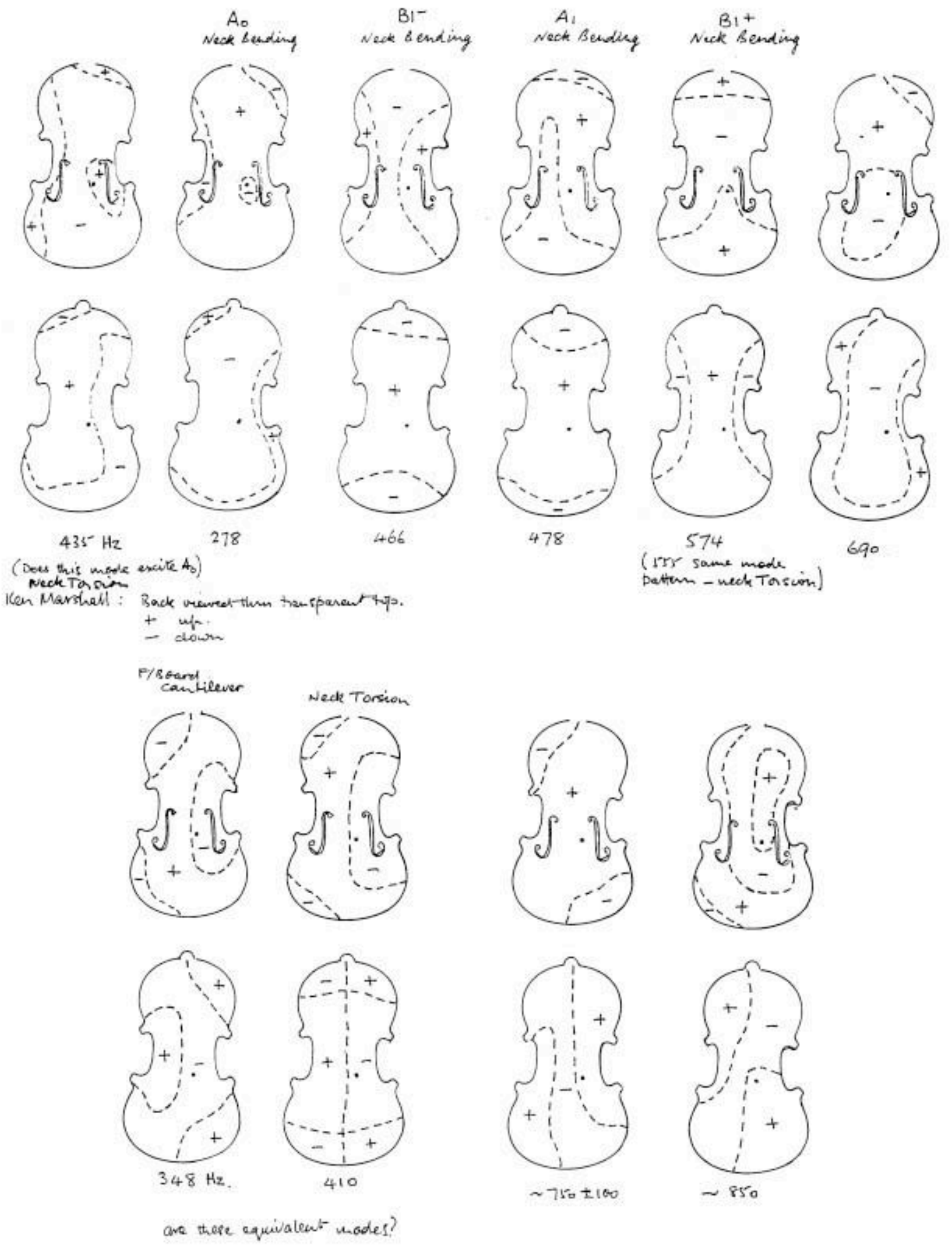

Figure 3.5 Experimentally determined nodal lines for resonances of a violin (the back viewed through a “transparent” top) [from 36]

3.9 The Soundpost

The function of the soundpost in the violin has been reviewed by this author [42] and its effect on plate nodal line positions, its interaction with the sides and the transmission of force to the back are discussed. The soundpost has been shown to be rigid at frequencies up to 8 kHz [43] above which it may have resonances but these are above the range of the violin. Firth [44] showed that the plate velocities at the ends of the soundpost were not equal over the range of the violin. Cremer [45] examined one of Marshall's [36] resonances at 656 Hz where the plates were not moving in the same direction and considered the soundpost to be acting as a stiff spring between two masses. Marshall's raw data [46] shows eight examples of this behaviour. The downbearing of the bridge due to string tension preserves interfacial contact. The violin would function without the soundpost but less efficiently and it would suffer in the long run by a depression of the top plate on the treble side.

As well as supporting the top from the forces exerted by the strings, the soundpost has an influence on the modes that appear in the vibration of the violin and their shape. Because of its structural role, it has to be located close to the treble foot of the bridge, usually a post width towards the lower bout. It has the effect of pulling the nodal line of the 2,1 body mode (figure 3.4) toward the treble soundhole thus enlarging the single phase area of the top plate. It has a similar effect on the back plate [47]. The soundpost stiffens the body [48], raises the frequency of A0 [49] and together with the sides forms a connection between the top and the back [50]. The measured impedance of several soundposts [48] showed that, for an impedance below 60 kg/s, the output of the lower strings was lower than that of the E string. It was also shown [51] that moving the soundpost from a position toward the centre of the violin to one outside the line of the treble foot, raised the output of the lower strings from a "no soundpost" condition to one of equality with the top string. The strength of notes on the top string, which depends largely on plate resonances, was mainly unaffected. It appears that lowering the stiffness of the soundpost or moving it toward the centre of the violin approaches a no soundpost condition with reduced output from the lower strings. There is also a greater risk of wolf notes. A solution to a wolf note problem may be to increase the stiffness of the soundpost by using one with more growth rings.

3.10 The Soundholes

The soundholes in the violin are f-shaped. They have evolved from other shapes [52] for example, outward as well as inward facing “C” shaped soundholes. They provide a necessary opening for the main air resonance to exist. The idea of turning out the lower half of the C shaped soundhole to make an “f” shape may have been a contributing factor in raising the output of the violin by enlarging the central area of the top. The distance between the upper finials of the soundholes are about the width of the bridge apart. Jansson et al [53] have studied the effect of modifying the f-holes on the mobility curve of the violin. They concluded that the cross-grain cutting had a greater effect than the along-the-grain cutting. The modern f-holes having no sharp corners, cracks along the grain are minimised. Thick edges assist in reducing cracks and contribute to the size of the vibrating air plug. The central region of the top, between the f-holes, while partially detached from the rest of the plate, does not radically change the nodal lines on the top plate. At A0, the soundpost creates a small island on the edge of the treble soundhole that is in phase with the back plate. This establishes the simple source radiating at these low frequencies. The partly detached central region has shown a greater amplitude at the free edge [36]. The spacing between the upper ends of the f-holes has been regarded as important, at 42 mm, but the author knows of no clear discussion. The most likely explanation is related to the width of the bridge and the position of the bassbar under the bass foot which has to lie inside the f-hole on that side.

3.11 Damping in the Violin

Several aspects of the construction of the violin inherently introduce damping. The pull of the strings puts the back in tension and the top in compression. When a violin is placed under tension all the parts of the body undergo an adjustment. Playing adds a small variation to this state of stress.

Wood with a “good ringing quality” indicates a high Q value i.e. low internal damping or low resistance (experimental techniques are described in Chapter 5). High Q value tone woods are necessary because Q values in the violin body tend to be reduced by the subsequent constructional steps. A low Q value allows the sound to decay quickly (and build up quickly) and indicates a higher resistance which is made up of two main components, internal friction in the wood and damping from the air. The internal friction in a violin will have contributions from shear in the cell structure of the wood and the built-in stress due largely to the tension of the strings. The internal damping of the wood is nearly constant up to 1 kHz and then increases with frequency. For bending at low frequencies spruce has a Q typically of about 125 along the grain and 65 across the grain. Maple has similar Q values. However for the assembled violin the Q values depend on the strength of air and body resonances. The desirable value for the main air resonance is about 15 and 30 for the body resonances to ensure the violin has a quick response and is free from wolf notes. To maintain stability, to minimise wolf notes and to produce high sound quality, the height of resonance peaks should be limited by moderate values of damping, thus widening the resonance and promoting ease of playing. The reciprocal of the damping is related to the quality factor, Q.

Expressed in terms of Q, the study of classical violins, has suggested values of between 25 and 50 for body resonances [54]. Saunders found in a study of old Italian violins a value of 20 for Q for the main air resonance, A0 [55]. The difference in height between the peaks and troughs should be about 12 dB [56], From observations made during this study, the depth of the "trough" between the main air resonance and the first body resonance which are of opposite polarity, is about 12 dB; for an anti-resonance it is about 24 dB. The only practical way to enhance the sound output of the violin is by raising the general level of the response curve. This has been done in connection with the "Violin Octet" [57] where the plate size of the violin was enlarged. To maintain the frequency of the main air resonance, the sides had to be reduced in height to give the same air volume. An increase of about 5 dB was achieved.

An important aspect of damping occurs when the player holds the violin. The neck is held and the body is supported by the chin and shoulder. Body resonances that involve the neck will be suppressed as well as modes that will be affected by clamping at the lower rim. Marshall [58] has studied these two aspects and found that below 1kHz the resonances are generally lowered in height but relatively little affected above this frequency. It is to be expected that the effect would be greater for Romantic playing than for Baroque playing as the violin was held very lightly because no chinrest was in use in the early period.

3.12 Analysis of Violin Sounds

Violin sounds can be analysed in a number of ways. The physical analysis of a note into its harmonic content gives the quality of the sound from the relative strengths of the partials. The open G string is known to have a weak fundamental and relies on the strength of the upper harmonics. It is known that the strength of the higher harmonics colour the sound of a note. The sound heard by a listener is affected by the player; the choice of bow, the use of vibrato and the variables; bow force, bow speed and bow position on the string; how much of the hair ribbon is in contact with the string and whether the left hand finger is lightly of heavily pressed on the fingerboard.
At present the only analysis that can combine all these variables into a single picture is the Long Time Average Spectra. The application of LTAS to recorded music phrases was explored in three papers by Jansson and Sundberg [59] in 1975. It was found that this technique applied to the recordings of bowed string instruments, Jansson [60], in a reverberant chamber, the result was not influenced by the position of the player of the microphone. The player and the violin in this study, together with the other variables above provided a large influence on the LTAS.

It was concluded that the LTAS in this context, represented a simple method of analysing a complex sound source. In 1979 Gabrielsson and Jansson [61] applied the analysis to twenty two “quality-rated” violins. The differences between two groups, eight “high” and seven “low” quality, were not large. The “high” goup were above the “low” group at both low and high frequencies. This test may take some of the subjective nature out of listening tests.

3.13 References

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Chapter 4

BAROQUE VIOLIN CONSTRUCTION and CONVERSION to ROMANTIC SETUP (including Properties of Associated Parts)

4.1 Introduction

This chapter describes the materials used and the method of making the violin for the work of this thesis. Where an item is connected with the construction of the violin e.g. graduating the two plates and the properties of the strings used, the method of test of these items and the result has been included in this chapter. The construction of the Baroque violin followed classical methods of hand construction with minimal mechanical aids. The traditional materials used and their physical properties are described.

4.2 Materials used

The outline for the violin was taken from the Guarneri (del Gesu) of 1733 owned and played by Fritz Kreisler but there was no attempt to make an exact copy]1]. European wood was used that had been naturally seasoned by air drying, for at least 40 years and was considered to be stable. The elastic properties are listed in Table 1.

European Spruce is a softwood, characterised by a close grained structure with pronounced annual rings of large thin-walled cells of spring and summer growth separated by dense thick-walled late growth that makes the wood very stiff along the grain and compliant across the grain. The structure contains medullary rays that run in a radial direction and may be an important stiffening component. It belongs to the Family *Pinaceae* and Genus *Picea excelsa*.

European Maple is a hardwood, characterised by less obvious grain structure. It has many pores. It belongs to the Family *Aceraceae* and Genus *Acer platanoides*. Sycamore and other hardwoods have been used. Poplar was sometimes used in place of maple.

The elastic moduli were determined using a Lucchi Tester that measured the time taken for a 60 kHz pulse to travel from the transmitter to the detector over a measured length of wood in the required direction [2]. The shear modulus and Q value (in shear) were measured using a sample as the suspension of a torsion pendulum. [3] Since wood is orthotropic, measurements were made in the Longitudinal (L), Radial (R) and Tangential (T) direction. Shear moduli required two directions as shown in table 4.1.

Table 4.1 Elastic Properties of the Spruce and Maple used.

		Spruce	Maple
Density (kg/m^3)		414	650
Elastic Modulus	E_L (GPa)	12.7	9.8
	E_R (GPa)	1.1	0.8
Shear Modulus	G_{LR} (GPa)	0.65	1.5
	G_{LT} (GPa)	0.5	1.2
Q value	G_{LR}	44	53
	G_{LT}	41	50

The density was determined by weighing an accurately machined test block.

Some comment on these tonewoods is justified in the light of the classical paper by Schelleng [4] on wood for violins. The wood in table 4.1 is average in terms of properties. The wave velocities, c, for the spruce were E_L 5540 m/s and E_R 1630 m/s and for the maple E_L 3880 m/s and E_R 1110 m/s. The c_L/density ratios were: spruce 13.4 and maple 6.0 being about half that of spruce as found by Schelleng for good European wood. These ratios suggest a good violin should result.

Willow was used for the inner blocks on which the sides (ribs) were glued. It was also used for the linings as it was light, without a pronounced grain and therefore unlikely to split. The bridges and tailpieces used sycamore, a relative of maple. The wearing surface of the fingerboard was a maple veneer on a willow core. Ebony was used for the pegs as well as the modern fingerboard and tailpiece.

4.3 Method of Construction

The outline of the violin was taken from an accurate STRAD Poster of the Kreisler violin. From this, thin aluminium templates were made for the outline of the plates and for the inner shape, allowing for the overhang and the thickness of the sides. Templates were also made for the neck and head as well as the soundholes.

The sides, 1 mm thick, were built up on an inside mould, 14 mm thick, supported on a flat surface on 8 mm spacers. For 30 mm wide sides, this put the mould roughly at the mid-height of the rib assembly. This allowed the linings to be glued to the edges of the sides with the mould in place thus preserving the shape of the ribs on removal from the mould. All gluing was done with hot water, animal based, gelatin glue.

After carving, the neck was fitted to the curve of the sides at the top block and glued, as was traditionally done. However, instead of nailing through the top block, two screws were used so that it could be easily dismantled later. A paper insert was used to allow the glue joint to be easily separated. Figure 4.1 shows the method of attachment and the final setup of the neck joint.

Figure 4.1 The method of attaching the neck to the sides and gluing on the back

The top and back were cut on the quarter and glued down the centre to make a "book joint" and give billets from which were carved the designed arching and thickness required for these parts.

While the final thicknessing was in progress, free plate mode frequencies were determined for the three lowest modes of most interest. This was done by supporting the plate freely on soft, foam pyramids over a 10 cm orifice above a 12 inch (30 cm) speaker driven by a sine wave generator via an amplifier. By placing the supports at nodal lines it was possible to determine the mode frequency and nodal pattern with unused tea leaves. By placing a small magnet at an anti-nodal point and monitoring the motion with a coil, the effective mass and stiffness, and Q value for the mode could be easily found. The plates were brought to a final thickness and soundholes were cut in the top but no bassbar was added for the initial series of tests.

After the sides had been taken off the mould and the linings completely fitted and the neck attached, the edges that were to receive the back were levelled on garnet paper glued to plate glass. The back plate was glued to the sides (figure 4.1), with care taken to line up the neck/fingerboard with the centreline of the plate. The other edge of the sides had been similarly levelled previously to give a rib height of 31 mm and the top glued on. Figure 4.2 shows the top being glued after the fingerboard has been attached, care being taken to ensure the neck/fingerboard lined up with the f-holes.

The neck was French polished and the outside of the violin was covered with a thin coat of a water emulsion of beeswax and glue to prevent soiling the surface while testing and before varnishing. This sealer was applied with the finger and burnished. The author thinks that this would not have significantly affected the behaviour of the violin as it is confined to the surface and expected to add negligible mass and stiffness.

“Fitting up” came next. This included installing a soundpost, fitting a bridge, tailpin, tailpiece and strings. The strings first used were a light commercial set of Pirastro Chorda gut, the length of which was set by the distance from the notches in the soundholes to the nut at the end of the fingerboard, i.e. 315 mm. These were later replaced by heavier gut strings more similar to those thought to be used more generally on Baroque violins. Figure 4.3 shows the baroque violin as finally fitted up.

The modal parameters for the Baroque violin taken from a later chapter are shown in table 4.2 and are to be compared with those for the Romantic version in table 4.16. In this table (and later) f (calc) is defined as $(s/m)^{1/2}/2\pi$, where s and m are the experimentally determined stiffness and effective mass.

Figure 4.2 Attaching the Baroque fingerboard and gluing on the top

Table 4.2 Effective resonance parameters for the Baroque violin as seen at the bass foot of the bridge. (~70% R.H.)

Resonance Mode	f (0) (Hz)	df/dm (Hz/kg)	m (kg)	s (MN/m)	Z (kg/s)	Q (kg/s)	R	f (calc) (Hz)
A0	286	4.25×10^6	0.034	108 N/m	1.92	13	0.15	--
C2?	411	1170	0.18	1.17	454	27	16	410
B1-	471	1940	0.12	1.06	375	31	12	473
B1+	582	6830	0.043	0.57	157	36	4	579
C4?	618	2290	0.14	2.04	525	40	13	619
	770	5080	0.076	1.77	367	31	12	768

The Chladni patterns and the tap response for the Baroque violin are shown at the start of chapter 10.

Figure 4.3 The finally assembled Baroque violin

4.4 Fashioning the Violin Plates

The two plates forming the top and back of the violin present an important task as they determine the performance of the violin. The wood for both plates had been cut on the quarter and had to be joined lengthwise to form a “book joint” with the outside rings of the tree joined in the centre of the plate to form a low pitched billet from which the outside arch could be carved. The glued surfaces for this joint were rubbed together, to make a so-called “rubbed joint” and not clamped, to avoid internal stress. The lower surfaces of the billet which would become the surface glued to the sides had previously been planed flat. The outline of the plates was marked using a half pattern. The glue line was used as the centre line. The centre bout edge thickness was set at 4.5 mm, the outer bouts at 4 mm and the corners were set at 5 mm.

The outside arching was carved and finished with scrapers. The top outside long arch was more like an ellipse while the back long arch was more like a parabola. The maximum height of the top arching was 15 mm while that of the back was 14 mm. These values are accepted as good practice. The cross archings were full, extending close to the edges. In forming the arch it must be realised that the stiffness along the plate depends on the form of the cross arch, hence the “tube effect” and stiffness across the plate depends on the form of the longitudinal arching. Arching templates were not used for this violin, the shape being determined by eye. The two plates were thicknessed from the inside; the top to 3.5 mm uniform while the back was thicker in the centre at 4.4 mm and tapering to 3.0 mm at the centre bout edges and 2.5 mm at the outer bout edges.

Figure 4.4 Setup for determining plate Chladni patterns and mode frequencies
The magnet was placed in an anti-nodal position for each mode.

Chladni patterns for modes 1, 2 and 5 were taken at regular intervals during thicknessing, together with the weight and mode frequency. The parameters of the two plates in this semi- finished state are shown in tables 4.3 and 4.4. Figure 4.4 shows the setup for determining Chladni patterns (in this case mode 5) and the peak frequency and Q value with the magnet and coil assembly. Masses up to 10 g were added near the magnet to determine df/dm for each mode and the resonance parameters shown in table 4.4. The anti-nodal positions are at: mode #1 the edge of the lower bout at the widest part; mode #2 at the bottom edge of the plate on the centreline; and mode #5 at the centre of the plate on the centreline. These indicate the positions of the magnet.

Table 4.3 Initial mode frequencies of the Top and Back plates (freely suspended).

Plate	mass (g)	mode frequencies f(exp) (Hz) and Q values. #1	Q	#2	Q	#5	Q
Top	77	92	-	176	48	365	52
Top (f-holes cut)	75	87	-	162	54	309	62
Back	117	120	-	178	59	392	56

Figure 4.5 shows the top plate modes with the f-holes cut. Figure 4.6 shows the back plate at the final stage.

Table 4.4 Vibration parameters of the Top and Back plates (freely suspended) at the corresponding stage in table 4.2.

Plate	mode	f (0) (Hz)	df/dm (Hz/kg)	m (kg)	s (MN/m)	Z (kg/s)	Q	R (kg/s)	f(calc)
Top	#2	176	2343	0.038	0.046	42	48	0.9	175
	#5	368	5400	0.034	0.18	78	52	1.5	366
f-holes	#2	162	2829	0.029	0.030	29	54	0.5	162
cut	#5	309	3171	0.049	0.184	95	62	1.5	308
Back	#2	178	2500	0.036	0.045	40	59	0.7	178
	#5	392	3971	0.049	0.299	121	56	2.2	393

Figure 4.5 Top plate Chladni patterns of modes #1, #2 and #5 without a bassbar as described in Table 4.2

A comment on R values might be in order at this point. As can be seen they are quite small, being less than 3 in this table, for free plates indicating that they are good radiators. For body modes where the values of Z are higher for similar Q values, R values are greater. Low values of R are to be preferred.

Figure 4.6 Back plate Chladni patterns of modes #1 #2 and #5 as shown in Table 4.2

The edges of the plates had to be further finished by adding the purfling and rounding the edges. Further, for the top, an ebony saddle had to be fitted for the tailgut to pass over to the endpin thus avoiding damage to the endgrain of the top. The bassbar was not installed at first so that acoustic tests on the violin could be done without it. However, the parameters at this intermediate point are given in table 4.5.

Table 4.5 Mode frequencies of Top and Back as first fitted to the violin.

Plate	mass (g)	mode frequencies f(exp) (Hz) #1	#2	#5
Top (no bassbar)	75.6	84	161	312
Back	116.5	120	178	395

The corresponding vibration parameters at this stage are shown in table 4.5.

The progress of thinning the plates was followed by the change in mode frequency with change in mass as shown in figure 4.7 before the final adjustments were made. At this stage the outside arching has been finished and this figure shows the change as wood from the inside is removed. The top thickness has been reduced to 3.3 mm and finally the f-holes are cut. The back thickness has been brought to 4.4 mm in the central region, reducing the top bout to 2.8 mm and the lower bout to 2.3 mm. Mode 1 is not shown.

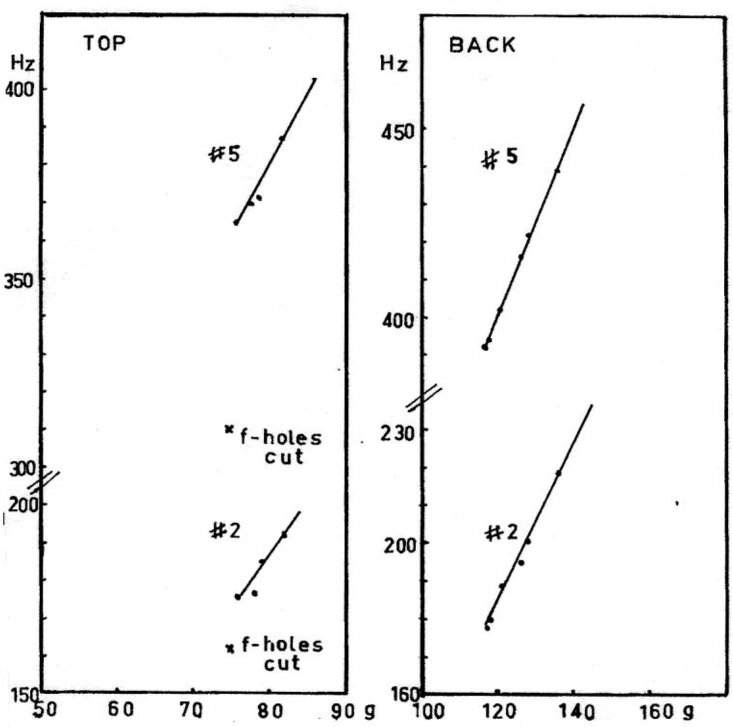


Figure 4.7. plate mode frequency change with mass loss due to thickness reduction

Table 4.6 Vibration parameters for the plates in table 4.4.

Plate	mode	f(0) (Hz)	df/dm (Hz/kg)	m (kg)	s (MN/m)	Z (kg/s)	Q	R (kg/s)	f(calc)
Top	#1	83	943	0.044	0.012	23			83
	#2	161	2700	0.030	0.030	30			159
	#5	312	3900	0.040	0.154	79	62	1.3	312
Back	#1	120	1171	0.050	0.029	38			121
	#2	182	4914	0.019	0.024	21	59	0.4	179
	#5	398	4400	0.045	0.283	113	56	2.1	399

Later when the bassbar was added and tuned, the mode frequencies for the top were redetermined as given in table 4.7.

Table 4.7 Top plate mode frequencies (freely suspended) with bassbar fitted.

Plate	mass (g)	mode frequencies (Hz) Q values ( )		
		#1	#2	#5
Top (bassbar tuned)	81.3	88 (31)	176 (45)	362 (53)

After tests were done on the violin with and without the bassbar, the top plate was regraduated by thinning the area between the f-holes and fitting a lighter bassbar in an attempt to give the violin a higher output and possibly lift the response in the 2.5 kHz region. The final parameters for the top plate are shown in tables 4.8 and 4.9. Figure 4.8 shows the top plate modes with the parameters in tables 4.8 and 4.9.

Figure 4.8 Top plate Chladni patterns on modes #1, #2 and #5
as finally fitted with bassbar tuned as shown in Tables 4.7 and 4.8

Table 4.8 Mode frequencies for the Top plate regraduated

Plate	mass (g)		mode frequencies f(exp) (Hz)		
			#1	#2	#5
Top	72.24	(centre regraduated)	84	152	339
Top	72.05	(bassbar lightened)	84	156	346

The magnet was placed in an anti-nodal position for each plate mode; #1 at the lower left, #2 at lower centre and #5 at plate centre.

Table 4.9 Vibration parameters for the Top plate regraduated.

Plate	mode	f(0) (Hz)	df/dm (Hz/kg)	m (kg)	s (MN/m)	Z (kg/s)	Q	R (kg/s)	f(calc)
Top	#2	152	2000	0.038	0.035	37	38	1.0	153
	#5	339	2173	0.078	0.135	165	42	4.4	337

4.5 The Properties of the Soundpost

The soundposts used for the Baroque setup were lighter than those adopted for the converted violin and used in most modern setups. The properties of the ones used in this study are shown in table 4.10 below. 'S' is the longitudinal stiffness in compression.

Table 4.10 Physical properties of the soundpost used.

Soundpost type	Baroque	Modern
mass (g)	0.355	0.701
length, l (mm)	52.5	52.0
diameter, d (mm)	4.5	6.4
density, ρ (kg/m^3)	425	419
sound velocity, c (m/s)	5833	5526
E_L (= ρc^2 GPa)	14.5	12.8
S (= Ea/l MN/m)	4.39	7.9
Z (kg/s)	39.5	74.4

The position of the soundpost is given by the notation e.g. 5/15, indicating that the distance, between nearer surfaces, of the soundpost from the treble foot of the bridge is 5 mm and it stands 15 mm in from the treble soundhole. The bridge is aligned with the back face on the line between the notches in the f-holes representing the stop of the violin.

4.6 The Measurement of String Tension

The tension in the strings, used in this study, when at A 415 Hz on the violin was measured by noting the deflection under load. The violin was mounted on its side on a surface plate with the strings in a horizontal position. A mass of about 100 g was attached to the centre of the string to be measured and the resulting deflection found with a measuring microscope. For a string length, L, and deflection, x, the expression for string tension, T, for small deflections is: $mg = 2T\cos\theta$ where θ is the included angle between the direction of action of the attached mass and the deflected string. Therefore cos θ = 2x/L. The tension, N = mgL/4x in Newtons.

Two sets of gut strings were measured; a medium set of Pirastro Chorda strings with a wound G string that was used for the preliminary playing test. A set of heavier gut strings, again with a silver wound G string, were used for most of the playing tests and shown in the tables below.

Table 4.11 measured string tensions of Pirastro Chorda strings. Vibrating string length 318 mm.

Chorda strings	Pitch (Hz)	dia. (mm)	area (mm^2)	Linear Density (kg/m)	Tension (N)	Impedance Z(kg/s)	Vibrating mass (g)
E	623	0.59	0.27	0.00035	53.7	0.137	0.111
A	415	0.72	0.41	0.00053	38.7	0.143	0.169
D	277	1.02	0.83	0.00107	33.0	0.188	0.34
G	184	0.77	-	0.0022*	24.1	0.230	0.70

* The string was weighed and its length measured to obtain an equivalent gut density. Gut density 1300 kg/m^3.

Some specialist string makers provide gut strings especially suited to the requirements of the Baroque violin player. Ephraim Segerman at N.R.I. in Manchester U.K. is one such. Typical of these strings and ones used for the major part of this work, have the tensions measured and shown in table 4.12.

Table 4.12 Measured tensions for special gut strings used in this study, vibrating string length 318 mm.

Strings	Pitch (Hz)	dia. (mm)	area (mm^2)	Linear Density (kg/m)	Tension (N)	Impedance Z (kg/s)	Vibrating mass (g)
E	623	0.55	0.228	0.00031	50.4	0.125	0.099
A	415	0.82	0.528	0.00069	50.8	0.187	0.219
D	277	1.16	1.057	0.00137	39.8	0.234	0.486
G	184	0.87	-	0.00274	38.3	0.324	0.871

The total string tension in these two cases was 150 N and 180 N respectively. Figure 4.9 shows the setup for measuring the string tension.

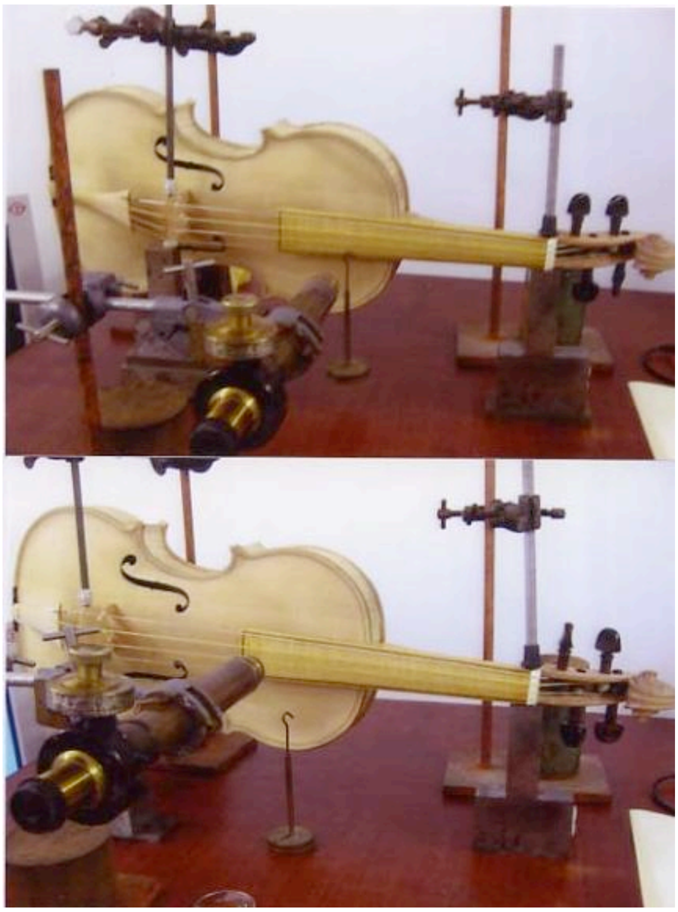


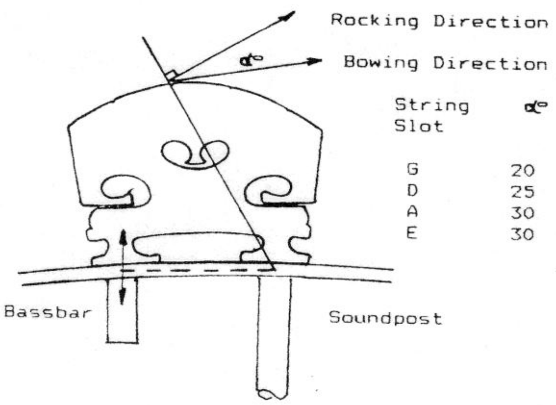
Figure 4.9 The setup for the measurement of string tensions as listed in Tables 4.10 and 4.11: Top: bridge in standard position, Bottom: bridge below f-holes.

It might be appropriate at this point to mention the thinking on the use of strings. In Baroque times it was recommended [5] that the strings should be of equal tension. This was thought to provide a uniform feel when stopping notes and applying bow force. This may have been adequate at the time since the clearance of the strings at the fingerboard was probably uniform due to a low arched bridge top.

Today, the bridge is more arched and the string clearance varies increasing from the E string to the lower strings, invalidating this advice. The tension in strings used today decreases in going from the E string to the G string. This has raised a different criterion for their selection. Schumacher [6] has suggested that string impedance should be made equal on all strings. With this string/fingerboard setup the feel would be fairly constant. complicated and involves the bridge contour, string angle and string mass.

Looking at the strings used in this study, table 4.10, the string tensions for the Pirastro Chorda gut strings, decreased from the E string to the G string. The impedance increased from about 0.14 to 0.23 kg/s. Plain gut strings favoured by Baroque players had equal tensions on the two top strings of 50 N and 40 N on the two lower strings. The impedances progressively increased from 0.13 kg/s on the E string to 0.32 kg/s on the G string, table 4.12. This set of strings satisfies neither criterion; equal tension or equal impedance.

Another factor in the transfer of force to the top plate is the lever ratio of the bridge. Figure 4.10 gives an example of the geometry of the bridge. With a ratio less than one, about 0.75 to 0.85, which applies to the lower strings and about 1.0 for the two upper strings, the force will be increased at the bass foot of the bridge for the two lower strings. This will be the case if the pivot point is taken at the treble foot of the bridge. Should it be a little inside the foot so the soundpost can act on the back, the above situation will be little changed. Moving the soundpost out toward the treble f-hole would enhance the transfer to the back. The impedance for the strings will be modified by the bridge and top plate for the transfer of force.



String Slot	α°	cos α	lever ratio
G	20	0.94	46/30
D	25	0.91	41/30
A	30	0.87	36/30
E	30	0.87	29/30

Figure 4.10 an example of bridge lever ratio geometry.

4.7 Strings used for the main Playing Tests

The values above were for the bridge at the notch in the f-holes giving a string length of 318 mm. Player tests were also done with the bridge below the f-holes which involved a string length of 356 mm. For a tuning of A 415 Hz and a necessarily higher bridge, the string tensions were higher as shown in table 4.13. The gut strings were the heavier strings used with the Baroque setup.

Table 4.13 Measured string tensions as fitted to Baroque violin. Bridge height measured from top plate centre -line.

String	Bridge Height (mm)	G	D	A	E	Total	Down-bearing (N)
Dia. (mm)		0.87	1.16	0.82	0.55		
Bridge at f-holes Tension (N)	38	38.3	39.8	50.8	50.4	179	74
Vibrating mass (g) 318 mm		0.871	0.436	0.219	0.099		
Br. Below f-holes Tension (N)	44	55.3	40.8	61.1	56.0	213	120
Vibrating mass (g) 356 mm		0.975	0.488	0.246	0.110		

The conversion from Baroque to Romantic setup involved replacing the neck/fingerboard resulting in a longer string length (by 10 mm) but little change in bridge height. The higher tuning to A 440 and heavier strings, gave somewhat higher string tensions as shown in table 4.14. The set of Thomastic Dominant strings had synthetic cores and the E string was a steel wire which is the modern practice.

Table 4.14 Modern setup: String length 328 mm, Tuning A440

String	Bridge height (mm)	G	D	A	E	Total	Down-bearing (N)
Gut: Dia (mm)		0.89	1.16	0.82	0.55		
Tension (N)	37	58.5	45.9	58.1	53.9	216	93
Vibrating mass (g)		0.899	0.449	0.226	0.102		
Dominant Dia. (mm)		0.80	0.81	0.68	0.33		
Tension (N)	35	37.7	44.9	57.3	77.9	218	94
Vibrating mass (g)		0.485	0.390	0.269	0.157		

The gut strings show an even tension across the violin except for the D string which was a ‘high twist’ string for greater flexibility. The Dominant strings show a rise in tension across the violin.

It will be noticed in tables 4.11 and 4.12 that the vibrating mass of ‘Chorda’ strings which were used for the first playing tests is smaller than that of the heavier gut strings used for the remainder of the study. In table 4.13 showed that the string mass was raised by placing the bridge below the soundholes. These figures were for tuning to A415. Tuning to A440 raised the vibrating string mass for gut strings. Also in table 4.13 the modern strings had a more uniform mass distribution. This data can be drawn together in a table 4.15 for comparison.

Table 4.15 comparison of string vibrating mass (g) for the strings used.

	Tuning A415			A440	
Bridge position	at f-holes		below f-holes	at f-holes	
String	Chorda	Gut	Gut	Gut	Dominant
E	0.111	0.099	0.110	0.102	0.157
A	0.169	0.219	0.246	0.226	0.269
D	0.340	0.486	0.488	0.449	0.390
G	0.700	0.871	0.975	0.899	0.485

Regarding the downbearing force that the component of the string tension exerts on the top plate through the bridge, not only the magnitude but the direction also is important. Traditionally, the rear surface of the bridge, that facing the tailpiece, was set normal to the plane of the violin, which was defined by the glue line between the sides and the top. In this violin the glue line along the centre of the top, coincided with the centreline of the instrument. On the baroque instrument, the string slots on the nut lay in this plane. The angle at which the neck was set in the top block of a modern violin together with the height of the neck step or overstand, is designed to ensure this alignment.

The geometry of the setup determines the direction of the downbearing force. It has always been understood that this should lie within the thickness of the bridge for structural stability and, in the case where it lies outside the thickness of the bridge on the side of the fingerboard there is a likelihood of the bridge bending in that direction. The direction of the downbearing force is the bisector of the included angle made by the strings as they pass over the bridge. This however, is not normal to the plane of the violin, defined above. The larger this included angle the closer is the direction of the downbearing force to the normal of the plane of the violin. Raising the saddle height increases this angle.

As an example for a modern setup, a top arch of 15 mm, string length 325 mm, a saddle height of 7 mm and a bridge 36 mm high give an included angle of 155° at the A string.

The D string will be similar but the G and E strings, which sit lower due to the curvature of the bridge top, will give a slightly larger included angle.
In this example, the line of action lies 3.5° from the vertical. For a bridge with feet 4.5 mm thick, the direction of the centre line is 2.5° from the vertical so that the line of action of the force is 1° closer to the fingerboard side of this centre line. This is well within the thickness of the bridge.

By lowering the bridge height to 34 mm the included angle, at the A string, is 157° and the direction of the force is 0.2° on the tailpiece side of the thickness centre line for bridge feet 5 mm thick.

For the Baroque violin used in this study, with a Renaissance bridge 38 mm high placed at the notches in the soundholes, a string length of 318 mm and all other alignments as given above for the modern setup, the included angle was 154°. The bridge feet were 6 mm thick which gave the angle of the downbearing force 3.1° inside the vertical surface of the bridge and 0.15° from the centre line of the bridge thickness, towards the vertical surface.

For the Romantic setup, with a bridge 34 mm high at the notches and a string length of 329 mm the included angle was 155.5°, the line of action of the downbearing force was 0.45° from the centre line of the bridge thickness on the fingerboard side. The downbearing force for both bridges lay within the thickness of the bridge.

For the case of the bridge placed below the soundholes on the Baroque setup, only an estimate can be made. The bridge was 44 mm high and the string length was 356 mm. The included angle becomes 153°. For bridge feet 4 mm thick in this example, the line of the downbearing force lies approximately 0.5° outside the sloping face of the bridge opposite the fingerboard.

4.8 The Conversion from Baroque to Romantic Setup

The conversion of the violin from the Baroque setup required the removal of the neck/fingerboard. This was done by first removing the top by splitting along the glue joint, removing the screws and separating the neck shoulder from the ribs and the button. A piece of paper had previously been put between the neck and the button to facilitate this operation. A film of part of this operation is available at www.phys.unsw.edu.au/music/people/mclennan.html

The top block was carefully removed, by cracking the glue joint with the back and wetting the rib. This was done to preserve the alignment with the Baroque neck for a possible later use. A new block was fitted and trimmed to the same dimensions as the one removed. The new neck/fingerboard assembly had then to be fitted. This required the shoulder to be squared off to allow for the overstand between the fingerboard and the top plate. A mortice was cut through the ribs and into the top block; the angles are important to give the correct alignment and allow for the correct bridge height and string clearance. The two necks are shown in figure 4.11 for comparison. The finished Romantic violin is shown in figure 4.12. The final mass of the violin was 450 g.

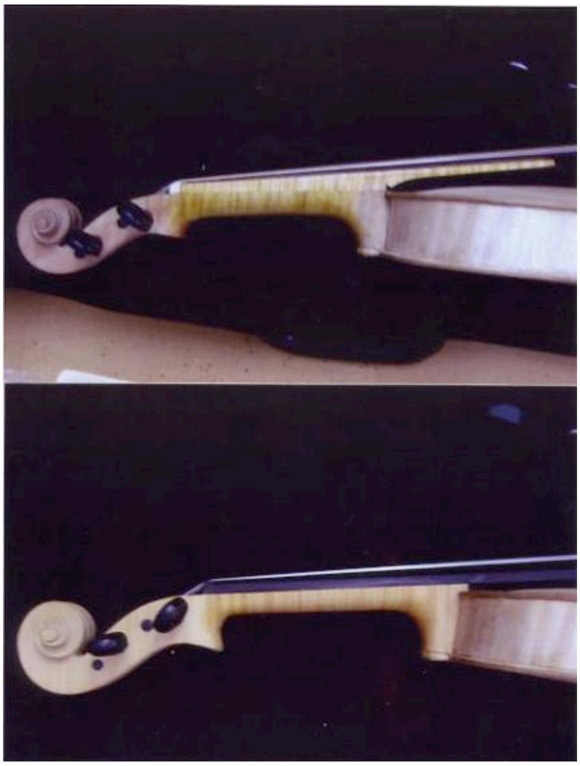


Figure 4.11 Comparison of the neck/fingerboard assembly of the Baroque (upper) and Romantic (lower) violin.

Figure 4.12 The Romantic (modern) violin with gut strings

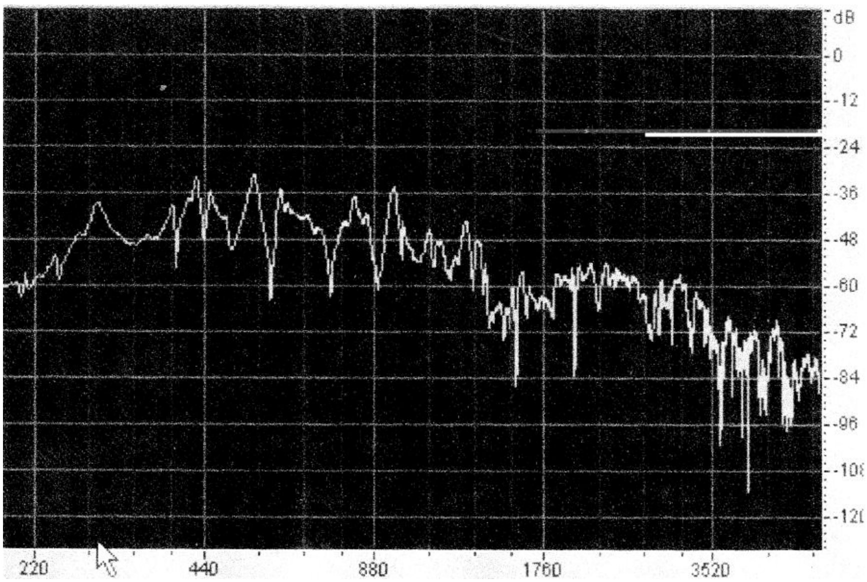


Figure 4.13 Tap response of converted violin. Gut strings A440. Modern bridge 2.19 g 37 mm high at the f-hole notches, soundpost 6 mm at 6/18.

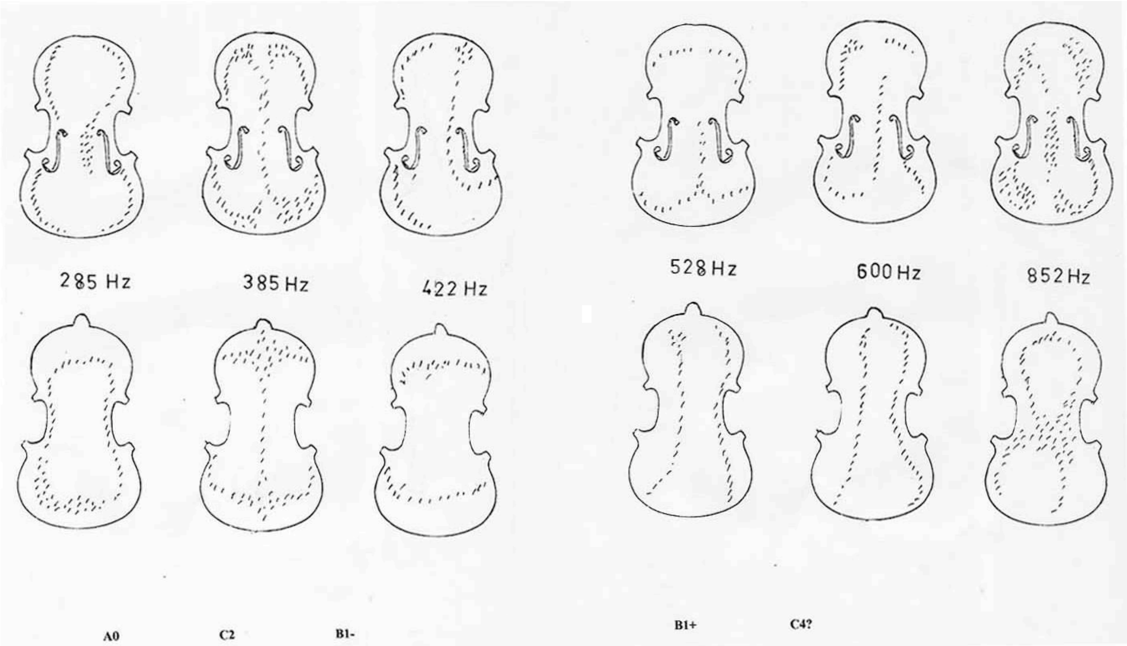
A Tap Response for this violin is shown in Figure 4.13. The violin was fitted with gut strings, a modern bridge (2.21 g and 37 mm high) and with the soundpost (6.4 mm dia. at 6/18). The bridge was set at the notches in the f-holes. It can be seen that the violin has present all the main resonances found in a well made violin. These are displayed in figure 4.14. Also included in this figure are sketches of the nodal lines for the Chladni patterns obtained for the converted violin, as some may appear indistinct. Using accepted nomenclature, they are A0 (285 Hz), C2 (385 Hz), B1- (T1) (420 Hz), A1 (480), B1+ (C3) (528 Hz) and C4 (600 Hz). Two higher modes present at 852 Hz and 950 Hz in this violin were not as prominent with the change in soundpost. The mode parameters for some of these modes were determined and are summarised in table 4.16.

Table 4.16 Summary of measured vibration parameters for resonances of the modern violin showing effective mass, m, and stiffness, s, the total resistance to bridge motion, R (see chapter 5.5)

Mode	f(0) (Hz)	df/dm (Hz/kg)	m (kg)	s (MN/m)	Z (kg/s)	Q	R (kg/s)	f(calc)
A0	286	4.25×10^6	0.034	108 N/m	1.92	14	0.14	--
C2	386	2943	0.066	0.39	160	77	2	387
B1--	423	2571	0.082	0.58	218	47	5	423
B1-- (2)	420	2229	0.094	0.66	249	47	5	422
B1-	450	554	0.41	3.27	1158	56	21	450
B1- (2)	447	514	0.44	3.43	1229	45	35	446
B1+ (2)	528	3543	0.074	0.82	196	38	5	530
B1++	540	4143	0.065	0.75	221	49	5	541
C4?	586	2771	0.106	1.43	289	84	5	585
?	878	1229	0.36	10.9	1978	37	54	875
?	944	19457	0.024	0.85	139	79	2	947

The second determination of the B1 modes shows the variation that can occur when the setup is altered slightly. The soundpost in this case, 5.8 mm dia. was in a different position at 5/15 i.e. 5 mm behind the bridge foot and 15 mm in from the treble f-hole, measured from the nearer surfaces. Most of the body modes were good radiators with the exception of B1- which probably had a small monopole content.

While positive identification of peaks labelled B—and B++ has not been done, it is known that the B1+ peak has shown a variant when the neck was in torsion giving a lower frequency than when in bending, Marshall [8] (private communication). Labelling resonance peaks is uncertain without direct identification with a Chladni pattern which in turn may not be a pure resonance pattern, as mentioned earlier chapter 3.7, but an Operating Deflection Shape. Strong peaks are likely to have Chladni patterns close to that of the true resonances.



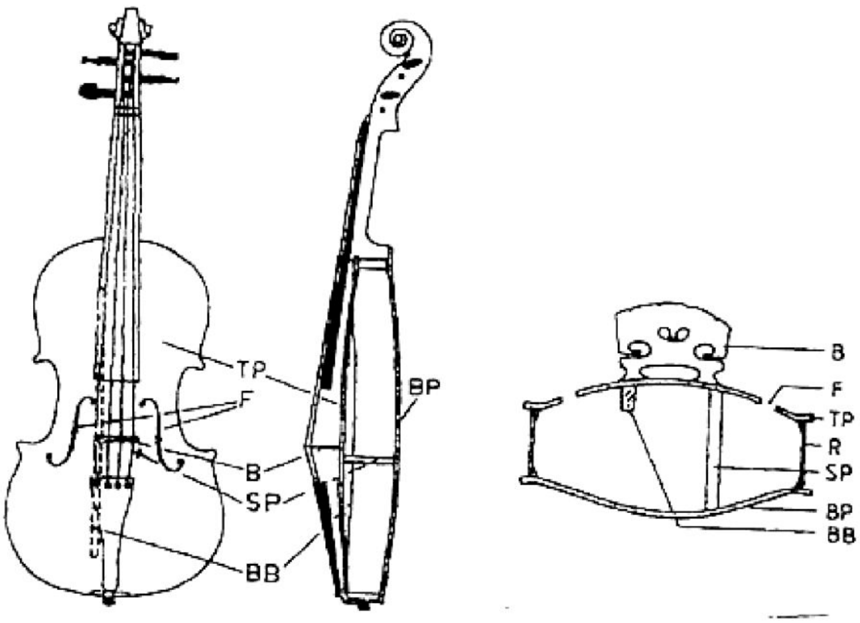
A0 C2 B1- B1+ C4 ?

Figure 4.14 Idealised Chladni patterns (top) and photographs (below) for the vibration modes in the Romantic violin

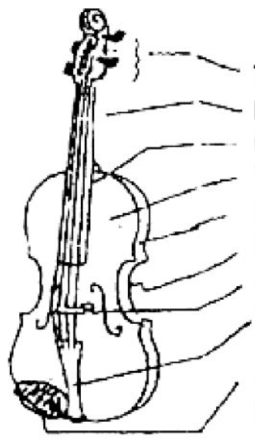
4.9 Summary

A violin has been constructed in the Baroque style using classical hand making methods. It has been converted to the Romantic or modern setup by replacing the neck and fingerboard. Every stage of the construction was explored for physical and vibration parameters of the parts as well as the completed instrument. The measurement methods are outlined in detail in the next chapter and subsequently used in the chapters following for detailed examination of other features of the violin.

The result of the making procedure outlined in this chapter is the violin shown in the frontispiece together with the Romantic version to which it was converted. The changes that are visible are the different neck/fingerboard, tailpiece and bridge. In the Baroque version the bridge is set below the soundholes as was commonly adopted to allow the gut strings to be more easily sounded. What is not obvious is that a lighter bassbar and soundpost (near the bridge) were fitted to the Baroque violin and a stronger bassbar and soundpost were fitted to the modern version. The parts of the violin are named and the actual masses for these two versions of the violin compared with typical values are shown in figure 4.15.



Outline of the violin seen from top, and sections seen from the side and the bottom end; bridge B, f holes F, top plate TP, ribs R, sound post SP, back plate BP, and bass bar BB.



	g	Baroque g	Modern g
Tuning pegs	15	116	165
Neck	85		
Fingerboard	65		
Top plate	80	72	75
Ribs	60	67	67
Back plate	110	117	117
Bridge	2	2	2
Tailpiece	20	5	14
Chin rest	35		
Total weight	450	379	440

Figure 4.15 Masses of violin parts (from Erik Jansson “Acoustics for Violin and Guitar Makers” 4th Edition 2002) with the masses for Baroque and Modern versions used in this study.

4.10 References

[1] Hargrave R. "Kreisler" del Gesu 2933, The STRAD 99 (1177) 1988 May, 403-406.

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Chapter 5

EXPERIMENTAL MEASUREMENT TECHNIQUES

5.1 Introduction

Three main measuring techniques were used. To reveal the resonances that contribute to the sound coming from the violin as simply as possible, an impulse method was applied. Both the mass of the impact bar and the microphone distance were studied. The impact bar chosen had a mass of 13.2 g. The output, or tap response, was mostly detected with a microphone placed 100 mm in front of the centre of the top plate. This was considered appropriate for resonances below 1 kHz. The input admittance was recorded with a small rare earth magnet (0.15 g) attached to the bridge. A second technique was to determine the Chladni patterns to delineate the nodal areas. This information allowed a choice of position for determining the effective mass and stiffness of selected resonances.

Two kinds of playing tests were recorded to provide sound samples from the two versions of the violin. One set employed professional violinists to play a set schedule and the other used a bowing machine to obtain modified Saunders Loudness Plots.

A range of other tests were used to obtain string tensions, downbearing forces, plate stiffness, etc.

The testing procedures have been those easily carried out on a bench with simple equipment except for a computer program that embodies Fast Fourier Transforms for the harmonic analysis of complex waveforms. Chladni patterns have been used to delineate both free plate and body resonance modes. The effective mass and stiffness parameters of resonances have depended on determining the dependence of resonance frequency on added mass; a small rare earth magnet (0.15 g) and a coil (~2000 turns and ~300 Ohms) was widely used to measure the velocity at selected modal points. These techniques applied to the violin parts investigated, are described in detail.

This study includes the determination of the vibration modes of the free plates and their Chladni patterns; determination of the mode frequencies of the resonances of the finished violin, their Chladni patterns and effective mass and stiffness; measurements of string tensions required to tune the gut strings used; the conduct of loudness tests and consideration of experimental variation where possible. Studies were also done on the main air resonance, A0, the fingerboard and the bridges used in the study. In general, the chinrest was not fitted for resonance studies.

Figure 5.1 frame and rubber band suspension used for determining the tap response, showing pendulum bar, the microphone and the magnet/coil.

5.2 Determination of the Frequency Response

The frequency response was determined by an impulse method. A hard tipped pendulum excites a wide range of frequencies in the violin, which enables the measurement of the Frequency Response Function, including the frequencies of the resonances present in the violin. The resulting Tap response was obtained with the violin (with strings damped) mounted vertically on a Dexion frame with rubber bands at the 4 corners and from the scroll. This suspension offers little restraint to the instrument and its resonance frequencies are much lower than those of interest. The strings were damped to remove their resonances from the frequency response. The treble edge of the bridge is struck by an aluminium rod (6 mm dia. x 15 cm long of mass 13.2 g with a rounded striking end and damped at the other with a foam collar to attenuate its own resonances) hung by two threads 10 cm long. A force sensitive plastic transducer was later cemented 5 mm from the striking end of the impact bar. This enabled the impact force to be measured if required. The sound response of the violin was recorded with a microphone at 100 mm in front of the bridge which would give those resonances that modulated the sound. Further, a magnet (0.15 g) and coil arrangement with the magnet glued to the bass edge of the bridge and a 300 Ohm (about 2000 turns of No 36 SWG enamelled copper wire) coil placed over it to record the motion of the bridge was also used. This would give all the mechanical resonances and record the input admittance since the coil would register the velocity of the magnet. Figure 5.1 shows the violin set up for a tap response with both a microphone and the magnet and coil in place. In operation the bar was places 5 mm from the bridge and withdrawn approximately 30 mm for the impact. The resonance frequency, f(0), was corrected for the impact bar mass.

The single tap response was analysed with commercial software ‘Cooledit 2000’ to give a plot of signal strength (dB) versus frequency to 4 kHz. For the present purpose this limit was regarded as sufficient as the output of the violin is known to fall off rapidly above 4 kHz. The sample rate was 44100 and 16 bits. The window used was Hamming size 8192 points. Successive taps gave good reproducibility.

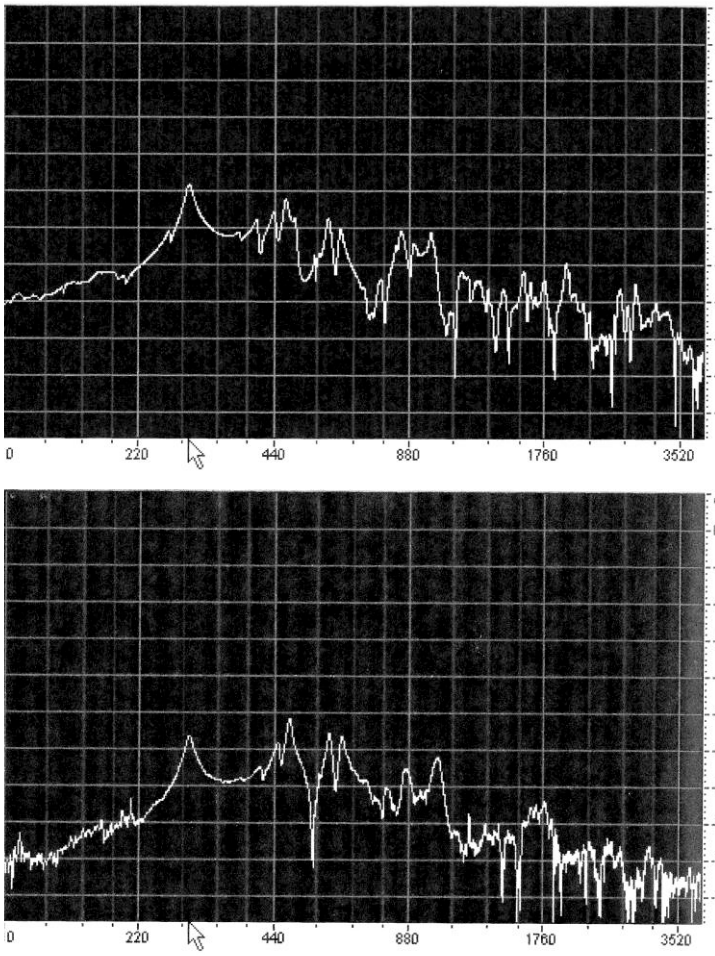

Figure 5.2 Tap response of Baroque violin, Chorda gut strings A415.
Upper plot: Soundpost 4.3 mm at 7/16, microphone at bass f-hole lower finial.
Lower plot: Soundpost 4.3 mm at 5/15, microphone at 100 mm in front of top centre.

5.3 Initial determination of Impact bar mass and microphone position

An impact bar was made from 6 mm dia. aluminium rod 150 mm long of mass 13.2 g rounded at the striking end and damped with foam at the other end. It was suspended by two 100 mm threads to give a pendulum that would be used to strike the treble edge of the bridge to excite the resonances present in the violin. Care was taken to set the distance from the edge of the bridge at 5 mm and the swing to 3 cm.

The sound from the resonances excited would be detected by a miniature microphone placed where all the resonances would be received with equal prominence. Positions in the soundhole, at 100 and 200 mm directly in front of the bridge were tried. In the soundhole the main air resonance dominated while at the two close positions the result was similar. Figure 1 shows the experimental setup. 100 mm was chosen for the position of the microphone as discussed in the addendum to this chapter.

The initial study of the position of the microphone was made by locating it in the lower larger finial of the bass f-hole. Two examples are given; figure 5.2 shows the difference in strength recorded for A0 when the microphone is placed in a soundhole compared with 100 mm in front of the top plate. A1 is not prominent in this figure. In this and subsequent similar figures, the horizontal axis is frequency in Hz and the vertical axis is in dB. A comparison response was recorded at 200 mm at centre front of the violin. The results are shown in figure 5.3.

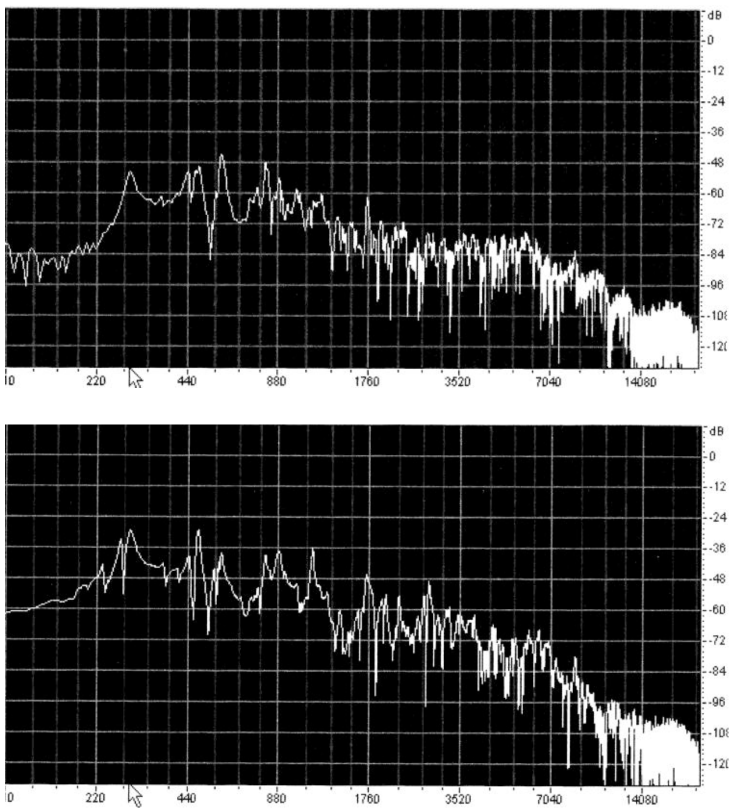

Figure 5.3 Tap response of Baroque violin Chorda gut strings A415. “Paris” bridge 1.365 g 30 mm high, soundpost 5 mm at 5/22.
Upper plot: microphone at 200 mm.
Lower plot: microphone at bass f-hole lower finial.

With the microphone in the soundhole the most prominent peaks of interest were A0 at 280 Hz and A1 at 485 Hz. B1- and B1+ are situated on either side of A1 but at a reduced strength. These two peaks become more prominent with the microphone at 200 mm and A1 is reduced in strength. A1 is the first higher air mode and has a pressure maximum at each end of the internal body space which largely determines the frequency at about 485 Hz governed by the length of the internal body space but radiates weakly. A1can be shown clearly by immobilizing the body as in the upper plot in figure 5.4 where the body modes are suppressed. In the lower plot, it appears that A1 is masked by a body mode, B1-, at 467 Hz.

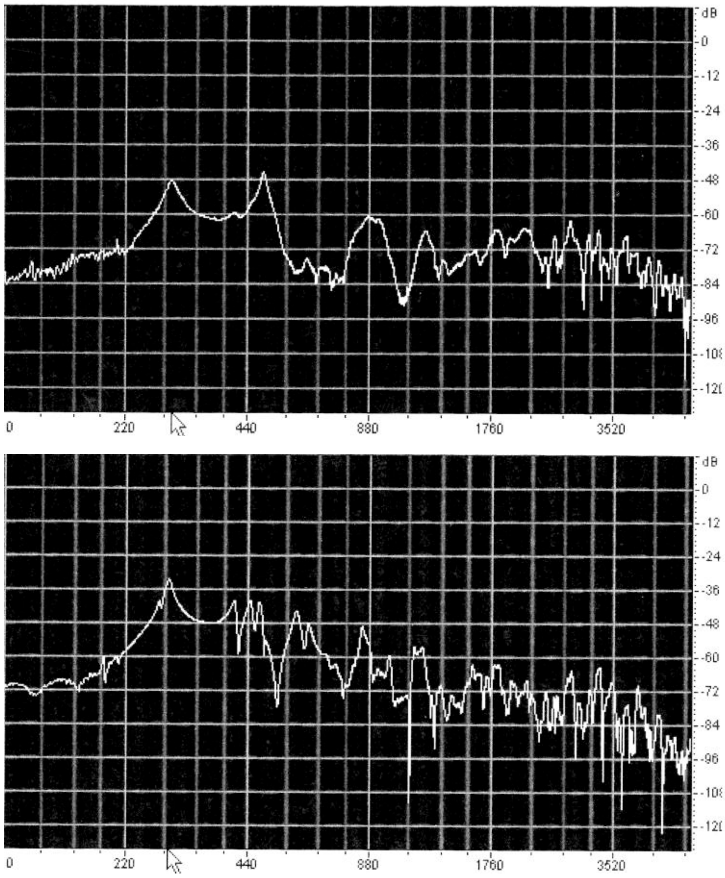

Figure 5.4 Tap response of Baroque violin at bass f-hole showing A0 and A1 air modes.
Upper plot: body immobilised, A0 at 287 Hz and A1 at 482 Hz.
Lower plot: body free, A0 at 280 Hz and A1 (again) at 482 Hz.

5.4 A comparison of Input Admittance and Sound Pressure Level curves

To investigate this experimentally, a force transducer (a stress sensitive plastic element) was attached 5 mm from the end of the pendulum bar with double sided adhesive tape. The tap was made on the treble edge of the bridge and would record the strength and duration of the pendulum tap. An input admittance curve using the magnet and coil attached to the bass edge of the bridge to record the response would receive two signals; one direct through the top of the bridge and the other induced by the interaction of the bridge with the body modes. This curve should record all mechanical resonances activated by the tap. A second response curve was obtained with a microphone placed generally at 100 mm in front of the violin which would give those peaks responsible for the sound radiated from the instrument. Both the signals and the response curves are shown in figure 5.5. The three time plots, from the top of the figure, are; (a) the response of the coil surrounding the magnet on the bridge to give the input admittance immediately below, (b) the time record next is the signal from the force element on the pendulum, and (c) immediately below that, the time plot of the signal from the microphone with the response curve below. The violin used was similar to the one made for this study with a modern setup and labelled No 2 in table 5.4.

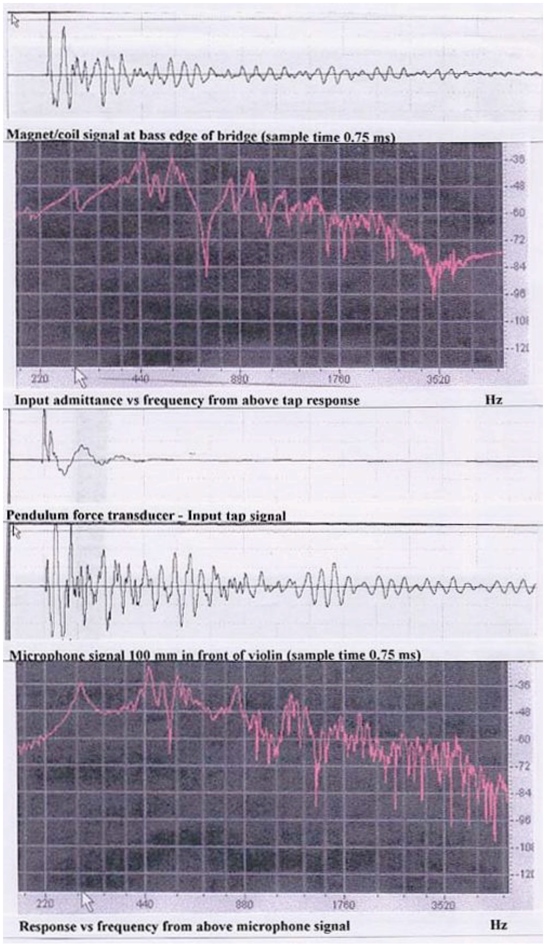

Figure 5.5 Frequency response curves: Top: Time plot using magnet/coil, second is spectrum of the above. Centre: Impact force transducer, time plot. Bottom: Time plot and spectrum for microphone.

It is interesting to observe, on figure 5.5, the difference between the strong effect of the A0 resonance on the radiated sound (lower spectrum) compared with the relatively weak effect of this resonance on the mechanical admittance (upper spectrum). The A0 resonance is largely due to the compliance of the air in the body.

The difference in the appearance of the main air resonance, A0, (arrowed in all response plots) between the input admittance at the bridge and the microphone response is due to how the phenomenon is displayed. Measurements at the bridge record the reactions of the body, the A0 peak is accompanied by an anti-resonance representing the Helmholtz frequency. The microphone records the sum of the output between A0 and the lower body modes where both have the same phase in this region.

5.5 Determination of Resonance Parameters

The violin itself (not counting the bow and strings) is regarded as a linear system as normally played by violinists who do not apply extreme forces to the instrument. The resonances can be regarded as damped mass/spring systems. In linear analysis, wood is approximated as a visco-elastic material and the playing forces are small compared with the static forces sustained by the violin with the strings at pitch. Typically, the total string tension is about 150 N whereas the forces exerted by the bow during playing lie between 1 and 4 N.

The violin has resonances of greatly different modal shapes. The easiest way to excite a resonance is at the anti-nodal point of maximum amplitude. Trying to excite a resonance at a nodal position would produce no motion; near the nodal position the effort required would be larger than near the maximum anti-nodal position. The effective mass and stiffness will be least near the anti-nodal position and become progressively greater as the nodal line is approached.

The body of the violin is excited by the feet of the bridge. The bass foot has been chosen in this study as the position where the effective mass and stiffness are determined because of its accessibility and a location where the bridge foot is likely to be near an anti-nodal maximum. A location near the treble foot would be too close to nodal lines. Ideally the position for this measurement would be the position of maximum amplitude of the anti-nodal area. An alternative method to the magnet/coil would be a force transducer under the bridge feet. Masses could be attached to the bridge top. The resistance felt by the bridge at the bass foot and the mode parameters are of interest to an understanding of the behaviour of the violin.

Resonances below 1 kHz are able to be studied in detail because they do not overlap and their Chladni patterns can be determined to show the nodal lines. A position near the bass foot of the bridge was chosen as a suitable location, away from nodal lines, to measure the change in resonance frequency with added mass, df/dm. From this was calculated the effective mass and stiffness for the resonance.

The violin was suspended over a speaker driven by a sine wave generator via an amplifier. The resonance parameters were determined by detecting the motion of a small magnet (0.15 g) attached to an anti-nodal region near the bass foot of the bridge with Scotch ATG 924 double sided tape (adhesive transfer tape) with a 300 Ohm coil (45 SWG enamelled wire ~2240 turns) via an amplifier to a Digital Voltmeter. Voltmeter readings at positions away from the peak (where possible) indicated very little baseline excitation. A frequency counter enabled an indication of frequency to the nearest 1 Hz. The Q value was found by measuring the bandwidth at 0.7071 peak height and dividing into the peak frequency. For the Q value to be reliable the peak had to be reasonably symmetrical. Q values were not obtained for every peak. One reason is the unreliability of this method for closely spaced peaks. The equations for effective mass and stiffness were taken from the work of Schelleng [1]. The effective mass and stiffness were calculated from the decrease in resonance frequency with the addition of small masses placed on an anti-nodal region, usually near the magnet. The masses were attached with double sided tape. The peak frequency was plotted against added mass, the slope yielding -df/dm (Hz/kg) used in calculating effective mass and stiffness for each resonance.

The effective mass, at a point and for a particular resonance at frequency f, can be defined in terms of the stiffness s measured at that point by $f = 1/2\pi(s/m)^{1/2}$. Later (below and in the appendix, §5.13) it is shown how this can be measured by the reduction in f as small masses are added at that point. The mechanical admittance A is defined as the ratio v/F of the velocity v of a point to which oscillating force F is applied. If an impulsive force is applied, the frequency components have equal amplitude, so the resultant velocity spectrum gives A, within a multiplicative constant. An example of this is figure 6.1.

The effective mass was obtained from:

$$m = -\frac{f}{2\frac{df}{dm}} \quad \text{where f is the resonance frequency.}$$

The effective stiffness was obtained from:

$$s = -\frac{2\pi^2 f^3}{\frac{df}{dm}}$$

From these values for m and s the effective impedance, $Z = (ms)^{1/2}$ and in turn, $R = Z/Q$, was obtained. Schelleng defined this as the total resistance to bridge motion.

Schelleng calculated the approximate radiation resistance from the average plate amplitude, the motion at the bass foot and the area of the two plates to determine the equivalent piston area, and from this using his equation:

Resistance to bridge motion, $R = \rho_o f^2 A^2/c$ Where:

ρ_o is the density of air, 1.2 kg/m^3
c is the velocity of sound in air, 342 m/s
A is the area of the equivalent piston for the resonance concerned, and
f is the resonance frequency.

The R values quoted throughout the thesis are the total resistance to bridge motion following Schelleng. Body modes below 1 kHz might be expected to have similar "equivalent piston areas" different from that of the main air resonance. Schelleng finds an area of 0.017 m^2 for B1-. It might be reasonable to assume the radiation resistance of body modes to be about 10% of the figures for R in the tables. This tells us that a low value of R will result in a good radiator in line with the tap response peaks.

To study A0 a different approach is required with a new formulation for R.

The success of the Schelleng equations depends on the determination of df/dm. There is a linear relation between the lowering of the resonance frequency and the mass added to an anti-nodal region (for small added masses). Ideally, the mass should be added at the position of maximum amplitude for the mode studied. A compromise was reached with the violin when masses were added to the top plate. A position was chosen near the bass foot of the bridge as this was an anti-nodal position for those resonances connected with the production of sound and, although not necessarily a position of maximum amplitude, would be where the bridge would connect with the resonance.

The frequency of the resonance was obtained from either the tap response, the value recorded with the magnet attached, including other experimental determinations, f(expl), or that calculated from the linear regression labelled f(0). The slope, df/dm, from the graph was rounded to the nearest 10 if estimated visually, while the linear regression was rounded to the nearest unit and gave coefficients above 0.95 and mostly 0.99. The final column in those tables that list the mode parameters shows the frequency, f(calc), calculated from the effective mass and stiffness. Comparison of this with the measured resonance frequency gave a check on the validity of the visually estimated slope of df/dm.

The values of m, s and quantities derived from them, depend on the position at which they are measured. The position was chosen here because it was an easily accessible point that is close to the bass foot of the bridge, and is the same for all resonances. The bass foot is arguably the most important position: this foot is not supported by a sound post, and so it has a larger amplitude of motion than the treble foot. Consequently it is here that, in most cases, most of the power is transmitted from the bridge to the body.

For these tests, the violin was suspended by rubber bands at the 4 corners and the neck from a metal frame over a 10 cm orifice above the speaker. This arrangement enabled Chladni patterns on both front and back to be easily obtained. Figure 5.6 shows the violin suspended over the speaker (with the orifice plate removed).

The Schelleng equations are derived in the appendix from the fundamental equation for the resonance frequency:

$$f = \frac{1}{2\pi}\sqrt{\frac{s}{m}}$$

The lowering of peak frequency with added small masses was determined.

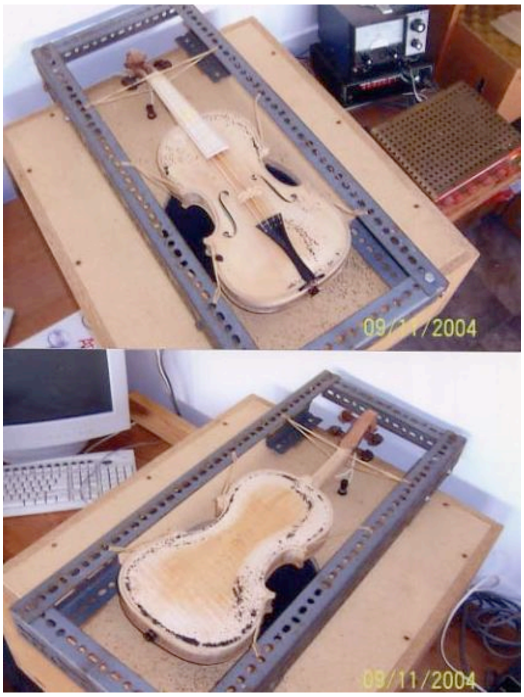

Figure 5.6 frame and rubber band suspension for determining Chladni patterns and resonance characteristic parameters

The location of the sensor and the small masses was placed near the bass foot of the bridge as shown in figure 5.7. This position seemed to be the best practical compromise as described above. The same small magnet (0.15 g) was attached to the top plate, allowing for the coil to be placed over it, and masses were placed nearby as shown. The signal from the coil was amplified 10x and indicated on a digital voltmeter. The peak maximum was recorded for each mass added to give a plot of df/dm against added mass. Examples of these results are shown in figures 5.8 and 5.9. Example plots in figure 5.8 are taken from results for the violin in the Baroque setup with the bridge in two positions i.e. at the notches in the f-holes and at a position immediately below the f-holes. For body resonances, masses up to 5 g gave satisfactory results with good regression coefficients; beyond 5 g results were erratic. The value of resonance frequency at zero mass obtained by extension of the df/dm plot to allow for the mass of the magnet only became important at high frequencies and high numerical values of df/dm. Figure 5.9 shows results for the violin in the Romantic setup with gut and modern strings. The gut strings were tuned to A415 and the modern strings to A440.

Figure 5.7 Arrangement of magnet/coil near the bass foot of the bridge and the placement of the added masses for determining df/dm.

The change in frequency with added mass was plotted and analysed by linear regression. Most df/dm plots had an accuracy with a regression coefficient greater than 0.98 and for an accuracy of frequency measurement of +/- 1 Hz, this was very good. The difference between the extrapolated f(0) and f(calc) will be small but larger between f(exp) and f(calc) where the slope of the plot is steeper. (The values of slope are not rounded in the tables. They are rounded on the graphs.)

The most important parameters are the mode frequency, f(0), and its Q value. While the effective mass, s, at the bass foot of the bridge is of interest, a value at the top of the bridge would relate directly to the player reaction. Some input admittance plots were done but the parameters for the resonances were determined near the bass foot of the bridge.

The df/dm lines for A0 in figures 5.8 and 5.9 refer to the motion of the body. The plot for the air is steeper and will be discussed in chapter 9.7.

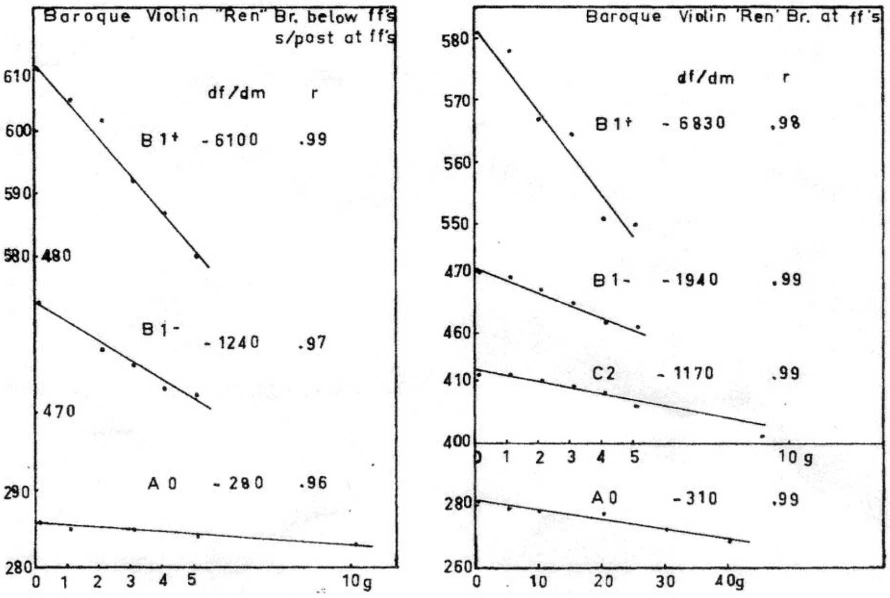

Figure 5.8 plots of df/dm for the Baroque violin, Renaissance bridge at the f-hole notches and below the soundholes, soundpost at the f-hole notches.

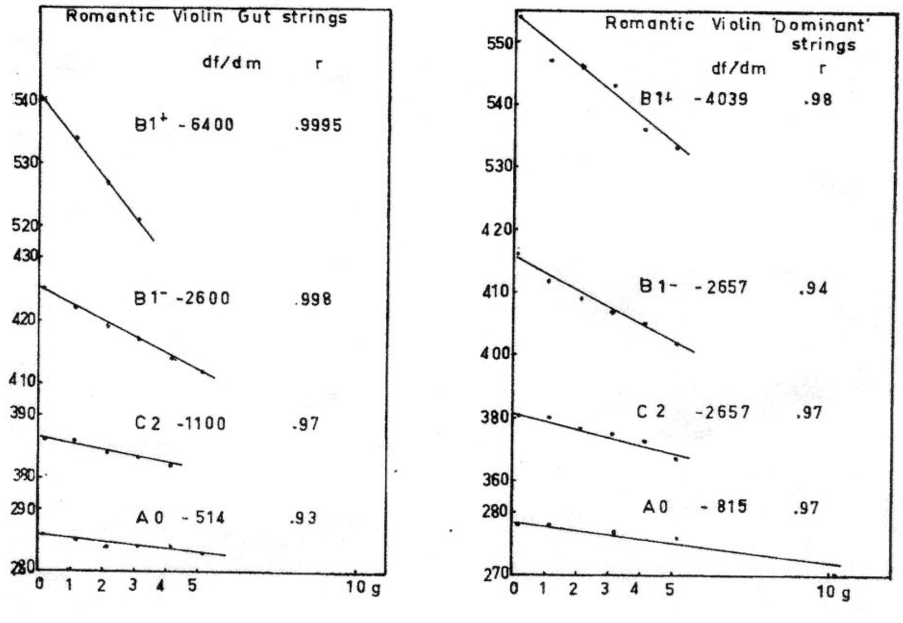

Figure 5.9 plots of df/dm for the Romantic violin, modern bridge at the f-hole notches. Gut versus Dominant nylon cored strings.

5.6 The Measurement of Effective Mass and Stiffness

The characteristics of each mode of vibration of the violin will depend on where the measurement is made. Each violin will be different in the nature of these characteristics. For the violin considered here, the number of modes present will be represented by resonance peaks in the tap response.

Table 5.1 Transformed violin, Body mode B1- (Chinrest, 42 g, fitted)

Position	f(0) (Hz)	df/dm (Hz/kg)	r	m (kg)	s (MN/m)	Z (kg/s)	Q	R (kg/s)	f(calc) (Hz)
Top: bass bridge foot	416	1800	0.96	0.104	0.71	277	38	7	416
Back: centre	417	1000	0.96	0.21	1.43	548	35	16	415
Back: lower bout	416	840	0.99	0.25	1.70	652	26	25	415

Table 5.2 Transformed violin, Body mode B1+ (Chinrest, 42 g, fitted)

Position	f(0) (Hz)	df/dm (Hz/kg)	r	m (kg)	s (MN/m)	Z (kg/s)	Q	R (kg/s)	f(calc) (Hz)
Top: bass bridge foot	554	1800	0.98	0.15	1.87	530	31	17	555
Back: lower bout	557	2027	0.97	0.14	1.7	488	31	16	555
Back: near nodal line	560	2037	0.97	0.14	1.7	488	26	19	555

The vibrating string drives the body through the bridge at the bass foot as well as the treble foot. The soundpost limits the movement of the treble foot to that related to the stiffness of the top and back at the treble foot. The motion at the bass foot of the bridge is dependent on the stiffness of the body at the bass foot. A point in the centre of the back and a point on the back in the lower bout were also chosen for a survey of the two main body resonances. The vibration parameters calculated using the method described above are shown in tables 5.1 and 5.2. The Baroque violin had been transformed to the modern setup with Dominant strings tuned to A 440. The chinrest had been left on. It appears that the chinrest has lowered B1- which is at about 460 Hz without the chinrest. The chinrest was attached at the bottom block arching across the tailpiece. This would add weight to the anti nodal area of both mode B1- and B1+. B1- seems to have been affected more than B1+.

The reliability of these results depends on the accuracy of the determination of df/dm. It has been found that consistent results for body modes are obtained with added masses below 10 g. The main air mode could tolerate masses up to 20 g and still yield a linear result for df/dm. Attaching the masses effectively was important and double sided adhesive tape was used in this case.

5.7 Playing Tests

Two kinds of playing tests were done. In one set, violinists bowed an octave of semitones on each string, *forte* with no vibrato, followed by short pieces that allowed them to assess the playing qualities of the instrument. This was repeated with the violin converted to the Romantic setup. The second kind of test was an octave of semitones on each string played with a bowing machine [2]. In both cases of this kind, the strength of the notes played was recorded with a Sound Level Meter. Tests were done in a semi-reverberant room which allowed meaningful results to be obtained with one microphone. This was placed about 1 m in the plane of the violin on the treble side. The position was not critical up to 1 kHz; above this the position chosen was a satisfactory compromise [3].

Both baroque and modern bows were used for the appropriate tests. These were supplied by the players, which gave the advantage of familiarity. Preliminary playing tests were carried out on the violin in Baroque setup at first with no bassbar and then with a light bassbar installed. The main series of tests was made with the violin in its final condition, the top with the final graduation and fitted with a light soundpost and bassbar. These trials employed three professional violinists. The entire test sessions were recorded on CDs for archiving.

One set of playing tests was done with the bridge placed below the f-holes as depicted in many paintings of the Baroque period. Recent research [4] has suggested that the placing of the bridge in this position was done to ensure a quicker response of the strings to the bow.
Extracts from the recordings of the playing tests are available at
www.phys.unsw.edu.au/music/people/mclennan.html

Analysis of the playing tests was done by averaging the sound level recorded from the Saunders Loudness Tests, SLT, for notes below 600 Hz and those above 600 Hz. The main body modes occurred below 600 Hz while above 600 Hz notes on the E string and a preponderance of plate modes occurred. Recorded violin phrases were analysed by determining Long Time Average Spectra for different combinations of variables. The LTAS plots are presented in chapter 7.

5.8 Effect of Sound Level Meter Weighting

Sound Level Meters can be set to weight the readings of sound pressure recorded. An ‘A’ weighting lowers the response below 1 kHz and above about 4 kHz, to compensate for the behaviour of the human ear [5]. The ‘C’ weighting has a more level response. For the low range of the violin beginning at 200 Hz, the A weighting is about 10 dB down rising to zero at 1 kHz.

To explore this, two comparison tests were done measuring the strengths of notes on the G string with fundamental frequencies ranging from 200 Hz to 400 Hz which effectively covers the violin range affected by the A weighting. A bowing machine (8) was used with a ‘bow’ force of 2 N, a ‘bow’ position of 35 mm from the bridge and a ‘bow’ speed of 0.4 m/s. Both the gut cored Pirastro ‘Chorda’ G and the nylon cored Thomastic ‘Dominant’ strings were compared on the same violin. Both A and C weightings are shown in the table below.

Table 5.3 bowing machine comparison of two G strings, sound level (dBA) and Standard Deviation (SD).

String		Chorda	Dominant
Average strength	dBA (SD)	84 (4)	85 (4)
	dBC (SD)	88 (5)	90 (4)

The average strength was that for an octave of semitones played on the G string, the Standard Deviation (SD) was that for the thirteen values in the octave. This table shows a difference of about 5 dB between the two weightings for the G string.

5.9 Saunders Loudness Tests

The assessment of sound output of a violin is very difficult. When a note is bowed everything on the violin that can be activated by the vibrating string will be. The contribution to the sound output will depend on how strongly this excitation takes place.

For assessment one has Saunders Loudness Test's, (SLT), Long Time Average Spectra, (LTAS), and harmonic analysis of the bowed notes. Added to this is the use of vibrato and playing loudly or softly as well as bowing near the bridge or the fingerboard. In conjunction with the microphone response curves, the SLT can correlate with the peaks present when notes fall in their vicinity. This requires very consistent bowing technique for which a bowing machine may reduce the number of variables. The LTAS is done on a musical passage and inherently includes many variables. The SLT is the least sophisticated test and can show peaks at notes related to the main air resonance, body resonances and the enhancement of lower notes by a second harmonic that coincides with a body mode. These effects are generally noticed in the lower range of the violin below about 1 kHz.

The Saunders Loudness Test is a quantitative test devised to measure the loudness of notes as they are played on the violin. F.A. Saunders [6, 7, 8] used this method to highlight pronounced resonances in the response of an instrument. He bowed very loudly to excite the main resonances by their effect at the fundamental frequency. He was able to identify the main air resonance at 280 Hz and a main wood resonance at 500 Hz in many early Italian violins. The strength of a note includes the effect of any contribution from the violin, notably harmonics of the fundamental that coincide with either a resonance peak of an anti-resonance trough. Saunders found that the main wood resonance at 500 Hz gave a peak an octave below at about 250 Hz. Vibrato is avoided to remove a variable that would tend to even out the effects sought. The usefulness of the test is limited because of several factors. These are; the directional nature of the sound emitted, up to 1 kHz the violin radiates approximately equally in all directions allowing one microphone to be used. Above this the average of more than one microphone is required. While a given level of output may be aimed at by the player, precise control of variables, bow force, bow position and bow velocity are not exact. A bowing machine can limit variation but there still remains the position of the finger stopping the note on the fingerboard.

A modified version of Saunders Loudness Test has been used in this study. The aim has been to determine the sound level on each string and ascertain the evenness across the range of the instrument. To excite participating resonances a *forte* level has been used and the microphone has been placed 1 m from the violin in the plane of the instrument on the treble side as a practical compromise. A sound level meter was used to measure the strength of the notes in dB. The note played contains the effect of all the overtones and the effect of the violin resonances. The average output from each string can be obtained in this way and can be related to the position of the soundpost [9]. Both hand and machine bowing was used for this purpose.

The average loudness (dB) for the notes on the three lower strings <600 Hz (notes G3 to E_b5) was calculated and the average for notes > 600 Hz (notes E5 to about A6) was calculated. The latter average was essentially for the E string except for six notes in the octave on the upper A string. This division at 600 Hz is made on the basis that the fundamentals of notes on the three lower strings occur in the region where the body resonances mostly also occur. Strong fundamentals are essential for good violin performance. Notes on the E string reflect the input of upper air and plate resonances rather than body resonances. The precision of these measurements was not expected to be high. For the bowing machine the estimate was +/- 1 dB but it was not possible to get an estimate for the hand bowed tests. One can look at the average level for each string to judge the evenness over the range and where the same note is played on two strings the level of agreement may be used to judge precision. However a change of string involves a change in string impedance which may be compensated for automatically by the player. The position of the finger on the fingerboard in this case may also introduce an error.

5.10 Measurement of Top Plate Stiffness

An attempt was made to determine the stiffness at the G and E string slots as felt by the strings. This was done by clamping the violin at the four corners and direct loading through a sensitive dial gauge with masses up to 200 g. Care had to be taken to ensure the violin was firmly based. It was necessary to tap the top plate to allow the system to adjust after adding each increment of mass. The dial gauge preloaded the violin 100g.

The top plates of the converted violin and violin No 2 had the same type of arching of height 15 mm. Violin had a top with a flatter arching 13 mm high. The soundposts were left in their original positions; the converted violin and No 1 at 5/20 and No 2 at 5/22. The effect of soundpost position on top plate stiffness is dealt with in chapter 8.10. The static deflections of the top plate at the Bass and Treble bridge feet were done by direct loading on a special, “plate” bridge with no cutouts and strings at pitch, on a violin very similar to the one in this study so as not to risk this instrument. Loads up to 200 g were used. The violin was mounted on a surface plate, on steel pillars capped with polythene buttons at the four corners. The stiffnesses are listed in table 5.4. Figure 5.10 shows the setup for measuring the stiffness at the treble foot of the bridge.

Table 5.4 static stiffness of the top plate of the violin as seen by the string using a “plate” bridge, a “modern” bridge and no bridge, for three violins.

Violin	Soundpost Position String slot	Stiffness (kN/m) “Plate”bridge G	E	“Modern”bridge G	E	No bridge G	E
Baroque (Guarneri)		82	70	70	70	–	–
Baroque (converted to Romantic)	5/14	91	69	73	59	49	68
Violin No 2 (Guarneri)	5/22	83	56	69	58	48	67
Violin No 1 (Stradivari)	5/17	69	67	57	57	68	111

The relatively strong effect on stiffness of the presence of bridge and strings is puzzling: obviously they introduce considerable complications to the mechanical system. Violin No 1 was made by me in 1988 on a Stradivari outline; violin No 2 was made in 1992 and was very similar to the Baroque violin. It had a thicker soundpost as did violin No 1. These two violins were made by the same methods as the Baroque violin used in this study but were not crucial to it. The results are for comparison purposes. The converted violin had gut strings fitted.

The stiffness values measured show some interesting features. Measured at the top of the bridge, the stiffness at the bass side is higher than that at the treble side for the Guarneri higher arched tops, whereas for the flatter Stradivari top, in this case, they are equal. The plate bridge gave higher values than the modern bridge. These results are to be contrasted with measurements taken with no bridge and taken at the position of the bridge feet. For this study the bass foot position shows a lower stiffness than the treble foot position. The strings were relaxed for this latter case.

Figure 5.10 Setup for measuring the static stiffness
as seen by the two feet of the bridge as shown in Table 4 (violin No 2)

The plate bridge represents an upper limit in providing a high "bridge" stiffness and measurements taken with the strings at playing tension while the "no bridge" condition is at the lower limit with no string tension present. The presence of downbearing from the string tension of 74 N (A415) and 94 N (A440) assuming an equal division at the two bridge feet, suggests a higher stiffness under such a preload at the bass string position than at the treble string position for the two Guarneri type violins. With no preload, the treble side has the higher stiffness. The soundposts were always set with no tension (stress) present.

For the two Guarneri style violins, the difference in stiffness between the bass and treble side was about 20 kN/m for the plate bridge and 10 kN/m for the modern bridge. The difference between these bridge types are the cutouts present in the modern bridge. There was no difference between the two sides with either bridge for violin No 1which cannot be explained at present.

A trial with the converted violin fitted with gut strings at A415 and measuring the stiffness at each strung slot gave: G 62.5; D 62.5; A 106 and E 83 kN/m. Violin No 2 fitted with Dominant nylon cored strings at A440 gave G 48; D 69; A 91 and E 53 kN/m. A similar trial with the same violin fitted with the same modern bridge but with the string tension relaxed, gave a bass side stiffness of 47 kN/m and a treble side stiffness of 59 kN/m equivalent to a no bridge condition.

5.11 The Measurement of Bridge Resonance

The bridges used in this study were of four types; Renaissance, Stradivari, Paris and modern which covered the period from about 1500 to the present. The modern bridge was introduced early in the 19th century. The resonances are the lowest and most influential for the violin, at 3 kHz and one at 6 kHz. The lowest resonance has a rocking motion of the top part of the bridge which is thought may assist body modes in the region of 2.5 kHz. The other resonance is thought to be too high to have much effect. It is not a rocking resonance but a vertical bouncing resonance

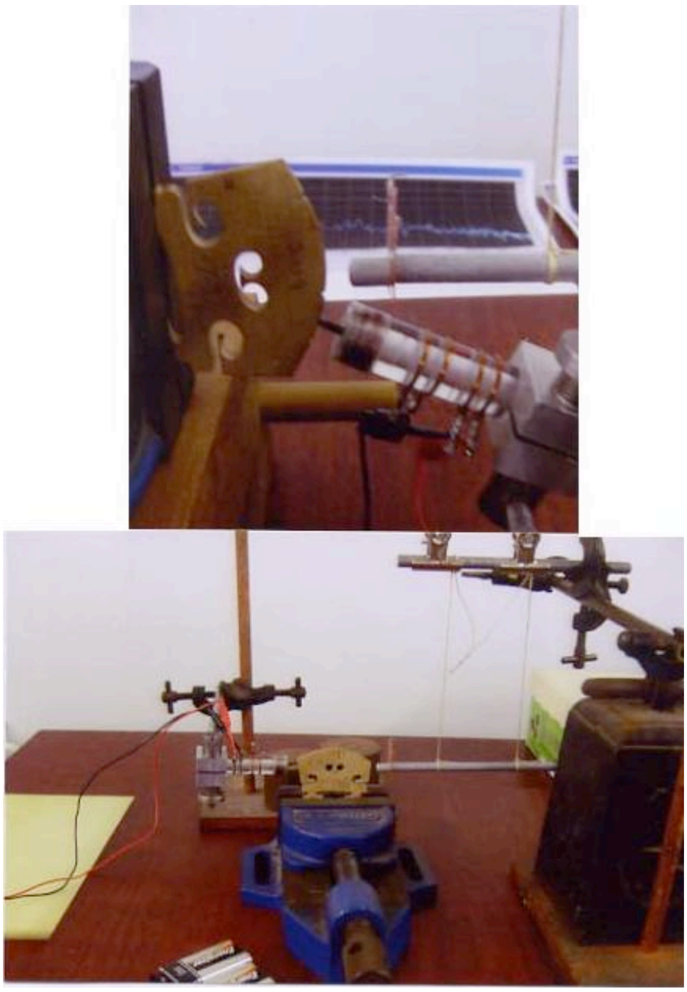

Figure 5.11 Setup for measuring the rocking resonance at about 3 kHz for a modern bridge mounted on a firm base

The method used was similar to that suggested by Joe Curtin [10]. The bridge was mounted in a machine vice on a flat surface. For the rocking mode the treble edge was struck with the pendulum used throughout these experiments and the response was picked up with the magnet and coil assembly. The frequency was found using the Fast Fourier Transform, FFT, of Cooledit 2000 on a computer. The results are discussed above when determining frequency response in this report. Figure 5.11 shows the general setup for this measurement. The higher resonance was studied by turning the vice on its side and the top of the bridge impacted by the pendulum.

Both response curves show the same peaks below 880 Hz except that at 710 Hz in the upper curve there is a large minimum which is not present in the response curve below taken with a microphone. Also this curve falls off rapidly above 1.2 kHz. The response curve for the magnet/coil transducer, the input admittance, has a peak at 950 Hz that is not prominent in the lower curve and is judged not to be prominent in the sound of the violin. The lower curve, taken with a microphone, shows a shallow valley between the main air resonance at 283 Hz and the first main body mode at 455 Hz characteristic of resonances with opposite polarity [11]. In the region between 550 and 830 Hz there appears to be a shallow valley similar to that between the main air resonance and 455 Hz. Again, this lower curve does not fall off above 1.2 kHz but remains higher to about 4 kHz which is indicative of influence by the bridge lower resonance at about 2.5 kHz. At 490 Hz there is evidence of the first higher air resonance, A1, and a minimum at 520 Hz with the next body mode at 555 Hz. The two body modes will have the same polarity.

5.12 References

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[11] Schelleng J.C. "On Polarity of Resonance" CASJ 4 (3) 2001, 26-29. Reprinted from CAS Newsletter #10, 1968, p 14-18.

Papers by McLennan can be downloaded from the website:

www.phys.unsw.edu.au/music/people/mclennan.html

5.13 Appendix

Derivation of equations for the effective mass and stiffness of a resonance.

The resonance frequency is a function of mass and stiffness given by:

$$f = 1/2\pi(s/m)^{1/2} \qquad 1$$

From which we can write by rearranging

$$s = (2\pi f)^2 m$$

To derive the dependence of resonance frequency on added mass leading to an expression for the effective mass we write:

$$(f + \Delta f)^2 = 1/4\pi^2[\ s/(\ m + \Delta m)]$$

Expanding:

$$f^2 + 2f\Delta f\ +\ (\Delta f)^2\ = 1/4\pi^2[s/(m + \Delta m)]$$

Rearranging, discarding $(\Delta f)^2$ and substituting for s, we get:

$$(2f\Delta f)(m + \Delta m) = f^2 m - f^2(m + \Delta m)$$

Thus: $$m + \Delta m = -(f^2\Delta m)/(2f\Delta f)$$

Which becomes, as Δm goes to zero:

$$m = -f/2[1/(df/dm)] \qquad 2$$

Similarly for the effective stiffness from equation 1

$$m = 1/4\pi^2(s/f^2)$$

Thus: $$(f + \Delta f)^2 = 1/4\pi^2[s/(m + \Delta m)]$$

Expanding: $$[f^2 + 2f\Delta f + (\Delta f)^2](m + \Delta m) = s/4\pi^2$$

Substituting for m and rearranging terms, we get:

$$2fs/4\pi^2f^2 + 2f\Delta f\Delta m = -f^2\Delta m$$

Giving: $s + 4\pi^2f^2 = -(4\pi^2f^4\Delta m)/(2f\Delta f)$

Therefore: $s = -2\pi^2f^3(dm/df) - 4\pi^2f^2\Delta m$

Substituting for f^2:

$$s(1 + \Delta m/m) = -2\pi^2f^3(\Delta m/\Delta f)$$

Which becomes, as Δm goes to zero:

$$s = -2\pi^2f^3[1/(df/dm)] \qquad 3$$

5.14 Addendum

The effect of Impact Bar mass and microphone position

After the study was completed using an impact bar of 13.2 g and a microphone distance of 100 mm for most of the measurements it was decided to see what effect a lighter impact bar might have.

The effect of bars with two different masses was studied, namely 5.2 g and 13.2 g. The bars had the same length of 15 cm and diameters of 4 and 6 mm suspended in the same way with 10 cm long threads to give a pendulum action. Figures 5.12 and 5.13 show the frequency analysis for the force transducer at the end (5 mm) of the 13.2 g impact bar analysed with Cooledit 2000. Not all the frequencies shown are present in the few tests done but either the 400 or 800 Hz are present as the lowest. Also represented are corresponding input admittance and microphone response plots and their frequency analysis.

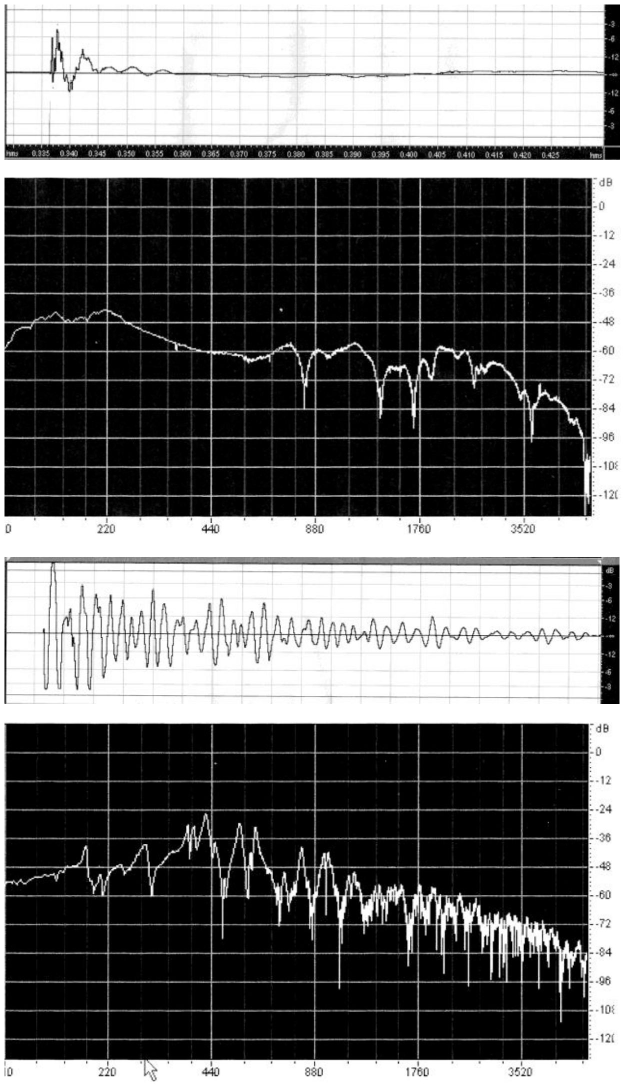

Figure 5.12 Force transducer response attached to 13.2 g impact bar.
Upper pair: time record and FFT showing impact frequencies, at about 800, 1250, and 1700 Hz. Lower pair: input admittance at bass edge of bridge.

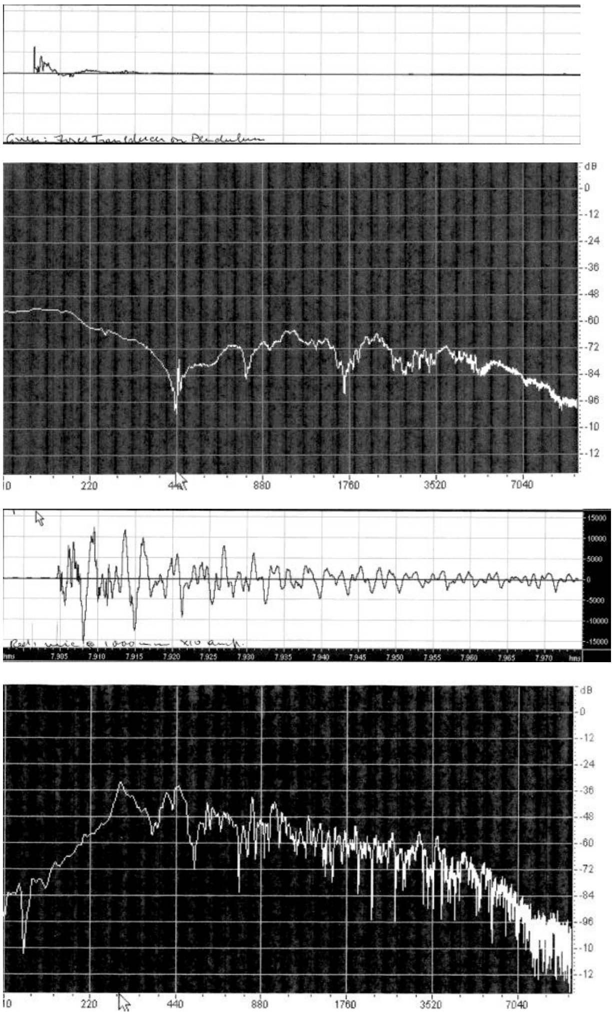

Figure 5.13 Force transducer response attached to 13.2 g impact bar.
Upper pair: time record and FFT showing impact frequencies, at about 439, 740 and 1700 Hz. Lower pair: microphone response at 1m.

The choice of microphone distance of 100 mm from the centre front of the violin was made on the results shown in figure 5.14 where it can be seen that the results were similar for 100 and 200 mm but differed for 0.5 and 1.0 m from the shorter distances. The distance of 100 mm allowed the microphone to be attached to a bracket on the frame on which the violin was mounted. Confirmation of this distance was obtained with later tests using Adobe Audition 1.5 as shown in figures 5.15 and 5.16. The microphone used throughout was a miniature omnidirectional Tie clip microphone 33-3013 labelled N26. No attempt was made to investigate the frequency plots taken at the longer distances. Figure 5.16 shows tap response plots for the 5.2 g impact bar to compare with those above.

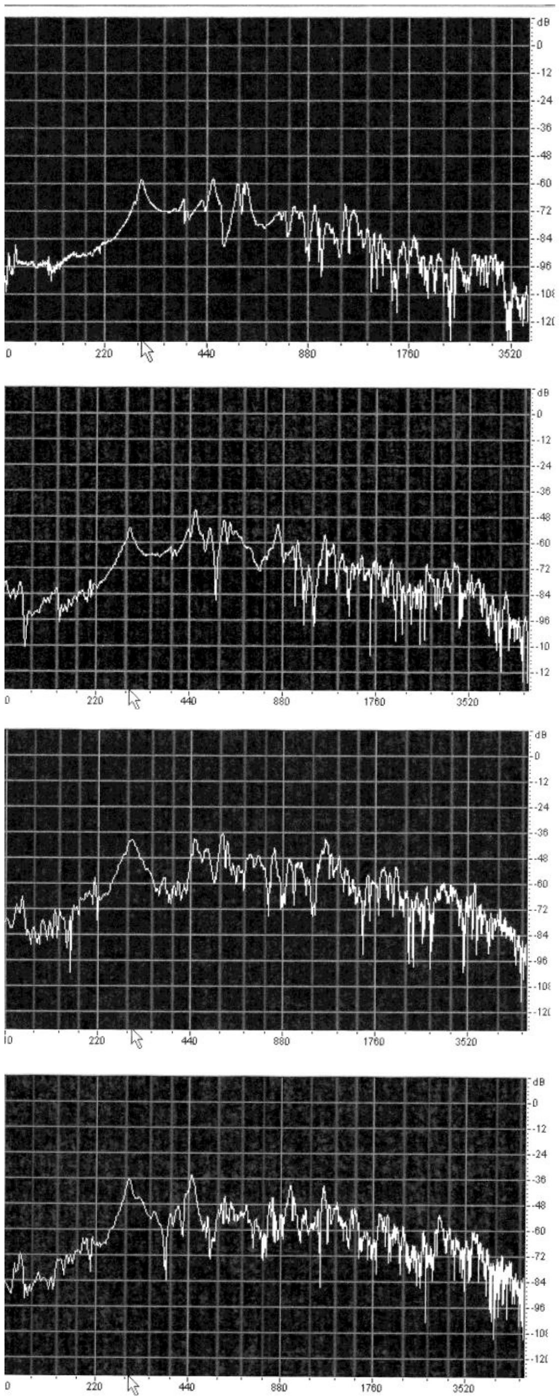

Figure 5.14 Tap response: effect of N26 microphone distance from top plate centre. Impact bar 13.2 g. Cooledit 2000 analysis. From the top: 0.1m, 0.2 m, 0.5 m, 1.0 m.

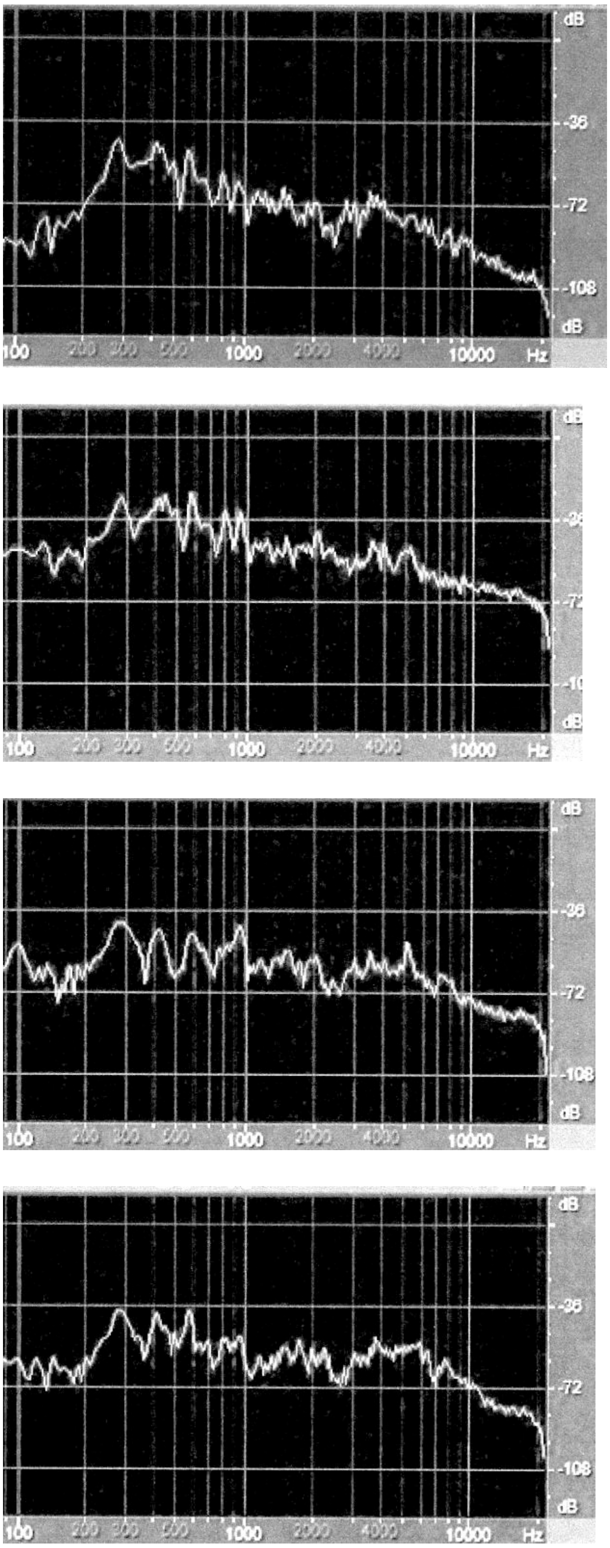

Figure 5.15 Tap response: effect of N26 microphone distance from top plate centre. Impact bar 13.2 g. Adobe Audition 1.5 analysis. From top: 0.1 m, 0.2 m, 0.5 m, 1.0 m.

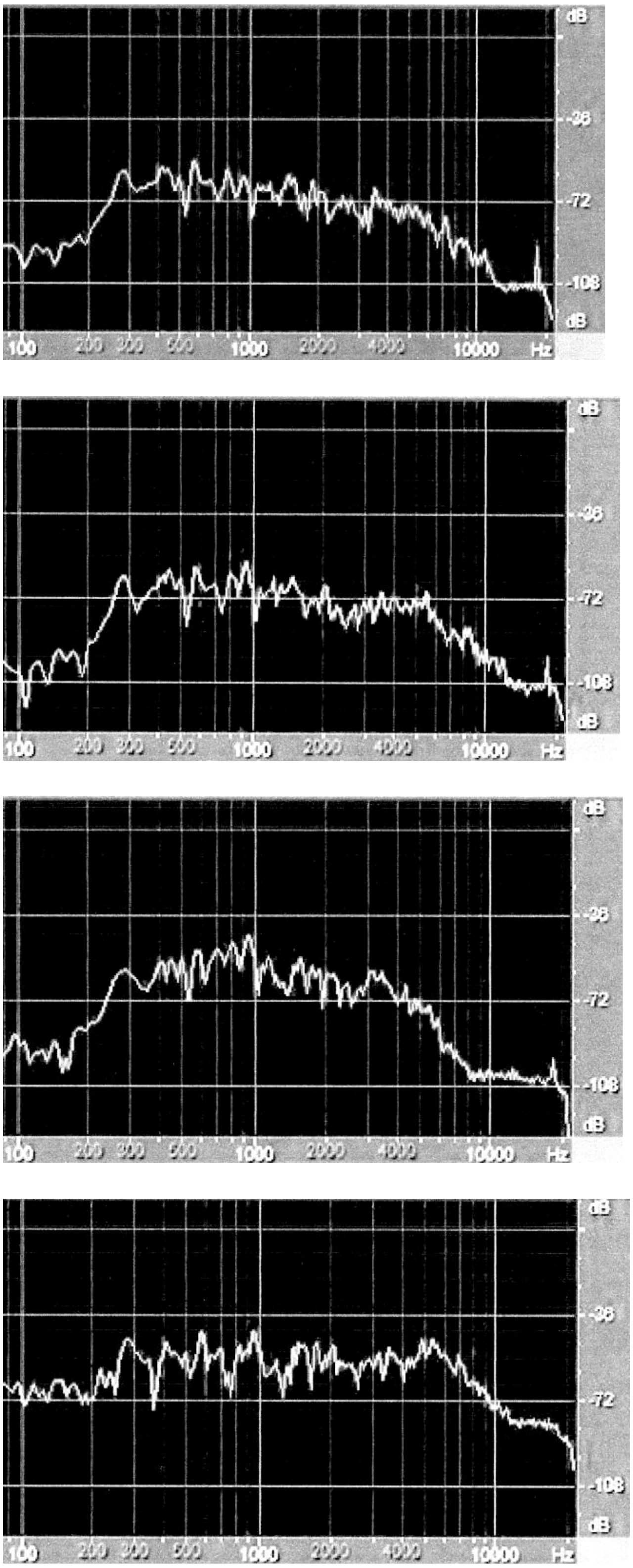

Figure 5.16 Tap response: effect of N26 microphone distance from top plate centre. Impact bar 5.2 g. Adobe Audition 1.5 analysis. From top: 0.1 m, 0.2 m, 0.5 m, 1.0 m.

Chapter 6

PLAYING TESTS on the BAROQUE and ROMANTIC VIOLIN

6.1 Introduction

It is difficult to relate the subjective assessment of players of the sounds they make with the physical characteristics of the violin measured in the laboratory. The input admittance for each version of the violin measured at the top of the bridge is shown in figure 6.1. Gut strings which are heavier than the Chorda gut strings used in the initial trial and favoured by current players of Baroque violins were fitted to both versions of the violin. These admittance plots may be related to the Saunders Loudness plots in figures 6.5 and 6.8 and to what the player’s experience.

Playing tests were conducted to determine the reaction of professional violinists to both the Baroque setup and, after conversion, the Romantic (or modern) setup. Four professional violinists with extensive Baroque playing experience in orchestras were enlisted for these trials. The main trials were done with the violin after the top was retuned with a light bassbar and soundpost and after the neck was reset to allow a higher bridge and to take advantage of heavier gut strings generally used by the players in this study.

One of the violinists carried out initial tests before the neck was reset and using lighter “Chorda” gut strings. The violin at first had a soundpost but no bassbar. Test results on the free top plate are shown in chapter 4. Saunders Loudness Curves were determined by the author, for each condition both by hand bowing and machine bowing as shown in figure 6.2. Figure 6.3 shows the tap response with no bassbar, but with and without a soundpost.

As a base for comparison, a Saunders Loudness Curve was determined for the violin setup with a “Renaissance” bridge (2.99 g) 30 mm high but with no bassbar and no soundpost. This is also shown in figure 6.3. There is some uncertainty as to when bassbars were installed as separate additions. Before this, the top plate was thought to have been left thicker on the bass side to provide additional support for the bridge.

Soundposts were quite early found to enhance the sound output as well as preventing the top from being distorted by the downbearing of the bridge [1, 2]. Figure 6.4 shows a repeat of the lower plot in figure 6.3.

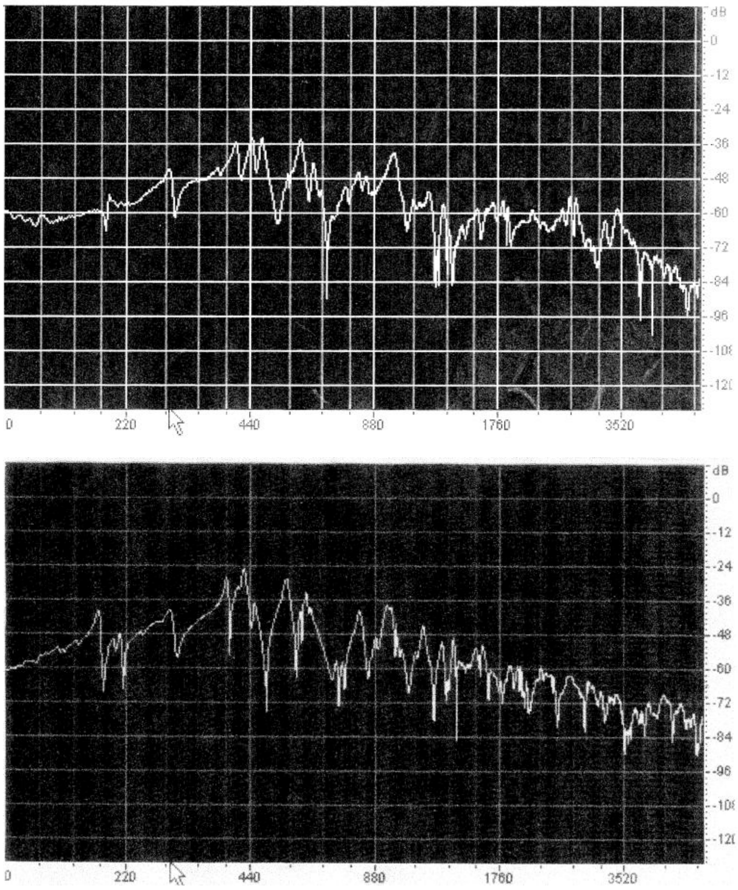

Figure 6.1 Tap response showing input admittance obtained with a magnet/coil at the bass side of the bridge upper edge.
Upper plot: Baroque violin, neck reset, gut strings A415, Renaissance bridge 2.60 g 38 mm high set at notches in f-holes soundpost 4.3 mm at 6/16.
Lower plot: Converted violin, gut strings A440, modern bridge 2.19 g 37 mm high set at notches in f-holes, soundpost 6 mm at 6/18.

6.2 Preliminary Playing Tests

In the bowing machine curves, the main air resonance, A0, appears to influence the output more so when the soundpost is present and there is also greater output around 300 Hz. The influence of the body resonance around 450 Hz without a soundpost has been moved up to 500 Hz. A frequency of 600 Hz was chosen arbitrarily as a divide between the main body resonances and those that essentially involve just plate resonances. It is also close to the frequency of the E string.

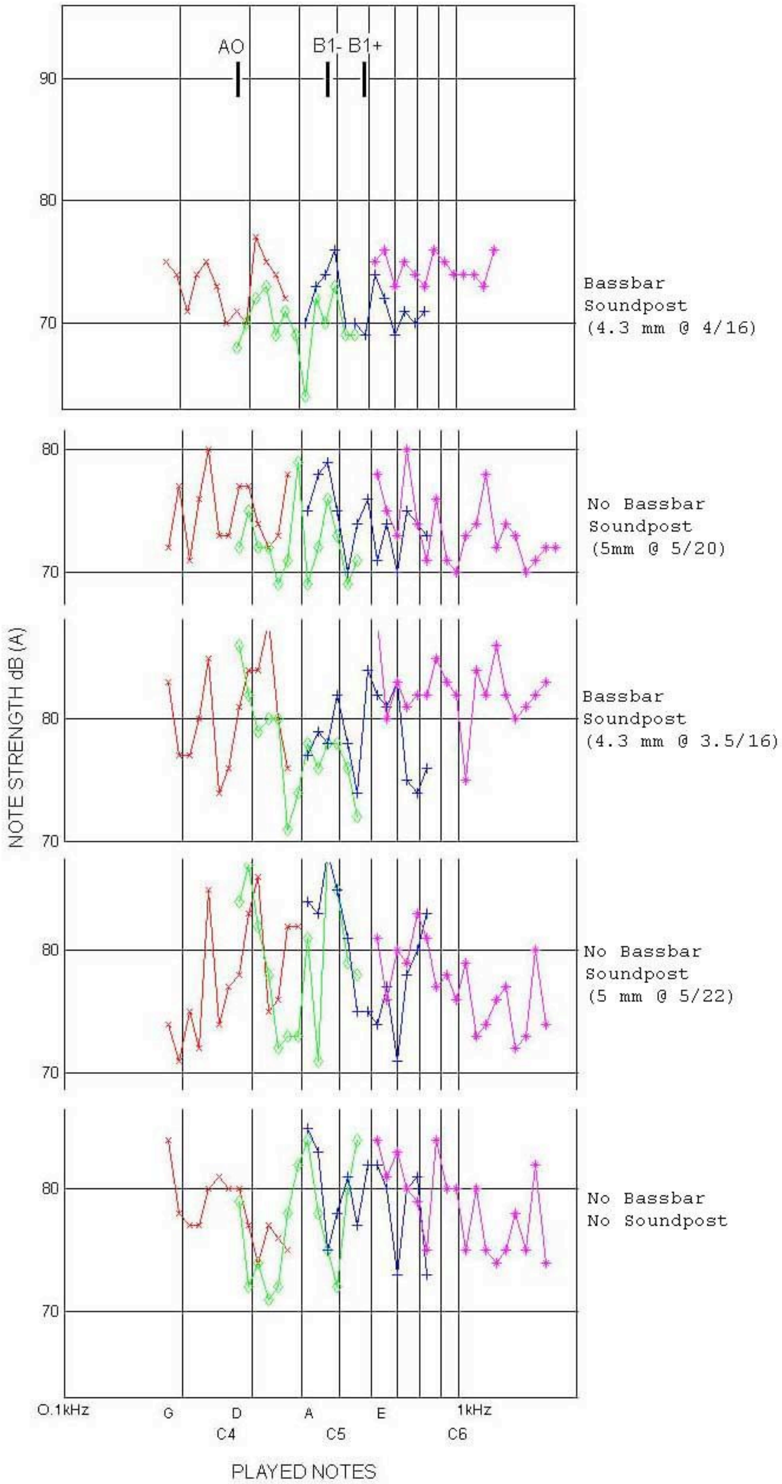

Figure 6.2 Saunders Loudness Curves for Baroque violin.
Upper 2 curves: hand bowing
Lower 3 curves: machine bowing
Black: G string; Green: D string; Purple: A string; Red: E string.

The position of the soundpost is indicated by the distance between the nearer surfaces of the bridge and the soundpost and the distance from the treble soundhole; thus 5/22.

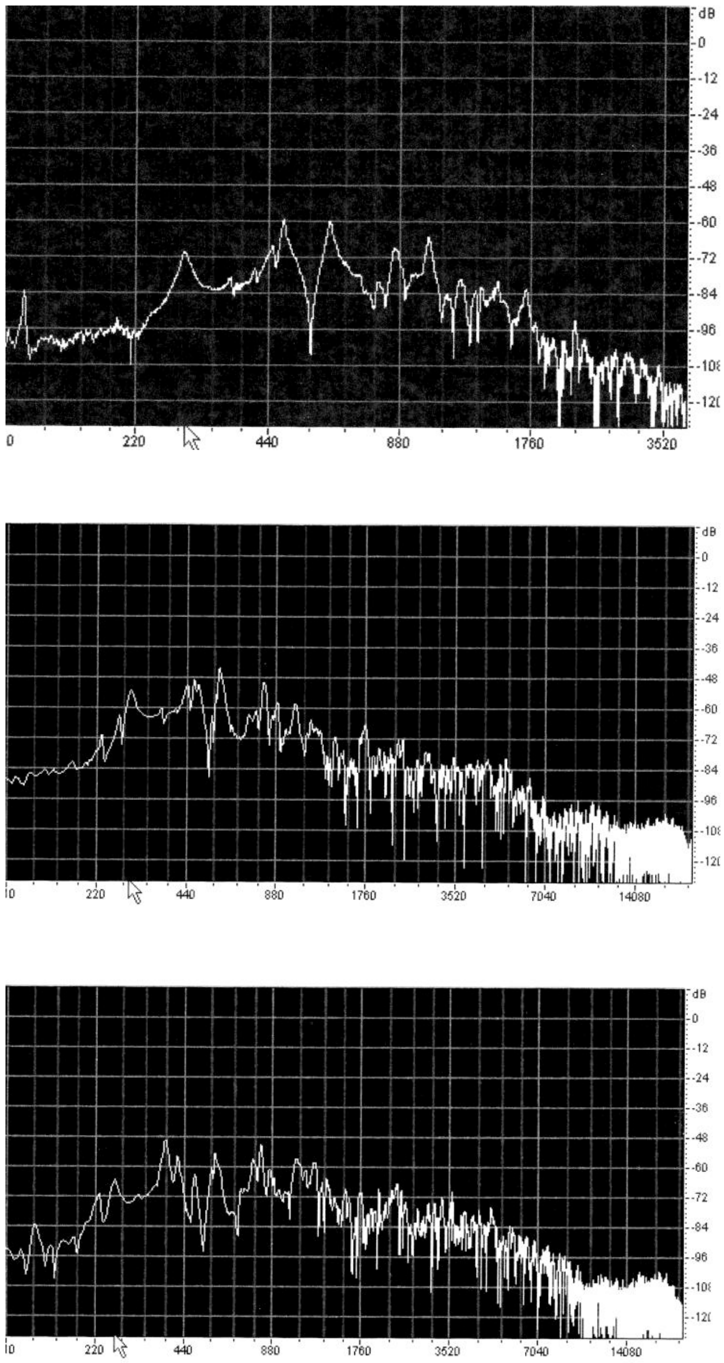

Figure 6.3 Tap response of Baroque violin, initial setup, Chorda strings A415, microphone at 100 mm.
Top: Renaissance bridge 2.12 g at f-holes, bassbar, soundpost 4.3 mm at 5/15.
Centre: Paris bridge 1.3675 g at f-holes, no bassbar, soundpost 5 mm at 5/22.
Bottom: Renaissance bridge 2.99 g at f-holes, no bassbar, no soundpost.

The Saunders test results (figure 6.2) show some interesting features. The strong peak near the open D string is simply the result of the A0 resonance, whereas notes immediately above D4 have no strong body resonances to support the fundamental.

Other features are the results of the harmonic content of the force exerted by the bowed string: For example, the peak between the G and D strings is due to the enhancement of the second harmonic, which falls near B1- for notes near A#3. The higher harmonics of nearly all notes fall in ranges where resonances are complicated and closely spaced.

Table 6.1 summarises the average level below and above 600 Hz and shows that when the bassbar is installed the output above 600 Hz is higher by about 2 dB. With a soundpost but no bassbar there is a suggestion that the output is slightly higher below 600 Hz. It is noticeable that the hand bowing results have less scatter than the machine bowing. It is suspected that players unconsciously compensate for variations in the output of the violin. It may be a measure of evenness across the violin. Comparisons made with and without the bassbar are inevitably complicated by the fact that different soundpost positions are used for the two cases.

The full schedule followed for these playing tests is shown as an appendix. The sessions were recorded which allowed sound samples to be discussed in chapter 7.

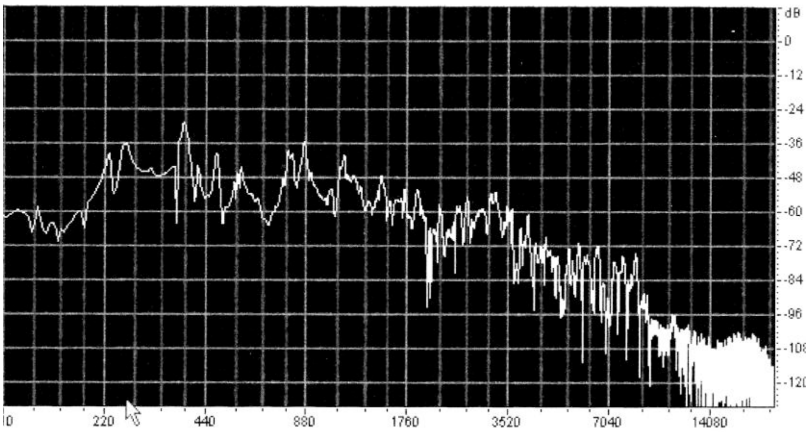

Figure 6.4 Tap response of Baroque violin, before neck reset. Gut strings A415, Renaissance bridge 2.99 g 32 mm high, at notches in f-holes, no bassbar, no soundpost.

Table 6.1 Baroque violin with Chorda gut strings. Saunders Loudness Tests, sound pressure levels averaged below 600 Hz and above 600 Hz. Standard Deviation (SD).

Violin setup	Bowing style	Average Sound Level (SD) <600 Hz	>600 Hz
No bassbar; No soundpost	machine	78 dBC(4)	79 dBC(4)
No Bassbar; S/post 5 mm	machine	79 dBC(5)	77 dBC(3)
Bassbar; S/post 4.3 mm	machine	79 dBA(4)	81 dBA(3)
No Bassbar; S/post 5 mm	hand	74 dBA(3)	73 dBA(3)
Bassbar; S/post 4.3 mm	hand	72 dBA(3)	73 dBA(2)

It will be noticed from table 6.1 that hand bowing gave a lower output with somewhat lower scatter than machine bowing with the light "Chorda" strings. In both cases the player was asked to play "forte". The conditions of the machine bowing were: Bow force 1.3 N: Bow Position 40 mm and Bow Speed 0.4 m/s. The conditions for hand bowing were not able to be determined. In both cases the microphone was placed 1 m from the treble side and in the plane of the violin.

Comparing features of figures 6.1 and 6.2 it can be seen that the main air resonance, A0, is present in both. Figure 6.3 shows A0 is present without a soundpost and is moved to a higher frequency when one is installed. The presence of a body mode at 440 Hz appears in both figures, moving to a higher frequency with a soundpost present.

The reaction of the player was not given for the no-soundpost condition. With a soundpost and no bassbar, the violinist gave an assessment that the playing qualities of the instrument were better than average. Table 6.2 below summarises the assessment for the conditions without and with a bassbar.

Table 6.2 Quality assessment of Baroque violin with Chorda gut strings.

Quality	No bassbar	Bassbar in place (4.3 mm soundpost)
Evenness	9/10 good	Good
Brightness	6/10	Good; slightly muffled except E string
Ease of Speaking	7/10	A little slow
Ease of Playing	6/10	Needs coaxing to set clean attack and hold tone.
Response	6/10	A little slow. Rich, brightness in high register.
Distinctive Character	8/10 G string	
	6/10 other stgs	Warmth of tone
Sensitivity to Dynamics	5/10	More change of colour in softer dynamics (This also applied to the No bassbar case)

Nothing could be said about Projection, and Loudness was not commented on.
With the 5 mm soundpost the violinist considered the A and E strings were clear and brighter, and the sound seemed fuller across the range.

6.3 Playing Tests, the Neck Reset, a Higher Bridge and Heavier Gut Strings

Preliminary playing tests suggested that Chorda strings were not suited to the instrument and as a higher, in this case Renaissance, bridge was desirable to raise the output with the heavier strings, the neck was reset. The final condition of the top plate and the parameters of the strings adopted were given in the Chapter 4, tests similar to those already described were carried out in a semi-reverberant room with three different players. An octave of semitones, played forte down bow, followed by the assessment of the violin by the player using the same set of qualities was followed. A summary of the average strengths of notes below and above 600 Hz are given in table 6.3 in the order of the Saunders Loudness Plots shown in figure 6.5. The strength of a note includes the harmonics and is recorded at the frequency of the fundamental. The numbers on the right of figure 6.5 (and subsequent figures) refer to the professional violinist.

Table 6.3 Baroque violin neck reset, heavier gut strings. Saunders Loudness Tests average sound level values from figure 6.5.

Curve	Average Sound Level dBA (SD)	
	<600 Hz	>600 Hz
Player 1	82 (3)	82 (3)
Player 2	81 (3)	81 (3)
Player 3	82 (3)	82.(3)
Machine bowing	84 (3)	85 (4)

These values indicate that the hand bowing was uniform from player to player and the violin was uniform across the range. Machine bowing was 2-3 dB higher.

Relating resonance peaks in the response plot to peaks in the Saunders Loudness Test's is very difficult. The approximate position of the main resonance peaks, A0, B1- and B1+ have been placed at the top of the Saunders Loudness Test figures but the positions chosen may not be accurate for each bowing exercise. One might be tempted to see a correlation in some plots but more confirmation would be needed to be certain because, at least, of the variability of the finger placement on the string.

For machine bowing, the sound pressure levels with the bridge at the notches in the f-holes was higher by about 2-3 dB than with the bridge below the soundholes when we compare figures 6.5 and 6.7. These results were found with the change to heavier gut strings preferred by the violinists.

It is interesting to compare the results shown in figure 6.7 with heavier gut strings with those in figure 8.4 which were done with lighter "Chorda" gut strings early in the study. The lighter strings gave average sound levels 6 dB lower when hand bowed as shown in tables 6.5 and 8.2 with the bridge at the f-holes. In figure 6.7 the upper plots by violinists are very different from the hand bowed plots that I made in figure 8.4. If the professional violinists intuitively compensated for sound level on the higher string to give an even response overall where I would not, has posed an interesting question. Certainly with the bridge below the soundholes in figure 8.4 the sound level of the highest string was about 6 dB higher than that of the three lower strings compared with the evenness in figure 6.7.

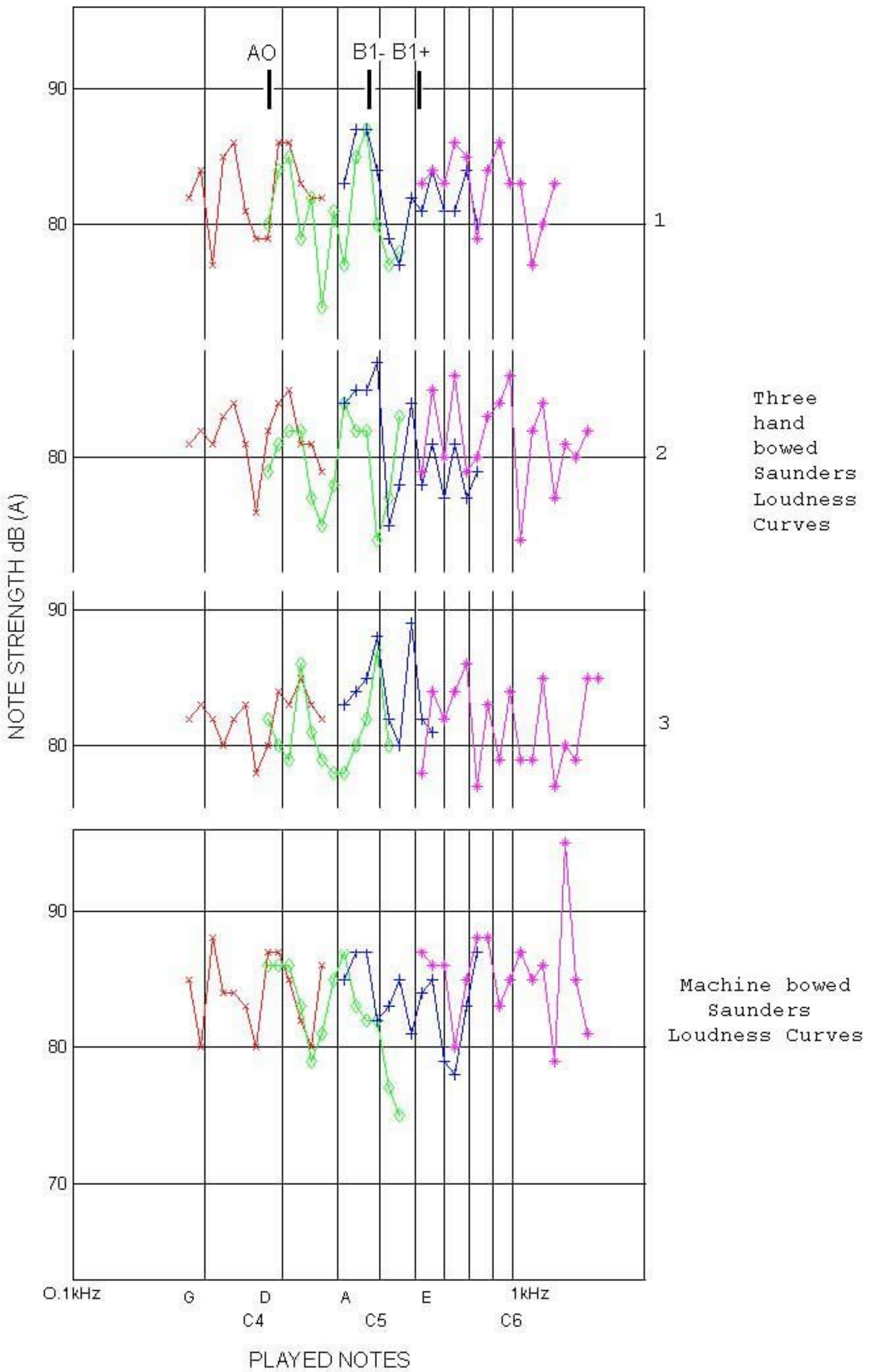

Figure 6.5 Saunders Loudness Curves for the Baroque violin, neck reset, Renaissance bridge, 2.6 g, 38 mm high at notches in the f-holes, soundpost 4.3 mm at 6/16

The assessment of the playing qualities of the violin by the three experienced Baroque violinists was done by way of a Baroque piece of his or her own choice, mostly Bach, and a Romantic piece of their choice. They used a Baroque and modern bow as appropriate. The qualities that would be looked for were:

Bright, clear /Dull, muffled
Full, rich / Thin, harsh
Open /Closed, boxy

In terms of response:

Ease of playing, physical comfort.
Ease of speaking, responsiveness.
Evenness across the range
Sensitivity to dynamics
Distinctive character

A scale of 1 - 10 was used to rate the impressions of the violinists together with specific comments. No assessment rated below 5 suggesting the violin was better than average. The lines, -------, indicate an opinion crossing two grades of assessment and the X's an assessment at one level. The overall assessment suggests that the violin would compare favourably with other instruments in an ensemble. The ratings in both tables 6.4 and 6.6 were for all violinists taking part. The letters of the strings in the tables indicate that the rating applied to them.

Loudness and carrying power were considered by the violinists as not easy to assess under the conditions but an opinion was expressed which lay between 6 and 9 for loudness and 8 for carrying power. The violinists differed in their approach to the instrument. One was very critical in judging the behaviour of each string; one was very enthusiastic in the search for good points and the other approached the violin as a "working tool". Table 6.4 sets out the ratings in, it is hoped, a readily understandable way. The ratings of all three players were recorded on the one table. Some qualities were not given a rating by a player.

Table 6.4 Baroque violin quality assessment, neck reset, heavier gut strings, bridge at notches in soundholes.

Quality	Rating	5	6	7	8	9	10	
Loudness			----------			x		
Carrying power					x			
Sound quality	Dull	A & D		x	E & G	x		Bright
	Thin		----------			x		Full
	Closed	x		----------				Open
Response				xx				

Ease of playing		---------	----------					
Ease of speaking		---------	x		x			
Evenness						x		
Sensitivity to dynamics				x--------x				
Distinctive character		x				x		

6.4 Player Comment on Violin Performance

The performance of the violin as a Baroque instrument was satisfactory. Being newly made, without varnish but with good quality wood the result was pleasing on the whole. Representative player comments show the kind of reaction generated. These have been selected to avoid repetition. It has to be remembered that professional gut strings and a light early period bow were used.

Player 1: “not too even; but I like this as a Baroque violin quality! (it) allows for natural voicing.”
“E string brighter, the others less so. I would like the A a little brighter and the D a little warmer” “A string not as easy speaking”

Player 2 “(tone) full, thin: this is a positive in a Baroque instrument.”
“(Sound) open sounding without varnish.”
“(tone) bright but not too bright (not an easy quality in a Baroque set up.)”
“quite easy (on speaking) but needs a heavier bow.”
“(distinctive character) lovely nice instrument for ensemble work - it will blend well - with some adjustments”
”(sensitivity to dynamics) great! easy to play at extremes of dynamics.”

Player 3: “(distinctive character) a bit young yet, but we only just met”

These comments are probably interesting to other players and to luthiers, but are subjective and of little scientific interest, because they cannot readily be related to objectively measured quantities. The comparisons of the Long Time Averaged Spectra (in LTAS) in chapter 7 allow some objective comparisons.

6.5 The Bridge below the Soundholes

There is evidence [3] that in Baroque and earlier times that it was common practice to place the bridge below the f-holes. Boyden thought that sound quality was the reason; a viola-like tone being obtained. More recently, as a result of careful study of artefacts and early paintings [4] another hypothesis has been proposed. The lower position of the bridge, which extended from about 10 mm below the notches to about 30 mm, was thought to be due to the quality of the strings available and that they spoke more easily with that arrangement. The problem was that footprints appeared to be absent from the tops of old violins in the area below the notches. Careful inspection has supported the idea that the tops were reworked in these areas and revarnished. There is evidence of a footprint in plate 86 in Jeremy Montagu [1] on a Lira da Braccio of c. 1525. As late as 1791, artists were painting violins with the bridge below the f-holes. It might seem that as the quality of strings improved, the position of the bridge was brought closer to the notches. For the same tuning pitch and to prevent a rise in string tension, the shorter strings must have been thinner. Improvement in string quality was probably in this direction as thicker strings are slower to speak.

Some conclusions can be drawn; for small displacements of the bridge below the notches in the f-holes. The existing bridge height would not lower the string clearance over the fingerboard significantly. The string tension would be little changed, but a greater displacement would require a higher bridge and higher tensions.

In performance technique, first finger in 3rd position stops the octave of the open string below it and the hand rests against the body of the violin. This note occurs at one quarter string length from the nut and varies from 79 mm to 90 mm from the nut for a change in neck length of 120 mm and a string length of 315 mm at one extreme to a neck length of 130 mm and a string length of 360 mm at the other extreme, with the bridge below the f-holes. These changes would be accommodated by the player fairly easily, so that moving the bridge would not be seen as a big change.

The opportunity was taken to do playing tests with the bridge in a position below the f-holes using the heavier gut strings which gave a string length of 356 mm and a higher string tension. The violin also required a smaller tailpiece weighing 3.45 g. A "Renaissance" bridge 3.18 g 44 mm high was placed below the f-holes but the soundpost was left in its place near the notches. In another trial, the same bridge was placed below the f-holes and a soundpost, 5.5 mm dia. was placed about 2 mm below the treble foot of the bridge. These tests were done before the neck was reset. For comparison, a tap response after the neck was reset is shown in figure 6.6 with the other two. Contrary to an earlier belief that the soundpost was not moved with the bridge, it became obvious during this work that the soundpost had to be moved to prevent the top being depressed. In figure 6.6, the tap response curves were taken with a microphone in front of the top, for both positions of the bridge. It can be seen that the main body peaks near 500 Hz are present with the bridge at or below the f-holes. The two resonances above 500 Hz appear to have opposite polarities similar to A0 and the resonance above it, and move closer with the bridge below the soundholes. At higher frequencies the response is different in each case.

Figure 6.7 shows SLT's obtained by the professional players with the bridge below the f-holes. While the scatter is wide the average sound level is reasonably uniform across the range. This figure should be compared with figure 8.4 as discussed above.

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The repositioning of the bridge below the soundholes produced some interesting changes in the response curves. Figure 6.8 shows both the input admittance and the microphone response for a Renaissance bridge place level with the lower edge of the soundholes (all bridges were placed in this position) with the soundpost placed 5 mm below the bridge for the Baroque version of the violin. The main air resonance remains in the same place but the appearance of body modes is different, compare with the microphone responses in figure 6.3 for the bridge in the usual position. There appear to be more body modes closer to the main air resonance. These changes are likely to affect the tonal balance and timbre of the instrument and perhaps to elicit different playing techniques from the player. Figure 6.9 shows a similar trend for the violin after conversion to the Romantic version.

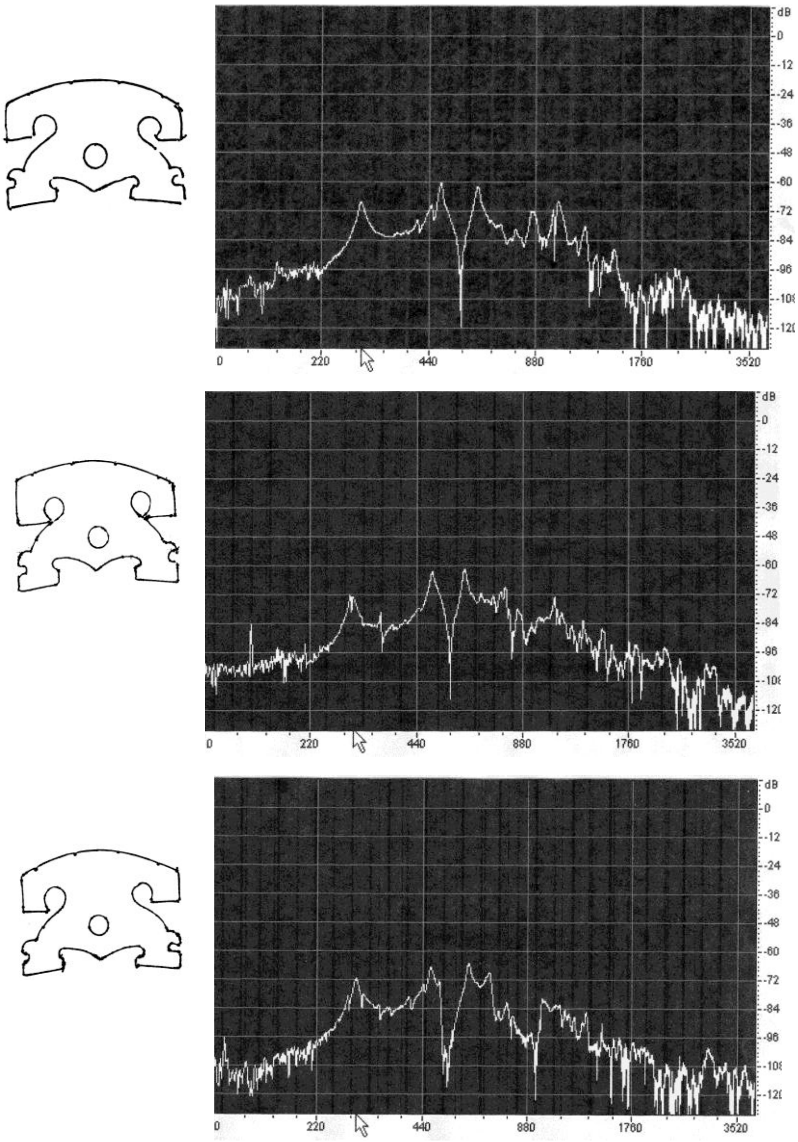

Figure 6.6 Tap Response Curves for the Baroque violin.
Top: Renaissance bridge 2.12 g 30 mm high at notches in Soundholes, Soundpost 4.3 mm @ 5/15
Middle: Renaissance bridg 2.82 g 38 mm high below Soundholes, Soundpost 5 mm dia @ 5/22 (near notches)
Bottom: Renaissance bridge 1.97 g 32 mm high, below Soundholes, Soundpost 5.5 mm dia @ ~ 4 mm below bridge treble foot

The resonance above B1+ has opposite polarity with it which becomes more evident lower in figure 6.6. This resonance is lowered in frequency with the bridge below the soundholes. This is similar to the situation with A0 and B1-.

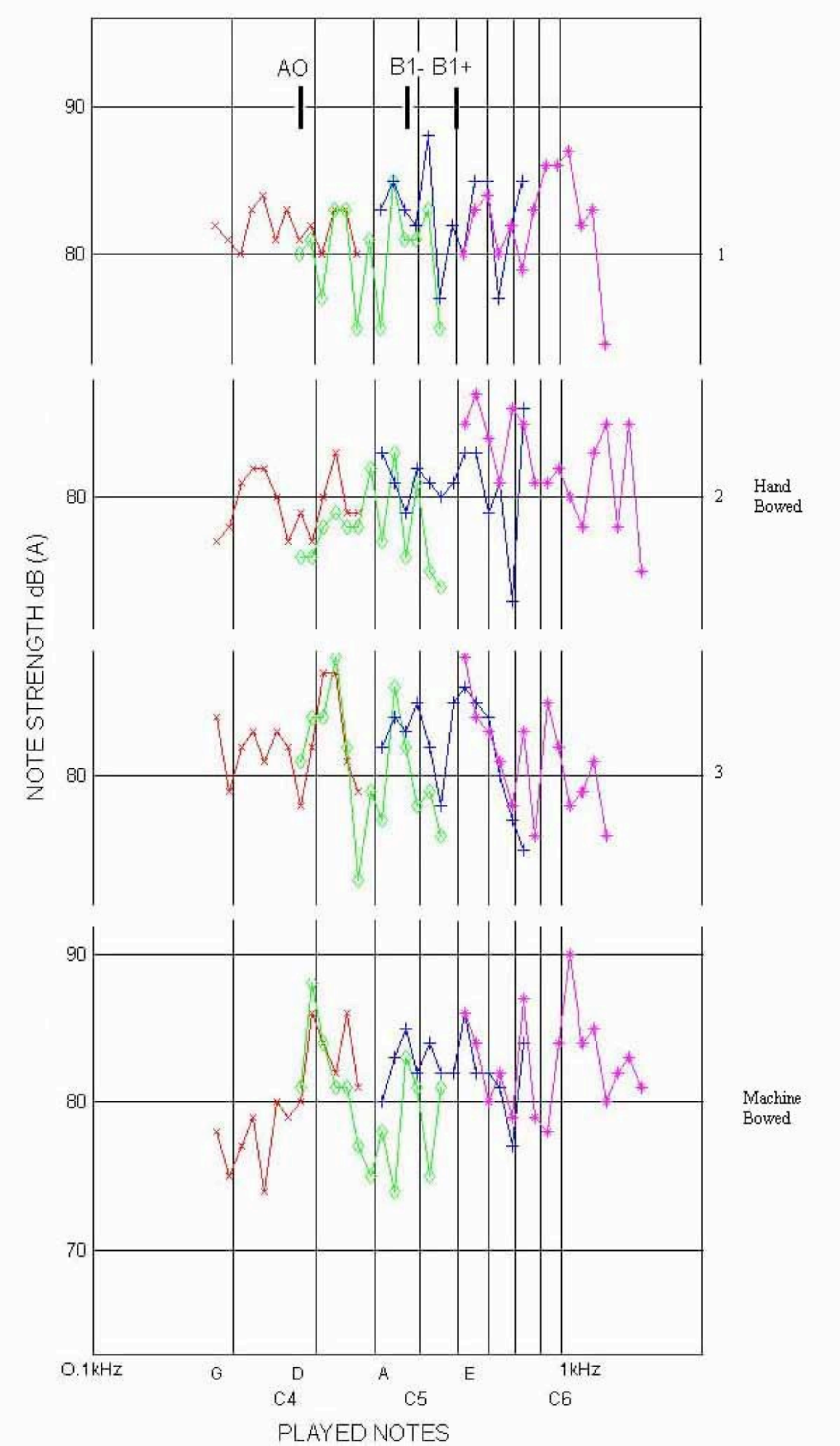

Figure 6.7 Saunders Loudness Curves for the Baroque violin with neck reset, the bridge below the soundholes. Renaissance bridge 3.18 g 44 mm high, soundpost 4.3 mm at 5/15 (near notches in f-holes).

The wide variations in sound level shown in the Saunders test in figure 6.7 are not seen in other tests shown later.

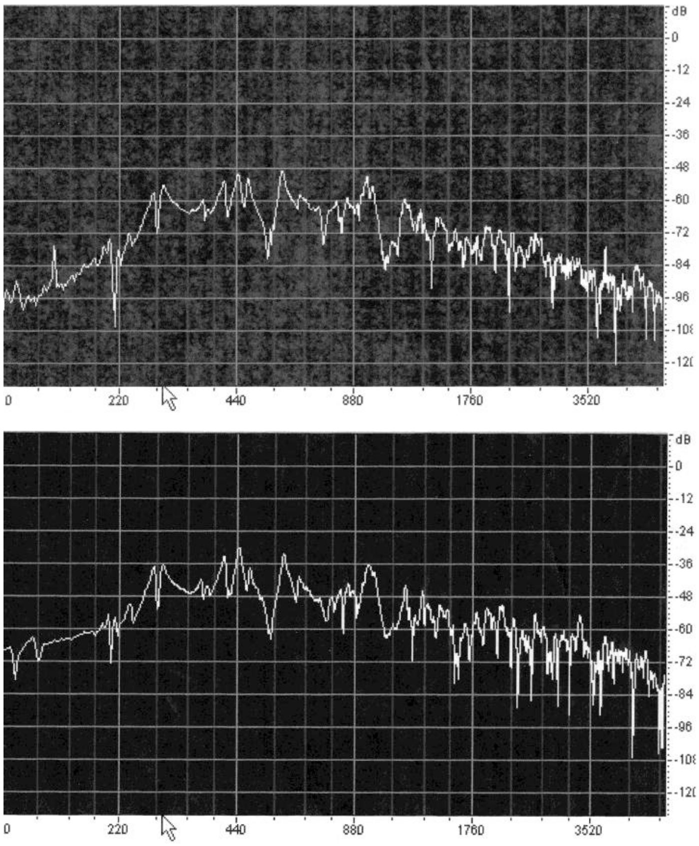

Figure 6.8 Tap response Baroque violin, neck reset for higher bridge, gut strings A415, soundpost 4.3 mm at 6/16 A0 appears as a doublet at 270/285 Hz, mic. at 100 mm.
Upper plot: Renaissance bridge 2.6 g 38 mm high at f-holes.
Lower plot: Renaissance bridge 2.47 g 38 mm high below f-holes.

Table 6.5 Baroque violin bridge below the f-holes. Saunders Loudness Test average sound levels from figure 6.7.

Violinist	Average sound level dBA (SD)	
	<600 Hz	>600 Hz
Player 1	81 (3)	82 (3)
Player 2	79 (2)	82 (3)
Player 3	82 (3)	81 (4)
Machine bowing	81 (4)	83 (3)

The results show a fairly even strength across the range. The machine bowing used a bow force of 1.4 N, a bowing position of 55 mm and a bowing speed of 0.4 m/s.

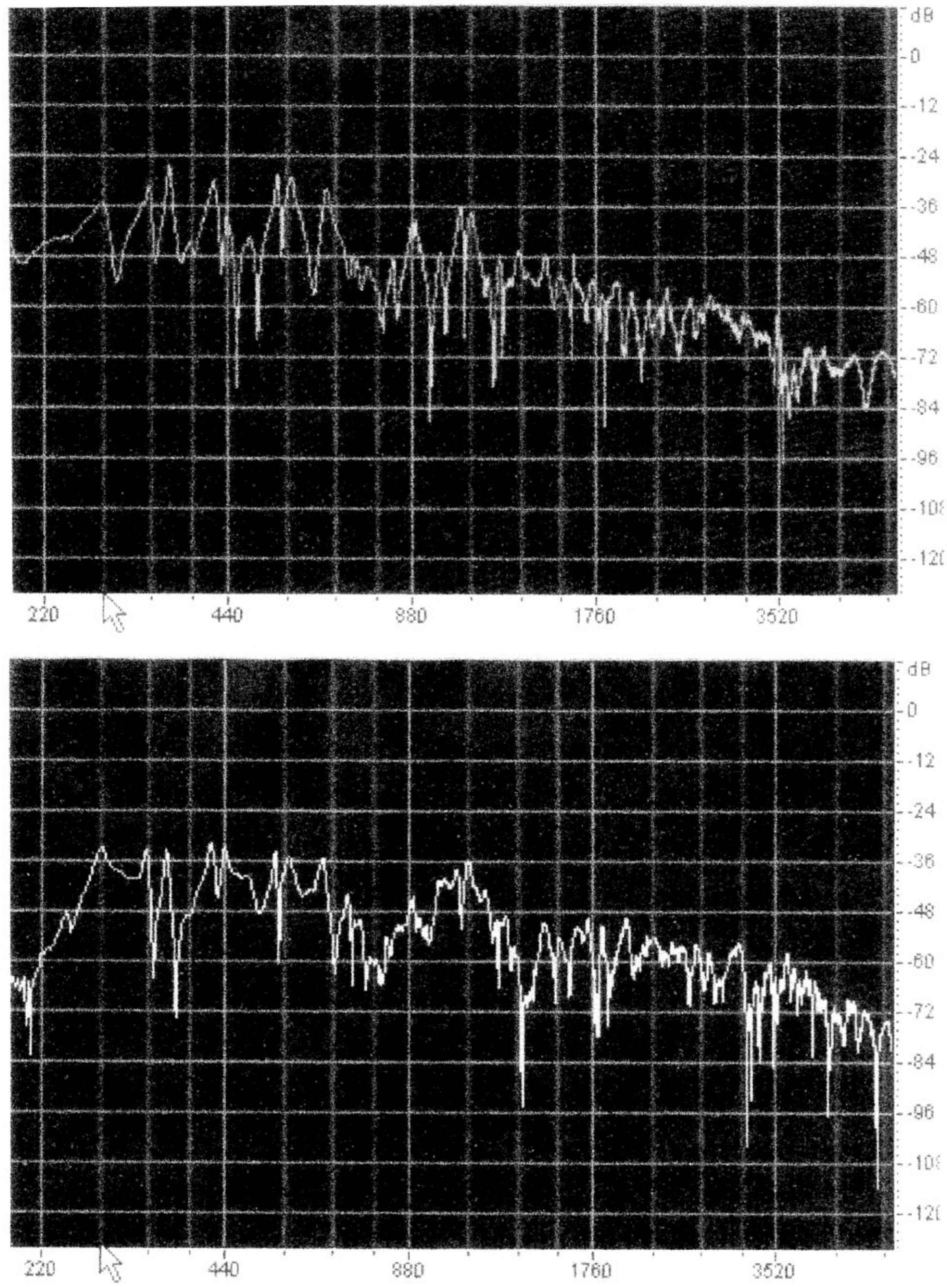

Figure 6.9 Tap response of Converted violin. Gut strings A415. Renaissance bridge 3.18 g 44 mm high, set below the soundholes, 5 mm soundpost at 5 mm below bridge.
Upper plot: input admittance at bass edge of bridge.
Lower plot: microphone at 100 mm in front of top plate centre.

Violinist No 3 was the only one to comment on the behaviour of the Baroque violin with the bridge below the soundholes. The violin had good loudness and projection with a full and bright sound but lacked in ease of speaking and responsiveness. It was somewhat uneven across the range.

6.6 Playing Tests on the Violin converted to the Modern Setup

The same set of qualities as used in table 6.4 was used by the violinists to assess the violin with the new setup. The same gut strings were retained as would have been the case when these changes were being made in the early 1800's. (These changes followed the introduction of the chinrest by Ludwig Spohr in about 1820 [5]). The results are summarised in table 6.6. The bridge was set at the notches in the soundholes and the strings were tuned to A440 for all playing tests on the converted violin.

Table 6.6 Romantic violin, Quality assessment, bridge at notches in f-holes.

Quality	Rating	4	5	6	7	8	9	
Loudness				x				
Carrying power								
Sound quality	Dull				xx		x	Clear
	Thin			x	x	x		Full
	Closed				x	x	x	Open
	Dark	x				x		Bright
Response								
Ease of playing			x		x		x	
Ease of speaking						x	x	
Evenness				x		x		
Sensitivity to dynamics						x	xx	
Distinctive character							x	

6.7 Player Comment on Violin with Romantic Setup

Converted to the Romantic setup, still unvarnished and still with the same gut strings, but using a modern bow, the following comments were relevant.

Player 1: "The instrument was difficult to play with the gut strings on it"
A and D seemed more muffled than G and E."
The sound was "raspy" when played softly.

Player 2: "(Sound) full gets 'brighter' as you go on D and E."
(Evenness) good for brand new instrument. D and E speak slightly easier - they are slightly brighter and more responsive than G and A"

“easy instrument to play, don’t have to work too hard for new instrument.”
“All ‘speaking’ and ‘having to work hard to get sound’ qualities to do with having gut strings on a modern set up.”

6.8 Saunders Loudness Tests on Romantic Setup

Hand bowed Saunders Loudness Tests were determined for comparison with previous results. Table 6.7 set out the note strengths for the Romantic (modern) setup. The machine bowing used a bow force of 2 N, a bowing position of 20 mm from the bridge and a bowing speed of 0.4 m/s. Figure 6.10 shows the Saunders Loudness Curves for the violin converted to the Romantic version with the neck/fingerboard replaced and the violin with a modern bassbar and thicker soundpost but with gut strings.

Table 6.7 Romantic violin bridge at f-holes, heavier gut strings. Saunders Loudness Test, average sound levels from figure 6.10.

Violinist	Average sound levels dBA SPL (SD) <600 Hz	>600 Hz
Player 1	84 (3)	83 (3)
Player 2	82.(2)	83 (3)
Player 3	82 (2)	82 (3)
Machine bowing	85 (4)	85 (3)

Table 6.7 shows that the violin is, on average, even across the range. When machine bowing, a force of 1.4 N was tried but the fundamental of the notes on the strings were not continuously excited, the note would revert to the octave, making the vibration of the string unstable. To avoid this, a higher force of 2 N was found to be sufficient. This result indicates the minimum force for the equivalent bow speed of 0.4 m/s used throughout. The player would automatically compensate to sound the fundamental.

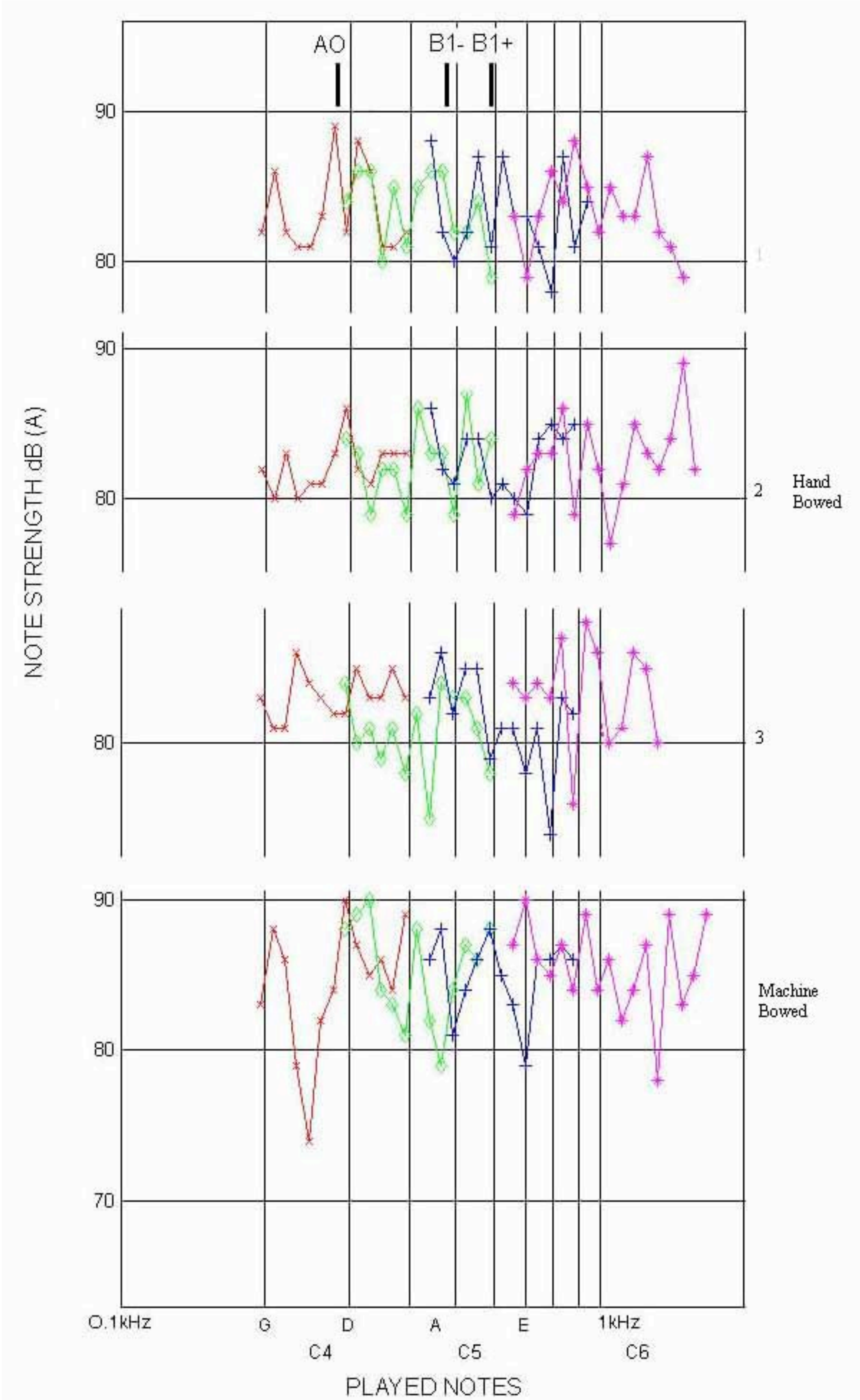

Figure 6.10 Saunders Loudness Curves for the violin fitted up to modern requirements with gut strings. The top three curves are hand bowed; the lower curve machine bowed.

6.9 Playing Tests with Modern Setup and Thomastik Dominant Strings

Thomstik Dominant strings are widely used. The D and A strings have nylon filament cores that are over-wound with a fine aluminium strip. The G string is usually over-wound with silver wire and the E string is a plain steel wire. There is a wide variety of strings available from over-wound gut cores to over-wound "rope" steel cores. Metal windings vary from aluminium in the case of "Dominant" strings to Chrome steel and tungsten. Figure 6.11 shows the input admittance and the microphone response for this version fitted with Dominant nylon cored strings. The bridge is placed at the notches in the soundholes. The Saunders Loudness Curves are shown in figure 6.12 and the summary of the average sound levels are given in table 6.8.

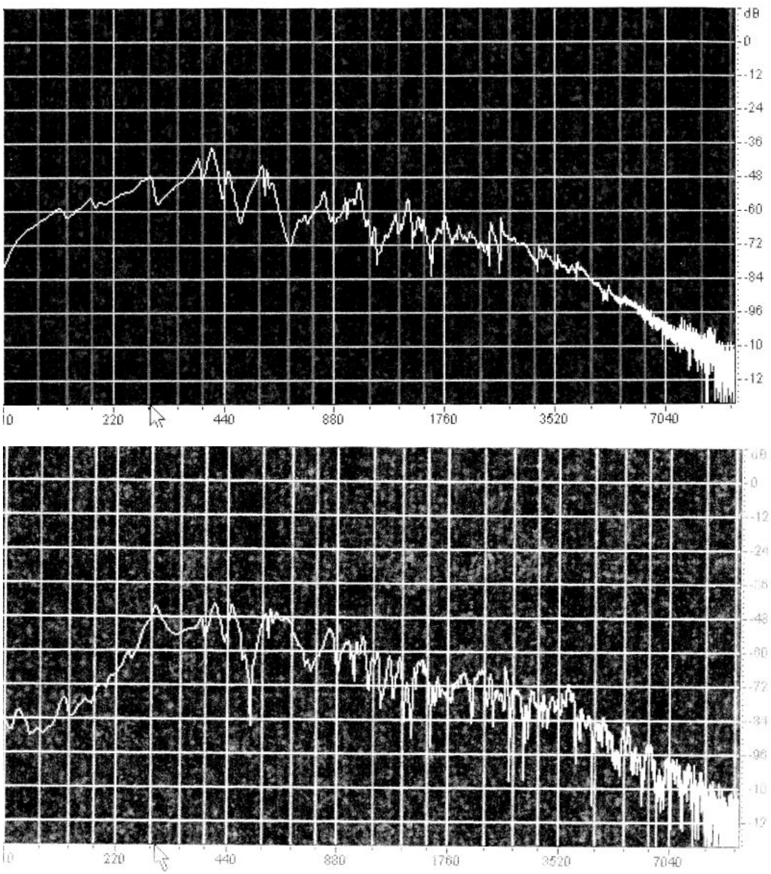

Figure 6.11 Tap response of converted violin. Dominant nylon cored strings A440, modern bridge 2.075 g 38 mm high, at f-holes notches, soundpost 6 mm at 6/18.
Upper plot: input admittance at top of bridge at the bass edge.
Lower plot: microphone at 200 mm from top plate centre.

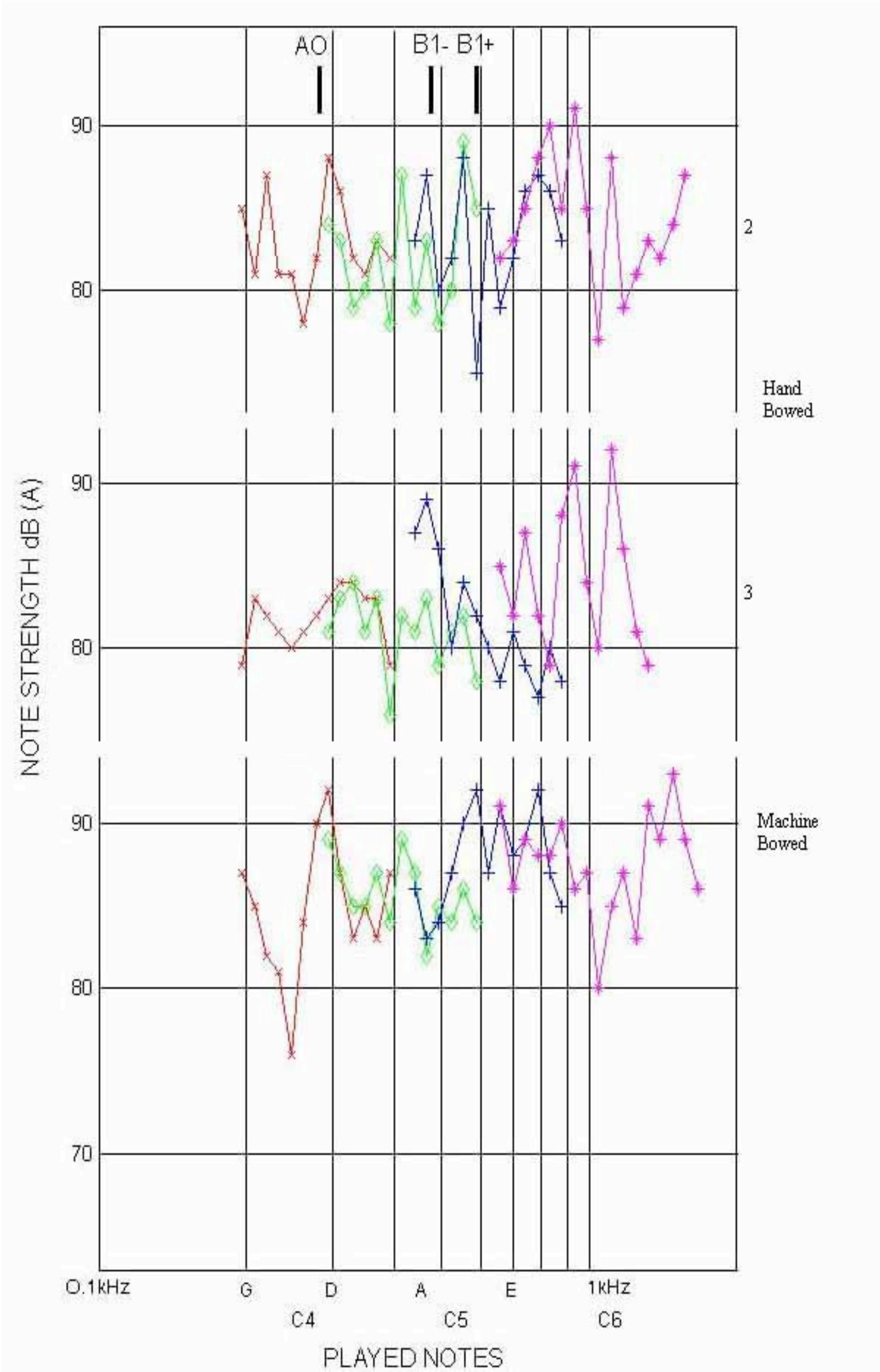

Figure 6.12 Saunders Loudness Curves for the violin converted from Baroque to Romantic (modern) setup by replacing the neck/fingerboard and fitting a larger bassbar and soundpost and retuning the top plate. It has *Dominant* brand nylon-cored strings. The upper 2 curves are hand bowed and the lower curve machine bowed.

Table 6.8 Romantic violin bridge at f-holes, Dominant nylon cored strings. Saunders Loudness Test from figure 6.12.

Violinist	Average sound level dBA SPL (SD)	
	<600 Hz	>600 Hz
Player 2	83 (3)	84 (4)
Player 3	82(3)	82 (4)
Machine bowing	85 (3)	88 (3)

For hand bowing, the variation in recorded dB levels for notes above 600 Hz was high but the average level was similar to that for gut strings. The level with machine bowing was higher than hand bowing in both frequency ranges and may have been due to the bowing conditions which were: bow force 2 N, bow position 20 mm and bowing speed 0.4 m/s. Hand bowing parameters were not able to be measured.

6.10 Player Comment using Thomastik Dominant Strings

The violinist's comments were generally more in favour of the Dominant strings than gut strings. Both considered the violin having more power; one (no. 2) mentioned the G string which is reflected in the Saunders Loudness Plots. This impression may have been related to the different weight of the two sets of strings. The violin was also considered to be brighter with a more open and fuller sound. It was easier to play, spoke more quickly and was even across the range.

Player 2: "Brighter and clearer with metal wound synthetic strings"
"Fuller on G and D with synthetic core and wound strings"
"more open and more even"
"'speaks' easier"
"more responsive than with gut."
"good 'new' instrument - will develop more character with continued playing."

6.11 Comparison of the Baroque and Romantic versions of the same violin.

The most obvious structural difference between the two versions was the style of the neck/fingerboard and the method of attachment to the body of the violin. The change from the Baroque to the Romantic setup was demanded by a change in the music being performed and the change in audiences. For the violin, there was a change in neck length from 120 mm to 130 mm giving a change in string length from 315 mm to 328 mm. There were changes in tuning but there was no universally adopted standard pitch and orchestras throughout Europe had their own standards. Since gut strings were still in use when the conversions were made, string tensions increased and as a consequence of this a heavier bassbar and soundpost were fitted. A pitch of A415 was adopted for the Baroque violin. A pitch of A440 was adopted as concert pitch in 1939 and was used for the Romantic violin.

With the change, the neck/fingerboard increased in mass from about 115 g to 165 g due to a change to a solid ebony fingerboard about 270 mm long weighing about 70 g replacing the shorter veneered one. Bridge height varied depending on the angle of the fingerboard for Baroque violins. In this study the setup was such that the bridge height was about 35 mm. The bridge was redesigned to what we have today.

To preserve the original pegbox and scroll, resetting and lengthening the neck required either an L-shaped insert at the mortice in the body or the graft of the pegbox onto a new longer neck. The left hand had no longer to hold the violin against the body of the player allowing greater freedom.

6.12 Comparison of the playing tests on the two forms

Physical aspects of the violin in its two states that can be compared are: the tap response and the effective mass (dependent on position) of the resonances of the two setups. The tap response gave the position of resonance modes. The frequency and their acoustic parameters can be calculated. The effective mass gives an indication of the playability. A smaller effective mass would be beneficial. Comparison of the Saunders Loudness Tests for both hand and machine bowing and assessment of playing qualities by professional players, a more critical but subjective evaluation of the two versions is possible.

This study has revealed modest changes in the behaviour of this violin on converting from one setup to the other. A change in average loudness from the Baroque to the Romantic with modern strings (tables 6.4 and 6.8) of 4 dB can be regarded as a significant difference. It would seem that for the same body, changes such as the replacement of the neck and other changes to fit the instrument for modern performance had apart from the loudness, only minor effects on the response. Players thought the modern setup improved the playing qualities and power of the violin.

To consider this in more detail, the comparison of average sound levels <600 Hz (i.e. for the three lower strings) and >600 Hz (i.e. essentially the top string of the violin) for the set of conditions: gut strings, hand bowing, bridge at the soundholes and the soundpost maintained at the same position, between the Baroque and Romantic setup showed little difference. It was important that the soundpost was not moved as it has an influence of the above and below 600 Hz [6]. The violin with the Baroque setup (Renaissance bridge) was tuned to A415 and the Romantic setup (modern bridge) to A440. Table 6.9 sets out the results for hand bowing with the same gut strings. Machine bowing gave the comparison shown in table 6.10.

Table 6.9 Sound level comparison with bridge between the soundholes.

Hand Bowing	Sound level dBA SPL (SD)	
	<600 Hz	>600 Hz
Baroque violin	82 (3)	82 (3)
Romantic violin	83 (2)	83 (3)

Table 6.10 Sound level comparison with bridge between the soundholes.

Machine Bowing	Sound level dBA SPL (SD)	
	<600 Hz	>600 Hz
Baroque violin	79 (4)	81 (3)
Romantic violin	85 (4)	85 (3)

The bridge was between the soundholes for the Baroque violin in table 6.10 but earlier tests showed little difference between levels below 600 Hz and above 600 Hz, due to bridge position. With hand bowing the modern setup gave an increase of about 1 dB while machine bowing showed an increase of 6 dB below 600 Hz and 4 dB above 600

Hz. This result suggests a potential gain to the player even though it was not demonstrated with the hand bowing tests.

The change in violin setup was reflected in the resonance frequencies of modes below 1 kHz. There was no change in the frequency of the main air resonance. However, body modes B1- and B1+ were lowered by the change; B1- from 478 Hz to 425 Hz and B1+ from 585 Hz to 528 Hz. In the adjustment of the top plate for the modern setup free plate mode frequencies showed a trend to lower values as shown in chapter 9 table 9.4.

Player reaction was mixed due to the newness of the instrument. In the Baroque form it was not always easy to play. The E strung had the brightest sound. The G and E strings were more responsive than the D and A strings. There was a slight tendency to wolf on the G' on the G string and F# on the D string. The violin would be good for ensemble work.

Again for the modern setup it was difficult to play with gut strings. The G and E strings were brighter than the D and A strings as before. It was difficult to play over the fingerboard. However it had good evenness across the range for a new instrument. These comments do not detract from the earlier assessments given in this chapter.

The players in this study, while practicing Baroque playing techniques and now specialising in the Baroque, most certainly would have begun their violin studies on Romantic instruments with a classical repertoire. Subsequent studies would have taken them to Baroque violins. They would, therefore, have been familiar with and competent on both Baroque and Romantic violins. There is probably still more to be learnt about Baroque playing.

The changes experienced in the conversion studied here are probably linked with the fact that there were only minor changes with the setting up. For example, there was very little change in the bridge height on conversion. Because of the lack of uniformity of construction, Baroque bridges varied in both style and height; also, necks and fingerboards were not precisely identical. A certain uniformity probably prevailed as a result of the changeover.

The frequencies of the resonances originally built into a good instrument remain largely unchanged in frequency and strength unless the body undergoes a major change. The frequency of A0 ranges between 260 and 290 Hz usually, B1- between 450 to 480 Hz and B1+ between 520 and 560 Hz. Newly made violins follow a classical pattern closely and wood is carefully selected. Provided the resonances listed earlier are present and the violin is about 400 g it should be easy to play and perform well.

6.13 Discussion

The sound of Baroque playing is not known for certain. However, a study of the violin setup and the music and what is known of bowing techniques has led to some conclusions. The music was mostly played with separately bowed notes and the bow was lifted off the string for the longer notes which allowed them to ring. With the bridge placed below the soundholes the notes would have had strong fundamentals similar to modern playing over the fingerboard with the possibility of weaker harmonics. Nicholas Kenyon [7] has offered an explanation for the early repertory remaining unknown today. It is “that the rapid, crisp articulation and true, piercing tone required by these Italian pieces is difficult, if not impossible, to realise on the modern violin.” He goes on to say that by recreating the old instruments brought this music to life. I am inclined to think that it was mainly the playing style aided by the early bow that made the difference and, to my knowledge, no Baroque violins have been played with the bridge below the soundholes with the early bowing techniques as depicted in so many early paintings.

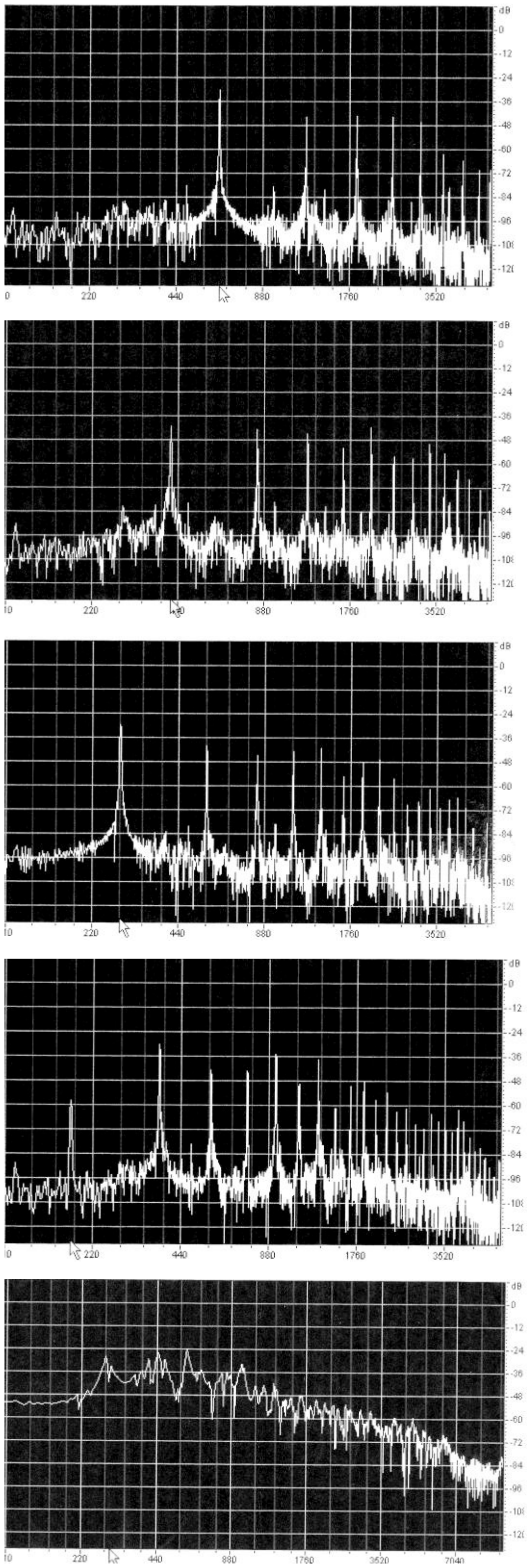

Figure 6.13 Tap response Baroque violin, neck reset for higher bridges, gut strings A415.
Renaissance bridge 2.60 g 38 mm high set at f-holes notches, soundpost 4.3 mm at 6/16.
Upper 4 plots: harmonic content of open strings.

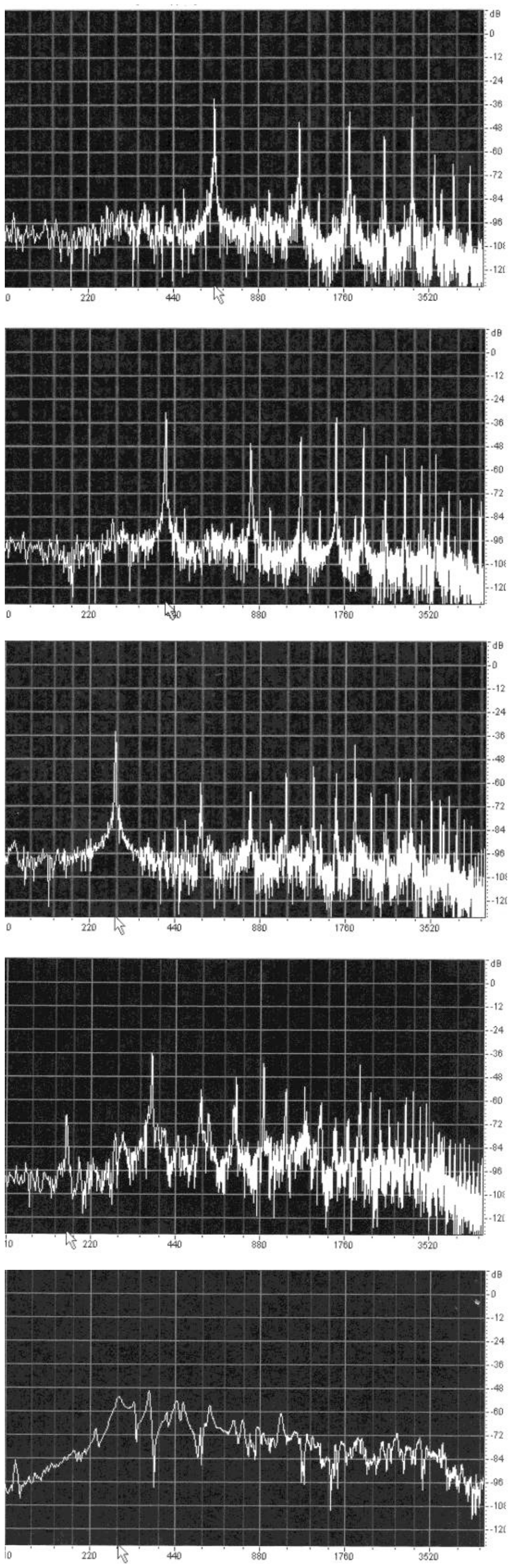

Figure 6.14 Tap response Baroque violin, neck reset for higher bridges, gut strings A415. Renaissance bridge 3.18 g 44 mm high set below f-holes, soundpost 4.3 at 6/16. Upper 4 plots: harmonics of open strings.

A comparison of the harmonic content of the open strings for the Baroque version with the bridge in the normal position and below the soundholes is shown in figures 6.13 and 6.14. The strings were bowed with a single stroke about 0.5 m from the microphone. The tap response is also included with the microphone at 100 mm from the violin top centre. The harmonic content is excellent and the fundamental on the G string is quite prominent which is not always the case.

The modern playing technique with the bow continuously on the string and placed near the bridge produces a sonority that is both rich and brilliant. The modern setup and playing style probably made greater use of the Bridge Formant at 2.5 kHz which became evident with the modern bridge. It would be of interest to replace the modern bridge on a violin with a known Bridge Formant, with an earlier style bridge to see if the Bridge Formant is retained.

Both the Baroque and Romantic setups appear to have served the player and musical demands of the period and this study has shown that with gut strings the Baroque setup may have been easier to play with the bridge in the lower position. The sound output appears to be some dBs higher with the Romantic violin. The advantage, at the change over, was to the player in the greater facility to play in higher positions with an instrument capable of a greater output, at least by a factor of 2, important for modern venues.

The benefit really came with the development of modern strings which gave more power and player assistance as indicated by the player reaction in this study.

6.14 References

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6.15 Appendix Playing Schedule for Baroque and Modern Versions.

Prepare violin: Record 1 kHz tone at position of violin

A. Warm up and familiarisation with the violin

B. Semitones for an octave on each string. These to be played without vibrato, each stroke to aim at forte but kept uniform across the range no matter what the response of the instrument. dB for each note to be measured at 1 metre, at the closer recording mic position.

Three octave scale with full romantic vibrato (for resonance scanning)

C. Record open strings for harmonic analysis. *Forte* bowing without vibrato,

D. Record a Baroque and romantic fragment using an early style bow.

Record a baroque and romantic fragment using a modem bow (for comparison)

E. Player comments on playability, etc. using topics supplied

F. Subjective assessment of sound output of violin

Judged as baroque with baroque how

Loudness

Projection, carrying power

Bright, clear/ dull, muffled

Full, rich, thin, harsh

Open/ closed, boxy

Other qualities:

evenness
ease of speaking
ease of playing, responsiveness
distinct character
sensitivity to dynamics

Judged as modern with modern bow

Chapter 7

RECORDINGS, LONG TIME AVERAGE SPECTRA and PLAYER SUBJECTIVE ASSESSMENT of the VIOLINS

7.1 Introduction

Professional violinists, with extensive experience in playing baroque, classical and modern violin, came to the laboratory to record the sounds of the violin in each of its incarnations. As well, the violin was assessed by recording the strengths of semitones played on each string by hand and bowing machine, as outlined in chapter 6. Acoustic tests were also done to determine the effective parameters of resonances that could be studied below 1 kHz which is the region where most of the fundamentals of the notes played lie. The importance of this region is such that strong fundamentals and low frequency harmonics are vital for good projection [1]. However higher harmonics, in the kHz range, are needed to give the distinct violin sound, as compared with, for example, the sound of the flute.

A problem for the violinists is the newness, to them, of the instrument and the short acquaintance the player has with it to make a judgment, especially because the violin-string-bow combination, and sometimes other details, was usually changed during an experimental session. The violin was studied in four different setups, with variants within each. Long Time Average Spectra, LTAS, are included to illustrate the similarities and differences for these comparisons. In places, players' comments on the instruments are included for comparison.

To summarise:

Setup No 1: The violin in Baroque form with light gut strings (Pirastro Chorda) tuned to A415 Hz, at first with no bassbar. Then a small bassbar fitted, with plates tuned and a light soundpost. The "Paris" bridge (1.365 g) was 30 mm high and placed at the notches in the soundholes. Compared to the romantic instrument, the main point of difference of the Baroque violin was the short neck with a light fingerboard (chapter 4) with a total mass of 116 g. The tailpiece was maple and a mass of 5.29 g. The string length was (usually) 318 mm because of the short neck. No chin or shoulder rest was used. A baroque bow was used: this had a pikes head stick and a narrow hair ribbon. Each player provided his/her own bow, to reduce the difficulty of playing the new instrument. The playing style was that chosen by the violinist as appropriate for the piece played.

Setup No 2: To accommodate heavier gut strings, the neck was reset to allow a higher “Renaissance” bridge, 38 mm high and a mass of 2.6 g. The tuning was kept at A415 Hz. This setup was used for all experimental sessions to study of the Baroque instrument, except for the first. Again no chin or shoulder rest was used. Here the same style bow was used as well as a light modern bow with reverse camber and a hatchet head. The hair ribbon was wider than on a baroque bow: 10 mm compared with 6 mm. Again, the playing style was that chosen by the violinist as appropriate for the piece played.

Setup No 3: This involved a major change as the violin was converted to the Romantic or Modern version. A stronger bassbar and thicker soundpost were added. A new, longer and more slender neck was morticed into the top block at a steeper angle. An ebony fingerboard was fitted with a total mass of 165 g. An ebony tailpiece was fitted, mass 11 g, and the bridge was of modern design of mass 2.1 g. For the first sessions on this instrument, the heavier gut strings were retained, because modern strings were not introduced until more than a century later. The pitch was raised to A440 Hz. The string length was increased to 328 mm by the change. A modern bow was mostly used. However, for comparison the baroque pieces were also played with the baroque bow. Bowing styles were chosen to suite the piece being played. A chinrest was fitted and a shoulder rest was used if required by the violinist.

Setup No 4: The violin remained unchanged but modern nylon cored strings (Thomastik Dominant) were fitted. A modern bow was used with an appropriate bowing style. A chin and shoulder rest were used for all but one player, who recorded pieces both with and without these.

7.2 Player Assessment of the Violin

Four professional Baroque violinists agreed to take part in making recordings and in playing evaluation of the two versions of the violin. The assessments for ease of playing and sound quality followed a set program (chapter 6 appendix) aimed at displaying the

strengths and weaknesses of the instrument and any changes to sound quality that occur on conversion. The two versions are briefly described in chapter 4.3 and 4.8.
Bowing styles were at the discretion of the players who chose a manner suited to the piece they were playing. A light baroque bow, and either a light classical or modern bow (which meant a hatchet head and therefore a change in balance toward the tip), were used throughout. Professional violinists become sensitive to subtle features of string sound and reaction to the bow.

The list of items given in the appendix to chapter 6 was intended as a guide for how they might assess the instrument. The bows used were owned by (and therefore familiar to) the violinists.

Each session was recorded with two microphones, one at 1 m at the height of the violin and in the direction of the treble bout, and another at 1.8 m. These sessions were later edited to provide the sound samples included in the multimedia appendix. Readers may therefore compare the sounds in the different setups and variants at www.phys.unsw.edu.au/music/people/mclennanappendix.html.

Long Time Average Spectra, LTAS, have been done on selected pairs of samples to highlight the effect of one variable, keeping the others the same. No chinrest or shoulder rest was used when playing the Baroque violin (unless specified). The player is indicated by the letters, A, B, C, D and the violin by the letter B (Baroque) or R (Romantic). The nature of the comparison is briefly indicated at the end of each of the following sections.

1 The Baroque Setup No 1

The first player assessment was the violin in Baroque form, with no bassbar, but with a light "Paris" bridge, a 5 mm diameter soundpost in the standard position 5 mm behind the treble foot of the bridge. Light Pirastro Chorda gut strings were fitted. A light Baroque bow was used and no chinrest.

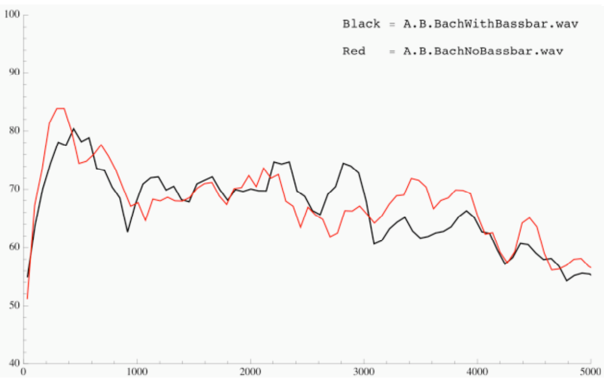
In this state, the G string was judged to have a "deep and individual voice", the D and A strings were strong while there was a loss of "sweetness" towards the E string.

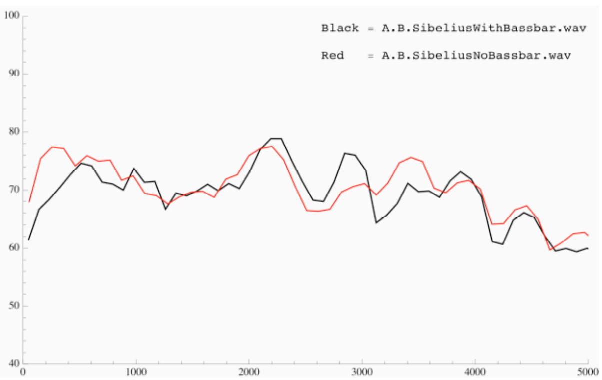
Nonwithstanding this, the violinist would have preferred more change of tone in “piano” playing. With the installation of the bassbar and the tuning of the top to match mode 2 frequencies at 177 Hz for the two plates, the sound across the range was judged to be “fuller”. It was “bright and clear” and “more open”. The violin had a “rich brightness in the high register” but “responds a bit slowly”. With a change in soundpost to one 4.3 mm diameter the sound was slightly “muffled”.

Long Term Average Spectra (LTAS) were calculated in two ways. The first used bins of 5000 points and a running average over three points. The second used 100 points and no averaging. In this chapter, only the former is presented.

The first comparison is with and without the bassbar on the Baroque violin using Chorda light gut strings. A selection from Bach and Sibelius are taken. A Baroque bow was used in both. LTAS for these two selections show the comparisons are:

A.B.BachNoBassbar.wav	A.B.SibeliusNoBassbar.wav
A.B.BachWithBassbar.wav	A.B.SibeliusWithBassbar.wav





The LTAS showed a higher sound level with no bassbar in the 0.1-1 kHz and 3-4 kHz regions but lower in the 2-3 kHz region than with a bassbar.

Setup No 2

Further playing tests were done with a set of heavier gut strings, with a silver wound G string, as described in chapters 4 and 6. These were similar to the strings in use by the violinists, who thought they were more suited to this violin. Three of the four violinists played this Baroque setup, using light bows and no chinrests.

The concensus was that the sound was generally full, clear and bright; evenness varied a little, which was thought by one player to be desirable. The E string was very bright. The A string did not speak as easily. (This may have been due to the presence of the main body resonances which lie on the A string absorbing energy).

One violinist considered the instrument to have a “lovely” character and would be good for ensemble work as it would “blend well”. It was easy to play at the “extremes of dynamics”.

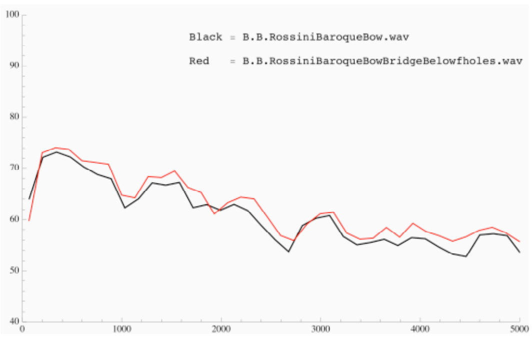
Here heavier gut strings were used and comparison was made with both a Baroque and a modern bow, as well as with the bridge at the notches in the soundholes (standard position) and placed below the soundholes. Passages from Bassano and Rossini with a Baroque and modern bow and again from Handel and Brahms are shown. Telemann is used to show the effect of a Baroque and modern bow. The LTAS for this section are:

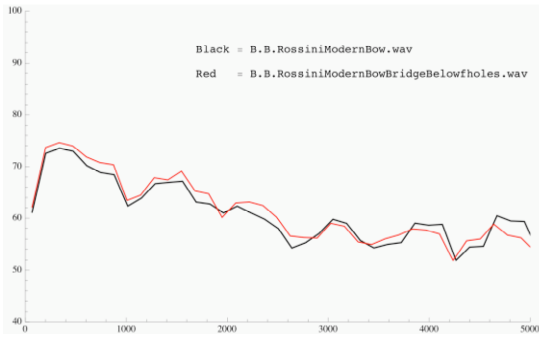
B.B.RossiniBaroqueBow.wav

B.B.RossiniBaroqueBowBridge Belowfholes.wav

B.B.RossiniModernBow.wav

B.B.RossiniModernBowBridge Belowfholes.wav



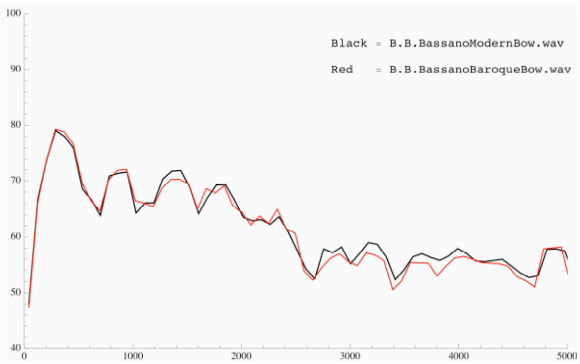


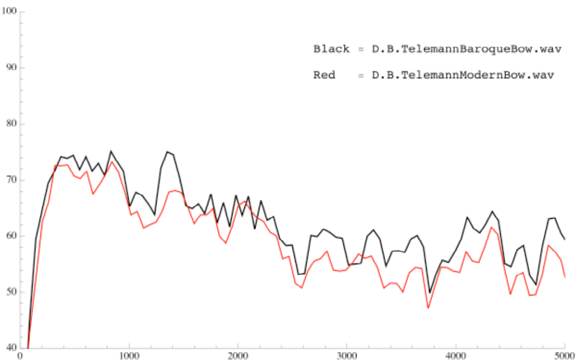
B.B.BassanoBaroqueBow.wav

B.B.BassanoModernBow.wav

D.B.TelemannBaroqueBow.wav

D.B.TelemannModernBow.wav





The upper pair show that with the bridge below the f-holes, the Baroque bow gives a higher sound level, 2 dB, than when at the f-holes; the modern bow shows a 1 dB higher level.
The lower pair show little difference, the modern bow 1 dB higher in the 2.5-4.5 kHz region with Bassano. With Telemann the Baroque bow gave a higher sound level in the 2.5-5 kHz region of about 5 dB.

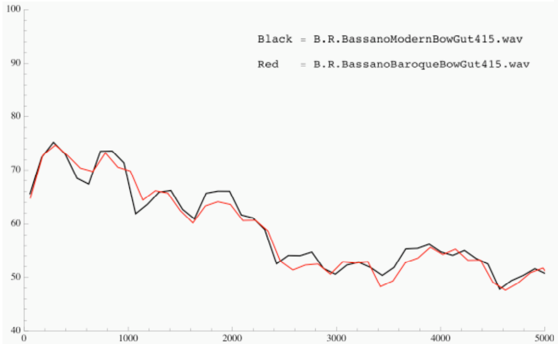
2. The Romantic Setup No 3

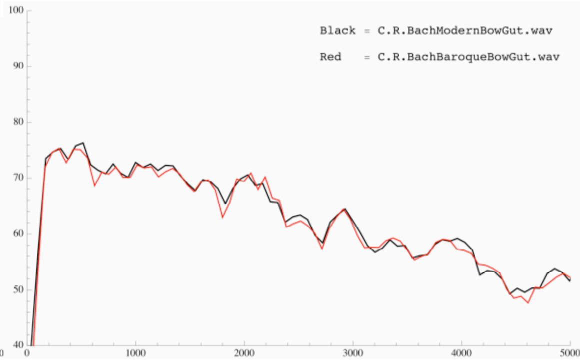
After conversion to the Romantic setup, which involved a change of bassbar as well as the neck and fingerboard, typical of the modern violin, the same strings were used (heavier gut with a silver wound G string) but a modern bridge was fitted. The pitch was raised from A415 Hz to A440 Hz. A modern bow was used, as well as a chinrest.

One violinist considered the violin was "difficult to play with the gut strings that were on it"; the D and A strings were more "muffled" than the G and E strings. A second violinist agreed that with the gut strings on a modern setup the "speaking" was slow and the player was "having to work hard to get the sound", yet the violin was "bright and clear"; evenness was good for "a brand new instrument". For another violinist the "D and E strings spoke slightly easier, were brighter and more responsive than the G and A strings". It was also "an easy instrument to play; (I) don't have to work too hard for a new instrument - would expect responsiveness to increase with continued regular playing".

Rossini and Bassano were again used with the Romantic violin to highlight the use of the two bow types. Here both gut and modern strings are compared; A415 and A440 tuning and both types of bow. Rossini and Bassano are again used as examples as well as Bach and Sarasate. A440 is unless specified. Pieces from Bach and Bruch also featured here. The LTAS for this section are:

B.R.BassanoBaroqueBowGut415.wav	C.R.BachBaroqueBowGut.wav
B.R.BassanoMosernBowGut415.wav	C.R.BachModernBowGut.wav



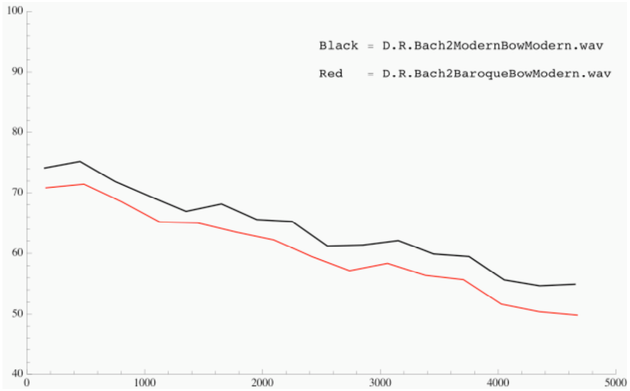


The LTAS show little difference between the bows with the Romantic violin.

Setup No 4

The last violinist in the above assessment reassessed the violin when the gut strings were replaced with a set of Thomastik Dominant nylon cored strings. It was "brighter and clearer" with these strings. It was more "open and more even with synthetic cored and metal wound strings". The violin "speaks easier - metal strings more immediate" "speak with the bow"; "easier to play setup like this"; more responsive than with gut"; "good new instrument - will develop more character with continued playing". Another violinist said the G string was "more powerful".

The selection here was Bach with modern strings at A440 showing the effect of both bows. The LTAS for these two selections are:
D.R.Bach2ModernBowModern.wav
D.R.Bach2BaroqueBowModern.wav



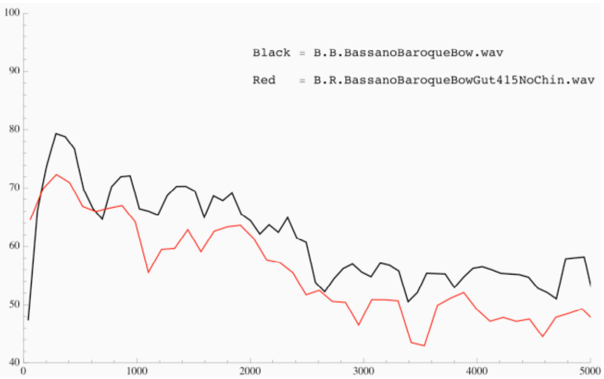
The modern bow gave a consistently higher sound level of about 3 dB.

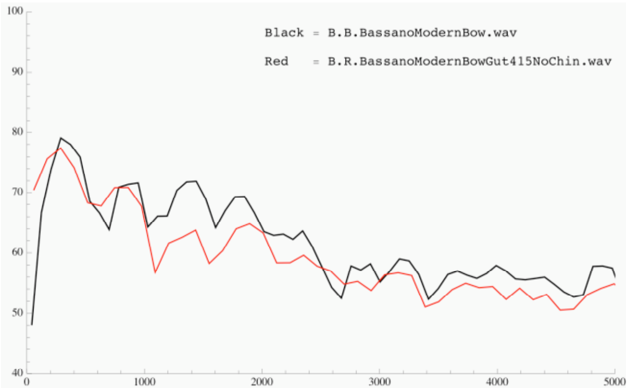
Comparison of the Baroque and Romantic violins

An interesting comparison is that between the Baroque violin and the conversion to the Romantic setup. For this purpose the LTAS are:

B.B.BassanoBaroqueBow.wav B.B.BassanoModernBow.wav

B.R.BassanoBaroqueBowGut415NoChin.wav B.R.BassanoModernBowGut415NoChin.wav





The LTAS show that with the Baroque bow the sound level is generally higher for the baroque violin by about 5 dB. With the modern bow the Baroque violin is still higher but the difference is not as great, about 1 dB in the 2.5- 5 kHz region and about 3-8 dB in the 1-2.5 kHz region,

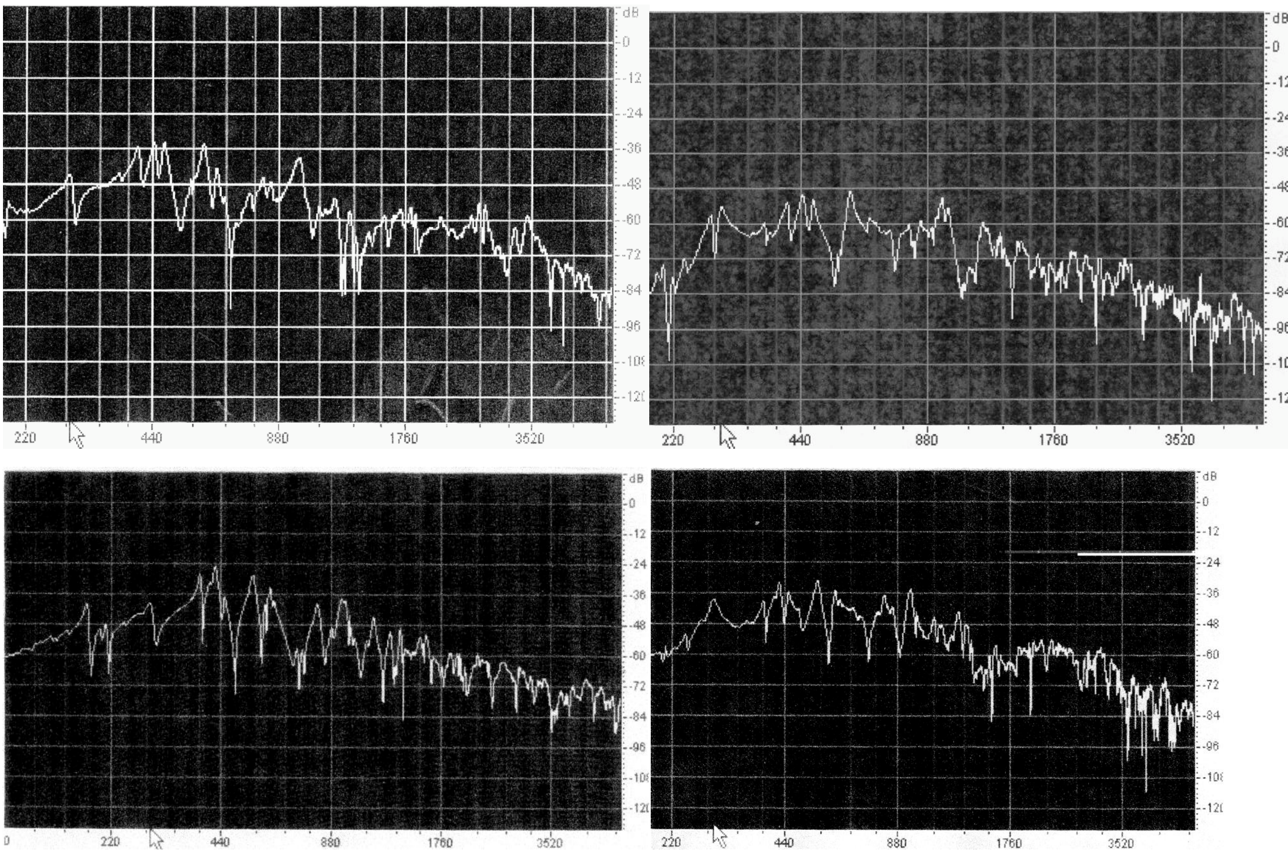
7.3 Acoustic Parameters associated with the two versions

To complement the player assessments, a summary of Resonance frequencies and loudness measurements has been added as follows.

The differences between these two setups, in terms of the expected radiation associated with the resonances present, are summarised in the tables below. The physical changes and the resulting acoustic parameters are shown in table 7.1.

Table 7.1 Physical and acoustic parameters of the Baroque and Romantic setup

Physical parameters			Acoustic parameters							
Mass (g)			Resonance frequencies (Hz)							
Total	Body	neck/fbd.	A0	C2	B1--	B1-	B1+	C4	?	?
Baroque violin										
385	255	116	281	411	450	470	581	620		775
Resistance to bridge motion (kg/s)			0.14	13	13	10	3	21		6
Quality factor Q			18	29	30	36	58	29		28
Romantic violin										
440	260	165	286	386	420	447	528	540	586	878
Resistance to bridge motion (kg/s)			0.14	2	5	35	5	5	5	54
Quality factor Q			14	77	47	45	38	49	84	37



Figures 4.6, 6.1 and 6.8 (repeated). At left is the tap response showing input admittance obtained with a magnet/coil at the bass side of the bridge upper edge, and at right the microphone response. The upper plots show the Baroque violin, neck reset, gut strings A415, Renaissance bridge 2.60 g 38 mm high set at notches in f-holes soundpost 4.3 mm at 6/16. The lower plots show the converted violin, gut strings A440, modern bridge 2.19 g 37 mm high set at notches in f-holes, soundpost 6 mm at 6/18.

The main change in the setup was a new modern neck, of mass 165 g which replaced the Baroque neck, mass 116 g. A recent test adding a 45 g chinrest at the bottom block lowered B1- by 6 Hz (see chapter 10 table 10.3). Tap response curves were routinely made without a chinrest fitted, although one was used when the violins were played in the Romantic setup but not in the Baroque setup. For playing, a shoulder rest was also used but the effect of the player holding the violin was not studied. Plasticine was used to study the effect of added mass on the resonance frequencies. When both chinrest and plasticine were added together B1- was lowered by 11 Hz. A0 and B1+ were not affected. Plasticine was the easier form of mass to use. It was added at the neck as described in chapter 10, table 10.3. The chinrest when first introduced was about 20 g, half that of the modern chinrest.

For the Romantic violin, the body mode frequencies were lower than those for the Baroque violin, although the main air resonance did not change significantly. These lower frequencies may have also been influenced by lower top plate frequencies resulting from the changes made when converting to the romantic setup, but the effect would appear to be small. These changes involved a new bassbar and slight thinning of the central area to correct the runout that appeared in mode 5 nodal line when adding the bassbar, as explained in chapter 10. The body modes with low values of R will be good radiators. The Romantic violin appears to have more resonances with low R values than the Baroque violin. The increase in mass of the violin, at the conversion, which included installing a heavier bassbar are the main structural difference between the two violin bodies. A body mode at 875 Hz appeared to be a poor radiator in the modern setup. This resonance is characterised in chapter 9, table 9.6 and figure 9.12.

Professionally made gut strings (e.g. E. Segerman at N.R.I. in Manchester U.K. as discussed in chapter 4), were used throughout on the early advice of a player as being more suited to the violin, except at the beginning in setup No 1, with which a lighter set of Pirastro Chorda gut strings were tried. Tables 6.1 and 6.2 in chapter 6 set out the results of the preliminary trial with Chorda strings. The major study of the Baroque and Romantic conversion was done with the heaviest gut strings. The Romantic version was fitted with Thomastik Dominant nylon cored strings for a trial at the end. The results are shown in table 7.2.

The loudness values in tables 7.2 and 7.3 were taken from the Saunders Loudness Test records in chapter 6, figures 6.1, 6.3, 6.5, 6.6 and 6.7. The table shows that hand bowing, played *forte*, produced very even response both over the range and also between the two forms of the violin. There was an increase in average loudness going from the Baroque version to the Romantic version as discussed in chapter 5 and shown in table 7.2.

Table 7.2 Saunders Loudness values for the Baroque and Romantic violins (hand bowing)

Strings used Length (mm)		Tension (N)	Condition	Sound Level dBA SPL (SD) <600 Hz	>600 Hz
			Baroque violin		
315	Chorda gut	150	no bassbar	74 (3.0)	73 (2.9)
			+ bassbar	72 (2.7)	73 (2.0)
	NRI gut	180	bridge at f-holes	82 (3.4)	82 (2.6)
			bridge below f-holes	79 (2.4)	82 (3.5)
			Romantic violin		
325	NRI gut	216	bridge at f-holes	83 (2.1)	83 (2.7)
	Dominant (nylon cored)	218	bridge at f-holes	83 (3.1)	84 (3.8)

The results for machine bowing show some differences. Table 7.3 sets out the results for both gut strings and the nylon cored strings.

Table 7.3 Saunders Loudness values for the Baroque and Romantic violins (machine bowing)

Strings used Length (mm)		Tension (N)	Condition	Sound Level dBA SPL (SD) <600 Hz	>600 Hz
			Baroque violin		
315	Chorda	150	no bassbar	79 (--)	77 (--)
			+ bassbar	79 (3.6)	81 (3.3)
	NRI	180	bridge below f-holes	81 (3.5)	83 (3.1)
			Romantic violin		
325	NRI	216	bridge at f-holes	85 (3.6)	85 (2.9)
	Dominant	218	bridge at f-holes	85 (3.1)	88 (2.9)

Machine bowing loudness levels are higher than those for hand bowing. This suggests that a higher bow force was used in the former case. It is not known how sensitive the players are to loudness levels and whether compensation occurred. The machine bowing showed differences of 2 to 3 dB between the low and higher range in the above table. The lighter Chorda gut strings showed large differences (see Chapter 6) for hand bowing. Machine bowing was not used at the time of the first experiments on the Baroque violin with Chorda strings. Summarising the quality assessments given for the instrument by the players in chapter 6, by adding the totals for all the players for each rating showed a slight overall gain on conversion, a total of 78% compared with 71% for the Baroque version, as shown in table 7.4.

Table 7.4 Summary of responses for each rating of the two violin setups (from chapter 6 tables 6.4 and 6.6).

Rating	4	5	6	7	8	9	Total
Baroque totals	-	5	4	10	7	5	31
as %		16	13	32	23	16	71%
Modern totals	1	1	3	5	6	7	23
as %	4	4	13	22	26	30	78%

More comments on the playing parameters were made on the Baroque setup than the modern one. The player assessments for the modern setup seem to bunch up toward the higher ratings while they are more spread out for the Baroque.

7.4 Played Sound Examples

A collection of recorded sounds from playing both versions of the violin is accessible at www.phys.unsw.edu.au/music/people/mclennanappendix.html There examples were made with the microphone at 1 m in the plane of the instrument on the treble side as being the best compromise in the small reverberant room used. A number of variables were explored; bridge type, string type, bow type; the presence or absence of a chinrest and shoulder rest. Combinations have been selected to allow comparisons to be made. Some of these recordings will be used in a future study to compare the salience of the changes in sound produced by the various adjustments and configurations of the instrument.

7.5 References

1. Loos U. "Investigation of Projection of Violin Tones" CASJ 4(8) Nov. 2003, 72-73.

7.6 Appendix: List of sound files, arranged for listener comparisons. The multimedia appendix is at www.phys.unsw.edu.au/music/people/mclennanappendix.html

Effect of the bassbar

Player A, baroque violin, no bassbar	Player A, baroque violin, with bassbar.
(A) Scale No Bassbar	(A) Scale With Bassbar
(A) Bach No Bassbar	(A) Bach With Bassbar
(A) Sibelius No Bassbar	(A) Sibelius With Bassbar

Effect of bridge position

Player B, baroque violin, Bridge at Standard position	Player B, baroque violin, Bridge below the f-holes
(B) Bassano Baroque Bow	(B) Bassano Baroque Bow Bridge Below f-holes
(B) Bassano Short Baroque Bow	
(B) Rossini Baroque Bow	(B) Rossini Baroque Bow Bridge Below f-holes
(B) Rossini Modern Bow	(B) Rossini Modern Bow Bridge Below f-holes

Effect of baroque vs. modern bow on a baroque violin gut strings

Player B, C, D baroque violin baroque bow	Player B, C, D baroque violin modern bow
(B) Bassano Baroque Bow	(B) Bassano Modern Bow
(B) Rossini Baroque Bow	(B) Rossini Modern Bow
(C) Handel Baroque Bow Gut No Shoulder Rest	(C) Handel Modern Bow Gut No Shoulder Rest
(D) Telemann Baroque Bow	(D) Telemann Modern Bow

Effect of Baroque vs. Modern bow on Modern violin (gut strings)

Player C or D, Modern violin, baroque bow	Player C or D, Modern violin, modern bow
(C) Bach Baroque Bow Gut	(C) Bach Modern Bow Gut
(C) Bruch Baroque Bow Gut	(C) Bruch Modern Bow Gut
(D) Bach2 Baroque Bow Gut	(D) Bach2 Modern Bow Gut
(D) Sarasate Baroque Bow Gut	(D) Sarasate Modern Bow Gut

Effect of chinrest on Modern violin Modern bow Gut strings

Player B Modern Bow No Chinrest	Player B Modern Bow Chinrest
(B) Bassano Modern Bow	(B) Bassano Modern Bow

Effect of shoulder rest on Baroque violin Baroque Bow Gut strings

Player C Baroque Bow No Shoulder rest	Player C Baroque Bow Shoulder rest
(C) Handel Baroque Bow	(C) Handel Baroque Bow

Effect of Bow on Baroque violin with Shoulder rest Gut strings

Player C Baroque Bow Shoulder rest	Player C Modern Bow Shoulder rest
(C) Brahms Baroque Bow Gut	(C) Brahms Modern Bow Gut

Effect of String type on Modern violin Modern Bow

Player D Modern Bow Gut strings	Player D Modern Bow Modern strings
(D) Sarasate Modern Bow Gut	(D) Sarasate Modern Bow Modern

Effect of Bow type on Modern violin Modern strings

Player D Modern violin Baroque Bow	Player D Modern violin Modern Bow
(D) Bach2 Baroque Bow Modern	(D) Bach2 Modern Bow Modern

Scales Effect of string type Modern violin Modern Bow

Player B and D Gut strings	Player B and D Modern strings
(B) Scale Modern Bow Gut 415	
(D) Scale Modern Bow Gut	(D) Scale Modern Bow Modern

Scales Effect of string type Modern violin Baroque Bow

Player B Modern violin Gut strings	Player B Modern violin Modern strings
(B) Scale Baroque Bow Gut 415	(B) Scale Baroque Bow Modern 415

Chapter 8

The BAROQUE VIOLIN – The Effect of Bridge Design and Bridge and Soundpost Position

8.1 Introduction

The bridge and soundpost are two movable parts of the violin. The first influences the playing length of the string. Both affect the response and evenness across the range and especially the output of the lower strings. In this chapter the sound output of the violin has been explored with different bridge styles, placed in either of two positions; at the notches in the f-holes, or below the soundholes as shown in figure 8.2. The corresponding response curves and Chladni patterns are discussed.

The bridge is a most important part of the violin. Its height can be adjusted and its position altered to meet the demands of current string technology and the wishes of the player. Bridge positions are normally fixed on string instruments that are plucked. This feature of the violin, at the time, added a useful variable to the function of the instrument. When one looks at the Classical record which consists mainly of paintings, from the 17th century and earlier, one is struck by the inconsistent position in which the bridge of the violin was placed. This has been reviewed by David Boyden [1] p 34. The reason for this was not discussed by him apart from suggesting the possible need for a longer playing string length to aid intonation and a difference in tone colour achievable, see figure 8.1.

Confining our attention to the bridge, paintings show it in positions varying from between the notches at the midpoint along the length of the soundholes to positions below the soundholes. It was also thought by earlier writers that moving the soundpost along with the bridge affected the sound adversely and therefore the soundpost has remained in its central position. (This is reviewed by the present author [2].) The bassbar was adopted later than the soundpost and was also used to support the top against the normal force or downbearing of the strings through the bridge. Its position, under the bass foot of the bridge has not changed although it has increased in size.

Figure 8.1 Bridge position from a painting by Michelangelo de Caravaggio (c. 1573 – c. 1610). David Boyden [1]

It appears a fourth string was added in the change from the Renaissance “fiddle” to the Baroque “violin”. Iconographic evidence is shown in paintings by Gaudenzio Ferrari in a fresco (c: 1535) in the cupola of Santa Maria delle Grazie, Saronno where a viola has three pegs clearly visible [1, plate 2] and a violin shown in plate XI [4] by the same painter (c: 1529/30) again showing three pegs. This painting is in the alter-piece of San Cristoforo, Verecelli. The fourth string was a rope wound gut G string.

All these early paintings show the bridge below the soundholes. It is this author’s belief that this practice carried over into the Baroque for ease of sound production. It wasn’t until the bassbar and soundpost were firmly established around 1600 and string making had improved e.g. silver wound G strings, that the bridge was moved up to the notches in the soundholes which now had become f-shaped.

Recent discussion [3] has questioned the belief that the bridge sat at a position other than between the notches in the f-holes, due to the apparent absence of “foot prints” on violins examined. It is possible that none of these early instruments have survived. There is one example on a Lira da Braccio of 1525 (pictured in Jeremy Montagu [4] p.114, plate 86) in which footprints are shown below the bridge which is at the notches in the f-holes. David Rivinus' [3] recent research showed that the bridge was mostly below the soundholes in early fiddles (before the violin). It was also thought to be difficult to install the soundpost below the bridge when it was below the soundholes although it could be done. Strutting was common in fiddles and was later simplified to the bassbar. The sound was conditioned by the fact that players rarely bowed near the bridge but at the C-bouts.

While on this question of evidence on early instruments, parchment patches were used at the location of the soundpost to protect the surface of the top plate. These have since been disused and the locations of earlier use have been lost. This chapter reports studies that investigate the effect of bridge and soundpost position.

The fiddles made before the Baroque era had C-shaped soundholes with no notches, the notches in the f-shaped soundholes probably appeared with them to set the 'stop' which was 195 mm from the upper end of the top plate. This gave a string length of 315 mm for the shorter neck in use at the time if the bridge was placed at the notches. Many paintings, as described by Boyden, show the bridge located in this position. Other paintings, however, depict bridges below this position and in some instances well below the soundholes. The integrity of these draftsmen, who include such noted realists as Caravaggio, cannot be in question; they recorded what they saw. It remains to question the care of the player although it seems more likely that the positioning of the bridge was done for a deliberate purpose. Segerman and Abbott [5] suggest the aim was to match the pitch level appropriate for an ensemble of 16th century viols or to match a higher opera pitch or lower one for chamber music.

It was considered that moving the bridge away from the notches in the soundholes caused a loss in sound quality [6]. Later work on nodal patterns has shown that the soundpost in the normal position is associated with a nodal line near the treble soundhole even when the bridge is moved. We know of no previous reports of how the nodal lines are altered by a large shift in soundpost position. Why moving the soundpost with the bridge to a position below the soundholes was not successful may have been due to little change in the vibration modes of the violin body. It is shown later that mode shapes are essentially unaltered.

8.2 The Violin setup used in this Study

Violin stringing during the Baroque era up to the mid 18th century was for equal tension on all strings [7]. Even though pitches were not standardised, a good working value of A415 has been taken in this study. Gut strings of low twist were used for the two upper strings in order to attain the tensions required together with a silver wound G string. The third string was usually high twist gut. The diameters, mm, and tensions (kg) are shown in table 8.1 for two string lengths for the above pitch,

Table 8.1 String parameters for two lengths of Gut strings with the A string tuned to A415 Hz.

String		G	D	A	E
String length	325 mm				
Diameter (mm)		1.3	1.0	0.75	0.60
Tension (kg wt)		3.3	3.6	4.1	5.8
String length	315 mm				
Diameter (mm)		0.85	1.02	0.72	0.59
Tension (kg wt)		3.0	3.0	4.0	6.3
Mass/unit length (g/m) Pirastro Chorda		1.90	1.06	0.58	0.40

The G string dia. as measured includes the silver winding and here is given in equivalent dia. gut [7]. This would be the diameter gut that would give the same mass per unit length. This corresponds to strings made today, notably, Pirastro Chorda as used in this work. The total tension for a string length of 325 mm was 17 kg wt or 170 N while the total tension was16.3 kg wt (163 N) for a string length of 315 mm. The silver wound G string at 0.85 mm has an equivalent dia., in gut, of 1.45 mm. This was the medium weight adopted then because the violin was a loud instrument by the standards of the day. When it was played in ensembles that included viols, it had to be strung so that it matched the viol in loudness more closely; a lighter stringing was used probably with a lighter setup soundpost and bassbar.

As mentioned previously, the violin used in this work was made on a Guarneri outline taken from the “Kreisler” Guarneri of 1733. The Baroque neck was butted to the sides, glued and screwed through the top block. The fingerboard was made on a willow core veneered with maple and shaped as a wedge to give the right string clearance. It was 220 mm long compared with 270 mm for the modern setup. With a maple tailpiece, the violin weighed 385 g when setup. The string length was 315 mm and the Baroque bridges weighed about 1.5 g. The bridges used on the Baroque violin and the two bridge positions are shown in figure 8.2.

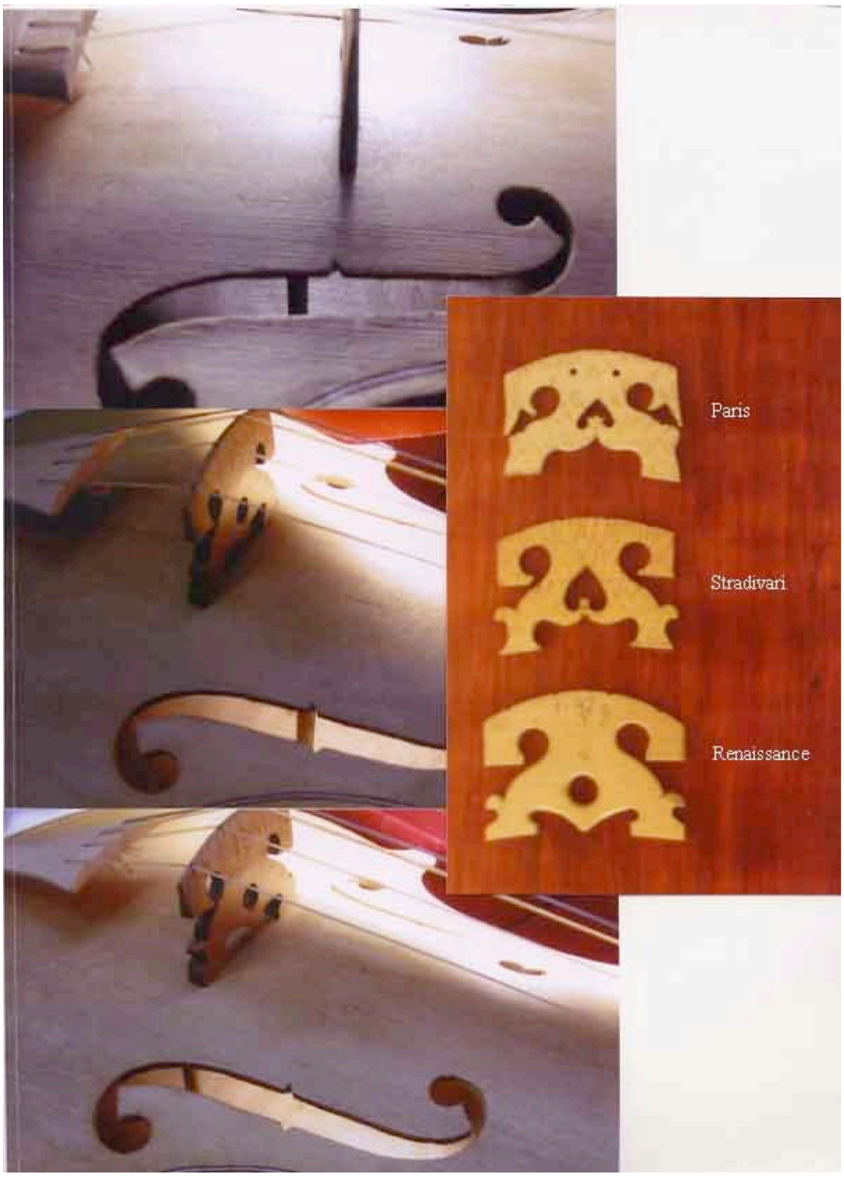


Figure 8.2 bridge types used in this study.
Bridge and soundpost positions for three cases: bridge and soundpost at f-holes; bridge below f-holes and soundpost at notches; bridge and soundpost below f-holes.

Typical tap responses for the three bridge types shown in figure 8.2 are given in figure 8.3 where a microphone was used. The responses are similar in their main characteristics. The bridges were all positioned at the soundhole notches. Note the similarity in the response at low frequencies, for which the bridge (below its own resonance frequencies) behaves as a rigid object.

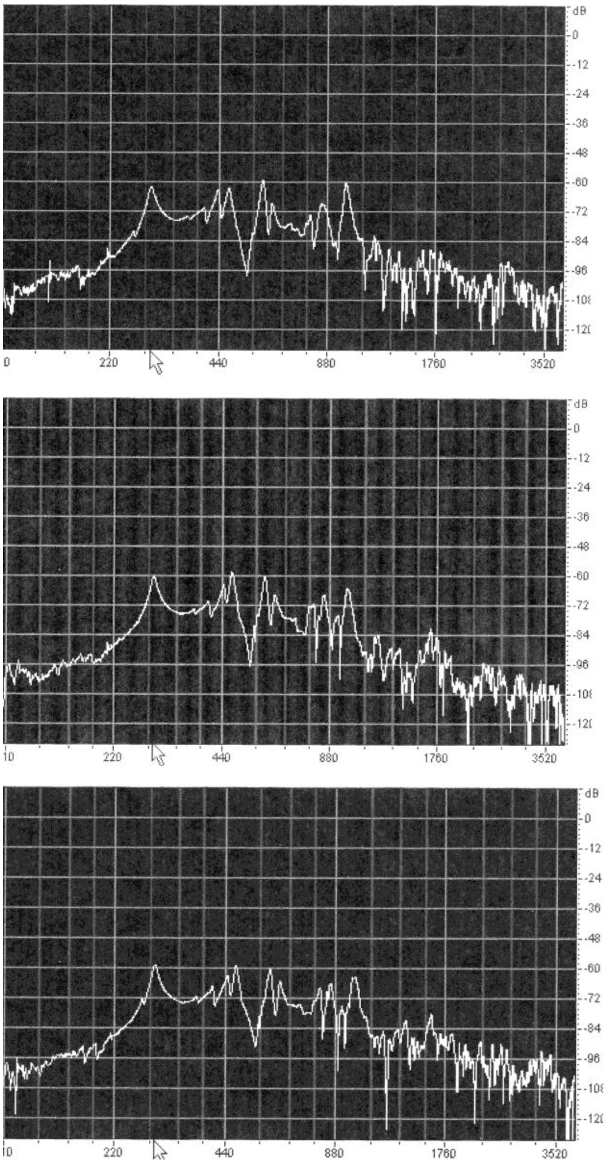


Figure 8.3 Tap response of Baroque violin, microphone at 100 mm, Chorda gut strings A415, bridges at f-hole notches. Response recorded by microphone at 100 mm.
Top: “Paris” bridge 1.365 g 30 mm high, soundpost 4.3 mm at 3.5/16.
Centre: “Stradivari” bridge 1.51 g 29 mm high, soundpost 4.3 mm at 6/17.
Bottom: “Renaissance” bridge 1.45 g 31 mm high, soundpost 4.3 mm at 5/15.

8.3 Experimental Procedure

Bowing tests were conducted on the violin with the setup unaltered except for the change in bridge position and the change of tailpiece necessary to accommodate this. The effect of this was to increase the string length requiring an increase in string tension to maintain the original tuning when using the same strings. The question arises: why was this done? In a previous study, the present author has also observed [2] that moving the soundpost when the bridge was moved reduced the sound quality.

The violin in the present study was fitted with gut strings (a silver wound G string) tuned to A415. For the first test the bridge, a “Paris” design (1.365 g) was placed at the soundhole “notches” with a 4.3 mm diameter soundpost at 5/15 (i.e. 5 mm behind the treble bridge foot and 15 mm in from the treble f- hole, using nearer surfaces) with a maple tailpiece (5.29 g). For the second test, the setup remained the same except that a “Renaissance” bridge (1.45 g) was place at the lower end of the soundholes requiring a different tailpiece (maple of similar design weighing 3.45 g). This gave a string length of 355 mm as against 315 mm. The soundpost remained in the original position, figure 8.2. The change from a ‘Paris’ to a ‘Renaissance’ bridge was required by the repositioning of the neck and both positions needing a higher bridge.

Bowing was done about 20 mm from the bridge when it was at the notches which placed the bow at the upper finial of the soundhole. With the bridge below the f-holes the bow was at the notches and still within the C-bout. It was then about 40 mm from the bridge. The aim was to make a forte sound; the bow speed for this would be about 0.4 m/s and the bow force about 1.5 N. It was not possible to be precise with human players but these values for the bow are those obtained from machine bowing.

8.4 Playing Tests

The experiments to explore the effect of moving the bridge (and the soundpost) were done in a semi-reverberant room by the author with a light modern bow. A constant bowing technique i.e. bow force and bow velocity, was maintained throughout. Light bow strokes, without vibrato. Following Saunders [8], the sound level in dB was recorded for each note in a chromatic scale over one octave on each string. The microphone was placed at one metre to the treble side and in the plane of the violin with a Sound Level Meter on A weighting and Fast response. The results of these bowing tests are shown in figure 8.4. The bowing tests gave some interesting results. With the bridge in the normal position at the notches in the soundholes and the soundpost behind the bridge where it is normally placed, the response was uniform over the range from

G3 to A6, about 3 octaves as shown by the lowest plot in figure 8.4. This evenness was also noticeable to a professional player who found the violin had a good response in this configuration.

The two upper plots in figure 8.4 show the results obtained by the author when the bridge was moved to a position below the soundholes while the soundpost remained in the normal position at the notches and also when the soundpost was moved to a new position below the bridge, the sound level on the E string and the upper notes on the A string were higher than the sound level of notes on the two lower strings. For the professional player, the violin was less responsive with the bridge in the lower position, and when the soundpost was moved, the two top strings were less responsive. A higher bow force in this case gave a better response.

To summarise the differences shown in figure 8.4, the sound levels on the three lower strings were averaged and the average of those on the E string listed separately. The results are given in Table 8.2. Duplicate bowing experiments, shown thus ( ), gave the same trends in sound level although there were slight differences in detail.

Table 8.2 Sound levels as a function of bridge and soundpost position, Baroque violin hand bowing. Pirastro 'Chorda' strings from figure 8.4. (2nd determination)

	Average Sound Level, dBA SPL		
	3 lower strings	E string	Difference
Bridge and s/post at f-holes	74	75	1
	(72)	(75)	3
Bridge below f-holes (s/post at f-holes)	77	85	8
	(74)	(79)	5
Bridge and soundpost below f-holes	72	78	6
	(74)	(77)	3

The sound quality was similar for all three setups as judged by the professional player. This may have been due to the similarity between the tap responses as shown in the next section. If these results are typical, moving the bridge below the soundholes with the soundpost in the normal position, thus raising the loudness of notes on the E string may have been an attractive feature.

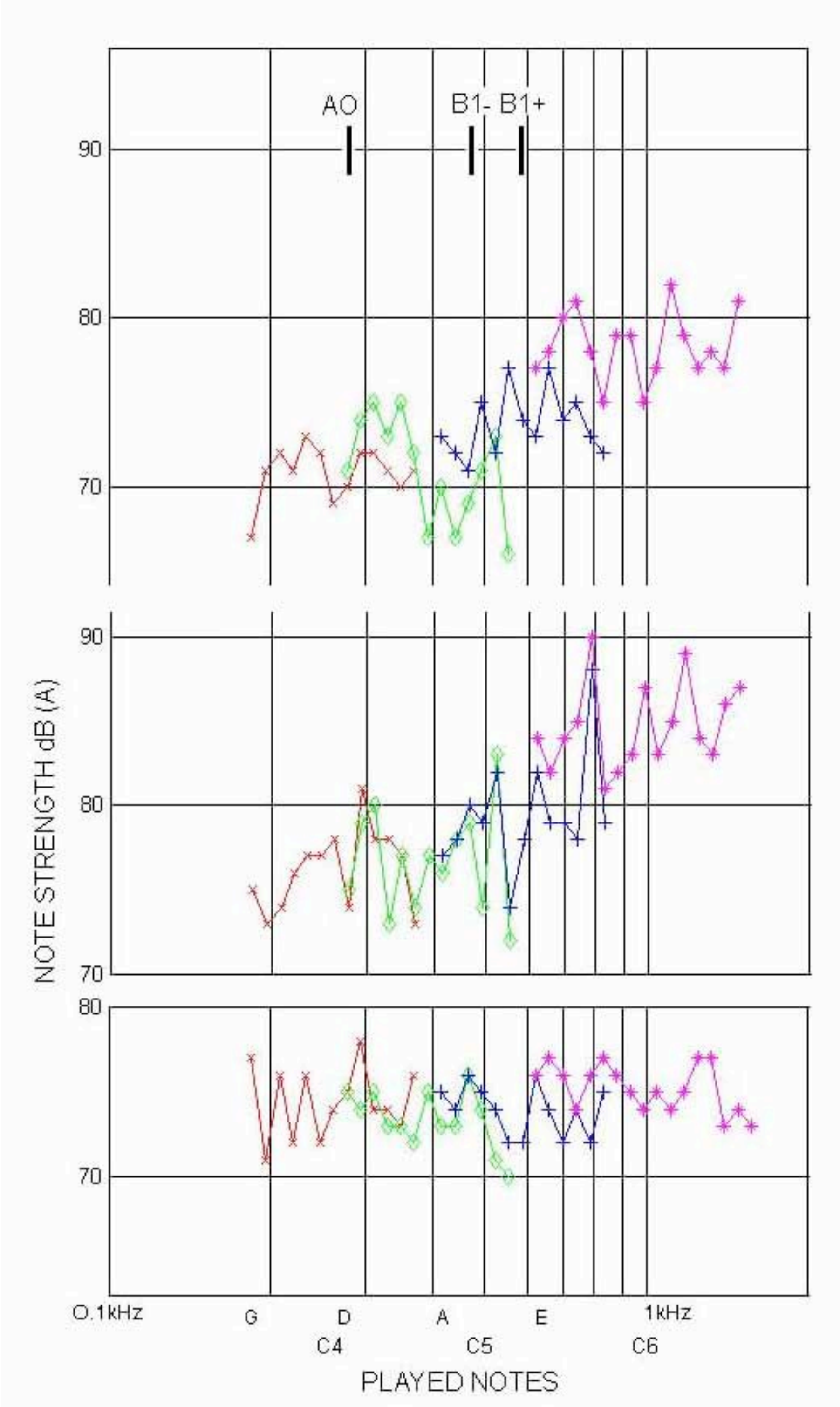


Figure 8.4 Saunders Loudness Tests on the Baroque violin with Pirastro "Chorda" gut strings, hand bowing, no vibrato. Top: Renaissance bridge 3.18 g 44 mm high set below the f-holes, soundpost 4 mm below the bridge. Middle: Renaissance bridge 2.47 g 38 mm high set below the f-holes, soundpost 4.3 mm dia. at the f-holes (5/15). Bottom: Renaissance bridge 1.45 g 32 mm high at notches in f-holes, soundpost 5 mm dia. at the f-holes (5/22). (see figure 8.2)

Loudness was the reason the violin supplanted the viol in the public arena. Loudness, while important for a violin, may be less important than evenness across the range (as is equal string tension to give a uniform feel when stopping notes). A well made violin will have a forte above 90 dB at 1m.

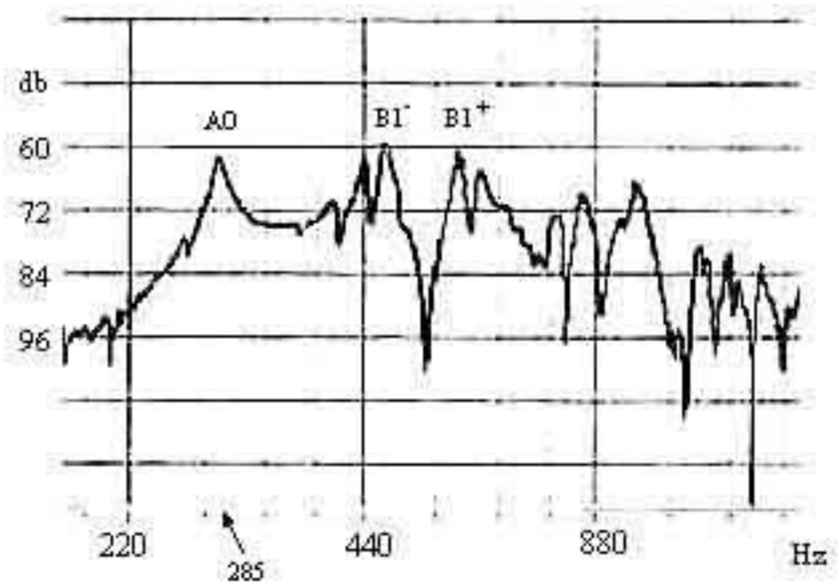
In an earlier study on the soundpost [2] the present author found that moving it from inside the treble foot to outside it raised the output of the three lower strings while that of the E string changed very little. The fundamentals of notes on the lower strings rely more on the breathing action of the violin. Notes on the upper E string are affected by modes that are more directional in the way they radiate. The standard position for the soundpost is behind and in line with the treble foot of the bridge.

8.5 Tap Response

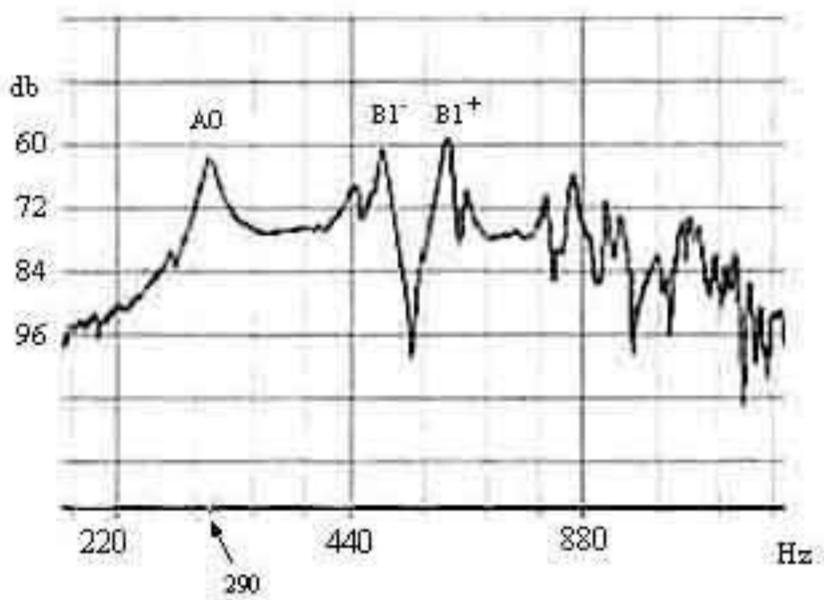
The tap responses in figures 8.5, 8.6 and 8.7 are separate determinations to those in chapter 6 figure 6.6 and show the repeatability of these determinations. An example of the tap response with the bridge and soundpost at the notches in the soundholes, regarded as the standard position, is shown in figure 8.5 for two different soundpost positions. The position 5/22 is that directly behind the treble foot of the bridge; the upper plot has the soundpost nearer to the treble f-hole.

Moving the bridge to a position in line with the lower edge of the soundholes but leaving the soundpost unmoved, did not change the basic form of the FRF's, only reducing the 'satellites" associated with B1- and B1+. The general level of the FRF's was similar for the body modes but A0 was lower, as shown in figure 8.6. While the Chladni pattern for A0, shown in figure 8.8, was obtained, it proved too difficult to determine the effective mass and stiffness for it.

The effect of moving the soundpost to a new position below the bridge is shown in figure 8.7. Here the main difference is the appearance of a peak at 690 Hz leaving a region at 880 Hz without resonance peaks. It would seem this change is mainly due to the repositioning of the soundpost. Figure 8.8a shows Chladni patterns for A0 and a peak at 690 Hz with the bridge and soundpost below the f-holes. The tea leaves have not formed distinct lines except for the back at 690 Hz. Figures 8.9 to 8.11 show the same two resonances, B1- and B1+?, for the different bridge and soundpost positions. There do not appear to be large differences although the nodal lines with the bridge below the soundholes appear to be closer to the margins of the plates. Small changes in these patterns will be important in the sound level from the violin.

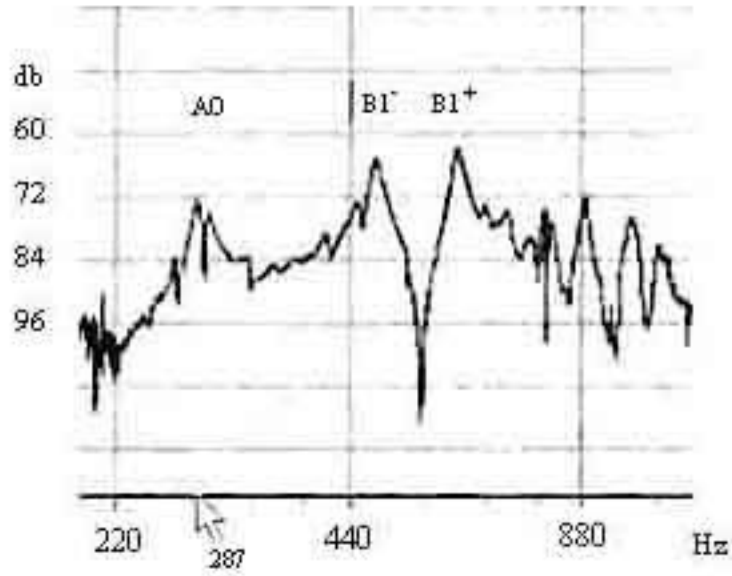


Soundpost: 4.3 mm dia 5/15

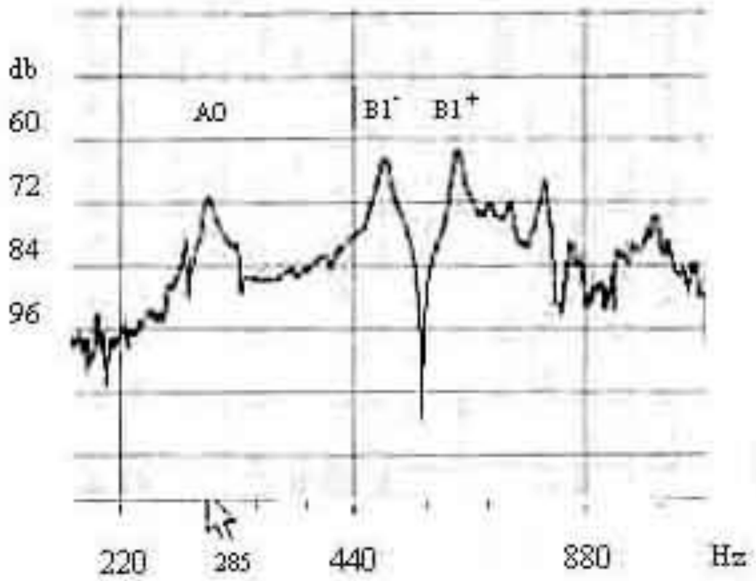


Soundpost: 5 mm dia @ 5/22

Figure 8.5 Tap response of Baroque violin Chorda gut strings at A415.
Effect of change of soundpost position on response curve, bridge at f-holes.

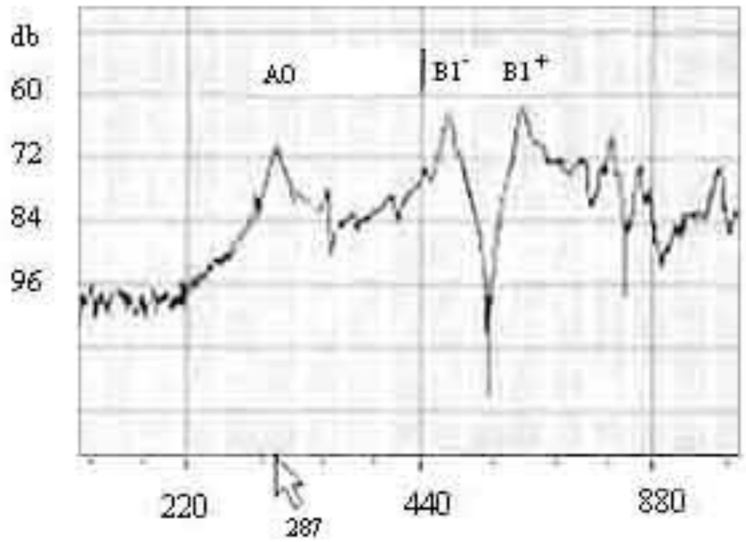


Soundpost: 4.3 mm dia @ 5/15

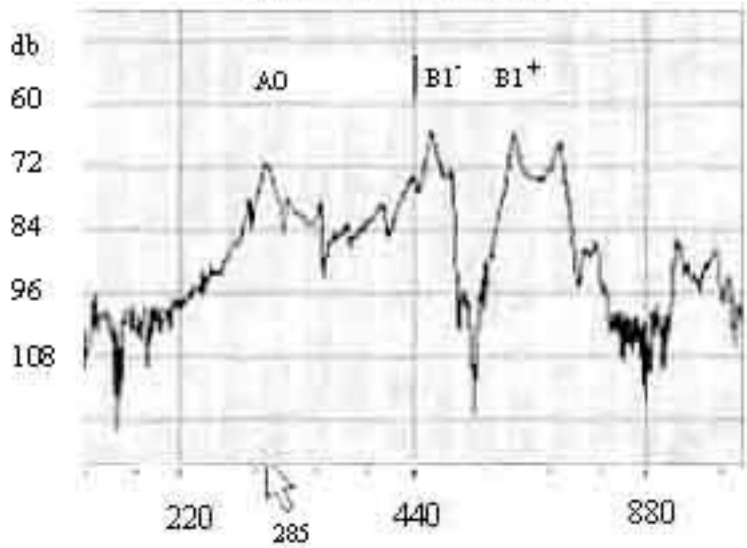


Soundpost: 5 mm dia @ 5/22

Figure 8.6 Effect of bridge position below f-holes on response curve but leaving the soundpost at the notches in the f-holes, soundpost position as in figure 8.5.



Soundpost: 5 mm dia @ 5/22
i.e. at the normal position



Soundpost: 4 mm dia @ 40/16
measured below notches
i.e. 4 mm below bridge

Figure 8.7 With the bridge below the soundholes, the effect of moving the soundpost below the bridge (lower) compared with a soundpost in the standard position (upper).

Figure 8.8 Baroque violin A0 280 Hz. Soundpost (4.3 at 7/15) at f-holes.
Left: bridge at f-holes. Right: bridge below f-holes

The FRF results for changes in the style of bridge and the position of both the bridge and the soundpost gave some interesting results. Historically, the style of bridge changed from a "Renaissance" form through a finer variation, the "Stradivari" form to the "Paris" form which altered the shape of the top of the bridge. In this work the latter two styles were used at the position between the notches in the soundholes. The first free bridge (rocking) resonance of those bridges used in this work occurred at about 3000 Hz for the Renaissance, Stradivari and Paris bridges, so that change of bridge was not expected to influence the results below this frequency.

The back face of the bridge was, for consistent practice, always aligned with a line drawn between the inner notches from which measurements of the position of the soundpost were always made. This line, which represents the "Stop" of the violin is at 195 mm from the edge of the top plate which together with the length of the neck, at 130 mm, gives the string length of 325 mm for the modern violin. The ratio of neck length to Stop is 2/3 in this case. For the Baroque violin with a neck of 120 mm (string length 315 mm) this ratio is 0.615 which is close to the "Golden Section" of 0.618, a number that is widely discussed in analysing art and architecture and which was thought to represent an important physical ratio. This ratio has been linked with the design of the violin as mentioned in chapter 2.

The most important property of the soundpost is its longitudinal stiffness in compression since it passes the motion at its point of contact on the top plate to the back. Its mass is less than 1 g and its stiffness is determined by the grain structure of the wood and its dimensions. The stiffness and effective mass determine the longitudinal mechanical impedance, $Z = (ms)^{1/2}$ where m is the effective mass and s is the effective stiffness. As was previously reported by this author [2] that Z should be higher than 60 kg/s for satisfactory performance. Baroque soundposts have an impedance of about 40 kg/s.

8.6 Characterisation of Peaks

The main resonances shown in the tap response were studied to see whether changing the bridge position altered their parameters. Comparison was made with the bridge in its normal position between the f-holes with a position below the f-holes. The parameters determined are the peak frequency, the effective mass, m, the effective stiffness, s, the Q value, the impedance, Z, and the total resistance to bridge motion, R. These were calculated following Schelleng [9]. The nodal lines on the top and back plates were delineated with tea leaves, for contrast, and are shown in figure 8.8 for the main air resonance, A0. Chladni patterns like this for other resonances are shown in succeeding figures.

The mechanical vibration parameters for resonances found on the Baroque violin at frequencies below 1 kHz where they are well separated are set out in table 8.3. Those resonances at A0, B1- and B1+ are always measured with reproducible values but the appearance of other resonances cannot be explained.

Table 8.3 Acoustic parameters of resonances on the Baroque violin (Renaissance bridge at notches in soundholes). (Values not rounded.)

Resonance Peak	f(0) (Hz)	df/dm (Hz/kg)	m (kg)	s (MN/m)	Z (kg/s)	Q	R (kg/s)	f(calc) (Hz)
A0 (s/post 6/17)	281	4.25×10^6	0.034	108 N/m	1.92	18	0.13	--
C2	411	1406	0.15	0.975	382	29	13	406
B1--	(448	1029	0.22	1.73	617	33	19	446
B1--	(450	1574	0.43	1.14	400	30	13	449
B1-	470	1940	0.12	1.06	357	36	10	473
B1+	581	6830	0.04	0.57	157	58	3	579
B1++) C4?	(620	1543	0.20	3.05	781	26	30	622
B1++)	(620	2000	0.16	2.35	499	29	17	610
?	775	10400	0.04	1.08	180	28	6	776

Some variability is present in these results. Further, there is some difficulty in determining bandwidths for complex response peaks such as those of the B resonances. For A0 a Q of about 15 is now considered optimum [8] so that values at half this are probably undesirable as the height of the peak will be lower. A compromise has to be made between a strong (high Q) resonance which can give rise to a wolf note and a weaker (lower Q) resonance giving quicker response and greater ease of playing. The bracketed determinations give an idea of the experimental variation encountered. These two peaks, one below B1- and above B1+, as seen in figure 8.6, have similar nodal patterns to that of the adjacent body peak. Marshall [10] has showed that, for a modern violin with a modern setup, the peak below B1- has the neck in torsion while B1- has the neck in bending. B1+ has the neck in torsion while the peak above it has the neck in bending. The Baroque setup has a different neck geometry and therefore resonances would be expected at different frequencies. It would also appear that B1+ is a more efficient radiator than B1-. The naming of the body modes B1--, B1++ is somewhat arbitrary. As the Chladni patterns resemble those of B1- and B1+ this was done but a close tie would require the behaviour of the neck and fingerboard to be determined.

8.7 the Main Air Resonance - A0

The Operating Deflection Shapes for A0 are shown in figure 8.8 for the two positions of the bridge studied. The A0 mode involves both compression and rarefaction of the air (as in a Helmholtz mode) and a “breathing” motion of the body. If the compliance of the body were zero, it would be a pure Helmholtz mode. This resonance can be excited by a sound of the same frequency e.g. C4# played on the piano coinciding with that frequency on the violin. This combined mode may also be excited mechanically, as in the case for the tap response and as shown by the Chladni pattern. Moving the bridge and the soundpost to a position below the f-holes still gave a Chladni pattern similar to that for this “body mode” but less distinct as shown in figure 8.8a.

Figure 8.8a The Baroque violin with the bridge and soundpost below the f-holes. Left: A0 285 Hz. Right: 690 Hz.

Table 8.4 A0 frequencies as a function of bridge position

	"Paris" bridge	"Renaissance" bridge		
	at the f-holes	at the f-holes	below the f-holes	
s/post	at the f-holes	at the f-holes	at the f-holes	below the bridge
A0 (Hz)	281	281	286	287

The frequency of A0 is not altered by this adjustment. Placing the bridge below the f-holes does affect the effective mass and stiffness measured at the bass foot of the bridge, on this violin. Figure 8.8 shows the Chladni pattern for A0 with the soundpost unmoved. Figure 8.8a shows the pattern after the soundpost has been placed below the bridge. The nodal line near the treble soundhole remains although the soundpost has been moved. Moving the bridge to a position below the f-holes puts it in a stiffer part of the top plate. This is indicated by the rise in frequencies of A0 by 5 Hz as shown in table 8.4 and in table 5, 7 Hz for B1- and 27 Hz for B1+ when the soundpost remains in the normal position and when it is moved to below the bridge, no effect on B1- and a rise of 21 Hz for B1+. The Chladni patterns are not significantly changed. The bass foot of the bridge remains in an antinodal region throughout.

As discussed later in chapter 9.7 the Schelleng equations have been applied but the dependence of the A0 frequency on change in mass has been obtained in a different way. It has not been possible to add small masses to an anti-nodal position. Instead the mass of the vibrating air plug has been changed by changing the ambient temperature thus altering the density of the air and hence the mass. A value for df/dm has been obtained that gives a resistance R that accords with the high radiating property of A0.

8.8 The Main Body Resonances - B1- and B1+

The parameters for the two main body modes were determined by the technique as explained above. The results are shown in table 8.5 and the Chladni patterns in figures 8.9, 8.10 and 8.11. The total resistance to bridge motion, R = Z/Q is a measure of the ability of the resonance to radiate sound. It appears that B1- radiates less effectively than B1+. From this it would seem that while a low impedance indicates a lower amplitude of vibration, a low Q means that it is spread over a wider range of frequencies.

Mechanical data for the body modes labelled B1- and B1+ are shown in table 8.5 and the tap response shown in figures 8.5, 8.6 and 8.7. For B1- df/dm decreases as we move across the table. Both the effective mass and stiffness increase, as does the impedance. The Q value remains essentially unchanged.

Because of logistics and player availability, only one player assessed the violin with the bridge below the f-holes. The player considered that the violin was not as responsive with the bridge in this position, although a full sound was obtained. The A and D strings had lost some quality of sound.

Figure 8.9 Baroque violin bridge and soundpost (4.3 @ 5/15) at f-holes.
Left: B1-471 Hz. Right: B1+585 Hz.

Figure 8.10 Baroque violin bridge below f-holes, soundpost at notches.
Left: B1-478 Hz. Right: B1+610 Hz.

Figure 8.11 Baroque violin bridge and soundpost below f-holes.
Left: B1-471 Hz. Right: B1+604 Hz.

Table 8.5 Acoustic parameters of the Baroque violin for B1- and B1+ as a function of bridge type and position.

		"Paris" Bridge	"Renaissance" Bridge		
	Bridge	at f-holes	at f-holes	below f-holes	
	Soundpost	at f-holes	at f-holes	at f-holes	below bridge
B1-	Frequency, f(0) (Hz)	471	470	478	472
	Calc. frequency (Hz)	470	471	478	473
	df/dm (Hz/kg)	2260	1940	1160	1470
	Effective mass, (kg)	0.10	0.12	0.21	0.16
	Effective stiffness, (MN/m)	0.91	1.06	1.86	1.41
	Effective Impedance, Z, (kg/s)	308	357	625	475
	Q value	28	36	17	27
	Resistance to bridge motion, R	11	10	37	18
B1+	Frequency. F(0) (Hz)	583	581	611	604
	Calc. frequency (Hz)	583	580	612	607
	df/dm (Hz/kg)	3420	6830	6114	3578
	Effective mass, (kg)	0.09	0.04	0.05	0.08
	Effective stiffness, (MN/m)	1.14	0.57	0.74	1.22
	Effective Impedance, Z (kg/s)	311	151	190	320
	Q value	58	58	28	41
	Resistance to bridge motion, R	5	3	7	8

Moving the soundpost to a position below the bridge in its lower position introduced a peak at 684 Hz, shown in figure 8.7, which was confirmed by repeated tap response. The nodal pattern was not well defined on the top plate and the back appeared to be divided into two antinodal regions, as shown in figure 8.8a and no values for the effective mass and stiffness were obtained.

The movement of the bridge and soundpost to a position below the f-holes has moved the frequencies of B1-, about 5 Hz and B1+ about 20 Hz, to higher values indicating a change in effective mass and stiffness as shown in table 8.5. There has also been an increase in the A0 frequency by 5 Hz.

8.9 The 800-900 Hz Region

A body mode at 875 Hz was studied for the case with the bridge below the f-holes but with the soundpost at the notches. The results are shown in table 8.6 and the Chladni pattern in figure 8.12.

Figure 8.12 Baroque violin bridge below f-holes, soundpost at f-holes.
Body mode at 875 Hz.

Table 8.6 Acoustic parameters of the Baroque violin for the body peak at 875 Hz.

	"Renaissance" Bridge below the f-holes
Frequency, f(0) (Hz)	875
Calculated f(calc) (Hz)	885
df/dm (Hz./kg)	32
Effective mass (kg)	0.13
Effective stiffness (MN/m)	4.02
Effective Impedance, Z (kg/s)	723
Q value	23
Resistance to bridge motion, R (kg/s)	31

This mode has only appeared with the bridge in this lower position. From the radiation constant, the peak is expected to be a good radiator of sound. The figure shows that there appears to be an anti-nodal region in both the upper and lower bouts of the top and in the upper bout with two in the lower bout of the back. In the bowing tests, figure 8.4, for the bridge below the f-holes and the soundpost unmoved (middle plot), a strong peak appears at about 800 Hz. This does not coincide exactly with the resonance peak described here, but perhaps this is because the bowing tests are done with a chinrest and shoulder rest mounted on the violin.

8.10 Stiffness measurements at the Bridge feet positions

The behaviour of the top central region between the soundholes is crucial to the sound output of the violin. The stiffness of the body as seen by the bridge feet determines the amplitude of vibration and the nature of the mode patterns in the top plate. The stiffness as seen by the bass foot of the bridge is determined by the bassbar and a thin light bassbar would allow the bass side of the central region to be more compliant. The soundpost while stiffening the violin generally will stiffen the treble side of the central region of the top. Where the soundpost is placed will determine the extent of this stiffening. The experimental setup is shown in figure 8.13.

Figure 8.13 Measure of static stiffness of the baroque violin

The results consist of three parts; (a) measurements by direct loading at the bass foot position and the treble foot position; (b) measurement of stiffness with no soundpost in place, and, (c) stiffness measurements with a variety of soundposts of different lengths carefully placed at different positions with respect to the treble soundhole edge but always at 5 mm behind the line of the inner notches which was the line of the rear face of the bridge. A piece of rib the size of the foot was placed at the bridge foot position to protect the top. In tables 8.7, 8.8 and 8.9, the results are for a series of soundposts made from the one stock in each separate case, and therefore will have the same diameter, density and generally equal longitudinal Young's Modulus.

Violin No 2 was chosen for this set of measurements. The results are set out in table 11.10 and plotted in figure 8.14 where the stiffnesses at the two bridge feet positions without the soundpost are about 32 kN/m at the treble foot and about 60 kN/m at the bass foot. The results with soundposts fitted show considerable variation. Ensuring that the violin was firmly supported was not easy. However a trend may be apparent. With the soundpost inside the treble foot position, the stiffness measured at the treble foot was lower than that at the bass foot. With the soundpost outside the treble foot position the stiffnesses were all higher than at the bass foot. The stiffnesses at the bass foot suggested an average value of about 70 kN/m, which was higher than the result with no soundpost. An attempt to put a curve through the results was difficult but it was possible that the stiffness would have an upper limit. There would be an input from the stiffness of the back as well as the soundpost.

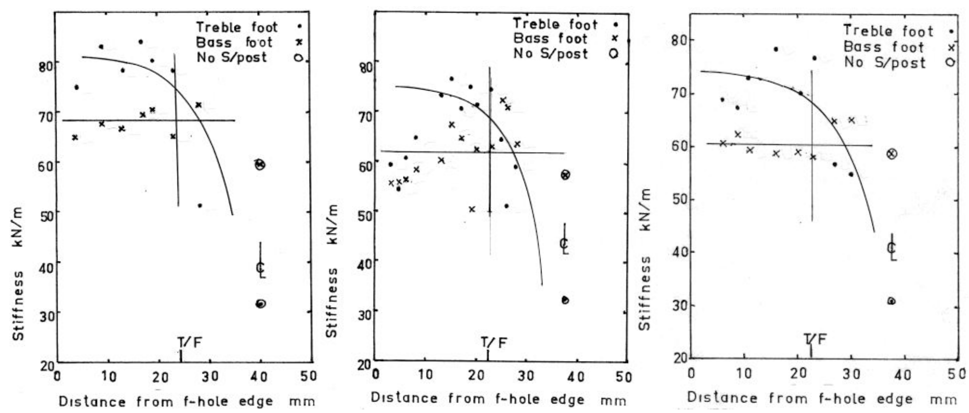


Figure 8.14 effect of soundpost position in relation to the treble foot (T/F) position, on the top plate stiffness at the bridge feet with no bridge present (left violin No 2, centre No 1, right No 3).

To locate the position of the axis of the soundpost, it is necessary to add the radius to the positions listed in the tables.

Table 8.7 body stiffness at the treble foot position for violin No 2 with no bridge in place, soundpost dia. 6.3 mm, soundposts 5 mm from bridge line.

Setup	Soundpost Impedance (kg/s)	Position from treble f-hole (mm)	Stiffness (kN/m) Bass foot	Treble foot
No bridge	No soundpost		59.5	31.3
	84.3	4	63.7	75.2
	90.8	9	67.6	83.3
	83.5	13	66.7	78.1
	88.3	19	75.8	80.6
	88.3	23	66.7	78.1
	87.8	28	71.4	51.6

Similar measurements were done on the other two violins featured in this thesis; the converted Baroque violin (No 3) and the earlier violin (No 1) made on a Stradivari mold. The general trend was similar to No 2 but showed some variability. In each case the soundposts were cut from the one stock for the particular violin. The results are shown in tables 8.8 and 8.9 and displayed in figure 8.15 and 8.16 where the centre line of the violin and that of the treble foot are indicated. With the soundpost inside the treble foot position, the stiffness at the bass foot position is higher than that at the treble foot position. With the soundpost outside the treble foot position the stiffness order is reversed; that at the treble foot position is higher than that at the bass foot position. With no soundpost in position, the stiffness at the bass foot position is about 30 kN/m higher than that at the treble foot position in these three violins.

Table 8.8 body stiffness at the bridge feet for violin No 3 with soundpost position. No bridge, and soundpost (6.0 mm dia.) 5 mm from the bridge line.

Setup	Soundpost Impedance (kg/s)	Position from treble f-hole (mm)	Stiffness (kN/m) Bass foot	Treble foot
No bridge	No soundpost		58.8	30.9
	61.8	6	60.6	69.9
	62.8	9	62.5	67.6
	61.9	11	59.5	72.0
	59.5	16	58.8	78.1
	61.5	20	59.2	73.0
	64.5	23	58.5	76.9
	64.5	27	64.9	56.8
	64.5	30	64.9	54.9

There appears to be a greater variability with violin No 1 which had a flat longitudinal arch compared with the other two violins. Figure 8.16 shows that as the soundpost is placed near the f-hole edge (within 10 mm) the stiffnesses become closer in value. No reason has been found for this. Great care must be taken to ensure accurate positioning and fitting of the soundpost; a slightly raised upper wing was used as a guide to the state of tension in the system.

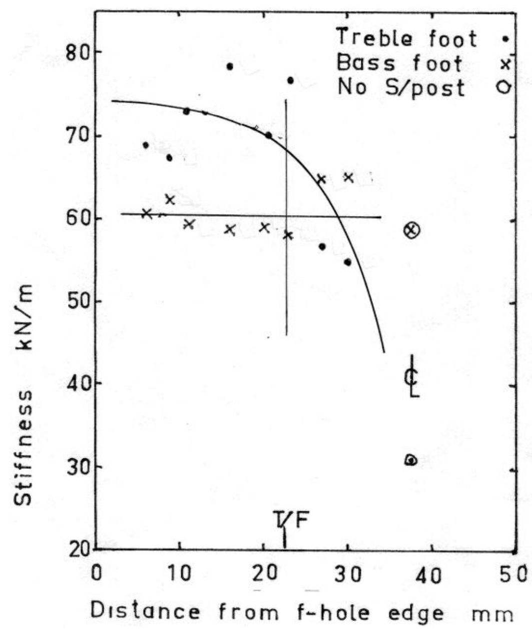


Figure 8.15 effect of soundpost position in relation to the treble foot (T/F) position on the top plate stiffness at the bridge foot positions for violin No 3 with no bridge present.

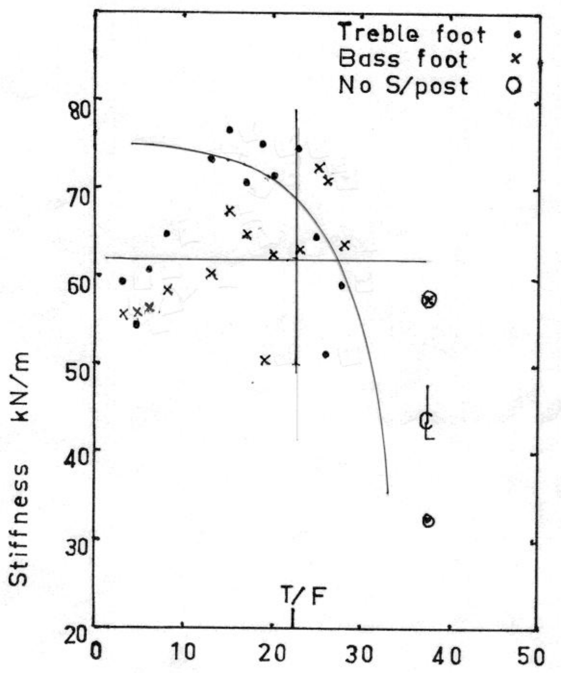


Figure 8.16 effect of soundpost position in relation to the treble foot (T/F) position on the top plate stiffness at the bridge foot positions for violin No 1 with no bridge present.

Table 8.9 Body stiffness at the bridge feet for violin No 1 with soundpost position.

No bridge, and soundpost (6.2 mm dia.) 5 mm from the bridge line.

Setup	Soundpost Impedance (kg/s)	Position from treble f-hole (mm)	Stiffness (kN/m) Bass foot	Treble foot
No bridge	No soundpost		57.5	32.5
	67.5	3	55.9	59.9
	67.5	4	56.2	54.4
	61.5	6	56.8	61.0
	67.3	8	58.1	64.9
	62.5	13	60.2	73.5
	62.0	15	66.7	76.9
	62.0	17	64.9	70.9
	66.0	19	51.6	75.2
	66.5	20	62.5	75.8
	66.0	23	63.3	74.6
	66.0	25	72.5	64.1
	66.5	26	71.4	51.8
	66.0	28	64.1	59.5

If a pattern of behaviour is present as a result of these measurements, one might venture some predictions. The stiffness at the treble foot, with no soundpost, will be influenced by the plate thickness while that at the bass foot will be set by the bassbar. It would appear that there is an upper limit to the treble foot stiffness with soundpost; in these results at about 70 kN/m. Some approximations are set out in table 8.10. This picture would be different for other violins. Its significance has yet to be established.

Table 8.10 Stiffness limits for the violins examined.

Violin	Position of treble foot c/line from f-hole (mm)	Position from (f-hole) of equal stiffness (mm)	Stiffnesses (kN/m) Bass	No S/post Treble	Max. Treble	Differences in stiffness at std. position
1	23	~25	58	32	75	+ 6
2	24	~27	60	32	80	+ 5
3	23	~27	60	30.5	75	+ 9

The standard position is that with the soundpost directly behind the treble foot of the bridge. The lines through the soundpost points in the figures are my best guess at this stage. This is decided by the conclusion that there must by an upper limit near the f-hole and that the stiffness must fall to near that of the no soundpost value inboard of the treble foot position and then possibly rise to that of the bass foot value.

This variation in top plate stiffness with soundpost position supports an earlier finding [13] that moving it out toward the f-hole raised the output of the three lower strings. To the authors knowledge no measurements of top plate stiffnesses have been recorded. This aspect of violin acoustics may explain the variety of earlier bassbars and the lower mode 5 frequencies found. This adds another factor to the question of top plate behaviour.

8.11 Discussion

No clear reason for moving the bridge to a lower position below the soundholes has been revealed by these experiments. There have been no radical changes to the FRF as determined by a tap test although some peaks became more prominent around 900 Hz. The Chladni patterns showed the well known nodal line patterns for the main air resonance, A0, and body modes B1- and B1+. What was surprising was the stability of the nodal pattern for A0 near the treble soundhole whether the soundpost was in the normal location or had been moved with the bridge to below the soundholes.

The major change occurred with the bowing tests. With the bridge and soundpost in their normal positions, the output was even across the strings as shown in figure 8.4. On moving the bridge alone below the soundholes and both the bridge and the soundpost below the soundholes, the output on the E string was raised by on average 6 dB. A violinist's reaction did not reflect the difference shown in the bowing tests. Instead the violin was considered not as responsive when the bridge was placed below the soundholes.

It is difficult to explain why the unusually loud E string of the bowing test with Pirastro Chorda gut strings as shown in figure 8.4, and earlier in chapter 6 with Thomastik Dominant strings and machine bowing, was not noticed by the player in free playing. While the Chorda E string was gut, the Dominant E string was steel. Perhaps it was because the baroque instrument, string and bow lack the E string brilliance of the modern combination. Or perhaps professional players are very accustomed to compensating for loud E strings.

In this context, it could be mentioned that for frequencies up to about 600 Hz i.e. to E5, the violin radiates approximately equally in all directions. At frequencies above this, which includes many harmonics, it radiates with strong dependence on direction. Strong fundamentals are therefore essential. The physical movements of the player will influence the high frequency spectral envelope received by the audience in a concert hall.

The relative stiffness of the top plate at the two bridge feet will influence the shape and amplitude of the resonance modes of the violin. A quantitative means of assessing the required properties of the bassbar and the position of the soundpost in relation to the output of the violin will assist in the more certain adjustment of the instrument. This result needs to be confirmed and studied further to determine its exact nature. Care has to be taken to ensure the soundpost is fitted correctly; too tight lifts the upper wing of the f-hole; too loose should be felt when setting the post in position. The soundpost was always set in a vertical orientation.

The bassbar in violin No 2 raised the stiffness of the top from 32 kN/m measured at the treble foot position with no soundpost in place, to 60 kN/m measured at the bass foot position, for an evenly thicknessed plate (the mode 5 frequency rose from 290 Hz to 350 Hz). The stiffness of the back plate measured at the soundpost position was 90 kN/m with no soundpost on this violin. The other two violins showed similar results. These results show that the stiffness at the standard position of the soundpost, behind the treble foot of the bridge is higher than that at the bass foot by about 6 kN/m for the violins tested. It has yet to be decided what the desirable difference might be and whether it has a better place using e.g. playing tests.

The top plate stiffness was measured before the violin was strung to pitch. If we consider violin No 3 as an example, the stiffness at the treble foot position was about 69 kN/m with the soundpost at the standard position behind the bridge foot and about 60 kN/m at the bass foot position. With gut strings tuned to A440 (chapter 4.9, table 13) the total string tension was 216 N with a downbearing of 93 N. Since the individual string tensions were about equal, it can be assumed that each foot position had about 45 N placed on it. The deflection at the bridge feet would then be: about 0.75 mm at the bass foot and 0.65 mm at the treble foot. The hysteresis that was noticed when unloading was not studied nor was the creep that was expected to be present with a sustained force. The first of these was not regarded as significant in practice as the strings are rarely relaxed and the second would be a second order effect. These stiffnesses and tensions are far in excess of the force applied to the string by the bow when playing which is of the order of 2 N.

It has been found that the stiffness of the top plate of violin No 3 (the violin converted from Baroque to Romantic setup) at the bassbar foot of the bridge, at 60 kN/m, was little affected by the addition of the soundpost when placed outside the treble foot but higher when inside the treble foot. The stiffness at the treble foot of the bridge was 32 kN/m with no soundpost and varied up to about 75 kN/m with the soundpost closer to the edge of the f-hole. Similar results were obtained for the other two violins tested. The stiffness at the treble foot was found to be about 6 kN/m higher than at the bass foot in the violins tested when the soundpost was behind the bridge foot. The bridge turns out to be a very important part of the structure. The interaction with the central region of the top between the f-holes is not yet understood.

8.12 References

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Chapter 9

EXPERIMENTS ON THE MAIN AIR RESONANCE, A0, OF THE VIOLIN

9.1 Introduction

This chapter sets out a method for evaluating the stiffness of the body of the violin and its effect on the main air resonance. The main air resonance of the violin is situated near C or C# on the lowest or G string. The sound radiated at A0 comes from the vibration of the air plugs in the soundholes. The A0 resonance of the violin is very important at low frequencies. Determining the frequency of A0 is complicated for several reasons. First, the compliance of the air in the body acts in parallel with the mechanical compliance of the body. The latter itself is substantially reduced by the presence of the soundpost. The 'vents' for this resonance are the two f-holes. Their shapes are geometrically complicated; their long aspect ratio has a function; they lower the frequency of the main top resonance. Their shape reduces the likelihood of longitudinal cracks in the highly orthotropic wood by avoiding sharp re-entrant corners. This shape makes calculation of the dependence of the A0 frequency a difficult enterprise. This chapter investigates its dependence on the various parameters independently.

The A0 resonance in the violin approximates a Helmholtz resonator, which in turn is a mass and spring oscillator. The mass is that of the 'plugs' of air in and near the soundholes; the spring is that of the air in the body. When the plug of air moves into the body the air is compressed slightly (an outward movement of the plug results in a decrease in internal pressure). The adiabatic rise in pressure provides the restoring force on the plug. An ideal Helmholtz resonator has a rigid body and would result in a frequency higher than A0. The violin body has a finite compliance so an increase in pressure distends the body slightly, making the spring of this oscillator a little less stiff than it would be if the body were rigid. Installing the soundpost raises the body stiffness as mentioned above. A general treatment of the Helmholtz Resonance is found in Fletcher and Rossing [1]. The main air resonance is approximately a Helmholtz resonance, with the finite compliance of the body in parallel with the rather larger compliance of the air in the body. The enhancement of the fundamentals of notes near A0 will be due to the main air resonance. Body resonances in the mid range, about 350

Hz to 1 kHz, and resonances in the high range, above about 1 kHz, of the violin, are responsible for radiating the fundamentals of high notes and harmonics of low notes. The compliance of the air is largely fixed by the geometry: The volume of air in the instrument is about 2000 cc which is determined by the plate area, about 500 cm^2, and the height of the sides, about 30 mm. The total area of the soundholes is about 14 cm^2. At frequencies up to about 1 kHz, where most of the fundamentals lie, the violin, with the help of the soundpost, radiates sound nearly equally in all directions, approximating a monopole source. At the lower end of the range, the violin is smaller than the wavelength of the fundamentals produced. As an example, at 200 Hz the wavelength in air is 340/200 = 1.7 m; the body of the violin is 0.36 m long, so the wavelength in air is more than 4 times the length of the instrument. For this reason the monopole action becomes especially important.

What excites the main air resonance in the violin? The rocking motion of the central area of the top plate in response to the bridge excites the air inside the violin. Below A0, the breathing action of the body is opposed to the motion of air in the f-holes i.e. as the volume of the body decreases, the air in the f-holes moves out. Above A0 the breathing action of the plates is moving in the same direction as the air in the f-holes i.e. as the plates move out the air in the f-holes moves out. Compliant walls, i.e. top and back plates, probably lower the Q value. There is little written about the effect of varying the parameters associated with the main air resonance, A0, of the violin other than the observation that when the soundpost is installed, the main air resonance rises in pitch by about 3-4 semitones (20-25 % in frequency) [2]. The soundpost stiffens the body but also enhances the breathing mode at this frequency. Changes in the volume of air enclosed in the body and the area of the soundholes has an influence on the frequency of A0.

Table 9.1 The acoustic parameters of A0 on the Baroque violin fitted with gut strings at A415 and a Renaissance bridge at the soundholes

Resonance Peak	f(expl) (Hz)	df/dm (MHz/kg)	m (mg)	s (N/m)	Z (kg/s)	Q	R (kg/s)
A0 (no s/post)	264	11.3	12	32	0.62	9	0.07
A0 (s/post 7/15)	281	4.25	34	108	1.92	8	0.24

It can be seen that the soundpost raises the frequency of A0 by about 20 Hz which is less than the Hutchins figure.

The frequency of the Helmholtz resonance was derived by Rayleigh [3] after Helmholtz, and given approximately by:

$$f_H = \frac{c}{2\pi}\sqrt{\frac{S}{VL}}$$

where c is the sound velocity in air, and for the parameters of the violin, S is the total area of the soundholes, L the effective length of the 'plug' of air in the soundholes and V is the volume of the violin body. For the violin the f-holes are considered baffled and if they were circular, an "end correction" of 0.85 times an equivalent radius of the soundhole would be appropriate on each side. The f-hole can be approximated by an ellipse whose area is πAB where A and B are the semi-axes; a "radius" might be taken as $[AB]^{1/2}$. In general terms, a 12% increase in volume lowers A0 by a semitone, while an increase in soundhole area of about 20 % raises A0 by a semitone. The larger percentage change occurs because increasing S implies an increase in L. Any change usually takes place in the width. Therefore moderate changes in these two quantities by a maker will not change A0 significantly from 280 Hz or about C4#.

9.2 The Calculation of A0

Following the simplicity of the equation derived by Rayleigh for the Helmholtz resonance, $f_{(H)}$, of a rigid vessel and corrections for the length of the vibrating air plug, attempts have been made to give an empirical expression for the main air resonance, A0, for the violin with a complex body shape, compliant though containing complex soundholes and sometimes fitted with a soundpost. Bissinger [4] has explored the calculation of $f_{(A0)}$ from the physical measurements of the violin. He has done this for a rigid model with flat plates in which the volume could be altered, thus producing an empirical equation similar to Rayleigh's as follows.

$$f_{A0} = f_H = \frac{c}{D}\sqrt{\frac{A}{(L + 1.5\sqrt{A})V^x}}$$

where D and x are empirical constants, L is the plate thickness at the f-holes. This equation was for a rigid cavity without a soundpost. (To be dimensionally correct, this equation requires that V be the ratio of volume to convenient measurement unit - cc - in his paper). With Bissinger's equation as presented in his paper and using values from the paper, [4], viz. V = 1800 cc, L = 0.3 cm, A = 8 cm^2 and c = 34200 cm/s and setting D = 21.48 and x = 0.538 gave a value of 283 Hz which lay near the plot in figure 2 of that paper. Because of this result, a new D was calculated for $f_{(H)}$ 300 Hz (on Bissinger's graph) of 55.42 and x = 0.269. With these numbers $f_{(H)}$ for V = 2000 cc was 295 Hz in close agreement with the graph. Extending the calculation to the numbers for the violin used in this study, gave $f_{(H)}$ = 341 Hz; a value higher than that determined experimentally of 290 Hz. Better agreement was obtained with an equation in a second paper [5] that examined a number of instruments and from their measurements arrived at another empirical equation for a violin with a soundpost.

$$f_{A0} = \frac{c}{4.26}\sqrt{\frac{A}{(L + 1.5\sqrt{A})V}}$$

With the numbers for the violin used in this work inserted in this equation, the calculated $f_{(A0)}$ is 276 Hz which lies on the curve in figure 3a of the paper [5].

Calculating $f_{(A0)}$ for a violin with soundpost installed introduces a complication because the properties of the wood vary, as do the dimensions of the post and its position.

9.3 The Parameters of A0

The parameters to be determined are the mass of the plugs of air and the stiffness of the "spring" providing the restoring force. The plug extends both inside and outside the soundhole. The long studied problem of radiation through apertures was reported by Rayleigh [2] when he considered the end effect on an open pipe with an infinite flange, or baffle, i.e. the pipe end consisted of an opening in an infinite plate. By contrast, the radiation from an ideal narrow pipe is unhindered and covers 4π sterradian solid angle (in other words it is omni-directional).

The soundholes in the top plate of the violin can be thought of as "baffled" or "flanged" since the "plug" of air that vibrates, radiates over 2π sterradian solid angle on each side. Rayleigh found that the correction for a circular opening in an infinite plate lay between 0.785R (π R/4) where there is loss to the outside and 0.849R (8R/3π) where there is no loss. He also considered openings other than circular. For an ellipse with small eccentricity the behaviour was similar to that of a circular opening of the same area. As an example, for an eccentricity of 0.866 (i.e. a ratio of major to minor axis of 2) the conductance of the ellipse was only 3% higher than that of the circular aperture. In the case of a violin soundhole, the effective length of the "plug" of air extends beyond the 3 mm thickness of the plate by about 6 mm because of the greater eccentricity and hence the calculation required is different.

Cremer [6] approximated a violin f-shaped soundhole with an equivalent ellipse for the same area to that of the soundhole and the same f-hole width of 8 mm, and thus obtained a calculated effective length in the plane of 92 mm. This determined the eccentricity (in the example Cremer considered it was 0.996). Small changes in eccentricity at this level result in large changes in conductance of an elliptical aperture [2]. A difficulty in choosing an equivalent ellipse for a violin soundhole resides in its complex shape.

9.4 The Purpose of this Study

Here I report experiments to investigate the parameters of the soundhole that determine the main air resonance of the violin. Two methods have been used to determine A0 and the Helmholtz resonance. One is to place a microphone near a soundhole and apply an impulse to the edge of the bridge (in this case the E string edge), the violin is suspended on rubber bands. The spectrum of the response shows A0, A1 and those body modes below ~1 kHz that contribute to the sound output of the violin. The other method is more restricted to plotting the shape of the A0 resonance peak, namely a microphone in one soundhole and a transducer delivering a single frequency signal to the other soundhole, whereby the response can be recorded with a digital voltmeter as the frequency is varied over the range of the peak. The resonance frequency and the peak height and width can be determined by both methods.

A0 is lower than the Helmholtz resonance because of the compliant walls of the violin body. For this reason, two methods of arriving at a value of the frequency of the latter resonance were tried. One was to immobilise the violin plates so that A0 should approach the Helmholtz resonance. The second was to construct a rigid 2 litre box with two soundholes cut in a 3.5 mm plywood insert on one side.

9.5 Preliminary Measurements

A number of matters were investigated prior to the experiments concentrating specifically on A0. These included the position of the microphone, the volume of air in the violin and the area of the soundholes.

The placement of a microphone near a soundhole of complex shape may result in a different response being recorded depending on its position. From the impulse response curves it was found that A0 could be detected with the microphone at any position near the soundhole. Placed in the large finial hole both A0 and A1 were well defined but body modes C2, B1- and B1+ were less prominent. At other positions along the soundhole A0 was less dominant and A1 gradually disappeared as expected from what are monopole, A0, and dipole, A1, sources respectively. With the microphone 100 mm in front of the violin, the body modes in addition to A0 were equally prominent, although A1 was still evident.

The volume of the violin was found by filling it with seed tapioca (approximately 2 mm spheres). This was then poured into a measuring cylinder. The volume was measured to be 2000 +/- 5 ml. Determining the area of the soundholes was done by an indirect method. The weight of a paper cutout of the soundhole was taken and from the density and thickness of the paper (80 gsm copy paper was used) the area was easily calculated to be 690 mm^2 for each soundhole.

9.6 The Helmholtz Resonance

1 Measurements on a "rigid" box. A box (inside dimensions, 138 x 135 x 106.5 mm approximately) was constructed to have a very low compliance compared with that shaped soundholes (see figure 1). The volume of the box was 1987 cc for which A0 was measured to be 295 Hz. This value was taken to be equal to the Helmholtz frequency for the calculation of the "end correction" for the soundholes using the Rayleigh equation.

$$f_H = \frac{c}{2\pi}\sqrt{\frac{S}{VL}}$$

where c = 342 m/s, S is the total area of the f-holes, V is the volume of the box and L is the corrected length of the vibrating mass of air. Having established L(= 2dL + t) for the 2 litre box and a value for S of 1375 mm^2 for the two soundholes and the experimental value of 295 Hz for $f_{(H)}$ using the Rayleigh equation, we can calculate the stiffness of the air in the box.

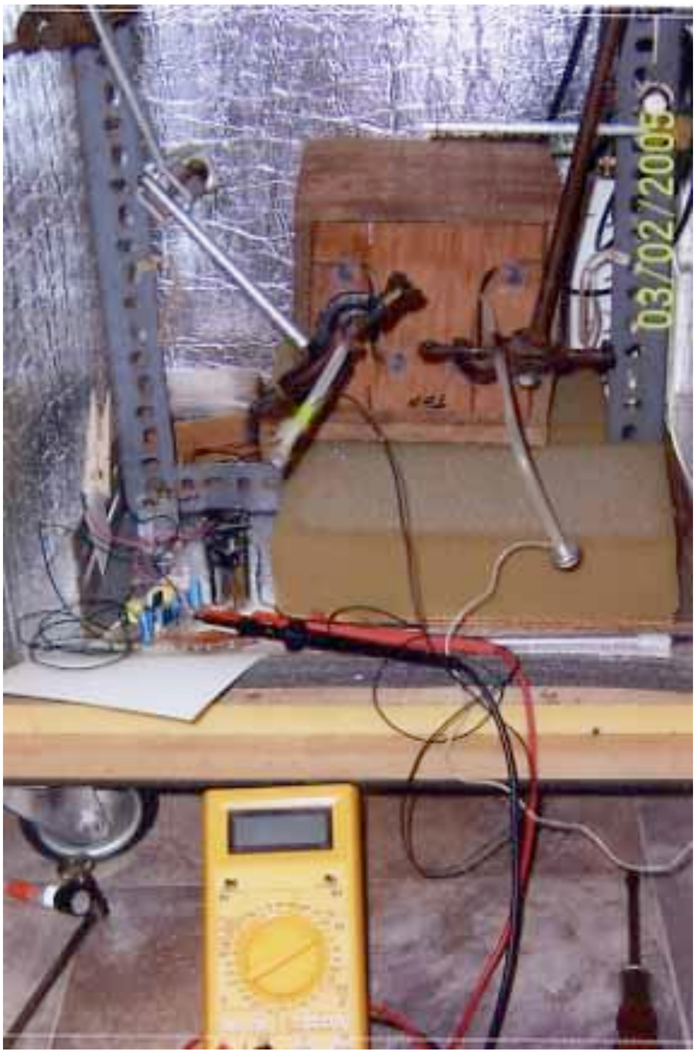

Figure 9.1 Two litre box with f-holes cut into a 3.5 mm insert for determining the Helmholtz resonance showing microphone (left) connected to a DVM via an amplifier and an exciter (right) connected to a signal generator/amplifier.

The mass of the "plug" is m = (2dL + t)S x D where D = 1.205 kg/m^3 is the density of the air. The stiffness = $m(2\pi f_H)^2$ N/m. The stiffness of the air varies with the area of the plug and hence its mass. The results of these calculations are shown in table 9.2.

Table 9.2 Calculated stiffness of the air in a rigid box at the Helmholtz resonance.

Box	width f-holes (mm)	area 2f-holes (mm^2)	"plate" thickness (mm)	f(H) (Hz)	length of plug (mm)	mass of plug (mg)	stiffness N/m	f (calc) (Hz)
f-holes fully open	7	1375	3.5	295	23.6	39	134	295
finials closed	7	875		284	16.2	17	55	286
finials only		500		213	16.4	10	16	201

The finial diameters were 9 and 7 mm and there were connections to the elongated part of the f-holes included in the total area.

2Measurements with differently shaped apertures. Besides f-shaped apertures, circular apertures with the same area and an equivalent ellipse were studied in an attempt to measure the effect on the Helmholtz resonance. The frequencies for one f-hole, an equal area circular aperture and an ellipse of equal area with an eccentricity of 0.998 which was arrived at by using the width of the f-hole as the minor axis (see appendix) were determined. These apertures were cut in a Perspex plate that could be fitted to the box. The results are summarised in table 9.3. The value for L was found using the Rayleigh equation having measured the frequency for the aperture concerned.

Table 9.3 Effect of aperture shape on air stiffness in rigid box at Helmholtz resonance.

Aperture	area (mm^2)	f(H) (Hz)	L (mm)	mass (mg)	stiffness N/m	f (calc) (Hz)
One aperture only						
Circular	688	220	21	18	34	219
f-shaped	687.5	279	13	11	34	280
Two similar apertures to equal two f-holes						
Circular	1376	270	28	46	134	272
f-shaped	1375	296	23	39	134	295
One circular	1353	275	27	44	130	274

The conclusions to be drawn from these results are that the length of the plug, and hence the mass, is different for apertures of the same area but very different shape. The stiffnesses are approximately equal despite the shape difference because of the use of the Rayleigh expression derived from adiabatic compression. By having two apertures, thus doubling the area, the stiffnesses are doubled. These stiffnesses represent the adiabatic spring of the air in the rigid container.

Kinsler and Frey [7] rearrange the expression for the Helmholtz resonance to get an expression for the effective stiffness, namely: Effective stiffness = $(\rho c^2 S^2)/V$ where ρ equals the density of air, 1.205 kg/m^3, c = 342 m/s, S = 1353 mm^2 and V = 1987 ml in this example. This gives a stiffness of 130 N/m for the current example.

9.7 The Determination of the effective mass and stiffness of A0

To place masses on the top near the bass foot of the bridge allows one to determine the resonance parameters of the body as described in chapter 5.5. At the air resonance one has to add mass to the vibrating air mass. This air mass lies in the soundholes and presents a problem in the determination of df/dm. Two ways allow the mass in the f-holes to be changed; one is to change the temperature of the air keeping the pressure constant, the other is to change the composition of the gas and thus the mass. Both ways have been used here to find df/dm from which the resonance parameters have been calculated.

Violin No 2 was set up for a tap test in two cool rooms at different temperatures and a microphone recording made on a laptop computer with Adobe Audition 1.5. The volume of air in the f-holes was estimated at 33 x 10^{-6} m^3 as used here, the density of air at 0^{o}C of 1.293 kg/m^3 were used to determine the mass at each working temperature. Table 9.4 summarises the result.

Table 9.4 The determination of A0 (violin No 2) as a function of ambient temperature.

Temperature Degrees C	Air density (kg/m$^{3)}$	Mass of air plug in f-holes (x 10^{-6})kg	A0 (Hz)
2	1.284	42.37	274.5
10	1.247	41.15	279.9
19.5	1.207	39.83	285.3

A plot of A0 versus mass gave a value for df/dm of 4.25 x 10^6 Hz/kg and if Schelleng's equations for effective mass and stiffness are applicable, using f(expl) of 285 Hz the calculated parameters are given in table 9.6. Using a reasonable value for Q of 14 gives a value for R of 0.14 which indicates the good radiating property of the main air resonance. A plot of these results is shown in figure 9.2.

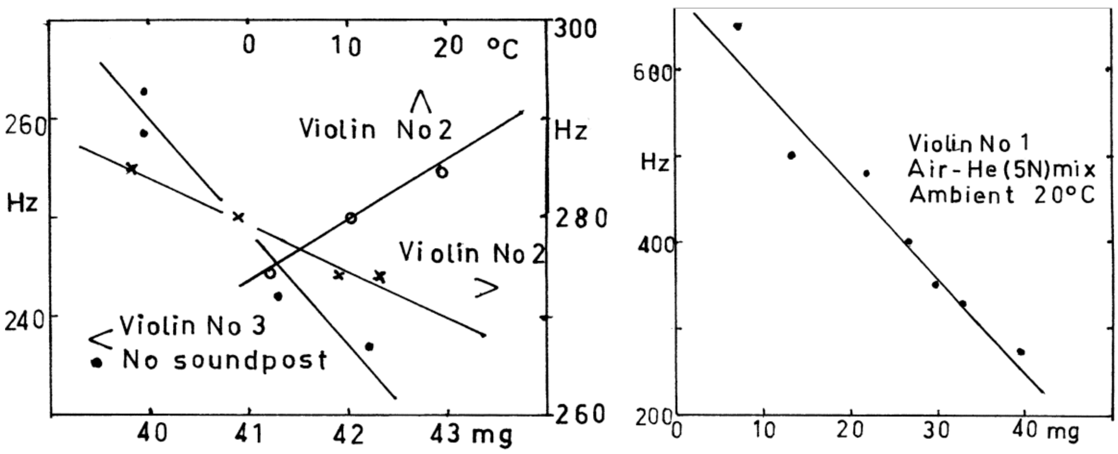

Figure 9.2 Plot of A0 frequency against f-hole plug mass at low temperatures. The total mass is in mg. A plot of A0 against coolroom temperature is included.

The method of changing the mass of the plug in the f-holes by changing the gas composition comes from a paper [8] where mixtures of air and He(5N) were used to determine the change in frequency of A0 with change in gas density. Table 9.5 sets out the change in mass from the density at 20°C of air 1.205 kh/m^3 and He(5N) 0.216 kg/m^3 and plug volume 33 x 10^{-6} m^3. A plot of A0 versus mass, shown in figure 9.2, gave a value of df/dm of 10.9 x 10^6 Hz/kg and using f(expl) of 275 Hz the calculated parameters are given in table 9.6.

Table 9.5 Frequency of A0 for different masses of air/He(5N) mixtures (violin No 1).

Gas mixture %		Volume (x 10^{-6} m^{3})		Mass (x 10^{-6} kg)		Total mass (x 10^{-6} kg)	A0 (Hz)
Air	He(5N)	Air	He(5N)	Air	He(5N)		
100						39.80	275
80	20	26.4	6.6	31.8	1.43	33.23	330
70	30	23.1	9,9	27.84	2.14	29.98	350
60	40	19.8	13.2	23.86	2.85	26.71	400
40	60	13.2	19.8	15.91	4.28	20.19	480
20	80	6.6	26.4	7.95	5.70	13.65	500
	100					7.13	650

The calculated f(0) was not used as it gave unrealistic results. The effective stiffness from the coolroom results agrees well with other results in this chapter.

Table 9.6 Effective mass and stiffness for A0 with bridge at the f-holes.

Method	A0 (Hz)	df/dm (MHz/kg)	m (mg)	s (N/m)	Z (kg/s)	Q	R (kg/s)
Coolroom (violin No 2)	285	4.25	34	108	1.92	14	0.14
Gas mix. (violin No 1)	275	10.9	13	12	0.39	14	0.03

Using the coolroom determination it can be seen that A0 rises with temperature and that this violin played for example in Darwin which has a temperature around 32^{o}C for most of the year, the frequency of A0 would coincide with that of the open D string. It might follow from this that to keep A0 on the G string for a violin played at these higher temperatures, the height of the ribs should be adjusted upwards or the f-holes decreased in area. This raises the question whether the range of temperatures in Northern Italy (18 – 25^{o}C) had an effect on the dimensions of the violin. No account has been taken of the effect of humidity as water content in the air would increase the mass of the air plug.

The area of the soundholes has been measured and found to be equal in all three violins. The volumes of the air plugs have therefore been assumed to be the same as the volume of air in the violins and the A0 frequencies are very similar.

9.8 Experiments Increasing the Stiffness of the Violin

Stiffening the violin body by installing two extra "soundposts" under the bassbar and damping the plates with foam rubber held by heavy rubber bands raised A0 to 292 Hz i.e. by 4%: the attempt to stiffen the body was successful. The tap response curves showed that the body modes were effectively suppressed. An additional trial was done encasing the violin in sand except for the central area of the top leaving the soundholes exposed. The results are shown in table 9.7. The f(calc.) uses the mass and effective stiffness to compare with the experimentally determined frequency for A0.

The sand tray was set on the floor and the sand had been thoroughly dried. The implied non-zero compliance of the body in the sand may be due to the part of the top plate near the f-holes, not being covered.

Table 9.7 Helmholtz resonance in violin with body immobilised compared with box.

Condition	A0 (Hz)	area/ f-hole (mm^2)	area/ 2 f-holes (mm^2)	corrected length L (mm)	air plug mass/2 f-holes (mg)	effective stiffness N/m	f (calc) (Hz)
Violin No 2							
no s/post	250	687.5	1375	24	40	98	249
s/post @ 5/22	283				40	125	281
extra posts + foam etc.	292				40	133	290
encased in sand	289				40	131	288
Box							
free on bench	294	688	1376	24	39	134	295
encased in sand	293				39	133	294

Having determined the stiffness of the violin (and box) with rigid sides (taken to be that of the Helmholtz resonance) and the total stiffness in the unrestrained condition, it was possible to estimate the unrestrained stiffness of the violin body from the relation for two stiffness elements in series with the vibrating mass.

Compliance = body compliance + air compliance

i.e. 1/total stiffness = 1/body stiffness + 1/air stiffness

This gives: k(body) = k(total) x k(air)/[k(air) - k(total)] where k is stiffness.

Thus k(body) = 125 x 133/8 = 2 kN/m

From the Rayleigh equation one can derive an expression for the stiffness of the air volume, viz: $k = \rho c^2 S^2/V$ where density, $\rho = 1.205$ kg/m^3, c = 342 m/s, S = 1375 mm^2 and V = 2000 cc. To determine the volume of air equivalent to the stiffness of the body which was about 2000 N/m, by substituting the values above and the value obtained for k we get the equivalent air volume of 130 cc.

This calculated value is with a soundpost in place. It is instructive to calculate the body stiffness without the soundpost. From the value of 98 N/m for A0 in table 3 the calculated value for the body stiffness is 370 N/m showing how much the soundpost stiffens the body.

This may by a useful parameter of the body to be reduced thus increasing the amplitude of the lowest body modes and probably others, raising the sound output. This stiffness would apply to the monopole radiator component of the body modes. The limit to lowering this stiffness would be set by plate thickness etc. so that the resistance of the body to static forces and its mechanical stability would be important.

9.9 Experiments on Modified Soundholes

1 Determination of L for the f-hole without the finials. The difficulty of assigning an equivalent ellipse to a violin f-shaped soundhole suggested determining the Helmholtz frequency of the rigid box with the finials taped leaving only the straight part of the soundhole active. This would enable a calculation for L from the Rayleigh equation and a comparison with the results for an equivalent ellipse as determined by Cremer. A determination of A0 for the f-holes with taped finials of the unrestricted violin was also made. The values found including those for mass and stiffness, for completeness, are shown in table 9.8.

Table 9.8 Stiffness of the air with finials covered for both box and violin.

Object	$f_{(H)}$ A0 (Hz)	area(taped finials) (mm^2)	total area (mm^2)	corrected length L (mm)	air plug mass (mg)	stiffness N/m	f (calc) (Hz)
Box	284	437.5	875	16	17	55	286
Violin	255			20	21	54	255

The value of L determined here is to be compared with that calculated by Cremer for an equivalent ellipse, as taken up in a following section. The straight part of the soundhole is similar to the shape of an ellipse.

2 The effect of increasing the mass of the plug on A0. With the finials closed, it was decided to study the effect of increasing the size of the plug of air in the soundholes. To achieve this end, the long sides of the soundholes were lined with stiff card using double sided tape. Card 10 mm and 13 mm wide, longer than the half width of the f-holes (3.5 mm) was used. The card was (i) centered in which case both edges were assumed to be unbaffled, and (ii) positioned level with the inside surface of the top in which case the inside edge was baffled. The correction for the unbaffled edges can be approximated by the factor 0.61 R and for the baffled edge inside the top plate, by 0.85R where R is the radius of an "equivalent circle". The results are shown in table 9.9.

Table 9.9. stiffness of the air with finials closed and air mass increased from ~20 to ~28 mg in the soundholes.

	A0 (Hz)	total area of 2 f-holes (mm^2)	corrected length L (mm)	air plug mass (mg)	stiffness (N/m)	f (calc) (Hz)
10 mm card						
centered	221	860	24	25	48	220
level inside	223		27	28	55	223
13 mm card						
centered	207	860	27	28	48	208
level inside	209		30	31	54	210

These experiments with card to increase the mass of vibrating air has lowered the value of A0 from about 257 Hz (table 2) to 220 Hz for the 10 mm card and to 210 Hz for the 13 mm card. Variation in the position of the card and adding an additional baffle, made little difference to the value of A0.

9.10 The Cremer Calculation of 2dL

Using the Cremer approach to determine L for this violin, we have (see appendix):

$$f = \frac{342}{2\pi}\sqrt{\frac{1375}{0.018*2000}}\ \text{Hz} = 340\ \text{Hz}$$

This frequency for A0 is much higher than that measured, which was 283 Hz. The difference must lie in the choice of the width and hence the eccentricity of the equivalent ellipse and neglecting the finite stiffness of the body of the violin.

By measuring the frequency of the air resonance with the violin body immobilised, simulating a Helmholtz resonator, it is possible to determine a correct value for L. For a frequency of 292 Hz together with the other geometrical factors of the violin required in the Rayleigh equation a value for L becomes 24 mm From this a calculation of the contribution of the body to the spring resisting the vibration of the air in the soundholes can be made as found above at about 2000 N/m for this violin.

The experiment with the rigid box gave a measured Helmholtz frequency of 294 Hz. The calculated value for L shown in table 3 has a similar value of 24 mm to the above.

Can the difference between the values for L obtained from the equivalent ellipse and that from knowledge of the Helmholtz frequency be reconciled? There seems to be no alternative to determining the Helmholtz frequency independently. By trial and error a choice of width for the equivalent ellipse to give L = 24 mm can be made. In this case a width of 14 mm results in a value for L of 24 mm which is the value obtained from the Rayleigh equation. It may be a coincidence that the width of the equivalent ellipse chosen is twice the actual width of the soundhole in the violin studied because the choice of width of the equivalent ellipse is an empirical one.

To further investigate this, the finials of the box were taped and $f_{(H)}$found to be 284 Hz. The value of L calculated with the Rayleigh equation, was 12 mm giving 2dL = 8.5 mm. We find by trial and error that an equivalent ellipse of length 206 mm and width 2.7 mm had a value for 2dL of 8.6 mm in reasonable agreement with the Rayleigh value. This equivalent ellipse is very different to the dimensions of the soundhole.

There is an alternative treatment for complex soundholes given by Malecki [9] p 395 who approximates the shape by a rectangle rather than an ellipse. Applied to the violin the area of the soundhole would be represented by a rectangle of length l and width b and using Cremer's example where the area of the soundhole was 5.78 cm^2 and b = 0.8 cm, l became 7.225 cm. The ratio l/b = 9 which converts to a factor of about 2 (from Maleki's figure 9.11, p 396, reproduced in figure 9.3) is used in an equation for the end correction 2dL = 2b = 1.6. This gives a figure of 0.8 cm to be compared with 1.53 cm from Cremer for 2dL. The conversion factor comes from work by Bruel [10]. This value for 2dL would lead to a value for $f_{(H)}$ in Cremer's example of 278 Hz, a lower figure than his of 295 Hz.

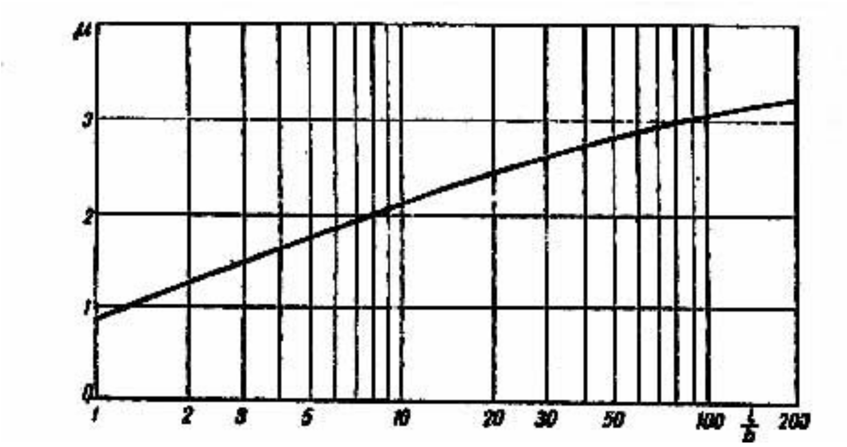

Figure 9.3 Coefficient μ as a function of the ratio *l/b* (after Brüel)

For the violin used in the present study, where $f_{(H)}$ was found to be 292 Hz, for a width equal to that of the soundhole, 7 mm, and an area of 687.5 mm^2, the Maleki approach leads to a rectangle with a length of 98 mm. The ratio, l/b = 14 and from figure2, μ_S = 2.3. As shown in the appendix, 2dL = 16 (c.f. Cremer 15.3). Using Rayleigh's equation $f_{(H)}$ is 323 Hz where L is 19.5 mm. Clearly, these approximations seem difficult to make for a complex soundhole, as in the violin.

9.11 Conclusion

The main air resonance in the violin is associated with the generation of a breathing mode whereby the body behaves as a monopole radiator. It has the characteristics of a Helmholtz resonance but with a compliant container which modifies the stiffness by putting the compliance of the body in parallel with that of the air. It is possible to measure the Helmholtz resonance of the violin by immobilising the body which gives a frequency about 5 Hz higher than A0 in the violin studied.

For a fixed volume of air, the frequency of A0 is affected by the area of the soundholes and whether the vibrating plug of air is increased by lining the soundholes with card. In the latter case a 10 mm card lowered A0 by 30 Hz and a 13 mm card lowered it by 50 Hz. Lowering A0 with the use of cards does not appear to be of practical use since access to the soundpost through the treble f-hole is necessary. Further, if it were desired to change the frequency of A0, a change in the width of the f-hole would be more practical.

Immobilising the body is a practical way to determine the Helmholtz frequency without the body compliance having an effect. It was possible to calculate the contribution of the body stiffness from the relation: total compliance equals body compliance plus air compliance. For the violin used, the body stiffness was 2 kN/m.

A method has been found to enable the effective mass and stiffness of the air plug in the f-holes to be determined. The mass in this case comes out to be 29 x 10^{-6} kg and the stiffness 91 N/m. This stiffness is to be compared with that found for the immobilised violin of 130 N/m.

The Cremer determination for the equivalent ellipse of an f-shaped soundhole gives an order-of-magnitude estimate but the choice of the width of the ellipse may be up to twice the width of the soundhole to obtain a realistic value.

In the present context, a more compliant Baroque body would lead to a slightly lower A0 frequency.

9.12 References

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9.13 Appendix

The calculation of the equivalent ellipse for the violin f-hole of width 7 mm and area 687.5 mm^2 (which gives a total area of 1375 mm^2 for 2 f-holes) as found in the violin used in this study. Cremer assumed the width of the f-hole for the ellipse in his calculations as 8 mm.

To calculate the eccentricity of the ellipse we find the semi-major axis, a, from the area of the ellipse, $A = \pi ab$, in this case:

$$a = 687.5/\pi\ 3.5$$
$$= 62.5 \text{ mm}$$

The eccentricity, e, is required to calculate the elliptical integral:

$$e = [1 - (b/a)^2]^{1/2} \text{ which in this case}$$
$$e = [1 - (3.5/62.5)^2]^{1/2}$$
$$= 0.998$$

To use the tables for the complete elliptical integral, we proceed

$\sin^{-1}(0.998) = 86.4$ degrees

Elliptical Integral = 4.157 (Handbook of Chemistry and Physics)

The correction 2dL = b x the integral

= 3.5 x 4.157

= 14.55 mm

Therefore the value of L = 14.6 + 3.5

= 18.1 mm

Using Maleki's method in this example we have

l = 687.5/7

= 98

and l/b = 14

From figure 2 $\mu_S = 2.3$ approx.

and 2dL = 2.3 x 7

= 16 mm c.f. Cremer 15.3 mm

Using the Rayleigh equation

$$f_{(H)} = 342/2\pi\ [1375 \times 10^3/(19.5 \times 2000)]^{1/2}$$
$$= 323 \text{ Hz.}$$

Chapter 10

BODY RESONANCE STUDIES

10.1 Introduction

This chapter looks at the body modes that have been studied throughout this thesis to enable a comparison of the two setups. Body modes are important in determining the strength of harmonics and hence the sound quality. It will be seen that not all resonances are strong radiators and that variations can occur depending on the level of humidity.

Body, plate and air resonances make up the response curve of the violin [1]. Tailpiece, neck and fingerboard resonances are also present [2, 3, 4] but have not been studied individually in this thesis. Apart from two lower frequency air resonances, the higher ones and plate resonances occur at frequencies above about 1 kHz where their number makes it difficult to study them individually. The main body resonances at frequencies below 1 kHz are well separated and their vibration parameters can be studied. They are important because they lie in the region of the fundamentals of the notes played. The conditions that determine their frequencies are important. What these conditions are and how to control them has not yet been completely understood.

The body of a violin vibrates in response to a varying force applied to the bridge top usually as one or more strings are excited by the bow. It will also respond to sound waves impinging from an external source. It can be thought of as a hollow shell with a strengthening bar along the bass side and a post between the top and the back on the treble side. These two additions add support to the top plate at the bridge where the combined force of the strings creates a downward load. The downward load increases as the height of the bridge increases, since the angle the string makes crossing it, decreases. A major effect of this string force, which tends to fold the violin up, is to put the top in longitudinal compression and the back in tension. The body vibrates under this statically stressed state as a shell with a connecting rod between the two plates. From the properties of the spruce top and maple back, together with their shape and thickness, it might be expected that the top is more active than the back but this is not generally the case [5].

With this background and the evidence of studies already carried out, one can make general comments about the position of nodal lines and anti-nodal regions in the violin, at least at frequencies below 1 kHz, where major resonances can be separately studied. The subdivision of the plates into many anti-nodal regions occurs increasingly above 1 kHz. The violin vibrates in many modes at the same time when a string is bowed and several of the harmonics might each excite a resonance. For the main low frequency modes, nodal lines in the top are usually close to the soundpost on one side and close to the soundhole on the other since the bassbar will make that region of the top, with an effective free edge, an anti-nodal region. For maximum monopole content, the nodal lines should be close to the margins of the plates. Nodal lines have to be continuous and pass across the sides from one plate to the other or pass along the rib to re-emerge on the same plate.

10.2 Resonance Modes in the Baroque Setup

Mechanical vibration parameters for the main low frequency modes for the violin in the Baroque configuration are shown in table 10.1. A Renaissance bridge, 2.18 g, located at the notches in the f-holes was used. Gut strings were in place and no chinrest was fitted. The tuning was A415.

Table 10.1 Effective resonance parameters for the Baroque violin as seen at the bass foot of the bridge. (~70% R.H.)

Resonance Mode	f (0) (Hz)	df/dm (Hz/kg)	m (kg)	s (MN/m)	Z (kg/s)	Q (kg/s)	R	f (calc) (Hz)
A0	286	4.3 x 10^6	0.034	108 N/m	1.92	18	0.11	--
?	411	1170	0.18	1.17	454	27	16	410
B1-	471	1940	0.12	1.06	375	31	12	473
B1+	582	6830	0.043	0.57	157	36	4	579
C4?	618	2290	0.14	2.04	525	40	13	619
?	770	5080	0.076	1.77	367	31	12	768

The highlight of these results are the resonances, A0 and B1+, as effective radiators and the other resonances less effective. Examples of the nodal patterns are given in figure 10.1 for the most prominent resonances. The frequencies vary from those listed in table 10.1 due to unavoidable variations in experimental conditions i.e. mainly ambient temperature. The mode at 411 Hz shows nodal lines across both bouts in the top and back for this violin. The B1+ resonance at 585 Hz is assumed to have the neck in torsion while the resonance at 620 Hz with a similar nodal pattern, probably has the neck in bending [5]. Both B1- and B1+ can exhibit this behaviour as shown in an earlier chapter. The mode at 770 Hz shows a ring pattern in the back as has been found by earlier workers. The pattern for the 875 Hz resonance was not able to be determined.

Upper pair: A0 282 Hz	B1-471 Hz	620 Hz
Lower pair: 411 Hz	B1+585 Hz	770 Hz

Figure 10.1 Baroque violin: Chladni patterns with bridge and soundpost at f-holes

The tap response for the Baroque violin with the heavier gut strings tuned to A415 is shown in figure 10.2. No explanation was found for the lower response shown.

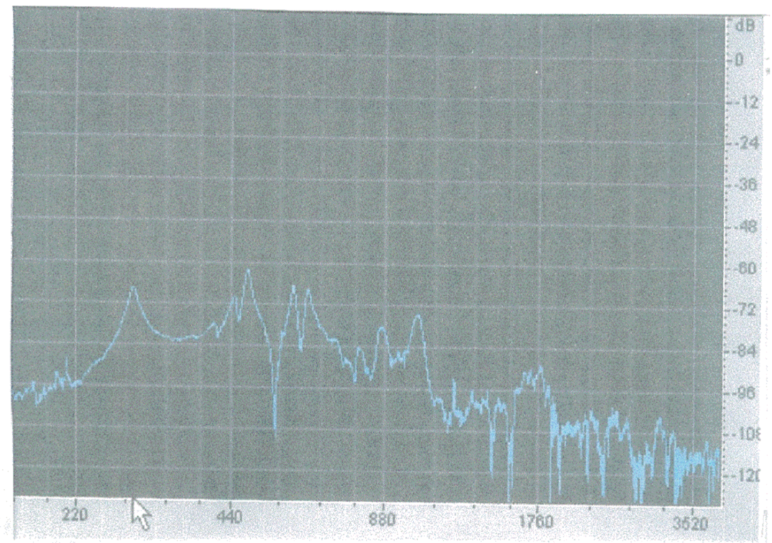

Figure 10.2 Baroque violin tap response: gut strings A415 (damped) no chinrest, soundpost 4.3 mm at 5/15, "Renaissance" bridge.

10.3 Resonance Modes for the Romantic Setup

With the change in configuration to the Romantic or modern setup with a longer neck, modern bridge and heavier bassbar and soundpost, there were changes in the resonance modes present. Gut strings were still in use when the changes were made in the early 1800's and so were used here. The tuning practice at the time is not certain but the tuning here was set at A440. The prominent resonances are shown in table 10.2.

Table 10.2 Resonance parameters for modes in the Romantic setup. (~70% R.H.)

Resonance mode	f(0) (Hz)	f(expl)	df/dm (Hz/kg)	m (kg)	s (MN/m)	Z (kg/s)	Q (kg/s)	R	f (calc) (Hz)
A0	286	285	4.3 x 10^6	0.034	108 N/m	1.92	14	0.14	--
C2	386	386	1100	0.18	1.03	431	77	6	388
B1-	425	425	2600	0.082	0.58	218	39	6	423
B1+	541	540	6400	0.042	0.49	143	49	3	544

These results show that for the violin in this condition all the modes were good radiators except A0. No explanation was available for this although the Relative Humidity was around 70% at the time. It was generally observed that the Relative Humidity ranged 65-75 % for all the laboratory work carried out.

The Chladni patterns for these body modes are shown in figure 10.2. The nodal lines for A0 lie near the outer margins of the two plates showing a large area of both moving in phase, with reference to the centre of mass i.e. both outward (or inward) to produce a breathing mode. It will be noticed that the soundpost draws the nodal line on the top to its position near the treble foot of the bridge.

The mode at 386 Hz, with a nodal line down the centre of the back and lines across the two bouts with the top showing three separate nodal lines, two on the outer bouts at left and a central nodal line enclosing an area on the right (see figure 10.2), has been associated with the neck in torsion. An associated mode sometimes occurs at a lower frequency with the neck in bending [6]. The main body modes, B1- and B1+ have the characteristic nodal patterns seen on most good violins. For B1- one nodal line along the top takes in the soundpost while the other is nearer the margin compared with the equivalent mode in the Baroque setup. This may have been due to the heavier bassbar. For B1+ the nodal pattern is that commonly observed [5]. The nodal pattern at 586 Hz may be the variation of B1+ with neck bending although the nodal line seems to continue along the centre past the soundpost. The resonance at 852 Hz did not allow the vibration parameters to be determined. The nodal pattern for this mode has a dipole in the lower bout although the nodal lines are not well defined. There is an anti-nodal region in the upper bout.

Upper row A0 285 Hz B1- 424 Hz C4 586 Hz
Lower row C2 386 Hz B1+ 528 Hz 853 Hz

Figure 10.3 Romantic violin: Chladni patterns after conversion, modern neck and fingerboard, modern bridge, heavier bassbar and soundpost, gut strings, bridge and soundpost at f-holes

The tap response for the Baroque violin converted to the Romantic setup but with gut strings and a modern bridge is shown in figure 10.4. The body resonances appear to be good radiators in this version.

10.4 The Effect of Neck/Scroll and Chinrest mass on Body Modes

The resonance frequency of the body modes were lowered when the change was made to the Romantic setup which entailed a different neck/fingerboard and slight modification to the top plate by way of a longer bassbar. The top central region was thinned slightly to adjust the mode 5 nodal line in the lower bout. The weight of the neck/fingerboard increased from 116 g to 165 g. These were attached to a body weighing 259 g.

Tests were made with the Romantic setup (with Thomastik Dominant nylon cored strings) by adding mass along the neck and scroll as well as fitting a chinrest. Table 10.3 sets out the frequencies from a tap response, the neck/fingerboard added 165 g.

Table 10.3 Mode frequencies f(expl) (Hz) for added (plasticene) mass to the neck/scroll. The mass of the chinrest (C/rest) was 45 g.

1 Mode	2 Body only	3 + neck/ f/board	4 + C/rest (45 g)	5 No C/rest (+ 49.5 g)	6 No C/rest (+ 77.45 g)	7 45 g C/rest (+ 49.5 g)	8 45 g C/rest (+ 126.95 g)
?	--	240	240	228	224	226	223
A0	278	280	280	280	280	280	280
C2	--	377	374	371	368	374	365
B1--	409	419	413	413	406	406	393
B1-	437	444	438	437	433	437	430
?	--	--	--	546	546	546	541
B1+	569	(567)	559	559	559	559	555
C4?	--	583	573	578	578	578	573
?	778	830	830	830	830	830	817
?	~980	940	932	924	940	924	940

This table shows that any added mass lowers the body resonances although some are not be affected viz. A0. The frequencies in columns 3 and 4 are the most relevant for discussion. The largest decrease occurs with B1+ of 8 Hz. There is a decrease with C4 and the peak at 940 Hz. The effect of the shoulder rest and holding the violin on mode frequencies has not been studied. As shown in the table, the largest mass added 126.95 g, destroyed the simple appearance of these peaks without affecting the general level of the response curve. It is not known what effect this would have on the sound. A study of the Chladni patterns for the B1 modes shows that the neck is an extension of the antinodal region of these modes. It is expected that the effect of this would be to lower the frequency due to the added mass. The chinrest clamped at the end block, would behave similarly. B1+ might be lowered by 5 to 10 Hz when adding a chinrest.

10.5 Discussion

A comparison of the mode frequencies for the two conditions, Baroque and Romantic, can be made. as shown in table 10.4. The violin had been fitted for the Romantic setup with Thomastik Dominant strings which are widely used by professional violinists.

Table 10.4 Frequencies of the prominent modes below 1 kHz (from earlier chapters).

Mode (Hz)	A0	C2	B1-	B1+	C4?	?	?
Baroque	282	411	471	585	620	770	
Q values	18	29	36	36	29	28	
Romantic	285	386	447	528	540	586	878
Q values	14	77	45	38	49	84	37

It can be seen that the main resonances, except for A0, have lower frequencies for the Romantic conversion than for the Baroque setup. The results in table 10.1 and 10.2 were obtained after the neck had been reset so that a higher bridge could be used with the heavier gut strings. During the conversion to the Romantic setup, the change to a heavier fingerboard; 76 g for ebony compared with 29 g for the Baroque fingerboard gave neck/fingerboard weights of 165 g and 115 g respectively. This increase in mass may possibly account for the lower frequencies of the body modes. The tuning of the top plate was restored when the larger bassbar was fitted during this conversion. Fitting the new bassbar resulted in the distortion of the #5 nodal line in the lower bout as shown in figure 10.4. In the process, the top was thinned, going from a mass of 74 g to 72 g in an attempt to correct the mode #5 nodal line. The free plate mode frequencies of the finished top plate are shown in table 10.5.

Table 10.5 Top plate mode frequencies obtaining for tests with the two setups.

Top plate mode	mass (g)	#1 (Hz)	#2	#5
Baroque	74	89	170	358
Romantic	72	84	152	339

A more recent determination of the body mode parameters is shown in table 10.6. The tap response corresponding to the results in table 10.6 is shown in figure 10.5. These results are to be compared with those in table 10.2. Duplicate determinations have been made at an interval of several weeks. Relative Humidity had changed over the period from about 70 % to 40 %. No correlation was attempted but variation of the kind suggested by these results may indicate the variable playing behaviour of the violin often experienced by violinists. The violin had been fitted for this final setup with Thomastik Dominant strings which are widely used by professional violinists.

Figure 10.4 The top plate with new bassbar fitted #5 showing nodal line runout (left) and after retuning (right) with the result in Table 10.5

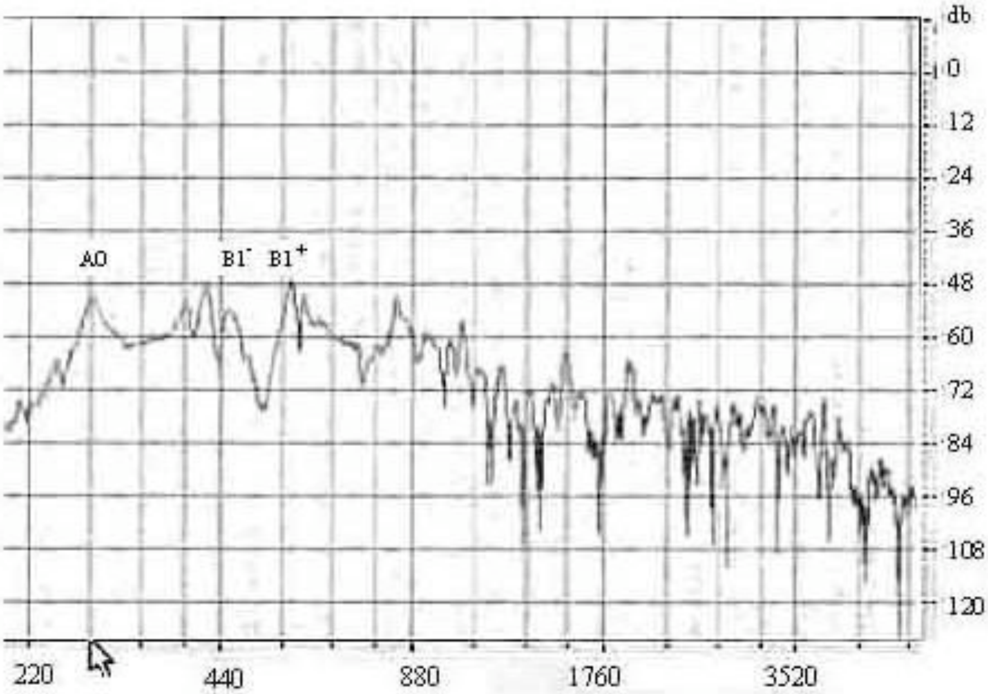

Figure 10.5 Romantic violin: Dominant strings, modern setup
Tap response, strings damped, microphone at 200 mm in front

Table 10.6 Effective parameters for the converted violin using Thomastik Dominant nylon cored strings. (11-07-07). R.H. ~70%.

Resonance	f(0) (Hz)	f(expl)	df/dm (Hz/kg)	m (kg)	s (MN/m)	Z (kg/s)	Q	R (kg/s)	f (calc) (Hz)
A0	278	278	4.25×10^6	0.034	108 N/m	1.92	13	0.15	--
C2?	416	416	2657	0.078	0.54	205	35	6	419
B1-	453	453	2314	0.98	0.79	278	35	8	452
B1+	567	558	6714	0.045	0.57	160	71	2	566
?	859	841	19686	0.022	0.64	118	47	3	856

A week of low humidity levels in the vicinity of 40% R.H. prompted a second determination of these parameters which was made on the 21-07-07 when the Relative Humidity was <50%. It was judged that the violin had time to adjust to the new conditions. These results are shown in table 10.7.

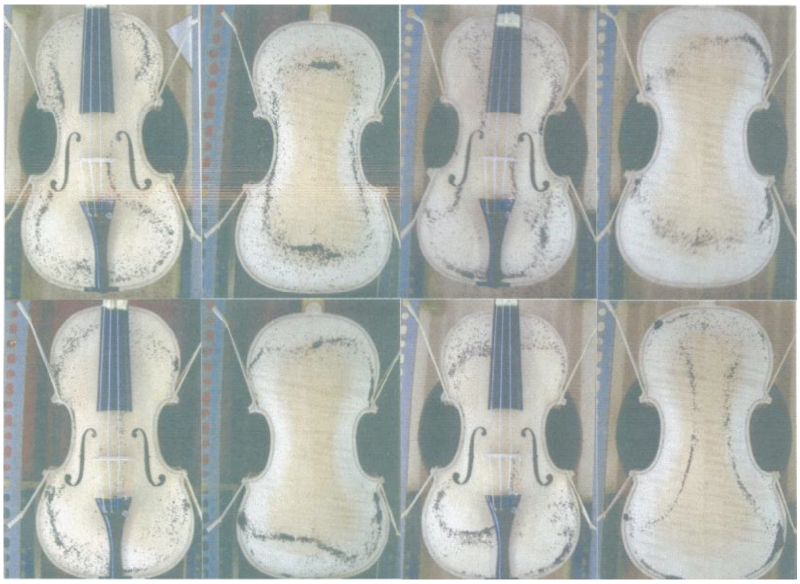

Figure 10.7 Romantic violin: Chladni patterns of body modes setup with Dominant strings. Upper row: A0 278 Hz, B1- 453 Hz. Lower row: 362 Hz, B1+ 560 Hz.

Chladni patterns corresponding to resonances in table 10.6 are shown in figure 10.7.

Table 10.7 Effective parameters for the converted violin with Thomastik Dominant nylon cored strings (21-07-07). R.H. <50%.

Resonance	f(0) (Hz)	f(expl)	df/dm (Hz/kg)	m (kg)	s (MN/m)	Z (kg/s)	Q	R (kg/s)	f (calc) (Hz)
A0	274	274	4.25×10^6	0.034	108 N/m	1.02	14	0.14	--
C2	386	386	1886	0.097	0.57	235	55	4	386
?	414	414	1314	0.16	1.08	416	32	13	412
B1--	448	447	863	0.26	2.06	732	24	31	448
B1-	464	460	2520	0.09	0.78	268	27	10	463
B1+	567	568	5629	0.05	0.64	180	95	2	569
C4	589	589	771	0.38	5.23	1410	46	7	590
?	794	794	686	0.58	14.4	2890	79	37	793

These results show the variation that can occur with time. It is known that wood when dried, normally carries about 7 % moisture in equilibrium with the atmosphere, and has unsaturated hemi-cellulose bonds that can take up water. Fryxell [7] has shown that wood loses moisture much faster than it absorbs and a %R.H. change 70 to 50 corresponds to a moisture change of 4%. This appears to be the case whatever the age of the wood. The effect of humidity changes has not been studied, except the above chance results, due to lack of humidity control. A further study is clearly indicated.

Some discussion of the resonance parameters calculated throughout this work is appropriate at this point. Using the equation $2\pi f = (s/m)^{1/2}$ one can calculate f from the values of m and s in the table to compare with f(expl). This checks the validity of the experimental value of df/dm. From the values in tables 10.1, 10.2, 10.6 and 10.7 we have:

Table 10.8 Verification of experimentally determined values of df/dm.

Mode	Table 10.1			Table 10.2			Table 10.6			Table 10.7		
	f(0)	f(expl)	f(calc)	f(0)	f(expl)	f(calc)	f(0)	f(expl)	f(calc)	f(0)	f(expl)	f(calc)
A0	286	286	285	286	285	287	278	278	278	274	274	274
C2	411	411	410	386	386	388				386	386	390
							416	416	419	414	414	412
B1--										448	447	446
B1-	471	478	473	425	425	423	453	453	452	464	460	460
B1+	582	610	579	541	540	544	567	558	566	567	568	564
C4	618	618	619							589	589	590
	770	770	768				859	841	856	794	794	793

A check on the value of df/dm by calculating the frequency using the effective mass and effective stiffness will differ from the resonance frequency, f(expl), recorded with the magnet in place. This could be the frequency coinciding with that for determining the Chladni pattern or coinciding with the height of the resonance peak when determining df/dm. The value of f(0) determined by linear regression, and used to calculate the effective mass effective stiffness should agree closely with f(calc). A poor agreement between the calculated frequency, f(calc), and f(0) could occur if a visual determine of df/dm is made.

10.6 References

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Chapter 11

VIOLIN BRIDGE RESONANCE STUDIES

11.1 Introduction

The purpose of this chapter is to record the results of a study of the vibrational properties of the bridges similar to those used as the violin evolved from the Middle Ages through the Renaissance, Baroque and Classical periods to the Romantic (from which it is little changed today).

The "Renaissance" bridge was used in essentially the same form throughout the Baroque era. The bridge had to lift the strings above the body for bowing as distinct from plucking and the sides of the body had to be indented, even though the top of the bridge had a lower arch than its modern counterpart. The other two bridges studied, the "Stradivari" and the "Paris" were probably typical of the classical period that followed the Baroque, from about 1720 to 1820 although there was undoubted overlap. The Romantic or modern bridge, brought in at the end of the classical period, was accompanied by other changes to the violin.

The modern bridge is made of sycamore (a species related to maple) and has the grain running horizontally to resist the pressure of the strings. It has feet about 4.5 mm thick and tapers to 1.5 mm at the top. It is about 35 mm high and weighs about 2.1 g. Bridge heights were measured from the top plate centre line. The feet are cut to fit the top such that the surface of the bridge facing the tailpiece is kept perpendicular to the plane of the instrument. A properly cut bridge has the medullary rays lying in this surface to strengthen the bridge against bending towards the fingerboard. The modern bridge resulted from many trials. Its history cannot be traced with any certainty, since (to a lesser extent, a similar comment could be made about bows), when it was changed, the bridge that was replaced was usually discarded.

Sycamore has a density in the range 650 to 700 kg/m^3 approximately. The longitudinal elastic modulus is about 20 GPa; the radial elastic modulus, in the vertical bridge direction, is about one tenth of this. This modulus may vary and depends inversely on the spacing of the annual rings. Wood for bridges is carefully chosen with annual rings about 2 mm wide.

11.2 The Function of the Bridge

The bridge on the violin has some obvious functions and others which are more subtle. Bridges on other instruments, e.g. guitar, serve to anchor one end of the string as well as elevating the playing length of the string above the soundboard and the fingerboard. On the violin it appears to simply elevate the strings above the body of the instrument as the ends of the string are anchored at the tailpiece and the nut. This setup gives the violin family the feature that the bridge only exerts a downbearing on the soundboard through the feet and exerts no torsional motion on the top plate in the string direction (Kotos and Sitars have a similar feature). The bridge has another obvious function by virtue of its curved top, in allowing the strings to be bowed separately or in pairs to give double stops. Before the modern ones, bridges had flatter top curves that allowed three or four strings to be played together. The hair on bows in use at the time was less taut, the tension often being controlled by the hand. The indented sides of the violin body, the inner bouts, allowed the two outer strings to be played more easily. The height of the violin bridge controls the static force applied to the soundboard via the angle of the strings. There was an increase in this force with the modern setup although it would have been more variable in earlier times due to the non standard practice of violin making. What can be said is that the modern setup is universally more consistent.

The bridge passes on the tangential force exerted by the vibrating string to the top plate through the two feet, one of which is located over a bassbar. The other, the treble foot, is located near the soundpost which limits the motion of this foot but at the same time connects the top plate to the back. The bridge is thus forced to perform a rocking motion about a point near the treble foot mainly at frequencies below about 1 kHz. At the higher frequencies both feet are active and may move in phase for some resonances that do not have a nodal line between them.

The bridge is effectively a lever with a ratio of the distance between the pivot and the string notch, to the distance between the pivot point and the bass foot. It varies for each string as shown in figure 11.1. The pivot point must lie inside the treble foot and the soundpost has to have a position outside the pivot point to enhance the breathing action of the violin. An important effect of this ratio is the force at the bridge foot which is greater than that delivered at the string notch by the string, except for the E string. A higher bridge will deliver a greater force and lead to a higher sound output. Table 11.1 sets out these dimensions for the bridges used in this study. They are typical values [9].

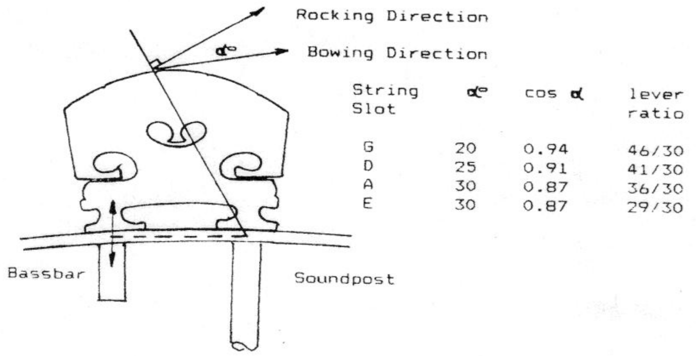

Figure 11.1 violin bridge lever geometry.

This simplified treatment assumes the treble foot is the pivot point. There is no consideration of a force transmitted by the treble foot. The force applied at the string notch has to be resolved into the rocking direction as shown in figure 11.1. For a pivot point between the bridge feet the geometry becomes involved as the treble foot is no longer stationary and the soundpost may also be outside the treble foot.

Table 11.1 Bridge lever dimensions and lever ratios (in parentheses).

Bridge Type	Height (mm)	Distance between feet (mm)	Distance from treble foot to string notch (mm) String G	D	A	E
Renaissance	28	30	41(1.37)	35(1.17)	29(0.97)	24(0.80)
Stradivari	29	29	40(1.38)	35(1.21)	31(1.07)	27(0.93)
Paris	29	31	41(1.32)	36(1.16)	31(1.00)	26(0.84)
Modern	35	30	45(1.50)	40(1.33)	35(1.17)	29(0.97)
Renaissance (neck reset)	33	30	44(1.47)	39(1.30)	34(1.13)	29(0.97)
Renaissance (below f-holes)	37	29	47(1.62)	43(1.48)	39(1.34)	34(1.17)
Modern (violin converted from Baroque to Romantic)	38	30.5	48(1.57)	43(1.41)	38(1.25)	33(1.08)

The force transmitted to the top plate has to take into account that the bowing direction is not normal to the line from the pivot point and the string notch. The force exerted by the string has to be resolved into this direction. To a good approximation [1], the bowed string generates a couple on the island area between the f-holes of bridge height x the horizontal component of the bowed string force.

This in-plane rocking motion transmits the spectrum of the string force to the violin body which then "colours" or filters it according to the coincidence of body resonances with the harmonics present. The modern bridge has another function in lifting the falloff in output due to losses in the wood and plate mode cancellation. At higher frequencies above 1 kHz, by virtue of a bridge top resonance that occurs at about 2.5 kHz in the violin, and has a rocking action, the response is kept higher than would otherwise be the case. Reinicke [2] has studied the in-plane resonances of a rigidly anchored bridge. He found two resonances relevant to the violin, both involving the top portion above the waist; a rocking mode at 3 kHz and a bouncing mode at 6 kHz. When measured on a violin these resonances occur at lower frequencies because of the compliant body.

Jansson and co-workers [3, 4] have made extensive studies of the effect of the first or rocking resonance on the response curve at about 2.5 kHz following a paper by Duennwald [5]. They proposed the existence of a "Bridge Hill" that lifts the response in the region of high aural sensitivity. Woodhouse [6] has analysed this using statistical vibration analysis on simplified theoretical models to outline the sensitivity of the Bridge Hill to bridge and body parameter changes. He found that bridge mass and stiffness, and top plate thickness had a significant effect on the Bridge Hill position and height, as did bridge foot spacing. Back plate thickness and position of the soundpost parallel to the violin axis had little effect on the position of the Bridge Hill. Beldie [7] has attempted to reconcile the bridge frequencies found on a rigid base with those obtained on the violin. He found there was an optimum bridge "rocking" stiffness which gave a maximum frequency of 2600 Hz for the, experimentally found, Bridge Hill

The bridge is not glued in place for the same reason the soundpost is not glued in place i.e. to allow adjustment. There may be other reasons yet unexplored. At some body resonances, one or both feet may be effectively decoupled from the top plate if the bridge is rocking but the plate centre is simply rising and falling. String tension holds the bridge in place. With the bridge this is most likely at frequencies where resonances do not have a nodal line between the feet, such that one bridge foot is out of phase with the top plate locally. This could happen for example, at the bridge bounce frequency at 3 kHz, the frequency at which this bridge resonance occurs in the present study.

The cutouts at each side of the modern bridge have been shown to prevent any out-of-plane motion of the bridge that would lead to a fore and aft rocking motion at the feet, from being transmitted to the violin top [8]. This is probably due to flexing at the waist. The higher resonance of the bridge at about 3 kHz (mentioned above), is an in-plane vertical motion of the top part. This may reinforce the motion transmitted to the top plate by the string tension change. This occurs at twice the transverse frequency of the fundamental of the note being played. This could strengthen the high frequencies and add to the brilliance of the sound on the upper strings. A study of the function of earlier bridge styles in this respect has not been made. The present author has investigated the behaviour of the modern bridge on the violin and the influence of string tension [9]. It was concluded that if the effect exists it would not be significant.

11.3 Naming the Parts of the Bridge

To describe the behaviour of the bridge, workers in the past have given anatomical names to some of its parts in line with other features of the violin; for example, the “feet”, the “eyes”, the “heart” and the “waist”, “b”. This becomes restrictive if changes are made to other parts of the bridge in deciding on suitable names. An alternative, as used by other workers, of labelling the parts of interest alphabetically has been adopted here. Figure 11.2 illustrates this situation. The “eye” is a particular case in point. The “waist” can be affected by elongating the eye while the region between the eye and the “heart”, “a”, can be thinned either by enlarging the top of the eye or enlarging the heart. These “connecting” features are also called ligaments.

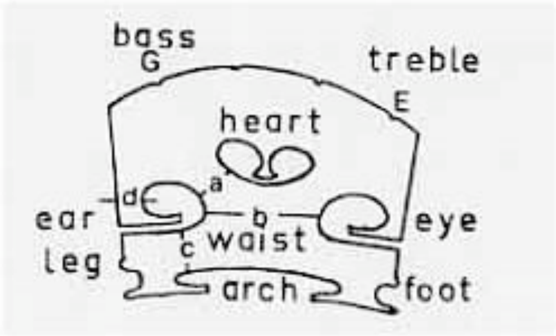

Figure 11.2 Parts of the bridge of interest in this study.

11.4 Bridge in-plane resonance measurements

Two sets of experiments were conducted, both exploring the effect on the resonance frequencies of the bridge mounted on a rigid base, after Reinicke [2]. The two in-plane motions of the bridge are shown in figure 11.3 and the method of study in figure 11.4. The results in tables 11.2 and 11.3 were obtained using Schelleng's equations as outlined in chapter 5. The frequencies were identified from the tap response and df/dm obtained by adding masses to the top o the bridges. The bridges were mounted in a machine vice clamping the feet to provide a rigid base. The experimental setup is shown in figure 11.5. The general levels of the quantities measured make for useful comparisons with those of other parts of the instrument.

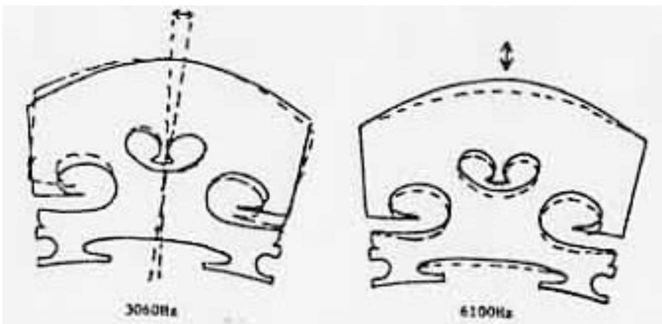

Figure 11.3 In plane bridge resonances showing the displacements; left, the rocking motion of the top part at the lower resonance, and right, the bouncing motion at the second resonance.

The modern bridge was further studied by reducing the stiffness by thinning the ligaments. The first study varied the dimension of the waist. As tapering of the top part of the bridge began above the waist, stiffness changes were related arbitrarily to changes in the cross sectional area of the waist. This was plotted against the resonant frequency resulting in the trend shown in Figure 11.6.

On a single bridge the other ligaments were progressively thinned with the result shown in Table 11.6. Here the effective mass was assumed to be unchanged since it related to the top part of the bridge. On this assumption, the effective stiffness resulting from the changes was calculated.

Finally, an attempt was made to determine the higher resonance at about 6 kHz by turning the vice holding the bridge on its side and applying the impulse to the top of the bridge between the A and D string slots. The magnet to measure the vertical bounce was placed as close to the pendulum as possible, as shown in figure 11.5. This was partly successful and tentative results were obtained. This was not attempted with the other bridges because of the different geometry.

11.5 Results on Bridges as first fitted

The purpose of these experiments was to determine the first, or rocking, resonance frequency and the associated vibration parameters of bridges used in the Baroque period for comparison with their modern counterpart.

Three fairly distinct styles preceded the modern bridge, namely the “Renaissance”, “Stradivari” and “Paris” bridges. This choice of bridge styles has been made for the purpose of this study. The bridges are shown in figure 11.4 and in Table 11.2 where the mass, rocking resonance frequency, effective mass and effective stiffness for this resonance has been listed.

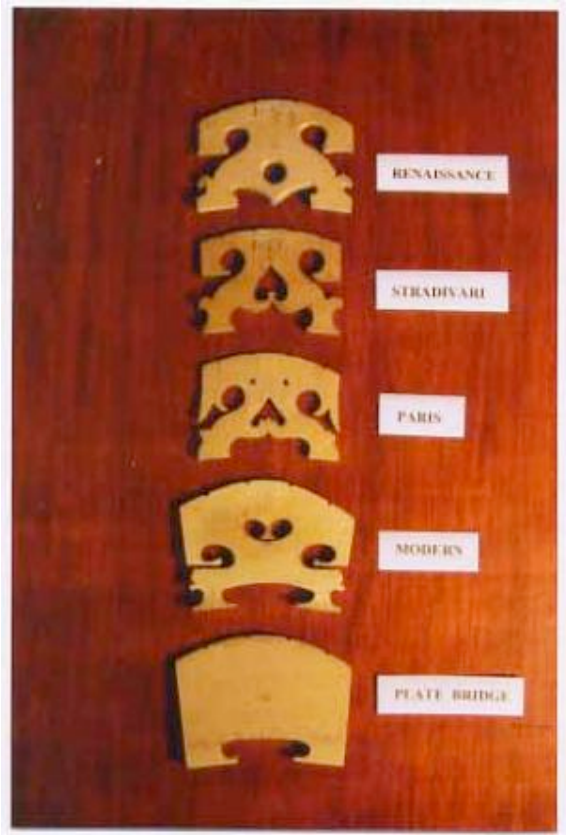

Figure 11.4 Bridge types used in this study.
The Plate bridge represents an extreme case of maximum stiffness.

Table 11.2 Rocking resonances for different bridge styles (on machine vice)

Bridge	Mass	Frequency		df/dm	Effective mass	Effective stiffness	Impedance	f(calc.)
		f(0)	f(expl)					
	(g)	(Hz)		(MHz/kg)	(g)	(MN/m)	(kg/s)	(Hz)
Renaissance	1.97	2730	3000	0.45	3.0	0.89	52	2741
Stradivari	1.51	3037	2950	1.27	1.2	0.44	23	3048
Paris	1.21	2466	2400	0.40	3.1	0.74	48	2459
Modern	2.19	2227	2788	0.43	2.6	0.51	36	2229
Plate	3.40	8600	8444	1.73	2.5	7.3	1351	8600

The differences in mass were largely due to the thickness of the bridges at the feet, with the Renaissance at 4.1 mm, the Stradivari at 3.5 mm and the Paris at 3.2 mm compared with the modern bridge at 5.1 mm. The arch between the feet of the modern bridge was raised from the ‘as received’ straight condition, as is customary practice, to be nearer the shape of the top in this region for mainly aesthetic reasons although some increase in flexibility at ‘c’, figure 11.2, might occur. In spite of their different designs, the effective mass and stiffness are remarkably similar, except for the plate bridge. Included in this table are the parameters for the plate bridge which represents the limit at one end of bridge style. The effective mass was low but the effective stiffness was high.

The variation in Renaissance and Baroque bridges is shown in Table 11.3 for three lighter bridges that were not used elsewhere in this study. The values for effective mass and stiffness must be regarded as tentative. The choice of f(expl) from the peaks presented was guided by the expected range in which the frequency would fall. While the regression coefficients for the plot of df/dm were high (0.98 and higher) there remained a doubt about the experimental choice of a 13.2 g impact bar. A redetermination of these results using a different technique is required.

Table 11.3 Rocking resonances for three different bridges (on machine vice).

Bridge	Mass (g)	Frequency f(0) (Hz)	f(expl) (Hz)	df/dm (MHz/kg)	Effective mass (g)	Effective stiffness (MN/m)	Impedance (kg/s)	f (calc.) (Hz)
Renaissance	1.45	2688	2500	0.40	3.4	0.96	57	2674
Stradivari	1.055	2891	3100	0.60	2.4	0.80	44	2906
Paris	1.365	2081	2060	0.48	2.2	0.37	28	2064
Paris	1.05	2345	3000	0.35	3.4	0.73	50	2332

These lighter bridges had similar values for the first resonance frequency but effective mass and stiffness differed from those shown in table 11.2. The Paris bridge, 1.05 g, was cut with more mass above the "heart" than the bridge above it, 1.365 g. While the bridge in question was 1 mm lower in height, it had more mass above the "heart", 12 mm compared with 10 mm for the heavier bridge. Both bridges had the same thickness, tapering from 3 mm at the feet to 1.5 mm at the top.

11.6 The Result of Variation in the Waist

The waist is regarded as an important feature determining the stiffness and hence the rocking frequency of the bridge. A number of modern bridges were taken from commercial batches and, where necessary, given different waist measurements and the rocking frequencies plotted against the cross section at the waist. The results are shown in Tables 11.4 and 11.5 and Figure 11.5.

The waist is narrowed by lengthening the eyes horizontally (see figure 11.2). There is a positive correlation between area of cross section and resonance frequency. This could be used for a rough prediction of the resonance frequency from the bridge measurements. For the bridges mounted in the machine vice, determination of effective mass and stiffness showed a similar trend. The results are shown in Table 11.5.

Table 11.4 Effect of Variation in the dimensions of the Waist on Bridge Resonance I frequency: bridges mounted in a machine vice. Different modern bridges were used. The last two columns are plotted in figure 11.5.

Bridge	Mass (g)	Waist (mm)	x	Thickness (mm)	=	Area (mm^2)	Frequency (expl) (Hz)
1	3.12	23.7		5.1		121	3910
2	2.395	22.7		4.0		94	3517
3	2.10	18.5		4.0		74	3133
4	2.31	18.0		4.0		72	3000
5	1.84	17.6		3.3		58	2444
6	2.19	17.3		3.5		61	2426
7	2.75	16.5		4.6		76	2842
8	2.59	15.7		4.0		63	2490
9	2.02	19.0		3.3		63	2540
10	1.93	19.0		4.0		76	3090

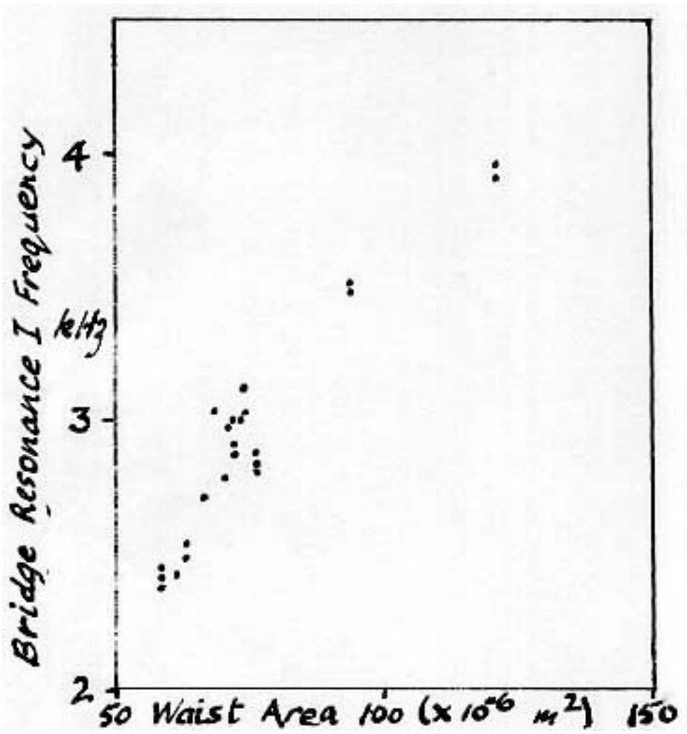

Figure 11.5 Plot of bridge resonance I frequency (machine vice mounted) versus stiffness (waist cross sectional area) from table 11.4.

Table 11.5 Effective mass and stiffness as a function of waist area for a number of modern bridges (from table 11.4) mounted in a machine vice.

Waist Area (mm^2)	Mass (g)	Frequency f(0) (Hz)	f(expl) (Hz)	df/dm (MHz/kg)	Effective Mass (g)	Effective Stiffness (MN/m)	Impedance (kg/s)	f(calc.) (Hz)
121	3.12	3560	3870	0.66	2.7	1.35	60	3559
94	2.395	3248	3560	0.63	2.6	1.07	53	3229
72	2.31	2826	3020	0.50	2.8	0.89	50	2838
76	1.93	2901	2700	0.58	2.5	0.83	46	2900
63	2.02	2809	3160	0.54	2.6	0.81	46	2809
61	2.19	2227	2460	0.43	2.6	0.51	36	2229
58	1.84	2341	2600	0.47	2.5	0.54	37	2339
57	2.18	2169	2450	0.42	2.6	0.48	35	2163
65	1.70	2260	3170	0.32	3.5	0.71	49	2267

11.7 The Effect of thinning the other Ligaments.

It is not unreasonable to expect the other ligaments to have an effect on the stiffness and hence the rocking frequency. These lie between the eye and the heart and between the eye and the arch as can be seen in figure 11.2. The ligament between the heart and the eye was first thinned by enlarging the eye position at ‘a’ followed by that between the eye and the feet at ‘c’. The progressive change in frequency and effective stiffness are shown in Table 11.6 for the different steps in this process. The effective mass was assumed to remain largely unaffected since this rocking resonance involves motion of the top half of the bridge. The bridge had been thinned from 4.0 mm to 3.7 mm at the waist prior to step 1 on the tapered side thus confining this reduction in thickness to the lower half.

Table 11.6 Variation in frequency with stiffness for a modern bridge of thickness below the waist of 3.7 mm. Bridge mounted in a machine vice.

Step	Bridge mass (g)	Waist (mm)	Ligament a	Ligament c	Frequency f(expl) (Hz)	Effective mass (g)	Effective stiffness (MN/m)	f(calc) (Hz)
1	2.37	16.5	6.0	6.5	2740	2.4	0.71	2737
2	2.29			5.0	2570		0.63	2579
3	2.22			4.4	2530		0.61	2537
4	2.18		5.0	4.4	2250	2.0	0.40	2251

These results suggest that the stiffness of all the ligaments including the waist is involved in the natural vibration modes of the modern bridge.

11.8 The Effect of Reducing the Mass

Reducing the mass can be done in two ways; removing wood from the surface facing the fingerboard which slopes back from the foot thickness, ~4.2 mm, to the top edge, ~1.5 mm, or, removing wood from the top half only of the same surface, above the heart, thus not affecting the stiffness but only the vibrating mass.

Two bridges were thinned in each of the above manners; the first altering the distribution of mass over the bridge height while the second is expected to affect, primarily, the mass above the waist. The results are set out in table 11.7.

Table 11.7 The effect of thinning a modern bridge (mounted in a machine vice).

Condition	Mass (g)	Thicknesses Feet (mm)	Thicknesses Ligament waist x thickness	Frequency f(expl) (Hz)	Effective mass (g)	Effective stiffness (MN/m)	f(calc) (Hz)
As received	2.19	4.2	17.3 x 3.5	2450	2.1	0.49	2431
Tapered	2.15	4.1	17.3 x 3.3	2800	1.3	0.39	2757
As received	1.93	4.3	19.0 x 3.5	2700	2.6	0.75	2703
Top Thinned	1.70	4.3	19.0 x 3.5	3000	1.1	0.38	2958

As can be seen from the table both methods are effective in reducing both the effective mass and stiffness. In the first case the resonance frequency was raised by 350 Hz and in the second by 300 Hz. The change in effective mass and stiffness reflect the change in bridge mass.

11.9 The Higher Resonance

An attempt was made to determine the higher resonance by turning the vice holding the bridge, on its side as explained above and repositioning the magnet to measure the bounce frequency as shown in figure 11.6.

Figure 11.6 experimental setup to determine bridge resonances on a rigid base

The frequency was found by extrapolating back from the mass dependency of the frequency, df/dm, which was 0.63 MHz/kg, to give a value of 5941 Hz. The effective mass was 4.6 g and the effective stiffness was 6.0 MN/m for the second modern bridge height of 38 mm and 2.19 g in table 11.2.

Figure 11.7 Violin setup for bridge rocking mode determination.

The bridge rocking mode was determined on the violin as shown in figure 11.7. The top plate was damped with foam under the fingerboard and tailpiece (not shown in this figure). Deciding which peaks in the response was very difficult and reduces the reliability of the results. After the peak with no added mass, the other peaks were chosen that gave a regression coefficient greater than 0.97. As shown in the appendix these results are questionable. The tap response shown in figure 11.15 shows the effect of damping the top plate.

Table 11.8 shows one bridge that, after the thinning of its ligaments between heart and eye, had a final rocking mode frequency of 2250 Hz. Thinning of its ligaments reduced its mass from 2.19 g to 2.075 g. For this bridge, the higher frequency resonance (the bounce resonance) was at 4929 Hz. The frequency dependence on added mass was 0.31 MHz/kg which gives an effective mass of 5.6 g and an effective stiffness of 2.7 MN/m.

Reducing this ligament between heart and eye has lowered these resonance frequencies. The further lowering of bridge resonances on the violin is related to the body stiffness at the bridge feet. In fact, if the stiffnesses of the body at the bridge feet are not equal, the bounce mode will in effect be a rocking mode with an axis of rotation beyond the feet of the bridge. The location of the pivot point for both the rocking and bounce motion of the bridge will be affected by the respective stiffnesses of the body at the bridge feet and are expected to be different.

Table 11.8 Rocking and Bounce Resonance frequencies of a modern bridge mounted in a machine vice and violin showing the effect of reducing the ligaments.

Mounting	Bridge mass (g)	Waist (mm)	Ligament "a" (mm)	Resonance frequency f(0) (Hz) Rocking Mode	Bounce Mode
Machine	2.19	17.3 x 3.5	5.5	2128	5941
vice	2.075	16.0 x 3.5	4.0	2250	4929
Violin	2.19			946	2426
	2.075			950	3030

For tests done away from the violin with the bridge glued to a heavy base, Jansson et. al.[10] has shown the effect of changing the stiffness and top half mass on the first resonance of the bridge. He does not identify the loss of mass at the waist as causing a change in stiffness. He shows an 11 % increase in mass loading at the top resulted in a drop in frequency of about 15 %. When 3 % of wood was taken from the bridge top, there was a 5 % increase in frequency. On the other hand he found a 1 % reduction in mass at the waist caused a 10 % fall in frequency. The waist was reduced from 23 mm to 16.5 mm. For the bridge of 2.35 g this was a loss of 0.024 g. Loss of mass in this region is not expected to be as significant as the change in stiffness.

In the present study, for a comparable change in the waist using two different but similar bridges, 2 and 7 in table 11.4, there was a 20 % difference in frequency, from 3500 Hz to 2800 Hz. The change in stiffness, whether due to taking wood from the arch, the waist or the other ligaments had a greater effect in lowering the resonance frequency than removing mass (in all a total of 6 % in the upper half) in raising it. This loss in mass caused no measureable alteration in the effective mass, 2.5 g, or effective stiffness, 0.5 MN/m. As the stiffness was lowered, by reducing the waist, the resonance frequency decreased. Plotting against the cross sectional area of the waist, the frequency dependence was approximately linear, figure 11.5. Reducing the other ligaments, for one bridge, also gave a linear dependence.

11.10 Phase Studies at the Bridge Feet

To further explore the behaviour of these two resonances, plastic piezo elements [11] were fitted under the bridge feet. These elements were calibrated to give 0.25 mV/N. The setup is shown in figure 11.8. The bridge was excited with an 8 ohm coil glued to the treble edge of the bridge and driven by an amplifier from a signal generator. The signal generator was set at a low output for all these measurements. Of interest was the phase relationship between the forces on the two feet. The plots in figure 11.8a were a stereo record that gave perfect alignment

At the rocking frequency of 2240 Hz, the force element at the bass foot leads that at the treble foot by 90 degrees. The amplitude of the force recorded at the treble foot was 5x that at the bass foot. At 3030 Hz the two feet were moving in phase with an equal value of the force measured at each foot. This is illustrated in figure 11.8a. The setup for measuring the bounce frequency is shown in figure 11.9 together with the tap response. These dynamic forces lie in the same direction as the static forces but they are of different magnitude. As discussed below, the static force at the bass foot is about two thirds that at the treble foot. The violin is more compliant at the bass foot. These phase measurements confirm the two motions of the bridge top reported by Reinicke [2].

Figure 11.8 Setup with force transducers under the bridge feet. The bridge was driven by a coil attached to the treble edge.

The phase relationship for the bounce mode at 3 kHz implies that the bridge could become decoupled depending on the phase of the top at this frequency and in the area of the bridge. If there is a nodal line between the feet one foot would move out of phase. This may alter the behaviour of the violin at this frequency.

While the force elements were in place, the phase relationship at the bridge feet for other resonances was studied. For the main air resonance at 280 Hz (A0) the two feet were 180 degrees out of phase with the force at the bass foot 1.5 times that at the treble foot as shown in figure 11.10 The waveform was not checked at the driving coil.

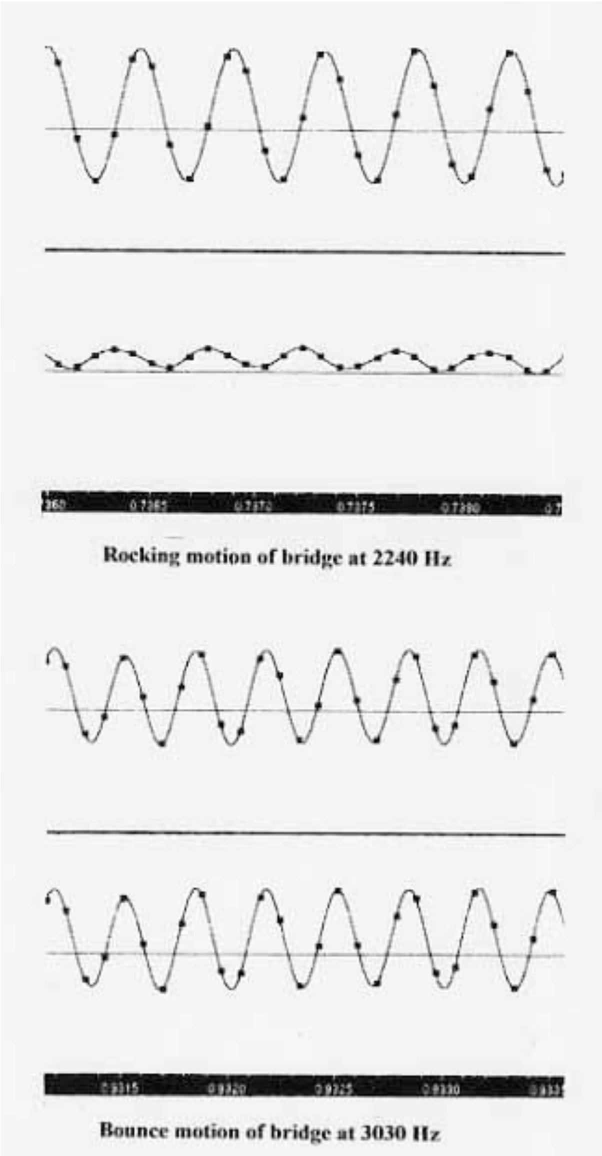

Figure 11.8a Response for the two lower bridge resonances measured at the bridge feet. The upper curve at the base foot; the lower curve at the treble foot. The upper pair show the rocking motion and the lower pair show the bounce motion.

There remains one aspect of the function of the bridge that has not been dealt with. This is the centre about which the bridge rotates during resonances that involve the rocking motion of the bridge. The pivot point must lie at the treble foot or between the two feet of the bridge. The soundpost has to lie on the treble side of this pivot point to be in phase with the back which implies that the treble foot and the top are also in phase with the back. The soundpost may lie outside the treble foot. It is possible to estimate the pivot point for the lowest resonance, A0, assuming it only involves the bridge rocking.

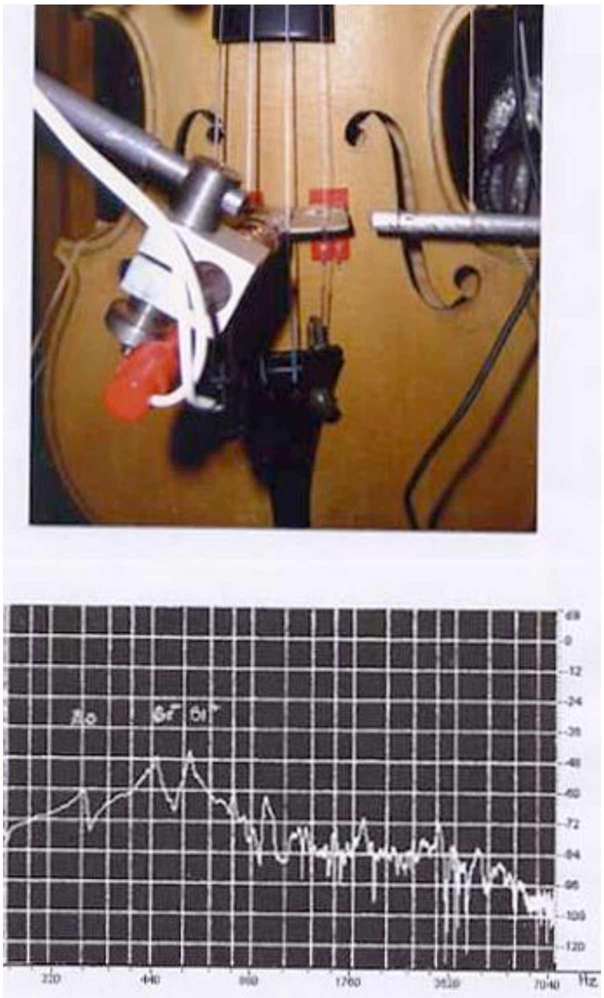

Figure 11.9 Measurement of bounce frequency at ~3000 Hz
Top: Violin setup for measurement
Bottom: Tap response with magnet/coil at bridge top

Figure 11.10 shows the force recorded at the bridge feet at the A0 frequency of 280 Hz as the treble edge of the bridge is excited by a signal as shown in figure 11.8. The waveforms have been lined up in figure 11.10 to show the phase relationship. It shows that the two feet are in anti-phase i.e. as one foot lifts the other is pushed down and that the fundamental dominates the harmonic series. The fundamental dominates the waveform and in the following the distortion apparent in the waveform has been ignored.

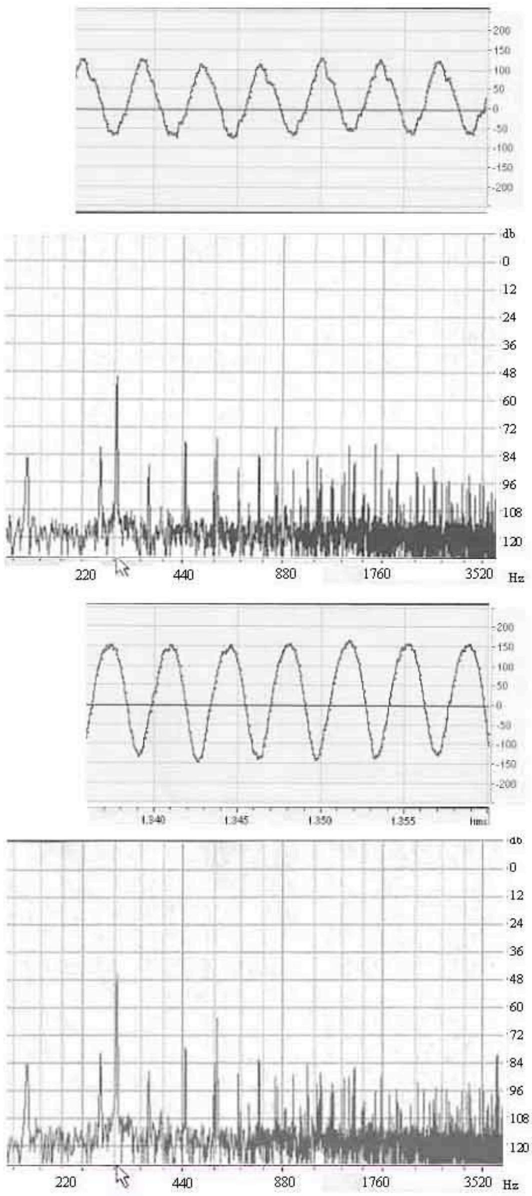

Figure 11.10 Force response at bridge feet (figure 11.7) at 280 Hz
Top pair: Treble foot wave form and harmonic content
Bottom pair: Bass foot wave form and harmonic content

By calibrating the force axis to estimate the value of the force acting at each bridge foot it should be possible to calculate the extent of the movement of each foot knowing the stiffness of the top plate at these positions. Ideally, one should extract the amplitude of the waveform for the fundamental in each case for this calculation. This has been assumed in this case as a first approximation.

Measuring the voltage at the bass foot force transducer gave a value of 0.25mV/ 100 scale units. From the calibration of the force detector of 0.25 mV/N, the force at the bass foot in figure 11.10 was 1.4 N and at the treble foot 1.05 N. From these results, the displacement (force/stiffness) at the two feet becomes 0.029 mm at the bass foot and

0.015 mm at the treble foot. This uses the stiffness of the violin body for the Romantic violin with no bridge, given in table 5.4 of chapter 5 which were 49 kN/m at the bass foot and 68 kN/m at the treble foot.

The pivot point calculated from the results in this case puts it at about 10 mm from the treble foot and hence 20 mm from the bass foot for a spacing of 30 mm between the feet. Therefore the pivot point for A0 in this violin lies between the bridge feet and nearer to the treble foot. The pivot point is certain to vary for different resonances. We may in reality have a multitude of pivot points. Two variables at least, the stiffness of the top locally and the position of the soundpost, will play a deciding role on the position of the pivot point. Its location, for example, for A0 may be linked with output balance across the violin range.

11.11 Out of Plane Resonance

In addition to the in-plane resonances of the previous sections, there is an out of plane resonance of the bridge that may be important in its effect on feedback to the string. Minnaert and Vlam [8] concluded that the side cutouts in the bridge prevented any out of plane rocking motion of the bridge reaching the top plate so any effect of this resonance was confined to the string. The amplitude of this out of plane vibration would be influenced by the stiffness of the after lengths of the strings behind the bridge. A short afterlength will increase the stiffness thus reducing the extent of the out of plane movement and vice versa. High tension strings would also reduce the extent of the movement.

To determine the frequency of this resonance and the associated parameters, tests were done by mounting several bridges, in turn, in the machine vice and exciting the out of plane resonance with the impact pendulum. The response was detected with the magnet and coil device and the parameters calculated using the Schelleng equations above. The setup is shown in figure 11.13 and the results are shown in Table 11.9.

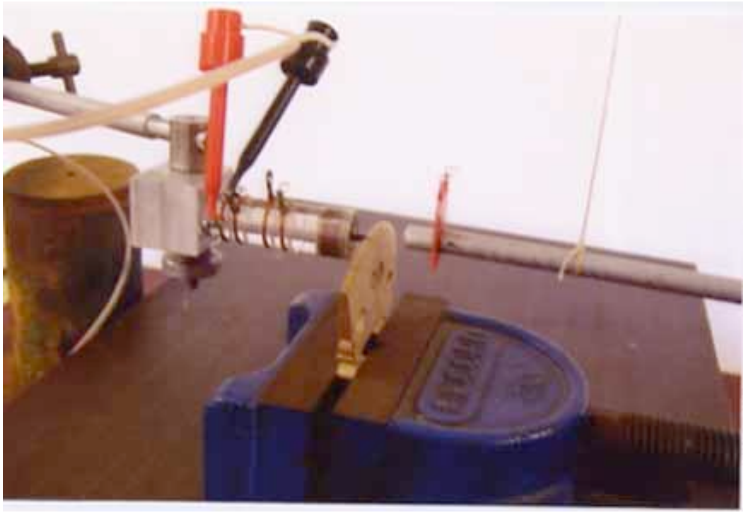

Figure 11.13 Setup for out of plane resonance measurements

Table 11.9 out-of-plane Resonance of the Modern Bridge, on a machine vice.

Bridge mass (g)	Frequency f(0) (Hz)	f(expl) (Hz)	df/dm (MHz/kg)	Effective mass (g)	Effective stiffness (MN/m	Impedance (kg/s)	f(calc.) (Hz)
3.12	3353	3500	0.61	2.7	1.22	57	3383
2.395	2837	2800	0.48	2.9	0.93	52	2850
2.31	2303	2050	0.36	3.2	0.66	46	2286
2.17	2228	2200	0.37	3.0	0.59	42	2232
2.15	2257	2270	0.41	2.8	0.55	39	2231
1.84	2123	2130	0.38	2.8	0.50	37	2127

These values compare favourably with those in earlier tables. The impedances seem to correlate approximately with the bridge masses. At a frequency of about 2000 Hz, this resonance coincides with the fourth harmonic of C5 on the A string. The loading of the strings on the bridge would lower the operating frequency by acting in the same way as a mute. The bridges listed in table 11.2 gave the out of plane results shown in table 11.10.

Table11.10 out of plane resonances for Baroque bridges, on a machine vice.

Bridge	mass (g)	Frequency f(0) (Hz)	f(expl) (Hz)	df/dm (MHz/kg)	Effective mass (g)	Effective stiffness (MN/m)	Impedance (kg/s)	f(calc.) (Hz)
Renaissance	1.97	1816	1840	0.21	4.3	0.56	49	1816
Stradivari	1.51	2088	2180	0.23	4.5	0.78	59	2095
Paris	1.21	2372	2380	0.38	3.1	0.69	46	2375
Modern	2.16	2301	2300	0.40	2.9	0.60	42	2289

11.12 Discussion

Bridge resonances, especially the first, have become an area of considerable interest. The reason for this interest is that the frequency of the first resonance falls in the range that is close to the sensitivity peak of the human ear. Singers are known to develop a formant in this region that allows them to stand out above an orchestral accompaniment. It is thought that a formant in this frequency range in a violin would have a similar benefit. So far a definitive demonstration of such a benefit in association with an orchestra has not been forthcoming although some top class violins have been shown to possess this formant [12].

Jansson [3, 4, 10, 12] and his co-workers have been the principal contributors on the subject of the Bridge-Hill, a feature of the response of a violin at about 2.5 kHz which he has attributed to the first resonance of the bridge, since they coincide at this frequency. The Bridge-Hill appears in the input admittance curve which is measured at the bridge top but is often less evident in the response curve recorded with a microphone. An aspect not studied here is the reversal in phase at the frequency of the bridge hill as demonstrated by Jansson [12].

Two papers have attempted to explain the existence of the Bridge-Body Hill. Woodhouse [6] has developed an explanation combining the behaviour of the body of are of interest. His figures 13,14 and 15 together with equation 19 can be used to assist in tuning a violin bridge to establish this feature in the characteristic of the instrument and of a nature to suit the future use of the violin. His equation 19:

$$2 \text{ x (bridge damping coeff.)} = R_\infty \, a \, (Km)^{1/2}$$

Where R_∞ is the rotational admittance for flat plates of infinite extent (R being that of the violin with flat plates) of the lower part of the bridge assumed to have zero mass and simply connects the rotating top of the bridge to the body. For practical use, in the range of interest, a value of 100 $rad^{-1}N^{-1}m^{-1}$ (from his figure 11) can be taken,

K is the stiffness at the bridge waist; bridge feet clamped,

m is the effective mass of the bridge rocking frequency; bridge feet clamped,

a is the distance from the waist to the bridge top, and

Ω_b is the clamped bridge rocking frequency.

This last symbol appears in another form of the equation above, namely:

$$Q^{-1} = R_{\infty} K/\Omega_b \qquad \text{where } Q^{-1} = 1/2(\text{bridge damping coeff.})$$

Q would be that for the Bridge Body Hill.
One could have a range of bridges to fit a new violin to determine the effect on the violin characteristic.

Beldie [7] describes an analysis that includes the stiffness of the violin body. This was based on bridge characteristics quoted by Jansson and Niewczyk [4]. An attempt to perform this analysis here was unsatisfactory due to the difficulty of measuring the bridge characteristics on the violin.

Concerning the effect of the bridge in general, its contribution to the impedance of the top presented to the string is about 50 kg/s at the first bridge resonance at about 2500 Hz. With the string impedance at about 0.2 kg/s, unstable action is unlikely. For the average body resonance the impedance is about 200 kg/s so again the instability that is associated with wolf notes is unlikely for these values in the violin.

11.13 Conclusion

The Baroque bridges have a typical A-frame form while the modern bridge has an X frameform. The mass above the waist in these bridges is therefore different. The importance of this lies in the possible difference in effective mass and stiffness which would influence the bridge resonances. The lever action would be similar for all the bridges transmitting the transverse motion from the string to the top plate (table 11.1).

The first resonance of the modern bridge can be varied over a wide range by changing the width of the waist and other ligaments thereby reducing the stiffness. Any effect of these changes would only be observed above about 1kHz and it would seem that the magnitude of the effect would depend on the stiffness of the top plate in the region of the bridge.

11.14 References

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[9] McLennan, J.E. "Second Harmonic Generation in the Violin" see website www.phys.unsw.edu.au/music/people/mclennan.html
[10] Jansson, E.V., Fryden, L., and Mattsson, G. "On Tuning of the Violin Bridge" CASJ 1(6), 1990, p11-15.
[11] Plastic piezo elements made by American Moulded Products, Type LDTO 028K, (0.25 mm thick and used in the security industry).
[12] Jansson, E.V. "The BH-Hill and Tonal Quality of the Violin" SMAC 03, 2003, p71-74.

11.15 Appendix Example of raw data used for table 11.8

Table 11.11 Tap response of modern bridge, mass 2.19 g

Mode	f(0) (Hz)	df/dm (MHz/kg)	m (kg)	s (MN/m)	Z (kg/s)
A: mounted on a machine vice					
Rocking	2128	0.42	2.5	0.45	34
B: mounted on violin No 2					
Rocking	946	0.032	14.7	0.51	87

The effective mass for the bridge mounted on the violin appears high and cannot be explained at this time. This could be linked with the uncertainty connected with the location of the correct peaks in the response. The parameters for the Bounce mode were not obtained because of experimental difficulties.

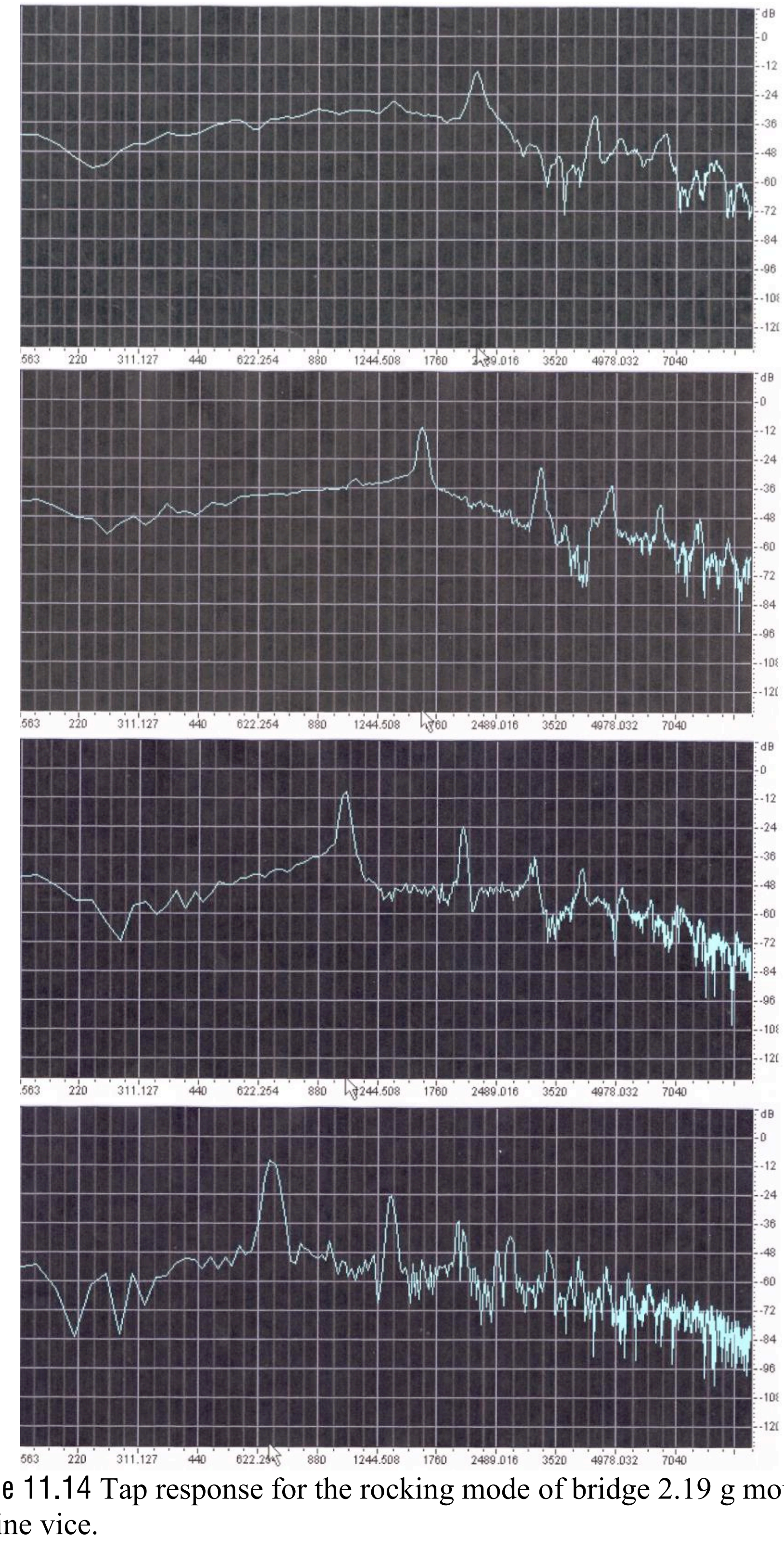

Figure 11.14 Tap response for the rocking mode of bridge 2.19 g mounted on a machine vice.

Added mass (g)	Peak frequency (Hz)
Magnet 0.15	2214
0.955	1611
2.19	1036
3.755	667

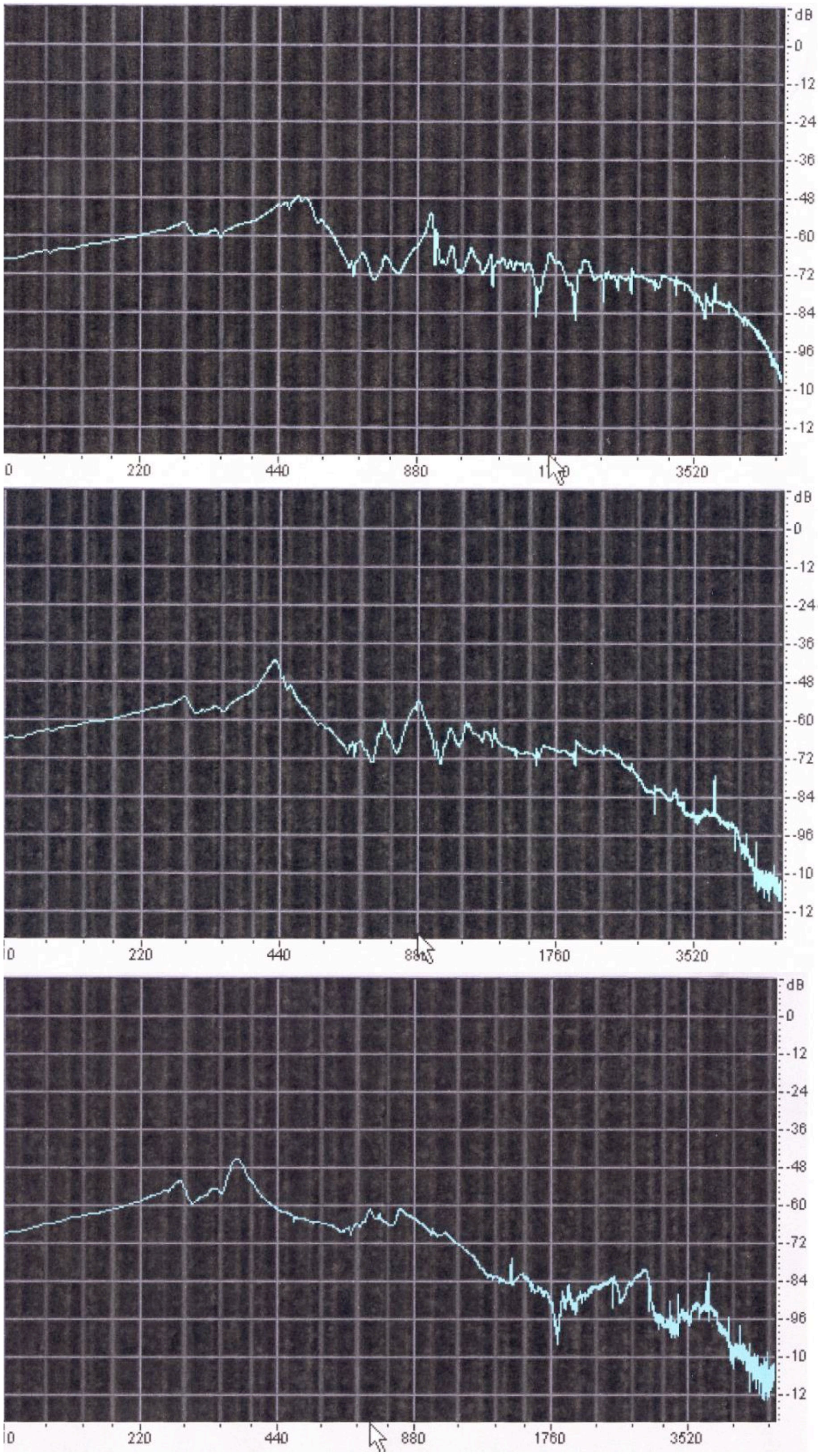

Figure 11.15 Tap response for the rocking mode of bridge 2.19 g mounted on violin No 2.

Added mass (g)	Peak frequency (Hz)
Magnet 0.15	940
2.19	880
3.755	824

Chapter 12

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

The conversion of a Baroque violin to a Romantic or Modern violin required some major changes. The most visible change was the replacement of the neck and fingerboard, bridge and tailpiece. The top plate was also strengthened by replacing the bassbar and using a stiffer soundpost.

12.1 Neck/fingerboard Change

The change to the modern neck/fingerboard while freeing the left hand from its supporting role, added about 50 g to the mass at the end of the body of the violin. The best estimates of the effect of this added mass in the present study, on resonance frequencies are:

Table 12.1 Comparison of main low frequency resonances f(0) (Hz) in the two versions.

Violin	Mass of neck & fingerboard (g)	A0	C2	B--	B1-	B1+	C4	?	?
Baroque	116	281	411	450	471	581	620		775
Q value		18	29	30	36	58	29		28
Romantic	165	286	386	420	447	528	540	586	878
Q value		14	77	47	45	5	5	5	37

The main air resonance is not affected, presumably because the air volume is unchanged and because the body compliance is little affected by the stiffer bassbar. However, the body resonances are lowered (ch.10 Table 4). One might expect the stiffer (but heavier) bassbar to raise some of the body resonances. However, this effect was offset by retuning the top plate which became necessary on fitting the bassbar (see chapter 10).

The chinrest that made the change to a longer slimmer neck popular only had a mass of about 20 g initially. The modern chinrest has a mass of about 45 g. A separate experiment conducted to illuminate this question, by adding mass to the neck (chapter 10 table 3) suggested that C2 might be lowered by 6 Hz, B1- by 6 Hz but B1+ not affected. The neck is attached to the body at an antinodal region for body modes B1- and B1+. This may be important depending on how this mass interacts with the bending of the body. For B1- the top is flexing across the plate while the back is bending along the plate. For B1+ the behaviour of the two plates is reversed. Adding a modern chinrest, mass 45 g, lowered C2 by 3 Hz and B1- by 6 Hz.

An innovation that might be considered is the use of a willow core veneered with ebony which would conserve an endangered species, to reduce the mass of the fingerboard .

12.2 Saunders Loudness Tests

The Saunders Loudness Plots showed a large variation in note strength. Comparing the average levels showed that going from light gut strings (Pirastro Chorda) to heavier gut strings raised the sound level by 9 dB for hand bowing (c.f. chapter 5 figures 1 and 3).

With conversion to the modern setup the sound levels remained the same with both the heavier gut strings and with modern nylon cored strings (Thomastik Dominant). There was an indication that with the bridge placed below the soundholes the E string output was on average about 5 dB higher than the three lower strings (ch.7 Table 2).

12.3 The Main Air Resonance

The main air resonance, A0, was consistently a strong radiator compared with other resonances. The radiation constant was typically 0.14 kg/s due to the low effective mass and lower Q values of ~15 where body modes had Q values of about 25 - 50. The peak heights were similar for A0 and B1- and B1+.

The radiation constant for A0 was not determined with the bridge placed below the soundholes. The radiation constant for B1- was raised by this change in bridge position but that for B1+ was not affected.

12.4 Body Compliance

The main air resonance is a Helmholtz resonance modified by a non-rigid container. It is activated by the sound from the string and by the breathing action of the body, both of which are weak effects at the frequency of the resonance. The result of the non-rigid body is to lower the frequency of the air resonance below that of the classical frequency of the Helmholtz resonance.
The A0 resonance is that of an air mass of 2.43 g, for the violin studied, opposed by the parallel combination of the compliance of 2 litres of air (7.5×10^{-3} m^3Pa^{-1}) and the body compliance, which is 2.7×10^{-3} m^3Pa^{-1} without soundpost and 4.8×10^{-4} m^3Pa^{-1} with the soundpost. The compliance of the air is about 10x that of the body. The body in effect is equivalent to adding 130 ml to the volume of air in the cavity.

12.5 The Soundhole Air Plug

An attempt was made to determine the effect of altering the effective thickness of the top at the soundholes. Increasing the 'thickness' by means of a 10 mm card glued to the long walls of the soundholes lowered the frequency of A0 by 60 Hz. While this measure is not feasible, it suggests that the top plate thickness at the f-holes is important and may provide a means of fine tuning A0.

12.6 Bridge Resonance

The behaviour of the 'Strad' and 'Paris' bridges were not studied extensively. The first two resonances of the modern bridge were investigated because of their importance in the region of 2-3 kHz in the response.

This study showed a direct dependence of the first bridge resonance on the stiffness of the waist of the bridge as represented by the area of cross section. For an area of 60 mm^2 the resonance frequency was 2.5 kHz with an approximately linear progression to 4 kHz for an area of 120 mm^2. The bridge thickness was about 3.5 mm at the waist.

That the bridge has resonance modes is now well known. It is not certain whether the lift in response in some violins in the range 2-3 kHz is a function solely of the first

bridge resonance alone or a combination of the bridge and the area of the top plate between the f-holes. The two lowest resonances of the modern bridge were determined on a solid base as well as on the violin. The lowest or 'rocking' mode was lowered from 3 kHz to 2.5 kHz when placed on the violin. The higher 'bounce' resonance of the bridge was lowered from about 6 kHz on a firm base to 3 kHz on the violin. This puts it in a position where it could influence the response of the 'bridge formant' which is thought to be responsible for the brilliance in the violin sound.
No further advance on this topic was made although the Beldie analysis suggested there was an effect in the violin used for this experiment as shown in chapter 10.

12.7 The Baroque to Modern Transition

All the characteristics discussed above belong to every violin. What is of interest are the subtle differences in the sound of the two versions caused by the necessary structural changes made. These changes were a consequence of the demands of the evolving nature of musical composition and the greater challenges to the player.

The introduction of the Tourte bow in about 1780 with its hatchet head and reverse camber so that the same bow force could be applied for the full length of the hair, and the arrival of the chinrest in 1820 by Ludwig Spohr, accelerated the structural changes. This meant the bowing style changed from mostly single note bow strokes to more continuous legato bowing. With a wider hair ribbon, 10 mm as against 6 mm, a greater number of higher harmonics were possible so that the sound was richer and not so 'flute-like'. An ability to apply a greater bow force would contribute to this modern style.

An example of the sound of the Baroque violin with and without a bassbar can be heard on the webpage. The top plate will be stiffened by the addition of the bassbar. A 'Paris' style bridge was also being used. Light gut strings were used for these sound tracks. The effect of a range of bridge types, of which the three mentioned in this thesis represent a useful selection, on the behaviour of the Baroque violin would make for an interesting study.

Changing to heavier gut strings made it desirable to use a higher (Renaissance-style) bridge that necessitated resetting the neck. A higher string tension resulted. Sound samples can be accessed playing both baroque and romantic pieces using baroque and modern bows.

Placing the bridge below the soundholes was a common practice perhaps making sounding the strings easier, even though their increased length requiring a higher tension for the same pitch, would have required more bow force. The bowing had to be further away from the bridge so the sound would be expected to have fewer high harmonics. The sound samples should show any difference. Any compensation by the player may mask the effect.

The conversion to the Romantic or Modern version was done by replacing the neck and fitting a heavier ebony fingerboard and ebony tailpiece. The bridge was a new design and because the string length increased (the new slimmer neck was 10 mm longer) and the pitch was raised to A440, the tension increased. This meant the bassbar and soundpost were made stiffer to support the extra load. The effect of these changes should be reflected in the music played which can be heard on the sound samples. Gut strings were still in use when these changes were made. This condition was preserved for the sound samples included here.

The sound samples have been concluded with the strings finally changed to modern nylon cored strings with the Romantic version. The ‘playability’ was much improved and the violin was thought to have more power. It is of interest to see if the sound samples support this player expectation.

The LTAS have shown some differences. No clear advantage was shown on the Baroque version for either the early or modern bow. With the bridge below the soundholes the early bow gave a small increase in sound level, 2 dB, where the modern bow was variable. Comparing the two versions, with either bow the Baroque version gave a higher sound level, the early bow with the Baroque version having a distinctly higher sound level, about 5 dB. The Romantic version with gut strings gave a similar sound level with either bow. However with modern strings the modern bow showed a consistently higher sound level of about 3 dB.

12.8 A Comparison of Resonance Characteristics for the two versions.

A comparison of the main parameters, all of which appear elsewhere in the thesis can be summarised as in table 12.2.

Table 12.2 Comparison of the main Tap Response parameters for the Baroque and Romantic versions of the same violin

Resonance	Baroque violin								Romantic violin							
	f(0)	df/dm	m	s	Z	Q	R	f(calc)	f(0)	df/dm	m	s	Z	Q	R	f(calc)
	(Hz)	(Hz/kg)	(kg)	(MN/m)	(kg/s)		(kg/s)		(Hz)	(Hz/kg)	(kg)	(MN/m)	(kg/s)		(kg/s)	
A0	286	~4 x 10^6	0.054	436 N/m	0.15	13	0.01	--	286	~4 x 10^6	0.054	436 N/m	0.15	14	0.01	--
C2	411	1170	0.18	1.17	454	27	16	410	386	2943	0.066	0.39	160	77	2	387
B1-	471	1940	0.12	1.06	357	31	12	473	447	514	0.44	3.43	1229	45	35	446
B1+	582	6830	0.043	0.57	157	36	4	579	528	3543	0.074	0.82	696	38	5	530
C4?	618	3290	0.14	2.04	525	40	13	619	586	2771	0.11	1.43	284	84	5	585
?	770	5080	0.036	1.77	369	31	12	768	878	1229	0.36	10.9	1978	37	54	875

For these parameters the bridge was positioned between the soundholes at the notches. The tap response was recorded by microphone 100 mm in front of the violin suspended on rubber bands.

Comparing the parameters of the two violins as displayed in this table shows the value of R to be higher in the modern setup for B1- while it is lower for A0 and C2. These resonances lie in the region of the fundamentals which should be prominent in good violin sound. The Chladni patterns do not show this distinction for A0. For B1-, the nodal lines in the top are closer together for B1- in figure 4.14 in chapter 4 than they are for B1- in figure 8.9 of chapter 8. The monopole component would therefore be less. For B1+ the nodal lines on the top of the Baroque violin are wider in figure 8.9 than they are in figure 4.14 suggesting a larger monopole component. However R is more favourable for B1- in the Baroque version but about equal for B1+ in both. B1+ is the better radiator in both versions. A Chladni pattern was unable to be obtained for C2 on the Baroque violin and a comment on the difference for R is not possible. The resonance at 875 Hz which is near A5/A5# on the E string may have been important in these two versions of the violin. The Chladni pattern was similar for both instruments at this resonance.

12.9 Suggestions for Further Work

A contextual study of the effect of putting the bridge below the f-holes would seem to be of some merit. With light gut strings e.g. similar to Pirastro Chorda, and violinists practised in Baroque bowing as referred to above, a concert by an ensemble with the violins suitably fitted up might be a revealing experience. Those violins that had been restored to the Baroque state may have had the bassbar changed as well and should be suitable for such an experiment. The only change would be a new bridge, tailpiece and strings. The violins could be returned to their current setup without damage.

In conjunction with the experiment above, a response curve before and after the change in the position of the bridge, to locate resonances and determine the presence or otherwise of a Bridge Formant would be of interest. Other non-invasive tests might be of value. Playing tests might be contemplated.

Much of the work of this thesis involved the measurement of resonance parameters. The mode frequencies of the plates are high when the plates are thick which makes them stiff and heavy. Reducing the thickness lowers the mass and stiffness; mass directly as the thickness and stiffness as the cube of the thickness. The aim of makers and acoustic research is to raise the response and hence the output of the violin. Only one attempt, that of Schelleng [1] and makers of the 'Violin Octet' where a violin with larger plates and reduced sides (to maintain the A0 frequency) was made [2].

To increase radiation, and hence output, requires that the impedance of resonances be low and the Q value high, though consideration of structural stability limits the lowest plate thicknesses possible. This means that the effective mass and stiffness are kept low. The form of the arching will influence the stiffness so a compromise between this and thickness is required. Free plate resonance frequencies are the criterion adopted. The Q value would have to be between 20 and 50 [1] for body resonances which would have to have only moderately high peaks and avoid very high Q values as well as the risk of wolf notes.

The critical measurement is the quantity df/dm which for the main air resonance seems to be about -500 Hz/kg and for the main body resonances ideally about -2000 Hz/kg as found in this study. This measurement has to be made at an antinodal point. Small masses placed at such a point lower the resonance frequency. To follow this logic, taking mass from such a point by thinning the plate, would raise the frequency (unless there was an effect in lowering the stiffness at that point). The latter is well known; the difficulty is that the antinodal point for one mode of vibration may be a nodal region for another and have an effect on the stiffness of that mode. Changing df/dm e.g. raising the value for A0 and lowering those for the body modes does not appear to offer any advantage.

The region of the top plate at the bass foot of the bridge is the most accessible site for the determination of df/dm and being adjacent to a soundhole which is effectively a free edge constitutes an anti-nodal point for body modes. The bassbar would add both stiffness and mass at this point so there may be an opportunity to control its influence by its depth to affect stiffness and its width to affect the mass. A more innovative shape would be to introduce cutouts to preserve the stiffness and lower the added mass. The measurement of top plate stiffness by direct loading may provide a means of arriving at a cut off point when thicknessing to prevent over thinning.

There is still much to discover about the behaviour of the bridge. The desirable stiffness of the bridge in relation to the top plate stiffness in the region of the bridge feet so that the rocking frequency assists the 'bridge formant' seems an area worth studying. The rocking motion of the bridge in relation to the relative phase of the bridge feet and the top plate at the bridge feet might have some interesting insights into the behaviour of this central region. If the 'bounce resonance' of the bridge moves into the upper range of the violin, its influence might be significant. The area of the top plate between the upper finials of the soundholes should be studied as it may be involved with the rocking resonance of the bridge in setting up the "bridge formant".

A more complete study of the body resonances in the Baroque version of the violin should be undertaken to include the effect of the neck and fingerboard which was not covered in this work. There is much that could be done with the bridge below the soundholes.

There is still so much to learn about the violin structurally and acoustically as well as the art of playing it. There are so many imponderables the maker can only be guided by a few basic rules like the most desirable arching, the pitch and mass of the plates and the total mass of the instrument [3].

12.10 References

[1] Schelleng J.C. 'The Violin as a Circuit' JASA 35(3) 1963, 326-338.
[2] Hutchins C.M. and Schelleng J.C. 'A New Concert Violin' J. Audio Engineering Society, 15(4), 1967.
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