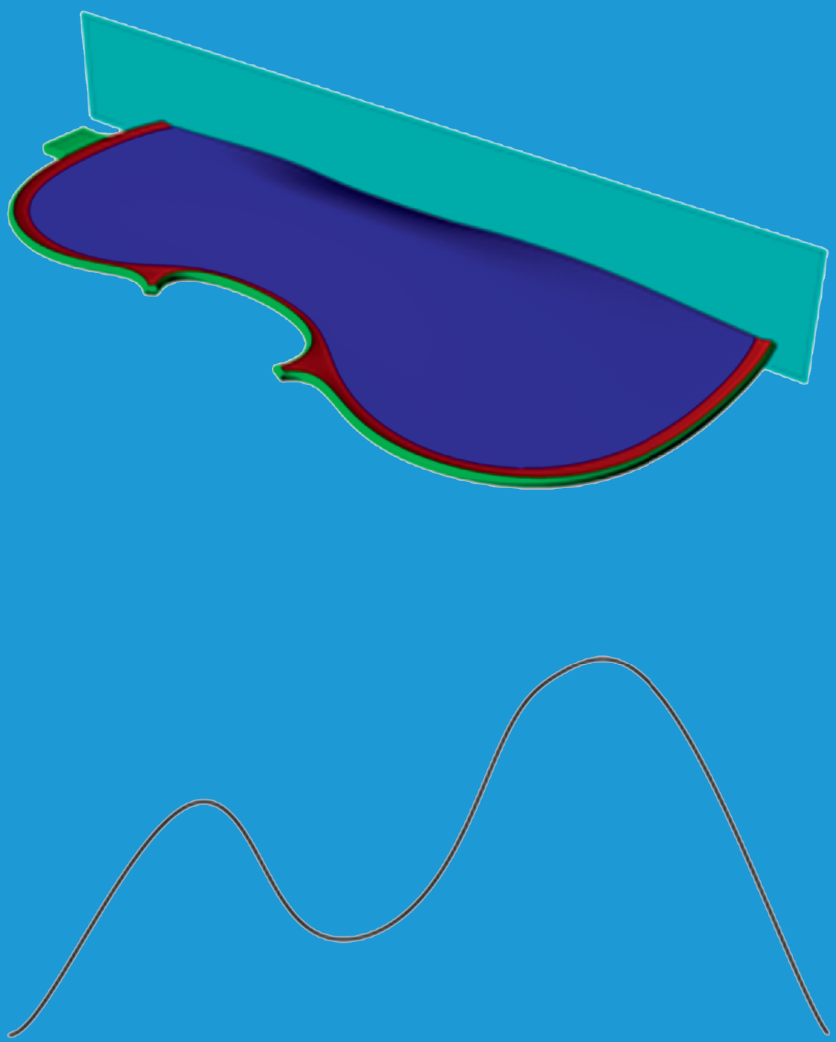
Journal of
The Violin Society of America

2018 • VOLUME XXVII, NO. 1

VSA Papers



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Information for Contributors

The VSA Papers is the authoritative forum for the publication of original peer-reviewed research furthering the advancement of the art and science of bowed stringed instruments. Contents include articles on auctions and appraisals, history of the violin and performers, playing technique and performance practice, making and restoration, tools, varnish, wood, graduation and acoustics. Current issues are published online, one or two times per year. Issues prior to Vol. XXVII are available at vsa.tarisio.com.

ARTICLE REQUIREMENTS

Articles must be the original work of the authors, written in correct English. They must not have been published elsewhere, except for translations into English of work not restricted by copyright. Authors are required to consent to the VSA's copyright agreement. Funding supporting the research should be acknowledged.

The article should add to the existing body of work on the subject in a meaningful way. Presentation of the main ideas in an article should be clear and accessible to the general VSA reader. Articles assuming significant background knowledge must include sufficient references to help an interested reader work through the paper. References should be listed in the manner prescribed by the Chicago Manual of Style.

Articles may be submitted in any widely-used electronic format, but authors should be aware at the outset that the printer requires that the final version be in Microsoft Word format. Graphics should be clear, informative, and of sufficiently high resolution for printing. They should be referenced from the text where appropriate.

REVIEW PROCESS

Peer review serves to establish the credibility, novelty, and originality of the submitted work. The review process is supervised by the administrative editor (paperseditor@vsaweb.org), and should typically take no more than ten weeks, including a minor update made by the authors.

The Violin Society of America

Founded in 1973, the Violin Society of America is a non-profit organization created for the purpose of promoting the art and science of making, repairing and preserving stringed musical instruments and their bows. Membership in the VSA is open to all who share an interest in the violin, viola, cello, bass and their bows, and thus reflects a broad and diverse range of interests and concerns, including craftsmanship, acoustics, innovation, the history of instruments and performers, technique, performance practice, repertory and other matters pertaining to instruments of the violin family.

To achieve these goals, the VSA has offered a number of important services to its members and the stringed instrument community in general. In even-numbered years the Society sponsors its world-renowned competition for new instruments and bows. A convention is held annually, offering lectures, exhibits, concerts, trips and other activities of interest to the members. The membership magazine, The Scroll, is published twice per year. The VSA, jointly with Oberlin College, sponsors workshops and holds an extensive collection of violin-related books.

The Journal of the Violin Society of America was established in 1976 under the editorship of Professor Albert Mell, Queens College. While most issues were research papers, some were devoted exclusively to the proceedings of the annual VSA meetings. As the meetings have grown in size, this distinction between Papers and Proceedings issues is no longer made. Presenters at the meetings are now asked to provide a written transcript of their presentation in order to be considered for publication. The merger between the VSA and the Catgut Acoustical Society stipulated that the VSA Papers serve as a replacement for the now-defunct Journal of the Catgut Acoustical Society, lending a greater focus to scholarly work on acoustics, historical research, instrument design, and materials.

Information about VSA membership, membership benefits, rates, and how to apply are available on the VSA website at www.vsaweb.org.

Advertising with the VSA: Contact the VSA office at 972-233-9107 x205 or send an inquiry via email to info@vsaweb.org.

Information for submissions to VSA Papers: Submissions are handled through vsapapers.org, which specifies submission requirements and explains the peer review process. Please contact publications@vsaweb.org with any questions.

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Contents

Editor's Perspective

This 2018 issue of the *VSA Papers* is the product of an exciting venture in which the VSA Directors' priority is to widely and openly disseminate academic knowledge. For the past year, articles published in the *VSA Papers* have appeared online for free. We trust that this foray into online journals has been a positive one. To those who have submitted or reviewed manuscripts to the *VSA Papers* and were willing to embark in this new endeavor with the VSA, I extend my thanks. To the membership which has been so patient during this process, please accept this special printed edition as a token of the VSA's gratitude.

Whereas previous issues of the *VSA Papers* grouped articles according to topic, the six articles included in this issue are presented chronologically, with online publication dates spanning from January to September 2018.

In his analysis of correspondence between violin virtuoso and composer Henri Vieuxtemps and the famous violin shop of Charles Francois Gand and his two sons during the period of 1838–1861, **Gael Francais** sheds light on the interdependent relationship between the musicians. Furthermore, Francais quotes conversations relating to sound issues, set up, and supplies in the letters, revealing musicians' struggles in the nineteenth century—particularly their search for high quality supplies for their instruments while touring. Francais concludes that such relationships and correspondence are not isolated to the nineteenth century, rather, the violin- and bowmaker remain integrally connected to the successful career of concert artists. Through an analysis of these bonds in past centuries, we gain a better understanding of its importance today.

In a written summary of a presentation made at the fall meeting of the VSA in 2015 in Baltimore, Maryland **Mike Carlson, Ross Hill, and Don Kennedy** share their perspectives on the advantages and disadvantages of both collapsible molds and different methods of collapsible mold construction. The authors agree that although traditional instrument building has typically relied on solid inside molds, this method presents some limitations in later stages of construction. Therefore, the authors argue collapsible molds simplify constructions and allow improved outline control. The authors provide images and diagrams to guide the reader's understanding of the collapsible molds, noting that the methodologies outlined in the article can be adapted to different preferences and needs.

In a return to historical topics, **Glenn Wood** presents his registry of baroque violin cases he has encountered during fifteen years of research. Although, as Wood argues, historical violin cases receive little attention from the violin enthusiast community, the historical knowledge they provide is invaluable. Wood begins his article with an historical backdrop of the baroque period and the evolution of violin cases then outlines the generalities that unify and divide baroque cases. The article concludes with stunning photographs of the case registry.

Robert Wilkins, Hongmei Sun, and Jie Pan present empirical research on torsional vibration—the cause of the open E-string whistle. The authors review previous attempts to measure torsional waves that relied on either attaching electromagnetic coils or a mirror to the string and note that these methods altered the string's response, thus distorting the measurement. The authors avoid this problem by using a laser vibrometer. Through a series of spectrographs, the authors present evidence that the bowed excitation of torsional vibration in the E-string is dependent on a number of factors including bow velocity, the influence of previous bowed A-string frequencies in the E-string, and the presence of sympathetically excited harmonics.

In the next article **David Golber** describes a construction method using computed tomography (CT) scan data of fine old violins to produce a 3D model of a violin arch, allowing the maker to construct a new, symmetrical instrument from the data of an old, asymmetrical instrument.

Golber argues that this method is advantageous because it is strongly based on the data from an instrument, completely defines the arch from edge to edge, involves minimal human choice, and allows controlled alteration of the arch. Throughout the article Golber provides diagrams, data, and tools to aid the reader in successfully implementing his method.

In the final paper of the issue **Jacques Pigneret** analyzes the impact of the tailpiece on the mechanical energy collected by the bridge of a viola. Pigneret argues that while previous studies used hammer tapping and magnets to analyzed tailpiece resonance by direct excitation, these studies do not account for excitation that comes from the horizontal bridge motion. Data collected from a monochord, a one-string viola with a tailpiece, and two-string violas in both symmetric and asymmetrical connections are presented in detailed graphs and diagrams throughout the article. In closing, Pigneret prompts the reader to consider the merits of the withdrawal of the tailpiece system as a way to diminish after-string length resonance problems.

Future Publication of the *VSA Papers* – The *VSA Papers* will remain the authoritative forum for the publication of original peer-reviewed research furthering the advancement of the art and science of bowed stringed instruments. Articles will continue to be published online to promote open-access and the wide dissemination of stringed instrument scholarship.

Over the past year or so, a great deal of effort has gone into the transition to online publication and review of articles. While not without difficulties, this was a worthwhile investment which will make publication easier and less expensive, allowing us to publish regularly. It also keeps a reliable record of the peer review process that I hope will serve editors of this publication long into the future. I could not have done it alone. I would like to thank the members of the VSA Publications committee for their efforts, and in particular Ted White for his mentorship, Evan Davis for his advice about procedures and submission requirements, and Elizabeth Kirkendoll for her help putting everything together for this issue.

Sean Hardesty, *Editor*

About the Authors

GAEL FRANCAIS is the last direct descendant of a long line of prominent luthiers and violin dealers that originated in the seventeenth century in Mirecourt, France. In 1880, Gael's greatgrandfather, Henri Francais, joined the renowned house of violin making and violin dealing of Gand & Bernardel Freres in Paris which was founded by Nicolas Lupot in 1796. In addition, the Francais family line has produced the famous houses of violinmakers and dealers of Caressa and Francais, established in Paris in 1901, and Jacques Francais in New York.

As the son of a French diplomat, Gael was born in Rio de Janeiro, Brazil and spent his youth living in many different countries in Europe, Africa, and Asia. At the age of 20, he decided to return to the roots of his family tradition and take up the craft of violin making. He began his training in the violin making school of Mittenwald, Germany, followed by an apprenticeship in the atelier of Apparut-Hilaire in Mirecourt, France. In 1974, Gael came to USA to join the violin shop of his uncle, Jacques Francais, in New York. Here he received his training in expertise by Jacques Francais and in repair and restoration by Rene Morel and Luiz Bellini.

In 1979, Gael opened his own violin shop in New York where he divides his time between repair and restoration, and dealing in rare antique and contemporary stringed instruments and bows.

In 1983, Gael became a full member of the American Federation of Violin and Bow Makers, Inc., an association of America's foremost professional violin makers and restorers. In 1986, he was accepted as full member of the International Society of Violin and Bow Makers (Entente Internationale des Maitres Luthiers et Archetiers d'Art), an organization of highest professional standards.

In 2012 Gael and his wife Angela decided to return to the place of her childhood, the Bavarian village of Piding, near the spa-town of Bad Reichenhall, located in close proximity (10 miles) to Salzburg and to relocate his shop there, under the name of "Gael Francais Geigen Atelier". This move enabled Gael to continue his craft and offer his professional service to all string players, within an environment which blends the energy of the Austrian city of music and Mozart's birthplace, Salzburg, with the natural beauty of the Alpine spa-town of Bad Reichenhall. He is looking forward to work with local musicians as well as visiting guest artists, and he is especially looking forward to welcome his musician friends from across the world during their visit to Salzburg or Munich.

M.R. (MIKE) CARLSON is a petroleum engineering consultant. He has over 35 years of experience in the petroleum industry, working for many different oil and gas operating and consulting companies. He has run his own independent consulting company since 1990 and specializes in computer modelling of oil and gas reservoirs. He has been building instruments since taking up the guitar about 10 years ago. He has made violins, a bass, gypsy jazz guitars and is currently working on a cello. He has dabbled in finite element modelling of the violin.

Luthier **ROSS HILL** has been working on string instruments for over 50 years. At the age of 10 Ross made his first violin under the tutelage of Ragnar Helin. Ross made 7 instruments under Helin's direction and won awards for each of these instruments. He has made in excess of 400 instruments: violins, violas, cellos, classical and steel string guitars. Ross has also made 8 Baroque instruments including violins, violas, cellos, two Baroque Bows and participated on a joint Viola da Gamba. Ross has a Bachelor's Degree in Education from the University of British Columbia and taught at the secondary level for thirty years. He runs a stringed instrument shop, Aeolian Strings, which provides instrument sales, restoration, as well as stringed instrument repair. Ross has been active in teaching lutherie.

DON KENNEDY is a graphic designer, photographer and technical writer. He works at a small graphics design company to a range of corporate clients. He has a B.A. from the University of Alberta in English, Philosophy and Computer Science. He has developed custom software to photograph instruments from a 360 degree perspective and is a photographer for the National Music Centre in Calgary, Alberta, Canada. Don has built a violin and is currently building a cello.

DR. GLENN P. WOOD is a long time researcher into vintage and antique violin cases. He has an extensive study collection of violin cases covering a span of 300 years which includes choice examples from the celebrated workshops of A. Stradivari and W.E. Hill & Sons. Representative of the major case producing areas such as England, France, Germany, Italy and USA are included and documented.

He is author of the book The Art & History of Violin Cases and has published many articles on the subject of violin cases. He recently published the definitive registry of all known violin cases from the baroque period, the result of 15 years research.

He is currently working on a second volume of historical violin cases concentrating on the Baroque, Georgian and Victorian periods with special chapters on the production of the Hill workshop in its golden age and cases owned by celebrity violinists such as Ysaye, Paganini, Tartini and Heifetz.

ROBERT WILKINS learned the violin from the age of ten. He has played in amateur orchestras for more than thirty-five years and together with his wife, a cellist, organizes a string orchestra. He made his first violin in 1985 after close association with the late Dr Carleen Hutchins and in the workshop of the late M. Peabody of Boston. Since then he has made 53 violins, violas and cellos. He has a diploma in electrical theory and practice, a BA (Experimental Research Psychology), LTh, Dip.ThS. (Theology), M.Ed, and Ph.D. (Cognitive Psychology). For more than twenty years Wilkins taught at Curtin University of Technology. His specialties include research and measurement, and the development of cognition. He has authored two textbooks and published forty journal articles on a diverse range of topics in education, cognitive psychology, philosophy and more recently, violin acoustics. He is a member of the Australian Rationalist Society. His interest in violin acoustics is pursued through the auspices of the UWA School of Mechanical Engineering, Center for Vibration, Dynamics and Acoustics where he is an honorary research associate and co-supervisor for students doing theses in violin related projects.

HONGMEI SUN is a research officer in the Centre for Acoustics, Dynamics and Vibration at the school of Mechanical and Engineering, University of Western Australia. Over the past 16 years, she has obtained substantial experience in the areas of acoustics and vibration. She is in the final stage of a Ph.D. and has been involved in many research projects in the area of room acoustics, industrial noise control and music acoustics. She has conducted experimental studies and supervised final year students on a wide variety of projects including some involving the violin and cello.

JIE PAN is a Winthrop professor in the School of Mechanical Engineering, University of Western Australia, where he is also the Director for the Centre for Acoustics, Dynamics and Vibration. Over the last 20 years, he has been working on many projects in the area of room acoustics, active noise control and structural acoustics. Music acoustics is a special interest. He has developed expertise in the acoustical mechanisms of bells, flutes and string instruments. Pan's teaching covers control and mechatronics, advanced control, vibration and signal processing, and acoustical engineering.

DAVID GOLBER has a Ph.D. in mathematics from the University of Chicago. He taught mathematics and then worked in computers. After retiring, he studied violin-making with Marilyn Wallin at the North Bennet Street School in Boston. He operates David Golber Violins in Boston, specializing in Hardanger fiddles.

JACQUES PIGNERET holds an electrical engineering degree, with honors from INSA, and a Ph.D. in nuclear physics from Lyon's University, France. He published in 1969 a reference book on electronic instrumentation in nuclear physics. With Jean-Jacques Samueli he started and developped Nucletudes, a scientific firm devoted to radiation hardening of components and systems. He published 30 papers in associated fields. For the last 15 years he combined violin making and string instrument acoustic measurements, and enjoys playing his own instruments in chamber music and orchestra.

The Demands of Nineteenth Century Concert Artists as Revealed Through Clients' Letters to the Gand House of Violin Making: An Inquiry into the Changing Relationships between Violin Virtuosos and French Houses of Violin Making through the 19th and 20th Centuries

GAEL FRANCAIS

Abstract

This article focuses on the correspondence of violin virtuoso and composer Henri Vieuxtemps with the famous violin shop of Charles Francois Gand and his two sons, during the period of 1838–1861. Not only does this series of letters reveal the interdependence between the Maestro and one of the most famous violinmakers and dealers of Paris in the 19th century but it also gives insight into their deep friendship which evolved over the years. In addition, correspondence between other prominent musicians of the period and the House of Gand, relating to sound issues, set up, and supplies is discussed. These letters reveal the constant struggle musicians had in finding the right strings and high quality supplies for their instruments, especially in a period where touring was still quite an adventure. The article will also shed some light on the relationship between the successors of Charles Francois Gand and their ever growing clientele, a relationship which was passed on from one generation to the next.[1]

We know that Henri Vieuxtemps began his studies with Charles de Beriot, who himself was a faithful customer of Charles Francois Gand. In an undated letter, Charles de Beriot asked Gand to take care of his Bergonzi violin, which had suffered from too much humidity, and to give it a little "jolt of energy." After 1833, Vieuxtemps visited various European capitals, impressing not only audiences with his virtuosity but also famous personalities such as Hector Berlioz and fellow virtuoso Paganini. By 1837, the years of study were pretty much over, and Vieuxtemps started touring not only in Europe but also beyond, as far as St. Petersburg, New York, and Boston.

In a letter, dated Brussels, December 18, 1838, Henri Vieuxtemps, who was about to leave to Moscow, wrote to Francois Gand about how delighted he was with the last sound adjustment for his violin which "has improved tremendously." In 1840, Vieuxtemps performed in Russia for the first time his recently composed Concerto No. 1 in E major with great success. The following year, he introduced it in Paris to the admiration of the audience as well as of other musicians and critics.

On June 26, 1840, Vieuxtemps wrote a letter from Brussels to Charles Francois Gand asking him to repair two violins belonging to one of his friends in Moscow who had heard of Gand and "his admirable repairs." He asked Gand: "take good care of them as if they were for me." Not a shy statement for a 20-yr-old virtuoso. As a matter of fact, the friend was actually Mr. Pahl, a concert master of the Imperial Theater of Moscow. He mentioned something rather interesting in this letter. "As travel by sea is halted in Russia in the first days of October, I beg you to take care of these violins at your earliest convenience in order to ship them before this period." The maintenance of violins for concert artists performing in Russia was very difficult during the winter season because instruments were mainly transported by steamboat. This inconvenience also affected Pablo de Sarasate, the last of the great nineteenth century virtuosos, during one of his frequent visits to Russia. He was compelled at some point to make the decision to have one of his Stradivarius (he owned the Boissier 1713 Stradivarius and a 1724 Stradivarius), which suddenly suffered because of the harsh winter conditions, dispatched by coach from St. Petersburg to the Caressa & Francais shop in Paris for an urgent sound adjustment. The round trip by coach probably took weeks. Nevertheless, it was a shorter period than waiting for the Russian winter to end and for the ice to melt in the Baltic Sea. It is also interesting to know that Pablo de Sarasate was one of the most sought after concert artists in the early twentieth century. In a note, dated October 1, 1906, written by him to Henri Francais, he mentioned that he will have to play thirty concerts from October 9 to December 13, and that he counts on Henri Francais to have his violins in top shape and ready to "impress" the English audience.[2]

In a letter, dated Brussels September 9, 1841, Vieuxtemps wrote to Charles Francois Gand[3]:

> I am very unhappy the way my violin sounds. I had the misfortune to break the good bridge that you made before my departure from Paris. Since that time, my violin sounds sick and no longer rings. The sound-post has also moved. I am afraid it is set up too tight, the sound is stiff and dry (...). Now, I have to tell you that I would like to start my voyage in the first week of October. You can see that there is no time to waste. I count on your usual experience to fix all that, with all the care and the attention possible. You would not believe how unhappy I am when this violin is not playing well. I am literally in agony. Will you have enough time? If you could return it to me in the last days of this month, you would render me an immense pleasure. (translation by Gael Francais)

In the same letter, he went on to ask Gand, "not to forget to cut some spare bridges, to wind some G strings, and to send him some good strings if they are available (…)." He concluded by writing: "my engagements in London went beyond any expectations."

In a letter, dated Brussels, June 3, 1842, Vieuxtemps asked Charles Francois Gand if he could render him a very special favor in evaluating a violin by Maggini being offered to him by Monsieur Trampenas and suggesting a fair price for the instrument: "I know you would not readily undertake such a task; however, I hope you will, for the sake of your friendship to me. I hope that you will not refuse, and I hope you will offer me an artist's evaluation." Then, he made an interesting remark: "You know that I do not always have much money." It would appear that concert violinists in those days earned much less than today's soloists, or that Henri Vieuxtemps was shrewd enough to use his good relations with Gand to arrange the purchase of a violin at the lowest possible price. Then, he added the following statement to reinforce his request: "In the strong belief that you will address this matter with all the loyalty and impartiality which distinguishes you, I await your kind and prompt reply." The elegant language reflects very much the customary courtesy of the 19th century.

A few days later, on June 12, 1842, Vieuxtemps wrote again to Charles Francois Gand to thank him for his "good and charming letter" and told him how much he congratulates himself every day to have him as a friend: "The favor that you just rendered is one more reason to be fond of you, to have a high opinion of you, and each time the opportunity presents itself to show you my affection." Today, such language could easily be misinterpreted, as nowadays nobody would think to write such a flowery letter bursting with obvious appreciation. However, in the 19th century, the language was as lyrical as the romantic music being composed. Not only our language has now become more casual and matter of fact in the high-tech world we live in but also human relations have changed to the point that it would be inappropriate to show such emotion, even in a friendly business correspondence. In the same letter, Vieuxtemps mentioned that “the favor” consisted in buying a Maggini violin at a reasonable price, for the amount of 1,200 francs, all arranged by Gand. However, he complained that the violin is not playable with the current string length, which is too long. He mentioned that the new violin he purchased from Gand is much easier to play than the Maggini violin, which is currently a “torture” for his fingers. Therefore, he asked Gand to replace the neck on the “new baby with all possible care (…). One recommendation that I have to offer is to avoid making the neck too thick.”

In another letter to Ch. F. Gand, dated Brussels, July 8, 1842, Vieuxtemps mentioned that he just finished a sonata for piano and violin. It is most likely the Sonata in D major, Op. 12 he refers to, which was published the next year. He made the following remark: “it is a style of music a little bit neglected, and I am upset about it because it represents a vast field, very much in line with the development of ideas. I am now planning to work on a concerto and I am not without hope to announce soon the birth of this new baby.” The sonata for violin and piano was perhaps composed with the inspiration of his future wife, the Viennese pianist Josephine Eder. The “new baby” (i.e., the concerto) was actually “born” later during a holiday in the town of Cannstadt near Stuttgart, in the summer of 1844, with the violin Concerto No. 3 in A major, Opus 25. This work was described later by his pupil Ysaye as a “great poem” rather than a concerto. Romantic music was definitely en vogue.

In a letter, dated Dresden, February 12, 1846, Vieuxtemps wrote to Adolphe Gand (Charles Francois Gand’s eldest son), calling him only by first name. He mentioned that his stock of G strings is completely depleted and that he would like to order a dozen of them. The G string in these days was simply called as the “4th string.” The G string was a gut string which was over-spun with either silver, copper, or with silver-plated wire. The French word for this method was “filer” which meant “winding with a thread of metal.” All other violin strings were of pure gut. He also complained that the strings found in this country (Germany) are pretty wretched. He asked Gand to over-spin them exactly like the sample he provides. He also presented his condolences to Adolphe for the loss of his father, who died a few months earlier, and affirmed that his pain was as intense as if he himself would have lost a close relative. He mentioned that he gave several concerts in Vienna with great success. He also remarked that next winter, he will present in Paris several new compositions—among those some concertos “which I hope will prove I did not waste my time.” He probably refers to the famous Violin Concerto No. 4 in D minor opus 31 which was composed in St. Petersburg, where he was working as a court violinist for Tsar Nicholas I and as a soloist in the Imperial Theater. In the same letter, he also mentioned having been bequeathed in Vienna, “one of the most beautiful violins by Joseph Guarnerius, grand pattern, with a golden varnish, superbly preserved.” “Waiting with impatience for the moment, I will be able to show it to you.” After he already had signed the last page of his letter, he suddenly remembered to confirm “the public rumor” that he is now married and writes that “he is very happy and very satisfied with his current position in the world.” He finished the letter telling Adolphe “not to make him languish with his 4th strings” because he has only one left that he “cherishes like the apple of his eyes and that he will use only as a last resort.”

In a note, dated April 15, 1847, Vieuxtemps begged Charles Adolphe Gand to believe that no consideration could ever change his feelings toward him and affect their relationship. Charles Francois Gand (Charles Adolphe’s father) died in 1845, but the relationship had already been passed on to the next generation of Gands.

In a letter to Ch. A. Gand, dated London, May 9, 1847, Vieuxtemps wrote that he has arranged a letter of credit for the amount of 500 francs with the financial institution Appenheim in Paris, to settle a bill of 453 francs and sixty cents owed to the Gand shop. He mentioned that this amount should cover the amount due, including the strings that he ordered but has not received yet, as well as future orders of strings. He added: “Needless to say, I am recommending that you give the utmost care to the winding of the strings. Consider that it is something essential, and that in Russia they are not to be found. Therefore, attend to it.” Here the tone appears to be sharper and slightly condescending. Vieuxtemps was always very demanding, but his tone was more nuanced when he wrote to Adolphe's father, for whom he showed great respect. Perhaps the age factor had something to do with it. He added at the bottom of his letter: "The fine Bergonzi is well and sings beautifully." This informs us that he played on a Bergonzi violin at this point of his career. We also know that Vieuxtemps owned a violin made by Charles Francois Gand that he cherished very much for its "ease of play."

In a letter, dated Brussels, September 17, 1854, Vieuxtemps asked Charles Adolphe Gand whom he calls Monsieur Adolphe (a more amicable and casual term to address a person, but this time he adds "Monsieur" to make it sound a trifle more formal), to send him as soon as possible some "4th strings with the same gauge of the strings hereby included. From the samples, you can see that the thickest one is a true G. I would be grateful, if you could send me a dozen of those and exactly of the gauge of the sample… the strings of the thinner gauge are for a string to be mounted at the UT (the old fashioned way in France to designate a C note). These must be wound over a 'chanterelle' (the treble viola A string was also called chanterelle) with an extremely thin winding." He mentioned that the local violinmakers are incapable of manufacturing any decent string. According to the biography of Vieuxtemps by Maurice Kufferath, Vieuxtemps was also a viola virtuoso. He would have played solos on the viola as well as having composed some viola pieces. (He was known to have owned a Gasparo da Salo viola).[4] Vieuxtemps finished this letter offering his respect to Adolphe's mother but only a "handshake" to his younger brother Eugene. In a postscriptum, he asked Adolphe, if he has any beautiful violin, "something remarkable," for sale.

Two important details emerge from this letter. The first one pertains to the supply of strings for musical instruments. In these days, very few workshops were able to manufacture decent gut strings. Because of the gradual taste in increasing the level of the tonal pitch and to the nature of the gut strings, these would often break or sound false. Furthermore, their quality varied tremendously, especially with the violin G strings, depending how the string was wound with a metal thread. Actually, the first G strings with metal windings were invented at the end of the 17th century and often used in France. But it is not until the middle of the 18th century, as evidenced by the advertisement of the old Parisian violinmakers that they were fully adopted. Since the second part of the 18th century, the best quality strings came from Italy and were called "strings of Naples." The Avallone brothers in Naples offered a first class gut string. The first mention of gut strings appears with the early 18th century Parisian violinmakers, such as Andre Castagneri. Being of Italian origin, it would make sense that Castagneri would want to promote these high quality strings in his adopted country of France. Then, in the second part of the 18th century, gut strings are mentioned more frequently. Guersan, Renaudin, and Huet, advertised "good and authentic strings from Naples." Joseph Gaffino and Antoine Saint Paul were offering their customers Italian strings from Naples, Rome, and Florence, as well as French strings from Lyon. So did Koliker, Nicolas Lupot, Thibout, and later the Gand shop. In addition, the shops of Gand and Sebastien Bernardel were offering their own version of strings, whereby the gut strings were prestretched before being wound on a spinning wheel. In an undated letter, written from St. Sauveurs-les-Bains in the Hautes Pyrennees, Charles Dancla, professor at the Paris Conservatoire de Musique, asked Charles Adolphe Gand to send him some treble gut strings and requested the following: "one A string and two chanterelles (E strings) played-in and tried beforehand on a violin." This would allow the musician to play them instantly without having to wait for the strings to stretch to the correct pitch. This also helped to avoid any premature breaking.[5]

Several letters, written from April to June 1848, by a faithful German customer of the Gand shop, the violinist Auguste Moeser not only give an insight into the political turbulence France was experiencing at that time but also provide some interesting details of the manufacturing of strings. They also illustrate how extremely difficult long distance communication was at that time. On the 22nd of February 1848, the French king, Louis-Philippe was forced to abdicate. Panic followed. Many people, especially the well-to-do social classes, were fleeing France. This also resulted in a significant flight of capital. Musicians and violin shops were deeply affected as well. This explains why Auguste Moeser wrote to Gand, how worried he was about the political situation in France and in Europe, and how "artists are right now destined to a miserable fate." For this reason, he decided to leave for Rio de Janeiro until the situation in Europe improved. All this explains why Moeser in a letter, dated April 28, 1848, placed a huge order of accessories, consisting of strings, six precut bridges, two sets of rather thick pegs for his Maggini violin, 12 boxes of "Villaume" [*sic*] rosins ("sorry for the choice but I particularly like it"), and 18 bundles of hair to rehair his bows that the artist wanted to take with him. The order of strings consisted of 420 chanterelles (E strings), "white and even", 150 A strings, 60 D strings, and 24 G strings. Even and well-proportioned gut strings were very difficult to obtain. Requesting E strings of a white appearance would perhaps indicate that fresher strings would be less brittle and last longer. The requirements for the G string were quite revealing. Auguste Moeser insisted on obtaining a G string as thick as an A string or slightly thinner: "The 'trait' (winding), made of silver plated copper, needs to be very thin." He also asked for the whole order to be packed very well in a wooden box and then wrapped in a wax cloth, as to withstand the humidity of sea travel. Not receiving an answer, and worried that his first order had not been received by Gand and that it might after all be insufficient, he wrote again on June 7, increasing the order, this time to 500 chanterelles, 200 A strings, 100 D strings, 50 G strings, and 30 bundles of hair. In this letter, he instructed Gand to ship them with the Steam Navigation Company to Lisbon via Southampton. In the meantime, Gand had complied with the first order which was already en route and confirmed it with a letter dated May 31. Realizing that, since the first order was already on its way, the total of the two orders would now exceed the maximum amount of items actually needed, Auguste Moeser, who was waiting in Lisbon impatiently for his accessories and for the next steam ship to Rio de Janeiro, wrote again to Gand on the 18th of June to cancel the second order of June 7 but to still send him the additional items before his departure, so that the total and final amount would correspond to the amount of the second order: "Since you did receive my first letter and the shipment is on its way, the order of my second letter should be cancelled. You tell me that at this time you have very good chanterelles - since during such a long travel one cannot have enough supplies, and because at this moment there is a sure and exact opportunity to ship immediately with a steam boat an additional package—I beg you to send me the additional items." At the end, the total cost of the two orders rose from 273 francs to 530 francs. A substantial amount of money, especially if one considers that the price for a new violin by Charles Francois Gand or by Francois Louis Pique amounted only to 200 francs and a violin by Nicolas Lupot to 600 francs! As we observed, 1848 was a very difficult period for any artisan and the order amounting to 530 francs, even if the profit margin was not as significant, must have come as a blessing to Charles Adolphe who was struggling to survive.

In another interesting letter, written earlier and dated October 21, 1832, by a cellist by the name of Grevout de Boisvobant to Charles Francois Gand, we can easily feel the frustrations of 19th century musicians with regard to the unreliability of strings. The quality of strings was a constant source of irritation and represented probably one of the greatest challenges musicians had to face. The cellist recounted how all the C strings he ordered from Gand for his Andreas Guarnerius cello broke at both ends. The best C string (UT) lasted more than 1 yr, but had to be rescued recently by adding some extensions at the ends. When it finally broke all together, he replaced it with another one, "rather new", which broke immediately at both ends. The third and last one he had lasted a little bit longer, but is currently on "life support," with one extension. Grevout de Boisvobant asks Gand to send him three new C strings with the same gauge as the sample included, which has a thinner metal winding (trait). He mentioned: "if the metal winding was even slightly thinner, the string would be more flexible under the fingers." It appears that the string which lasted the longest was of a thinner gauge. It was more flexible, could stretch easier, sound better, and last longer. As far as the "chanterelles,"[6] he received from Gand, he noted: "they are excellent, considering that the one which has been on my cello already for several months, has a good ring and is holding up with all the weather changes."

Another interesting concern of concert artists was to find the ideal violin at a so-called "artist's price." The second detail noticeable, as already mentioned earlier in the 1854 letter from Vieuxtemps, is that concert artists were, and are still to this day, always on the look-out for the ideal violin, at a so-called "artist's price." In another letter, dated Baden-Baden, July 30, 1860, Vieuxtemps asked Monsieur Gand, if he could try out during his next concerts a Stradivarius that he saw a week earlier at his shop. Vieuxtemps writes: "If the violin fulfills all the requirements as a concert instrument, I will keep it at the offering price." However, Vieuxtemps made sure to add between parentheses that, as an artist and a friend, he expected a very special price.

In a letter dated Frankfurt, August 5, 1860, Vieuxtemps rejected the offer from the Gand Frères to try out the Stradivarius because the violin appeared to have been repaired with a "patch," mentioning that "patches lead to all sort of headaches, especially for an artist", and that he would only consider a violin in perfect condition.

In another letter, dated London, April 17, 1861, Vieuxtemps mentioned again that his stock of strings was depleted, and that he needed to order new ones, and insisted again on obtaining strings of the proper gauge and not too thick. It appeared that it was very difficult to manufacture strings with the correct gauge. He also recommended to Gand to pack them well as not to be affected by the humidity of the sea. (As mentioned earlier, strings were wrapped with a thick wax paper before being shipped by sea.)

Long-lasting relationships between virtuosos and violinmakers, occasionally leading to sincere friendships, were not rare in the 19th century and were still alive at the beginning of the 20th century. The transformation of violin shops in the later part of the 20th century, becoming more orientated toward business, slowly eroded this special type of friendship, which was so prevalent in earlier times. It is interesting to take notice that violin shops with long traditions, especially when one thinks of Nicolas Lupot and his successors, maintained very deep ties with renowned concert artists and important violin professors of the Paris Conservatoire de Musique. Certainly, Pierre Baillot and his pupil Francois Habeneck were faithful customers of Nicolas Lupot as illustrated in a work memo written by Lupot for Francois Habeneck in 1808.[7] It showed that Habeneck owned two precious violins, one made by Lupot purchased on May 17, 1808 for 240 francs, and a Stradivarius, dated 1734. Although Habeneck adopted the shop of Lupot for the maintenance of his violins, other concert artists, such as Delphin Alard, one of his most famous students, instead adopted the shop of Jean Baptiste Vuillaume and even married Vuillaume's daughter Emilie in 1849.

We have seen through the correspondence between Vieuxtemps and the Gand family, the profound respect they had for one another, and the sincere friendship which evolved. Ysaye, the most famous pupil of Vieuxtemps, also followed suit and embraced the successors of the Gand family. Eugene Ysaye and Jacques Thibaud became very close to the Caressa & Francais shop (the successors of the Gand shop).[8] The various memorabilia, dating from 1905 to 1929, still in existence today, include portrait photographs and portrait drawings, with warm dedications to Caressa & Francais and to Emile Francais. They bear witness to these profound friendships.[9]

Actually, few people know that Jacques Thibaud was the violin teacher of Lucile Caressa (daughter of Albert Caressa, and Emile Francais' future wife) and that he was also the god-father of Jacques Francais (Emile and Lucile Francais' youngest son). At a later date, the same type of close relationship evolved between Yehudi Menuhin and Emile Francais. Menuhin lived between 1930 and 1935 in Ville d'Avray near Paris. During that time, many musicians came to visit him. Chamber music sessions with Jacques Thibaud, George Enescu, and Nadia Boulanger were a frequent occurrence. It is during this period that Emile Francais made a replica, in the shop of his father-in-law Albert Caressa, of Yehudi Menuhin's Khevenhuller 1733 Stradivarius. Menuhin played for several years on this particular replica. The relationship with the Francais family continued as Menuhin acquired one of the most outstanding violins in existence in 1978 from Jacques Francais in New York, the famous 1742 "Lord Wilton" Guarnerius del Gesu.

In the 20th century, the era of enduring relationships between important houses of violin making and concert artists, music professors and their students which spread over generations, was slowly coming to an end. Personal relations of course still persisted. However, the general trend was toward new types of relationships which became more business-like and shorter-term, at times, impersonal and shallow, reflecting the general matter-of-fact, interpersonal rapport of today.

Going back to the 19th century (which marked the height of the Industrial Revolution in France), the competition between the major violin shops in Paris such as the houses of J.B Vuillaume, Gand & Bernardel Frères, and Chanot, among others, was indeed intense. Competition was fostered through various national and international fairs, such as the Paris Exhibition of 1849 and the world exhibitions of 1855, 1867, 1878, 1889, and 1900, which gave houses of violin making the opportunity to show off their latest creations and innovations. The world fair of 1900 was attended by Gustave Bernardel (successor of Gand & Bernardel), and many other fine violinmakers such as Hippolyte Silvestre and Joseph Hel who both received grand prizes. Among the so-called associates, Albert Caressa and Henri Francais both won gold medals. Shops in these days were competing at a different level, where craftsmanship played an important role in winning the best prizes, and was central to the promotion of the image of a particular shop on the world stage.[10]

As we have seen earlier, in the past, important houses of violin making were producing almost everything from stringed instruments and bows to accessories like rosins, instrument cases, and even finishing gut strings by wrapping them with metal wire. This was the case, for example, with the Caressa & Francais shop, where until 1920 almost everything which had to do with stringed instruments was produced on the premises, and was certainly the case with the firm of W.E. Hill & Sons, which continued this tradition well into the 20th century.

As mentioned before, the later part of the 20th century has seen the erosion of large violin shops. Houses of violin making were being replaced slowly with medium sized shops. Activities became more specialized. Manufacturing and wholesale companies were created supplying violin shops with all the accessories they needed from preshaped fingerboards, precut bridges, half-finished pegs to finished products, such as strings, tailpieces, chinrests, and cases. As a result of this diversification, violin shops started now to concentrate mainly on repair, restoration, and dealing. Other smaller shops began to specialize in making new, stringed instruments. The 21st century is now a different world, with a new brand of soloists who have to play an ever expanding repertoire with many interpretation challenges, and a new generation of outstanding violinmakers still in the pursuit of the perfect-sounding instrument. All things considered, one cannot underestimate the continued, hidden but crucial, role of the violin- and bowmaker in the successful career of most concert artists. This aspect has certainly not changed since the dawn of violin making.

NOTES

1. All the letters quoted in this article are from the archives of Gael Francais, the last descendant and violin maker of the Caressa-Francais lineage. All of them, except the one dated September 9, 1841, were transmitted from Emile Francais (Gael's grandfather) who was the successor to the famous house of violin making, founded by Nicolas Lupot, and his pupil Charles Francois Gand. All translations from French to English were made by Gael Francais.

2. Handwritten card, signed by Pablo de Sarasate, dated Biarritz, Villa Navarra, 1906. Private archives Gael Francais.

3. Milliot, Sylvette. Nicolas Lupot, ses contemporains et ses successeurs, vol.1, p. 132. Messigny-et-Vantoux: JMB Impressions, 2015.

4. Kufferath, Maurice. Vieuxtemps, sa vie et son oeuvre. Brussels: J. Rozez, 1882.

5. For a history of string manufacturing, see, Milliot, Sylvette. Histoire de la lutherie parisienne du XVIIIe siècle a 1960, vol. 2, p. 175. Les Amis de la Musique, 1997.

6. As for violin and viola, the A string for cello was also called "chanterelle," meaning a treble string with a "singing quality."

7. Document from Gael Francais archives, illustrated in Milliot, Sylvette. Nicolas Lupot, ses contemporains et successeurs, vol. 1, p. 58. Messigny-et-Vantoux: JMB Impression, 2015.

8. In 1901, Caressa & Francais took over the succession of Gustave Bernardel. Earlier, the Bernardel brothers were partners with Eugene Gand. A detailed chronology of successions of the house of violin making, founded by Nicolas Lupot, can be found in *Les Tresors de la Lutherie Francaise du XIXe*. Paris: Musicora, Probomabo, 1993.

9. Photos and portrait drawings of Eugene Ysaye, Jacques Thibaud, Pablo de Sarasate with dedications to Caressa & Francais are in the private archives of Gael Francais.

10. In the first world fair of 1834, Jean Baptiste Vuillaume took the lead, exhibiting two quartets, modeled after Guarnerius and Stradivarius and promoting his latest innovations, e.g., the famous hollow steel bow. However, most of the violin makers and bowmakers working for shops such as J.B. Vuillaume, the Gand Frères, Gand and Bernardel Frères, or W.E. Hill & Sons, remained in general anonymous. By contrast, nowadays violin makers rarely compete on the world stage under the umbrella of the shop they work for, but rather under their own name, at fairs like Mondomusica of Cremona and New York, or at various international violin competitions.

The Use of Collapsible Molds for Violins, Cellos, and Basses: Resolution of Two Common Variations on the Inner Mold

MIKE CARLSON, ROSS HILL, AND DON KENNEDY

INTRODUCTION

This article represents a written summary of a presentation made at the fall meeting of the VSA in 2015 in Baltimore, Maryland.

TWO METHODS

Traditionally there are two common ways of building a stringed instrument, both using an internal mold. In the first method, the ribs and linings are assembled. Then, the mold is removed, and the ribs are attached to the back. This is the classic Cremonese methodology, as described in Johnston and Courtnall.

Some technique is required to do this, which might include the following: working really fast to a scribed outline, using pins, a dry clamping followed by glue placement with a palette knife in sections, or the use of a spider (that holds the ribs in the prescribed shape with many legs). Figure 1 shows a spider and Fig. 2 shows the use of a palette knife on a cello from a YouTube video by Matteo Fanltoni [1].

The second common method is to glue the ribs onto the back with only the lower linings attached*. The mold is then removed with the back on. The upper linings are then attached afterward. This methodology is described in books by Juliet Barker [2] and Karl Roy [3], or the DVD series by Prier [4]. This technique is taught at Mittenwald. In Mirecourt, France, the mold is sometimes offset vertically to the top, allowing lower linings to be attached. Some technique is required for this, which includes a delicate touch for removing the blocks, usually done with a tap of a hammer and careful removal of the mold.

PROS AND CONS OF DIFFERENT METHODS

The first method can be a bit tricky when it comes to removing the ribs from the mold. It is easier to do if the mold is thinner. A thinner mold means less control on the vertical orientation of blocks and ribs. While attaching the back, the ribs are positioned to a scribe line around the back. If you clamp the ribs down on the inside of the line or outside of the line, the ribs end up a bit crooked. It is also important to make sure the clamps are directing the clamping force just downward and not at an angle. Good quality clamps can help with this, although they are more expensive and care is still required.

The second technique keeps the ribs straighter. It is an indicator of provenance. (It's still best to have the clamps well vertically oriented.) The mold cannot be taken out with the upper linings on because they block the removal of the mold. It is very difficult not to change the shape of the ribs slightly when adding the top linings.

In summary, the major underlying issues are outline control and keeping the sides vertical. These problems become more acute with deeper ribs. It is, therefore, critical on basses and cellos and somewhat less critical on a violin. There are clearly pros and cons to both methods. A summary table is included below in Table 1.

OBJECTIVE

We have developed a number of molds that are collapsible and which represent another option. This eliminates the compromises with the two

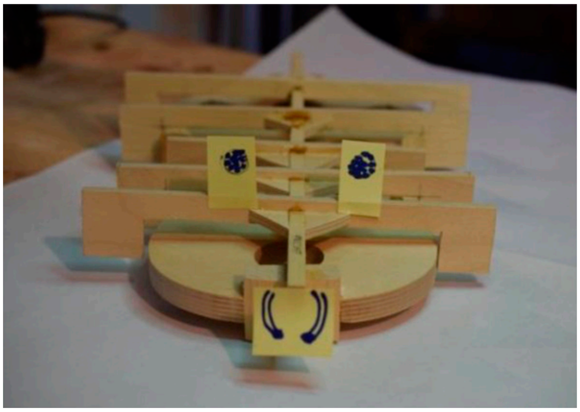

Figure 1. Outline spider for gluing.

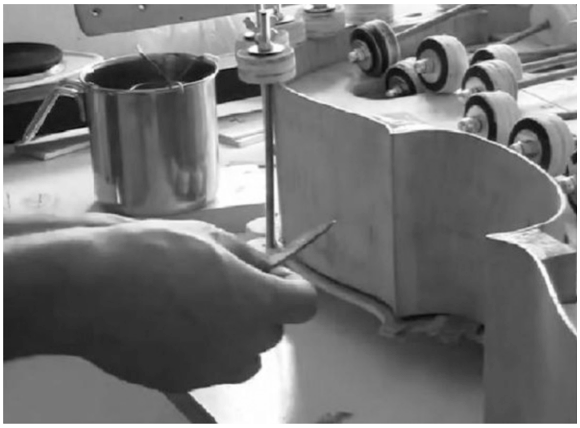

Figure 2. Palette knife glue Matteo Fantoni [3].

most common existing traditional methods. Both sets of linings are attached on a stable mold and the back glued on with the ribs straight and with a fixed outline. More work is required to build the mold. This simplifies the process of removing the mold and can be used many times. On balance, it's about the same amount of work. A collapsible mold can also be used for repairs. There are a couple of other objectives associated with an improved mold design:

A number of comments are in order. Making the mold out of heavy plywood makes the molds heavy and difficult to handle, especially for a bass. The solution here is to use more layers with thinner wood and an internal frame to hold the shape.

Good clamping options are important, in particular, good angle and force for the corner blocks to get a tight fit.

The lining process is actually a laminating process. When the laminations (rib and liner) are glued together, there is a big increase in stiffness and the shape is locked in. This is best done with the outline tightly controlled i.e. on the mold.

With small wooden blocks on top and bottom, it is possible to lift the edges of the instrument up and thereby protect the edges from getting damaged. If one unscrews the blocks, then you can put the entire instrument on a flat/level sandpaper surface and ensure that the edges are even and flat. The lift blocks can then be reattached.

Table 1. Comparison of methods for traditional molds.

Cremona	**Mittenwald**
Both linings are placed in the mold	Only bottom linings on the mold
The ribs have to be extracted from the mold to glue on the back	The sides are definitely straight (clue in identification)
The sides are trickier to get straight	Outline on the back is locked in when attached to the back
Outline with pencil	Slightly more difficult to get mold out–be gentle while removing blocks
Preclamp and glue sections	
Use spider to hold sides vertical	
More difficult to get outline control	Shape will change slightly as upper linings are added
Typically see holes in the mold for clamping	Typically see square opening for clamping

Table 2. Objectives for collapsible molds.
Light weight–easier handling
Good clamping options and angles
Install upper and lower linings on the mold
Protect linings while supporting the instrument
Flatten the top and bottom of the ribs and blocks on the mold
Trim linings with some support and ease of access
Collapse mold with back glued on–with both sets of linings
Can use clamps to pull the mold off blocks controlled force and no follow through

The use of a controlled hammer blow to remove blocks takes a considerable touch. One option is to use screws, particularly on larger instruments, such as cellos and basses. With a collapsible mold it is possible to get access to the screws during disassembly.

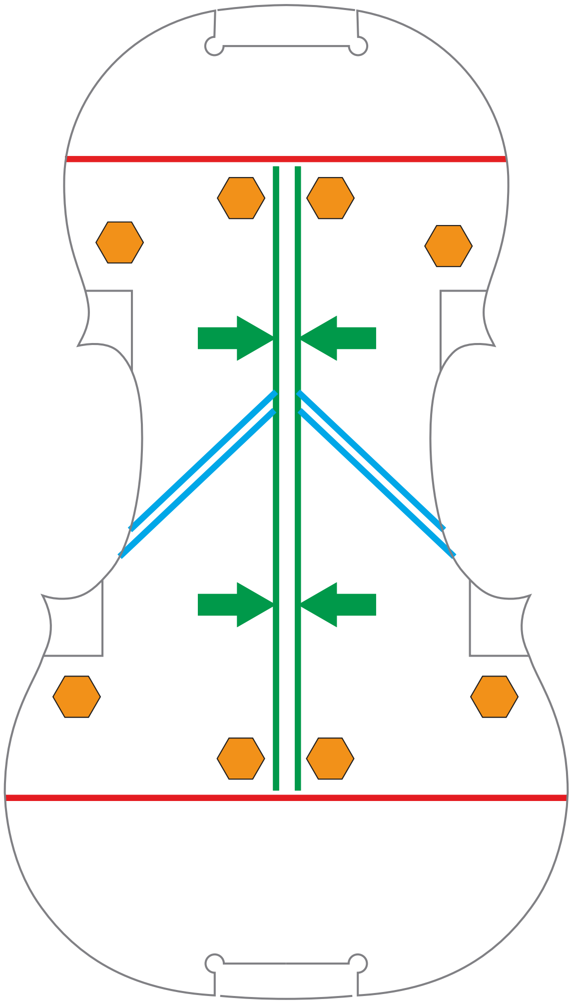

Figure 3. Upper layer.

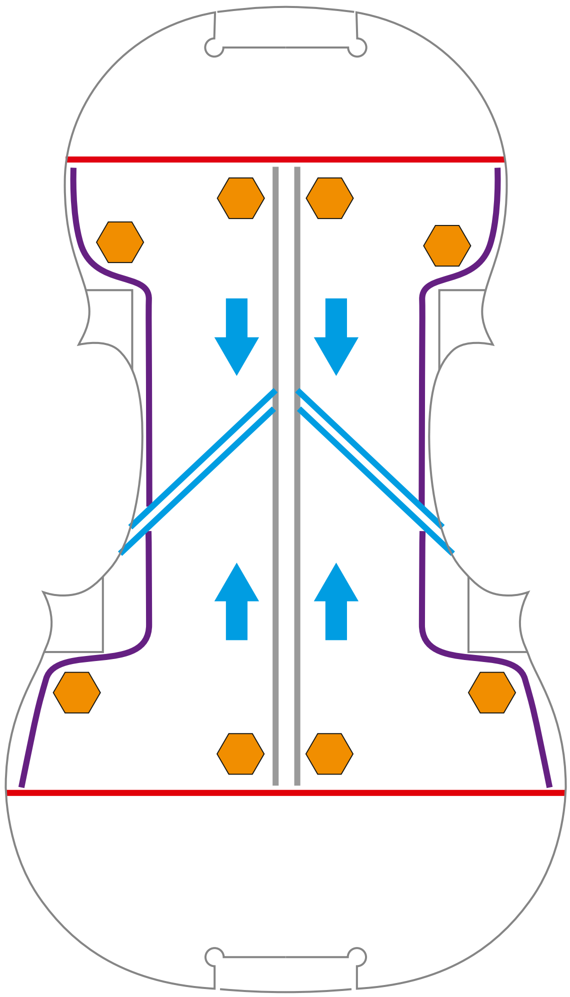

Figure 4. Middle layer.

One interesting option with hand clamps is that they can be reversed and used to pry the instrument off the mold. There is less follow through with a steel bar clamp, and this reduces the potential from a hammer blow that is stronger than necessary.

With partial disassembly of the mold, the linings can be trimmed with the instrument outline still supported. The objectives are summarized in point form in Table 2.

MECHANISM

There is more than one way to make a mold. The example below is for a violin. However, the principles can be adapted to all instruments. Essentially, you have two choices, to start from the end blocks or start with the corner blocks. We have started with the sides. The mold is made in three layers.

A gap must be placed in the middle to allow the inward collapse. This provides for clearing the linings and the removal of the mold in parts. Figure 3 shows the first step.

The screws that go through to the bottom layer are removed. Then, the middle sections of the top layer are moved inward and off the corner blocks. Note the gap between the green lines in Figure 3.

The middle layer shown in Figure 4 also has a gap between the two blue lines. Note that the upper redline must be located above the widest part of the upper bout, and the lower red line must be located slightly below the widest part of the lower bout.

There is a gap between the instrument outline and the outside of the middle layer in the center section shown with the purple line. The end sections are moved toward the center and removed.

This leaves two pieces of the center section on the bottom (shown in Fig. 5) that are easily removed directly.

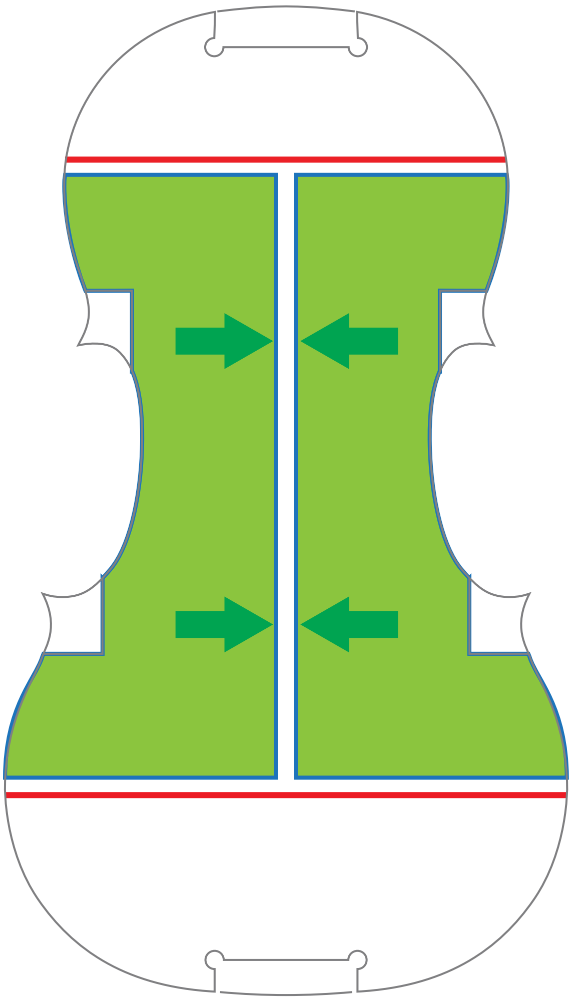

Figure 5. Violin mold.

MOLD USAGE

The entire mold is shown in Fig. 6. It is used almost exactly the same way as a classic violin mold. The blocks are glued in with hide glue and a layer of paper. The small wooden blocks held on with brass screws provide lining protection. The layers are held together with small stove bolts from the local DIY store. Nuts are countersunk and glued. Clamping zones have also been supplied that are a hybrid of the traditional circles and the large square opening.

MOLD CONSTRUCTION

Construction of the molds is not difficult. Three layers are laid out from outlines as shown in Fig. 7. Guide holes and pins are used for indexing. The red lines are located above the widest point in the upper bout and below the widest point in the lower bout.

The outline is cut with all three layers together using pins.

The middle section has a gap between the two blue lines. Note that the middle layer is

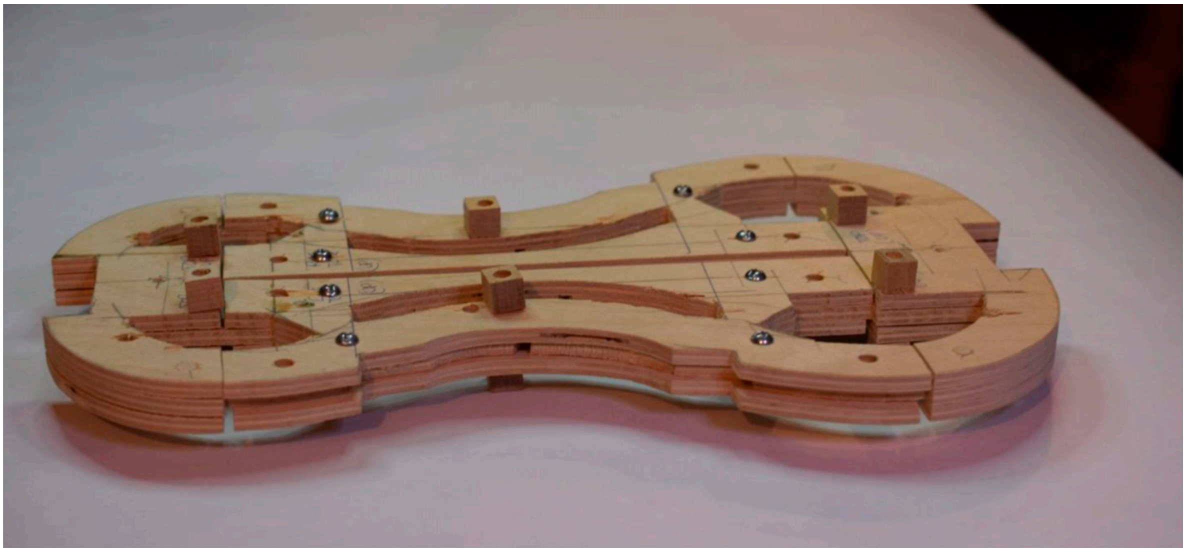

Figure 6. Construction.

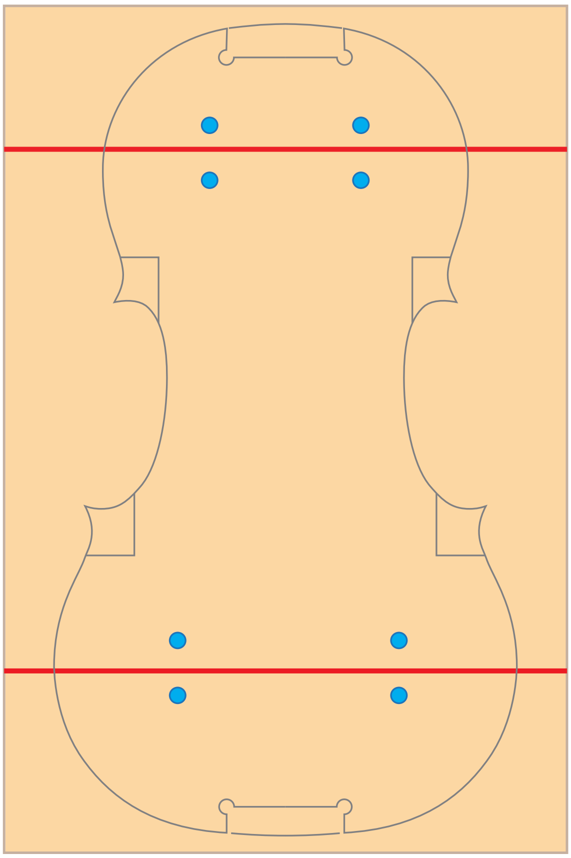

Figure 7. Lower layer.

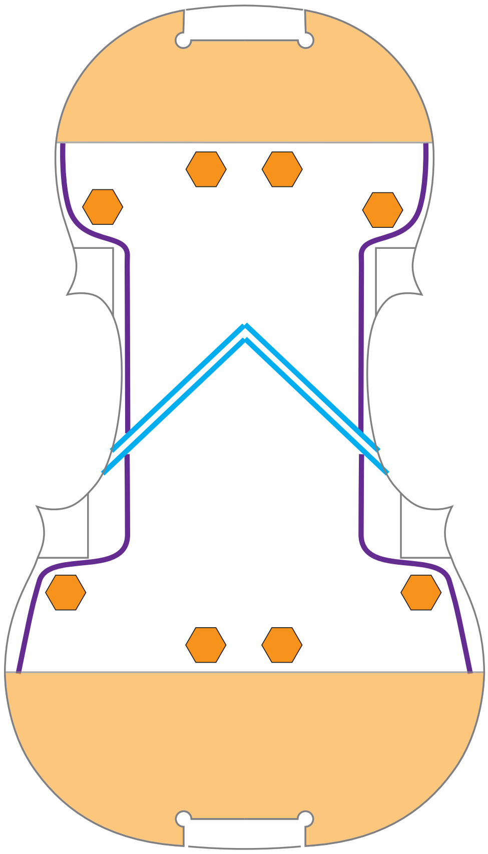

Figure 8. Construction II.

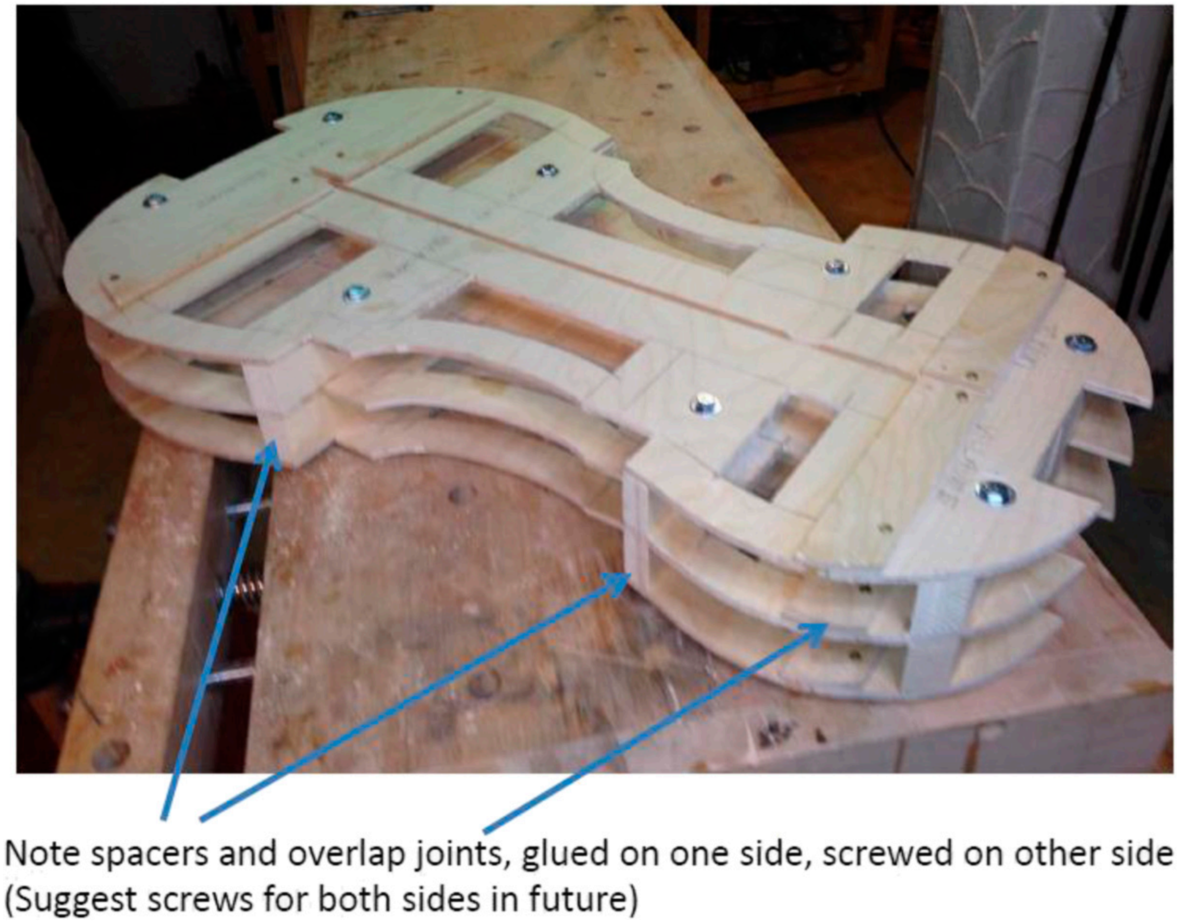

Figure 9. Cello mold with three layers.

trimmed along the purple line to provide clearance, such as for the corner blocks. All three layers are glued together at the upper and lower ends of the middle layer and the end sections are therefore thicker.

A gap in the middle is required in the upper and lower layer. I have included a gap in the picture of the third layer in Fig. 8. This may not be necessary. When the three layers are unscrewed the middle layer lifts up.

SPACERS

For cellos, the best method includes some spacers to allow the full height of the ribs to be defined. Note that the top and bottom layers leave room for the linings to be attached with the mold. See Fig. 9.

In this mold, the bolts have been put through the spacers to hold them in place. There are flat strips added to hold each layer with screws on the detachable side (the ends) and glue on the permanent connection side (in the middle). Note that wood blocks were glued to the middle layer to attach the corner blocks to—see the next Fig. 10. Also note the clamp openings. These also significantly reduce the weight of the mold and make it easier to handle. More holes or sections can be added as necessary.

Figure 10 also shows the screws used to hold the corner blocks in place. This is also done for the end blocks. Holes were added to the top and middle sheets to make separation of the end and middle sections easier for the disassembly of the middle and bottom layers. The center spine is held in place by the spacers and layers and simply pulls out during disassembly.

Figure 10. Cello Mold with top layer removed.

Clamping is straight forward as shown in Fig. 11. This is for the last rib added. Note the stronger screw clamp and cauls used to get a tight fit on the corner blocks on the RHS lower bout.

BASSES

For the bass, a more defined “skeleton” works better. This provides more stiffness for the mold and ribs. The cross pieces are notched on the center spline and on the cross-piece. They are then glued together. Reinforcing triangles have been added to keep the cross pieces oriented correctly as shown in Fig. 12.

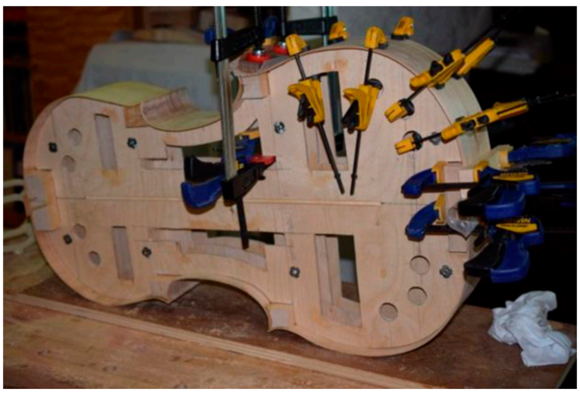

Figure 11. Rib clamping.

Holes also Reduce Weight

On the LHS of Fig. 12, the top layer has been removed. This is for a double bass. There are two layers for this mold on top and bottom. There is a reinforcement in the center section in a middle layer. For this mold, the top and bottom were divided in quarters. While this worked, the system used on the cello and violin works better. Note that the linings have been glued on with the mold on. The neck block is attached with a total of four screws. The back has a bend and this requires support as shown in Fig. 13.

It is much more difficult to get the ribs vertical on a bass due to the high rib height. Figure 14 shows the inside view of a bass that has had the back attached with the mold inside. Gluing

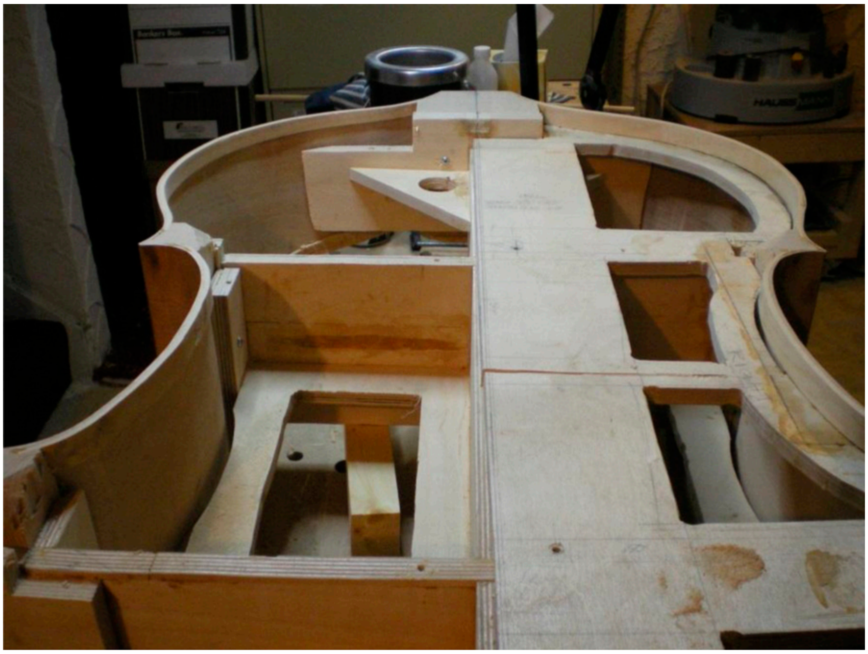

Figure 12. Top of bass being flattened.

Figure 13. Bass collapsible mold.

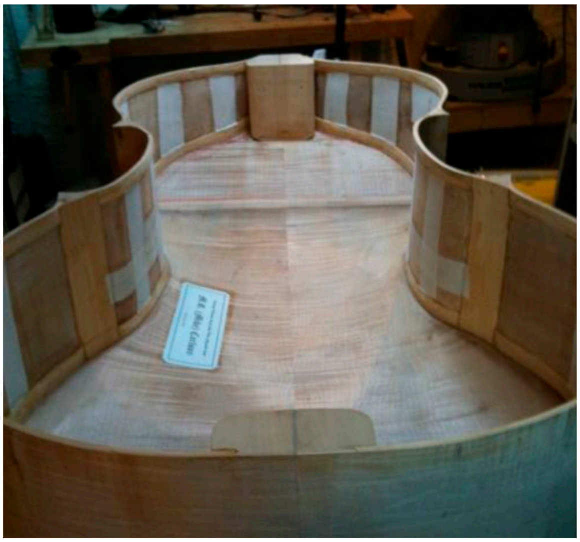

Figure 14. Sides vertical on large instrument.

Figure 15. Top glued on–last step.

Figure 16. Mold with end collapse [5].

Figure 17. End collapse mold exploded [5].

Figure 18. Ribs shortened on mold.

Figure 19. New linings being installed.

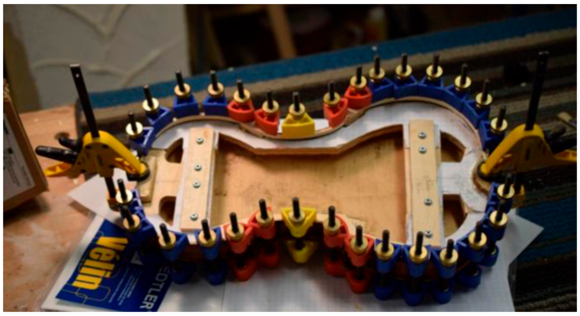

Figure 20. Ribs glued to back.

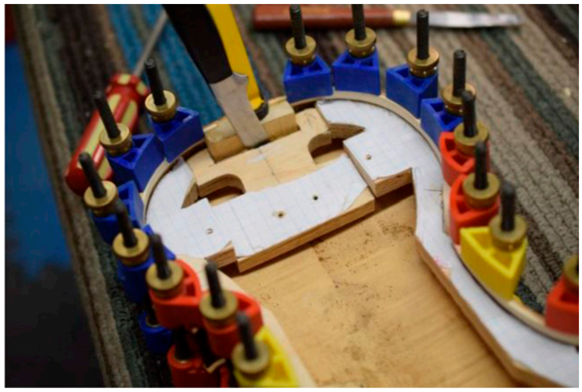

Figure 21. End block being collapsed.

the top on is the last step in assembling the instrument body, as shown in Fig. 15.

OTHER METHODS

There are other variations on the methodology outlined previously. One such variation for a violin is shown in Figs. 16 and 17. This design is from Christian Bayon and originated in Portugal [5].

It is hoped that others will be able to adapt the methodologies shown to their own applications. Most luthiers will make their own variations that suit their working style and their instrument design.

PRESENTATION

During the course of the session in Baltimore, the presentation moved to a hands own discussion of how the molds went together. The cello and violin mold were rapidly dissected by those in attendance, with the aid of a few tools. Quite a bit of discussion was generated.

One attendee showed a picture of a mold from the Oberlin construction project for cellos based on the mechanism shown in Figs. 16 and 17. The mold was laminated from MDF and was cut out with a computer cutter, a high precision variation. Collapsible molds are being used.

REPAIR

Since the presentation in Baltimore, a collapsible mold has been used for a repair. This repair was for a German factory violin on which the top had shrunk over the last 90–100 years. The violin restoration included fixing some three rib breaks, cracks in the top, as well as shortening the ribs. The top and back have shrunk more than the ribs.

The outline of the top and the back are traced onto a piece of paper and a new outline made up to fit inside both the top and bottom, with appropriate overhang. This mold uses a mechanism that collapses first off the end

Table 3. Features of collapsible molds.

Light weight–easier handling	Yes
Good clamping options and angles	Yes
Install upper and lower linings on mold	Yes
Protect linings while supporting the instrument	Yes
Flatten top and bottom of ribs and blocks on mold	Yes
Trim linings with some support and ease of access	Yes
Collapse mold with back glued on–with both sets of linings	Yes
Can use clamps to pull mold off blocks–controlled force and no follow through	Yes

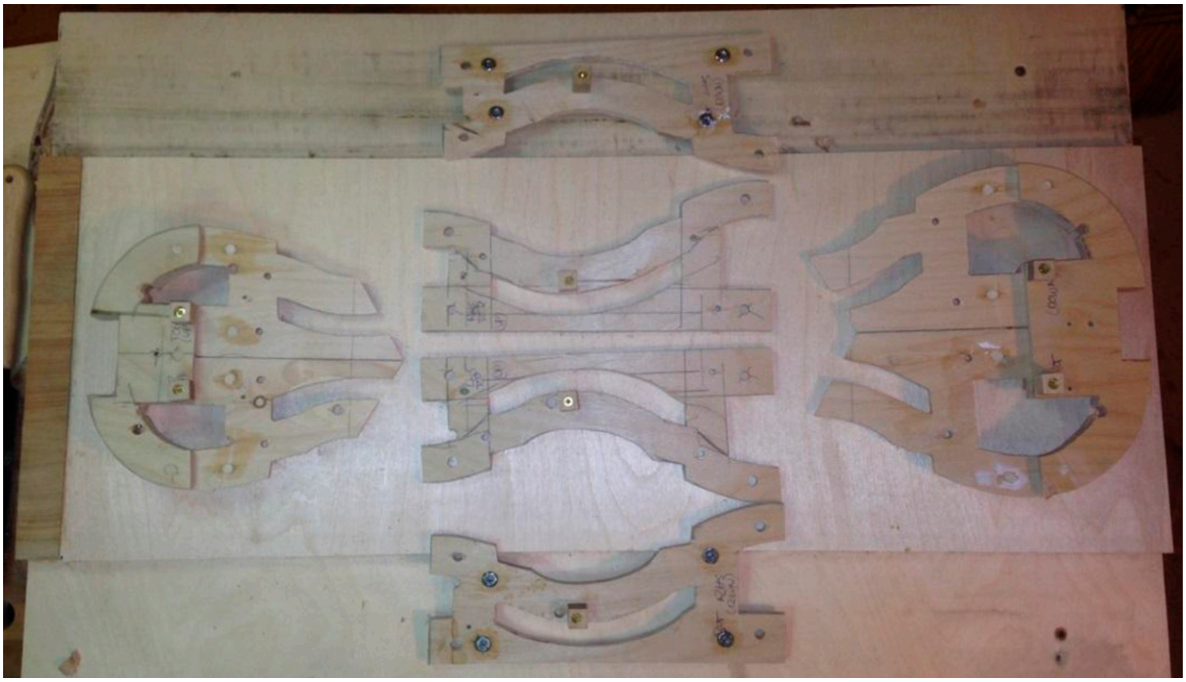

Figure 22. Violin mold exploded.

blocks. The mold keeps the ribs vertical and controls the outline. Figure 18 shows the ribs at the tail block. Note that there is a minor part of the endpin hole remaining on the right hand side. This shows the shortening.

Figure 19 shows new linings being attached with the mold inside the ribs. After this the ribs are glued to the back, similar to construction as shown in Fig. 20. The end blocks are then removed as shown in Fig. 21. Note the knife used to break the glue. The clamps are left on to provide support to the ribs as the glue joints are broken.

FEATURES

The molds outlined were designed to have a number of features that are summarized in Table 3. They do require somewhat more work to construct. The extra time must be weighed off against improved quality and ease of construction. The molds can be reused.

SUMMARY

The principles of a collapsible mold were presented for stringed instruments from violins through double basses. The reasoning and advantages were presented, as well as a number of variations. Construction of the molds was also outlined. The methodologies can be adapted to different preferences and needs. Discussions indicated that different variations of collapsible molds are being used. Figure 22 shows an exploded view of a typical violin mold.

REFERENCES

[1] YouTube; Matteo Fantoni, "Series of videos," is found at https://www.youtube.com/watch?v=T46uqUtNDbw&list=PLAzW_93em9h7h_PNZiWNq2f-YzUSvM65p.

[2] J. Barker, *Violin Making: A Practical Guide*. (Crowood, Marlborough, 2001).

[3] K. Roy, *The Violin Its History and Making*. (Karl Roy Private Printing, Barrington, NH, 2006).

[4] P.P. Prier, *When Trees Sing; The Complete Guide to Violin Making 15 Disc DVD Set*. (Peter Paul Prier Inc., Salt Lake City, UT, 2010).

[5] C. Bayon Maestronet, Portugal, is found at http://www.christianbayon.com.

Violin Cases of the Baroque Period

GLENN P. WOOD

Historical violin cases constitute a small subset of antique collectibles and have hitherto received very little attention even from the violin enthusiast community whom they have served for centuries. Violin cases dating to the baroque period (approximately 1600 -1750AD) are very rare and are mostly to be found in museum vaults or private collections. Here, for the first time, Dr. Wood presents his registry of all the specimens of baroque violin cases he has encountered during 15 years of research. All are from Europe, most are from Italy and some are believed to be from the workshop of Stradivari. These silent sentinels of history have survived wars, pestilence and the ravages of time in their duty of protecting valuable violins.

The baroque period in Europe is loosely defined as the century and a half from 1600 to 1750. This period corresponds to the emergence of the violin as the dominant successor to the viols for concerted and soloist work. Its form was more or less established by the Amati family in Northern Italy in the 16th century and came to a glorious culmination a century later in the Cremonese workshop of Antonio Stradivari.

Our knowledge of this evolution is still evolving through careful scholarship and study of the instruments and documents which have survived. It is reasonable to suppose that bows and cases were made in similar quantities to accompany the violins but much less is known about them. This is because neither of them were regarded as highly as the violin itself. Bows broke easily and cases suffered in their line of duty which was to protect the instrument from the seven perils that traditionally threaten antiques; namely, thermal shock, humidity changes, light, pests such as boring insects and rodents, humans and their careless handling, air pollutants, and oxidation.

The client base would have been drawn largely from the nobility and the church because that is where the wealth and culture of the age was concentrated.

Most of these instruments had to be delivered to clients who often lived a long distance from where the instrument was made and such a journey was inevitably bumpy and perilous, and so the case transporting it took on the character of a trunk charged with the protection of its valuable contents. As such, and in spite of it having an appearance befitting its illustrious owner, it never received the reverence of the violin, and when ravaged by damp and worm in the discharge of its protective duties, it was summarily replaced.

In the absence of reliable data, this author estimates European case production from 1600 to 1750 as follows. Italy, France, Germany, and England accounted for most of the violin production during that period. Assuming that 100 luthiers were active at any given time during those years with an average output of 100 violins a year, then 1,500,000 would have been made. If we estimate that only 10% have survived, that implies 150,000 violins. A number of these would have been pairs requiring just one double case, so let us assume that 100,000 cases of varying qualities would have been required to accommodate all these violins. After more than a decade of intense interest and research in this field, only a mere 40+ cases have been identified by us from this period. Undoubtedly there are more, but we can only discuss what we know and remain hopeful that more survivors will emerge from the shadows over the coming years.

It is only when we see enough of these items can we begin to understand them. Unfortunately, there was never a tradition of labeling them so their origins remain speculative. That said, there are a few "anchor cases" whose provenance can be asserted with some confidence, and when we compare others with them, some patterns begin to emerge.

We will begin this brief dissertation by stating five generalities which unify and divide the cases of this period.

1. The method of construction involves the formation of a wooden carcass into a kind

of box which is generally protected on the outside with leather and on the inside with less durable linings such as paper, cloth, and suede.

2. Relatively local materials were used in the construction of cases. Wood was always available and deciduous hardwoods such as walnut and oak were preferred. These were the woods most commonly used for furniture in the 17th century as mahogany, a fine grained and nicely figured wood, did not become readily available until it was imported from Cuba, Santo Domingo, and further afield in the 18th century.
3. The most distinctive outer feature is the attachment of the leather to the wooden base using metal studs with a domed surface. In contrast to a regular nail, the dome served to maximize the area of contact with the leather. Each one was handmade and represented an investment in time and materials.
4. The clever preparation and use of leather has a very long history, but it seems to have been the book binders who most influenced the way it was used on cases. One often observes crosshatching which tended to disguise imperfections in the leather. Tooling, especially with gilding, was a form of decoration which afforded a sense of importance to books and cases alike. We believe that the leather of the best baroque cases presented a luxurious appearance to the cases being brightly colored with golden accents so that the brown we see today is a pale shadow of the former splendor.
5. The cases are always fitted with a metal lock and stout, metal hinges.
6. The cases fall into two, broad types. The first is the so-called "holster" case which is opened at one end and the violin slid, scroll first, before the end is closed and secured. This type of case is much rarer than the chest type and probably its forerunner. It only ever accommodated a single instrument. The second in the form of a flat chest with hinged lid that is lifted to reveal the violin (or violins) lying horizontally in the space below. The chest type was more suitable for housing a pair of instruments.
7. The chest type invariably has a metal handle centrally located on the lid. The holster type typically has no handle but is often fitted with one or two metal rings to which a carrying chord could be attached.

Before describing each of the cases in detail, two more generalities can be mentioned. Chest cases to holster cases occur in the ratio of 2:1. This ratio has remained constant over the years of our record keeping. Our sample is probably too small to make this ratio statistically significant, but in our experience, surviving examples of holster cases are rare and the reasons for this would be speculation. But if we are permitted to speculate, there could be two possibilities. The first is that fewer were ever made and the second is that fewer have survived. There is little doubt that the holster is less practical than the chest from the point of view that it is less convenient to stow and withdraw the bow and violin and frequently causes wear and tear to the varnish as can be seen from flattening of the back of the scroll caused by sliding it in and out.

It may be that early violin owner/players were forced into choosing between the convenience of portability (the holster was lighter and easier to handle) and the greater security of the chest case which was heavy and clumsy in comparison.

The same portability and convenience of the holster may have inflicted greater wear and tear on the case itself leading to its deterioration and ultimate replacement in later centuries.

We should mention in passing that the brass studwork falls basically into two classes. Either the studs were applied touching each other to give a continuous line of domed heads or they were placed alternately with a gap of approximately 2 cm between adjacent heads. Given that each stud had to be handmade with the shaft being soldered to the domed head, the spaced placing meant a saving of 50% of the studs allowing the case to be finished more quickly and at reduced cost. Generally, the holster cases are nailed in this way implying that they were a cheaper item than the chest but this is a rule with frequent exceptions.

Our Registry of baroque violin cases consists of three sections: holster cases (H), chest type single cases (S), and chest type double cases (D). Each case is uniquely identified according to its classification and position within that classification. Each is followed by a brief description which acts as an aide-mémoire for the author and the italicized entry in parenthesis indicates who took the photo and when).

SECTION 1—HOLSTERS

1H1—Italy? 2009.

1H2 Strad violin label (C. Beare 2007).

1H3 Decorated Holster (C. Beare 2005).

1H4 NMM Vermillion, USA (Author 2007).

1H5. Milan holster, Italy (D. Musafia 2016).

1H6 Stradivario case, Chi mei Museum Taiwan (Author 2016).

1H7 ex Paganini (R. Scrollavezza 2009).

1H8 Tartini case, Castello Sforzesco Milan, (D. Musafia 2016).

1H9 Sotheby's (Author 2001).

1H10 Yale University, USA (A. Dipper 2016).

1H11 Yale University, USA (A. Dipper 2016).

1H12 NMM Vermillion A. Maggini Cremona (Author 2007).

1H13 Castello Sforzesco. Milan, Italy (D. Musafia 2017).

SECTION 2—SINGLES

2S1 CF Single (C. Beare 2004).

2S2 Sforzesco collection. Milan, Italy (D. Musafia).

2S3 NMM Vermillion, USA (Author 2007).

2S4 NMM USA, Padua lute case 17thC (Author 2007).

2S5 Amati ex Una Elliott (Author 2016).

SECTION 3—DOUBLES

3D1 Decorated double (C. Beare 2004).

3D2 NMM Vermillion, USA (Author 2007).

3D3 Crevelli Case London, UK (Author 2011).

3D4 ex Una Elliott (Author 2016).

3D5 Gasparo case (Lyon & Healy catalog).

3D6 Decorated case #1 (Author 2002).

3D7 Decorated case #2 (Author 2002).

3D8 MV case (R. Scrollavezza 2009).

3D9 Strapped case (R. Scrollavezza 2009).

3D10 BE Case (R. Scrollavezza 2009).

3D11 Washington, DC ex W.E. Hill (Author 2014).

3D12 Lindholm case, Stockholm, Sweden (S. Lindholm 2013).

3D13 Natta family case, Chi Mei Museum, Taiwan (Author 2016).

3D14 'Landolfi' case ex Bisiach (L. Negri 2007).

3D15 L Spohr case (T. O'Donnell 2016).

3D16 Sforzesco collection, Milan, Italy (D. Musafia 2016).

3D17 Castello Sforzesco, Milan, Italy (D. Musafia).

3D18 Castello Sforzesco, Milan, Italy (D. Musafia).

3D19 Princess Lilian, Belgium (T. de Launoit).

3D20 Decorated double with tray (Author 2016).

3D21 Pierre Franck. Paris, France (P. Franck 2017).

The Influence of Torsional Vibrations in the Bowed Violin E-String

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Abstract

This research is an empirical exploration of the torsional vibration that is the cause of the open E-string whistle. Measurements were taken directly from the violin string with a laser vibrometer. Evidence is presented that the bowed excitation of torsional vibration in the E-string is dependent on bow velocity, the influence of previously bowed A-string frequencies in the E-string, and the presence of sympathetically excited harmonics in the E-string that coincide at the torsional frequency.

INTRODUCTION

Sometimes when a player does a down-bow on a note on the A-string and then slurs across to the open E-string, the bow just slides over the string, the fundamental tone does not sound, and a high pitched whistle is heard instead. This can be very embarrassing for a performer. It can happen on any violin, even a Stradivarius. The open E-string whistle is not caused by the violin but by a high-frequency radial twisting of the bowed string.

In 1860, Helmholtz [1] showed how the bowed string vibrates laterally in a series of stick/slip saw tooth wave motions. Bow-hair contact displaces the string sideways to form a corner. When the restoring spring force becomes greater than friction, the string slips away from the bow and the corner traverses the string following the line of a parabolic envelope (see an animation of Helmholtz motion [2]). There has been extensive research on Helmholtz transverse string vibration [3, 4]. The term "lateral vibration" is used in the text, though "transverse vibration" means the same.

The high-pitched E-string whistle has been identified by Stough [5] as a torsional vibration. It differs from Helmholtz lateral vibration in that the bow has a small leverage tangential to the circumference of the string that twists the string along its length around a central axis. Torsion is an internal shear spring force that drives its own slip/stick motion against the bow. At the bowing point lateral and torsional displacements of the string occur together. Under normal playing conditions Helmholtz lateral vibration is dominant. The bow grips the string and displaces it further and for longer than it does for torsion. If and when torsion occurs alone, lateral displacement becomes only a very small accompaniment to the higher frequency torsional displacement of the string. Torsion research is challenging because torsional vibration is difficult to isolate and measure. The conditions under which torsional waves occur in the bowed violin E-string is the subject of this paper.

MEASURING BOWED STRING TORSION

Previous attempts to measure torsional waves relied on either attaching electromagnetic coils or a mirror to the string [6–9]. Adding mass anywhere on a string changes the way the string responds to excitation and distorts the measurement. This problem was avoided in the present research by using of a Polytec Scanning

Vibrometer 7.4 to focus a laser beam on the string between the bow and the bridge in the direction of bowing. Transverse string velocity is measure by a Doppler shift in the reflected laser light that returns a signal to a computer [10] where it is transformed into time history and spectral images. Except where otherwise shown, the sampling rate is 16.38 kHz for a frequency range of 6.4 kHz and a measurement time of 2 s.

Bow contact is tangential to the circumference of the string. It both twists the string in a radial motion and also pulls it laterally. This dual action means that when torsional vibration is bowed a small amount of lateral motion is of necessity phase-locked to it. The laser vibrometer records the frequency and magnitude of this motion as well as any small perturbations in the string that might signal transitional changes from Helmholtz lateral motion to torsional motion or vice versa.

The E-string whistle phenomenon presents us with an excellent opportunity to study torsional vibration in the bowed string. We have found that any violin that is fitted with a plain steel E-string is capable of making an E-string whistle. A wound string does not do this. The quality of the violin makes little difference. Two violins that were made according to bimodal plate tuning [11] were used in this research. One had a Dominant medium plain steel E-string, the other a Dominant strong plain steel E-string. In trials where the laser vibrometer was used, the violin was placed in a frame on a bench and held at the chin rest and neck to simulate the way a player would hold it. All bowing and string crossing was bowed by an experienced player using a down-bow. There is a learned knack in bowing the torsion whistle that requires using a fast light bow with rapid string crossing. Any departure from this bowing results in the E-string sounding at its normal pitch.

The whole sequence of bowing the E-string whistle is shown in Fig. 1. The measurement is taken with the laser beam on the E-string between the bow and bridge. First, the A-string is bowed at D = 587 Hz and then the bow crosses to the open E-string. The E-string torsional vibration starts early within the A-string decay. It appears emerging from the A-string decay and continues for ~1 s. Finally, the open E-string sounds at E = 659 Hz. The whole sequence is shown in a 2-s time window.

THE EFFECT OF BOW VELOCITY AND WEIGHT

According to Stough [5] the open E-string whistle is caused by a torsional vibration that results from bowing a plain steel open E-string with a

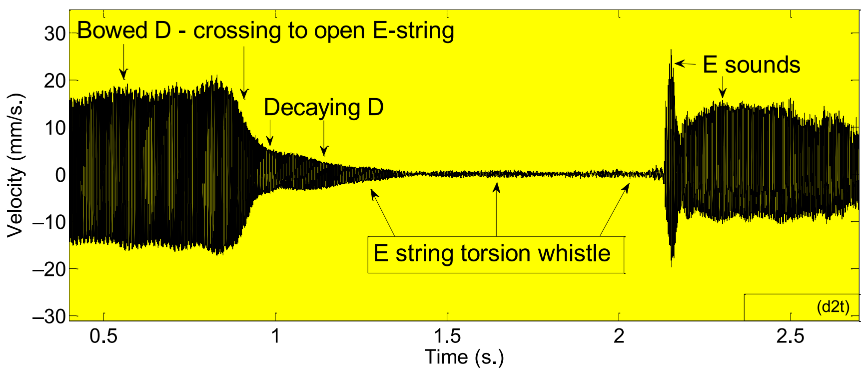
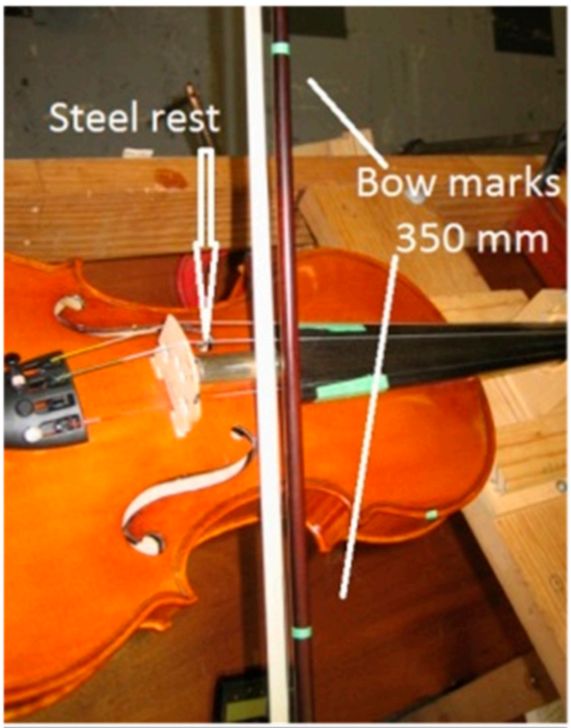


Figure 1. This time history shows the sequence of bowing the torsional whistle. Measurement is taken from the laser on the E-string between the bow and the bridge. On the left is the resonance from the bowed A-string sounding the note D = 587 Hz*, which decays after the bow crosses to the E-string. The torsional vibration emerges from the decaying D and lasts for ~1 s. The torsional vibration is an audible whistle-like sound at ~4900 Hz. On the right the open E-string finally sounds at* E = 659 Hz.

fast light bow. To verify this claim, it is necessary to locate a threshold for a combined bow velocity and force above which torsional vibration occurs and below which only Helmholtz lateral motion takes place. Bowing thresholds for Helmholtz motion have been modeled by Schelleng [12] and Guettler [13, 14]. Although these studies are instructive for bowing Helmholtz later motion, they are not readily applicable to specifying just how much bow velocity and force are required for achieving torsional vibration in a violin E-string.

The bow velocity measured in this research makes use of the player's skill in both holding and bowing the violin. For measuring bowing distance, two pieces of tape were placed on the bow stick at equal distances from the center so that they were 350 mm apart and could be seen by the player (see Photograph 1). The bow was then drawn back and forth between the two markers to keep pace with the clicks of a metronome. A down-bow was then changed to the open E-string. The metronome markings were adjusted up or down until the lowest bow velocity was found that could make the E-string whistle.



Photograph 1. Shows a stainless steel bow rest and bowing distance marks.

There was variability in bowing but over many trials this was selected out by discarding every bow stroke except one. The bow velocity threshold was defined as the one bow stroke that could achieve the torsion whistle with the least velocity.

Tests were done using a Dominant medium plain steel E-string. Three different bows weighing 57, 60, and 63 gms were used. Bow force on the string was not measured. Bow weight is something less than bow force. For example, it does not allow for the force supplied by the player. So each bow was loaded at its center with 10 gm of putty. Although this extra loading still does not give an accurate measure of bow force, it does give an additional increment of bow loading on the string that by comparison could indicate whether or not force is a relevant factor alongside bow velocity in determining the minimum requirement for bowing torsion.

Table 1 shows the bowing threshold velocity values for three bows of different weights and again when they were each loaded with 10 gm of putty.

Measurements of the minimum bow velocity for bowing a torsional vibration in the violin E-string were always considerably less for the unweighted bows than Stough's estimate of 420 mm/s [5]. The 63 gm bow was different from the other two. It had very coarse hair and a stick with less spring resistance to tightening and an opposite camber that might explain why its measured velocity differs from the other two bows. From these data it appears that there is a threshold of bow velocity relative to each bow and that additional bow weight as a component

Table 1. Torsion thresholds relative to bow velocity and weight.

Three Bow Weights (gm)	Bow Velocity (mm/s)
57	367
60	385
63	350
57 + 10	402
60 + 10	466
63 + 10	548

of force on the string leads to an increase in the velocity required to bow torsional vibration. Bowing the string below these thresholds always resulted in the open E-string sounding.

So far we have demonstrated that a combined bow velocity and weight above a certain threshold is a necessary condition for bowing torsional vibration. However, as will be shown, there are marked differences in triggering and sustaining torsional vibration when crossing from notes on the A-string. This suggests that there might be multiple factors that contribute to torsional vibration in the bowed string.

HOW RESONANCES COMBINE ON STRING CROSSING

Bowed torsion in the open E-string does not exist in isolation from other coexisting sources of vibration. The first of these vibrations comes from the A-string that is bowed before crossing to the E-string. The bowed A-string couples through the bridge and violin body and can be recorded in the E-string. It dominates the unbowed E-string but also weakly excites the E-string's natural resonance.

Figure 2 shows a forced resonance from the bowed A-string = 535 Hz with harmonic multiples in the unbowed E-string. A weak natural E-string resonance = 655.5 Hz is also shown with its harmonic multiples. It is of interest also that the 9th harmonic of E and the 11th harmonic of the forced A-string resonance add in superposition when they coincide at ~5887 Hz. This high resonance is not torsional but does illustrate the general principle of coincident superposition that later will be shown to be important for understanding how torsional vibration can sometimes interact with other frequencies.

THE FREQUENCY OF BOWED TORSION

To measure the frequency of bowed torsional vibration the violin was held in a frame and bowed above the torsion threshold. The A-string was removed to eliminate A-string influence in the open E-string. A stainless steel bow rest that had no contact with the bridge was substituted in place of the A-string (see Photograph 1). This allowed the bow to gather velocity before crossing to the E-string. The E-string was a Dominant strong plain steel string tuned to 659 Hz. The torsion whistle was heard before the E-string sounded. Figure 3 shows torsional vibration at 4970 Hz. In this case torsional vibration appears part way between the 7th and 8th harmonic of the open E-string. It therefore cannot be attributed to a natural harmonic of the E-string. In this test there is no influence from the absent

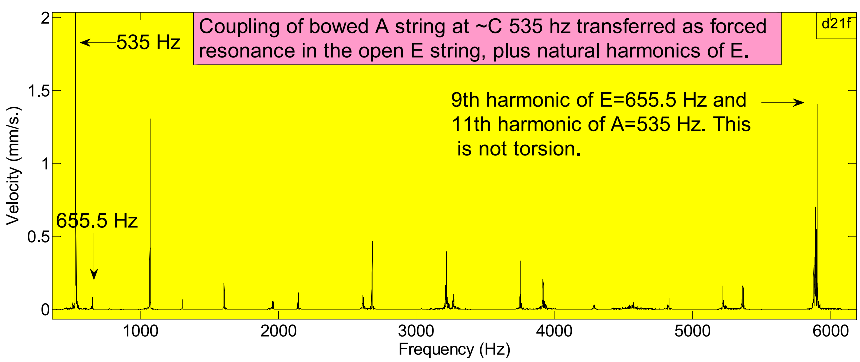


Figure 2. The laser is on the E-string near the bowing point and the A-string only is bowed at 535 Hz. The bowed A-string couples through the bridge to the open E-string. There is a forced resonance at 535 Hz with harmonic multiples in the unbowed open E-string. There are also weak natural resonances of the E-string at multiples of E = 655.5 Hz. *Both sets of harmonics combine to form a high-amplitude frequency around 5887 Hz. Note: This is not torsional vibration but does exemplify the principle of coincident superposition.*

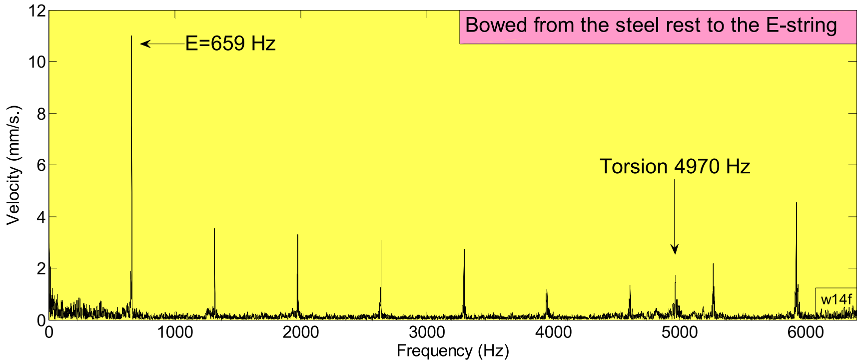


Figure 3. The spectrograph shows that there is torsional vibration between the 7th and 8th harmonic of the bowed E-string. Torsional vibration = 4970 Hz, Velocity = 1.7 mm/s. The measurement was taken from the laser on the E-string between the bridge and the bow. Torsional vibration and the E-string harmonics though seen here together are sequential events similar to the Figure 1 time history. A Dominant strong string was used in these measurements.

A-string or the violin sound box and the magnitude of the torsional vibration is very low compared with that of the open E-string.

HYPOTHESIS 1: A-STRING INFLUENCE ON TORSION

The observation from Fig. 2 that a harmonic from the bowed A-string can couple in superposition with a natural harmonic in the unbowed E-string gives rise to the most interesting part of this research. Different A-string and E-string frequency relationships were used to test whether coincident frequency couplings and/or noncoincident frequency couplings have any effect on torsional outcomes.

Our first hypothesis is that the A-string forced resonance in the unbowed E-string has a disruptive effect on the bowed start-up of the open E-string that allows the torsional stick/slip action to start first and gain dominance. When the bow is about to initiate a Helmholtz stick/slip sequence that matches the natural resonance of the E-string at 659 Hz it meets a string that is already resonating strongly at a different lateral frequency. The bow cannot get instant traction to start-up the lateral stick/slip process. If the bow velocity is high enough, torsional vibration starts first.

To give demonstrable proof of this hypothesis many tests were performed varying the frequencies of the bowed A-string so as to produce forced resonances in the E-string to see what differences they make to the start-up of torsional vibration. The laser vibrometer was focused on the E-string between the bow and the bridge to record what was actually occurring in the string before and after string crossing. The results of testing show the following two ways the A-string resonance clearly influences the outcome for torsional vibration.

First, in complete contrast to our hypothesis for the start-up of torsional vibration, if the note $E = 659$ Hz is stopped and bowed on the A-string before crossing to the open E-string, the torsion whistle never occurs, not even with a very high bow velocity. This is because the bowed A-string sets up a sympathetic resonance in the E-string with a lateral displacement that the bow stick/slip mechanism can easily continue without interruption when the bow crosses to the open E-string.

Second, when a different note is bowed on the A-string it introduces a forced resonance in the E-string. The start-up of the natural resonance in the E-string is disrupted by the forced resonance giving the torsional radial motion the advantaged to start first and set up a stick/slip rate seven times faster than required for the open E-659 Hz. If the note bowed on the A-string has a harmonic that is coincident with the torsional frequency, then the forced resonance now becomes a sympathetic resonance at the torsional frequency and the two resonances become phase-locked under a matching stick/slip rate at the bow. In this circumstance there is a greatly increased probability not only of just bowing a torsional vibration but also of increasing its magnitude and of giving it a shorter transition time at start-up. Figure 4 shows a high magnitude = 7.6 mm/s at the torsional frequency = 4883 Hz when the eleventh harmonic of the bowed A-string is coincident with the torsional frequency. Figure 5 shows two time history plots that illustrate the start-up time for torsional vibration when the bowed A-string is noncoincident and coincident with the torsional frequency.

Figure 5 shows details in two time history plots of bow string crossing from the A-string via transitions to torsional vibration in the E-string. In Fig. 5:1a and 1b, the A-string resonance is noncoincident with the torsional frequency and the transition time is ~60 ms. In Fig. 5:2a and 2b, the A-string harmonic is coincident at the 7th harmonic with the torsional frequency and the transition time is ~35 ms. The shorter transition time when a harmonic of the A-string forced resonance is coincident with the torsional frequency supports our hypothesis. We have also observed that different coincident A-string harmonic frequencies show similar shorter transition times than when they are noncoincident with the torsional frequency.

HYPOTHESIS 2: E-STRING INFLUENCE ON TORSION

The second major hypothesis extends and completes the notion that coincident frequencies influence the outcome of torsional vibration by including those that exist within the E-string itself. When the E-string is tuned up or down so that one of its natural harmonics is coincident with the A-string forced frequency and the torsional frequency, there is a dramatic increase in the magnitude at the torsional frequency. At the bowing point, the torsional stick/slip mechanism phase-locks the other two harmonic resonances to the torsional frequency. Figure 6 shows just one of many examples of this triple coincident combination. The 8th harmonic from the forced A-string = 577 Hz and the 7th harmonic of the open E-string = 655 Hz coincide with the torsional vibration at 4603 Hz in a high magnitude response = 21 mm/s. Notice that all other lower harmonics that normally belong to the two lateral string resonances are prevented from appearing when the torsional vibration and coincident harmonics combine.

Figure 6 raises the question of whether torsion controls the phase-locking of all three

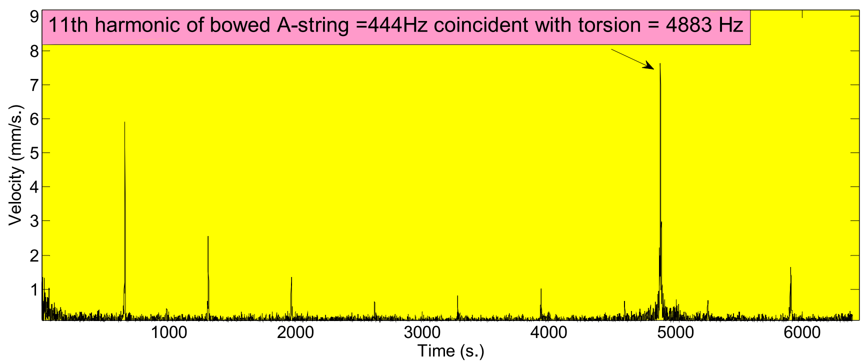


Figure 4. This spectrograph shows the E-string torsional frequency = 4883 Hz with a velocity magnitude of 7.6 mm/s. The bowed A-string was stopped at 444 Hz and has its 11th harmonic coincident with the torsional vibration = 4883 Hz. The torsional frequency falls between the 7th and 8th harmonic of the open E-string that sounds only after the torsional vibration has ceased. A Dominant medium string was used in these measurements.

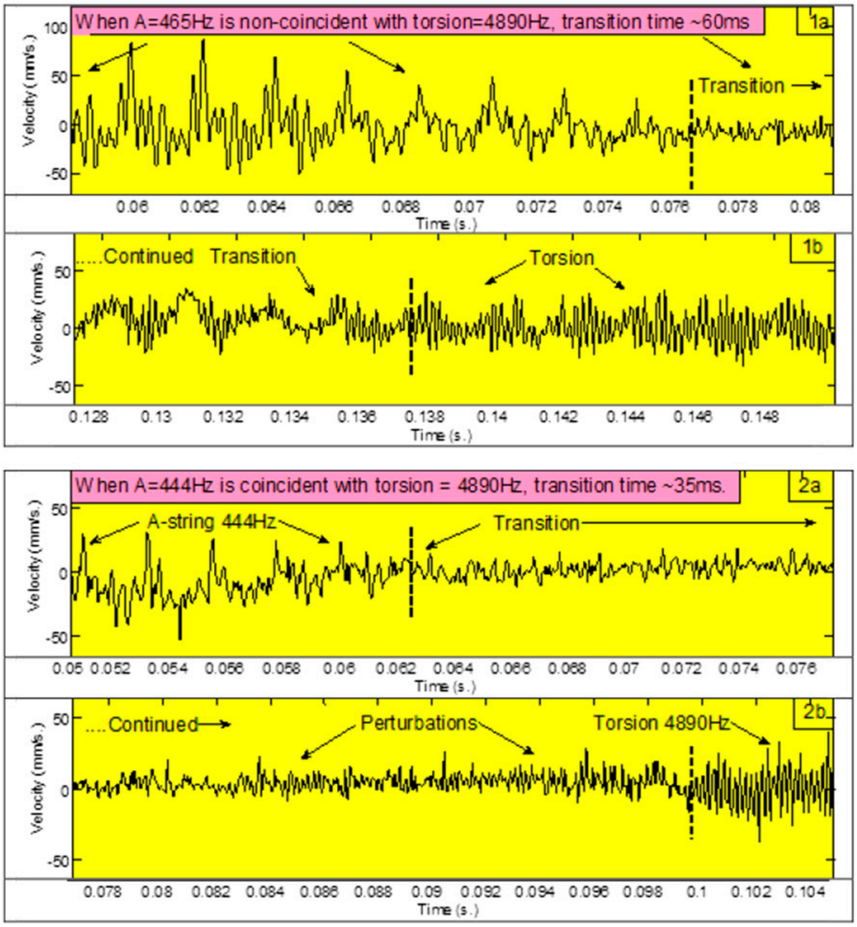


Figure 5. In sections 1a and 1b there is a transition time of ~60 ms from the bowed A-string to torsional vibration when the forced resonance A = *465 Hz is noncoincident at a harmonic with the torsional frequency. In Sections 2a and 2b, the transition time is ~35 ms when the forced resonance* A = *444 Hz is coincident at the 11th harmonic with the torsional frequency. Time plots 1a and 1b are not continuous. There is intervening time that is not shown for reasons of space. The vertical dotted lines indicate where the measurements of transition time begin and end. A Dominant strong string was used.*

coincident resonances or if it is just a simple superposition of two harmonics with the torsional vibration. This can only be answered if in a separate trial the torsional vibration can be removed while leaving the A-string and E-string resonances in place. In earlier experiments on the E-string torsion whistle, it was discovered by chance that if a small piece of masking tape 3 mm × 4 mm is either placed on or wrapped around the E-string on the bow side close to the bridge, then it becomes impossible to bow the torsional vibration no matter what bow speed is used. A series of tests were performed, with the tape "off" to include torsional vibration and with the tape "on" to exclude torsional vibration.

Figure 7 shows that when torsional vibration is excluded, by adding the small amount of masking tape to the E-string on the bow side close to the bridge, the A-string and E-string

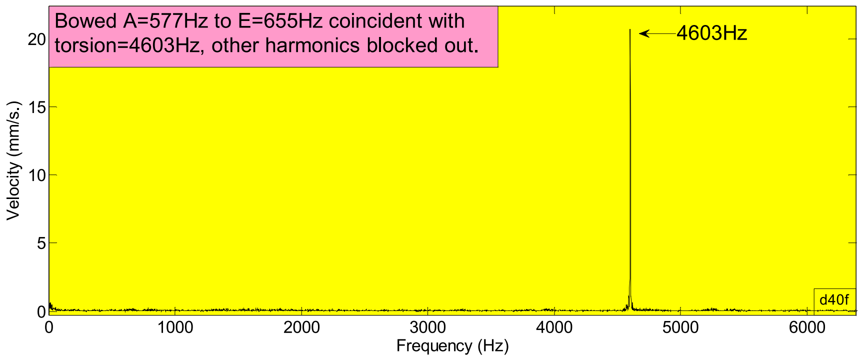


Figure 6. The 8th harmonic of the forced resonance from the A-string = 577 Hz and the 7th harmonic of the open E-string = 655 Hz are coincident with the torsional vibration = 4603 Hz. All three combine in one high magnitude resonance = 21 mm/s and all lower harmonics from the A and E strings are excluded. The bow stick/slip phase-locks all three resonances at the torsional frequency. A Dominant medium string was used in these measurements.

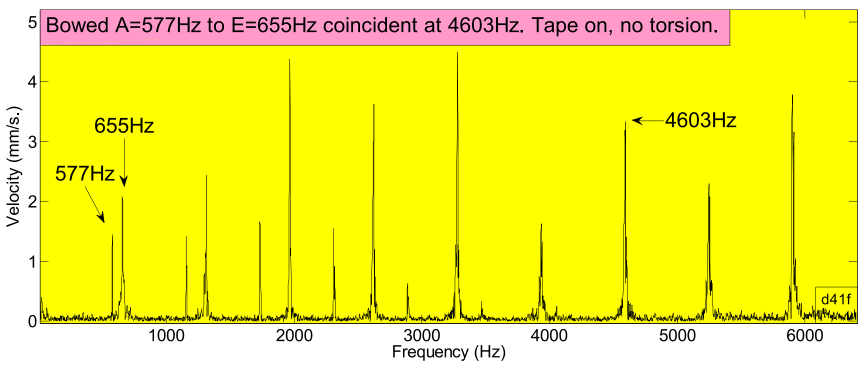


Figure 7. In this trial, following the Fig. 6 trial, torsional vibration was removed by the addition of a small piece of tape 3 mm × 4 mm on the bow side of the string close to the bridge. Without torsional vibration the A-string and E-string resonances still have a coincident harmonic resonance at 4603 Hz but the amplitude falls from 21 to 3.5 mm/s and all the lower harmonics for both strings have returned.

harmonic resonances remain coincident at 4603 Hz but their combined magnitude has fallen from 21 to 3.5 mm/s. Furthermore, all the lower harmonics of the A-string and E-string resonances have returned. It is as though the tape effectively damps torsional vibration and then in the absence of torsional vibration the Helmholtz lateral motion returns to its former harmonic spectrum.

HOW TORSION CONTROLS BOWED STRING HARMONICS

The contrast between Figs. 6 and 7 provides evidence for describing how torsional vibration holds the other coincident frequencies in a harmonic superposition. When torsional vibration is started by a fast bow and when the other string resonances have frequencies coincident with the torsional vibration some very remarkable things happen in the bowed string.

First, bowed torsion prevents Helmholtz lateral motion from getting the energy it needs from the bow. At the torsional frequency, the Helmholtz fundamental at best can only get one-seventh of its sticking time. One-seventh of bow friction is not enough to give the Helmholtz stick/slip motion the traction it needs for full lateral displacement. If the Helmholtz tuning of the string has a harmonic that is coincident with the torsional frequency, then only that harmonic can get the sticking time it needs to become excited. When the tuning of the string is noncoincident at a harmonic integer with the torsion frequency, then Helmholtz lateral motion does not get any regularly synchronized frictional sticking time at the bow and therefore cannot become excited.

Second, in violin playing, a player plays a harmonic by touching the string lightly at a node so as to damp all other resonances leaving only the chosen harmonic to sound. A node is a point on the string where the displacement of the lateral wave passes through zero. When an E-string natural harmonic resonance and an A-string sympathetic harmonic resonance combine at the torsional frequency they pass through zero at a common node. And that is just where the expected influence of torsion's radial motion around the string's central axis would be most concentrated. It appears as though torsion substitutes for the player's finger by damping at this node. As demonstrated in Figs. 6 and 7 when torsion is removed by placing a little tape on the string, the harmonic node for the coincident A-string and E-string resonances has no means to survive on its own. When torsional vibration is removed by damping the pattern reverts to the whole spectrum of Helmholtz lateral motion. We leave it to physicists to work out the complexities of how torsion might be operating in this circumstance.

Third, as a corollary of two and three above, when frequencies progressively get closer to each other and finally coincide at a common harmonic, their frequency differences have reduced to zero and the magnitude of their joint resonance has become large. This is due to the superposition principle and is seen in Fig. 6 when the A-string forced resonance and E-string natural resonance both have harmonics that coincide at the torsional frequency = 4603 Hz.

EVIDENCE FROM TIME HISTORY PLOTS

A closer look at time history plots of torsional motion will show more about the relationship between coincident lateral frequencies and torsion. First, when harmonic resonances in the E-string are coincident at the torsional frequency the stick/slip pattern becomes regular, (see Fig. 8:1). Second, when the E-string harmonic resonances are noncoincident the string's lateral stick/slip motions show perturbations. It is as though they are about to lose their connection with the bow but cannot quite do it. Then they return and spasmodically phase-lock at the repetition rate for torsional vibration, (see Fig. 8:2). Third, there are other patterns that combine motions found in 1 and 2, (see Fig. 8:3). Here there are perturbations that drift back into coincidence with the torsional frequency for ~4 ms. Such a drift could be caused by frequencies close to but not exactly coincident with torsion that superimpose briefly before parting again and/or by a small sideways shift in the bowing position relative to a node for the lateral frequency in question. There are also amplitude differences seen by the laser at the point of measurement a few millimeters away from the bow. When the resonances are exactly coincident the lateral extension is greater as in Fig. 8:1. When the resonances are noncoincident the lateral extension is less as in Fig. 8:2. Data measured from the E-string during trials of coincident and noncoincident harmonic frequencies with the torsional frequency always show similar contrasting patterns in the time history plots.

There are others variations to the three time history examples shown in Fig. 8. These variations have patterns that fall somewhere between complete coincidence and noncoincidence. An interesting one is shown in Fig. 9 because there are two alternating repetition rates for the torsional vibration. The E-string was tuned so that the torsional vibration would fall exactly half way between its 7th and 8th harmonic, which is at 7.5 multiples of E = 659 Hz. A low-amplitude torsion was expected but a much higher one resulted. In looking for an explanation, it was

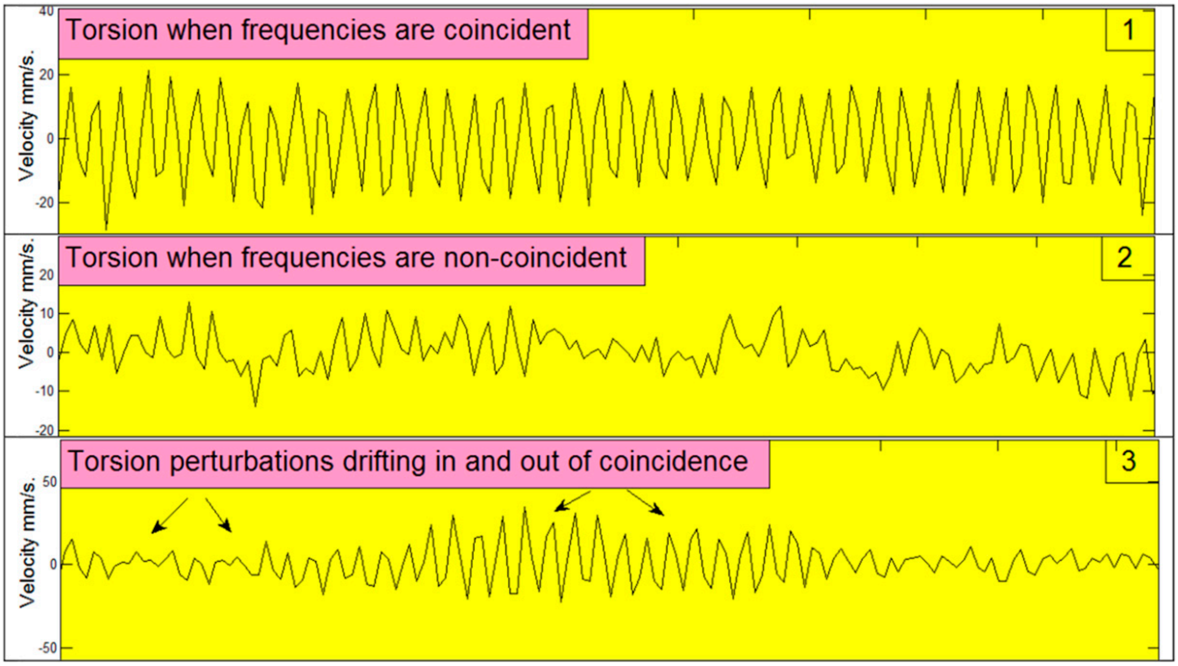


Figure 8. All three samples have the same torsional frequency = ~4890 Hz. The pattern in 1 is regular and is formed by coincident coupling of the A-string and E-string harmonic resonances at the torsional frequency. The pattern in 2 shows perturbations in the bow stick/slip continuity. The perturbations are spasmodic interruptions when the A-string and E-string harmonic resonances are non-coincident with the torsional vibration. In 2 the A-string resonance was 655 Hz, 1:7.47 noncoincident with the torsional frequency. The E-string resonance was E *= 659.5 Hz, 1:7.4 noncoincident with the torsional frequency. The pattern in 3 shows perturbations drifting in and out of coincidence with the torsional vibration for ~4 ms. A Dominant strong string was used. The time window is 0.009 s in all three plots.*

retested with the time window extended so that the second harmonic of torsion could be seen. Figure 9 (lower) holds the answer. What was noncoincident at the 1st harmonic of the torsional vibration became coincident at the 2nd because 7.5 × 2 = 15th harmonic of E and that is equal to the 2nd harmonic of the torsional vibration = 9938 Hz. This was a very rare event because tuning the E-string to that degree of accuracy is almost impossible because any error is multiplied 15 times at the 2nd harmonic of torsion. Much trial and error testing was required to replicate the exact ratio 1:7.5 so as to get exactly 1:15 for the 2nd harmonic of the torsional vibration.

In the time history plot of Fig. 9 (top), the higher alternate peaks are where the 2nd harmonic combines in superposition with the 1st harmonic. In the lower figure, the spectrograph of the 1st harmonic of torsion is noncoincident at a 7.5 multiple of E = 662.5 Hz. The 2nd harmonic of torsion is coincident at the 15th harmonic and therefore has a higher magnitude = 32 mm/s. Normally an E-string tuned as noncoincident with the torsional frequency would have a torsional magnitude of ~0.5 to ~2 mm/s but the spectral plot is up to 23 mm/s that suggests that the coincident 2nd harmonic with a magnitude of 32 mm/s changes the string dynamic to enable torsion to channel extra energy into the 1st harmonic.

By now the reader should have no doubt that coincident and noncoincident A-string and E-string harmonic resonances couple with the torsional vibration to influence the extent of its occurrence or nonoccurrence. There are other odd examples worth mentioning. It is very difficult to bow torsional vibration from the

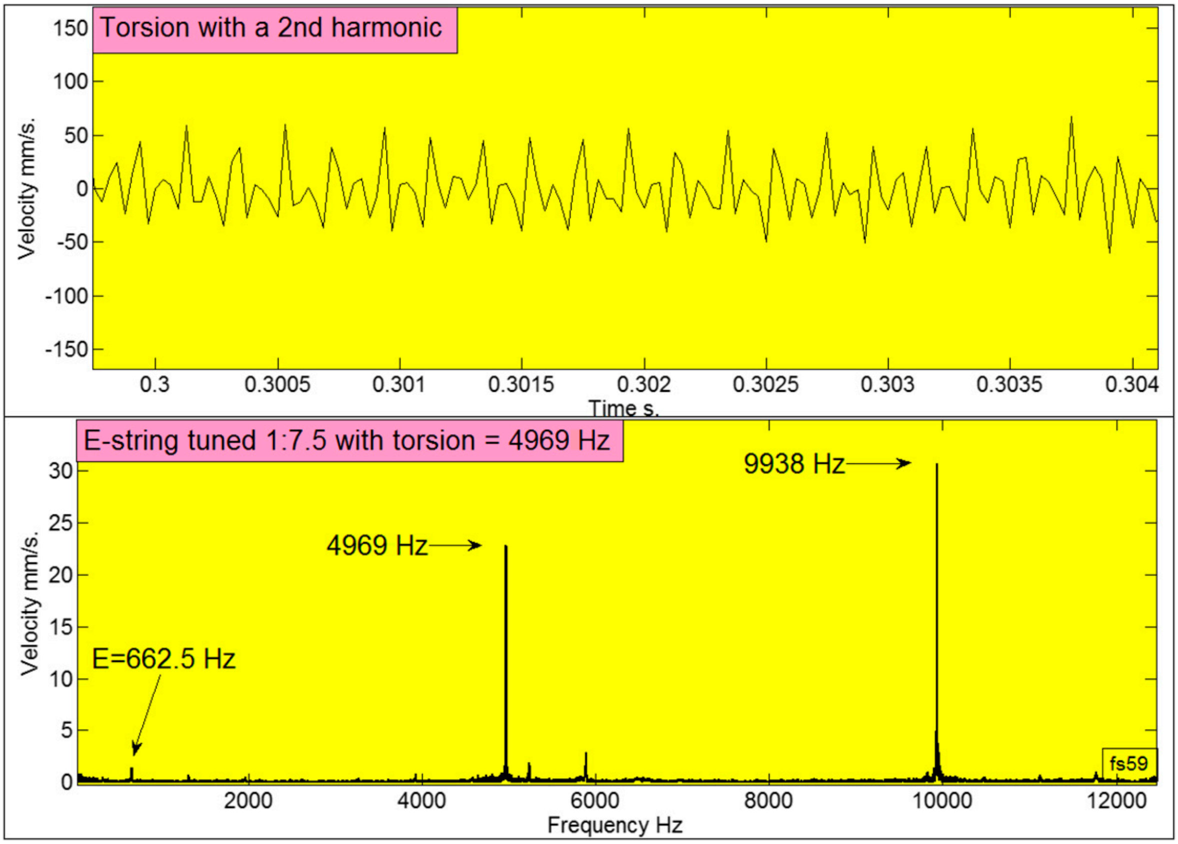


Figure 9. At the top, the time history plot shows double the repetition rate for the torsional fundamental frequency. The higher alternate peaks are where the 2nd harmonic combines in superposition with the 1st harmonic. The lower spectrograph shows the 1st harmonic of torsion = 4969 Hz as noncoincident at a 7.5 multiple of E *= 662.5 Hz. The 2nd harmonic of torsion = 9938 Hz is coincident at the 15th harmonic of E and therefore has a higher magnitude = 32 mm/s. A Dominant strong string was used. The sampling rate is 32 kHz for a frequency range of 12.5 kHz and a measurement time of 1.024 s.*

open A-string if it has a strong 3rd harmonic which it often has. This is because the 3rd harmonic of A is an E and, as was stated earlier, a sympathetic A-string resonance coupled to the E-string favors the bow connecting directly to E so that the torsional vibration cannot be bowed. At one stage during this research, with the A-string off, torsion in the E-string could still be bowed crossing from notes stopped on the D-string. Obviously, torsional vibration could not be bowed from *E* = 330 HZ, the octave below the open E-string, for the reason just stated above. However, torsion could be bowed from other positions on the D-string especially where the principle of coincident frequencies applied even when they were an octave lower than their A-string counterparts.

EVIDENCE FROM QUANTITATIVE DATA

Figure 10 is provided to give quantitative evidence in support of our hypotheses: (1) that there will be a higher response magnitude in the bowed E-string at the torsional frequency if the bow first crosses from an A-string tone with a harmonic that is coincident with the torsional frequency than if the A-string tone is noncoincident with the torsional frequency; and (2) that this response magnitude will be higher still if the

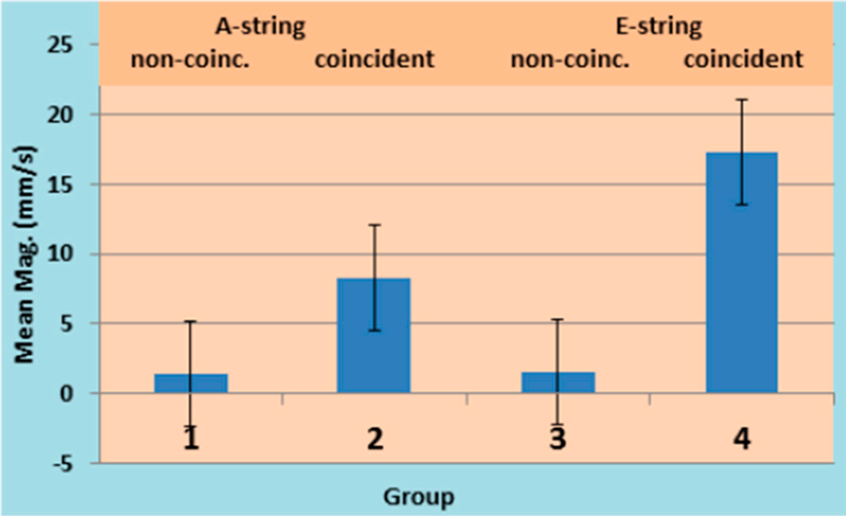


Figure 10. The histogram bars are mean magnitudes in mm/s for the E-string response to bowed torsional vibration. Bars 1 and 2 relate to hypothesis (1) and compare the E-string response when A-string harmonics are noncoincident and coincident at the torsional frequency. Bars 3 and 4 relate to hypothesis (2) and compare the E-string response when the E-string is tuned to be noncoincident and coincident with the torsional frequency. Error bars are included and a statistical test is shown below.

E-string is tuned so that a harmonic is coincident with the torsional frequency than if it is noncoincident with the torsional frequency.

Figure 10, shows histogram bars representing mean response magnitudes in mm/s for the E-string when it was bowed at the torsional frequency. Bars 1 and 2 compare this response when an A-string tone was bowed before crossing to the E-string that had a harmonic that is noncoincident and coincident with the torsional frequency. Bars 3 and 4 compare this response when an E-string harmonic is also noncoincident and coincident with the torsional frequency.

The paired comparisons 1 with 2 and 3 with 4 were analyzed using a one-tailed statistical t-test, with degrees of freedom = 19 and 30, respectively. Each test returned a probability <0.01. Therefore both of the hypotheses stated above can be accepted with confidence. The error bars give a visual indication of any overlap in the mean variance relating to data sets 1 and 2, and 3 and 4. The statistical tests give much greater substance to the comparisons by giving calculations of probability supporting high levels of confidence.

TORSIONAL FREQUENCY RELATED TO STRING LENGTH

Does bowed torsional frequency change with string length and tension? Torsional frequencies were measured as the string was made shorter starting with 20 mm increments. These had to be changed to 10-mm increments as the string became shorter until finally torsion could no longer be bowed at string lengths less than ~230 mm. The E-string frequency was held constant at 659 Hz and therefore had to be retuned for each reduction in string length.

Predicted torsional frequencies were calculated for string lengths between 230 and 340 mm. The formula as described in Stough's paper [5] was used for the 1st natural frequency of the torsional vibration for a string of length L with fixed ends:

$$f_1 = \frac{1}{2L}\sqrt{\frac{G}{\rho}}$$

where $G = 7.68 \times 10^{10}$ Pi and $\rho = 7{,}842\,\mathrm{kg/m^3}$ are, respectively, the shear modulus and mass density of the string.

Both the measurements and calculations were plotted and are shown in Fig. 11. There is good general agreement between the predicted and measured torsional frequencies however the calculated frequencies are ~4% less than those measured. Unlike the Helmholtz lateral pitch of the string which changes according to length and tension, torsional frequency is inversely related to string length but did not change with changes in tension.

CONCLUSION

Torsion is an alternating radial motion that has its own stick/slip contact with the bow. Unlike normal string pitch that can be varied by changing string tension or length, torsional frequency does not change with string tension but changes inversely as the string is made shorter. This feature has allowed experimental manipulations that were used in this study to test the relationship that torsional vibration has with other bowed string resonances.

Multiple factors influence the switch from Helmholtz motion to torsional motion in the bowed steel E-string. First, there is a minimum bow velocity and force on crossing from the bowed A-string to E-string that starts the rapid stick/slip motion of the bow at the torsional frequency. This is variable according to characteristics of the bow and string.

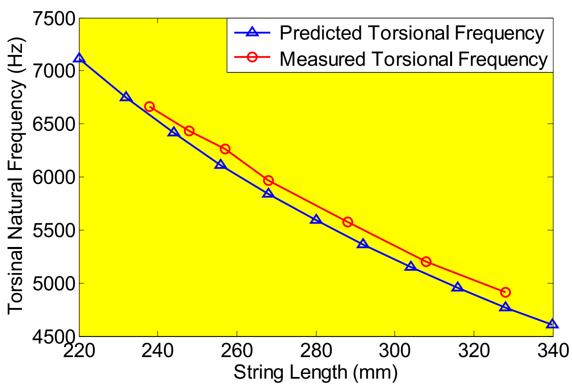


Figure 11. The (red) line shows the measured torsional frequency of a bowed violin E-string with changes to the string length while the string frequency was adjusted so as to be held constant at 659 Hz. The (blue) line shows the calculated torsional frequency for changes in string length. There is good general agreement between the predicted and measured torsional frequencies, though the calculated frequencies are ~4% less than those measured. A Dominant medium string was used for the measurements of torsional frequency.

A high bow velocity at string crossing is not always enough to guarantee torsion. At string crossing either Helmholtz motion or torsional motion can occur depending on whichever one finds a favorable preexisting resonance in the open E-string. Most often when the A-string is bowed it couples through the bridge and violin body to induce a forced resonance in the E-string. This forced resonance interrupts the Helmholtz slip/stick mechanism before it can gain traction and torsional vibration starts instead. However, if the A-string is bowed at the same frequency as the open E-string, a preexisting sympathetic harmonic resonance transfers to the E-string and that favors the start-up of Helmholtz motion. In this circumstance torsion cannot be bowed regardless of bow velocity.

Furthermore, if before string crossing the A-string is bowed at a harmonic frequency that is coincident with the torsional frequency, the transition time required to start the torsional resonance in the E-string is less and the velocity magnitude at the torsional frequency is greater. Similarly, if the E-string is also tuned so that a harmonic resonance is coincident with the torsional frequency, then the E-string velocity magnitude at the torsional frequency is very large.

The fact that bowed torsional vibration can couple with and maintain coincident harmonic resonances in opposition to the more usual Helmholtz harmonic series is because of timing. The high frequency of torsional vibration leaves insufficient time in its bowed short stick/slip window for Helmholtz lateral motion to gain traction at the bow. When bowed torsion controls the string coincident frequencies at a harmonic belonging to either the bowed A-string or originating in the bowed E-string, or when both combine in superposition, the response magnitude at the torsional frequency is greatly increased. This coupling of harmonics is held in place by torsion. If torsional vibration is removed by damping the string close to the bridge, the Helmholtz fundamental and its harmonic series comes back and the open E-string sounds.

The methodology used in this study has examined the forced and sympathetic resonances that couple at harmonic frequencies with the frequency of torsional vibration. This methodology has potential uses that could extend bowed string research to a wider range of vibrational and musical effects. These could include variations in transition response time after string crossing and tonal shifts due to the coupling and superpositioning of coincident harmonics.

Our analytical comments are those that more closely relate to what can be observed in the empirical data. There is much more theorizing that can be done and we invite others including theoretical physicists to take up that challenge.

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Analysis and Synthesis of Violin Arches

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Abstract

Modern methods provide extensive data on the shape of fine old violins. This should allow makers to copy the arches, for example, of old violins—except that a modern maker would not want to copy exactly the arch of an old instrument. The arches of old instruments are asymmetrical, and have asymmetrical outlines and bottom edges which are not flat. The modern maker wants to make a symmetrical arch, with a symmetrical outline, and flat bottom edges. So the problem is to use the data from an old asymmetrical instrument to somehow construct the arches of a new symmetrical instrument. In this article, we describe a construction method that starts from computed tomography (CT) scan data, and (1) is strongly based on data from an instrument, (2) completely defines the arch from edge to edge, (3) involves minimal human choice, and (4) allows controlled alteration of the arch. The method produces a 3D model of a violin arch. The model can be used, for example, to drive a CNC router or 3D printer, to cut cross-section templates ("quinte"), or to be part of modeling the acoustic behavior of an instrument.

OUTLINE

In this article, we describe the arch as built in three pieces: a central part, the edge, and a fill section (Fig. 1).

The edge can be designed very simply using standard computer-aided design (CAD) tools. The central part is the real concern. The fill section must smoothly bridge the gap between the central part and the edge. Designing the fill section is difficult, but has no great significance, and will not be discussed in detail.

An important concept is what we call the "low curve". The arch descends from the center toward the edge. Before it reaches the edge, it turns up slightly. Look at the lowest points (Fig. 2); the collection of all these lowest points is the "low curve". In our description, the low curve is the edge of the central part of the arch. Outside the low curve, the "fill section" begins.

Although our approach is not the only possible one, we think of the central part of the arch as built from cross-section curves sitting on top of the low curve. For readability, see Figure 3, which shows cross-section curves at 30-mm intervals. The actual spacing used was 2 mm.

Defining these cross-section curves is the real meat of the method. The method defines a family of curves with enough parameters (adjustabilities) to describe the cross-section data of a violin, but not too many to be manageable. We find these parameters for the old instrument ("analysis"), and build a new arch using these parameters ("synthesis").

THE DATA

We begin with a CT scan of a fine violin.[1] The scan data consists of X-ray densities of little cubes about half a millimeter on each side. Notice that we usually describe violin dimensions to 0.1 mm; the data we are starting with here

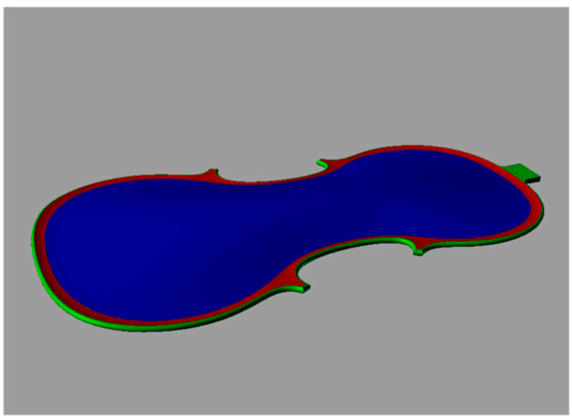

Figure 1. Edge, fill, and central parts.

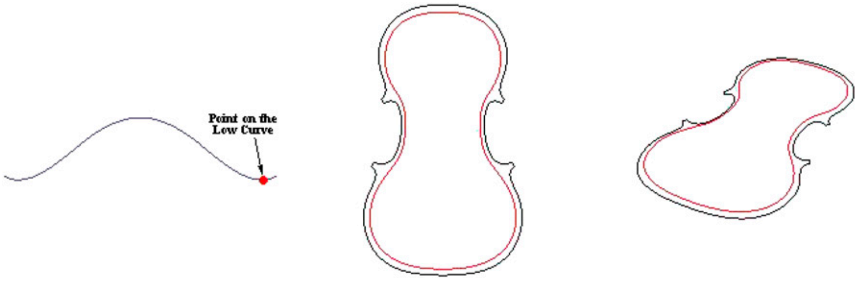

Figure 2. The "low curve".

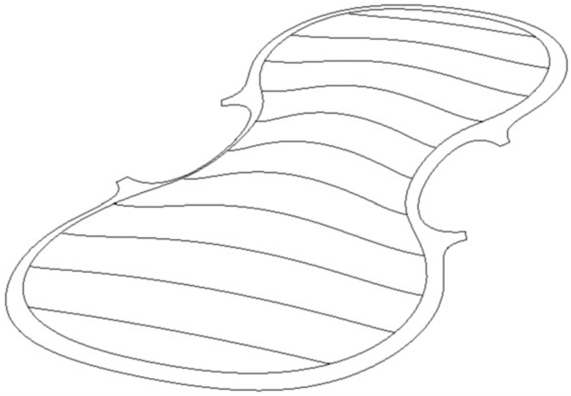

Figure 3. Cross sections sitting on the low curve.

is in some sense five times coarser! Figure 4 shows a cross section including the fingerboard. Figure 5 is a close-up of the data in the small rectangle. Each square is about 1/2 mm on a side. Figure 6 shows the values along the vertical line given in Figure 4. Adjacent points are separated by about 0.5 mm. Note the complicated behavior at the edges of the bottom, top, and fingerboard. The point here is that getting fine resolution measurements from CT data is not a simple matter.

The first step in using the CT data is to extract the surfaces of the instrument—inside and out. This is a substantial operation; it was performed for me by Biomedical Modeling Inc. of Boston, MA, USA. Biomedical Modeling chose to use the stereolithography (STL) format for the extracted surfaces.

The basic idea is that the surface is assumed to be at a certain X-ray density ("threshold"). Choosing a different threshold will cause the surface to move in or out, as shown in Figure 7.

The shape of an arch in the extracted surface will vary very little with change of threshold, because arches are fairly flat curves. For example, Figure 8 shows two curves. The upper curve is offset by 1/2 mm from the lower. But, if we pull the upper one down by 1/2 mm to make the ends coincide, then the maximum distance between the two curves is only 0.035 mm. In other words, the two curves have nearly the same shape.

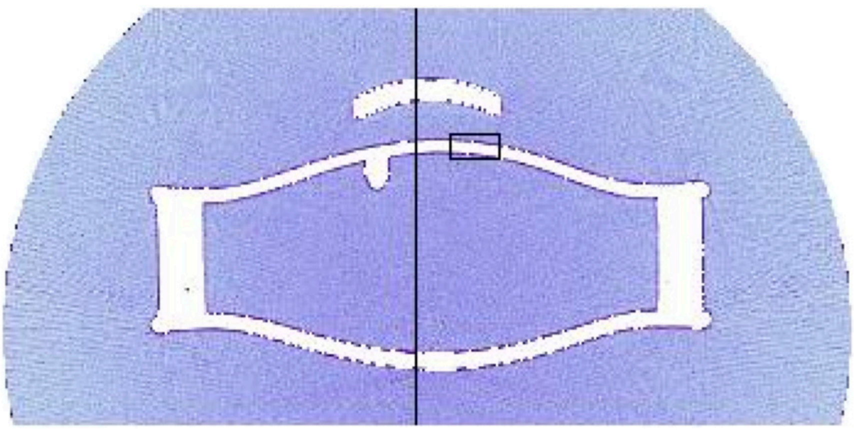

Figure 4. Cross section including the fingerboard.

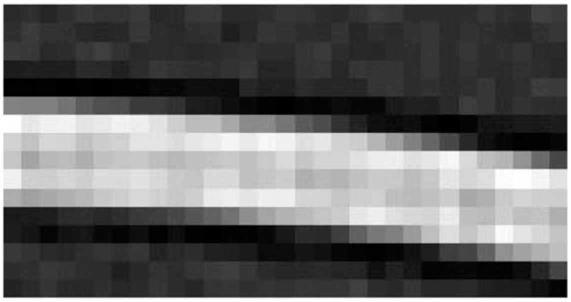

Figure 5. Close-up of the data.

On the other hand, a thickness found from the extracted surfaces will depend on the threshold, and will typically require a correction to make it match reality.

The following analysis works entirely off the STL file. In one place, a thickness (graduation) is involved, and a correction will be explicitly made. Otherwise, only shapes are involved, and no correction is made.

ANALYSIS OF CROSS SECTIONS

Figure 9 shows the outside cross section of the back, 75 mm above the tail end. The view is looking up from the tail end toward the scroll. The instrument is turned over, with its back up, so the bass side is on the right. The points are taken from the STL file at 1-mm intervals, and have been moved so that the lowest points are on the base line, equally spaced on the two sides.

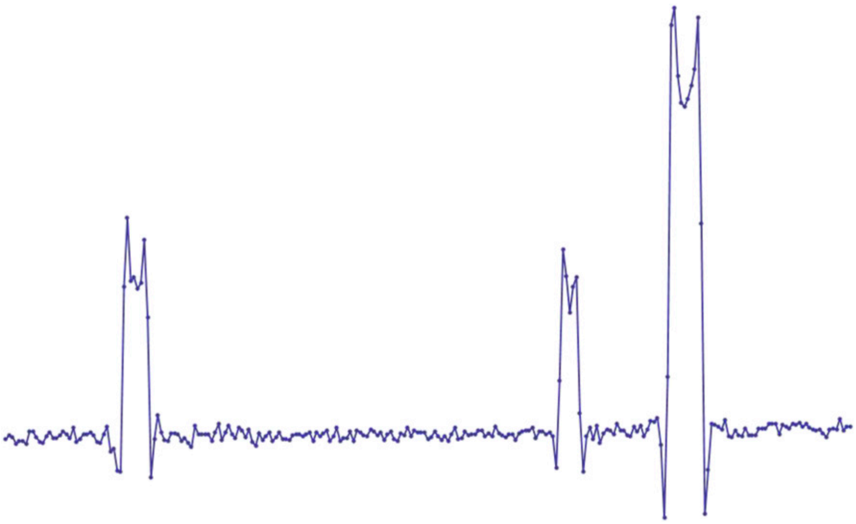

Figure 6. Values along the vertical line.

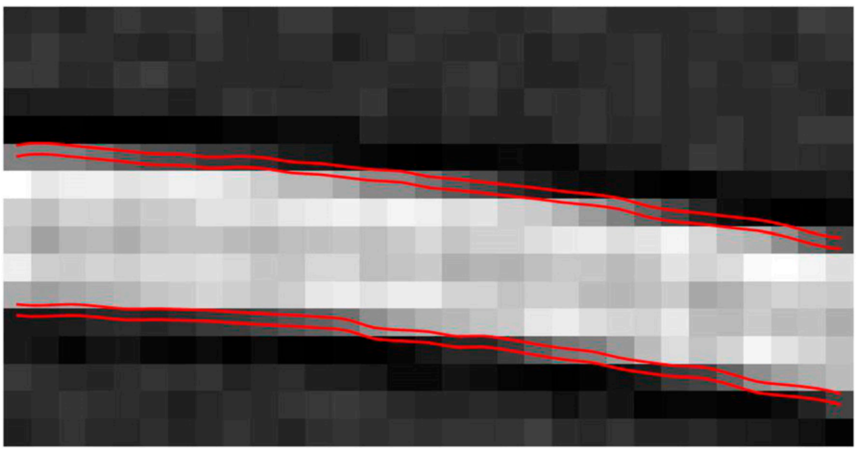

Figure 7. Different surfaces from different thresholds.

Figure 8. Offset curves.

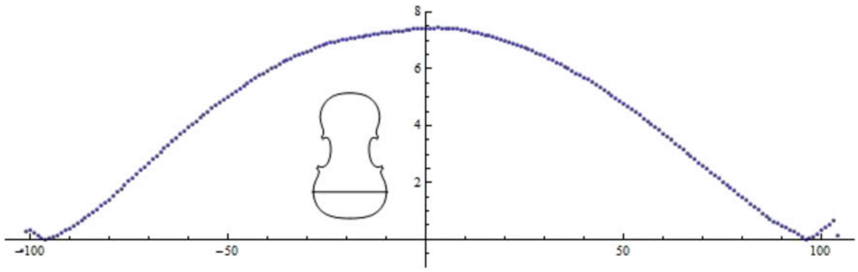

Figure 9. Seventy-five millimeter above the end.

The scales in the two directions are different so that the curve can be seen well.

In the following analysis, only the data on the bass (right) side is used, in the hope that it is less distorted by the sound post.

The Curtate Cycloid

One candidate that has been proposed to describe the cross-section curves is the curtate cycloid. Figure 10 is the result when we approximate the data (bass side only) with a curtate cycloid.

In each case, the cycloid is centered with low ends at the low ends of the data, and is adjusted to give the best possible fit to the data (the bass side data).

We see that the cycloid gives a reasonable fit to the data near the bridge and in the upper bout, but not a good fit in the lower bout.

Also, as we said in the abstract, we want a method that allows alteration of the arch. But, the cycloid is completely determined by its height and width; once the height and width are set, the curve cannot, for example, be made more or less "plump".

More Flexible Curves

This section defines a family of curves, which we call "B3 curves". A B3 curve has three parameters (adjustabilities), rather than the two of curtate cycloids, and is therefore more "flexible".

This section is the only section of this article containing actual algebra. This section needs to be read only if the reader actually wants to implement the method of the article. Otherwise, the reader can skip this section; the article is intended to be readable without this section.

First, we need to define the coordinates we are using (Fig. 11). The curves we are defining are varieties of Bèzier curves. Rather than referring to the literature, we define the curves completely here. Let

$$
\begin{aligned}
b_1(t) &= (1-t)^4 \\
b_2(t) &= 4t(1-t)^3 \\
b_3(t) &= 6t^2(1-t)^2 \\
b_4(t) &= 4t^3(1-t) \\
b_5(t) &= t^4,
\end{aligned}
$$

then, given five points (P_1, P_2, P_3, P_4, and P_5) in the xz plane and five weights (w_1, w_2, w_3, w_4, and w_5), we have the 5-point parametric Bèzier curve:

$$
\begin{aligned}
\text{Curve}(t) = [&w_1 P_1 b_1(t) + w_2 P_2 b_2(t) + w_3 P_3 b_3(t) \\
&+ w_4 P_4 b_4(t) + w_5 P_5 b_5(t)] \\
&\div [w_1 b_1(t) + w_2 b_2(t) + w_3 b_3(t) \\
&+ w_4 b_4(t) + w_5 b_5(t)].
\end{aligned}
$$

The curves we are looking at are symmetrical around $x = 0$, based on the line $z = 0$, and flat at the ends, where they come down to the line $z = 0$. For such curves, we have

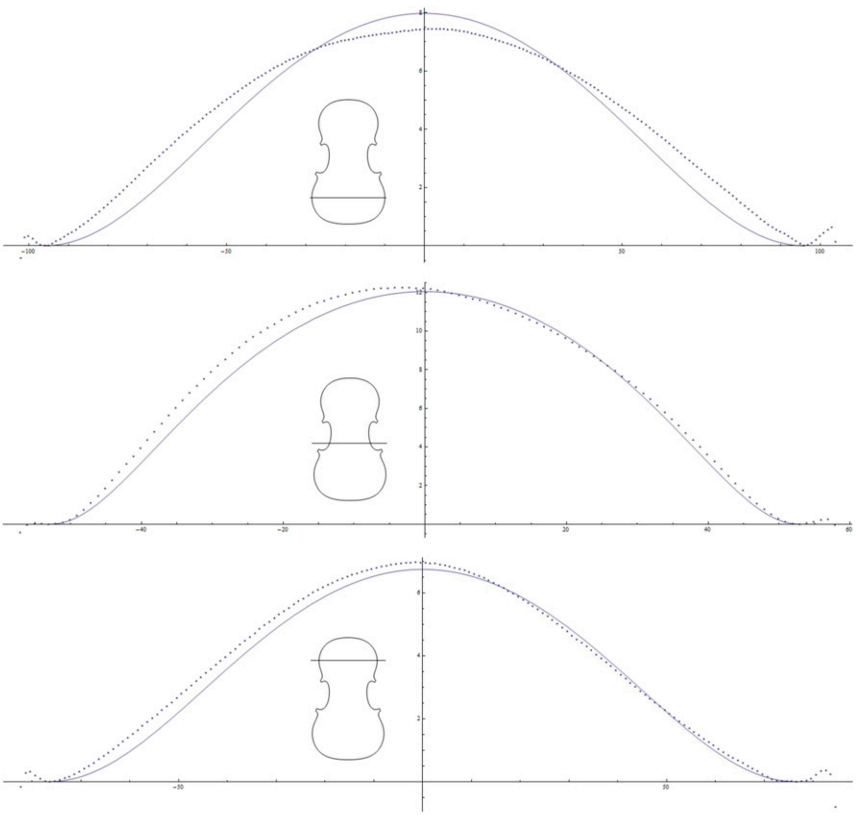

Figure 10. Approximation by a cycloid at 75, 166, and 288 mm.

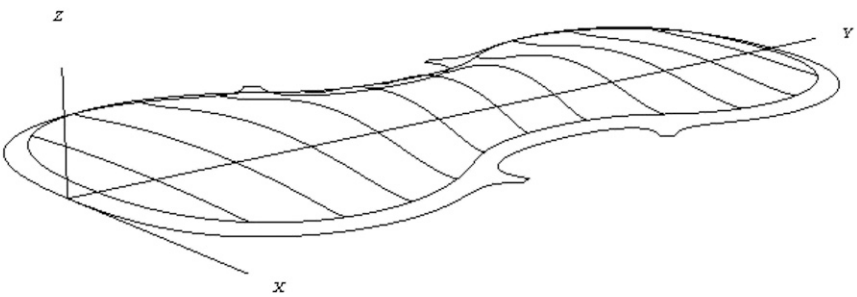

Figure 11. Definition of coordinates.

$$w_1 = w_5 = 1$$
$$w_2 = w_4$$
$$P_1 = (-\text{width},0)$$
$$P_2 = (-x_4,0)$$
$$P_3 = (0,z_3)$$
$$P_4 = (x_4,0)$$
$$P_5 = (\text{width},0).$$

So, here, we have a family of curves with the right general shape, with five parameters: width, x_4, z_3, w_3, and w_4. After considerable trials, I realized that this was too many parameters. It turned out that taking $w_3 = 1$ and $w_4 = 5/4$ reduced the number of parameters to three and still left enough flexibility to give a good representation of the cross-section data. This choice of w_3 and w_4 also makes z_3 = three times the height of the curve, which is very convenient. The x_4 parameter in some sense controls the bulginess of the curve, so we define bulge = x_4/width. Legitimate values of bulge are between 0 and 1.

Thus, we have a family of curves, which I call B3 curves. For parameters height, width, and bulge, we set $z_3 = 3 \times$ height, x_4 = bulge × width, and define P_1, P_2, P_3, P_4, and P_5 and $w_1 = 1$, $w_2 = 5/4$, $w_3 = 1$, $w_4 = 5/4$, and $w_5 = 1$ according to the previous formulas. Then, the five-point Bèzier defined previously is the curve.

Using the B3 Curves

The previous section defines a family of "B3 curves". For a given height, width, and a third number called "bulge", we get a curve. Figure 12 shows how these curves look for various values of bulge. We compare the fit of the B3 curves and the cycloid in Figure 13

In each case, the width of the B3 curve is fixed, and the height and bulge are adjusted to give the best possible fit to the data. Similarly, the width of the cycloid is fixed and the height is adjusted. The best-fit B3 and cycloid curves are shown. We see that the B3 curve fits the data better than the cycloid. So in the rest of this work, we use only B3 curves.

ANALYSIS

We now begin the actual "analysis" of the data: For cross sections from 30 to 324 mm, measured

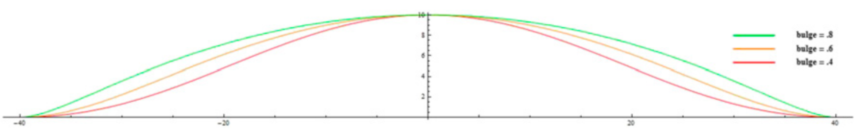

Figure 12. Various values of "bulge."

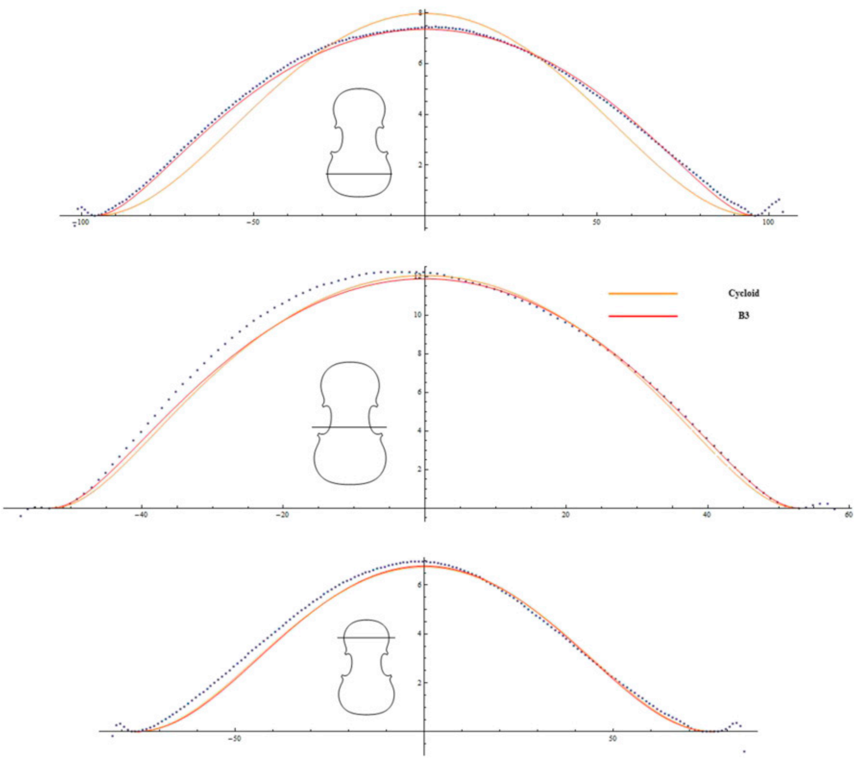

Figure 13. B3 and cycloid curves.

from the tail of the instrument at intervals of 2 mm, we fit a B3 curve to the bass side cross-section data. (For about a dozen cross sections, the edge of the instrument is worn enough that there is no "lowest point" at the edge, and so, it is not possible to perform the analysis in the way we are doing it. So, there are gaps in the data for these cross sections.) For each cross section, we have a width, a height, and a bulge (Fig. 14).

Figure 15 shows the height, width, and bulge of the cross sections (shown against the outline of the instrument). Note that the low curve (width of the cross sections) pushes slightly into the corners.

The cross-section curves sit on the "low curve". So, we need data about the low curve. The widths of the cross-section curves, shown previously, give the location of the low curve, as seen from above. The height of the low curve is the thickness of the plate under these width points. In Figure 16 we are measuring a thickness from the STL file, so a thickness correction is applied.

The red points are the thicknesses read from the STL file. Subtracting a correction[2] of 0.6 mm gives the green points; these are the heights of the low curve. The outline of the instrument is shown for comparison. The figure shows that the thickness at the low curve is about 1 mm greater in the C bout than in the outer bouts.

Getting the B3 parameters and the low curve heights constitutes the "analysis" of the old violin.

SYNTHESIS

Smoothing

For each cross section, from 30 to 324 mm above the end of the instrument, at 2-mm intervals (with some gaps), we have a height, width, and bulge. These define a B3 curve. And, we have the low curve that the B3 curves sit on. So

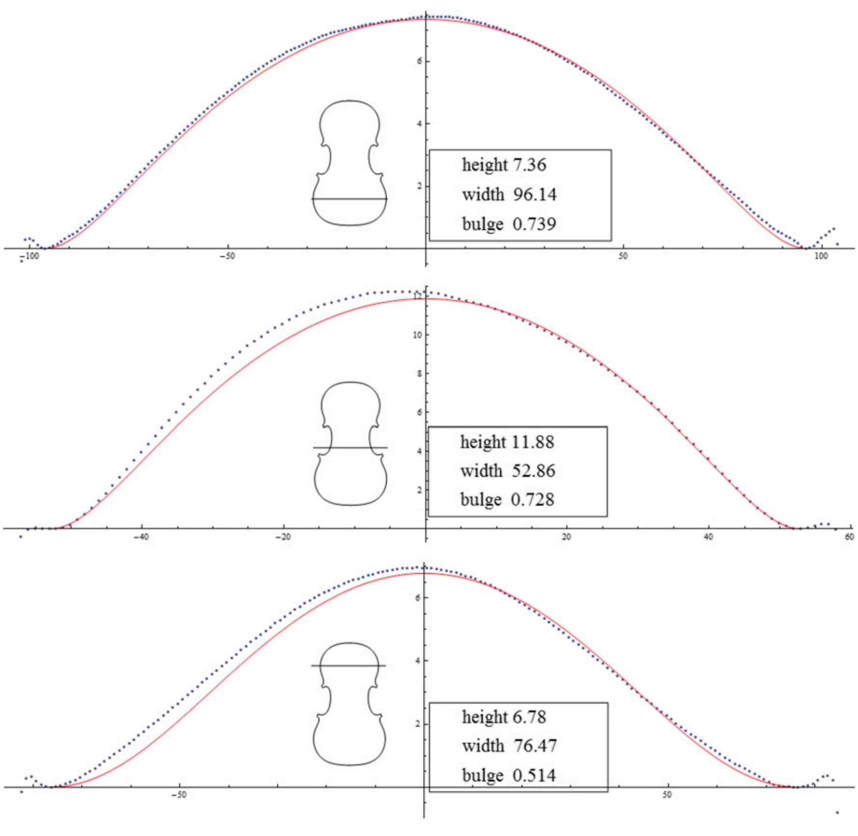

Figure 14. B3 Curves fitted to cross-section data.

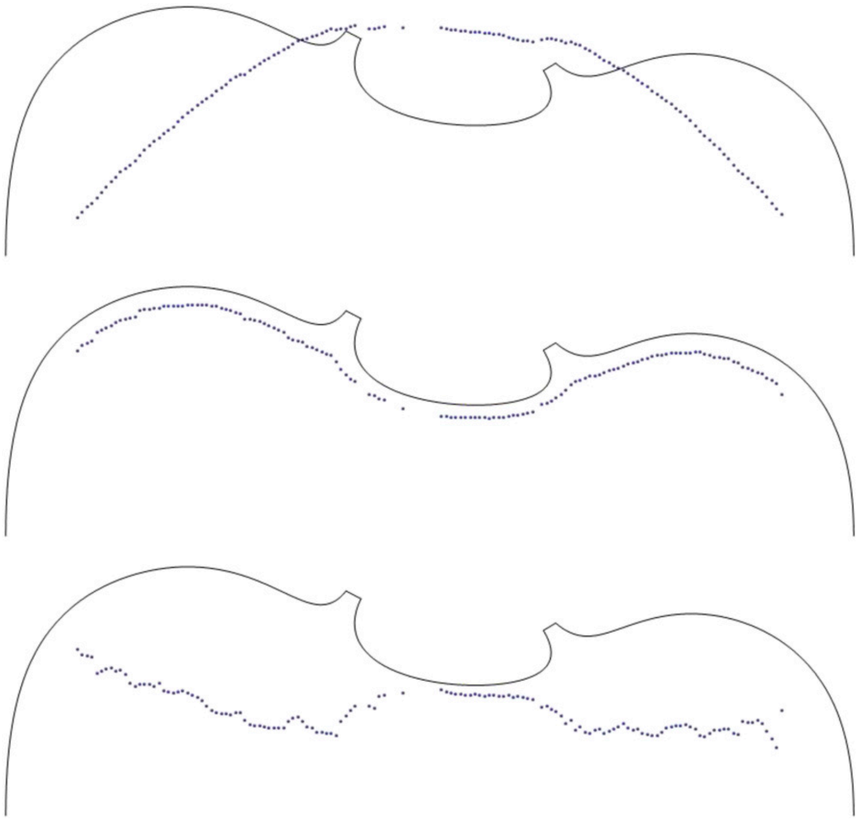

Figure 15. Height, width, and bulge of the cross sections.

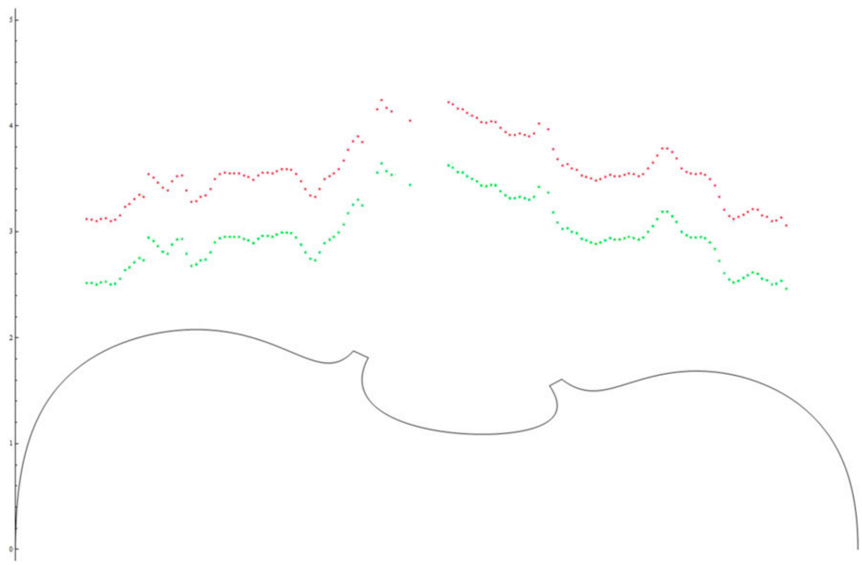

Figure 16. Low curve heights with correction.

we could just put all these B3 curves in place to form an arch. But, if we do this, we get a jagged surface. The center line appears as shown in Figure 17.

The problem is that each cross section, and each low curve height, was found independently, with noise and imprecision from the CT data, the STL conversion, and so on. They do not fit together into a smooth surface. So, we have to smooth things out.

Figure 18 shows smoothed versions of the B3 height, width, and bulge, and the height of the low curve. The outline of the instrument has been included for orientation.

Notice that the width data projects slightly into the corners, whereas the smooth width curve does not. I can produce a smooth width curve that does project into the corners like the data, but if I do, these methods, including various modifications and extensions, produce arches with unacceptable lumpiness.

Building the Arch

We now have the following:

- smoothed low curve
- smoothed B3 width
- smoothed B3 height
- smoothed B3 bulge

We can now build an arch. From the smoothed B3 height, width and bulge, we build cross sections from 10 to 342 mm (above the tail of the instrument) at intervals of 2 mm. We put these on the smoothed low curve. This forms the central part of the arch.

We look at the lengthwise sections as a check. The section is 45 mm from the center line as shown in Figure 19.

The sections, from the center line all the way out to the edge, are as expected, without any unacceptable lumpiness.

The edge and fill parts are added to the central part to form the complete arch of the plate.

POSSIBLE DIFFICULTIES

Slight variations in the smoothing of the curves sometimes lead to a surface with an unacceptable kink. One can check for a kink by looking at the lengthwise sections. Figure 20 shows an example of a kink. This is a lengthwise section 45 mm from the center line, with points every 2 mm. The remedy for this problem is to fit a smooth curve to the section, as demonstrated in Figure 21. The bulge is then modified to force the cross sections to pass through this smoothed curve.

ALTERING AN ARCH

This method allows for altering an arch. Suppose we have an arch built with these methods and we want it to be slightly plumper in the upper bout, about 288 mm above the tail of the instrument. We increase the bulge at 288, enough to add about 1/2 mm there, and taper the alteration off to zero (Fig. 22).

Using the modified bulge, with the other pieces unchanged, we get a new arch. Figure 23 is a comparison between the altered and the original arch.

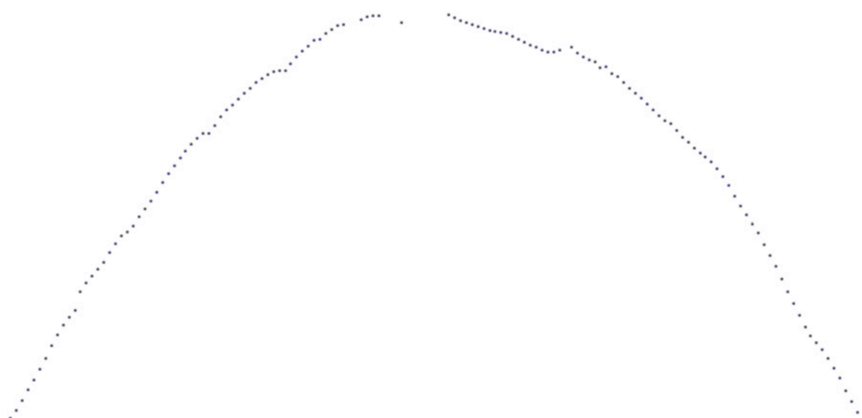

Figure 17. Jagged center line from un-smoothed data.

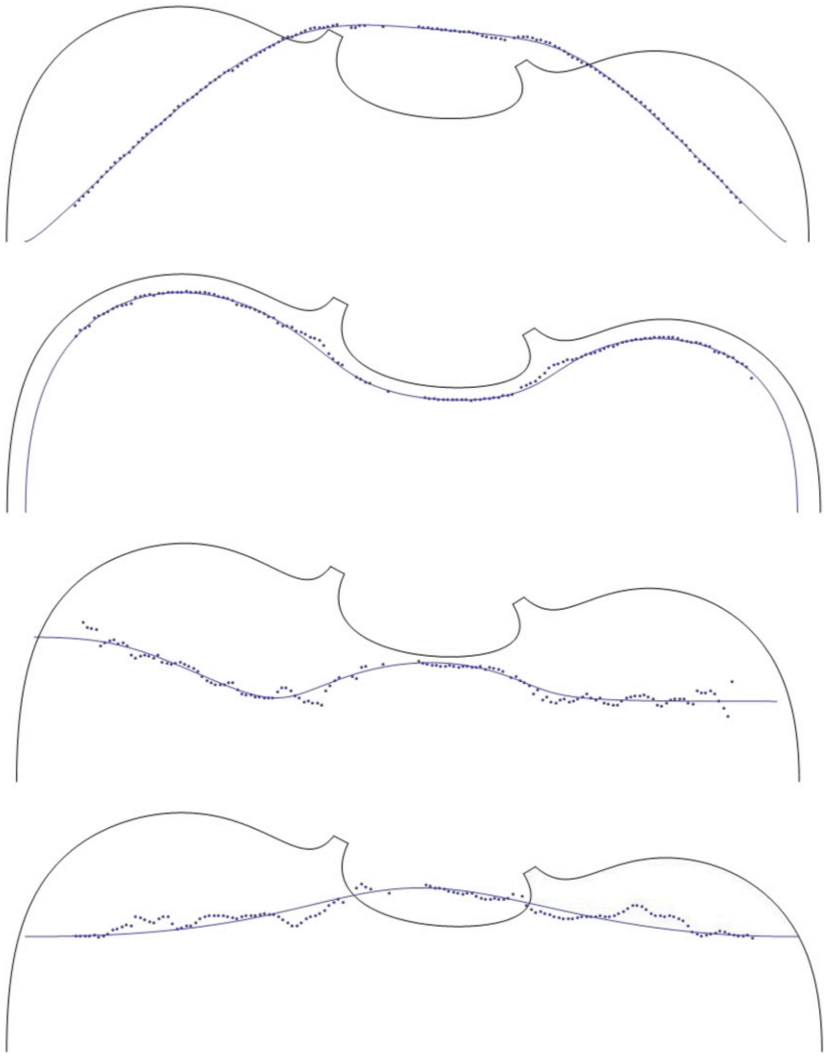

Figure 18. Smooth versions of the B3 height, width, and bulge, and the low curve height.

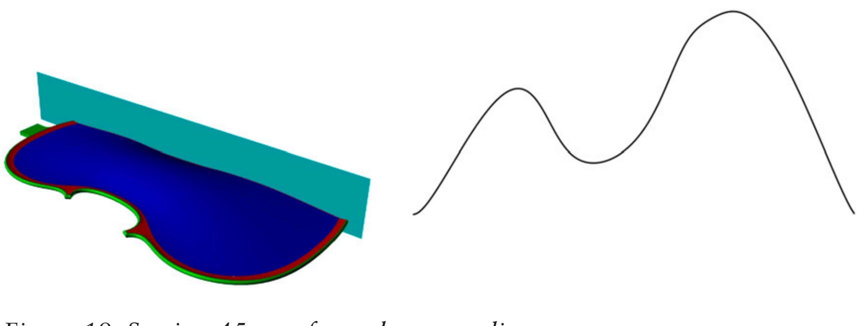

Figure 19. Section 45 mm from the center line.

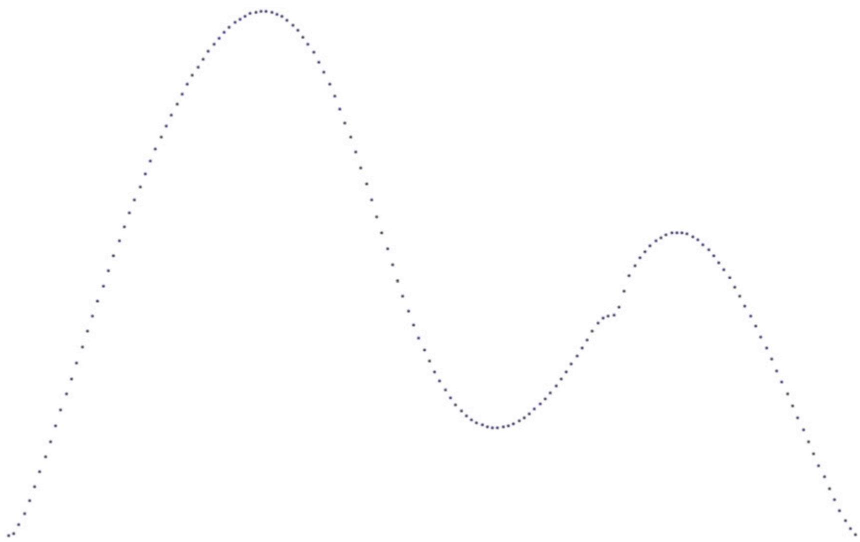

Figure 20. Section 45 mm from the center line showing kink.

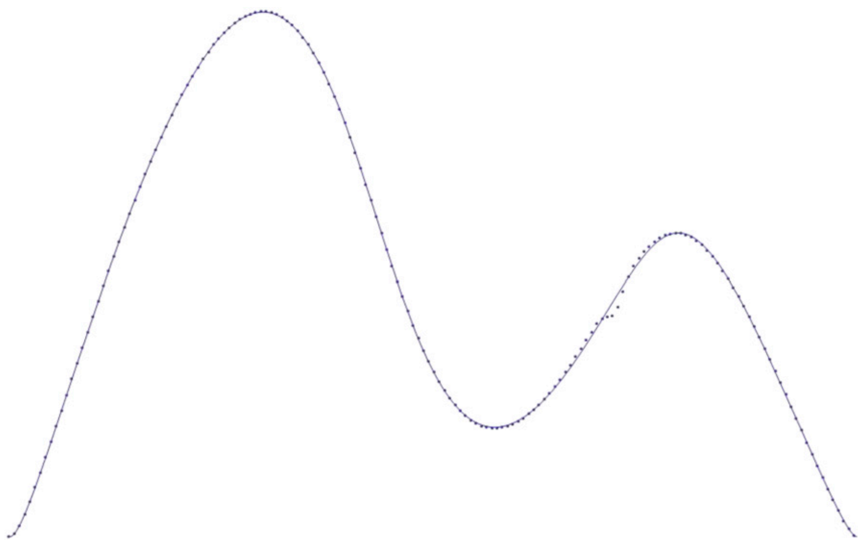

Figure 21. Smooth curve fitted to the kinked section.

ADAPTING TO A DIFFERENT OUTLINE

The previous procedure used the low curve from the original data (cleaned up and made smooth and symmetric). This goes along with using the outline from the original data (also cleaned up and made smooth and symmetric).

If one wants to use the arch data from the old instrument, but on a new instrument with a substantially different outline, the 2D low curve needs to be adapted to the new outline. Some examples of recipes that might be used to construct an appropriate 2D curve are as follows:

- The low curve lies over the inner edge of the linings;
- The low curve lies 6 mm from the edge;
- The low curve is 6 mm from the edge in the lower bout, 4 mm from the edge in the C bouts, and 8 mm from the edge in the upper bout.

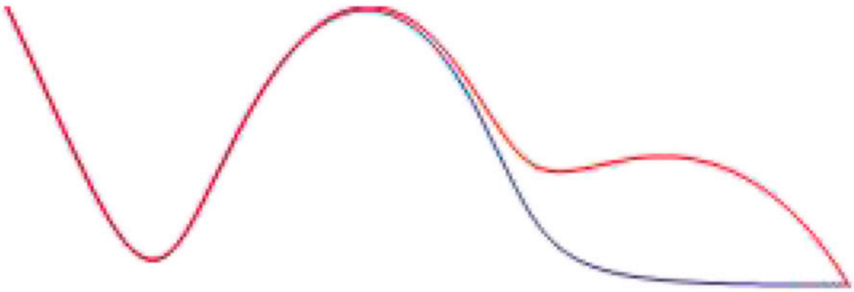

Figure 22. The altered bulge.

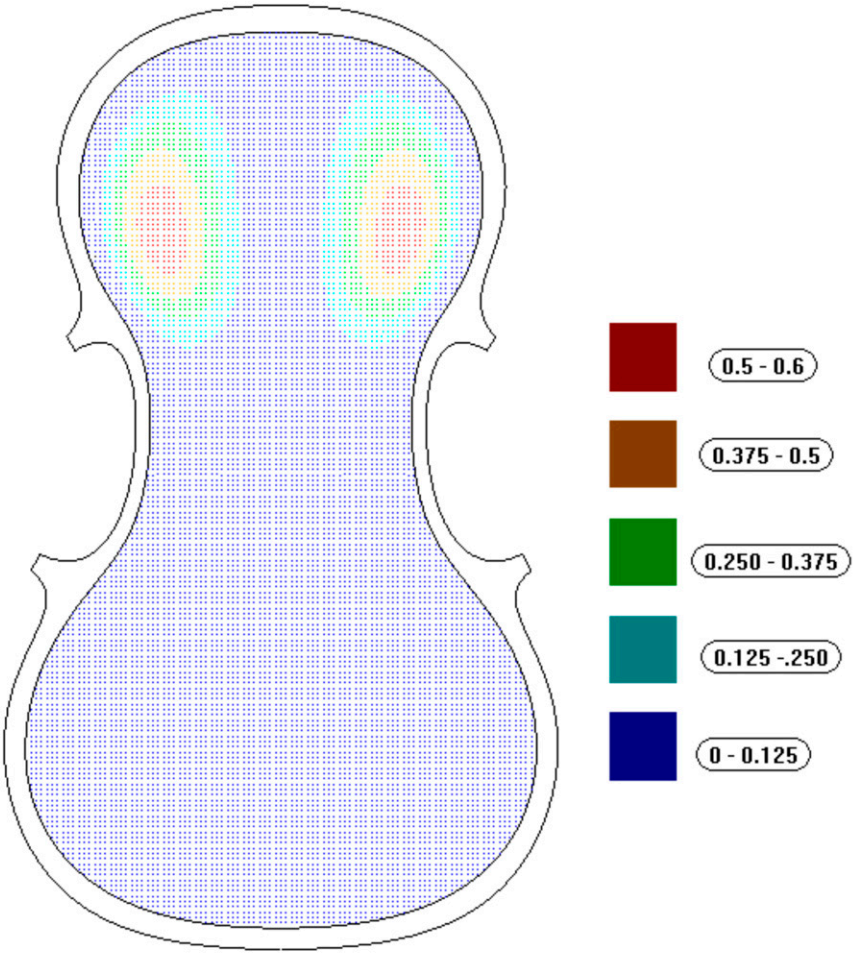

Figure 23. Differences between the altered arch and the first arch.

TOOLS AND TECHNIQUES

The major tools used were Mathematica and Rhino. Mathematica is a sophisticated and powerful tool for performing mathematical calculations, both symbolic and numerical. Unfortunately, it is difficult to use, partly because it is poorly documented. Rhino is a 3D CAD tool. An add-on, RhinoCAM, generates instructions for a computer numerical control (CNC) router.

I wrote functions in Mathematica for reading CT data (DICOM files) and STL files, and developed methods for transferring data back and forth between Mathematica and Rhino.

The calculations were performed in Mathematica. After the cross-section curves and low curve were found in Mathematica, they were transferred to Rhino, where the actual surface was produced. The edge was produced completely in Rhino. The basic idea of the fill surface is to invent a function something like a temperature function, moving from one temperature (height) at the low curve to a higher temperature (height) at the edge.

All curves are Bèzier curves of appropriate degree. A curve is "fitted" to data points by adjusting the Bèzier parameters (control points and weights) to minimize the sum of the squares of the distances from the data points to the curves. Specifically,

- The edge curves (upper, C, and lower bouts) are order 5 Bèzier curves (5 control points). The curves are fitted to data points consisting of the STL points where the normal (perpendicular to the surface) is close to the horizontal.
- The smoothed B3 width is an order 9 Bèzier curve (refer to Fig. 18). The data points in the corners were omitted, and the points in the C bout were emphasized by weighting them heavily.
- The smoothed low curve height is an order 5 Bèzier curve. It was not fitted to the data; the curve parameters were adjusted by hand ("eyeballed") instead.
- There is a tricky point about adjusting the B3 height: The curve we care about is not the B3 height itself, but the actual center line height of the arch, which is the sum of the B3 height and the low curve height, because the cross-section curves sit on the low curve. So, the process is as follows:
  - Add the B3 height data (the points in the first part of Fig. 18) to the height of the smoothed low curve (just found).
  - Fit an order 6 Bèzier curve to the resulting heights.
  - Subtract the height of the smoothed low curve, giving the smoothed B3 height.
- The smoothed bulge curve is an order 8 Bèzier curve. Some of the data points are deleted, to prevent the fitting process from producing a curve with very sharp turns.
- The smoothed curve fitted to the kinked section is an order 7 Bèzier curve.

If you are having difficulty implementing this method, you are invited to contact the author.

NOTES

1. Because these data have not been publicly released, the violin will not be identified.

2. This correction is based on an analysis of a CT scan of a sample violin (not the fine instrument which is the subject of the analysis) with marked locations of known thickness.

What about the Tailpiece?

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Abstract

Although there are studies on positioning the tailpiece or choosing different essence of wood, the tailpiece still conceals its added values in the violin setup. Is it a simple string holder? This article studies the impact of the tailpiece on the mechanical energy collected by the bridge of a viola. A rig, which simulates a viola without a body, provides the measurements for this article. This work uses fine measurements of string, bridge, and tailpiece motions, which represent a wide range of geometrical and physical parameters. This article discusses data collected from a monocord, a one-string viola with a tailpiece, and two-string violas in both symmetric and asymmetrical connections. These data reveal the varying resonances and the phase reversal mechanism, which cause amplitude and sound tone modulations in bridge motion. This bridge motion is the source of body vibration. This article also demonstrates that the physical parameters of the tailpiece, as well as the attachment cord, have little effect on the resonances present within the bridge compared with the length of the after-strings (ASs). Selective lengthening of these ASs, when connected to an asymmetric tailpiece, can increase the partials of played notes without a significant impact on mean available energy.

PURPOSE OF THIS WORK

This article delves again into the problem of attaching after-length strings to the body of a bowed instrument. All stringed instruments need a way to support the tension of strings without compromising their structural integrity or adversely affecting their sound. Other instruments, such as the guitar, harp, and piano, incorporate unique solutions to this problem. In the case of the violin family, however, the tail cord or tailpiece plays this role. Previous works have documented the contribution of the after-length string system by analyzing the after-length string, the size of the tailpiece, the shape and mass of the tailpiece, and the length of the attached cord [1–3]. These articles focused mainly on analysis of the mechanical behavior that was present within several resonance modes. These covered a spectrum from below the lowest note played and up to 1 kHz. Researchers obtained these measurements through tapping techniques. These resonances are useful during the tuning process of any stringed instrument.

This article focuses on the "output" of the vibrations of the bridge, which is to say the intensity of sound, the richness of sound, and the ease of playing the instrument. Different inputs, determined by the physical parameters of the after-string (AS) system, can positively or negatively affect these qualities. As the size and shape of a tailpiece can affect the length of each AS, the tailpiece affects multiple aspects of the instrument.

Although modern digital simulators can describe some elements of this behavior, they cannot precisely model the friction which occurs between the hairs and string. In addition, these simulations cannot account for variations in stiffness of strings at the bridge notch at pitch. Therefore, we have used an experimental approach with an emphasis on precise, reproducible measurements. For this reason, this article also discards body contribution to focus on the driving forces on the bridge. To achieve these goals, this work uses a rigid wood dead rig, which records the forces acting on the top of the bridge as shown in Fig. 1.

The rig models a viola-sized (41 cm) instrument. It has fixed angles, string length, and tension which model an instrument of that size, but allows full freedom to adjust the position, mass, and three-dimensional inertia of the tailpiece. In addition, the tailpiece can connect to a single vibrating string or two vibrating strings. The

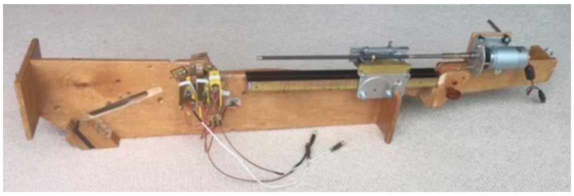


Figure 1. Rigid wood-built rig.

vibrating length is L_{m0} = 375 mm, with a bridge to saddle distance of 200 mm.

This article uses data gathered from three rig configurations:

1. No tailpiece with a single string stretched from nut to saddle
2. Rigid tailpiece with variable tail cord types and lengths
3. Rigid tailpiece with two strings and variable after-lengths

Acronyms used in this article are listed in the Glossary.

INSTRUMENTATION

The rig has a pseudo-bridge (BR), or string-holder, which replicates the bridge of a viola. Previous measurements of the static transverse stiffness (K) at the top bridges, taken across five violas, provide a range of K = 20–30 N/mm. Testing violas with a dynanometer, operated by a calibrated spring, shows applied forces (F) in the range of 2–10 N on bridges. Using dx under dF derives a stiffness equation of $K = dF/dx$, measured in N/mm. These measurements correspond to violas with strings, a bridge alone with clamped feet, and the pseudo-bridge, as shown in Fig. 2.

The stiffness of the pseudo-bridge (holder) is adjusted by carving the rod, made from an epicea post. The mass, transverse resonance frequency, and Q are similar (~3 g, 1300 Hz, 22), as well as the admittance curve obtained by tapping techniques, to real bridges on viola. Forces on the holder have been recorded by a homemade quartz force sensor, horizontally, when in blocked mode (horizontal quartz force sensor [HFS]). Transverse displacements have been measured by homemade laser position sensors (LPS) (Fig. 3).

The added mass of the tiny tube modifies string vibrations, as do the wolf-eliminators placed on the ASs. In the latter case, the mass of the tube is much higher than that of the string. In our experiment, the tiny tube is a local perturbation, as would be an imperfect string. To evaluate this perturbation, we performed an experiment to determine the variations. We use a monochord of length (L) and linear mass (μ), loaded by mass (m) attached at distance (x) to one end. The added mass reduces the root note (f_0) when we pluck or bow the string. Using these parameters, we can find the frequency shift for a given string:

$$x_r = x/L,\ m_r = m/(\mu * L),\ f_r = -df/f_0$$

When x_r and m_r are lower than 0.3, we can approximate the results using the following equation:

$$f_r(\%) = k * x_r * m_r, \text{ with } k = 500$$

Viola strings have a μ range from a maximum of 8 g/m for C to 1.4 g/m for A. The plastic

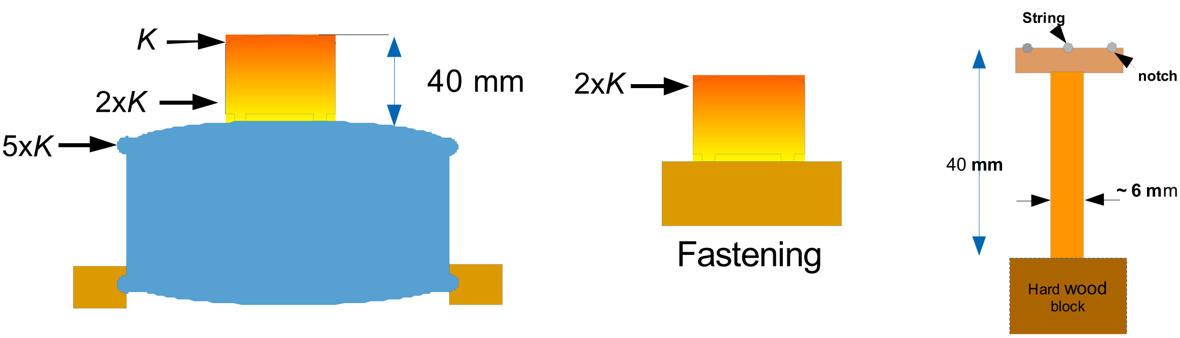


Figure 2. Stiffness scaling and string holder.

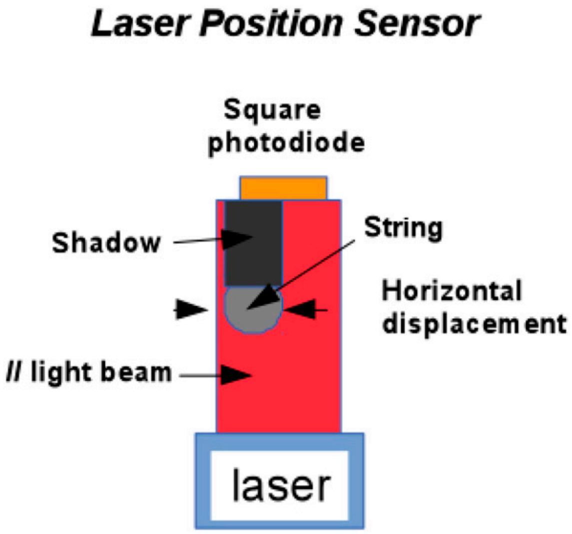


*Figure 3. LPS principle. A 5-mm diameter parallel laser beam impinges normally on a BSW34 PIN 2.35-mm square photodiode. The upper face, which is used for the bridge, intercepts approximately half of the beam that is aimed for the diode. For the strings, which are usually no more than 1 mm in diameter, we had to increase this diameter to ~3 mm by a set of 4-mm long black, thermally retractable tubes. When the string has a synthetic core, the user must use a flat iron tip at low temperature. The tube can slide, with some effort, along the string, after tuning, to reach the right position in front of the diode. The full-view photocurrent is measured on a 1-kΩ resistor. This voltage (V_0) normalizes the full scale. Each measured dV(t) corresponds to an elongation dx(t) = 2,650 * dV(t)/V_0 micrometers. The rms noise has a value of 0.5 μm. The frequency response is not a problem as it has a pin diode rise time less than 10 ns. A spinning shutter provides a V(t) response, which converts to V(x) using the precise tangential velocity. The mean slope is deduced with a 3% inaccuracy.*

tube weighs 25 mg for a length of 4 mm, and is placed at 2 cm from each side of the bridge. *L* varies, depending on measurements, from 20 to 37 cm on main string (MS) and from 7 to 13 cm on AS. Table 1 shows the frequency shift of f_0 induced by the tiny tube. This demonstrates the low impact that the tube has on the MS motion

Table 1. Tube loading frequency reduction effect.

		f_r %	
	L (cm)	μ, max = 8	μ, min = 1.4
MS	L_{max} = 37	0.2	1.3
	L_{min} = 15	1.4	7.9
AS	L_{max} = 20	0.8	4.5
	L_{min} = 7	6.4	36.4

in the C and G strings, which have a *μ* higher than 3 g/m. We verified this conclusion by repeating some records using balsa wood tubes, seven times lighter (3 mg). The three LPS simultaneously record the horizontal motion of the vibrating string and the AS at 20 mm from the holder, and the horizontal motion of the holder. A mechanical bow, with controlled velocity and pressure, excites the vibrating string within the normal range of playing. We built a special bow for this experiment by gluing a normal head and frog onto an 8-mm carbon fiber tube. A plastic wheel rolling over the tube is loaded vertically by adding lead pieces, which sets the pressure on the string, as seen in Fig. 4. As the bow moves, pressure varies, because of the bow mass contribution, from 1.1 N at the tip to 1.3 N at the middle. The bow translation is performed by using a low-noise direct current motor to turn a round-threaded screw on which is wound a carbon braided-wire loop, which in turn drives the frog. The motor axis position is monitored by a coupled potentiometer. Position and bow speed can also be precisely checked by a digital linear optical scale attached to the bow carbon tube. With a motor power supply range of 4–15 V, the up and down bow speed can be selected between 10 and 40 cm/s.

The rig plays the string by applying a roller as a player would apply a finger. A second DC-motor moves the roller along the fingerboard in fixed steps by turning a threaded rod attached to the roller, as seen in Fig. 1, thus reducing the vibrating length *L*. We use a 1.5-octave glissando, as used to analyze the effect of sound-post placement and bridge resonances [4]. The motor commands are synchronized in the following

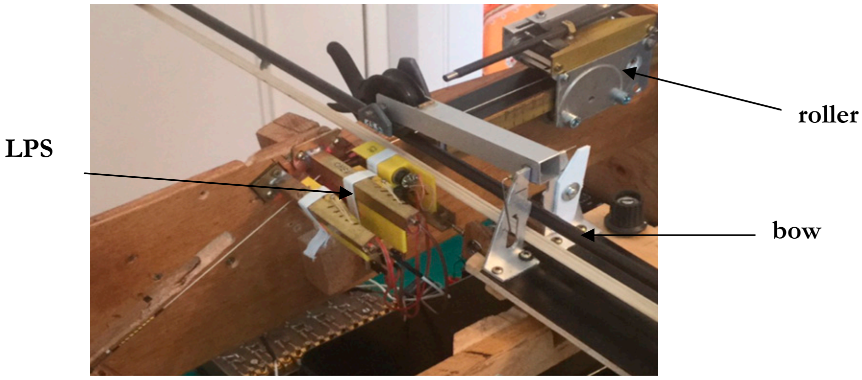


Figure 4. LPSs setting, bow motion, and roller.

typical sequence: down-stroke and roller for 1 s, stop 1 s, up-stroke for 1 s, stop 1 s, etc. The roller motor voltage is chosen to produce less than a semitone frequency variation per down-stroke, to achieve high frequency resolution when a 1.5-octave sweep is performed. A much lower voltage is used to delve around a resonance.

We adjust the LPS in front of the tubes at $V_{0/2}$ at rest, using the same response sign, to obtain the correct phase shifts between signals. We used computer-assisted analysis offered by the shareware Sigview to extract pertinent quantities, including amplitude, harmonic content, and phase shifts. As the motion signals $dV(t)$ are not sinusoidal, we calculated amplitudes in micrometers rms units.

$dV(t)$ rms = moving average of $(dV * dV)^{1/2}$ on 1,000 samples at a sample rate = 16 kHz (dt = 62 ms) and $dx(t)$ micrometers rms = 2,650 * $dV(t)$ rms/V_0, 2,650 being the linear range of the LPS in micrometers.

Unless we specify otherwise, the bowing has the following parameters: bow-hair ribbon 1 cm wide, with pressure of 1.2 N, and velocity of 19 cm/s.

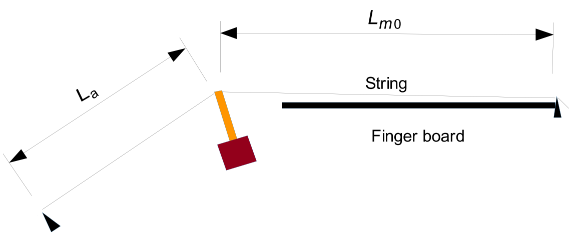


Figure 5. Geometry.

Data show the system consistently achieving ±1 dB results in both fidelity and stability over several months in use.

RESULTS

For One Bare String (Saddle to Nut)

While operating on the C string in blocked mode at 130 Hz, the holder cannot move (Fig. 5). The attached quartz force sensor (HFS) provides the force transmitted to the holder by MS (Fig. 6). The data clearly demonstrate the Helmoltz shape, similar to MS and the pressures which piezzo sensors demonstrate when placed under the feet of the bridge on a viola.

These data quantitatively verify the formulation of L. Cremer ([5], §3.4, equation number 3.22). We can calculate the peak force at the bridge using the equation:

$$F(0) = (Fx * m')^{1/2} * vb * L/xb,$$

where Fx = tension, m' = string linear mass, vb = bowing speed, L = string length, and xb = bow–bridge distance. Here, Fx = 58 N, m' = 5.7 g/m, xb = 2 cm, L = 37.5 cm, and vb = 19 cm/s. This provides a force $F(0)$ of 2.05 N.

The HFS measured $F(0)$ = (1.4 N/mV) * 3 mV = 4.2 N, if we take the peak-to-peak measured values.

The holder also functions as a force sensor through its compliance. A sawtooth signal provides a peak to rms value of $3^{1/2}$ = 1.73. Here, BR/MS = 0.25 and MS peak to peak = 0.9 mm (see Table 2). As a result, $F(0) = K$ * 0.9 * 0.25 = 4.3 N, as K = 19.4 N/mm.

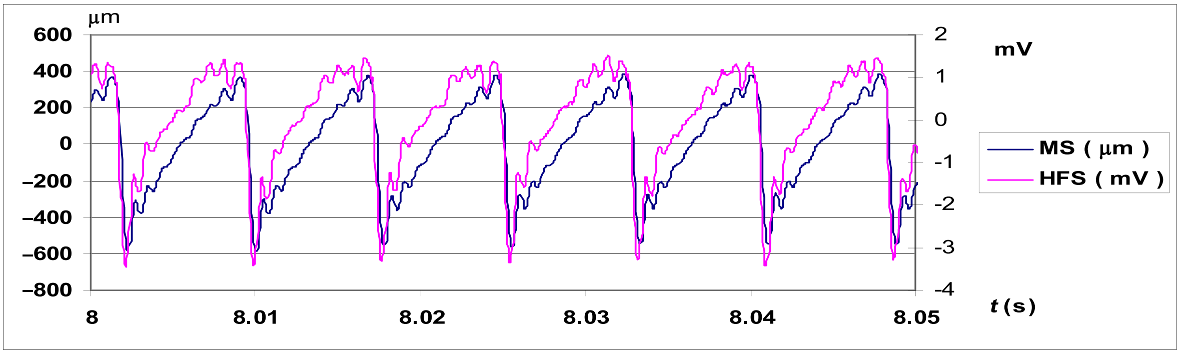


Figure 6. Blocked mode: MS motion at 2 cm from holder and force on holder.

The tests provide a generic record or the movements of a C string at pitch under arco (bowed) conditions (Fig. 7). These $dV(t)$ data demonstrate the motions of a MS of length (L_m), an AS of length (L_a), and simili-bridge (BR), recorded in 196 s and corresponding to a frequency span of 134–324 Hz. We tested an extra-long C string of 575 mm (L_m = 375 mm and L_a = 200 mm).

The analysis demonstrates that:

1. MS amplitude decreases slowly as the sweep increases from 134 to 324 Hz when the pull is 10% higher than the push (hair-scale effect),
2. AS resonances are strong with an amplitude that is often higher than that of the MS, with $L_m = L_a$ = 200 mm, and $L_m = 3/2 * L_a$, with Q ~ 100.
3. BR amplitude dips after the main AS resonance (fr = 216 Hz). The data show a 5-dB loss in mean rms level on a semitone.

Displacements, which we have expressed in micrometers (rms), are shown in (Fig. 8).

The MS motion has many harmonics. Resonances occur based on the formula:

$$n * f = m * fr \quad (1)$$

where f is the played note and fr is the first AS resonance frequency. At f = 148 Hz, n = 3, and m = 2, AS vibrates at 432 Hz. At f = 216 Hz, n = 1, and m = 1, syntonization occurs.

A very slow sweep near 216 Hz provides a closer look at the coupling process.

Table 2. The first three columns demonstrate open string excitation. The fourth and fifth columns refer to the main 1–1 resonance. Note that a more flexible holder increases both amplitude and loss. This experiment used the following extra-long strings: Corelli-Alliance for the C and G strings, Helicore for the D string, and Jargar for the A string. Arco parameters were 19 cm/s at 1.2 N.

K holder (pseudo-bridge)	String	Amplitude MS open	Amplitude ratio AS/MS open	Amplitude ratio BR/MS open	Amplitude ratio AS/MS at reson	BR dip = dB – *df/f* (cents)
19.4 N/mm	C	260	0.35	0.25	2.6	5 – 65c
	G	176	0.4	0.23	1.6	4.2 – 75c
	D	123	0.55	0.36	2.15	7 – 65c
	A	77	0.5	0.45	1.6	3.5 – 65c
		Microns				
K holder-10.4 N/mm	C	331	0.38	0.26	1.2	11 – 37c

AS = after-strings; BR = pseudo-bridge; MS = main string.

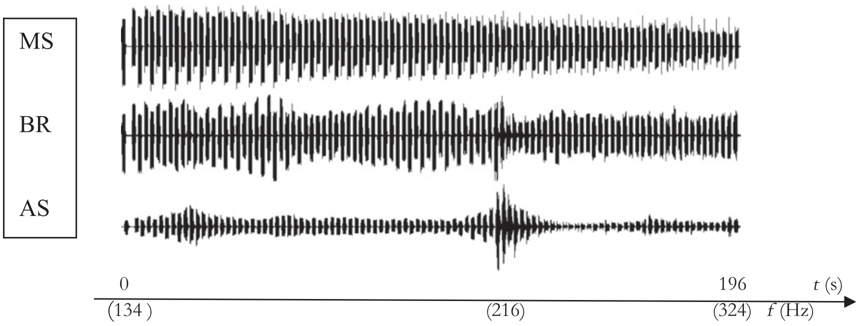


Figure 7. Up to down MS, BR, AS recorded dV(t) signals given by LPS as a function of the roller travelling time. Notice that the frequency, 1/L dependent, does not increase linearly with time.

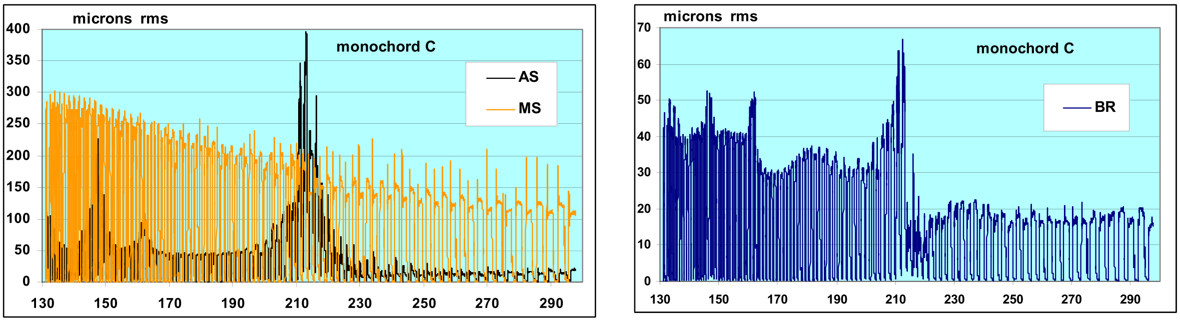


Figure 8. Motion profiles as a function of MS frequency. The notes spacing increases as the string length reduces.

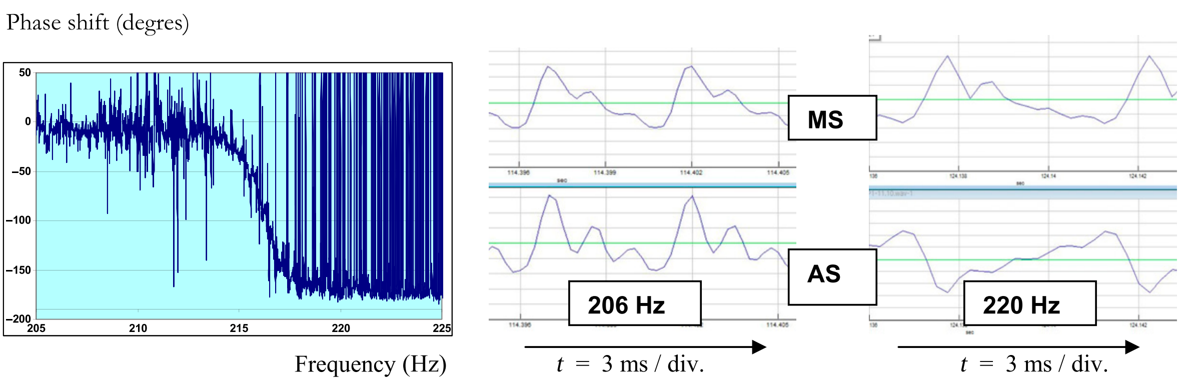


Figure 9. Slow sweep. Phase shift between AS and MS fundamentals, from 205 to 225 Hz. The time signals show the "curve veering," after passing the resonance frequency at 216 Hz.

Performing this sweep demonstrates the well-known phase shift between AS and MS harmonics near resonance and real time signals (Fig. 9):

1. The phase shift on fundamentals is 0 at $f < fr$ and −180 degrees at $f > fr$. The bridge seems to act as a pivot, as if the string was stiff and transfers a significant part of the vibrating energy to the AS.
2. The fundamental component of resonance is strongly present in BR.

Real time signals around fr = 216 Hz demonstrate the phase shift reversal. While

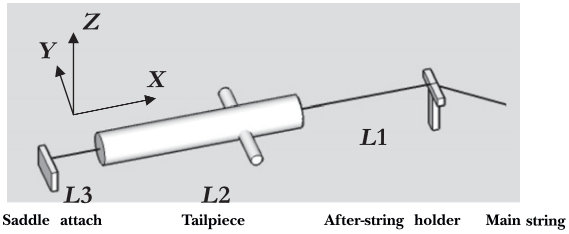


Figure 10. Geometry.

approaching *fr*, the AS helps the MS transfer energy to the bridge. Above *fr*, the effect slows down and deadens the bridge motion. This would cause a viola to emit a less intense A note. Similar situations occur for other strings, as summarized in Table 2.

For Single Strings with Cylindrical Aluminum Tailpieces

We shortened the AS and loaded it with a pseudo-tailpiece (Fig. 10).

Lateral posts affix horizontally or vertically along the cylinder to increase mass and inertia. These can cover all shapes and materials used in conventional tailpieces. We measure inertia along the three axes using a torsion pendulum. To choose the correct mechanical parameters, we have measured commercial tailpieces and compared them with our set of three cylindrical aluminum samples. All devices had an $L2$ = 100 mm. After-lengths ($L1$) of 7, 8, and 9 cm have been tested, with corresponding attachment cords with length ($L3$) of 3, 2, and 1 cm (Table 3).

To give an example of the data recorded, we present in Fig. 11 the three motions in arco condition on a C string, in micrometers rms, and in Fig. 12 the frequency shift vs. $L3$.

The bridge motion demonstrates the steps in the resonance when we excite the AS on partials n = 4, 3, and 2 of the MS. BR amplitude increases as we approach these frequencies and decreases afterward. This demonstrates the coupling effect explained previously.

Tailpiece resonance

Bruce Stough [1] identified five tailpiece resonance modes on violins. The three lowest do not alter the response of the instrument, but the two highest make a strong difference. Chladni

Table 3. Mechanical parameters for commercial and pseudo-tailpieces.

Viola type	Mass (g)	Length (mm)	Max width (mm)	Min width (mm)	Inertia ($kg * m^2$) Jy	Jx	Jz
Standard ebony—1 adjuster	21.1	125	44	18	3.7×10^{-5}	3.0×10^{-6}	4.1×10^{-5}
Ill rosewood—4 adjusters	23.5	128	46	16	2.4×10^{-5}	1.7×10^{-6}	2.5×10^{-5}
Wittner 916131	32	125	47	17	3.8×10^{-5}	3.5×10^{-6}	4.2×10^{-5}
Cordiera assym pear tree—3 adjusters	10.7	130	30	16	1.6×10^{-5}	1.9×10^{-6}	1.7×10^{-5}
Cordiera assym ebony—3 adjusters	13.5	130	30	18	1.3×10^{-5}	1.1×10^{-6}	1.4×10^{-5}

Aluminum sample	Mass (g)	Length (mm)	Diam. (mm)	Jx	Jy,z
Al-1	7.2	100	6	3.3×10^{-8}	6×10^{-6}
Al-2	11.7	100	8	9.2×10^{-8}	9.8×10^{-6}
Al-3	26.5	100	11.3	4.2×10^{-7}	2.3×10^{-5}

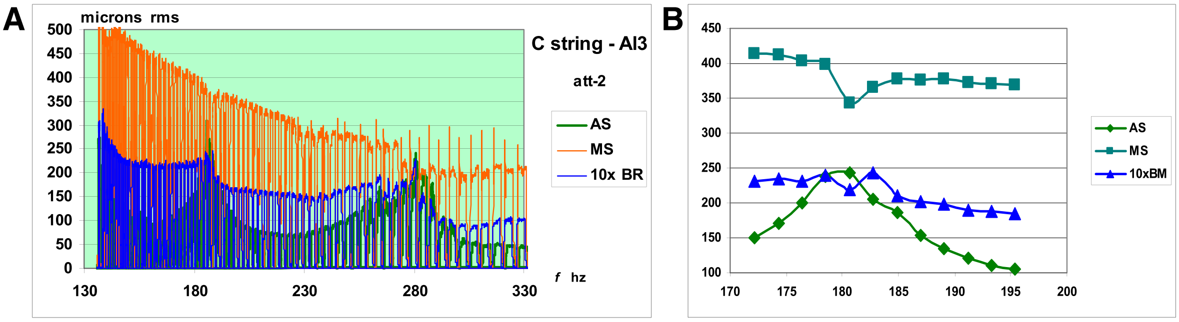


Figure 11. A) Motion diagrams for after string AS, master string (MS), and bridge (BR) with the Al-3 tailpiece. B) Close-up view of the AS resonance at 550 Hz on partial 3 of MS (180 Hz).

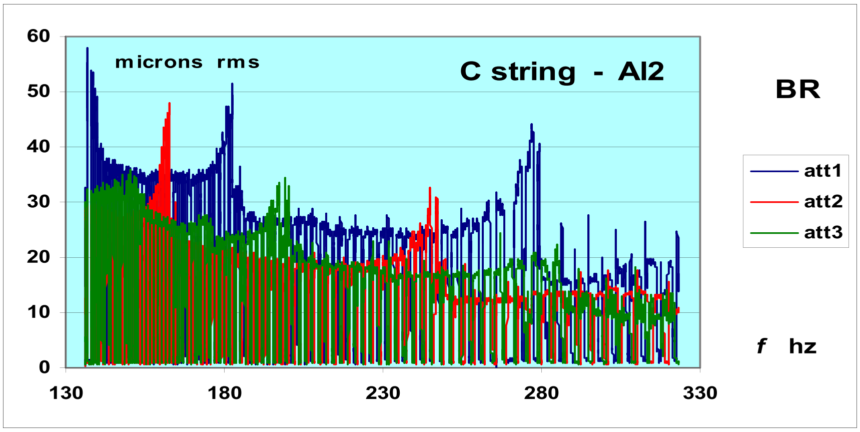


Figure 12. Bridge motion as a function of att. of 1, 2, and 3 cm, with the Al-2 tailpiece.

visualization was used under direct magnetic tailpiece excitation. Our experiment was performed with only one or two strings at pitch. When we pluck the AS near the tailpiece, the damped AS motion shows a very low resonance frequency (*fr′*) of the mass–string system. In all cases, *fr′* is lower than the open MS frequency, lower than 100 Hz for the C string. We have measured *fr′* for the bare aluminum cylinders and for the Al-2 tailpiece loaded with heavy H-shaped masses (Fig. 13).

+Pb: m = 40 g, Jy = 7.8 e-5 kg $*$ m^2

+Brass: m = 62 g, Jy = 10.5 e-5 kg $*$ m^2

If we load the aluminum cylinder with two brass posts of 30 mm, horizontally, adding 10 g across the front of the cylinder, we observe a reduction of *fr′* for any MS string (Fig. 14).

Under the same pluck, the horizontal tail motion is recorded by an LPS placed at various positions along the cylinder: "front" means bridge side and "back" means saddle side. The tailpiece resonance frequency is close to *fr′* (Fig. 15). In addition, we observed that the tail motion is always out of phase with the holder.

After-length string resonance

Next, we examine AS resonance under MS arco conditions (Fig. 16).

Interestingly, this *fr* seems to be independent of the mass or inertia of the tailpiece within the range of tested parameters. We find that *fr* is between 10% and 20% lower than fr_0, calculated for an AS fixed at both ends:

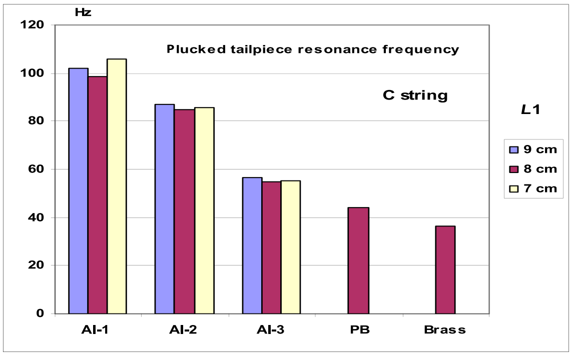


Figure 13. Resonance frequency fr′ obtained from plucking the AS. Pb and Brass loading of Al-2.

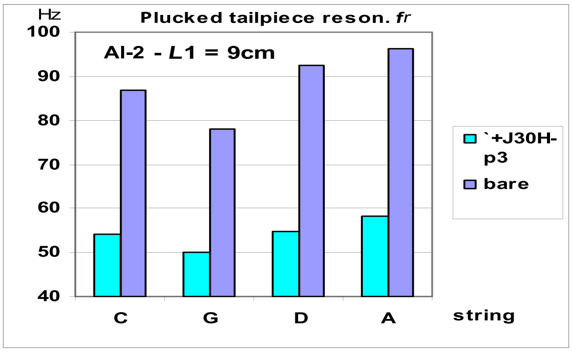


Figure 14. The impact of adding lateral posts to the Al cylinder on the resonance frequency.

$$fr_0 = 1/(2 * L1) * (Fx/mu')^{1/2},$$

where according to *L*. Cremer notations [5], *Fx* = tension and *mu′* = linear mass.

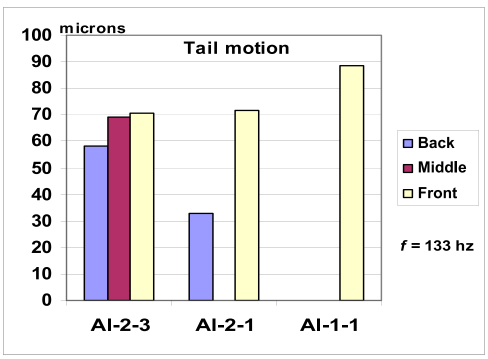
The *fr* reduction comes in part from the tube loading effect and in part from the silk end. This reduction is observed for the large inertia range investigated (Fig. 17).

As the AS mass is always less than 5% of the tailpiece mass, we infer that the tail provides an almost fixed point, even when including four string tension.

The effect of the attachment cord

Violinmakers often espouse that a more flexible attachment would improve the sound by leaving more freedom for the bridge to move. We have tested this notion by comparing three cases. The first configuration has one thin carbon braid with $\phi = 0.2$ mm. The second has two parallel thicker braids with $\phi = 1$ mm. The third has a fixed metal strip which connects the body on one end to the cylinder via a vertical pivot point. We tested three cord lengths with attachment lengths (att.) = 1, 2, and 3 cm and corresponding AS lengths of 9, 8, and 7 cm. We plotted, in Fig. 18, the results for four among the nine cases, for an 11.7-g Al-2 tailpiece (fine and metal cords, att. 1 and 3 cm). The frequency sweep shows almost equal amplitudes and similar modulation in the bridge motion, with larger resonances on shorter cords. A heavier 27.5 g Al-3 tailpiece smooths the BR undulations.

In conclusion, the cord att. is a way to adjust the AS resonance frequency, but has no effect on the bridge motion.



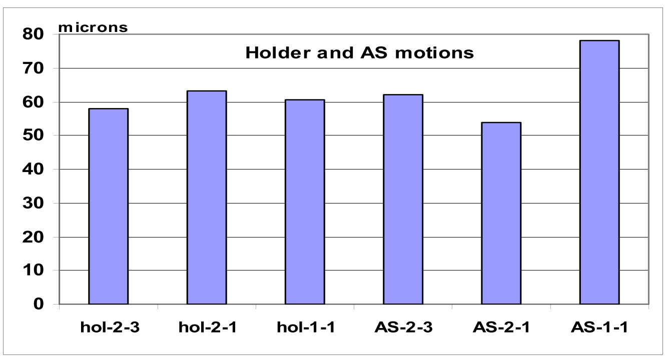


Figure 15. Left graph shows the horizontal tail motions, in micrometers rms. Right graph shows the corresponding holder (hol) and AS motions. Conditions: open C string (133 Hz) and an unloaded tailpiece. Coding: first indice = tail type, second indice = cord length, L3.

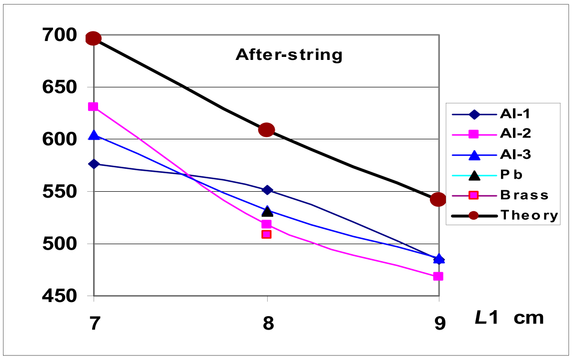


Figure 16. AS resonance frequencies fr.

Harmonic enhancement

In all cases, spectral analysis of the BR motion reveals local enhancement of its partials when they coincide with the AS resonance frequency (*fr*).

For Two Strings Attached Symmetrically or Asymmetrically to a Cylindrical Aluminum Tailpiece

Next, we attach a second string to the side of the pseudo-tailpiece. Here, the lower notes have longer after-lengths (Fig 19). The multiple strings on the bridge increases the number of coupled resonators. We now measure five motions.

Carleen Hutchins was the first to suggest the adjustment of the sympathetic vibrations of the ASs to the harmonics of the open strings as a way to modify the sound [6]. For some years, "Cordiera Cantabile" has promoted triangular shaped tailpieces. These tailpieces adjust the after-length of strings at a fixed ratio between the notes played in the back and front of the bridge (Fig. 20). We call this ratio

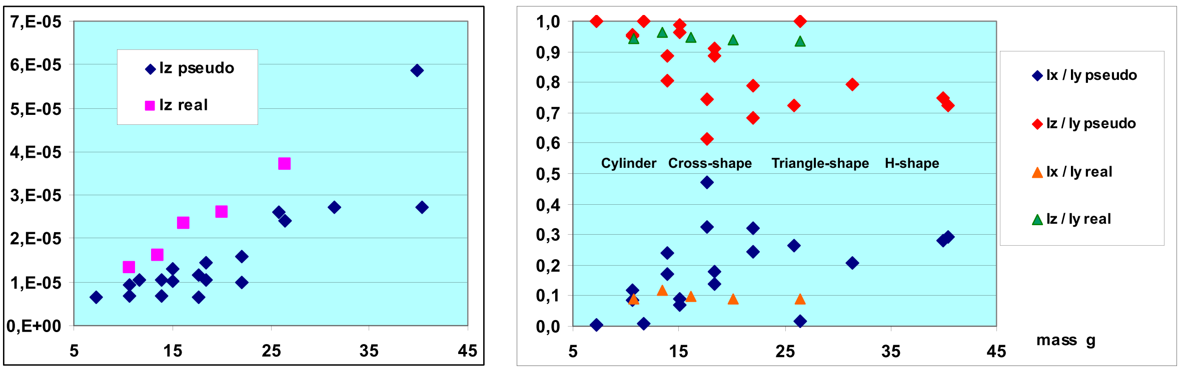


Figure 17. Inertia range investigated, as a function of tailpiece mass. "Real" refers to the commercial tailpieces shown in Table 2.

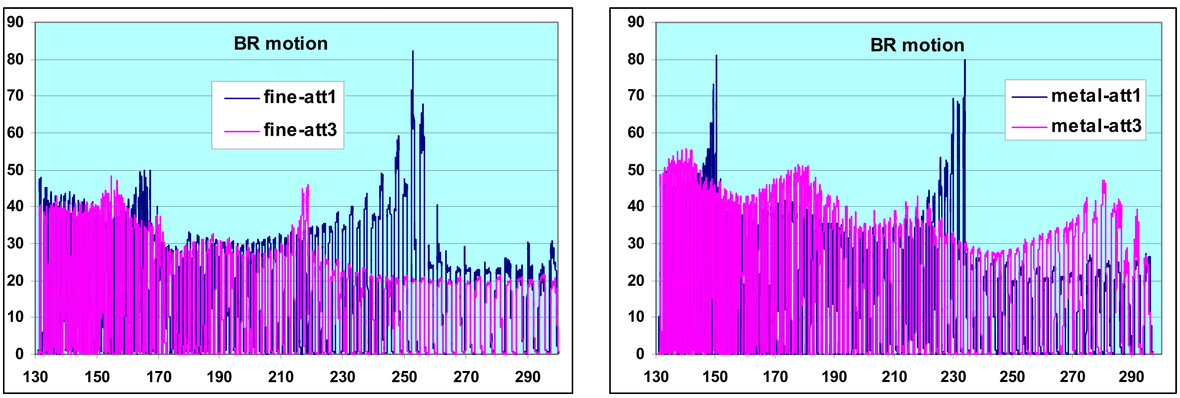


Figure 18. BR motion sensitivity to attachment cord type. Al-2 tailpiece—C string—sweep from 135 to 305 Hz. Fine set at one thin braid, att. = 1 for cord length = 1 cm.

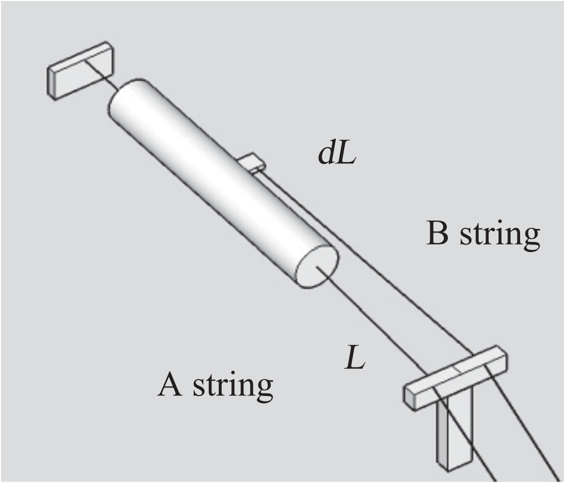


Figure 19. String B is longer than string A: dL.

Figure 20. Viola cordiera cantabile tailpiece.

the "mode." The mode can, for example, be 3, 4, 5, and 6 for strings IV to I. This design intends to free the bridge from the suspected damping effect of short AS lengths. Acoustical measurements and auditions, performed on violins, violas, and cellos, have shown this tailpiece to produce a warmer tone and better expressiveness, particularly for the III and IV strings.

Our goal here is to investigate the influence of *L*1, *dL*, and the att. on holder motion. For clarity purposes, we are only reporting results obtained on a C string with $L + dL = 140$ mm, coupled to a G string with $L = 95$ mm and att. = 10 mm. We used the Al-2 tailpiece to set mass and inertia. We played the C string, and then the G string, and recorded all motions (Fig. 21).

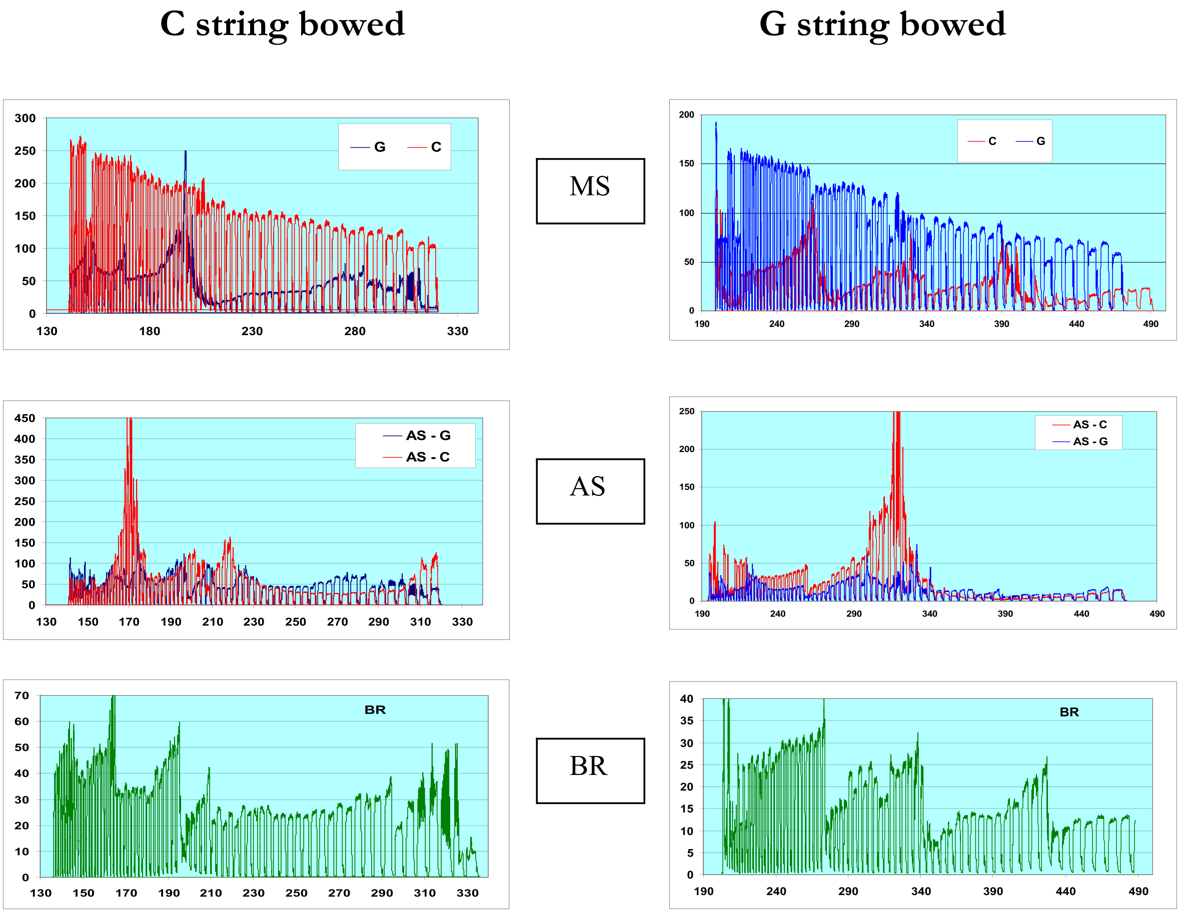
Modulations in the holder motion amplitude (BR) occurs in steps, as seen before in a single string configuration. We localized transition zones at ±1 tone. The MSs resonate at their fundamental or harmonic frequencies when other strings are sounding at harmonic combinations. Soloists experience this frequently. As before, the fr_0 data shown in Fig. 21 is within 85–94% of the theoretical values. Doubling the string's tension slightly increases the lowest resonances of the tailpiece (fr') to more than 108 Hz. We can then infer that when four strings are attached and even when using light tailpieces, normal play will not excite this lowest mode. We obtain similar results with the G–D pair. If we play the C string, coupled successively to the G, D, and A strings, we reveal the impact on the BR and the open strings (Fig. 22).

Mean BR motion holds near 30 µm, but added steps shift in frequency. Only the AS-C resonance impacts the BR motion when coupled with the G string. The D and A open strings only create resonances leading to bridge steps.

We now consider an instrument from the violin family, fitted with four strings and tuned in fifths with an asymmetric tailpiece adjusted to the 3, 4, 5, and 6 modes. Vibrational energy flows from the bowed string to the body and the present resonators (Fig. 23).

The simulation is carried out by playing the 13 rising chromatic notes, numbered 1 to 13, of one octave on each I–IV string, and all the possible resonances up to the 10th partials are recorded. Table 4. The lowest note is normalized to 1.

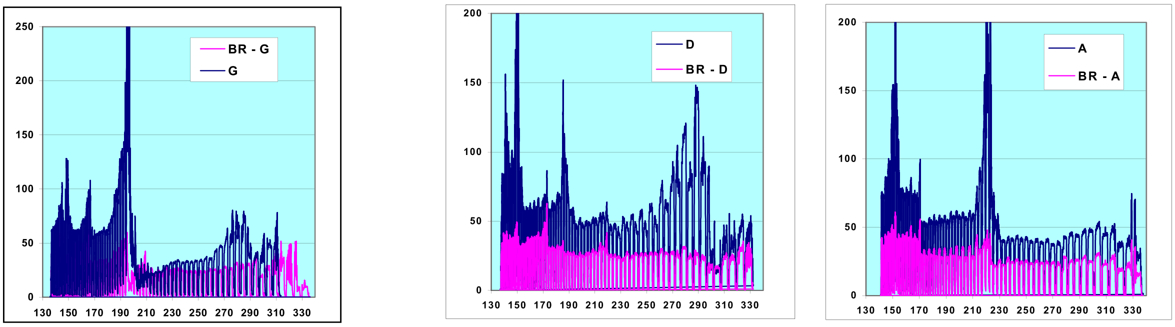
As the partial levels decrease in $1/n$, we extract the h1 or h1 + h2 as modulating candidates. These sums indicate three or seven modulations in ASs and five to eight modulations in open strings. If we compare this with a standard tailpiece with a mode of six for all strings, only the AS-IV coupling of 11 h1's exists, which is a G# bowed on an A string. These amplitudinal and tonal modulations are transmitted via the bridge to the body, matching to the air through impedance transfer function. The body itself, as a complex resonator, does not interfere with bridge motion unless a very strong coupling occurs [5].



f - C string bowed	Resonances G fr_0 = 193	AS - C fr_0 = 322	AS - G fr_0 = 662	Step BR
145	4-3			
165		2-1		
195	1-1			
209		3-2		
326		1-1		

f - G string bowed	Resonances C fr_0 = 130	AS - C fr_0 = 322	AS - G fr_0 = 662	Step BR
194	2-3	3-1,8	3-1,1	
207				
227		3-1	3-1	
255		4-3		
274	1-2			
306	2-1,1		2-1,1	
314	3-7			
322		1-1		
333	2-5	2-1	2-1	
341				
372	2-6			
427	min level			?

Figure 21. Resonance summary for the C and G string assembly. L_1 = 95 mm. $L_1 + dL$ = 140 mm. Att. = 10 mm. fr_0 indicates the resonance frequencies of the open string and after-length strings. The tables list the peak motion frequencies observed on each resonator, expressed by the n–m partial factors involved in Eqn. (1) at the corresponding bowed string frequencies f. Green steps show where we observe bridge motion reduction. Note that the frequencies of the bridge steps coincide with the G or C AS when we bow C. Step positions are just above the resonances which occur when we bow G. In the last case, we observe combined resonance.



Played note on C string, in Hz **C – D string pair** **C – A string pair**

f - C string	Resonances					
	AS-C	G	BR - G	D	BR - D	A	BR - A
	fr_0 = 322	fr_0 = 193		fr_0 = 293		fr_0 = 440	
145		4-3		2-1		3-1	
161	2-1	2-1,66					
166							
171						5-2	
179				3-2			
191	3-1,75	1-1					
203							
210							
217						2-1	
277	2-3	2-3					
283				1-1			
323	1-1						

BR step origin BR step position

fr_0 AS - D = 1031 fr_0 AS - A = 1133

*Figure 22. Peak resonances which occur when coupling the bowed C string with other open strings. Each cell uses n * (f) = m * (fr*$_0$*).*

During the sixteenth century, viola makers fitted violas d'amore with eight sympathetic strings, which they tuned to add a reverberant and rich sound to the instrument. The Indian sitar and sarangi similarly use sympathetic strings to achieve a rich sound.

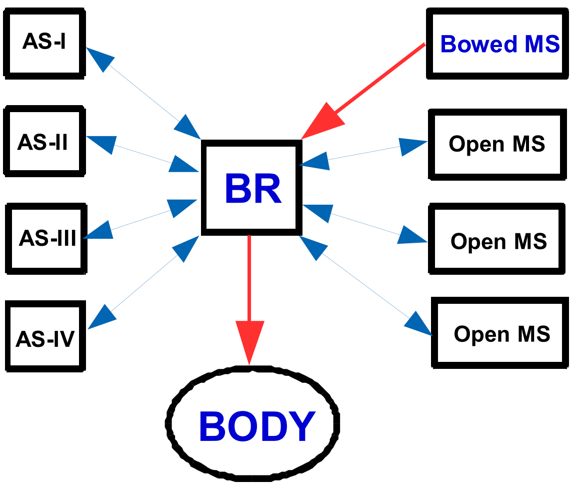


Figure 23. Energy flow from bowed string to the body, including all present resonators.

DISCUSSION

What can we conclude from our measurements of the tailpiece's effects on the transmission of energy to the body? First, the physical design parameters of the tailpiece, such as mass and material, are not relevant at first to bridge motion. Rather, adjusting mass or position can shift the frequency of all resonant modes of the back bridge system, as identified previously by White et al [3]. Second, previous works have looked for tailpiece resonances by direct excitation by hammer tapping [2] or using magnets [1], and have discarded the correlation with the bridge's induced motion. I suspect that these methods can lead to the identification of modes that do not appear strongly when excitation comes from the horizontal bridge motion. However, the parameter sensitivity analysis of tailgut or AS lengths, performed by Stough [1], is confirmed

Table 4. Normalized resonances between the bowed spectrum and open or after-length strings. Each cell provides the first played note and its corresponding partial. For example, 8-h2 on a viola's C gives a G (196 Hz), whose the second partial excites the AS-IV mode (3 × 131 = 393 Hz).

MS bowed	IV	III	II	I	h1	h1 + 2
After string resonances						
AS-mode	3	4	5	6		
AS-IV	8-h2	13-h1	6-h1	11-h1	3	4
AS-III	8-h4; 4-h5	13-h2; 6-h3	6-h2		0	2
AS-II	7-h8; 5-h9	12-h4; 8-h5; 5-h6; 2-h7	10-h3; 5-h4	10-h2; 3-h3	0	1
AS-I		10-h8; 8-h9; 6-h10	8-h6; 5-h7; 3-h8	8-h4; 4-h5	0	0
				Sum	3	7
Open main string resonances						
MS coupled						
IV		6-h1 (h1/2)				
III	8-h1		6-h1 (h1/2)		2	2
II	3-h2	8-h1		6-h1 (h1/2)	2	3
I	3-h3	3-h2	8-h1		1	3
				Sum	5	8

AS = after-strings; MS = main string.

here and quantified. Third, we find that the large number of amplitude and tone modulations present in the bridge have a localized frequency of 1 tone and a modest amplitude of 6 dB. A resonant body, however, can strengthen these modulations. Fourth, we have found that tailpiece asymmetry does not modify the mean sound intensity, but rather adds harmonic content in the lower range of frequencies. Could the withdrawal of the tailpiece system be a way to clear a lot of after-string length resonance problems? This idea would deserve to be discussed.

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Glossary	
AS	After-string
MS	Main string
BR	Pseudo-bridge (holder)
L_{m0}	MS open string length
L_m	MS vibrating length
L_a—L_1	AS length
$L2$	Pseudo-tailpiece length
$L3$	Attachment cord length
dL	Extra AS length
f_0	Open string frequency
fr	AS resonance frequency
fr'	Low resonance frequency of the tail-AS system
mu'	Linear spring mass
LPS	Laser position sensor
HFS	Horizontal quartz force sensor

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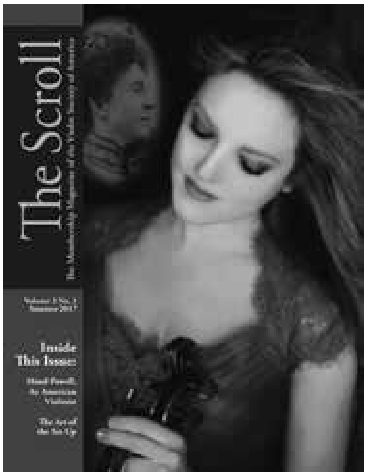

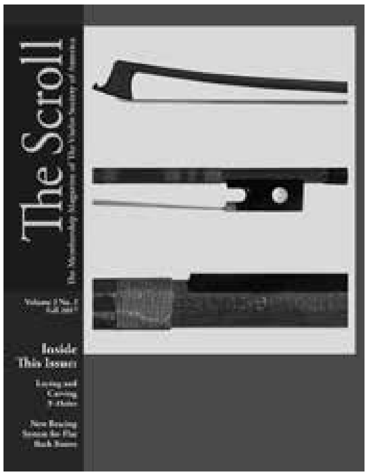

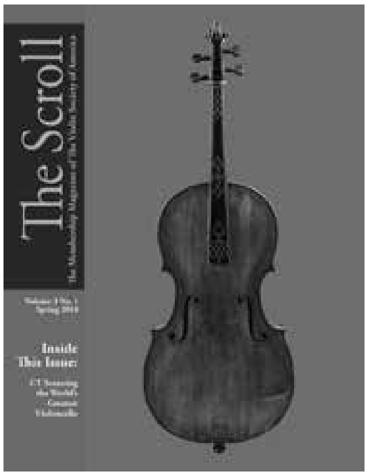

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