Acoustical Studies on the Flat-backed and Round-backed Double Bass

Dissertation zur Erlangung des
Doktorats der Philosophie
eingereicht an der
Universität für Musik und darstellende Kunst Wien

von

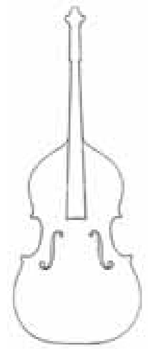
Mag. Andrew William Brown

Betreuer:
O. Prof. Mag. Gregor Widholm
emer. O. Univ.-Prof. Mag. Dr. Franz Födermayr

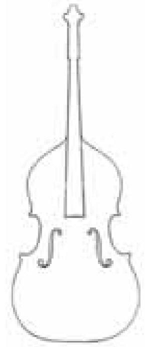
Wien, April 2004

“Nearer confidences of the gods did Sisyphus covet; his work was his reward”

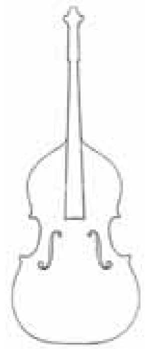
Table of Contents



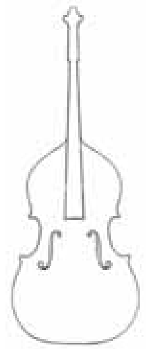
List of Figures



List of Tables

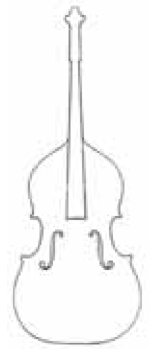


Forward



I am indebted to a number of parties for their active participation in this project. First and foremost, the technical assistance of instrument maker Heinz Fischbach of Ohlstadt, Bavaria, made this study in its final form possible. Frau Christina Burkhardt and Walter Rührig supplied six good microphones on behalf of AKG Acoustics. For the supply of top-quality strings, Helmut Frank and Mihaela Rodica Talmaciu of Thomastik-Infeld were of great assistance, as well as Franz Klanner, Heinz Kovacs and especially Wolfgang Vogl for tips and moral support. Peter Donhauser and Ingrid Prucha of the Technical Museum Vienna enabled measurements with the Polytec Laser Vibrometer, and kindly lent the B&K shaker used for the majority of the experiments. Knut Guettler planted important seeds with his advice on measurement techniques. I'm grateful to my colleagues at the Institut für Wiener Klangstil, and to Franz Födermayr of the University of Vienna for accompanying a musician through this academic performance. Thanks go to Marc Strümper, Wilfried Kausel and Gregor Widholm for their (sometimes excruciating) proofreading. Gerald Sonneck kindly lent his copy of "The Division Viol". Last but not least, I thank the musicians, instrument makers and dealers who took the time to participate in interviews and listening tests and thereby made the evaluation of sound differences possible. These included Josef Niederhammer, Werner Fleischmann, Micheal Kosman, Charles Beare, Marcel Richters of Machold Rare Violins, Christine Eriks, Wolfgang Panhofer, Alexander Lackner, James Rapport, the 2XBasslist archiver Paul Anderson and all the contributors to that list.

1 The Back Plate of the Double Bass



1.1 Introduction

In the following work, the double bass will be observed from a new perspective: in terms of the back plate. The back will be measured, photographed and otherwise tested to establish new knowledge about the double bass' acoustic behavior.

1.1.1 The Goals of This Study

Observations of the contemporary use of a flat back plate in modern bowed instruments lead to several hypotheses on the acoustics of modern double basses. While there is likely an important difference in the timbre and acoustical behavior between flat-backed and round-backed bowed instruments, this difference may be less noticeable in the low frequency ranges where the double bass most often is played due to factors of human hearing perception. It is the goal of this work to document the measurable acoustical differences between the two types, and to draw conclusions about the significance of these differences in practical situations.

Surveys among instrument makers, dealers and players will be used to gain an overview of contemporary opinions regarding the sound of flat-backed and round-backed basses and their everyday use. Then, test instruments with flat and rounded backs will be measured and analyzed using several different techniques, to verify or falsify the following proposed hypotheses:

1.1.2 Hypotheses

Hypothesis 1: There is a basic, measurable acoustic difference between the two back types.

Hypothesis 2: Flat-backed basses have a characteristic radiation pattern that is distinct from rounded models.

Hypothesis 3: In practice, these measurable differences are difficult for listeners to distinguish due to psycho-acoustical and room-acoustical characteristics.

1.2 The Form of the Double Bass

Of the modern bowed instruments, the form of the double bass is the least standardized. While the violin, viola and violoncello are clearly members of the violin family, the double bass possesses some elements which are attributable to the viola da gamba family. The falling shoulders, blunt c-corners, and most of all, the flat back plate commonly found on double basses are typical characteristics of the gamba.

1.2.1 Two Types of Double Bass: Flatback and Roundback

The form of the double bass can generally be divided into two types: that with a flat back and that with a round (arched or carved) back. Most basses either have a viol-like flat back plate with a unified thickness, upper break, and three or four inner braces, or a violin-like rounded back plate with variable thickness, no break and no inner braces. Basses in use, however,

Fig. 1.1. Two bass variants, left to right: flatback with break, roundback without break

do not adhere to standards of size and form, therefore all sorts of instruments are yet to be found on the concert podium. Because of this variety of forms (for example, an almost flat back with no inner braces, or a flat back with just one inner brace [soundboard] under the soundpost), the exact definition of types is difficult. Evidence suggests that neither type is more commonly used today.

The modern double bass has a few other characteristics in common with the viol family: the sloping curve of the bouts toward the neck joint and the deep ribs. Many basses have square or blunt corners at the c-bouts (see Fig. 2.1 on page 16). Tone holes of basses are sometimes seen in the form of Cs or "flaming swords" rather than traditional Fs. Classic Viennese basses have edges between the ribs and top and back plates that are flush, i.e. with no overlap. These elements are, with the exception of the flush edges, independent of the form of the back.

The history of the double bass' development is less well known than its smaller cousins. A quick look to Grove's Dictionary of Music and Musicians indicates the discrepancy in scholarship: the article on the violin (Boyden, et al, 1984) is 39 pages long, the article on the bass (Slatford, 1984) is only four pages!

Studies about the history of the double bass came about in the late 19th Century, much later than comparable works on the violin. After the appearance of purely pedagogical methods (M. Corrette, 1773, J. Fröhlich, 1829), A. C. White's "Method" (London, 1893) was the first publication to deal with the story of the instrument's history. A few years later, the visionary double bassist Friedrich Warnecke published "Ad infinitum: Der Kontrabass, seine Geschichte und seine Zukunft" (Hamburg, 1909). Warneke attempted to offer a "general overview" on the history, playing techniques and a "basis for research," which according to Warnecke did not yet exist at that time. Further works about the bass' history were written by Edward Elgar (1967a), Duane Rosengard (1992), and Paul Brun (2002). Planyavsky's "Geschichte des Kontrabasses" [History of the Double Bass] (Tutzing, 1984) and his extensive bibliography is noteworthy. The origin and development of the largest bowed instrument are at times still hotly debated.

The forms of flat-backed and round-backed double basses are somewhat rooted in regional instrument-making traditions, which were influenced by individual makers at certain points in time. Below is a rough estimate of

Table 1.1. Regional Preferences

Region	1700–1800	1800–1900	1900–2000
Italy	flat/round	flat/round	round
France	flat/round	round	round
U. S.	—	flat (German influence)	flat/round
London	flat	flat (Italian influence)	flat/round
Germany	flat	flat /round	round
Austria	flat	flat /round	flat /round

which types predominated during different periods, based on the author's experience. It is not meant to give absolute values, which don't apply except in special cases like in Vienna before 1800, where only flat-backed models were made.

In “A New History of the Double Bass”, French author Paul Brun is convinced that the double bass belongs to the violin family, rather than to the gamba family as is often claimed. He writes,

> “*In effect, neither the cello nor the double bass are in any way derived from instruments they simply superseded. The offshoots of the bass-violin, both of these instruments have been consistently in use from their inception in the late 17th Century to our own time. Admittedly, as a result of the demise of the viol family, a number of contrabass viols were converted into double basses at some point in history. But it is our view that the interpretation of the particular point should not lead to unsubstantiated generalizations, nor should it constitute an article of religion, to be accepted with unquestioning faith.*” (Brun, 2000, 43)

In spite of a rigorous search through the available literature, definitive information on the two forms of double bass back plates compared to one another was not found. Therefore, literature sources covering other instruments and empirical observations made at instrument museums and of actual use have been called upon.

1.3 The Form of Other Bowed Instruments

Instruments such as the viola da gamba, viola d’amore, baryton, and flat-backed double basses are the main representatives of flat-backed, bowed instruments. Over time, viols were forced from the scene by violin instruments like the violin and violoncello. The bass became the sole survivor among flatbacks to be used in “mainstream” western classical music.

Instrument collections contain not only treasured examples of frequently-used instrument types, but also have on hand innumerable curiosities of past centuries. The creativity invested in musical instruments by past inventors is often baffling. Rudolf Hopfner, the director of Vienna’s Collection of Old Instruments, said in a personal interview with the author: “Among musical instruments, the non-existent doesn’t exist.” It is often said that the instruments of a certain epoch aren’t better or worse than instruments from other ages, but that they are “more suited” to the contemporary taste in sound. Over the centuries, standardized instruments have arisen from the multitudes of newly developed musical instruments. Instrument makers, by using traditional methods and empirical innovations, arrived at new solutions, many of which were successful and popular. These improvements came increasingly closer to realizing the current acoustical ideal.

An example of such a development is described in Ian Woodfield's "The Early History of the Viol" (Cambridge, 1984, 125–127).

> *"[The] original belly of the Ebert viol was a flat plate, arched transversely and supported, like the belly of the Linarol instrument, with arched, transverse barring. This top presumably collapsed at a fairly early stage in the instrument's life and had to be replaced by the carved belly. If this speculation is well-founded, then the Ebert viol remains an eloquent testimony to the problems faced by early 16th-Century Italian viol makers trying to adapt the flat belly of the vihuela to withstand the arched bridge of the viol. Evidently the transverse bending of a flat plate did not always work."*

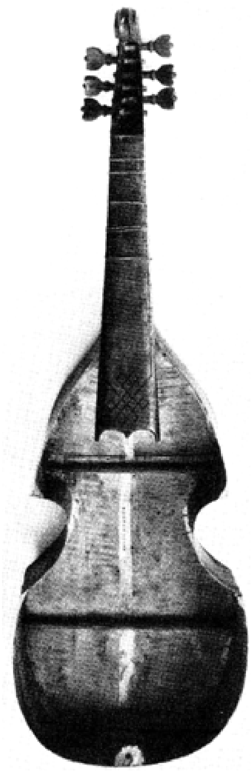


Fig. 1.2. Left: a Venetian renaissance gamba by Hainrich Ebert. The back plate has two horizontal braces, but no sound board (Woodfield, 1984). Right: a "modern" Italian double bass by Enrico Bajoni (1878) with two braces and a sound board.

Because of the requirements of musicians in 16th-Century Venice, bowing on single strings became necessary, and this resulted in a new, rounded bridge. Woodfield asserts that the arched, carved top plate of modern bowed instruments have their origins at this time. A stronger structure was needed to withstand the greater downward pressure of the strings. Contemporary luthiers were confronted with new demands, and developed new solutions accordingly.

1.3.1 The Success of the Violin Form

New, successful instruments were functional not only in supporting the static pressures on them, but in achieving the desired musical effect that players were after. These are the instruments that were further developed. Through the constant maturing of musical style and taste, many instruments flourished while others waned.

The 17th-Century gambist Christopher Simpson published his treatise "The Division Viol" (London, 1665) dealing with a soloistic and virtuosic style of playing. The author describes his opinion about the difference in sound between the two types, preferring the carved instrument (*"digged out of the plank"*) because it is more resonant, faster, and sounds more lively, *"like a violin"*. According to this view, arched instruments are better for soloistic playing, which intimates the trend at the time leading to the overwhelming success of the violin in the following century.

Sadie quotes Charles Burney describing the collision of musical eras during the twilight of the viola da gamba in the 18th Century:

> *"The baryton was practiced longer in Germany than elsewhere; but since the death of the late Elector of Bavaria […] the instrument seems laid aside. […] The tone of the instrument will do nothing for itself, and it seems with Music as with agriculture, the more barren and ungrateful the soil, the more art is necessary in its cultivation. And the tones of the viola da gamba are radically so crude and nasal, that nothing but the greatest skill and refinement can make them bearable. A human voice of the same quality would be intolerable."* (Sadie, 1984, 165)

Modern authors have compared the sound of the gamba family as "soft", "sweet", "reedy" to "nasal". The violin is, in contrast, "fuller", "stronger", and "more expressive" (Boyden, et al, 1984, 765–804). The Columbia Encyclopedia[1] describes the viola da gamba:

> *"[It] is a chamber instrument with a soft, sweet tone, incapable of the dynamic extremes and brilliance of the violin; this helps to account for its decline."*

1. Columbia Encyclopedia, Sixth Ed. (2001). Available at http://www.bartleby.com/65/vi/viol.html

Today, the viola da gamba is experiencing renewed interest from musicians, instrument makers and audiences, as seen by the increasing supply of recordings, concerts and teaching centers. In addition to the musical style and historical aspects, the *timbre* of the viola da gamba is fascinating to its followers. The flat back is one of the predominant parts of the gamba's form distinguishing it from the violin. Whether the sound difference depends primarily on the type of strings used (gut vs. metal), the typical bowhold (overhand vs. underhand), or the form of the back plate or other features of the form is not clear. It will be shown, however, that the back may be a major contributor to timbre differences.

1.3.2 Conversion of "Old-Fashioned" Flat-Backed Instruments

The viola d'amore was a very popular instrument in the 18th Century, as

Fig. 1.3. A Viola d'Amore from the collection of the Carolino-Augusteum, Salzburg. It was rebuilt as a four-string viola but is no longer played today (Birsak, 1996).

demonstrated by the large numbers of extant, masterful examples of instruments in collections. The sound is described as "not as brilliant or powerful as a violin or viola, [but] singularly sweet" (Rosenblum, 1984, 760). In the early 19th Century, the viola d'amore lost popularity. It is not known whether its downfall is attributable to changing tastes in sound, and if so, to what extent the flat back was responsible.

These instruments were often modernized in the 19th of early 20th Centuries by converting them into four-stringed violas. It is interesting to note that of all these instruments, they and their flat backs, are almost absolutely absent from the concert podium, yet seem to fill silent instrument collections from St. Petersburg to Rome. It can therefore be reasonably concluded that the sound of such a flat-backed viola fails to meet modern standards of sound production.

Another example of a converted instrument is a five string viola da gamba built by Antonio Stradivari in the later 17th Century. Due to the quality of the instrument, its appropriateness for conversion, and the fame of its builder, it is still played today and known as the “Ex-Iwasaki” violoncello (Mikisaburo, 1984, 134). Sacconi’s “The ‘Secrets’ of Antonio Stradivari” (Ed. von Stietencron, Frankfurt am Main, 1997) contains several illustrations showing gamba patterns from the Stradivari estate, which are preserved in the Cremonese State Museum, “Ala Ponzone.” In this collection, there are a set of patterns for a bass gamba, inscribed, *“Built for Contessa Cristina Visconta 1684”*.

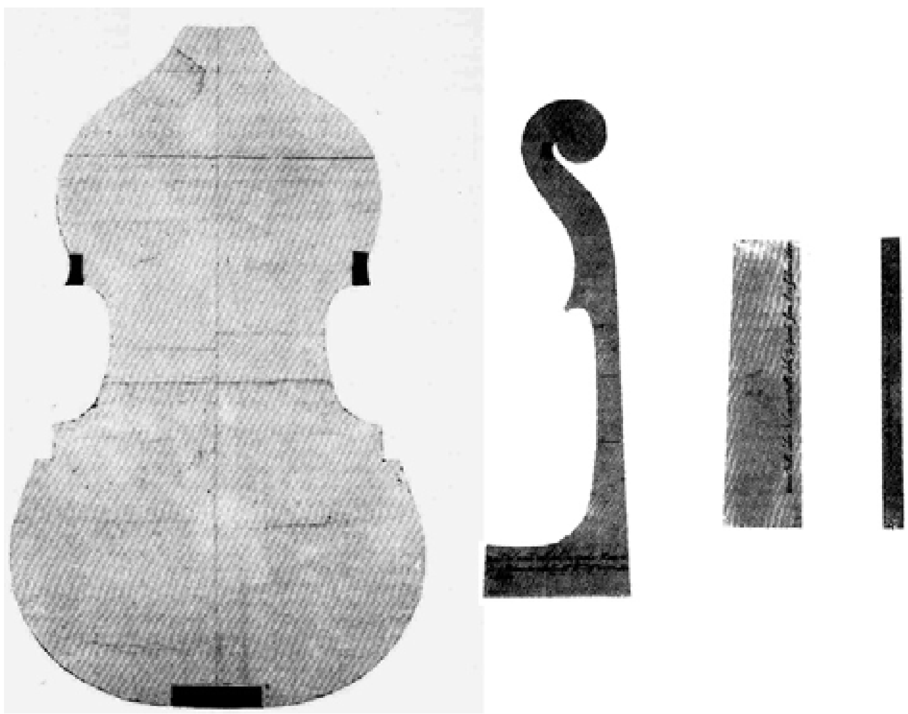


Fig. 1.4. Patterns for a flat-backed viola da gamba by A. Stradivari (Sacconi and Stietencron, 1997, 194–196)

The instrument was originally built in the style of a violin (scroll, violin corners at the c-bouts, and f-holes) with the exception of the flat back (without braces), the sloping shoulders and the number of strings. Through the years, the neck and the shoulders were rebuilt, the break in the back straightened, and the instrument reduced in size. In the late 19th Century, the firm Hill in London built a new, arched back for it, and the metamorphosis to a modern cello was complete. The original back was kept with the instrument, which allowed a unique opportunity to compare the sound of a flat back and a round back with a first-class instrument.

The firm John & Arthur Beare attempted in the early 70's to sell the cello with the original flat back refitted. In a letter to the author, found in the appendix (see Fig. 9.1 on page 104), Charles Beare describes the sound with the flat back as a "splendid quality of sound with plenty of resonance".

> *"After about one year of failing to sell it despite its being much admired we reluctantly re-assembled the cello with the Hill back and although the quality diminished, the volume became what one would expect from a Stradivari and it was sold in a very short time!"*

This story illustrates how the current tastes, and perhaps even visual prejudices, exercise an acute pressure on instrument makers and dealers.

Another case, with a more of less similar instrument, leaves open questions. A small bass instrument, found in the music instrument collection of Rome (Cervelli, 1994, 312) is described as "Violoncello piccolo a 4 corde." Its form resembles the finest forms of classical Italian double basses of the

Fig. 1.5. A flat-backed, bowed instrument that is slightly smaller than a violoncello (Cervelli, 1994, 301; 312)

17th Century, but its total length is at 64 cm only half as long! The sloping shoulders and flat back indicate gamba or double bass form, the mensur indicates a bass gamba or violoncello, the corners of the C Bouts, F holes and scroll are violin traits. In contrast to the Stradivari gamba, this instrument is 10 cm shorter than a modern cello, and was therefore never a candidate for conversion. It is obviously a master instrument, and it is probable that it would have been converted like the Stradivari viol and a multitude of other gambas to a round-backed violoncello, had it been the right length. But instead, this charming instrument rests in peace, mute behind glass.

In conclusion, the absence of smaller flat-backed bowed instruments in modern western music is noteworthy. Though examples of viola- and violoncello-like instruments with flat backs are commonly found in historical references and collections, they are seldom found in modern symphony orchestras. This observation leads to the conclusion that a major sound difference between the two types must exist.

References

Birsak, K. & A. Birsak (1996). Gambe-Cello-Kontrabass. In: *Jahresschrift des Carolino-Agusteum (Salzburger Museum für Kunst und Kulturgeschichte).*

Boyden, D. D., B. Schwarz, P. Cooke, A. Dick, et al (1984). The Violin. In: Sadie, S. (Ed.), *The New Grove Dictionary of Musical Instruments*, Macmillan Pub. Ltd. London, 765–804.

Boyden, D. D., and A. M. Woodward, (1984). The Viola. In: Sadie, S. (Ed.), *The New Grove Dictionary of Musical Instruments*, Macmillan Pub. Ltd. London, 753–759.

Brun, P. (2000). "A New History of the Double Bass." Paul Brun Productions, Villenuevre d' Ascq.

Cervelli, L. (1994). "La Galleria Armonica: Catalogo del Museo degli strumenti musicali di Roma." Inst. Poligrafico e Zecca dello Stato, Roma.

Corrette, M. (1773). "Méthode pour apprendre à jouer de la contre-basse à 3., à 4. et à 5. cordes." Paris.

Elgar, R. (1967a). "Introduction to the Double Bass." St. Leonards on Sea.

Fröhlich, J. (1829). "Kontrabass-Schule." Würzburg.

Mikisaburo, O. (1984). "Antonio Stradivari in Japan." Gakken, Tokyo.

Planyavsky, A. (1984). "Geschichte des Kontrabasses," 2nd ed. Hans Schneider, Tutzing.

Rosenblum, M. (1984). The Viola d'amore. In: Sadie, S. (Ed.), *The New Grove Dictionary of Musical Instruments*, Macmillan Pub. Ltd. London, 760–763.

Rosengard, D. (1992). "Cremonese double basses." Ed. Turris, Cremona.

Sacconi, S. F. und J. von Stietencron (1997). “Die Geheimnisse Stradivaris.” Erwin Bochinsky, Frankfurt am Main.

Sadie, J. A. (1984). The Baryton. In: Sadie, S. (Ed.), *The New Grove Dictionary of Musical Instruments*, Macmillan Pub. Ltd. London, 163–166.

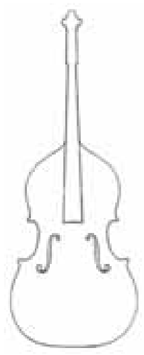
Slatford, R. (1984). The Double Bass. In: Sadie, S. (Ed.), *The New Grove Dictionary of Musical Instruments*, Macmillan Pub. Ltd. London, 590–594.

Warneke, F. (1909). “Ad infinitum: Der Kontrabass.” Im Verlage des Verfassers, Hamburg.

White, A. C. (1893/1934). “The Double Bass.” London.

Woodfield, I. (1984). “The Early History of the Viol.” University Press, Cambridge.

2 *Surveys and Literature on the Flat-backed and Round-backed Double Bass*



2.1 Surveys of Instrument Makers

Unlike the violin, the double bass has not yet reached a standardized, perfect form: even now, basses with either flatbacks or roundbacks are still being made. Compared with builders of violins or violoncellos, the bass maker consequently has more freedom in his choice of form. What are the maker's motivations when choosing a form?

2.1.1 Motivation of instrument makers

It is important to consider makers' intentions if one tries to understand the development of the flat-backed and round-backed double bass models.

An instrument maker who works by hand is a craftsman and artist who expresses himself with the object he makes thorough the sound and appearance of his product. He or she is also a business-person that necessarily must sell his or her work. The instrument maker's dependence on musicians' preferences, wishes, and demands determines to a large degree the objects that luthiers produce. The acoustical, structural and aesthetic qualities of the instruments are criticized sharply by musicians, who are highly skilled and also dependent on the instrument for their own livelihood.

According to correspondence with instrument makers[2], there are still dynamic changes happening today in the demands musicians have of instruments. For example, the cello and bass maker Michael Kosman of Maryland, U.S.A., explained in an interview[3] that the desired cello sound has changed even in the last fifteen years. Apparently due to its shape, the "Belgian" bridge sounds more brilliant and focussed than the formerly standard "French" bridge type. The Belgian bridge has become much more popular of late due to changing tastes in sound.

In a similar way, the wishes of bass players express themselves through

2. All correspondence presented in Sections 2.1 and 2.2, unless otherwise stated, comes from e-mail responses to the author's survey or searches on the same subject, both of which are currently available in the archives of the 2XBasslist: http://home-pages.inf.ed.ac.uk/dcspaul/bassist/archive.shtml.
3. Telephone conversation, 8 January, 2002.

the observable work of bass makers. But the violoncello and its culture, due to its long use as a soloistic instrument, is arguably further developed than the double bass. Kosman believes that the bass is yet in a developmental stage and he expects that a more “sophisticated” form will develop with its maturing culture. It is possible that the issue of flat and rounded backs in double basses will eventually be settled when one form prevails.

2.1.2 Innovation in Instrument Making

Innovations in instrument design are introduced onto the market, offering solutions to musical problems and keeping the maker competitive among fellow suppliers. Successful innovations survive and are distributed by being copied by other instrument makers. It is, however, important to note that musical instruments are sold not only by their musical virtues but also by advertising, fashions and by clever marketing.

Horst Grünert of Penzberg, Bavaria, builds copies of original basses, but a pamphlet advertising his Joseph filius Andrea Guarneri model (2003) clearly leaves it up to the client to decide between a flat or rounded back:

> *“The instrument is available with four of five strings and with flat as well as round back.”*

Regional preferences for one type may play a role in the selection of the back type. Giovanni Mariotto, bass-maker in Mantua, said in a personal interview that he builds basses with a rounded back. This is because the sound and look of such basses appeals to him, and also because he builds in the modern Italian tradition, which uses principally round-back models. Both forms are found frequently in classic Italian basses. The “classic” Viennese bass, on the other hand, always has a flat back. Thomas Martin, bass-maker in London, wrote in an e-mail that he builds exclusively flatbacks because of his convictions about their physics and sound qualities. Today, regional traditions are interlaced, influenced by individual instrument makers, and are hardly separable. Even the orchestral bass collections of conservative Vienna have been mixed for quite some time.

2.1.3 Maker’s Opinions on Sound

Makers of hand-made instruments consider the sound of their instruments of prime importance. North American restorer Bob Monroney wrote, not altogether conclusively:

> *“I restored two old German flat-back basses this past Summer and their finished sound was as good or better than many roundbacks I’ve seen.”*

The account reveals, however, a prejudice in favor of rounded backs.

Martin Sheridan, bassist, dealer and restorer in the U.S., wrote that the form of the back is not an important factor for the sound:

> *"The general consensus is that flat-back basses have a better sound. Personally I think the design of the bass and the top have a lot more to do with the sound than the back does."*

Bass makers are generally convinced that the flat back sounds more "focused" and "direct". From the bass makers asked, Michael Kosman, Tom Martin, Zak Stolk (Canada), Barrie Kolstein (New York), David Gage (New York), und Oliver Radke (Füssen, Germany) described the flatback as sounding "punchier", "boomier", "overtone richer", or simply as "better". Rounded backs sound reportedly "rounder" or "fuller". Some think that the cross braces in the back give the sound "more support". There were no opinions on the aesthetic, visual qualities of the backs.
Tom Martin, who has many years of experience as an orchestral musician, soloist and in recent years as an instrument maker, compares acoustics to a tennis ball. He describes his opinion about the flat-backed bass:

> *"Throw a tennis ball straight at the wall — it goes 'smack' and comes straight back straight away. Throw the same ball at the corner — it hits one side bounces to the other and comes back a little later to perhaps not quite the same place. There you have the difference in a nut shell between a flat and round back. Of course, it's not quite that straightforward but not far off. The table throws the sound (á la woofer) at the back and is thrown back. The flat back is a sharp and immediate in response whilst the round is more diffuse in character. There is conjecture in the round whether the sound that hits the right side is thrown to the left etc. In the flat back, the center brace is very important — the round back does not normally have one. If you add the center brace to the equation, the round back (supported by the arch) is thinner than the flat (supported by the brace)! I like to make flat backs for the sound (response is a serious consideration on the bass!) but, as one person mentioned, they are more structurally fragile."*

Apart from structural factors, do the braces have an important influence on the sound? Monroney wrote about the braces of contemporary maker Jackstadt:

> *"I have yet to hear if the 'X' bracing on Jackstadt flatbacks is effective."*

Michael Kosman explains why he thinks flatbacks sound "punchier" and richer in overtones:

> *"The cross-grain of the bars in the flatback support the sound-post more firmly."*

Canadian Bassist Dallas Selman wrote about his instrument, built by Zak Stolk.:

> *"All I know about the subject is my new acoustic flatback has a slight camber on the back, and on this model they did not tie the braces into the ribs, so the braces are 'floating' so to speak, which the builder concludes improves the projection..."*

2.1.4 Static Problems of Flat Backs and Their Solutions

The general structural stability of the double bass, as with all instruments, is highly important. Great static (string tension) and dynamic forces (environmental influences) act constantly on the entire instrument. Bass makers must make instruments that are structurally stable. For acoustical reasons, it is advantageous to build as strong a structure as possible while keeping the mass to a minimum, and instrument-makers strive to find an ideal balance between mass and structural stability.

The braces inside a flat-backed bowed instrument often cause inner tension with changing atmospheric conditions. Wood expands when it absorbs moisture under conditions of increasing air humidity. Because the grain of the softwood braces and hardwood back plates are glued at right angles to one another, tension often arises between the parts, resulting in deformation of the plates, the braces or ribs becoming unglued form the back plate, or not uncommonly causing cracks in the back. Even if there are no such visible signs of inner tension, the resulting strain may yet have an influence on the vibration characteristics of the entire bass.

Charles "Chuck" Traeger, an American bass repair specialist, claims that these "design flaws" have caused the rounded back to become more prevalent:

> *"It is because of these design problems that flat-back basses have become unpopular."* (Traeger, 1988, 14)

This type of problem is especially critical in the case of classical Viennese basses. Like a gamba, the edges of the top and back plates are glued flush to the ribs. Therefore, any shrinkage of the top or back plate, which is quite likely over the years owing to the orientation of the grain, results in a gap at this joint.

The rounded back is not subject to problems of inner tension or the "missing" plate edges. Bass restorer Barrie Kolstein wrote:

“The bass I am restoring [...] is a round back bass. The design lends itself structurally to this wood [Bird’s-eye Maple]. [This] bass does not have the problems that a flat-back bass could potentially incur.”

The rounded form allows for changes in the expansion and contraction due to changes in humidity that are not limited by the inner braces, thereby avoiding structural damage. The double bass manufacturer Heinz Fischbach (Bavaria, Germany) reports that the demand for rounded backs is by far greater in importing countries like the U.S. or Spain on account of this type’s climatic stability. With modern manufacturing techniques, the production of a rounded back is not any more time consuming than a flat back, and is even less complicated since the step of adding the braces is eliminated.

The overhanging edges of the violin-like form allows much more flexibility in the exact placement of the seam between the ribs and the top plates.

(photos by the author)

Fig. 2.1. Viennese-style bass with gamba c-bouts and no overhanging edge, left, and Italian bass with violin c-bouts and overhanging edges

Double basses are subject to changing string height due to varying humidity (Brown, 1999, 4). It has yet to be demonstrated if one type of bass back is more subject to changing string height than the other. Oliver Radke claims that the flat back, when properly made, offers a better "climatic balance" of the instrument.[4] "Measurements at between 25% and 90% humidity showed no change in the height of the strings." If the changes in string height are principally due to swelling in the wood of the neck, this argument is not particularly significant.

Oliver Radke believes that the quality of the material and the method of crafting them are the determining factors in avoiding inner tension and other problems. Not only the optimal storage of the wood and the proper moisture content (under 8%) at the time of construction, but also the proper technique of shaping and gluing the braces to the back is essential for the stability of the instrument. Radke uses a popular technique known as "springing" the braces, that is, the ends of the braces are contoured to create some tension toward the outside of the instrument when completed. Both ends of the brace are reduced in thickness, causing pressure in the center of the brace toward the outside. Maker Zak Stolk leaves a gap, like Radke, of approximately 6 mm at the ends.[5] Thomas Martin wrote:

> *"I found that when I sent a European braced (unsprung) bass to North America, the back tended to dish inwards, so I now spring the braces. I was initially trepadacious but found, to my surprise, that the sound improved as well!"*

To avoid further problems, the braces should be fitted with some distance between the ends and the ribs. Bob Monroney:

> *"The conventional bracing on flatbacks is definitely a problem but I have found that if they are not connected to the ribs at their ends (this confirmed by Barrie Kolstein) the problems of shrinkage and warping are minimized."*

Even though none of the participating instrument makers mention a disadvantage of "springing" the braces, the German physicist W. Güth rejects any positive effect from this technique, which is similar to "springing" the bass bar.

> *"It was established that a mechanical tension, which is used by some violin makers, has no influence on the quality of the wood. That this tension has no influence on the structure, because the effect of the tension disappears within a short time, has already been written."* (Güth, 1989, 60)

4. Telephone interview, 8 January, 2002.
5. Telephone interview, 10 January, 2002.

Whether this claim also applies to double bass backs has yet to be established, though it is obvious that most makers who replied to the survey would disagree with Güth's assertion.

2.1.5 The Choice of Back Materials

As previously mentioned, the flat back plate can be more or less work-intensive than a round back plate, depending on the applied techniques. It is easier to plane a flat plate during manual production than to gouge out a carved back with contoured thicknesses from the raw wood.

Oliver Radke works exclusively by hand, and wrote:

> *"With serial production and the assembly of basses from pre-produced parts, the flat back has fallen out of fashion, because the braces must be applied by hand under special conditions to avoid cracks and loose braces."*[6]

The illustration demonstrates that a flat back requires less material than

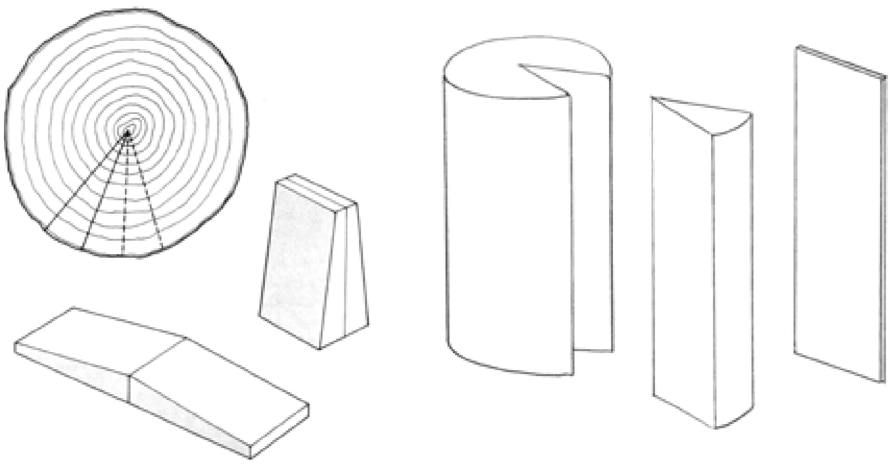


Fig. 2.2. Left: the principle of using quarter-sawn lumber for violins (Boyden, et al, 1984, 767). Right: material costs with basses: the tree trunk, the blank for a rounded back, the blank for a flatback.

a carved back. During modern production, technical means are employed to save time. The advantages of saving costly material are secondary to saving even costlier time and muscle power. The rounded back can therefore be more efficient to build. This factor, combined with the overwhelming de-

6. From Radke's website, currently available at: http://ourworld.compuserve.com/homepages/Stephan_Radke/flatbk_e.htm

mand for round-backed basses from customers, is the reason why Heinz Fischbach produces only about 5 flat-backed instruments out of nearly 400 per year. Flatbacks are delivered only on special order.[7]

Prestige may be a factor in the choice of the type because the rounded back requires more material and may be considered "more expensive" and therefore desirable.

Amateur bass makers and restorers are very creative in their solution to problems. One anonymous North American participant in an e-mail list mentioned that he had tried as a soundpost, "everything from Engleman spruce to a billiard cue," but even so failed to improve the sound of his instrument! Another wrote:

> *"I recently acquired an old bass of solid woods except the back which had been replaced with 1/4" plywood. In spite of a million sloppily epoxied cracks, this box [Bass] is much clearer than my current laminated Framus cutaway, although it feels heavier. [I will] re-back it with something less lumberyardy…"*

Finally, an unnamed bass restorer working in the eastern U.S. should be mentioned. To "improve" the sound of old instruments, he has often replaced the original back with plywood. Even valuable instruments have suffered this fate, where the original back somehow becomes lost. While the affect on sound quality is uncertain, this practice amounts to vandalism, destroying the integrity of the original instrument.

2.1.6 Conclusions

Bass makers can choose from a variety of form elements that have yet to be standardized on the double bass, including the flat or rounded back plate. In the case of the flat back, the maker must also determine the type and number of inner braces. Makers are motivated by a number of factors, such as the wishes of their clients, the economics of making and selling the models, the regional making tradition, and their own aesthetic, structural, and most of all, acoustical opinions and preferences.

There are a variety of opinions about the sound characteristics of flat and round back plates, many appearing scientifically well-founded and others not. The majority of bass luthiers think that the flat backed model sounds "more direct" and "more focused." It was also mentioned often that flat backs are subject to structural problems and that special building techniques can be used to prevent such problems.

7. Personal interview, August, 2002.

2.2 Surveys Among Musicians

Musicians have high expectations when choosing their instruments. Several factors contribute to this decision: to which extent the instrument in question fulfills the musician's own and culturally influenced sound concept, the playability of the instrument, its condition, the aesthetic (visual) taste of the musician and his cultural environment, its price and value, and its prestige. Does the form of the bass' back play a role in the choice of an instrument? What experiences have players had using basses with flat or round back plates?

2.2.1 Opinions of Bassists Are Contradictory

Numerous e-mail messages and personal contacts confirm that current opinions about the acoustics of the flat-back and round-back bass can be extremely contrasting. The tendency is, however, that bassists more often describe the flatback's sound as "more direct," and the roundback's sound as "rounder" or "fuller." It it also clear that players are aware of flat back plate's structural weaknesses.

Brent Nussey, bassist in Japan, wrote that the sound impression of the type is filtered through one's own experiences with individual instruments.

> *"Here's the thing, from my perspective. There are a ton of things in construction that alter the sound of the instrument. How we think flat vs. round backs sound different is going to be really affected by exactly which instruments we have played. I've been lucky to try a lot of different basses out, and it's really hard to try to identify the reasons each bass sounds the way it does, there are just SO many variables."*

A generally applicable rule about the sound difference between the two types of double bass is problematic. Each instrument is an individual. The wood, fine tuning of the plates during assembly, varnish, previous repairs, setting of the soundpost and bridge, string type and other factors can influence the sound of the bass greatly and are independent of the back. In spite of these problems of isolating the influence of the back on the sound, the majority of players agreed that flat-backed basses have a distinctive sound.

2.2.2 Bassists' Response to the Survey on the Sound of the Two Types

As with the instrument makers, a majority of bassists claimed that the flat-backed model sounds "focused" or "directer" compared to the roundback. The roundback is said to sound "rounder", "fuller" or "darker".

> *"Roundbacks are said to have a deeper (less shallow) sound."*

Brent Nussey wrote,

> *"My own personal experience has been that (good quality) flat-backs have a little faster response [...]"*

Bob Comrow (U.S.A.) wrote,

> *"All things being equal, flatbacks speak faster and are brighter. Round backs can have a fuller, darker sound. But all things are rarely equal."*

"*All things*" applies to all the other influential factors that can affect the sound of a bass. Another bassist wrote a suggestion as to where the difference comes from:

> *"I would think that the darkness in a roundback could be caused by a larger volume, that would lower the resonant frequency of the body."*

Viennese bassist Josef Niederhammer (professor of double bass at the University of Music and Performing Arts Vienna) has a definite opinion about the sound difference between the two types:

> *"The flatback responds faster, and sounds more direct than the roundback"*[8]

He knows exactly (for himself) that his 19th Century Viennese instrument by Bittner, because its rounded back sounds "fuller" and "rounder," is better for use in chamber music situations and accompaniments. In contrast, his Lemböck, also built in Vienna somewhat earlier, sounds "penetrating" because of its flat back, and is therefore better suited to soloistic playing. Because of his extensive experience playing orchestral, chamber and solo music on these basses, his conviction as to the sound difference is notable.

Werner Fleischmann, bassist of the Vienna Symphony Orchestra, mentioned a very interesting idea during his response to the survey questions.[9] He said that though he has little experience with the study of acoustics,

> *"[...] I can somehow imagine that [the flat back sounds more direct]. I can imagine a mirror: as a flat mirror reflects light waves directly back, the flat back could radiate directly. A convex mirror diffuses the reflected waves in different directions."*

8. Personal interview, September, 2002.
9. Personal interview, September, 2002.

Perhaps it’s so with the rounded back. This interesting idea could not be directly proven during this study but is good material for musical acousticians to think about.

A recurring theme of the survey responses was the visualized description of the sound: while the flatback sounds “more direct,” the carved back sounds “rounder” and “fuller”.

2.2.3 Contradictions in Opinions

In spite of the majority, the opinion that the flat-backed bass sounds “more direct” is often contradicted by musicians. Bassist Steve Wish (U.S.A.) wrote,

> *“My basses are so different, but in mine the flat backs are ‘boomier’ and the carved backs seem to punch more and have more dynamic range.”*

“Punch” may be understood to mean “faster in the response” or even “directer.” “Dynamic range” was mentioned only once in the surveys. The Dutch bassist Wout Moerman wrote,

> *“I have a feeling that a flat back gives a deeper sound than a carved back.”*

“Deeper Sound” may be understood as “fuller.” William Olsen (U.S.A.) wrote,

> *“I am not happy with the sound of a flatback. The sound appears to be more mellow (if that's what one wants) but it doesn't appear to be as focused which is what I'm generally looking for in an orchestral setting. The flatback sounds good in a small room or in an intimate setting but it doesn't cut it in a large concert hall setting. This is probably the area where those who play flatbacks will disagree.”*

Most of all, J. Niederhammer would disagree with this statement, since his response to the survey question was the exact opposite.

Other musicians find no difference between the two types. Jeff Aaron (U.S.A.) wrote,

> *“As far as I know, the whole swell- vs. Flat-backer doesn't seem to make a whole lot of difference […]”*

Brent Norton (U.S.A.) wrote that, while the braces of flat backs often require repair,

> *"[The] sound (interestingly enough) seems unaffected by the shape of the back."*

To emphasize his opinion that the question is insignificant, bassist Dan Miley (U.S.A.) showed his sense of humor:

> *"I am not an expert on acoustics or psycho acoustics, but I do know that: the roundback basses are more stable in heavy seas. The flatbacks work better for bass* [Ger.: Barsch] *fishing in shallow water."*

It can be seen that the opinions of bassists on the subject are diverse. A spectrum of bassists contains bassists that believe the difference is clear and important and others who believe there is no significant difference. Many of the responding bassists are somewhere in between, unsure if a real difference in sound between the two types exists.

2.2.4 Aesthetic Tastes and Regional Preferences

Opinions dealing directly with the appearance of flat or round backs were not mentioned in survey responses. Musician's decisions apparently have little to do with visual aesthetic preferences.

Though the forms of flatbacks and roundbacks are somewhat rooted in regional instrument-making traditions, it is questionable if the form of the back would stop a player from buying an instrument because of its appearance. Since forms and regional styles have been so mixed during the development of modern bass lutherie, it is difficult to attribute regional traditions to the choices of back forms.

One exception would be the case of players who play ancient music on historical instruments. Especially in Vienna, the use of traditional, classical Viennese double basses (Thir, Posch, Dallinger, etc.) or copies of original instruments is important in ensembles like Concentus Musicus under the direction of N. Harnoncourt.[10] The choice of such a bass is immediately connected with a flat back plate, since all Viennese basses of this period were built in this way. Oskar Kappelmayer of Passau, Germany, builds new copies of classical Viennese basses for international clients who order copies of original instruments.[11] The exact role that sound plays in these choices has yet to be defined.

10. Personal interview with bassist Andrew Ackerman, September 2002.
11. Personal interview, October 2001.

2.2.5 The Value and Condition of the Instrument

The existence of a definite price difference between the two model types could not be established. Although roundbacks are seen to be more costly, this plays no obvious role in the production of new instruments. However, many of the least expensive instruments are built with flat backs. Since flat back plates require less of the costly material, it may be that flat-backed basses may appear "cheaper" and therefore less desirable than their round-backed cousins. A short look at the current websites advertising double basses for sale shows generally three price classes: low (under $5000.–), middle (from $5000,– to $20,000.–) and high (above $20,000.–). Both types are found in all three categories, even though the roundbacks seem to be slightly in the majority. There are plenty of both types even in the most expensive category.

Musicians know that flat back plates tend to have stability problems. Of course, the stability of the instrument is of importance for successful music-making with the instrument, as well as for its preservation as a financial investment. Brent Nussey wrote:

> *"It is well known that flatbacks are less stable, and usually require the back to be rebuilt after 90 or 100 years, because of the way the braces are made."*

Another anonymous colleague wrote,

> *"Flatbacks are easier to make, but may be more prone to cracks as the wood expands/contracts along one plane only. I have had problems with mine as the cross bars have come loose, causing rattles and buzz. This may have been caused by back plate movement due to change in air humidity."*

Bill Bentgen (U.S.A.) wrote:

> *"I've been told that flat backs have expansion/contraction problems. That's why I paid extra for a carved back when I bought a new bass. Barrie Kolstein told me that the flat back bass he sells has bowed bars so that the back can flex when it expands and contracts."*

In spite of the knowledge of these problems, flatbacks are still in use today.

2.2.6 Conclusions

Though some bassists have a definite opinion about the difference in sound between model types, for example that the flat-back bass sounds "more direct", there is no general rule. Many bassists find the acoustical qualities of the back of importance while others don't. The individual musician's experiences with individual instruments may filter opinions of the two types, making general judgements difficult. Tendencies in the judgements of bassists regarding the back plates may also be influenced by visual associations, cultural and regional preferences and financial considerations.

2.3 Literature on the Acoustics of the Flat-backed Bass and the Round-backed Bass

Previous research dealing specifically with flat and round-backed double basses is certainly a rarity. With the exception of Brun's words, no specific references to the form of the back and its sound could be found in the historical or reference works on the double bass.

The earliest comparison of the two types of backs mentioned here is by the 17th-Century gambist Christopher Simpson, published his treatise "The Division Viol" (London, 1665).

Fig. 2.3. Two gambas from "The Division Viol": an arched, violin-like form at left and a flat-backed gamba form at right (Simpson, 1665, 1).

Two types of gamba are introduced that even include a description of the sound:

> *"Forma Chelyos utravis Minuritonibus apta, sed Prima resonatior."*

The meaning of the colloquial Latin phrase is obscure, but a plausible translation follows:

> *["Both gamba types are suitable for Division, but the first is more resonant."]*[12]

Simpson continues,

> *"A viol for division, should be of something a lesser size than a Consort bass; that the hand may better command it: more or less short, [etc.] The sound should be quick and sprightly, like a violin; and Viols of that shape (the Bellyes being digged out of the plank) do commonly render such a sound."*

Simpson describes his opinion about the difference in sound between the two types. He prefers the instrument carved-backed instrument ("digged out of the plank") because it is more resonant, faster, and sounds more lively, in his words, "like a violin" (Simpson, 1665, 1).

Recently, an acoustical study (Ågren and Stetson, 1972) reported results of measuring resonances of treble viol plates by hologram interferometry, which includes a documentation of modal patterns of a flat back with three cross bars or braces. The authors identify two "traditional design mistakes" in the treble viol: that rib depth is deeper than that of a violin, and that the body length, at 36 cm, is too short to support the lowest string tuned to D at 146 Hz. The authors designed an "improved" model called the *magnum treble viol*, whose back is pictured below (see Fig. 2.4 on page 27). They write,

> *"It is difficult to say to what extent these back plate resonances aid or detract from the instrument as a whole."*

The article "Preliminary Studies of Flat-Backed Basses" (Wall, 1985) deals directly with the sound quality and modal patterns of flat back plates. Wall compared Chladni patterns of three back plates made for a small test bass that had different materials and thicknesses. The author also recorded "response curves" of the instruments, albeit in his backyard. Wall identifies the A0 and T1, or A1, resonances at 51 Hz and 100 Hz based on response curves, which is surprising given the small size of the test instrument. It is

12. Translation by Peter Söllner, Prof. of Latin in Munich

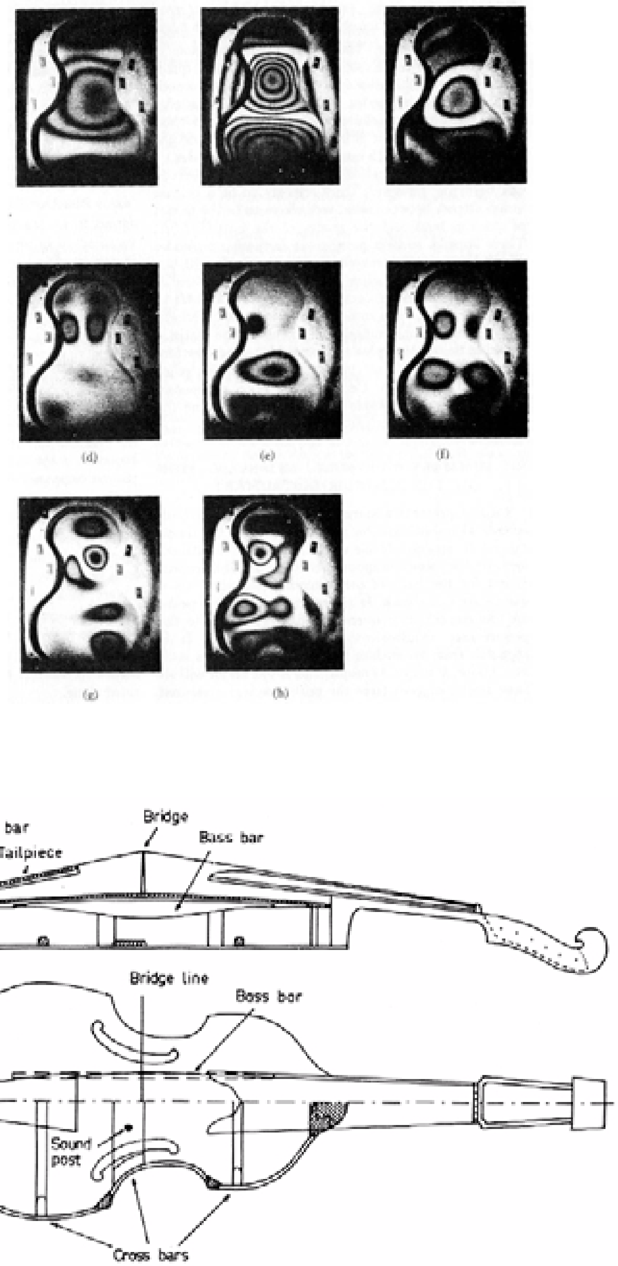


Fig. 2.4. Top: modal pattern reconstructions of the magnum treble viol back plate (Ågren and Stetson, 1972, 1981): 424 Hz, 512 Hz, 724 Hz, 1097 Hz, 1157 Hz and 1254 Hz. Bottom: schematic drawing of the structure, including braces (cross bars) (Ågren and Stetson, 1972, 1972)

a pity that the shapes of modal patterns are reproduced so poorly in the paper.

The general significance of Chladni patterns has been recently called into question because the modal patterns change drastically when the plates are finally glued to the assembled instrument (Schleske, 1992).

The article “Tuning Flatbacks” (Traeger, 1988) deals with the tuning of bass flat back plates using a specific bracing configuration and Chladni tuning. According to his system, only three bars should be found in the bass; if it was built with four braces, Brace 2 (see Fig. 4.2 on page 52) should be removed. The three remaining braces should be of specified dimensions; if they are not, then they must be replaced. The back plate is then tuned according to Hutchins (Hutchins, 1981) and the appropriate tuning frequencies achieved by planing the braces. The ring mode should be between 80 and 100 Hz. Traeger wrote, however, that the tuning should not jeopardize the structural integrity of the back plate:

> *“It is unfortunate that sometimes a compromise between optimum tuning and optimum structural support must be reached.”* (Traeger, 1988, 15)

The author wrote in a second article (Traeger, 1996) that a distance between the ends of the braces and the ribs is necessary to promote a good tone and to avoid structural problems between the back and ribs

Traeger’s article is conceived as a practical guide for bass luthiers, rather than a scientific paper. His experiences are presented as “truths,” which are valuable but probably not universally valid. His invasive techniques (removing the original braces) also go against the recent general consensus that an instrument should be preserved and restored in the spirit of its maker. Admittedly, the preservation of an instrument in its original form is often at odds with contemporary acoustical tastes: should an instrument continue to “live” and be played in a modified state, or should it be preserved in its original state even if unusable? But this is a question for other research.

A published interview with French luthier Jean Auray describes his invention of a new, hybrid back plate in which the sound board (central brace) and two other supports are carved out of the back (see Fig. 4.2 on page 52). In his opinion,

> *“The quality of the sound comes from the back. I decided to place a bar in the middle of the bass back, in order to strengthen it.”* (Double Bassist, 1999, 10)

Other helpful articles on the general acoustics of the double bass include papers by Askenfelt, Meyer, Tro, et al. and Bissinger. Askenfelt published at least two articles on basses: “Eigenmodes and Tone Quality of the Double Bass” (Askenfelt, 1982) and “Über die akustische Eigenschaften von schwingenden Podium und Podeste—Resonanzkörper für Celli und Kontrabässe?” (Askenfelt, 1993). In the first, the lower resonances of five test instruments were identified by using input admittance measurements, and interesting quality parameters were suggested based on them. In the second, vibration transfer from the bass via the end pin into the podium was observed, suggesting that the acoustics of the floor can significantly help radiate bass sounds. Meyer (1995) investigated the directivity of the double bass in "Akustik und musikalische Aufführungspraxis". "Sound radiation from a double bass visualized by intensity vectors" (Tro, Pettersen and Kristiansen, 1983) demonstrated how two microphones could be used to visualize intensity vectors of double bass radiation, and included such diagrams for two frequencies. "Normal mode analysis of violin octet scaling" (Bissinger, 2001) contains information on the essential modes of the largest members of the violin octet, giving hints as to the proportions of major resonances related to instrument size. Other works on the acoustics of the double bass include Abbas (1989), Brown (1999), Fricke (1992) and Rudert (1991).

References

Abbas, E. (1989). Klangliche Eigenschaften des Kontrabasses. In: *Kölner Beiträge zur Musikforschung, Akustische Reihe Band 13*. Gustav Bosse Verlag Regensburg.

Ågren, C.-H. and K. A. Stetson (1972). Measuring the resonances of treble viol plates by hologram interferometry and designing an improved instrument. *J. Acoust. Soc. Am*., **51** (5), Pt. 2, 1971–1983.

Askenfelt, A. (1982). Eigenmodes and Tone Quality of the Double Bass. *Catgut Acoust. Soc. Newsletter,* No. 38, 34–39.

Askenfelt, A. (1993). Über die akustische Eigenschaften von schwingenden Podien und Podesten—Resonanzkörper für Celli und Kontrabässe? *Das Musikinstrument*, **42**, 6-7, 22–28.

Bissinger, G. (2001). Normal mode analysis of violin octet scaling. Proceedings of the ISMA 2001. 113-116.

Brown, A. (1999). An Acoustical Study of Double Bass Bridge Height Adjusters (wissenschaftliche Hausarbeit), IWK, Univ. f. Musik u. darst. Kunst Wien.

Boyden, D. D., B. Schwarz, P. Cooke, A. Dick, et al (1984). The Violin. In: Sadie, S. (Ed.), *The New Grove Dictionary of Musical Instruments*, Macmillan Pub. Ltd. London, 765–804.

Brun, P. (2000). "A New History of the Double Bass." Paul Brun Productions, Villenuevre d' Ascq.

Double Bassist (N. N.) (1999). French Connection: French Luthier Jean Auray. In: *Double Bassist*, Orpheus Publications, Harrow, Middlesex, **10**, 54–57.

Fricke, J. P. (1992). Die durch induktive Messung festgestellten Besonderheiten an Klavier- und Kontrabasssaitenschwingung, *Instrumentenbau* 2/3.

Güth, W. (1989). "Physik im Geigenbau." E. Kurz & Co. Stuttgart.

Hutchins, C. M. (1981). The Acoustics of Violin Plates. In Hutchins, C. M. and V. Benade (Ed.), *Research Papers in Violin Acoustics 1975–1993*, 2 Vols. Acoustical Society of America, Woodbury, New York. 413–424.

Meyer, J. (1995). "Akustik und musikalische Aufführungspraxis." 3rd ed. Erwin Bochinsky, Frankfurt/M.

Moens, K. (1984). Entwicklung von Baumerkmalen im frühen Bassstreichinstrumentenbau. In: *Kontrabass und Bassfunktion*.

Rudert, G. (1991). Violone Kontrabass: Eine Gegenberstellung zweier 16-Fuß-Streichinstrumenten. (wissenschaftliche Hausarbeit), IWK, Univ. f. Musik u. darst. Kunst Wien.

Schleske, M. (1992). Modalanalyse im Geigenbau, Teil II: Zur grundsätzlichen Funktion der Geige: Wie schwingt der Geigenkorpus? *Das Musikinstrument*, **41,** 6, 10–14.

Simpson, Christopher (1665). "The Division-Viol." (Facsimile of the original, 1965), J. Curwen & Sons, London.

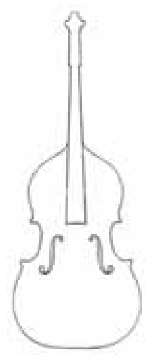
Traeger, C. (1988). Tuning flat backs. *J. Catgut Acoust. Soc*. **3** (2) (Series 2), 40–44.

Traeger, C. (1996). The setup and repair of the bass violin for optimum sound. *J. Catgut Acoust. Soc*. **3** (2) (Series 2), 40–44.

Tro, J., O. Kr. Petterson and U. K. Kristiansen (1983). Sound radiation from a double bass visualized by intensity vectors. *Catgut Acoust. Soc. Newsletter*, **40**, 7–9

Wall, E. (1985). Preliminary Studies of Flat-Backed Basses. *Catgut Acoust. Soc. Newsletter*, **44**, 28–33.

3 Experimental Techniques in Bowed Instrument Research



While the "philosophical" side of music acoustics is primarily concerned with the quality judgements of musicians and audiences, the "scientific" side tries to quantitatively describe instruments' physical properties. Objectifying musical instruments, whose essential usefulness lies within the realm of the subjective experiences of musicians and listeners, is not an easy task (Brown and Bertsch, 2004). When designing experiments to measure the physical properties of musical instruments objectively, the music acoustician must limit or eliminate the influence of the musician (input signal), the room acoustics (transmission medium), and the listener (signal receiver). This requirement at times removes the experimental situation from the practical one rather extremely. It is therefore an important aim in instrumental acoustics research to select instrument stimulation method, acoustical environment, and a recording and analyzing method that is objectively repeatable <u>and</u> delivers data that is relevant to subjective musical practice.

Rossing and Fletcher write,

> *"The first and major role of [musical] acoustics is [...] to try to understand all the details of sound production by traditional instruments."* (Rossing and Fetcher, 1998, vii–viii)

Researchers have used a variety of experimental and theoretical methods to investigate the physical properties of bowed musical instruments, primarily the violin. Experimental methods can be divided into roughly two categories: the measurement of mechanical motions and frequencies of plates, strings or bridges with physical experiments, and the quantitative measurement of sound radiation with acoustical experiments. Non-experimental simulation of the modal behavior of violin bodies and strings has also been important. The ultimate goal of many researchers is to develop theoretical simulations that closely correspond to experimental mobility and radiation data, thus accurately describing the mechanics of bowed instruments.

The foundations of bowed instrument research were laid by scientists such as Felix Savart (1840), Hermann v. Helmholtz (1877), C. V. Raman (1918), Minneart und Vlam (1937), Hermann Backhaus (1929) and his student H. Meinel (1937), F. A. Saunders (1937) and others, whose work is described in more recent standard works on music acoustics such as “Fundamentals of Musical Acoustics” (Benade, 1976), and “The Physics of Musical Instruments” (Rossing and Fletcher, 1998), and “Musical Acoustics, Parts I & II” (Hutchins, 1975 and Hutchins, 1976). The latter devotes an entire chapter to “Instrumentation and Methods for Violin Testing.” “Research Papers in Violin Acoustics 1975–1993,” (Hutchins and Benade, 1997), offers a good overview of even more recent work and contains published papers grouped according to specific aspects of violin research. Lothar Cremer’s book “Physics of the Violin” (1984) is an important work.

Below is a selection of key experimental techniques that have been used traditionally and recently to measure bowed instruments.

3.1 Frequency Response Curves of Radiated Sound

Saunders (1937) used spectral analysis of individual, played violin notes recorded on photographic paper to piece together “response curves.” A bowing machine with celluloid disks was developed, though Saunders also used a hand-bowing technique as the input signal. Recordings were made on a “sound stage” in a half-anechoic environment, and a single “moving coil microphone,” placed within 1 m of the violin was used to capture the signal. Saunders also used a “noise meter” to obtain “total intensity curves.” In a second paper (1945), Saunders presented response curves recorded as before, but generated by electro-magnetic input at the bridge.

Meyer (1972) basically followed the traditional set-up of his German predecessors Backhaus, Meinel and Lottermoser, using electro-magnetic sine stimulus at the bridge in an anechoic chamber for his measurement of radiation patterns of stringed instruments. The microphone, arranged in the bridge plane and the bass bar plane, was at a distance of 1 m from violins and violas and 3.5 m from the violoncellos and basses. The instrument was mounted on a turntable and coupled to a sound pressure recorder, yielding polar diagrams of radiated sound pressure and data on directivity.

Dünnwald (1988) used a new type a transducer at the bridge while the rest of his set-up was similar to that of Backhaus, Meinel, Lottermoser and Meyer (Dünnwald, 1991, 77). The single microphone was placed in the far field at the same position where an audience would listen to a solo concert. A sine sweep was put into the bridge by a special, zero-mass-loading transducer, and over 700 violins were analyzed. His findings suggest that old Italian violins have common characteristics in their response curves.

Schleske (2002) measured frequency response by using an impulse hammer at the bridge and recording the radiation of the violin with a microphone mounted on a turntable. He calibrates the acoustics of his lab room by measuring the room every 10º (36 times). Knowing the characteristics of the

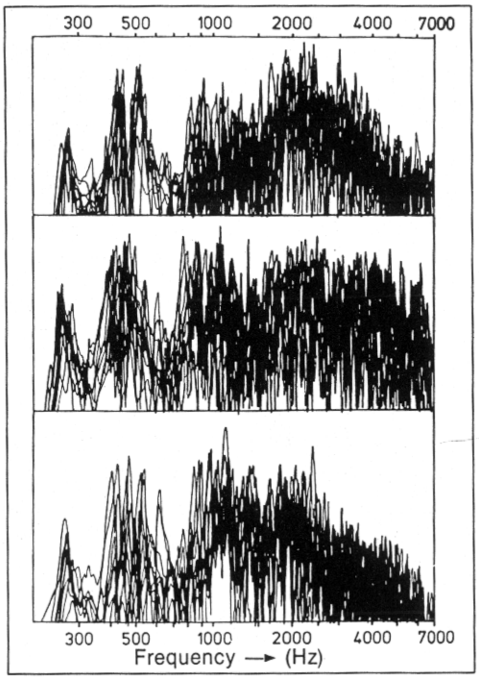


Fig. 3.1. Dünnwald’s frequency response curves of 10 old Italian violins (top), 10 master instruments, and 10 factory instruments (Dünnwald, 1991, 78)

room, he can then measure the violin in six different angles (every 60º) and subtract the room acoustical influence. He is of the opinion that such radiation measurements are easier in an echo chamber as opposed to an anechoic chamber, because an anechoic chamber requires many more microphone positions (every 10º) to get an accurate idea of the radiation, while an echo chamber needs theoretically only one.[13]

3.2 Near-Field Acoustical Holography

Near-field acoustical holography (NAH) is a technique for reconstructing the three-dimensional sound field, including particle velocity and acoustic intensity, from a two-dimensional set of complex pressure measurements using several microphones. Tro, Petterson and Kristiansen (1983) published a related work measuring a double bass. Wang and Burroughs (2001) measured acoustic radiation from bowed violins using a bowing machine and NAH, with an array of 15 measurement microphones and one reference microphone. These measurements were performed in semi-anechoic environment.

13. Telephone interview, January 2002.

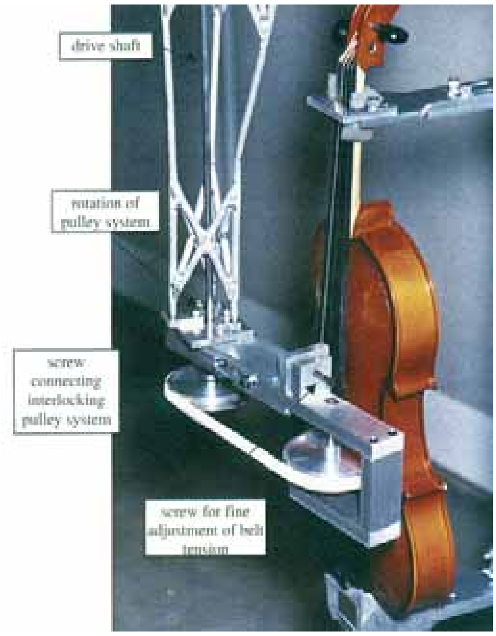


Fig. 3.2. Wang's bowing machine (Wang, 1999)

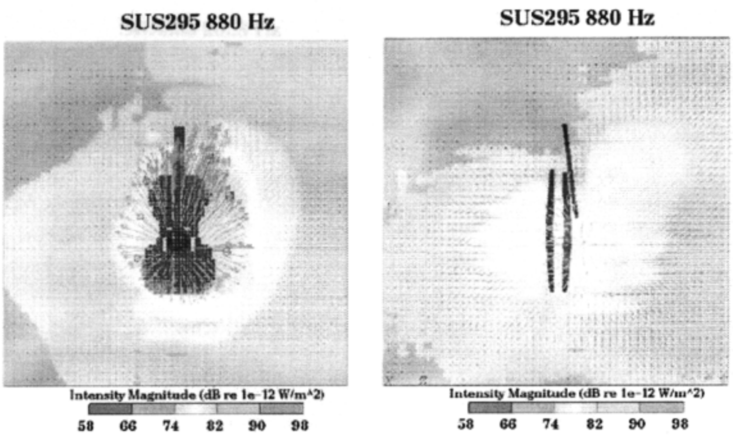


Fig. 3.3. Example of NAH results from Wang and Burroughs (Wang and Burroughs, 2001, 549)

3.3 Input Admittance

Input admittance is defined as velocity over force, and is the reciprocal of input impedance as described in Rossing and Fletcher (1998, 20). The output is measured directly at the instrument, generally at the bridge, which greatly reduces the problem of room acoustical errors. Beldie (1974) used narrow-band noise input via shaker at the bridge in a reverberant room to show the correlation between input admittance and radiation.

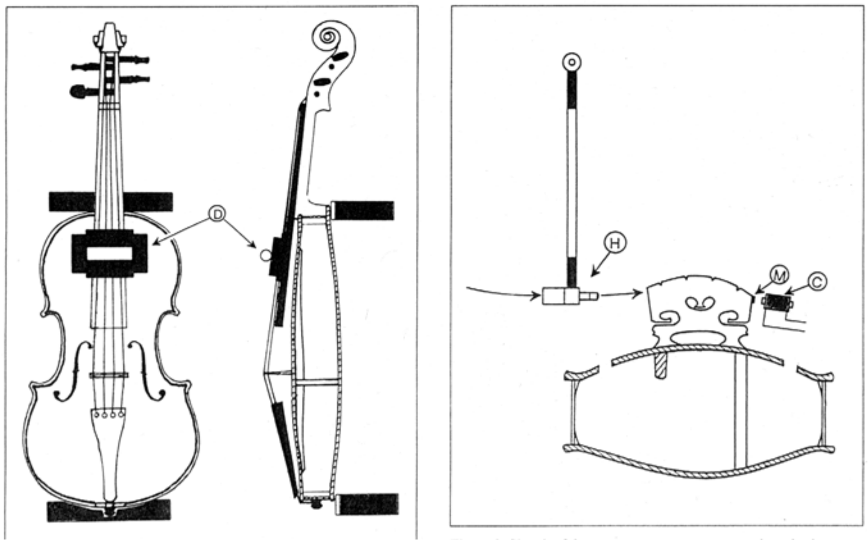


Fig. 3.4. Input Admittance setup, showing string damping mute (D), impulse hammer (H) and magnet and coil (M, C) in (Jansson, 1995, 338)

Moral and Jansson (1982) wrote an important article using an impulse hammer for the input signal and a low-mass magnet and coil to deliver an output. Askenfelt (1982) used the same technique to measure the input admittance of violoncellos and basses. The resulting input admittance curves of a violin and a double bass are shown below (see Fig. 3.5 on page 36).

The system VIAS, developed at IWK in Vienna (Haberl, Kausel and Meyer, 1998), uses a transducer related to Dünnwald's for the input signal combined with an integrated laser-optical sensor to record the output signal. An important characteristic of input admittance results is the under-representation of air resonances in resulting curves of bowed instruments (Zopf, Brown, 2001).

The method of support is important with this and other measurement techniques, as significant vibrating frequencies may be dampened depending on how and where the supports are mounted. Some techniques use a holding system that imitates the playing situation (with support at the neck and chinrest of a violin, for example), or with a minimum of contact at places on the body that do not vibrate significantly. Backhaus (1929), Meinel (1937) and Marshall (1985) illustrate some holding methods.

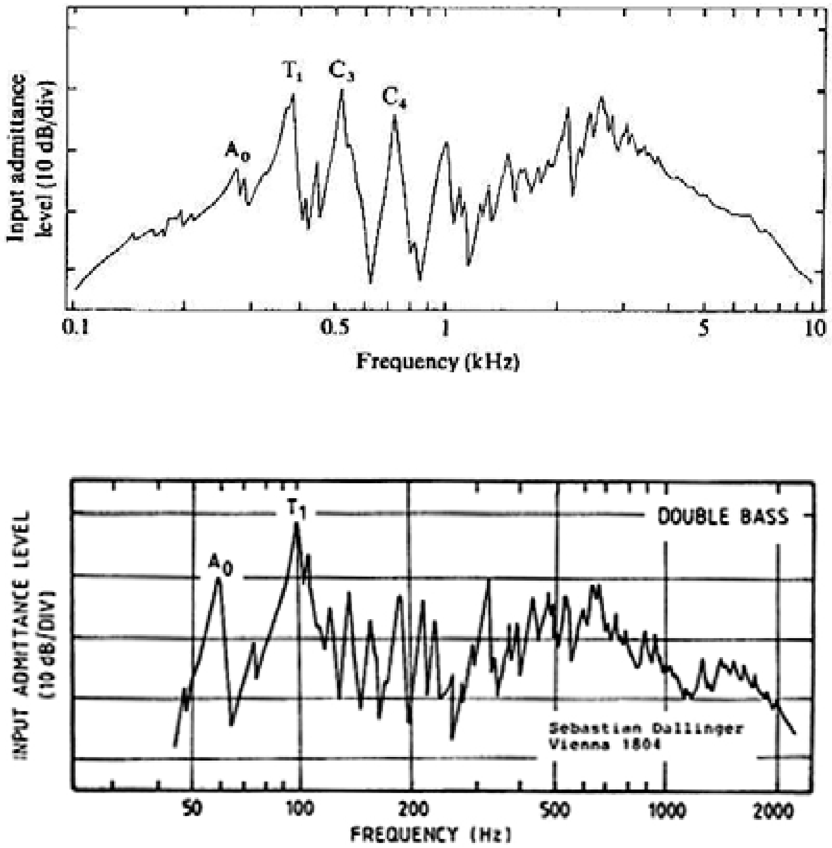


Fig. 3.5. Input admittance of a good violin, top, and a good double bass (Askenfelt, 1982, 34)

3.4 Modal Analysis

Modal analysis is a technique developed for structural engineering applications, but has been used on bowed instruments. Modal analysis is the process of characterizing the dynamic response of a structure by describing its vibrational motion through use of a suitable set of mathematical relationships, generally referred to as modal properties.

Savart (1840) was the first to investigate modal patterns of the violin by applying the discoveries of Chladni, using his own experimental, trapezoidal instrument. Backhaus (1929) took advantage of new electronic equipment and was the first to map vibrational modes of the violin. He used a bowing machine as the input signal and two capacitors in direct contact with the front and back plates of the violin, recording the analyzer output onto photographic rolls. The radiation characteristics were then calculated from the modal patterns.

An implicit assumption of modal analysis is that the violin structure behaves in a linear manner, which is reasonable if the object operates with small displacements and damping (Marshall, 1985, 696). Today, the input signal is usually generated by an impulse hammer and the output signal is transduced by an accelerometer mounted at some location on the body. Since the response function is symmetric in a linear system, the object may either be driven near the bridge and measured at points on the body, or vice versa. While the body of a bowed instrument behaves linearly, the bowed

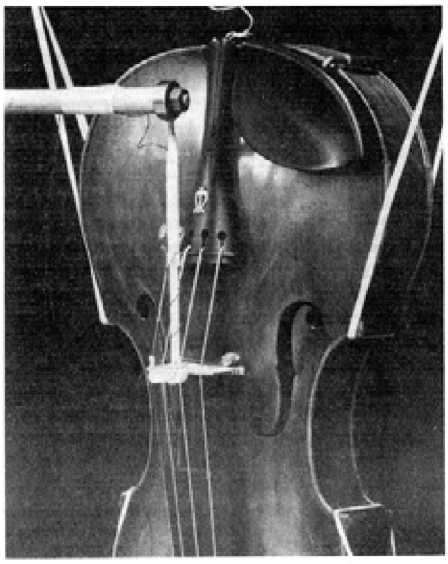


Fig. 3.6. Marshall's set-up, using an impulse hammer applied vertically to the bridge and an accelerometer above the bass bar (Marshall, 1985, 697)

string has been shown to behave non-linearly (Rossing and Fletcher, 1998, 144), complicating correlation between modal analysis results and the actual acoustics of a concert situation.

Marshall (1985) clearly describes his method of a complete modal analysis of a violin in playing condition in the first paper published on the subject. The instrument was suspended by five rubber bands to reduce damping in the holding system, tapped at 190 points with an impulse hammer, and recorded with an accelerometer mounted on the top plate above the bass bar and next to the bridge. He used a multi-degree-of-freedom approximation procedure called the *least-square complex exponential algorithm* to reveal 35 vibrational modes below 1300 Hz (Marshall, 1985, 701).

Schleske applies modal analyses when making his "tonal copies" of classical violins. He uses a small impulse hammer that records up to 5N force, a mini-acclerometer at the bridge, and a laser mapping system of the instrument to ensure that the driving points on the body are consistent, to analyze the original instrument and the copy as he is working on it.[14]

3.5 Finite Element Analysis

A primary method of simulating bowed instruments is the Finite Element Method, which is the theoretical modelling of a structure by breaking it down into a number of mass-spring systems. After modal properties have been determined, subsequent calculations can be performed to determine how the structure will respond to various types of inputs. Applications of FEM in music acoustics include sound synthesis: accurate models can be indicated by realistic-sounding synthesized tones. Work by Kishi and Osanai (1991) used the FEM to model two types of violoncello bridge in a free state and attached to a rigid support. Knott (1987) modelled a complete violin using measurements and material properties in the literature, which resulted in simulated modal patterns in agreement with the experimental data of Marshall (1985). This method allows arbitrary manipulation of parameters on a purely virtual basis, saving time and materials to make experimental instruments. The simulation is, however, computationally expensive, requiring a huge initial entry of data. Knott's work also omits neck, bridge and string modes and disregards air resonances. Additional complexities of anisotropy of wood and the damping of individual parts of the whole system make a truly accurate simulation of a violin particularly difficult (Bissinger, 1995, 22).

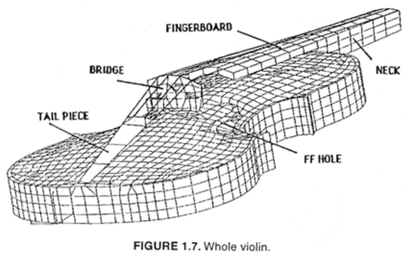


Fig. 3.7. Knott's violin simulation using the finite element method (Knott, 1987, 511)

14. Telephone interview, January 2002.

3.6 *Laser Optical Methods*

Laser-optical methods, such as time-average holographic interferometry, electronic TV holography, double-pulsed hologram interferometry and scanning laser doppler vibrometry have been used to document the modes of vibrating objects. Used on musical instruments as early as 1967 (Hutchins, 1975, 95), hologram interferometry allows detailed and comprehensive data on the modes of violins to be collected. Laser-optical methods function by splitting a laser beam into two parts, one directed at the measurement object and one is used as a reference, and using the interference between the two wave signals. This was previously projected onto photographic paper, but is now analyzed by computer software to find the velocity of the object relative to the measurement point.

Ågren and Stetson (1971) measured a flat-backed treble viol with holographic interferometry, and Jansson, Molin and Saldner (1970) documented

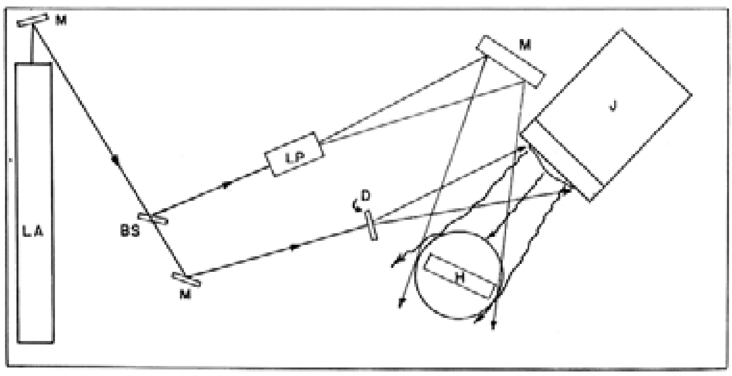


FIG. 7. The holographic system used for these measurements. LA is the laser, the three M's are first surface mirrors, BS is a glass plate beam splitter, LP is a lens-pinhole holder, D is a diffuser, L is a cylindrical lens, J is the viol plate jig, and H is the hologram plate holder.

Fig. 3.8. Schematic setup of the system used by Ågren and Stetson (1972). (Ågren and Stetson, 1972, 1974)

vibration patterns during the various construction stages of a violin. Modes were stimulated at particular points in order to drive a particular mode while damping others (Moral and Jansson, 1982, 331). An impulse hammer or sine wave input via shaker or loudspeaker may be used as stimulus. Using sound from a loudspeaker as stimulus is non-invasive and cause no damping but the input energy is difficult to quantify. Holographic interferometry has a disadvantage in measuring bowed instruments because the measured object must be tightly clamped, significantly altering some modal patterns (Rossing and Fletcher, 1998, 290).

Scanning laser doppler vibrometry, such as the system produced by Polytec,[15] was designed for industrial applications. Bissinger (2001) used this technique to correlate mobility with audio data simultaneously collected. Esposito (2003) has used this technique for a variety of applications, including measurement of solid-body electric guitars. Zipser and Franke (2003) have used Mach-Zehnder Doppler interferometers to measure pressure waves within musical instrument models.

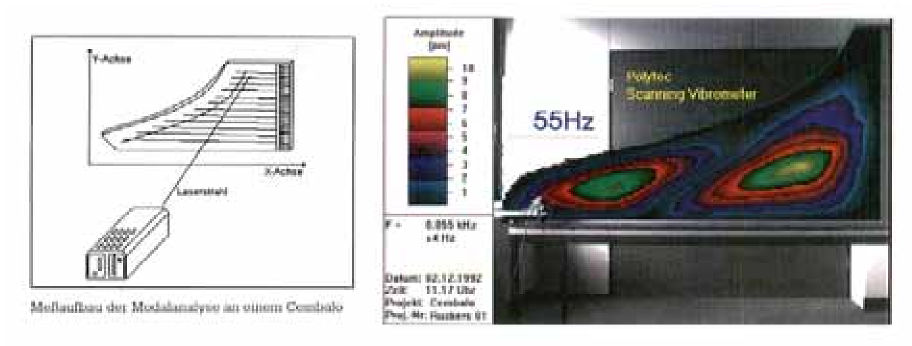


Fig. 3.9. Schematic of laser vibrometer set-up, left, and actual measurement of a harpsichord sound board, from a Polytec advertising brochure

Laser Doppler vibrometry is extremely precise, requires only low input signals, and is absolutely non-invasive, making it an extremely useful tool for measuring musical instruments.

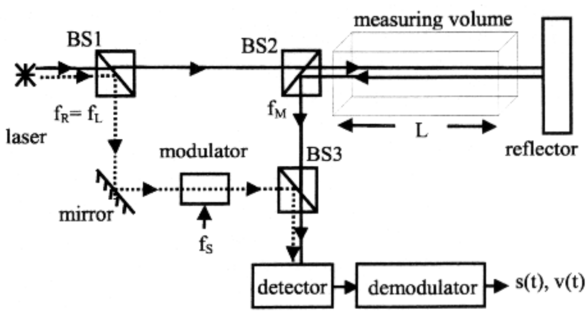


Fig. 3.10. Schematic of Doppler Vibrometry Function (Zipser and Franke, 2003)

15. “Vibrometer University: How it Works“. Information section of the Polytec Homepage, currently available at: http://www.polytec.com

3.7 Combined Methods

Using a combination of experimental methods can provide a more comprehensive understanding of measurement objects. In the words of Fletcher and Rossing,

> *"Applying two or more methods to the same instrument and comparing the data is probably the most effective strategy for modal analysis of violin body vibrations."* (Rossing and Fletcher, 1998, 291)

Hill, Richardson and Richardson (2001) used input admittance, measurement of the acoustic pressure field, and holographic interferograms to find the relative ease with which a mode is excited by string motion, and the efficiency with which the mode radiates. The input admittance gives data on the mode frequency, bandwidth, and effective mass of the object. The acoustic pressure measurement provides source strengths for the modal patterns, and holography isolates the modal pattern and helps to relate acoustic field patterns to mode shapes (Hill, Richardson and Richardson, 2001).

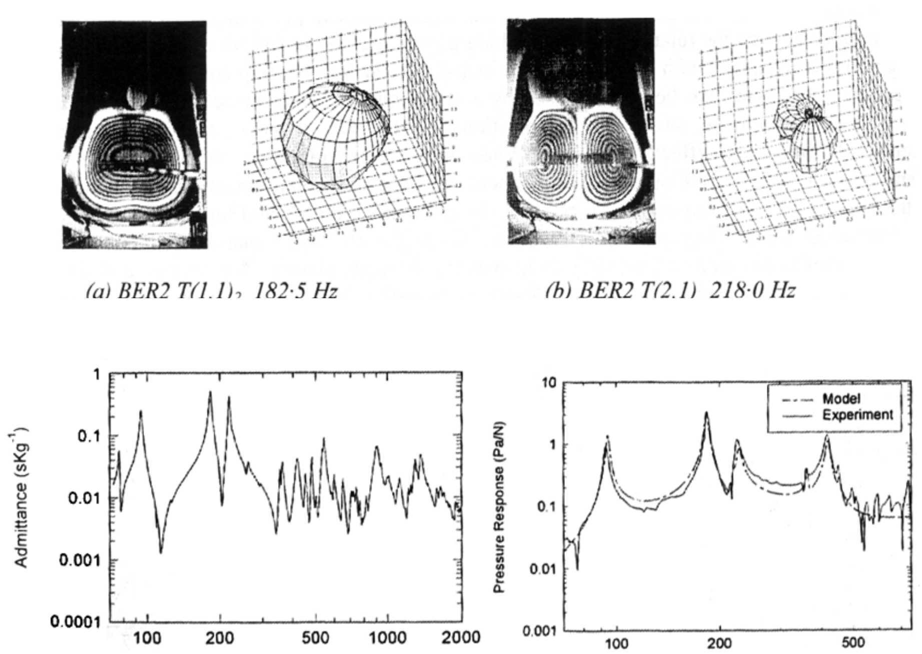


Fig. 3.11. Combined methods used by Hill, Richardson and Richardson: holographic interferogram, sound field, input admittance and sound pressure response for the same guitar (Hill, Richardson and Richardson, 2001, 418)

Bissinger used experimental modal analysis, acoustic measurements in the violin interior, and room averaged acoustic radiation in his studies of the

Violin Octet (Bissinger, 2001). Modal analysis was performed using a zero-

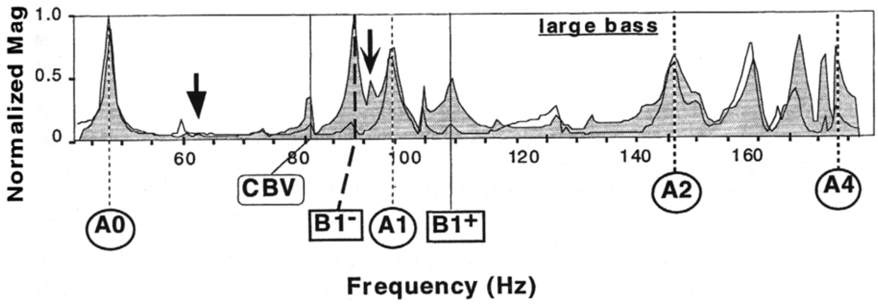


Fig. 3.12. Bissinger's curves for averaged mobilities and averaged acoustic output for the Large Bass of the Violin Octet (Bissinger, 2001, 115)

mass-loading impulse hammer at a fixed position on the bridge and a scanning laser vibrometer to collect mobility frequency response functions for more than 500 points on the violin body. The "interior measurements" were made with two small microphones inserted through the f-holes to pick up the A0 and A1 air modes. The acoustic radiation used the hammer as input signal and was recorded with a "sound quality head" with high quality microphones, in his reverberant lab in a corner treated with 15 cm foam wedges, and the signal was then Fourier analyzed.

Combined techniques allow an exact quantitative assessment of the relation between input energy and output energy in the form of mobility and/or radiated sound from the instrument, allowing for the calculation of the radiation efficiency of the object and also of the damping.

3.8 Summary

Researchers have been confronted with experimentally objectifying aspects of bowed musical instruments since the work of Savart and Helmholtz in the 19th Century. Their goal is to describe relevant aspects of instruments while controlling the input stimulus, acoustical environment and output receiver elements of the musical situation. Researchers have investigated the physical mechanics and acoustical radiation, primarily of violins, by experiment and simulation, or both. Simulation methods include the finite element method and experimental methods include radiated frequency response, near-field acoustical holography, input admittance, modal analysis and laser-optical methods. Combining methods has led to a more comprehensive understanding of the details of sound production by bowed instruments.

References

Ågren, C.-H. and K. A. Stetson (1972). Measuring the resonances of treble viol plates by hologram interferometry and designing an improved instrument. *J. Acoust. Soc. Am.*, **51** (5), Pt. 2, 1971–1983.

Askenfelt, A. (1982). Eigenmodes and Tone Quality of the Double Bass. *Catgut Acoust. Soc. Newsletter,* No. 38, 34–39.

Backhaus, H. (1929). Physikalische Untersuchungen an Streich-instrumenten. *Die Naturwissenschaften* **17** 811–18, 835–39.

Beldie, I. O. (1974). Vibration and sound radiation of the violin at low frequencies. *Catgut Acoust. Soc. Newsletter,* No. 22, 13–14.

Benade, A. (1990). "Fundamentals of Musical Acoustics." 2nd ed., Dover Publications, New York.

Bissinger, G. (1995). Modal Analysis, Radiation and the Violin's Soundpost. *Sound & Vibration*, **29** (8), 18–22.

Bissinger, G. (2001). Normal mode analysis of violin octet scaling. *Proceedings of the ISMA 2001*, 113–116.

Brown, A. and M. Bertsch (2004). The paradox of musical acoustics: objectivizing the essentially subjective. *Proceedings of the 1st Conference of Interdisciplinary Musicology, Graz* (publication pending).

Cremer, L. (1984). "The Physics of the Violin." Translated by J. S. Allen, MIT Press, Cambridge, Massachusetts. "Physik der Geige." S. Hirzel Verlag, Stuttgart, 1981.

Dünnwald, H. (1991). Deduction of objective quality parameters on old and new violins. In: Hutchins (ed.) "Research Papers in Violin Acoustics 1975-1993," 2 vols. Acoustical Society of America, Woodbury, New York, 59-64.

Esposito, E. (2003). A comparative study of the vibro-acoustical behavior of electric guitars produced in different decades. *Proceedings of SMAC 03, Stockholm, Sweden.* 125–128.

Haberl, F., W. Kausel and A. Meyer (1998). Eingangsadmittanzmessung an Streichinstrumenten. *Jahrestagung '98 d. Fachausschusses für Akustik der Österreichischen Physik Gesellschaft gemeinsam mit der Österreichischen Gesellschaft für Akustik* (AAA/ÖGA), Graz.

Helmholz, H. v. (1877). "On the Sensations of Tone," 4th ed. Translated by A.J. Ellis, Dover, New York, 1954.

Hill, T. J. W., B. E. Richardson and S. J. Richardson (2001). Measure-ments of acoustical parameters for the classical guitar. *Proceedings of the ISMA 2001*. 417–420.

Hutchins, C. M. (1975). "Musical Acoustics, Part I. Violin Family Components." Dowden, Hutchinson and Ross, Stroudsberg, Pennsylvania.

Hutchins, C. M. (1976). “Musical Acoustics, Part II. Violin Family Functions.” Dowden, Hutchinson and Ross, Stroudsberg, Pennsylvania.

Hutchins, C.M. and V. Benade (editors) (1997). “Research Papers in Violin Acoustics 1975–1993,” 2 vols. Acoustical Society of America, Woodbury, New York.

Jansson, E. V. (1995). Admittance Measurements of 25 High Quality Violins. *Acustica*, **83**, 337–341.

Jansson, E. V., N. -E. Molin and H. Sundin (1970). Resonances of a violin studied by hologram interferometry and acoustical methods. *Phys. Scripta* **2**, 243–256.

Kishi, K. and T. Osanai. (1991). Vibration analysis of the cello bridge by the finite element method. In: Hutchins, C.M. and V. Benade (Ed.) “Research Papers in Violin Acoustics 1975–1993,” 2 vols. Acoustical Society of America, Woodbury, New York., 359–367.

Knott, G. A. (1987). A modal analysis of the violin using MSC/ NASTRAN and PATRAN. In: Hutchins (ed.) “Research Papers in Violin Acoustics 1975–1993,” 2 vols. Acoustical Society of America, Woodbury, New York, 507–549.

Marshall, K. D. (1985). Modal analysis of a violin. *J. Acoust. Soc. Am.*, **77** (2), 695–709.

Meyer, J. (1972). Directivity of the Bowed Stringed Instruments and Its Effect on Orchestral Sound in Concert Halls. *J. Acoust. Soc. Am.*, 51(6), Pt. 2, 1994–2009.

Meinel, H. (1937). Über die Beziehungen zwischen Holzdicke, Schwingungsform, Körperamplitude und Klang eines Geigenkörpers. *Elek. Nachr. Tech.*, **14** (4), 119–134.

Minnaert, M. and C. C. Vlam. (1937). The vibrations of the violin bridge. *Physica*, 4, 361–372.

Moral, J.A. und E.V. Jansson (1982). Eigenmodes, Input Admittance, and the Function of the Violin. *Acustica*, **50** (5), 329–337.

Raman, C. V. (1918). On the mechanical theory of the vibrations of bowed strings and of musical instruments of the violin family, with experimental verification of the results. Bull. 15, The Indian Association for the Cultivation of Science.

Rossing, T. D. and N. H. Fletcher (1998). “The Physics of Musical Instruments.” Springer, New York.

Saunders, F. A. (1937). The mechanical action of violins, *J. Acoust. Soc. Am.*, **9**, 91–98.

Saunders, F. A. (1945). The mechanical action of instruments of the violin family. *J. Acoust. Soc. Am.*, **17**, 169–186.

Savart, F. (1840). Des instruments de musique. Translated by D. A. Fletcher. In: Hutchins (Ed.), *Musical Acoustics, Parts I & II* (1976), 15–18.

Schleske, M. (2002). Empirical Tools in Contemporary Violin Making: Part II. Psychoacoustic Analysis and Use of Acoustical Tools. *J. Catgut Acoust. Soc*. **4** (6) (Series 2), 43-61.

Tro, J., O. Kr. Petterson and U. K. Kristiansen (1983). Sound radiation from a double bass visualized by intensity vectors. *Catgut Acoust. Soc. Newsletter*, **40**, 7–9.

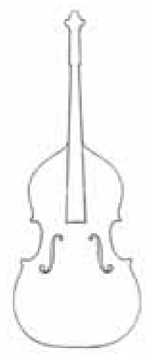
Wang, L. M (1999). Radiation Mechanisms from Bowed Violins. Doctoral dissertation, Penn. State U.

Wang, L. M., and C. B. Burroughs (2001). Acoustic radiation from bowed violins. *J. Acoust. Soc. Am.*, **110** (1): 543–555.

Zipser, L. and H. Franke (2003). Refractoscopic visualization of sound in musical instruments. *Proceedings of SMAC 03, Stockholm, Sweden*, 763–766.

Zopf, S. and A. Brown (2001). Input admittance measurements and their relationship to the sound characteristics of violins and violas. *Proceedings of the ISMA 2001*. 137–140.

4 *The Double Bass Under Acoustical Study*



Papers on the acoustics of the double bass are rare; for every article on the acoustics of the bass, there are innumerable violin articles. Fletcher and Rossing write,

> *"Acoustical research on bowed string instruments has traditionally been concentrated on the violin. Although in a typical orchestra there are about one-third as many violas and cellos as violins, one must search diligently to find 1 or 2% as much published material on their acoustical behavior."* (Rossing and Fletcher, 1998, 318)

The application of results on the acoustics on the violin to other bowed instruments, including the double bass, is an important question as to the necessity for new research. The principal vibrational modes of a cello are quite similar to those of a violin and frequencies ranging from about 0.3 to 0.4 times the violin frequencies. Although the vibrational modes of a double bass have not previously been reported, input admittance curves suggest that they are also quite similar.

In the words of Martin Schleske, the double bass has up until now "unjustly been a step-child" of stringed instrument research.[16] Possible reasons for this are easy to find. The form of the violin's structure is more or less standardized, conveniently sized and its frequency range is in a "pleasant" area of human hearing, where our ears hear at their best. The fame of the classical violin makers, the countless popular violin virtuosos, and the astounding financial values of some violins leave other instruments in its shadow. Violins and violinists also happen to be more numerous than other stringed instruments and players.

The double bass hardly possesses any of these attractive advantages for the bowed instrument researcher. The instrument is not standardized in its form, is of an inconvenient size, requires special support methods and measuring equipment, and has a frequency range that is difficult for players and audiences to hear and that presents difficulties while measuring.

16. Telephone interview, January 2002.

Martin Schleske's opinion on the acoustical qualities of flatback vs. roundbacks is of particular interest. But he explains that, though he's interested in the subject:

> *"[...] I'm probably not the right one to comment on the subject, because I have almost nothing to do with basses. I find it very interesting to research these instruments, however, since, in my opinion unjustly, they have been the step-children of instrument makers and acousticians."*

Schleske emphasizes the reasons for this:

> *"To make an acoustical copy of a Guadagnini bass, it would cost almost as much as the original instrument. The ratio between the cost of an original violin (DM 1,000,000.—) and an acoustical copy (DM 40,000.—) is much more attractive than as with a bass (DM 150,000.— and DM 75,000.—)."* [17]

These disadvantages for the researcher yield one great advantage at the present, however: scientific *terra nova*. Up until now, only a handful of bass-lovers have researched and published papers about the instrument's acoustics. The necessity of filling this gap depends partly on one question: to what extent is the research on the violin applicable to the bass and other instruments?

Violin-specific research has surely brought much generally applicable knowledge on the nature of bowed instruments. But its limits will first be known with more research on the viola, violoncello and double bass. After many years of experience, Thomas Rossing (2001, 12) wrote that expanded studies of the other bowed instruments will be among the "hot topics" of musical acoustics in the coming years. Anders Askenfelt (1982) of the KTH in Stockholm made admittance measurements on cellos and basses, coming to the conclusion that the bass essentially behaves as a large cello. The results presented in Chapter 6 of this dissertation indicate that this indeed applies to basses with a round back. Studies by Bissinger (2001) on the violin octet are a great contribution to the question of general applicability of violin research.

On the following pages, a few characteristics of the double bass as a static object and as a sound source will be discussed from the scientist's perspective.

17. Telephone interview, January 2001.

4.1 The Double Bass as a Static Structure

Instruments of the violin family have an amazing resistance to the large force of the tightened strings acting on it. The stability of an instrument is naturally dependent on the quality of its individual parts and how they are put together. One Swedish luthier wrote in the context of violins and their parts that the “chain is only as strong as its weakest link”. With a violin, the neck is fit into the upper block, and the upper block fits between the top and back plates and the ribs, which are glued with traditional hide glue. The upper and lower blocks support the tension of the strings, and their resistance strength is dependent on the quality of the joints.

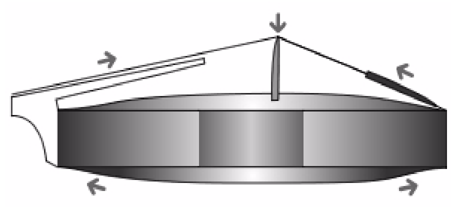


Illustration courtesy of J. Bollbach

Fig. 4.1. Static forces acting on the body of the double bass. The upper block is inside the bass body at left, the lower block at right.

A description of the physics of these static forces can be found in “Physik im Geigenbau” (Güth, 1989, 16). Güth calculates the tension of the strings, the pressure of the bridge onto the top plate, the compression of the top plate through the tail gut and the torsion acting on the neck joint. Calculating in this way, the bass top must support around 530 N of downward pressure, compared to 112 N in the case of the violin.[18]

With the example of the violin top plate, Güth writes:

> *“Considering these forces, the conception of the top plate aims for an optimum ratio between static stability and sound quality. The result will always be a compromise. The old violin makers who gave the modern violin its form were most certainly well aware of this.”* (Güth, 1989, 16)

If one considers classical architecture, the structural advantages of the arch that bridges a span are comparable to the arching of the plates of a violin. The form of an arch offers more strength per unit mass. Compression occurring on the top plate between the upper and lower blocks and stresses

18. Fletcher and Rossing write that the downward pressure of a violin is “about 90 N” (Fletcher and Rossing, 1998, 275). The pressure on the bass top plate would then be approximately 425 N.

from outside forces are more evenly distributed over an arch.

The use of arching for structural, acoustical, aesthetic, or whatever reason the early makers used it for was an important step forward in the development of bowed instruments (Woodfield, 1984, 118–119). The ingenious structural form of the violin body shows its value by example of the innumerable venerable classical instruments that are still played into the 21st Century. In this context, the arched back of the round-backed double bass is presumably more robust than a flat back. But according to Güth, the arching of the back shouldn't make a significant difference in the stability between the upper and lower blocks, since wood has a high tensile strength in this direction (Güth, 1989, 27).

Back to the example from architecture: if a similar same span is bridged by a straight lentil, this lentil must be more massive than the arched one. The thickness of a modern bass' back plate is between 4 mm and 9 mm. A flat back of this thickness without support would be too weak to withstand the statics and dynamic forces acting on it. Therefore, this strength is increased by inner braces of light wood, which keep the mass of the plate relatively low while significantly increasing the stiffness.

4.1.1 String Pressure on the Back Plate

The back plate of the double bass is subjected to strong forces. The back serves as the anchor for the upper and lower blocks, as a platform for the ribs, and supports the downward string pressure on the top plate through the soundpost. Each of these areas must be strong enough to support the static forces, as well as dynamic forces during playing and transport. About 2/3rds of the downward string pressure is supported by the soundpost, which may be calculated to about 353 N. According to Güth,

> *"The tension of the strings acting on the back plate is only one-third of the tangential compression acting on the top plate. Therefore, the upper part of the back should be made much thinner than usual because wood has a much higher tensile strength than compression."* (Güth, 1989, 22)

4.1.2 Environmental Influences

Dynamic forces also act upon the instrument, for example the influence of temperature or humidity changes, or contact with the instrument during playing and transport. Higher temperature leads to expansion of the warmed parts while cool parts shrink. When humidity increases, wood expands perpendicularly to the direction of the yearly rings. As reported in Chapter 2 (see Section 2.1.4 on page 15), the dynamics of the wood often result in structural problems in the plates and braces of flatbacks. The moisture content of wood is temperature-dependent, as moisture leaves the wood at vapor temperature. Forces during routine play, simply holding or "resting on" the bass during rehearsals, and accidents often put the strength of a bass to the test. Therefore, the form of the instrument, and again the quality of the materials and workmanship, are decisive factors in structural stability.

4.1.3 Material Characteristics

The essential acoustical characteristics of materials can be described in terms of the density, elastic moduli and damping coefficients. Wood is an orthotropic material, meaning that it has differing elastic characteristics in the different perpendicular planes. Therefore, it is necessary to describe these characteristics with nine independent values such as the Young's Moduli, Poisson's Ratios and Shear Moduli. A good introduction into the topic of building materials can be found in "The Physics of Musical Instruments" (Fletcher, Rossing, 1998, 721–723).

It should be mentioned that a variety of materials have been used for making the back plates of double basses. Though maple is the most common species of wood, black poplar *populus nigra*, walnut *juglans regia*, willow *salix alba* and other types are found in older and modern examples. The English bass maker Paul Bryant has used for the back and ribs plain tree *platanus occidentalis*, poplar *populus pyramidalis* or Bosnian maple *acer psydoplatanus*, and for the top plate American cedar *thuya picata* or balkan spruce *picea omorika*. This bass-maker writes about the materials of the old Italian masters,

> *"I'm sure many modern makers are much too narrow-minded in their choice of materials. The old Italians in particular just found [any] wood and made a bass. It is common knowledge that some of the great master basses of the past were made with what would, today, be considered very unpromising materials: for example, Francesco Goffriller with his seven plank fronts, or the great Vincenzo Panormo with his slab sawn 'floorboard' fronts complete with large knots. In the past basses were cheap and had to be made from the most economic timber possible."*[19]

Otto Möckel, the well-known German violin-making master and author of "Die Kunst des Geigenbaus" (Möckel, 1930) writes,

> *"Earlier, softer woods were chosen, and only later did violin makers realize that spruce used with maple unites the best sound qualities. Back plates of poplar or pearwood as well as the harder fruitwoods became increasingly rare. The combina-*

19. From the maker's homepage, available currently at: http://www.bryant-basses.co.uk/materials.htm

> *tion of spruce and poplar, as was common in Nicóla Amati's time, lends a beautiful timbre, but the sound is often veiled and the response bad. Maple,* acer pseudoplantanus*, succeeded as a material partly due to the rich flamed grain of its wood. Deeply flamed specimens of maple are more highly prized today than medium- or non-flamed wood. But not-too-deeply flamed maple should be used for the sound, and because it is also easier to work."* (Möckel, 1930, 124)

> "Picea excelsa— *Spruce comes from the Alps, Carapathians and Pyrenees, growing to 40–50 cm and up to 300 years or more. The wood is like the place where it grows. If the ground is hard and filled with broken stones, the yearly rings will have little sap, and the wood is therefore lighter, splits straight and is especially suited to instrument-making. The straighter and more regularly the yearly rings run, the better it will vibrate."* (Möckel, 1930, 126)

> *"The poplar,* populus pyramidalis *is found among others in old Italian violoncellos and violas. Because of its very soft, loose tissue, the backs are usually left very thick. Instruments made of this material indeed sound very soft, because the damping of the back is high, therefore the carrying power of the tone, which is found around 3000 Hz, is missing."* (Möckel, 1930, 124)

> *"The red beech,* fagus silvatica*, has fairly hard wood that splits well, planes well and has a reddish-brown color. Its elasticity makes it more appropriate for the use of ribs, necks and linings than for the back. Because of its cheapness, it is sometimes used in the backs, ribs and necks of basses."* (Möckel, 1930, 128)

Plywood is commonly used in current bass construction, either for the entire instrument, for the back and ribs, or only the back. For example, the brand name *Kay* builds bass made bodies completely of plywood which are highly robust and have been very popular. Basses have been introduced of plate- and cast aluminum, fiberglass and carbon fiber. A popular compromise is to mount a solid spruce top plate onto ribs and a back of plywood.

4.1.4 Configuration of the Inner Braces in Flatbacks

There are several examples of brace configurations found in flat-backed

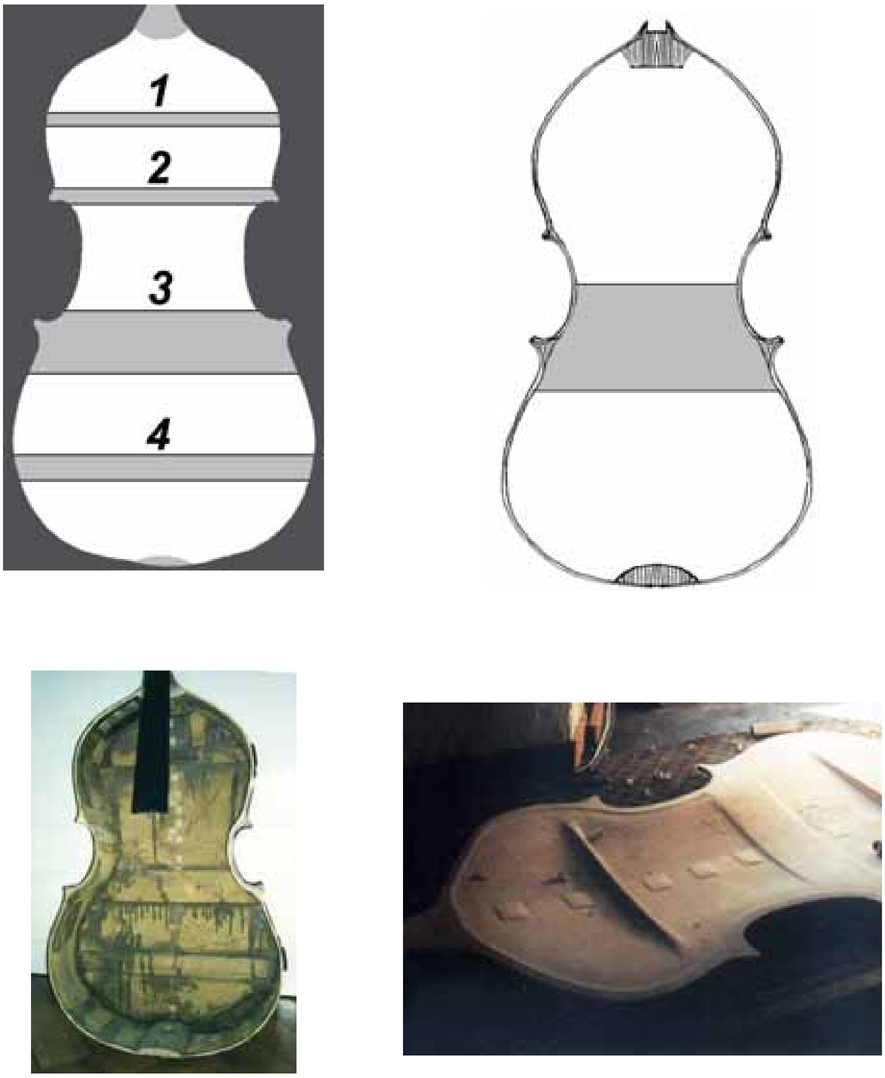


Fig. 4.2. Different brace configurations. Clockwise from upper left: German, French, Auray's mixed form (Double Bassist, 1999, 55), Italian

double basses. The "Standard" German model that is popular throughout the world has four braces, as shown (see Fig. 4.2 on page 52). Italian examples often have three braces. A French bass known to the author (Jacqué, ca. 1860) has an extremely wide single sound board that is approximately 16 cm x 16 cm. There are also individual examples of X-form braces (Prescott, New Hampshire, U.S.A., ca. 1810), and the contemporary maker Jackstadt (Ohio, U.S.A.) also uses this system. A further American example (M. D. & L. Dearborn, New Hampshire, U.S.A., 1831) has one vertical brace, though it is likely that this brace is not original. Another contemporary maker (Auray, France) has created a mixed form by carving brace-like stiffening out of the rounded back (Double Bassist, 1999). Anything is possible!

On account of thorough investigations of guitars and previous observations of flat-backed basses, it is expected that the braces play a decisive role in the acoustical characteristics of basses. However, the variety of configurations in use does not give many clues as to which sounds best.

4.2 The Double Bass as a Sound Source

Study of the acoustics of the double bass is fraught with interesting challenges. The instrument's large size and low frequency range with its long wavelengths make for difficulties in the collection of measurement data and in judging sound qualities objectively.

While judging the sound of a bowed instrument, it is difficult for a player to separate the sound from how the instrument responds, i.e. how it "plays." The musician includes his feelings about his or here interaction with the instrument more than the listener sitting at a distance. Therefore, his or her sensation of the instrument's sound is influenced by these factors.

More "bass-specifically," it is especially difficult to make judgements about the timbre of the double bass in a normal playing situation because its tone color is arguably dependent on the room acoustics to a large extent. Due to the long wavelengths of bass sounds and the radiation characteristics of the top plate, the bassist necessarily sits within the near field of his or her instrument's radiation. The reflections are, of course, filtered through the room's acoustics, and the resulting mix arriving at the ears of the player may be difficult to judge. The player is thus greatly dependent on reflections to hear how the instrument sounds in the hall. Perhaps the same bass played by the same player in different rooms sounds more different than the same player with a different bass in the same room! A violinist arguably hears a greater percent of the directly radiated sound because the plate of the violin radiates directly in his or her ears.

The characteristic frequencies of the bass (Meyer, 1995, 222) are in a range of human hearing which is particularly insensitive. The *Fletcher-Munson diagram* (see Fig. 4.3 on page 54) shows the dependence of the perceived loudness level in Phons upon intensity level (dB) and frequency (Hz). This data was originally collected using a sine wave with the source directly ahead of the listener (Roederer, 1975, 97). Comparing the fundamental frequency of the bass' lowest string (42 Hz) to the violin's lowest string (196 Hz) shows that the former must have a level difference 25 dB (about 300 times more intense) to cause a loudness level equal to 196 Hz.

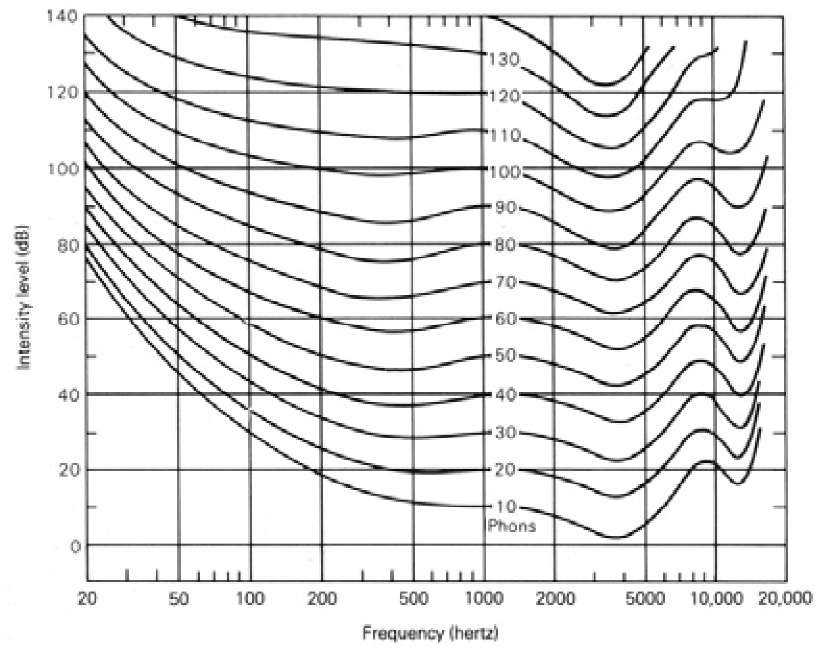


Fig. 4.3. Fletcher-Munson diagram showing loudness in Phons per intensity and frequency (Roederer, 1975, 97)

Roughness also plays an important part in music with the double bass, because the partials of the double bass on the lowest notes are within critical bandwidths of each other under 500 Hz, as Askenfelt wrote (Askenfelt, 1982, 37). If the characteristics of the bass in the low register include a "hole" in the spectrum which happens to fall where the offending second partial is found, the response and the resulting masking of the weaker partial may act as a sort of comb filter to eliminate unpleasant roughness.

Slight variances in the frequency of the low notes can easily cause the relatively dense partials to clash while playing with other instruments. The bassist must thus intonate all the more exactly to avoid "unpleasant" beats and roughness. Considering the ponderous dimensions and the radiation characteristics of the instrument, this is no easy task.

Timing is another complication that bassists face on the podium. Like all orchestral musicians, bassist should produce punctual entrances. But their situation is somewhat different, due to their position on the podium and also to psychoacoustical factors. In one of any standard orchestral positioning schemes, the bassists are significantly further away from the conductor, compared to the concert master, which leads to a time delay in arrival of the direct sound. If the principal bassist is 15 m away from the conductor, and the concertmaster 3 m, the sound will arrive, at 26º C (speed of sound=447.6 m/s) in 43 ms and 9 ms respectively. If the sound is reflected from a ceiling 8 m high, the sound from the concertmaster arrives in 49 ms and from the bassist in 97 ms. And if the sound of a bass is reflected from a back wall that is 4 m behind the player, this adds another 23 ms.

One theory of pitch recognition states that humans need three periods of a harmonic vibration to determine the frequency.[20] This adds 15 ms to a pitch at 196 Hz, but 71 ms to a sound at 42 Hz. A reflected sound with this cumulative delay is not separable from the direct radiation, but the tone color will have been altered significantly by the time it reaches the conductor and the audience. It is arguable that the bassist also needs a longer time to correct timbre and adjust pitch because what he or she is hearing is based on delayed reflections and needs longer cognitive processing time.

References

Askenfelt, A. (1982). Eigenmodes and Tone Quality of the Double Bass. *Catgut Acoust. Soc. Newsletter,* **38**, 34–39.

Bissinger, G. (2001). Normal mode analysis of violin octet scaling. *Proceedings of the ISMA 2001*. 113-116.

Detloff, J. A. (1985). Statistical relationships between acoustic parameters of violin tonewoods. *Catgut Acoust. Soc. Newsletter,* **43**, 13–24.

Güth, W. (1989). “Physik im Geigenbau.” E. Kurz & Co. Stuttgart.

Double Bassist (N. N.) (1999). French Connection: French Luthier Jean Auray. In: *Double Bassist*, Orpheus Publications, Harrow, Middlesex, **10**, 54–57.

McIntyre, W. E. and J. Woodhouse. On measuring wood properties, Part 2. *Catgut Acoust. Soc. Newsletter,* **43**, 18–24.

Meyer, J. (1995). “Akustik und musikalische Auffhrungspraxis.” 3rd ed. Erwin Bochinsky, Frankfurt/M.

Möckel, Otto. (1930). “Die Kunst des Geigenbaus, Zweite neubearbeitete und ergänzte Auflage von Fritz Winckel.” (1954). Bernh. Friedr. Voigt, Berlin.

Roederer, J. G. (1975). “Physiologische und psychologische Grundlagen der Musik.” Springer-Verlag, New York.

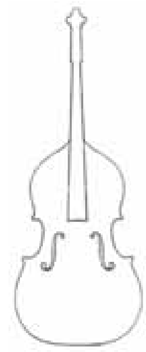
Rossing, T. D. and N. H. Fletcher (1998). “The Physics of Musical Instruments.” Springer, New York.

Rossing, T. D. (2001). Musical Acoustics in the 2nd and 3rd Millennia. *Proceedings of the ISMA 2001*. 7-26.

Woodfield, I. (1984). “The Early History of the Viol.” University Press, Cambridge.

20. Stated in the lecture “Psychoakustik 3”, University of Vienna, W. A. Deutsch, 2001.

5 Experiments



Four main experimental methods were used in the current study to test the acoustics of flat-backed and round-backed basses: frequency response curves, input admittance data, laser-optical observation of vibration patterns, and objective comparative listening tests. A description of the test instruments, special problems encountered, sound analysis methods, and the experimental set-up follows.

5.1 Test Instruments

In total, ten instruments were measured for this study. A special, flat-backed cello (code-named Fbc), a high quality, flat-backed double bass (Bfb), two standard cellos (Rbc, Frbc), a cello-sized viola da gamba (Fbg), and five new basses of similar design (Plyfb, Pfb, Prb, Mfb, Mrb) were measured. “Fb” in the identification code always means “flat back”, “rb” means “round back”. The in-depth measurements and analysis of the two matched pairs of test basses Pfb, Prb and Mfb and Mrb are the main foundation of the work presented here. Fbc was originally a violoncello with a ruinous crack in the back plate that was donated by Eriks Geigenbau in Vienna. The back was replaced with a new, unvarnished flat back with two braces and a sound board. This instrument was measured in the anechoic chamber, by laser vibrometer, and was also played in informal listening tests and tone judgement sessions. The high quality double bass, two cellos and the test bass Plyfb were measured in the anechoic chamber only.

The five principal test basses were made especially for this study by Mr. Heinz Fischbach of Ohlstadt, Bavaria, and kindly lent to the author by the manufacturer for one year. Fischbach’s standard model is a round-backed bass with no break, but he delivers flatbacks on special order. The test basses are middle-quality, ¾-sized instruments, with gamba corners at the c-bouts. Two of them have rounded backs, three have flat backs with braces. The top plates of the test basses are made of the same spruce tree, the back plates either of poplar, maple or plywood, and the ribs are either poplar or maple. The back and ribs of the poplar basses (Pfb and Prb) are made from the same tree, as are those of Mfb and Mrb. The calculated air volume is approximately 0.204 m^3 or 200,412 cm^3 (without the arching), the area of both the f-holes is 0.0101 m² or 101 cm², and the thickness of the top plate at their opening is 3.5 mm.

The components of the instruments were made using a computer controlled routing machine, the top plates were partially tuned by hand and assembled. The accessories (fingerboard, tailpiece, strings and endpin) are practically identical among the five instruments. The bridges and soundposts were mounted as similarly as possible and controlled before each experiment to ensure the same position. The instruments were unvarnished.

Fig. 5.1. Five test instruments made especially for this study: Plyfb, Mrb, Mfb, Prb, Pfb. Note the matching wood, design and tuners

A closer examination with the Hacklinger magnetic thickness gauge showed that the tolerances for thicknesses were within ± 0.5 mm, with two important exceptions. The top plate thicknesses varied as much as 1.7 mm at the edges where they were tuned by hand. Also the inner brace numbers 1, 2 and 4 of the flat backed maple bass (Mfb) were double the thickness (20 mm instead of 10 mm) of the other two flatbacks, which is significant.

The five test basses and the five additional tested instruments are identified on the following table:

Table 5.1. Test Instrument Description

Instrument: Name / Type / Value	Material: Top / Back / Ribs	Back Plate Shape / Length (mm)	Width of Upper Bouts / Lower Bouts (mm)	Depth of Ribs (mm)
1. **Plyfb** / Cb / < €5000.–	spruce / poplar plywood/ maple	flat / 1095	480 / 620	210
2. **Pfb** / Cb / < €5000.–	spruce / poplar / poplar	flat / 1095	480 / 620	210
3. **Prb** / Cb / < €5000.–	spruce / poplar/ poplar	round / 1095	480 / 620	210
4. **Mfb** / Cb / < €5000.–	spruce / maple / maple	flat / 1095	480 / 620	210
5. **Mrb** / Cb / < €5000.–	spruce / maple / maple	round / 1095	480 / 620	210
6. **Rbc** / Vc / < €1000.–	spruce / maple plywood	round / 750	350 / 440	120
7. **Frbc** / Vc / > €5000.–	spruce / maple	round / 750	350 / 440	120
8. **Fbc** / Vc / < €1000.–	spruce / maple / maple plywood	flat / 750	350 / 440	120
9. **Fbg** / Viola da Gamba / > € 5000.–	spruce / sycamore	flat / 800	330 / 430	120
10. **Bfb** / Cb / > €5000.–	spruce / poplar / poplar	flat / 1070	490 / 650	215

5.2 Setup of Frequency Response Measurements

A radiated frequency response analysis was chosen from a variety of methods (see Chapter 3) that was derived from the RMS signal energy analysis for microphone channels representing the radiation in the given direction. The ten listed flat-backed and round-backed test instruments were recorded in an anechoic chamber using a constant signal input source at the driving point on the bridge. The near-field radiation energy was received by an array of microphones and the radiation signals in eight directions yielded frequency response curves.

The input signal for all recordings in the anechoic chamber was a com-

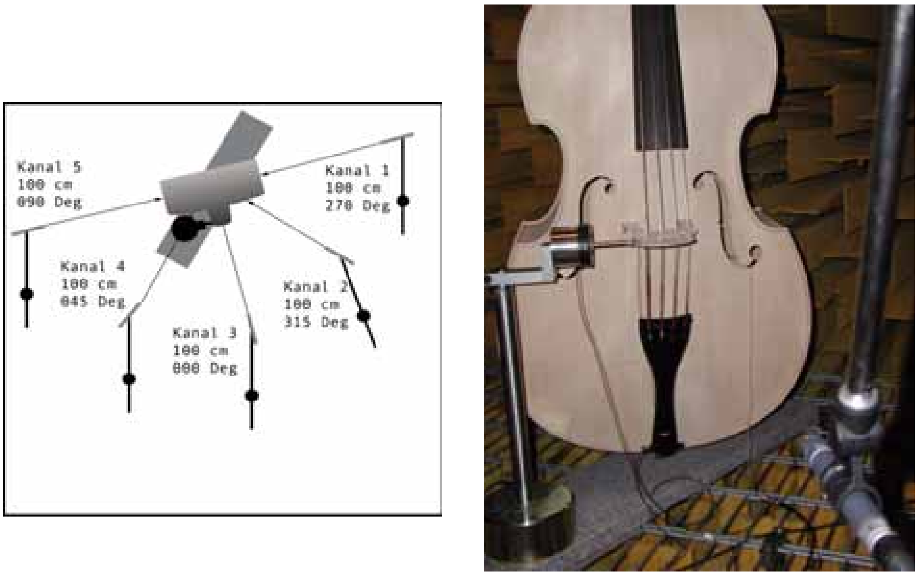


Fig. 5.2. Set-up in the anechoic chamber; left: schematic from above, r: the actual object, showing (l. to r.) mounting, shaker, Prb and AKG CK92 microphone

puter-generated logarithmic sine sweep from 40 Hz to 3500 Hz over either 30 or 60 seconds. This signal was amplified by the Uher amplifier set at the power level "6" and connected to the B&K Mini Shaker Type 4810. The shaker was fixed on a heavy steel (15+ kg) mounting that rested on the stone, allowing a stable coupling of the shaker to the bridge of the instrument, and reducing the wire mesh floor vibrations. A needle was affixed to the shaker probe, driving the bass side of the instrument's bridge through the frequency range of interest. The height of the shaker was adjustable as necessary to a maximum of 75 cm to allow for different types of instruments.

The output signal of one sweep radiated by the instrument was recorded using an array of five AKG CK92/300SB microphones with a spherical characteristic. They were arranged at bridge height in a half-circle at a distance of 100 cm at the angles 270°, 315°, 0°, 45° and 90° relative to the front (bridge) of the instrument. The microphone signals were recorded onto five ADAT channels, and a sixth channel was recorded as a reference using the B&K accelerometer 4374 mounted on the bridge immediately next to the driving point (see Fig. 5.10 on page 67). After the completion of a sweep, the instrument was then rotated 180° (because of the limited space in the anechoic room) to complete a full circle, measuring radiation then from 90°, 135°, 180°, 225° and 270°. These channels (12 in all) were then transferred to computer storage for later analysis. To have more information on the room acoustics of the anechoic chamber, the instruments Mfb and Mrb were measured with the bass pointed in two additional directions, at 90° to the previous sessions. For a detailed description of frequency response procedures, please see Appendix 9.2 on page 105.

5.2.1 Analysis of Frequency Response Audio Signals Using S_Tools

Several different audio analyses are available using S_Tools.[21] During this study, RMS signal energy analysis and FFT spectral analysis were used.

The following screen shot shows four analyses of a sine sweep output signal recorded using a microphone positioned directly in front (0°) of the test instrument Prb. At upper left, the wave form at the cursor position (20 s), at upper right the spectrum of the cursor position (bandwidth 6 Hz, 75% overlap, window: Blackman-Harris). At the center is a spectrogram

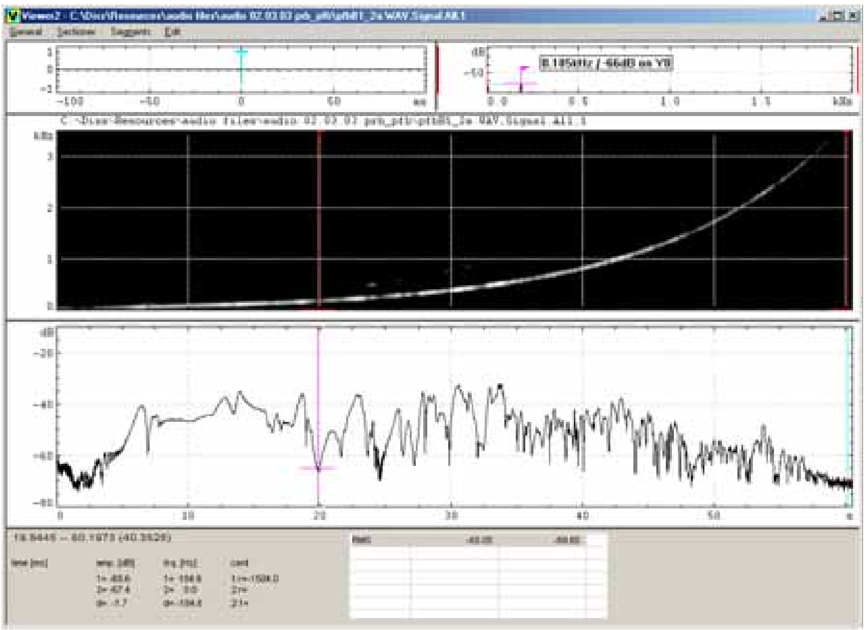


Fig. 5.3. Screenshot of S_Tools interface, showing time domain (upper left), spectrum at cursor (upper right), spectrogram of the sine sweep (black background) and RMS analysis of the sine sweep

showing the contour of the sweep in the frequency domain. At the bottom is an RMS signal energy analysis on the time axis. At the cursor position the sweep has reached 185 Hz. The spectrum window at upper right shows the frequency analysis of the signal at the cursor position. Throughout the progress of the sweep, the frequency is referenced to the elapsed time. The

21. Documentation currently available at: http://www.kfs.oeaw.ac.at/software/stx_manual/index.htm

relative amplitude of the signal is shown by the color intensity of the spectrogram at that point.

5.2.2 RMS signal analysis as a frequency response curve

The illustrated RMS signal energy analysis of the signal transduced by the microphone yields a frequency response curve. The RMS analysis of a sine wave is defined as the peak value divided by the square root of 2, and gives the effective value directly related to the energy content of an acoustical signal (Veit, 1996, 16). For a complex waveform with harmonic content, three steps are necessary: the square of the waveform function is determined, the function resulting from step (1) is averaged over time, and the square root of the function resulting from step (2) is found. The energy of the radiated output signal at a given time is the response at an isolated frequency since the input signal is, in theory, a sine sweep logarithmically increasing over a given time.

The cursor's position at 20000 ms and at 185 Hz (see Fig. 5.3 on page 60) shows a relatively weak response at this frequency with this audio signal. The same instrument measured by the same method but from the front (0°) and the back (180°) shows that the frequency response toward the back is generally weaker and characterized by frequency bands that do not radiate in this direction (Fig. 5.4).

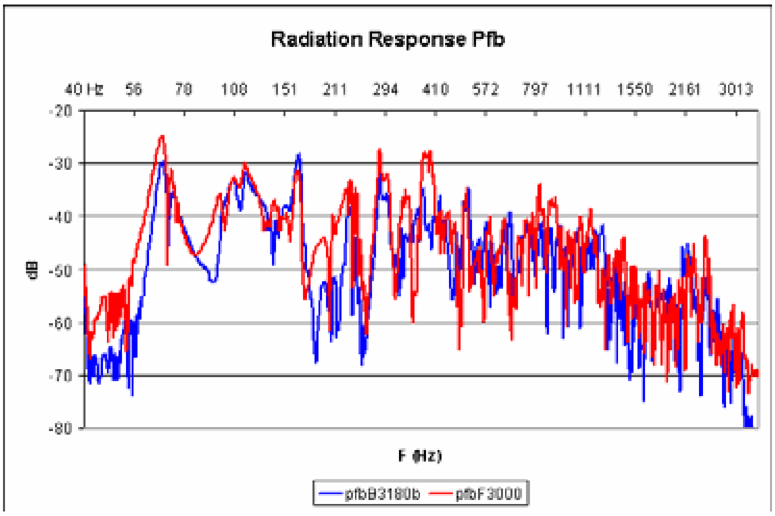


Fig. 5.4. RMS frequency curves of pfb radiation at 000° (red) and 180° (blue), created in S_Tools and formatted in a commercially available table program.

RMS analysis forms the main part of frequency response comparisons of the tested instruments. This curve is stored in the dataset file of STX and can be subsequently imported as an ASCI file into an Excel table for a variety of further manipulations.

5.2.3 Supporting the Double Bass During Frequency Response Measurements

While some methods used an instrument played in vivo, being held by the player in his or her natural position, the frequency response, admittance and laser vibrometry methods used in this study require a special support system for the measurement object. Methods for supporting bowed instruments during measurements have been discussed greatly in the literature, but mostly with the violin. Violins can either be supported in a similar way to being played (Morset, et al, 1998) or supported with as little external damping as possible (Marshall, 1985, 697). The holding system should be stable and support repeatable measurements, and may never cause any damage to the instrument. Practically no information in the literature is available regarding hands-off experimental support systems of the double bass.

Fig. 5.5. Close-up of artificial endpin on the wire floor of the anechoic chamber

Several support methods were tried early in this project, but a particular problem experienced was the instability of the support system on "soft" floors like that of the anechoic chamber: each footstep during set-up brought the sensitive measuring equipment coupled to the bass out of adjustment. The support method finally chosen mounted the instrument on a 15 kg granite plate by means of an "artificial endpin" fixed to the stone. To set up the bass, the real endpin was removed from the instrument, the instrument was inserted over the artificial endpin and the endpin plug's screw held the instrument fast. The stone was padded on the bottom with a piece of carpet, and it could be placed arbitrarily in the room.

5.2.4 Damping the Strings

Because opinions diverge in the literature on the subject of string damping during measurements, an experiment was made with the test basses "Pfb" and "Prb". They were measured with dampened and undampened strings. The predictable needle-like peaks found in the frequency analysis of the bass with undampened strings muddle the response curve of the corpus. The application a high-pass filter above 25 Hz also indicated that low frequency noise content was higher with undampened strings. Significant damping of practically inaudible fingerboard resonances were not found while damping the strings with foam rubber. Consequently it was decided to dampen the strings for a "cleaner" set of response curves.

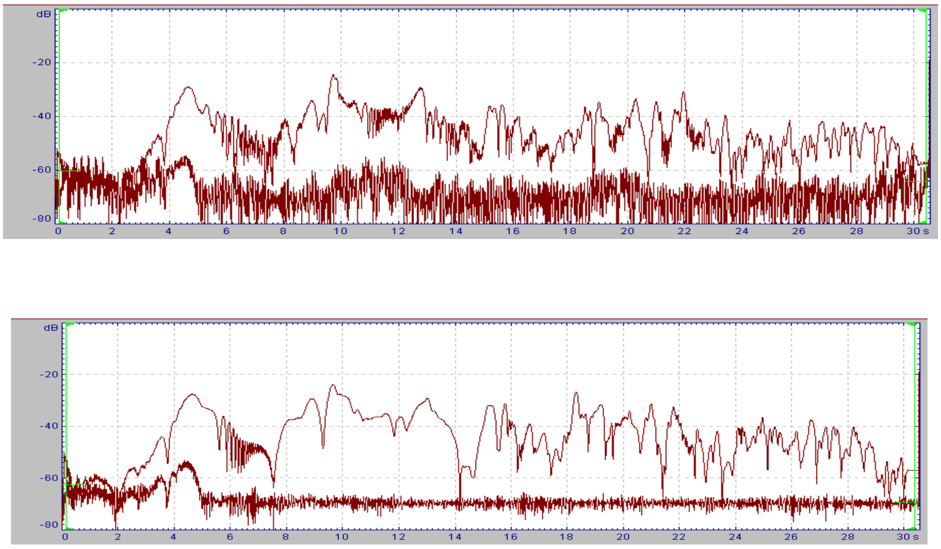


Fig. 5.6. RMS curves of Prb radiation in two bands, 0–25 Hz and 26–3000 Hz, of sweeps measured with undampened (top) and dampened strings

Additional tests were made by sweeping from high frequencies to low frequencies (reverse sine sweep) to identify disturbances caused by strings, the holding structure, etc. The sweeps were recorded by microphone at 0° (directly in front of the instrument), RMS-analyzed, the graph captured, and second diagram was flipped horizontally with graphics software, showing a good match. With dampened strings, no such disturbances were found.

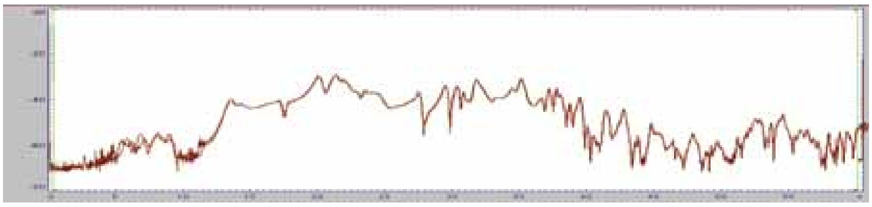


Fig. 5.7. Two practically identical RMS sweeps, from bottom to top of frequency range, and from top to bottom

Input admittance measurements have shown that changing the driving point from the bass side of the bridge to the treble side may influence obtained data (Moral and Jansson, 1982, 334). To test this, radiation and admittance curves were made, changing only the driving point. No significant differences in the resulting curves were found between driving the bridge parallel to the top plate in either direction.

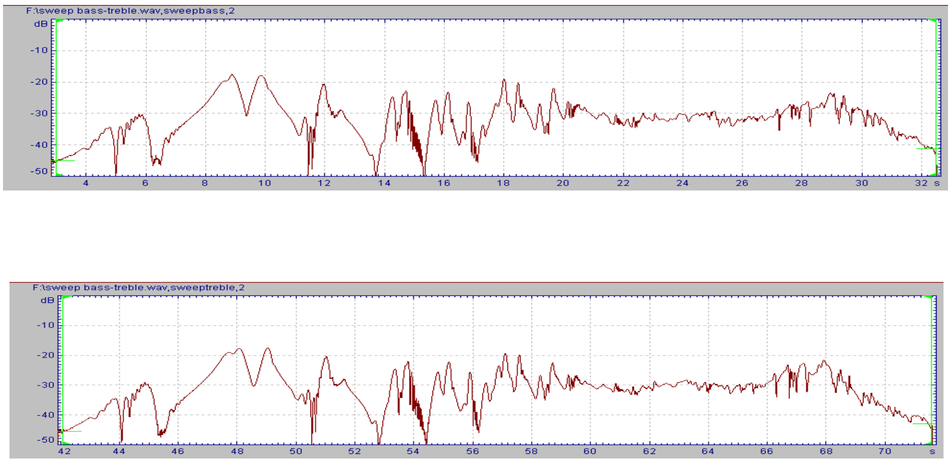


Fig. 5.8. Two practically identical RMS sweeps, with bass-mounted accelerometer signal driven from the bass side of the bridge (above) and the treble side (below)

5.2.5 Limitations of the anechoic environment

Each anechoic environment has a cutoff frequency based on the relationship of the wavelength to the profiles of sound-absorbing material in the room (Veit, 1996, 111). It has been assumed for this study that while standing waves are unavoidable at the lower frequencies of the double bass' range, the deviation should be similar for all measured instruments if factors like the position and angle of the bass remain constant in the room. It should thus still be possible to recognize differences among the types being investigated.

Measurements of the anechoic chamber at the IWK show that disturbances from standing waves and other acoustical phenomena are problematic. The theoretical cutoff frequency of the room at IWK should be lower than 150 Hz, but evidence shows that yet higher frequencies are the source of errors: deviations up to 10 dB were found at varying positions in the room, especially below 100 Hz. A omni-directional sound source was not available to calibrate the room, but a comparison was made using test basses Mbf and Mrb. The instruments were measured not only from the standard position (front and back) but at 90° and 180° to the sides: the radiation at 0° was measured at microphone positions 1, 3 and 5 (see Fig. 5.2 on page 59). The accelerometer signal was used as a reference. Fig. 5.9 shows the RMS

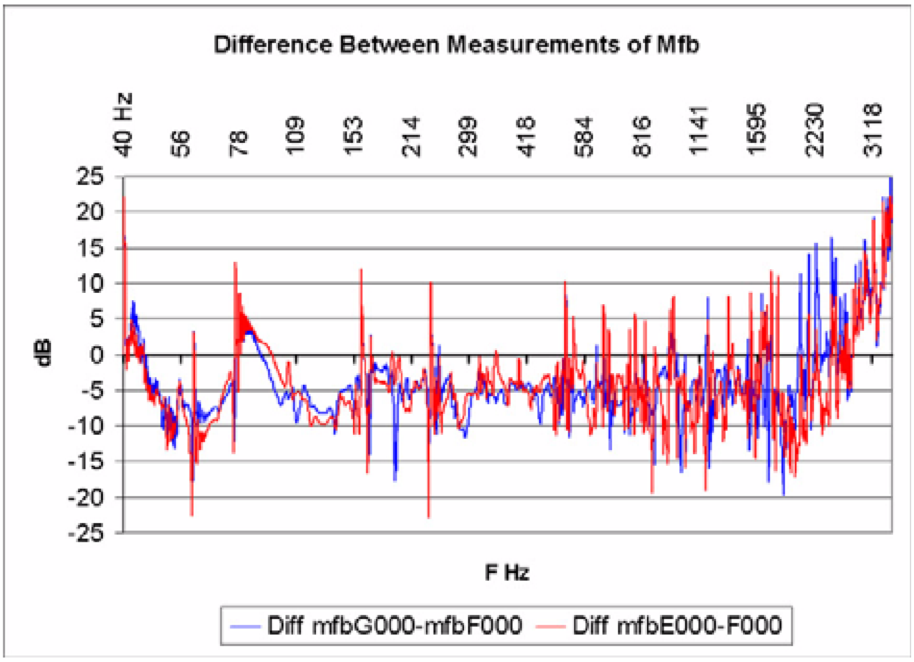


Fig. 5.9. Comparison of measurements recorded from different microphone positions

of microphone signal 3 subtracted from signal 1 (red) and signal 5 (blue). Since most of the difference lies in the negative range, Channel 3 (at the room's center) picks up more signal reflections, contributing to a level between 5 and 10 dB stronger than the side positions from 40–78 Hz and from about 200–500 Hz. Tests of both Mfb and Mrb showed that the largest error is similar for both types, but that the roundback's curves have more narrow band errors that are attributable to reflections in the chamber.

The limited area of the anechoic room at IWK is another problem for the double bass. The dimensions of the room allow only for near-field measurements since the longest wavelength of the lowest string at 41 Hz is about 8 m. The near field is defined such that the distance from the source to the receiver is less than twice the wavelength, and the far field is more than twice the wavelength distant. According to this definition, radiation measured at 1 m is in the near field below 640 Hz, which excludes the double bass' characteristic "o" and "u" formant frequencies (Meyer, 1996, 222). The mixture of overtones that a listener in a concert hall environment would hear is obviously very different from that which the microphones at 1 m distance are able to record. It is theoretically possible to calculate the far field radiation based on the near field spectral content, but this study will not attempt to reconstruct far field radiation. Instead, it will simply compare the signal energy at a given frequency at a distance of 1 m between the two types being investigated.

5.3 Setup of Input Admittance Measurements

The input admittance, or mechanical mobility, curves presented here are a by-product of the frequency response measurements. The B&K accelerometer, which was fixed with wax to the bass side of the bridge, was used to record the accelerance immediately next to the driving point during measurements in the anechoic chamber. This signal served not only as a reference of the magnitude of the input signal, but also provided valuable data in its own right. In calling the resulting data curves "input admittance", two important facts should be kept in mind: the input force at the driving point is assumed to be constant in the frequency range of 40–3500 Hz. Also and the accelerance was not integrated to obtain the velocity for these measurements. Since the accelerance is closely related to the velocity, the resulting mechanical mobility curves, here referred to as input admittance curves, are sufficient for the comparisons within the scope of this paper. The data is easily obtainable and is well repeatable.

5.4 Setup of Laser Vibrometry Measurements

Measurements with the Polytec scanning laser vibrometer were made possible with the support of Mag. Donhauser and the Technical Museum, Vienna. The measurements used in this study took place at the museum in a relatively small room (4 m * 8 m * 4 m = 128 m^3) with smooth concrete walls and floor. The instrument and shaker were mounted on the stone plate as in the anechoic chamber, at a distance from the camera of approximately 4 m. The top and back plates of Pfb, Prb and Fbc were measured using a periodic chirp from 5–2000 Hz, the bridge was driven on

Fig. 5.10. Close-up view of the B&K accelerometer, mounted just next to the needle tip of the shaker. The instrument is the flat-backed cello, Fbc.

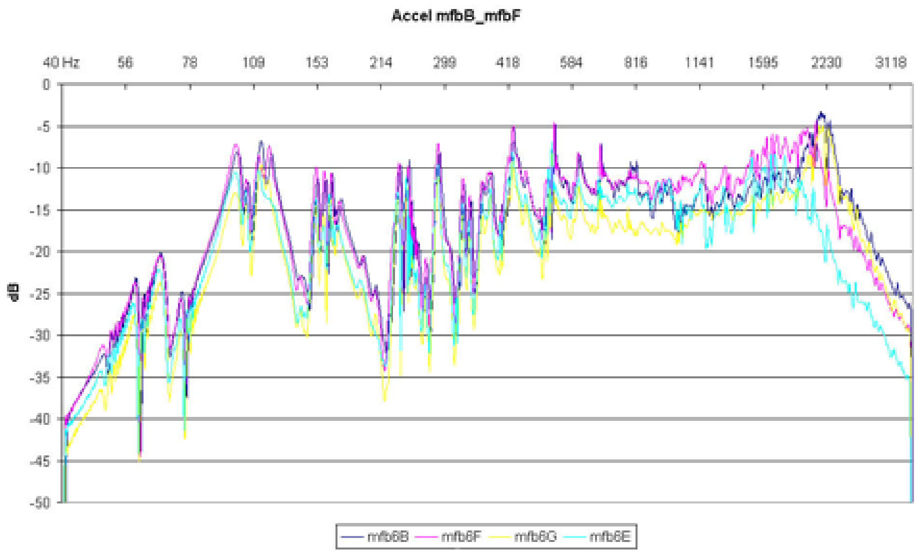


Fig. 5.11. Accelerometer signals for four measurements of mfb

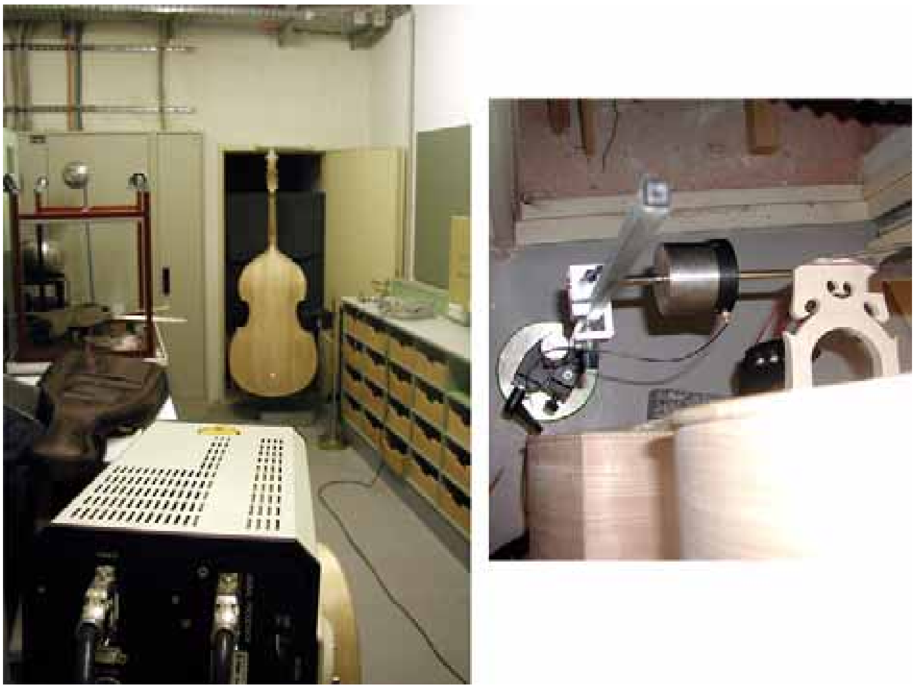


Fig. 5.12. Setup in the Technical Museum Vienna

the treble side and the strings were not dampened. Measurements with a loudspeaker input signal were attempted, but the small speaker delivered too little amplitude at low frequencies. No additional audio data was collected and no reference signal was recorded.

The test instruments, Pfb, Prb and Fbc were especially suited for laser vibrometer measurements because the materials of the back, top plate and sides are from the same trees, and the matte finish of the unvarnished plates reflected the laser beams optimally, unlike the glossy varnish of finished instruments.

A variety of analyses are available with the accompanying Polytec software.[22] Velocity and displacement analysis of area scans and individual measurement points yielded qualitative data on the resonant frequencies and operational deflection patterns of the top and back plates. The analysis can then be visualized by several means, including animation.

22. Documentation of the Polytec scanning laser vibrometer is currently available at: http://www.polytec.com

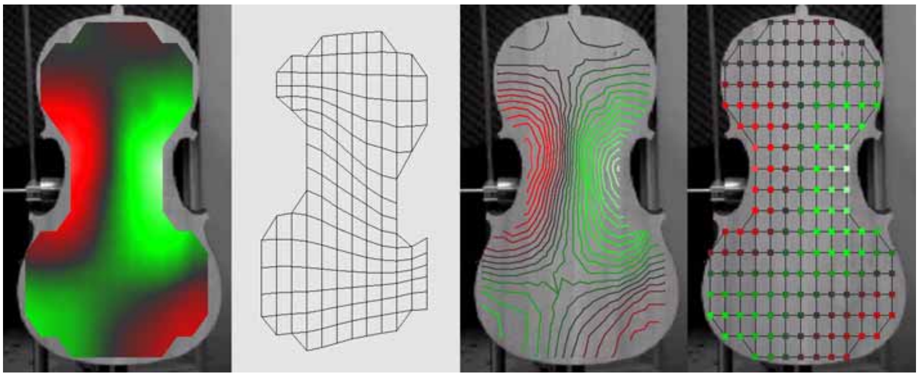


Fig. 5.13. Four available views of the same measurement (Fbc back at 190 Hz): Colormap, 3D Mesh, Isolines and Color Dots.

5.5 Setup of Listening Tests

Two listening tests were performed using Pfb and Prb: a live, blind test where Pfb and Prb were played behind a screen in a concert hall (Listening Test 1), and a recorded survey using audio data collected during the live test (Listening Test 2). The recordings were made in a concert-hall

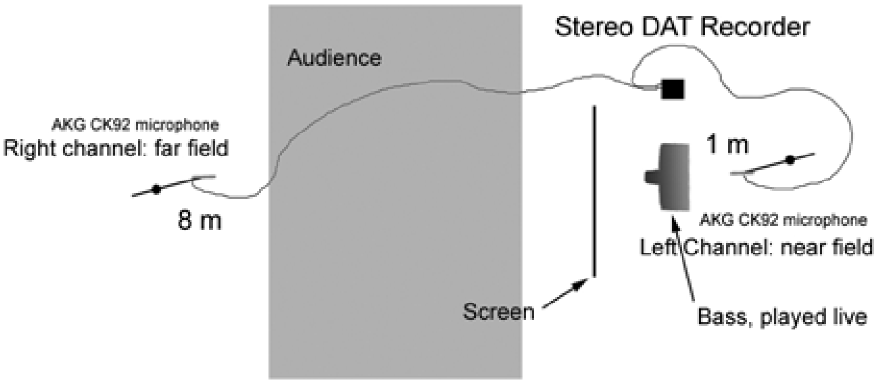


Fig. 5.14. Recording setup in a concert hall

environment with a live audience and one near-field and one far-field microphone. Surveys were collected from the live audience. The recordings were then spectral analyzed, edited, and combined for the second listening test where participants were asked to match samples based on audible differences between the two test basses.

5.5.1 Part I: Live Listening Test and Recording Session

Played sound examples of single tones and short musical phrases were selected by analyzing frequency response data and choosing notes where the greatest differences occur, i.e. notes that were likely to sound different to survey participants. 150 Hz, 183 Hz and 263 Hz represent some of the largest differences in the response curves, so played tones were chosen according to where noticeable differences in timbre were expected. For example, f_2 of the open D-string (f_1=73 Hz) at 146 Hz, f_1 of the stopped note F#3 (f_1=185 Hz) at 185 Hz, and f_4 of the low C (f_1=65 Hz) at 261 Hz were played. Of additional interest were the lowest note of the bass (E1 at 42 Hz), and notes in a musical context from Richard Wagner's "The Valkurie" and W. A. Mozart's "Jupiter Symphony". Each of the test examples was played in pairs four times, with either Pfb first or Prb first, resulting in 28 listening test decisions.

Before the live test, the four participants were given a survey form asking *a) what kind of sound they would expect from an instrument with a flat back compared to one with a round back*. Listeners were then asked, according to their expectation of the sound quality of the two types, *b) which of the two instruments was played first*. During the live test, the order of Pfb and Prb was varied according to a pre-determined, quasi-random list, and to help "confuse" the listeners, the instruments were moved around even if the same bass was used for the next example. The single tones were played *f* with one downbow stroke, while the musical examples were all played with the same bowing. A discussion followed.

The audio data was recorded using two AKG CK92/SE300B microphones, one in the near field, 1 m behind the player, and one in the far field, behind the audience. The signals were recorded onto the left and right channels of a portable DAT (digital audio tape) recorder.

5.5.2 Part II: Recorded Listening Test

The four pairs of each sound example recorded in both the near field and far field resulted in a total of 56 short audio files stored onto computer hard disk. These files were grouped according to microphone channel (near or far field) and example class (note value or musical sample) and edited with the program Sound Forge, yielding fourteen different groups of audio samples. These groups were then spectral-analyzed, and the average spectra of a group of tones was used to synthesize examples representing the average timbre of the sample groups. This minimized the influence of the player while representing the general timbre of the instruments.

For the second listening test, ten played single-tone pairs, two played musical sample pairs and six synthesized single-tone pairs were selected for an ABX-scheme test. During the test, three examples were played back from CD either over AKG K240 Studio headphones, or over loudspeakers. The listeners were asked to identify audible differences by grouping the two matching examples, resulting in either ABA or ABB. For example, the note C2 for pair Prb and Pfb in the far field was compared by creating the 3-second sound file “CrbfbrbFF.wav” from a short excerpt of the roundback in the far field, the flatback in the far field, and again the roundback. The correct answer is ABA, and this answer during the survey indicates an audible difference between the test instruments at this frequency. Listeners were also asked to identify themselves as to their musician status (Non-Musician, Hobby Musician, Music Student or Professional Musician), instrument (Bassist or Non-Bassist), and to note how often they had previously taken the test.

46 listeners participated in the second listening survey, of whom three took the test twice and one took the test three times, giving a total of 51 tests. The results were entered into an Excel table and analyzed according to musician status and instrument type, or in groups of example classes, showing which groups heard most accurately, and at which frequencies differences were audible.

References

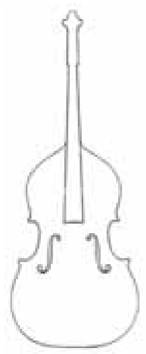
Marshall, K. D. (1985). Modal analysis of a violin. *J. Acoust. Soc. Am.* **77** (2), 695–709.

Moral, J.A. and E.V. Jansson (1982). Eigenmodes, Input Admittance, and the Function of the Violin. *Acustica* **50** (5), 329–337.

Morset, L. H., A. Krokstad and O. J. Lokberg (1998). A Computer-based Method for Quality Control of Violins using Impulse Excitation. *Proceedings of the ISMA 1998*. 23–28.

Veit, I. (1996). “Technische Akustik: Grundlagen der physikalischen, physiologischen und Elekroakustik.” 5. Auflage. Vogel-Buchverlag, Würzburg.

6 Results



6.1 Results of Radiated Frequency Response Measurements

The radiated frequency response was analyzed by two means: plotting curves of the RMS of the microphone signals, and deriving radiation directivity diagrams from this data. The radiated frequency response curves show that flat backed and round backed instruments have differences in the order, amplitude and bandwidth of the their main resonances. All flat-backed stringed instruments measured, including six basses, the special flat backed violoncello, and a cello-sized viola da gamba, are characterized by narrow band peaks and valleys in the response curve showing extreme amplitude differences within the range of middle body modes. The radiation directivity diagrams show that in the near field, the round-backed basses Prb and Mrb have wide frequency bands where they behave as 0-radiators, while the flatbacks Pfb and Mfb have directed patterns at a variety of frequencies. All measured response curves are shown in the Appendix (see Fig. 9.5 on page 110).

6.1.1 The Response Curves

The radiated responses of the test instruments Pfb and Prb characterize the general difference between flat and round-backed types. The radiated frequency response averaged over all eight recorded microphone channels of the poplar flatback and poplar roundback test instruments are illustrated in the figure below (Fig. 6.1). Pfb shows troughs in radiated energy occurring at 175, 205, and 260 Hz which do not occur in its round-backed twin. In spite of the large differences, the two instruments nevertheless have major characteristics in common, including the general shape of the curves below ca. 150 Hz and above 350 Hz. This is not surprising since these instruments are so similar. This also indicates the areas in these frequency bands are not affected as significantly by the form of the back. The second graph shows the averaged response curves of the maple test basses Mfb and Mrb. Again, the largest difference occurs slightly below

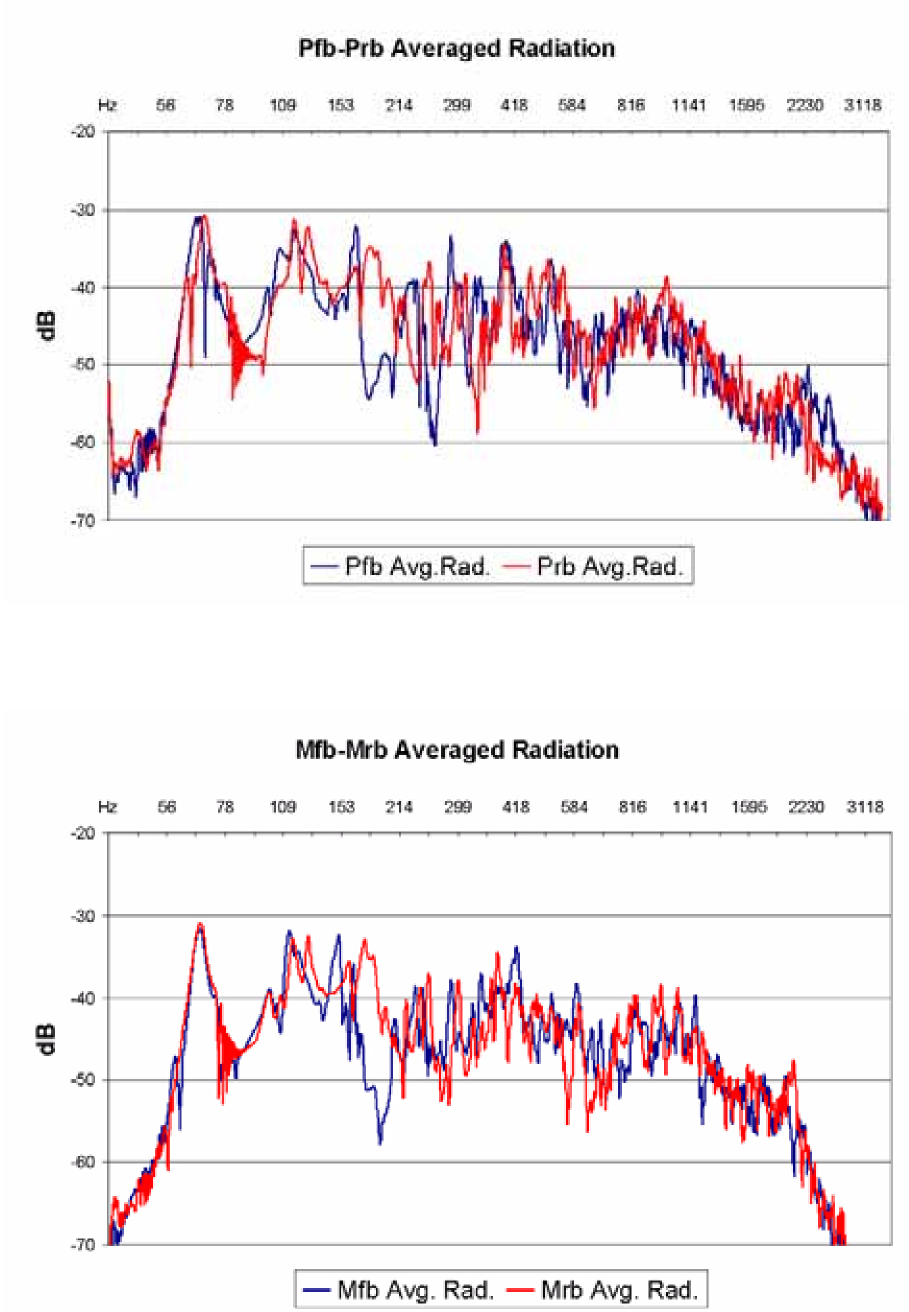


Fig. 6.1. Radiated response curves of pfb and prb averaged over eight channels (top) and of mfb and mrb (bottom)

200 Hz at 190 Hz, where the curve of the flatback dips significantly. The large difference that occurs at 260 in the poplar models, however, does not appear here strongly.

The finding that the response curves of flat-backed instruments are less smooth than roundbacks is in agreement with reprinted bowed loudness curves (see Fig. 6.2 on page 75).

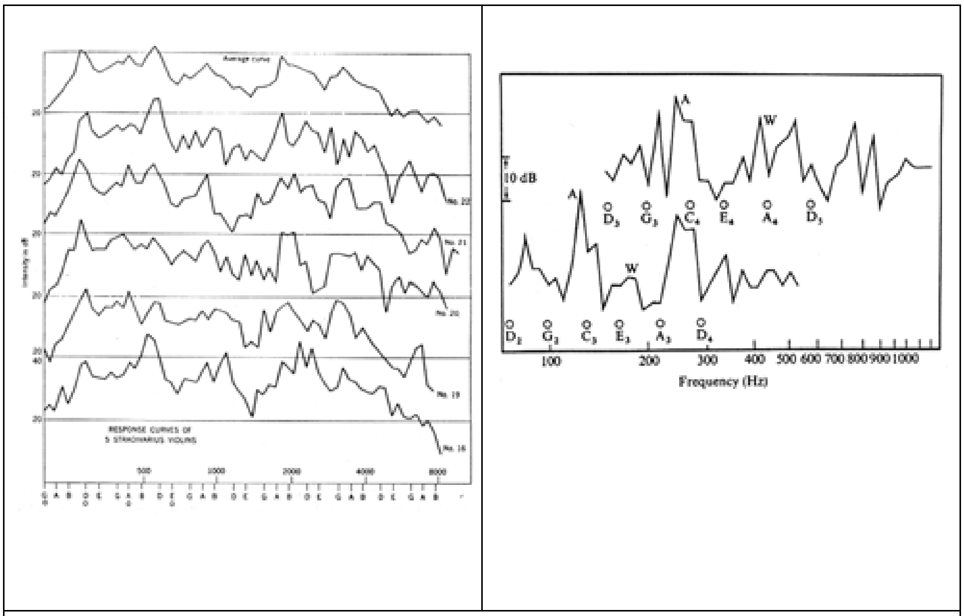


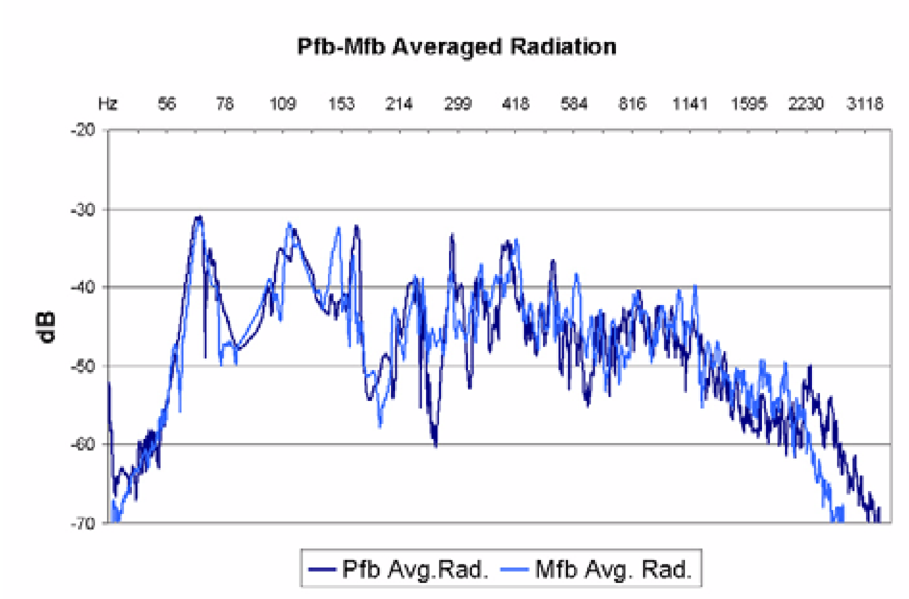
Fig. 6.2. Loudness curves from played instruments (reprinted in Rossing and Fletcher, 1998, 307; 322): six violins (Saunders, 1937) and two viols (Ågren, 1968). Note the extreme peaks of the viol curves.

The violin curves appear much smoother in the range of the main air and body resonances (Saunders, 1937), while the curves of the viols (Ågren, 1968) show the high, narrow peaks that are typical of flat backed instruments.

The two flat-backed basses Pfb and Mfb are plotted on the same graph in the figure below. The significant differences of response between Pfb and Mfb at 150 Hz and 290 Hz are attributable to the different thicknesses in braces 1, 2 and 4, which the reader will recall are double the height in Mfb than Pfb (see section 5.1 on page 56). This will be discussed in detail below (see section 6.3.3 on page 87). The plot of both round-backed basses shows that they conform to one another more closely, indicating that the effect of choosing poplar or maple for the back and ribs has far less influence on the response curve than the form of the back and braces. The amplitude of extremely low and high frequencies was higher with Pfb and Prb than with Mfb and Mrb. This may be attributable to the differing types of wood, the fact that Pfb and Prb were fitted with bridge height adjusters (Brown, 1999, 29), or some measurement error.

The total radiated level is 5 dB higher in the direction 0° (front) than for 180° (back). The strongest average radiation at 1 m occurs at 315°, though only stronger than 0° by an average of ½ dB.

The bandwidth of peaks is one of the three acoustical properties describing a resonance, along with frequency and peak level. These acoustical properties are related to the mechanical properties of a resonator: stiffness, mass and friction (Jansson, 2002, 2.11). The bandwidth is defined as the width of the peak 3 dB below the peak level. Curves of the flat-backed instruments tested possess narrow-band resonances in the lower and middle frequency range relative to roundbacks.



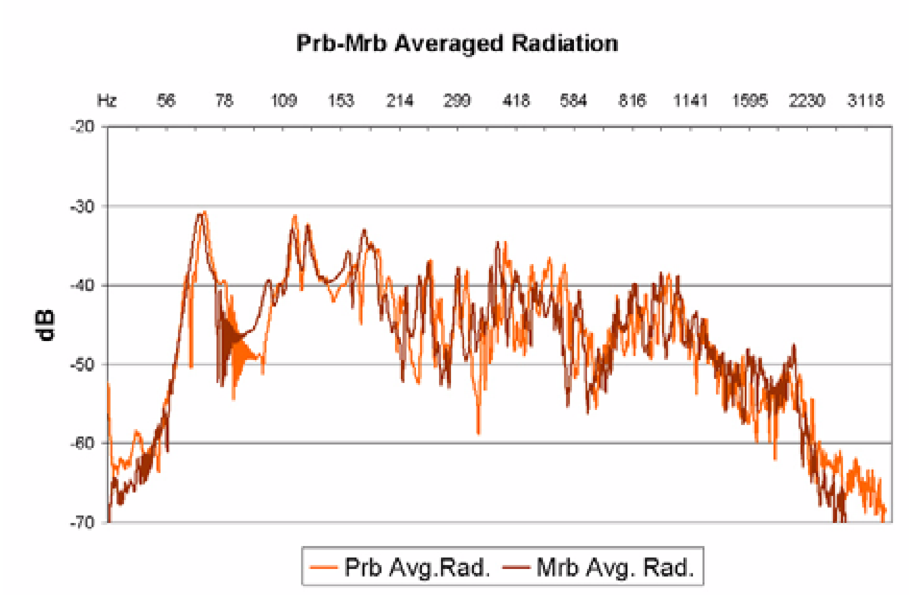


Fig. 6.3. Averaged response curves of Pfb and Mfb (top) and Prb and Mrb

6.1.2 Directivity Analysis Based on Response Curves

Diagrams of the recorded radiation characteristics in the bridge plane of

Fig. 6.4. Directivity diagrams for Pfb and Prb at 235 Hz. Amplitude in 25 dB increments.

Pfb, Prb, Mfb and Mrb were made by entering the RMS analysis for each of the eight channels (the repeated 9th and 10th channels at 90° and 270° were averaged) into an Excel table creating web-diagrams from the data columns. Frequency bands were chosen at given intervals to compare to existing studies (Meyer, 19965, 319), and to show areas of noticeable differences or similarities between the measured instruments. An extensive graphic documentation of the radiation patterns is found in the Appendix (please see Appendix 9.6 on page 112).

These diagrams show that the flatbacks Pfb and Mfb have directed patterns at a variety of frequencies while the round-back basses Prb and Mrb behave as 0-radiators in wide frequency bands. The peak values are around -25 dB and were most often radiated from the round-back models.

Certain frequencies are outstanding. At 60 Hz, the amplitude increases from the weak radiation at 40 Hz. The A0 Helmholtz main air resonance is found in the test instruments near 65 Hz. All models have a similar pattern with stronger radiation to the front three microphone positions, except Mfb, which has a “blind angle” at 255° that is 25 dB weaker than the radiation at 0°. At 70 Hz, the patterns are quite consistent among all models: strong radiation dominated by 0,° 45° and 315° in front of the f-holes.

At 115 Hz, all models have similar circular patterns, with a strong, uniform radiation in all directions within 10 dB of one another. The angle 0° dominates by a few dB in the case of the roundbacks. This frequency coincides with the coupled A1/T1, or main top plate resonance and second air resonance (see Fig. 6.6 on page 80) and is among the strongest radiating frequencies of these test instruments.

In the range of 140–175 Hz, the flatbacks radiate weaker and have more irregular directivity patterns than the roundbacks, which remain consistently strong and circular in radiativity. The pattern of all models at 185 Hz and 200 Hz is circular, but the flatbacks are around 20 dB weaker than the roundbacks. At 200 Hz, Prb is the most circular, Pfb the most directional.

Above 200 Hz, the diagrams show increasing variety. At 235 Hz, the flatbacks radiate principally to 45°, 20 dB stronger than 135°. Pfb also radiates strongly at 225°, while Mfb does not. The roundbacks are somewhat weaker than the flatbacks. Prb radiates 10 dB stronger to 315° and 135°, and Mrb radiates about 15 dB stronger forward. At 270 Hz, Pfb and Mfb have "holes" in the radiation at 225° and 135° respectively. The roundback pattern is circular.

At 300 Hz, the patterns of all instruments are different. Pfb is dominated by radiation to the front left and rear left, 25 dB stronger than the rear right. Mfb shares this, but less extremely. Prb radiates stronger to the right front and rear left, while Mrb radiates significantly stronger in an "X" pattern, at 45°, 135°, 225° and 315°. At 330 Hz all models radiate mostly to the front and sides. But at 350 Hz, the flatbacks again change directivity patterns rapidly and extremely. While the roundbacks are relatively circular, Prb radiates principally to the front left, while Mrb shows an "X" pattern. At 400 Hz, radiation is strongest to the front for all models. Pfb is the strongest radiator at this frequency. At 500 Hz, both the flatbacks radiate weakest to the front, while both roundbacks radiate strongest to the sides about 5 dB stronger than to 0°.

At 600 Hz, Pfb and Prb share patterns and amplitudes, as do Mfb and Mrb, which occurs only once in this way among the diagrams. This may have to do with the bridge/soundpost setup, which was done in pairs, some specific measurement parameter, or the different construction materials.

At 700 Hz, Pfb and Mfb radiate stronger to the sides, Prb shows a "Y" pattern, and Mrb radiates to the front right and rear left. At 800 Hz, the flatbacks radiate strongly to the front right and left rear. Roundbacks are more even, though the radiation of Prb is about 10 dB stronger to the front than to the rear. The flatbacks are again more directed than roundbacks at 900 Hz.

Above 1000 Hz, radiation patterns become predictably more directional, though the roundbacks remain somewhat more circular. The amplitude at 1000 Hz is still above -50 dB and, but decreases below -50 dB by 1250 Hz. All patterns become increasingly irregular and different from one another, and the amplitude decreases with increasing frequency. By 3000 Hz, the radiation of all models is weak; the maximum value is about 30 dB below the peak values.

It is interesting to compare this data with the results of a previous directivity study (Meyer, 1995, 131). Meyer gives no indication of the back plate types of bass used for his “Häufungsdiagramme” [Cluster diagrams], but it is likely that flatbacks were an important part of the study, since the radiation directivity is so pronounced. His diagrams for the violoncello are more what one would expect from a round-backed bass, with more even distribution in every direction over a broader bandwidth in the low register. Generally, however, the results of this directivity analysis are in agreement with Meyer’s results: that individual instruments differ greatly except for the area of the A1 air resonance near 115 Hz for the test basses.

6.1.3 Summary of Radiated Response Curve Analysis

The radiated frequency response graphs show that flat-backed and round-backed instruments have differences in the order, amplitude and bandwidth of their main resonances. A comparison of the curves of Pfb, Prb, Mfb and Mrb indicates that the qualities of the braces in flatbacks directly affect the radiated response, and that the choice between poplar and maple seems to have far less influence on the response curve than the form of the back and braces.

The radiation directivity graphs show that the round-back basses Prb and Mrb have wide frequency bands where they behave as 0-radiators, while the flatbacks Pfb and Mfb have directed patterns in the range above 140 Hz.

6.2 Results of Input Admittance Measurements

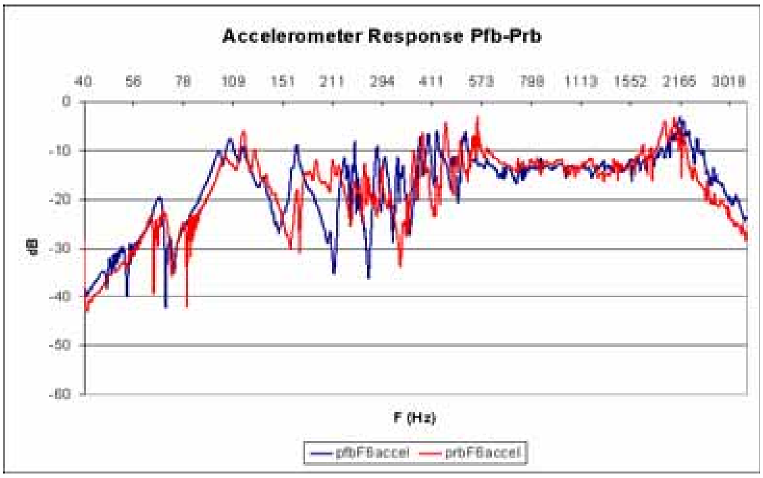


Fig. 6.5. RMS of accelerometer signals of Pfb and Prb

The signal from the accelerometer placed very near the driving point was planned for use as a convenient and reproducible input reference signal in the absence of a force transducer. This proved, however, to be useful as an indicator of input admittance. The input admittance is defined as the Velocity *v* over the Force *F*, which is the reciprocal of the input impedance. The measurements here are not strictly input admittance curves, since *F* of the input signal was not measured but assumed to be 1, the accelerance of the driving point was not integrated to derive *v*, and the mass of the driving structure and accelerometer were assumed to be 0. Still, the accelerance is directly related to the velocity and was judged sufficient for the qualitative comparisons presented here. These curves will also be referred to here as the *mobility* curves.

The admittance curves clearly show the characteristic frequency response of flatbacks and roundbacks: again, Pfb has a less even response in the range of 180–300 Hz. For a documentation of the accelerometer response curves for all tested instruments, please see Appendix 9.5 on page 111.

A combined analysis of radiation curves and mobility curves can show at which frequencies the radiated energy depends on air resonances (Zopf and Brown, 2001). The contribution of the air resonances in string instruments to the radiation is substantial, especially in the low registers. The black curve below was attained simply by subtracting the value of the accelerance from the averaged radiated response. Peak areas of the difference curve represent radiation not directly related to the mobility of the bridge, where troughs are areas of high mobility that do not radiate efficiently (blind power). This technique was used to help identify some air mode dif-

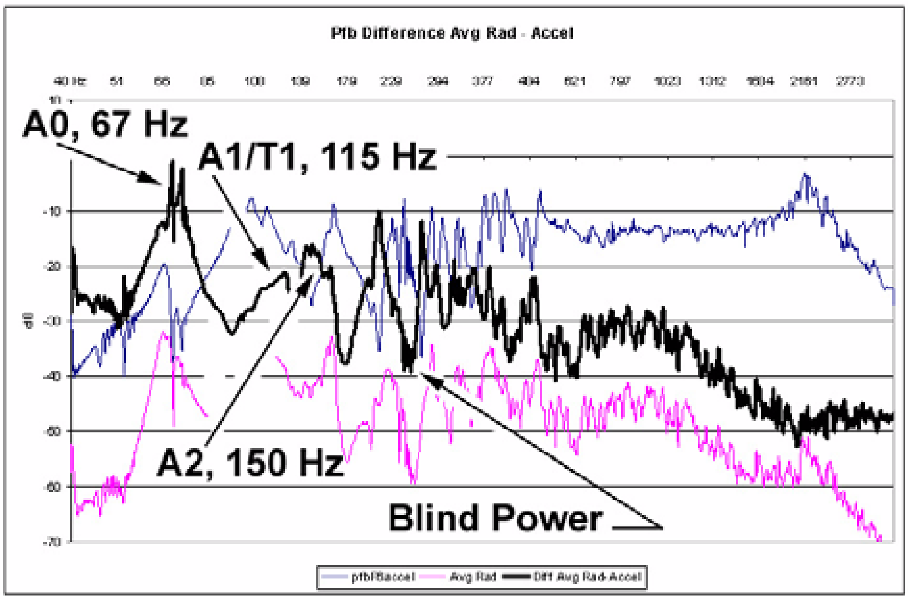


Fig. 6.6. Difference curve, radiation minus mobility, showing resonances of Pfb

ferences between the two models: the A0 mode at 67 Hz appears as expected in the radiation curve stronger than in the mobility curve. The T1/A1 mode appears at 115 Hz in both Pfb and Prb, as its frequency is dependent on the body dimensions. The next appearance of an apparent air mode is the suspected A2 at 150 Hz in the flat-back and 158 Hz in the round-back. High mobility and low radiation is found in both basses at around 100 Hz, indicating blind power. Such values are also found in the flatback at 175 Hz and 250 Hz and in the roundback at 230 Hz.

6.3 Results of Laser Vibrometry Measurements

Modal shapes revealed by laser vibrometry show that basses with rounded backs behave somewhat like large violins, while the braces in flatbacks cause modal shapes that are like a viol. The flat-backed instruments often share top plate modes with the roundbacks, but the back plates show completely different operational deflection patterns throughout the entire frequency range of 80 Hz to 2000 Hz. Combined methods indicate that the broad band, asymmetrical mode of the roundback from 125 Hz to 160 Hz is a major contributor to the smoother response curve in that band.

The resonances of the individual braces in the flat-backed bass can be easily isolated with the laser vibrometer and confirmed by impulse response tests on the back. An averaged RMS over the entire bandwidth shows that the flat back tends to vibrate symmetrically along the vertical axis, divided into sections by the braces, while the rounded back shows asymmetrical patterns along the length of the back. Correlating this asymmetrical pattern with radiation response curves suggests that the round-backed model radiates more efficiently.

6.3.1 Documentation of Modal Patterns

Given the large amount of literature on the modal behavior of the violin, it was entertaining to discover many of the same patterns in the round-backed double bass and sometimes in the flat model. Due to technical difficulties, the laser measurements under 80 Hz are only of limited value, so the first corpus bending modes and tailpiece resonances that should be found around 50 Hz (Bissinger, 2001, 115) could not be observed by this method. Also the A0 mode, which was determined at 67 Hz (by combined radiation response and input admittance measurements) falls into this range and is not well visible.

The T1/A1 mode is very clear at 115 Hz in both basses, corresponding to the response curves of this study and illustrations from related literature. It is however remarkable that the top plate in both models vibrates as the violin does, but that the back plates vibrate completely differently: the rounded back seems to behave as a large violin while the flat back with braces behaves like a viol (Fig. 6.8).

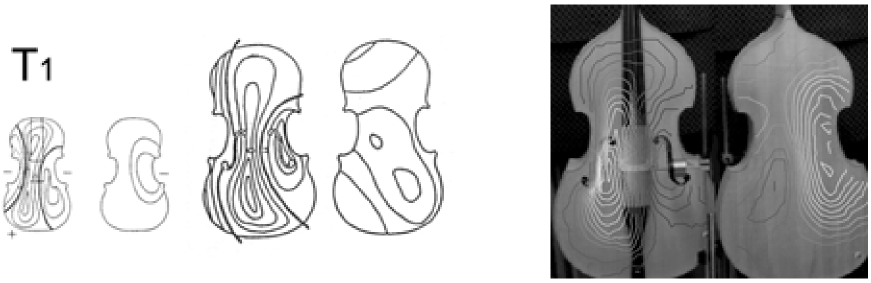


Fig. 6.7. The T1, or main top plate resonance: violin 460 Hz (Moral and Jansson, 1982), violoncello 219 Hz (Bynum and Rossing, 1997) and Prb 110 Hz

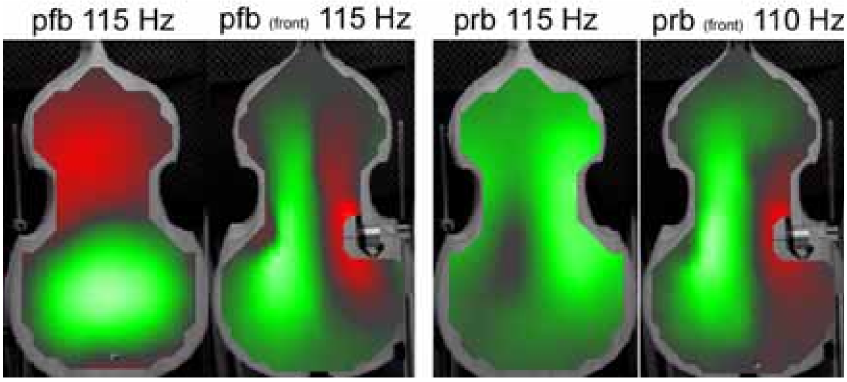


Fig. 6.8. Pfb (back and front, at left) and Prb (back and front, at right) at the T1/ A1 resonance

Another example is the suspected C3 in Prb at 155 Hz, which occurs clearly in the round-backed model but not the flatback (see Fig. 6.9 on page 83). The round-backed model compares favorably to the literature on violin instruments (Bynum and Rossing, 1997, 320), the flatback does indeed resemble Ågren's "magnum" treble viol at 512 Hz (see Fig. 2.4 on page 27). The bass top plates do not compare at this frequency.

Exact correlation to modal shapes in violins (Moral and Jansson, 1982) has been found for A0, A1 (T1), C4 (130 Hz in Prb). The ratio of mode frequencies (vln/bass) ranges from 2.7–5.4. The ring mode in the back of Prb is found in various forms all the way from 125 Hz to 175 Hz, where a dipole plate eigenmode begins. The ratios are much closer between the cello and bass, ranging from 1.2–2 (see Table 6.1 on page 83).

Patterns of the backs in the test basses remain different to varying degrees throughout the measured range of 80 Hz–2 kHz. The ring pattern in the rounded back is present at a lower frequency (125 Hz) relative to the violin (650–700 Hz) on account of the bass plate's relative thinness, and re-

Fig. 6.9. Comparison of C3 mode, 219 Hz (Bynum and Rossing, 1997) and Prb, 155 Hz.

Table 6.1. Ratios of modes in violins, cellos and Pfb and Prb

Mode	Violin/Hz	Cello/Hz	Bass/Hz	Ratio Vln/ Bass	Ratio Vcl/ Bass
A0	275	102	65	4.2	1.5
T1	460	203	115	4	1.7
C2	405	170	145 (Pfb)	2.7	1.2
C3	530	219	155	3.4	1.4
C4	700	195	130 (Prb)	5.4	1.5
A2	816	302	150	5.4	2

mains dominant in a broad band reaching to 160 Hz. The flat back, in contrast, goes through a rapid transition between deflection patterns within narrow bandwidths (see Fig. 6.10 on page 84). The pattern of the flat back at 145 Hz is also characteristic of flat back plates, and was found at 190 Hz in the back of the flat-backed cello, Fbc. This motion, “C-Bout vertical translation”, is known to have high mobility but low radiation efficiency (Bissinger, 2001, 115).

The figure below shows the RMS average of the total deflection for the laser measurements of the back plates (see Fig. 6.11 on page 84). An RMS average of both backs over the entire measured bandwidth shows that the flat back plate generally vibrates symmetrically along the vertical axis, divided into sections by the braces, while the rounded back shows asymmetrical patterns along the length of the back, divided vertically from upper block to lower block.

Correlating this asymmetrical pattern of the round back plate with radiation response data shows that it is a major contributor to the smoother ra-

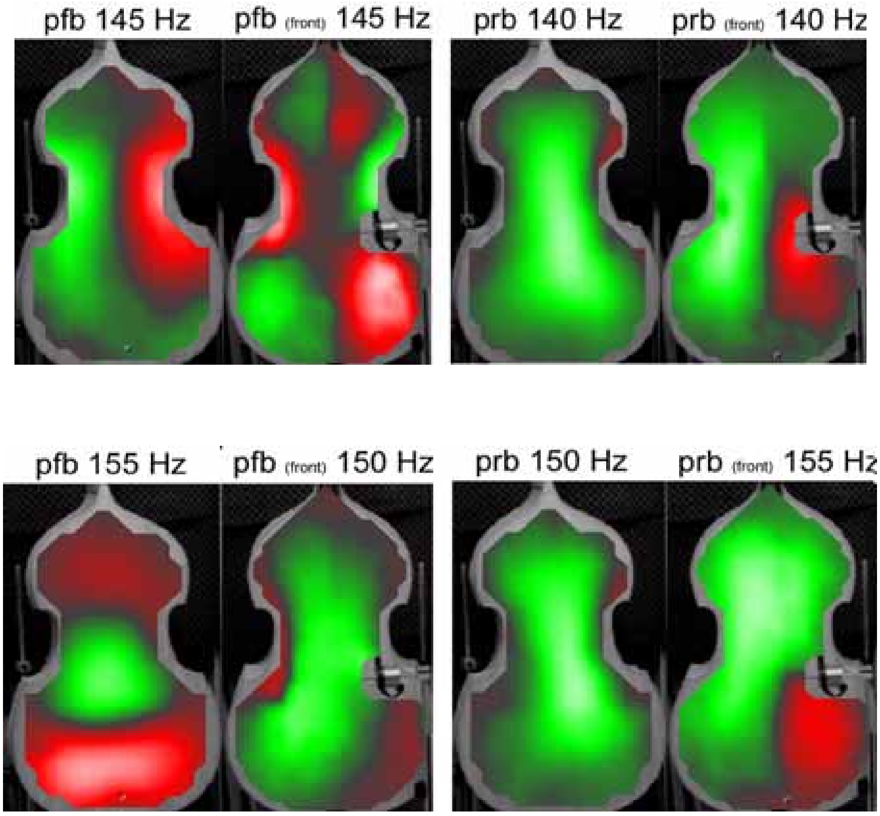


Fig. 6.10. Laser vibrometer analysis of Pfb (left) and Prb at 145 Hz and at 155 Hz

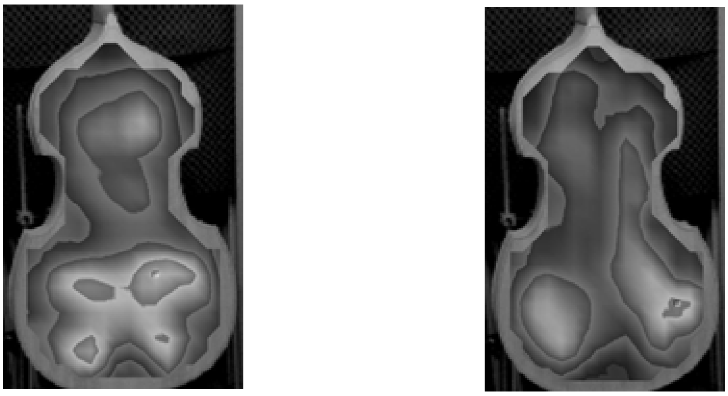


Fig. 6.11. Averaged RMS over the entire bandwidth of 5 Hz–2 kHz, back plates of Pfb (l.) and Prb (r.)

diated response curve from 115-160 Hz. It also suggests that the arched back plate causes the instrument to radiate more efficiently and as a 0-order radiator (in the bridge plane) in this band. The flatback's rapid transition within narrow bandwidths between deflection patterns is the probable cause of its more directed radiation. This may be caused by narrow-bandwidth modes that radiate poorly, for example at 150 Hz, and by cancellations from the symmetrical deflection areas, for example at 300 Hz.

As frequency increases, patterns develop in the flat back plate which are obviously related to the resonances of particular braces. Therefore, the influence of the braces was more closely investigated.

6.3.2 Resonances of the Individual Braces

Eigenfrequencies of the individual braces can be identified by impulse response tests directly on the back plate. The B&K accelerometer 4347

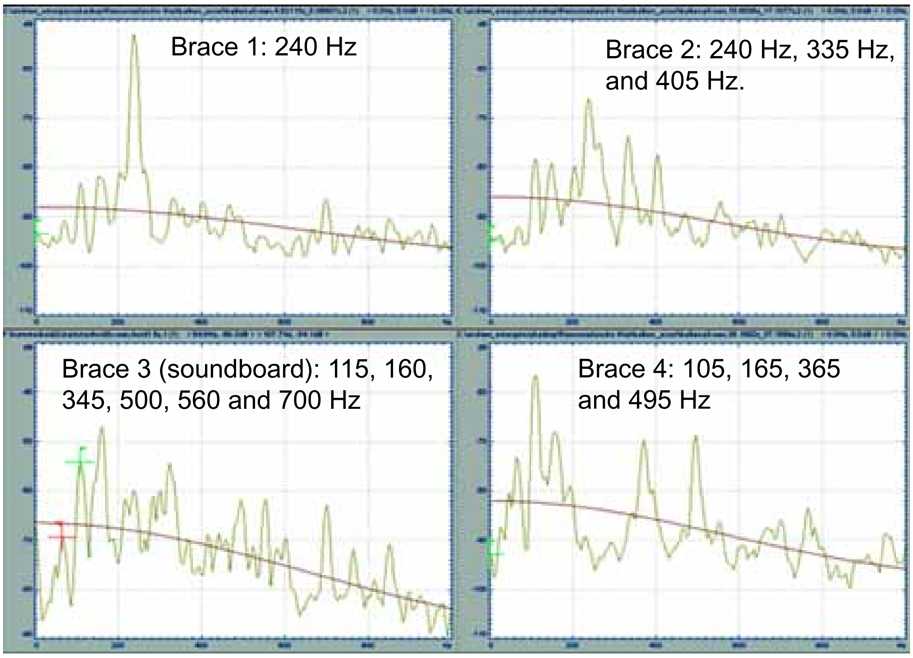


Fig. 6.12. FFTs of impulse response measurements at the position of the braces on Pfb

was mounted with bee's wax on the outside of the back plate in the center of the brace position, an impulse from a hammer was made at the bridge, and a FFT spectral analysis was performed over 1 s of the response, yielding the resonant frequency of the brace area.

Brace 1 has the highest, narrowest peak and is quite isolated, while the other braces have more complex and inter-related vibration modes. The accelerometer FFT of Brace 1 shows a narrow band peak very near 240 Hz

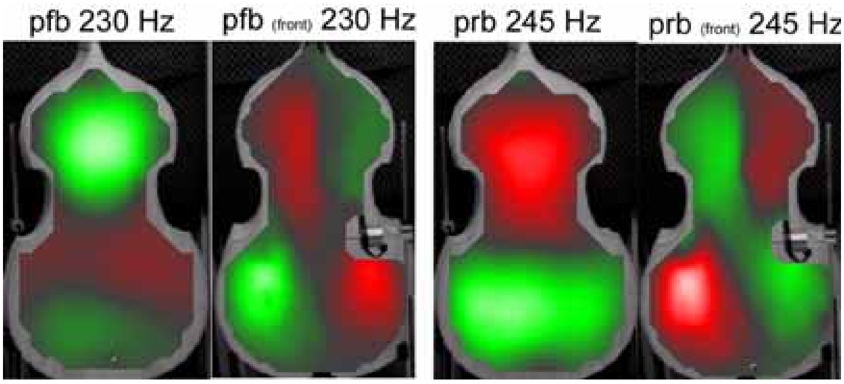


Fig. 6.13. Pfb and Prb at 230 Hz. The back plate of Pfb is dominated by the resonance of Brace 1. The top plates vibrate similarly.

(237 Hz) (see Fig. 6.12 on page 85). Its maximum towers 30 dB above the surrounding frequencies. Consequently the “knocking tone” of Brace 1 is very clearly a B natural, if a bit flat at 240 Hz. This same resonance is visible in the vibrometer analysis of the same area. This particular peak is primarily dependent on the properties of the wooden brace glued to the inside of the back. The frequency and the bandwidth of this peak can be rather easily manipulated by the maker: had the instrument maker decreased the thickness of this brace, the resonance frequency would decrease accordingly and its peak would be broader and lower.

The resonance of Brace 2 is dominated by the strong peak of Brace 1, but has eigenfrequencies at 335 Hz and 405 Hz. The largest and most important brace is Brace 3, or sound board, which supports the soundpost and has a significantly greater mass than the other braces. The resonances of Brace 3 are the most complex, and least easy to hear by knocking. The sound board is likely of primary importance in the coupling to the top plate through the soundpost, and consequently to the main radiation, and deserves special attention when being shaped and tuned by the instrument maker. Suggestions as to the characteristics of the sound board can be found in (Wall, 1985, 29), (Traeger, 1988, 14) and (Traeger, 1996, 44). Brace 4, being the longest and proportionally thinnest, has the lowest eigenfrequency at 85 Hz. Table 6.2 shows the brace eigenfrequencies and their mode patterns (see Table 6.2 on page 87). “Mode pattern” refers to the normal modes of bars described in Rossing and Fletcher (1998, 35). These patterns are easily visible with laser vibrometer analysis.

Table 6.2. Normal modes of brace areas of Pfb, based on impulse response and laser vibrometry measurements

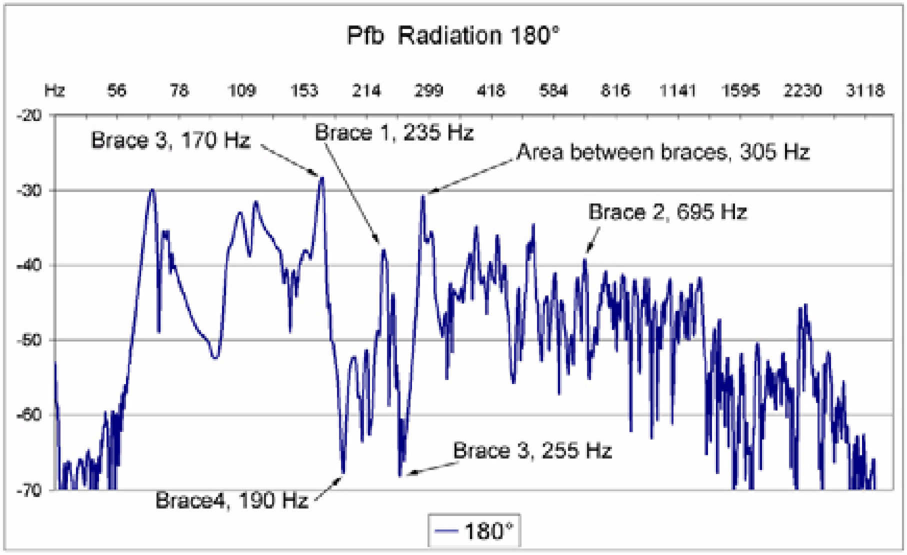
	Frequency in Hz	Mode Pattern
Brace 1	240	1
	385, 415, 445–465	2
Brace 2	275	1
	695	2
Brace 3 (Sound board)	115, 160–170, 235–255, 335	1
	465, 560, 700	2
	860	3
Brace 4	85, 110–130	1
	190, 210, 245, 695	2
	365	3
	520	4

6.3.3 The Braces' Influence on Radiation Response

Modal patterns of the brace areas found by laser vibrometer analysis were then compared to radiated response curves. The resonant frequencies of the brace areas of the back plate can either increase or diminish radiated sound energy to the front or the back. A comparison with the response curves shows some correlation (see Fig. 6.14 on page 88).

Laser vibrometry analysis also shows the importance of not only the bending properties of the braces but also the torsional properties. Brace 3 is at a node at 520 Hz between four antinode areas (see Fig. 6.15 on page 89). The torsional stiffness of the sound board at this area will influence the amplitude and bandwidth of this mode. A single, central brace after the French model (see Fig. 4.2 on page 52) would effectively eliminate this modal pattern, and a thinner, more narrow board would inculcate more amplitude and narrower peaks. A similar twisting mode is seen at Brace 3 at 700 Hz.

The influence of the eigenfrequencies of the individual braces makes it possible, and indeed necessary, for the instrument maker to vary the form and quality of the braces in a flat back plate to achieve a desired configuration of resonances. Higher, stiffer braces will yield narrower bandwidth peaks, isolating resonances and bringing out the "flatback" character in the response curve. Lower, flatter braces will have a broader bandwidth, spreading the brace eigenresonances over larger frequency bands and bringing a more "violin-like", smoother response curve.



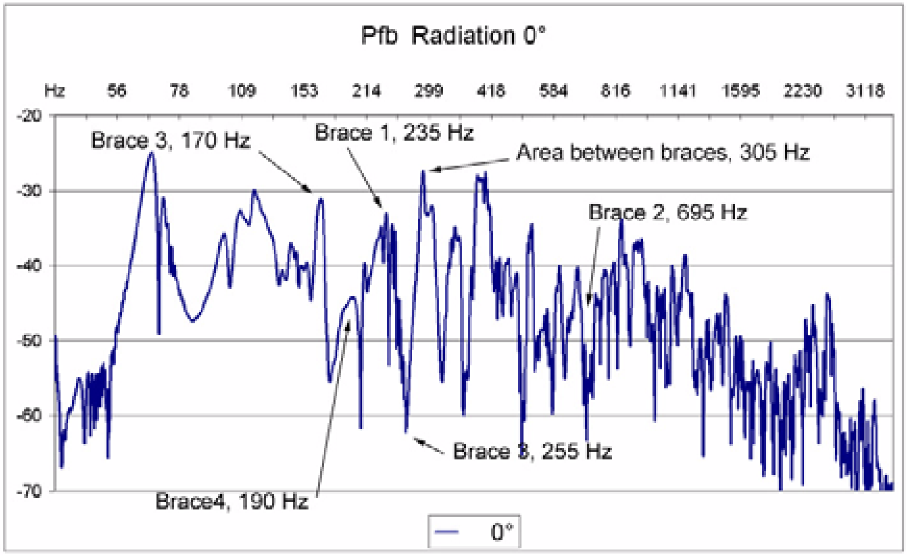


Fig. 6.14. Eigenfrequencies of braces and radiated response toward the back (above) and toward the front

6.3.4 Summary of Laser Vibrometry Analysis

The main result of laser tests indicates that basses with a rounded back show modal shapes like large violins, while the braces in flatbacks cause modal shapes that are like viols. The rounded backs are consequently characterized by a smoother response among lower and middle range modes and less symmetrical modal shapes. This is due to the placement of

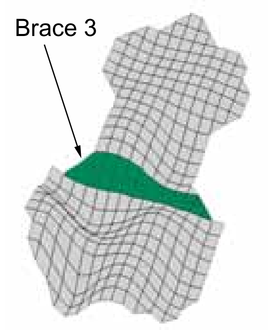


Fig. 6.15. Torsional motion of Brace 3 at 520 Hz

the soundpost directly on the back plate, which directly influences the radiated frequency response and directivity. Instrument makers can influence these factors by manipulating the parameters of the braces.

6.4 Results of Listening Tests

6.4.1 Results of Listening Test 1

Pfb and Prb were played behind a screen in a concert hall for an audience, and the played tones were recorded in the near field and the far field. The four live audience participants were asked to respond to two tasks: A) to state what kind of sound they expected from a flat-backed bass compared to a round back, and B) which instrument was played first in a series of pairs. The comments of the four listeners as to their expectations (Task A) are listed:

Listener one, a professional double bassist, wrote, "I would expect a bigger and rounded sound from the round-back instrument [and a] direct and sharper sound from the flatback." Listener two, a student of the double bass, wrote that he had "no pre-conceived ideas about this [question]." Listener three, an amateur bass-guitarist, described his expectation by drawing two diagrams like a Hi-Fi equalizer, describing the spectral response curve of the flatback with a stronger middle range and of the roundback with a stronger lower and upper register. Listener four, a semi-professional gambist, wrote that he expected the flatback to sound "softer" and more "gamba-like", with more overtones. The roundback was expected to "sound stronger", "perhaps more timbre differences possible," and "harder".

During the identification part of the test, all listeners had difficulty in answering the tasks of b) correctly. The professional bassist and bass student differentiated Pfb and Prb most accurately, but their score of 53.6% is very near the binomial probability of p=0.5. The bassists were only slightly better able to choose the flatback or roundback on account of their expectations of the sound. The gambist, listener 4, did the least well, scoring 42.9% correct. Because he expected the flat-backed bass to sound "softer" than the "harder" roundback, which goes against the observations of the majority of surveyed bassists who had an opinion (see 2.2.2), it is likely that the flatback does indeed sound "harder". In all, however, the main result is that no listener was easily able to tell the difference based on their pre-conceived ideas of what kind of sound to expect from either type. Because the sample population of the first test was so small, a more detailed statistical analysis was made of the responses Listening Test 2.

6.4.2 Results of Listening Test 2

The results of the second listening survey are based on the responses to 18 tasks from 51 different tests. The tasks were chosen according to example class (note value or musical sample), field (near or far field) and audio type (synthesized or real). The short audio files were then grouped in an ABA or ABB scheme and included the example classes E1 (42 Hz), C2 (65 Hz), D2 (73 Hz), A2 (110 Hz), F#3 (185 Hz) and a short musical excerpt from Wagner containing C2 and B1 (65 Hz and 61 Hz). For a list of the 18 examples please see Appendix 9.4 on page 108. (Note the soundfile name code: E [example class, i.e. note] fb [flatback] rb [roundback] fb [flatback] FF [far field]).

Most of the participants were music students (33; 64%), followed by professionals (11; 21.5%), amateurs (7; 13.7%) and one non-musician (2%). Of the participants, there were 7 bassists (13.7%) and 44 non-bassists (86.2%). Data was analyzed by filtering with an Excel pivot chart, according to musician status or instrument status (see Fig. 6.16 on page 91). The diagram shows the percent correct for the groups examined. Among the music students, the bassists (80%) chose slightly more accurately than other musicians (78.2%), while among the professionals, the non-bassists (84.6%) chose more correctly than bassists (77.8%). Non-musicians differentiated the sounds least accurately (55.6%), showing a nearly random distribution. Still, the total average of 77.9% correctly matched ABA/ABB examples shows that there are indeed audible differences under test conditions between the two back types for the given sound examples.

From preliminary tests it was clear that the synthesized versions of near field and far field were more easily identifiable than the audio files of real instruments being played by a musician: 92.5% of the total responses were correct for synthesized tones. Professional bassists matched 100% of synthesized examples correctly, while non-musicians matched 83.3% correctly.

Much less easy to hear were the differences between actual played tones, with a total average of 70.6% correct. Professional non-bassists matched real tones most accurately with 77.8% correct, while professional bassists matched only 66.7% correctly. Bassist and non-bassist music students matched around 72% of the played examples correctly. The non-musician identified the least number correctly, 41.7%. The 3-dimensional diagram

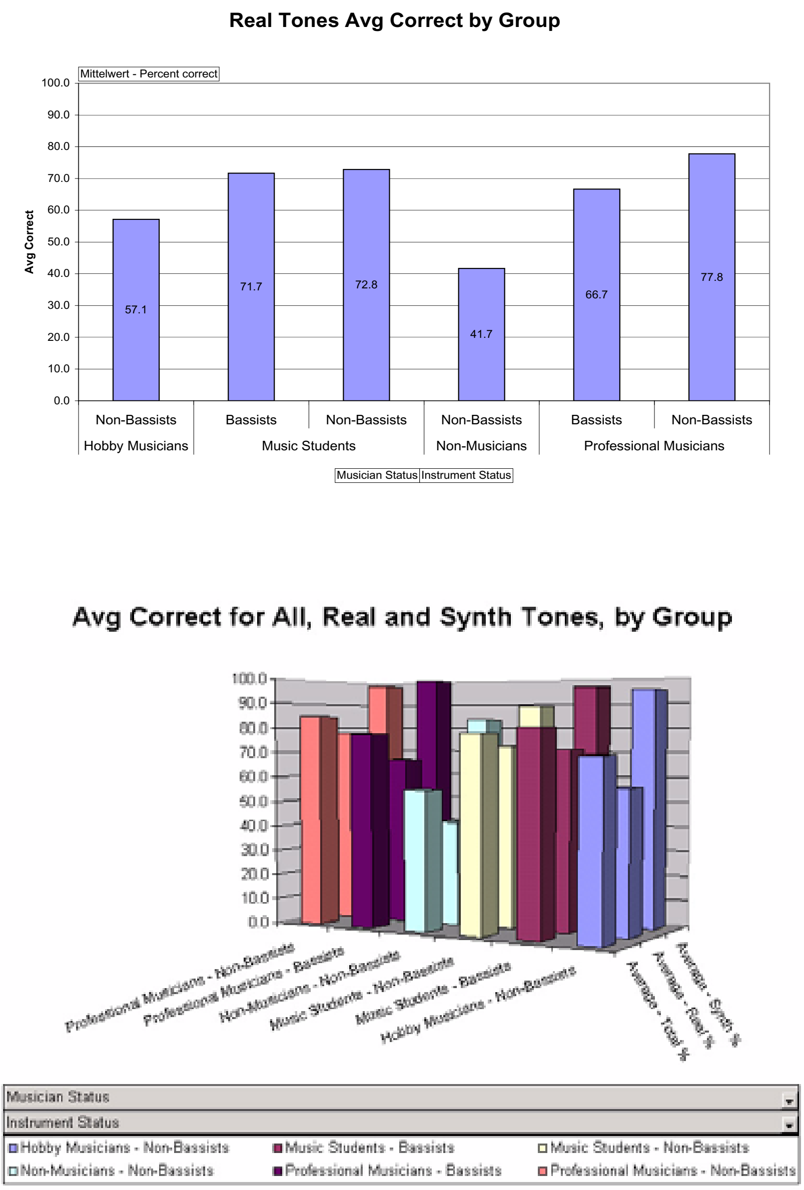


Fig. 6.16. Real Tones average correct (top), and a 3-D diagram of all groups and audio types (bottom).

shows the total results, synthesized tone and real tone results according to group.

A second analysis was made according to the correct responses per sound example to find out at which frequencies the two back types were easiest to differentiate. The examples were grouped by class, field and audio type. The results show that it was easier to distinguish timbre differences between the synthesized tones than for real recorded tones. As seen in the

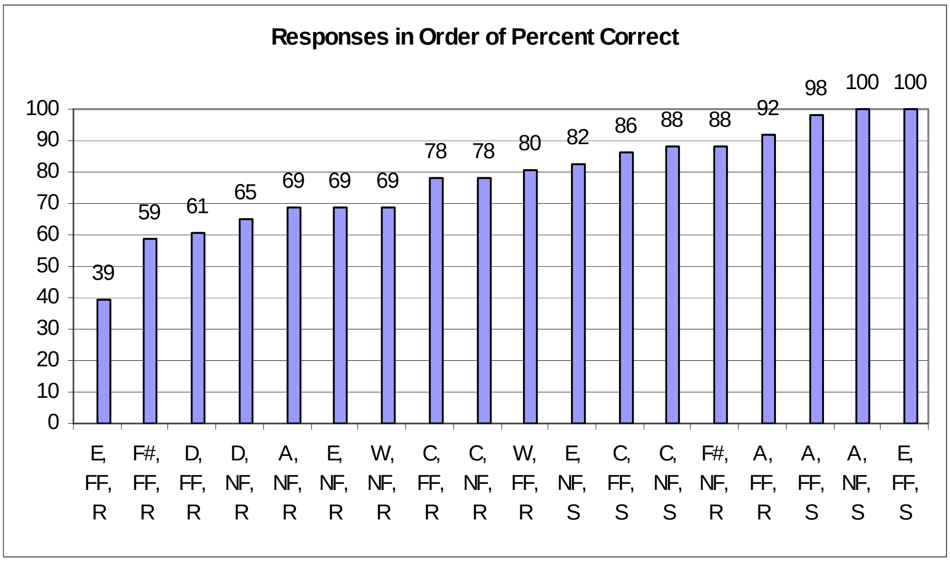


Fig. 6.17. Responses listed by percent correct

diagram of responses listed by percent correct, the 10 least distinguishable examples are recordings of played tones, and six of the eight most distinguishable are synthesized tones. In all, listeners distinguished real recordings correctly 71% of the time and synthesized versions 92% of the time. This would indicate that the influence of the player of the real tones can mask the intrinsic timbre of the back plate. The two instrument types have indeed differing spectral radiation when averaged, but this difference is controlled or masked by the player to a more audible degree than the acoustical limitations of the back types.

There is evidence that the far field and near field have an influence on the ability to differentiate, though a pattern is not discernible. Though the three least distinguishable examples are from the far field, the influence of the room acoustics seems to vary according to the specific tone played.

Somewhat more clear are the tendencies among the classes of examples, with E (54%) and D (63%) being among the differences most difficult to hear, and C (78%) and A (80%) being easier to hear. Still, anomalies do occur. Why should the played sample of the model types be correctly matched with the high F# (185 Hz) in the far field only 59% of the time, while the near field 88%? A look at the averaged spectrum of the live recordings shows that the near field of Prb contains a fundamental at about -9 dB, which towers over the second partial by more than 20 dB. The corresponding frequency for Pfb has an amplitude of -25 dB, and is only 10 dB stronger than its next neighboring peak. The overtones of the far field average are more balanced, with the first partial of Prb at -22 dB now only 15 dB stronger than the second partial, while the values for Pfb remain at -28 dB and -38 dB. In this case, the difference between the first and second partial of 20 dB with Prb should be clearly audible in the near field, and less so in the far field, which is reflected in the percentages of correct answers shown. In this case, the room acoustics levelled the spectrum.

Correlating this with the frequency response curves of Pfb and Prb indeed indicates that an audible difference should be expected here: the measured radiated response of Prb at 185 Hz shows an amplitude of -35 dB evenly towards the front and back. The same frequency for Pfb, however, is quite different: this bass radiated -48 db toward the front and only -64 dB toward the back in the anechoic chamber. The radiation of the flatback is directed in this range while the roundback radiates evenly and more strongly in all directions. The cause of this directivity has likely to do with the important resonances of Braces 3 & 4 at 160 Hz and 165 Hz.

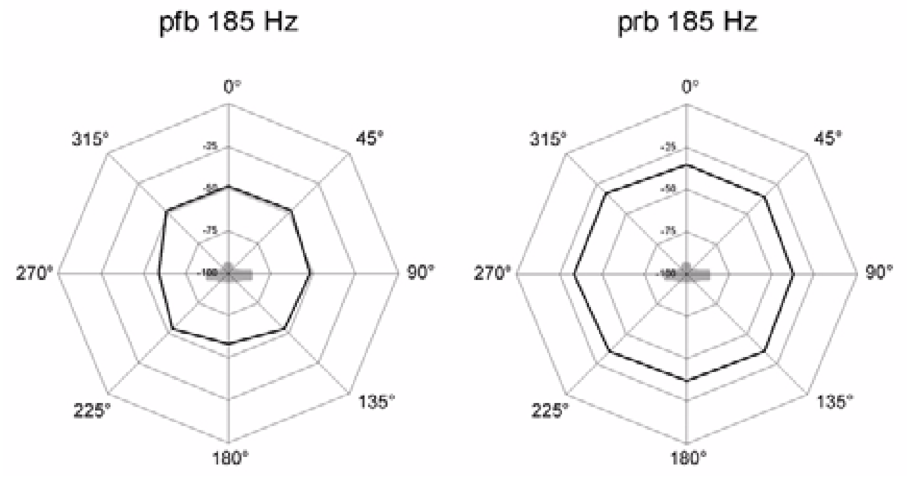


Fig. 6.18. Radiation level and directivity of Pfb and Prb at 185 Hz (F#3)

Given the probability of 0.5 for each binomial task, the total average of 71% for recordings of real basses and 92% for synthesized tones is proof that an audible difference between the two types can be heard under the test conditions. The discrepancy between the test results for real and synthesized tones suggests that the musician is a more significant factor in the produced tone color than the intrinsic acoustical characteristics of the back plate type. For more information on the informal listening tests that occurred throughout this study, please see Appendix 9.3.3 on page 109.

References

Ågren, C. -H. and K. A. Stetson (1972). Measuring the resonances of treble viol plates by hologram interferometry and designing an improved instrument. *J. Acoust. Soc. Am*. **51** (5), Pt. 2, 1971–1983.

Bissinger, G. (2001). Normal mode analysis of violin octet scaling. *Proceedings of the ISMA 2001*. 113–116.

Jansson, E. (2002). Acoustics for Violin and Guitar Makers (4th Ed.). Kungl. Tekniska Högskolan, Stockholm. Currently available at: http://www.speech.kth.se/music/acviguit4/part2.pdf

Meyer, J. (1995). "Akustik und musikalische Aufführungspraxis." 3rd ed. Erwin Bochinsky, Frankfurt/M.

Moral, J. A. and E. V. Jansson (1982). Eigenmodes, Input Admittance, and the Function of the Violin. *Acustica* **50** (5), 329–337.

Rossing, T. D. and N. H. Fletcher (1998). "The Physics of Musical Instruments." Springer, New York.

Saunders, F. A. (1937). The mechanical action of violins, *J. Acoust. Soc. Am.* **9**, 91–98.

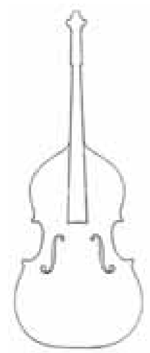
Traeger, C. (1988). Tuning flat backs, in *J. Catgut Acoust. Soc*. **3** (2) (Series 2), 40–44.

Traeger, C. (1996). The setup and repair of the bass violin for optimum sound. *J. Catgut Acoust. Soc*. **3** (2) (Series 2), 40–44.

Wall, E. (1985). Preliminary Studies of Flat-Backed Basses. *Catgut Acoust. Soc. Newsletter* **44**, 28–33.

Zopf, S. and A. Brown (2001). Input admittance measurements and their relationship to the sound characteristics of violins and violas. *Proceedings of the ISMA 2001*. 137–140.

7 Conclusions



It has been the goal of this work to document the measurable acoustical differences between flat-backed and round-backed double basses and to draw conclusions about the significance of these differences in practical situations. Two of the three hypotheses introduced in Chapter 1 were verified by this study: 1) there is a basic, measurable acoustic difference between the two back types, and 2) flat-backed basses have a characteristic radiation pattern that is distinct from rounded models. The third hypothesis, that these measurable differences are difficult to hear because of room-acoustical and psycho-acoustical factors, requires further work. While the listening tests prove that sound differences are audible for experienced listeners, the example of the F# at 185 Hz shows that room acoustics can significantly filter the overtone mix for players and listeners. Further, the intrinsic timbre qualities of the two types tested, represented by the synthesized examples, can be masked by the player. So, it remains to be exactly explained why it's possible for these acoustically distinct types of double bass to interchangeably fulfil the same musical role.

7.1 Summary of Chapters 1–5

Of the modern bowed instruments, the form of the double bass is the least standardized and can generally be divided into two types: that with a flat back plate and that with a round (arched or carved) back plate. Definitive historical and acoustical information on the two forms of double basses compared to one another was not found. Empirical observation of some instrument museums and of contemporary use led to the hypothesis that some sound difference between the two types must exist.

Surveys were made among instrument makers, dealers and musicians. This revealed that in spite of various and contradictory opinions, words like “punchy”, “direct” and “focused” are often used to describe the sound of a flat-backed bass, while “rounder”, “darker” or “fuller” more often describe a roundback. It is known that the flat back plate is prone to structural problems because of the inner braces. There is a scarcity of reliable literature on the acoustics of bass back plates, but Simpson’s treatise of 1665 and Ågren and Stetson’s work on the viol are of particular interest.

Researchers have been confronted with experimentally objectifying aspects of bowed musical instruments since the 19th Century, and have investigated the physical mechanics and acoustical radiation, primarily of violins, by experiment, simulation, or both. Simulation methods include the finite element method and experimental methods include radiated frequency response, near-field acoustical holography, input admittance, modal analysis and laser-optical methods. Combining methods has led to a more comprehensive understanding of the details of sound production by bowed instruments.

The construction of a double bass must satisfy structural and acoustical needs, which are manipulated by the form, workmanship and materials of the maker. There are a variety of materials and flat back forms used in practice. The double bassist is faced with special acoustical problems such as limited perception of far-field timbre and time delays.

Four main experimental methods were used in this study to test the acoustics of flat-backed and round-backed basses: frequency response curves, input admittance data, laser-optical observation of vibration patterns, and objective comparative listening tests.

7.2 Summary of Chapter 6 (Experimental Results)

The radiated frequency response curves show that flat-backed and round-backed instruments have differences in the order, amplitude and bandwidth of the their main resonances. All flat-backed stringed instruments measured, including six basses, the special flat backed violoncello, and a cello-sized viola da gamba, are characterized by narrow-band peaks and valleys in the response curve showing extreme amplitude differences within the range of middle body modes. The bridge-plane, near-field radiation directivity diagrams based on these response curves show that the round-backed basses Prb and Mrb have wide frequency bands in which they behave as 0-radiators, while the flatbacks Pfb and Mfb have directed radiation patterns at a variety of frequencies.

The admittance curves clearly show the characteristic “hilly” frequency response of flatbacks and the smoother response of roundbacks.

Laser vibrometry analysis yielded two main results: an extensive graphic documentation of modal patterns of flat-backed and round-backed basses from 80 to 2000 Hz, and in combination with audio data, the identification of back-related resonances and their effect on radiation of the entire instrument. Modal shapes show that basses with rounded backs behave somewhat like large violins, while the braces in flatbacks cause modal shapes that are like a viol. The flat-backed instruments often share top plate modes with the roundbacks, but the back plates show completely different operational deflection patterns throughout the entire measured frequency range of 80 Hz to 2000 Hz.

An averaged RMS over this range shows that the flat back plate tends to vibrate symmetrically along the vertical axis, divided into sections by the braces, while the rounded back shows asymmetrical patterns along the length of the back. Combined methods indicate that the broad band, asymmetrical mode of the roundback from 125 Hz to 160 Hz is a major contributor to the smoother response curve in that band.

The resonances of the individual braces in the flat-backed bass were identified with the laser vibrometer, confirmed by impulse response tests and then compared to radiated response curves. The resonant frequencies of the brace areas of the back plate can either increase or diminish radiated sound energy to the front or the back. The influence of the eigenfrequencies of the individual braces makes it possible, and indeed necessary, for the instrument maker to vary the form and quality of the braces in a flat back plate to achieve a desired configuration of resonances. Higher, stiffer braces will have isolated, narrower bandwidth resonances which bring out the "flat-back" character in the response curve. Lower, broader braces will spread the brace eigenresonances over wider bands, bringing a more "violin-like", smoother response curve.

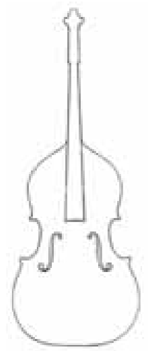
Results of a live, blind listening test show that audible differences between the two types do exist and indicate that the flat-backed model sounds "harder" than the "fuller" roundback. A second recorded listening survey in an ABX scheme included 18 synthesized and played tasks tested 51 times. The total average of 77.9% correctly matched ABA/ABB examples shows that there are significant audible differences between the two back types under the test conditions for the given sound examples. Synthesized versions of near field and far field were more easily identifiable than the audio files of real instruments being played by a musician, indicating that in spite of intrinsic timbre differences between the two types, the player significantly influences the resulting sound and can mask the influence of the back.

There is evidence that the location of the listener within the far field and near field has an influence on the ability to differentiate types, though a pattern is not discernible. The three least distinguishable examples are from the far field but the influence of the room acoustics seems to vary according to the specific tone played.

7.3 Conclusion

The most significant finding of this work is that, at least from the acoustical perspective, a double bass with a flat back is a substantially different instrument than one with a round back. This makes it all the more interesting that both types continue to be used interchangeably. As to the discussion of the contrabass stringed-instrument nomenclature (Brun, 2000, 43), one way of settling it would be to define basses with flat back plates as members of the viol family and those with round back plates as members of the violin family.

8 Bibliography



Abbas, E. (1989). Klangliche Eigenschaften des Kontrabasses. In: *Kölner Beiträge zur Musikforschung, Akustische Reihe Band 13*.Gustav Bosse Verlag Regensburg.

Ågren, C.-H. and K. A. Stetson (1972). Measuring the resonances of treble viol plates by hologram interferometry and designing an improved instrument. *J. Acoust. Soc. Am*., 51 (5), Pt. 2, 1971-1983.

Askenfelt, A. (1982). Eigenmodes and Tone Quality of the Double Bass, *Catgut Acoust. Soc. Newsletter*, No. 38.

Askenfelt, A. (1993). Über die akustische Eigenschaften von schwingenden Podium und Podeste Resonanzkörper für Celli und Kontrabässe? *Das Musikinstrument*, 6/7, Frankfurt/M, X 22-28.

Backhaus, H. (1929). Physikalische Untersuchungen an Streichinstrumenten. *Die Naturwissenschaften* **17** 811-18, 835-39.

Beldie, I. O. (1974). Vibration and sound radiation of the violin at low frequencies. *Catgut Acoust. Soc. Newsletter,* No. 22, 13-14.

Benade, A. (1990). "Fundamentals of Musical Acoustics." 2nd ed., Dover Publications, New York.

Birsak, K. & A. Birsak (1996). Gambe-Cello-Kontrabass. In *Jahresschrift des Carolino-Agusteum (Salzburger Museum für Kunst und Kulturgeschichte).*

Bissinger, G. and Hutchins, C.M. (1978) Tuning the bassbar on a violin plate. *Catgut Acoust. Soc. Newsletter,* No. 30, 23-27.

Bissinger, G. (1995). Modal Analysis, Radiation and the Violin's Soundpost. *Sound & Vibration*, **29** (8), 18-22.

Bissinger, G. (1995). Some mechanical and acoustical consequences of the violin soundpost. *J. Acoust. Soc. Am.,* **97** (5), 3154-3164.

Bissinger, G. (1996). Acoustical normal modes below 4 kHz for a rigid, closed violin-shaped cavity. *J. Acoust. Soc. Am.,* **100** (3), 1835-1840.

Bissinger, G. (2001). Normal mode analysis of violin octet scaling. *Proceedings of the ISMA 2001*. 113-116.

Bissinger, G. (2001). Radiation damping, efficiency, and directivity for violin normal modes below 4 kHz. (Submitted for publication).

Boyden, D.D., and A. M. Woodward, (1984). The Viola. In Sadie, S. (Ed.), *The New Grove Dictionary of Musical Instruments,* Macmillan Pub. Ltd. London, 753-759.

Boyden, D.D., B. Schwarz, P. Cooke, A. Dick, et al (1984). The Violin. In Sadie, S. (Ed.), *The New Groves Dictionary of Music and Musicians*, Macmillan Pub. Ltd. London, 765-804.

Brown, A. (1999). An Acoustical Study of Double Bass Bridge Height Adjusters (wissenschaftliche Hausarbeit), IWK, Univ. f. Musik u. darst. Kunst Wien.

Brown, A. and M. Bertsch (2004). The paradox of musical acoustics: objectivizing the essentially subjective. *Proceedings of the 1st Conference of Interdisciplinary Musicology (CIM04), Graz.*

Brown, C. (1994). "Discovering Bows for the Double Bass." Beaux Arts Editions, St. Paul.

Brun, P. (2000). A New History of the Double Bass. Paul Brun Productions, Villenuevre d' Ascq.

Campbell, M. and C. Greated (2001). "The Musician's Guide to Musical Acoustics." Oxford Univ. Press, Oxford.

Cervelli, L. (1994). "La Galleria Armonica: Catalogo del Museo degli strumenti musicali di Roma." Inst. Poligrafico e Zecca dello Stato, Roma.

Corrette, M. (1773). "Méthode pour apprendre à jouer de la contre-basse à 3., à 4. et à 5. cordes." Paris.

Cremer, L. (1984). "The Physics of the Violin." Translated by J.S. Allen, MIT Press, Cambridge, Massachussetts. "Physik der Geige." S. Hirzel Verlag, Stuttgart.

Detloff, J. A. (1985). Statistical relationships between acoustic parameters of violin tonewoods. *Catgut Acoust. Soc. Newsletter* **43**, 13-24.

Dossing, O. (1988). Structural Testing: Part 1: Mechanical and Mobility Measurements. Brüel & Kjaer, Naerum.

Dossing, O. (1988). Structural Testing: Part 2: Modal Analysis and Simulation. Brüel & Kjaer, Naerum.

Dünnwald, H. (1988). Ableitung objektiver Qualittsmerkmale aus Messungen an alten und neuen Violinen. In "Qualittsaspekte bei Musikinstrumenten," pp. 77-85. Meyer, J. (ed.), Moeck Velag, Celle.

Dünnwald, H. (1991). Deduction of objective quality parameters on old and new violins. In: Hutchins (ed.) "Research Papers in Violin Acoustics 1975-1993," 2 vols. Acoustical Society of America, Woodbury, New York, 59-64.

Elgar, R. (1967a). "Introduction to the Double Bass." St. Leonards on Sea.

Elgar, R. (1967b). "Looking at the Double Bass." St. Leonards on Sea.

Elgar, R. (1967c). "More about the Double Bass." St. Leonards on Sea.

Esposito, E. (2003). A comparative study of the vibro-acoustical behavior of electric guitars produced in different decades. *Proceedings of SMAC 03*, Stockholm, Sweden. 125-128.

N.N. (1999). French Connection: French Luthier Jean Auray. In *Double Bassist*, Nr. 10, Orpheus Publications, Harrow, Middlesex, 54-57.

Fricke, J. P. (1992). Die durch induktive Messung festgestellten Besonderheiten an Klavier- und Kontrabasssaitenschwingung, *Instrumentenbau* 2/3.

Fröhlich, J. (1829). “Kontrabass-Schule.” Würzburg.

Guettler, K. (2001). On the development of the Helmholtz motion in bowed strings. *Proceedings of the ICA Meeting 2001. Rome.*

Güth, W. (1989). “Physik im Geigenbau.” E. Kurz & Co. Stuttgart.

Haberl, F., W. Kausel and A. Meyer (1998). Eingangsadmittanzmessung an Streichinstrumenten. *Jahrestagung ’98 d. Fachausschusses f. Akustik d. Österr. Phys. Ges. gem. mit der Österr. Ges. f. Akustik* (AAA/ÖGA), Graz.

Hall, D. (1991). “Musical Acoustics,” 2nd ed. Brooks/Cole Pub. Co., Belmont, California.

Harwood, I. (1974). An Introduction to Renaissance Viols, in *Early Music*, Nr. 2, 234.

Helmholz, H. v. (1877). “On the Sensations of Tone,” 4th ed. Translated by A.J. Ellis, Dover, New York, 1954.

Hill, T. J. W., B. E. Richardson and S. J. Richardson (2001). Measurements of acoustical parameters for the classical guitar. *Proceedings of the ISMA 2001*. 417-420.

Hutchins, C. M. (editor) (1975). “Musical Acoustics, Part I. Violin Family Components.” Dowden, Hutchinson and Ross, Stroudsberg, Pennsylvania.

Hutchins, C. M. (editor) (1976). “Musical Acoustics, Part II. Violin Family Functions.” Dowden, Hutchinson and Ross, Stroudsberg, Pennsylvania.

Hutchins, C.M. (1981). The Acoustics of Violin Plates. In Hutchins, C. M. and V. Benade (Ed.), *Research Papers in Violin Acoustics 1975-1993, 2 vols*. Acoustical Society of America, Woodbury, New York. 413-424.

Hutchins, C.M. and V. Benade (editors) (1997). “Research Papers in Violin Acoustics 1975-1993,” 2 vols. Acoustical Society of America, Woodbury, New York.

Jansson, E. V., N. -E. Molin and H. Sundin (1970). Resonances of a violin studied by hologram interferometry and acoustical methods. *Phys. Scripta* **2**, 243-256.

Jansson, E. V. (1995). Admittance Measurements of 25 High Quality Violins. *Acustica*, **83**, 337-341.

Jansson, E.V., H.O. Saldner und N.E. Molin (1996). Vibration modes of the violin forced via the bridge and action of the soundpost. *J. Acoust. Soc. Am.*, **100** (2), 1168-1177.

Jansson, E. (2002). Acoustics for Violin and Guitar Makers (4th Ed.). Kungl Tekniska Högskolan, Stockholm. Currently available at: http://www.speech.kth.se/music/acviguit4/part2.pdf.

Kishi, K. and T. Osanai. (1991). Vibration analysis of the cello bridge by the finite element method. *J.Acous. Soc. Jap*. **47** (4).

Knott, G. A. (1987). A modal analysis of the violin using MSC/NASTRAN and PATRAN. In: Hutchins (ed.) “Research Papers in Violin Acoustics 1975-1993,” 2 vols. Acoustical Society of America, Woodbury, New York, 507-549.

Kondo, M. N. Hirano, M. Hirota, and H. Kubota. (1980). Principal directions of elasticity of a bridge on belly and holographic maps of the soundbox excited in those directions. *Proceedings of the 10th International Congress on Acoustics: Vol. III.*, Paper K7-3.

Marshall, K. D. (1985). Modal analysis of a violin. *J. Acoust. Soc. Am.*, **77** (2), 695-709.

McIntyre, W. E. and J. Woodhouse. On measuring wood properties, Part 1. *Catgut Acoust. Soc. Newsletter*, **42**.

McIntyre, W. E. and J. Woodhouse. On measuring wood properties, Part 2. *Catgut Acoust. Soc. Newsletter*, **43**, 18-24.

Meinel, H. (1937). Über die Beziehungen zwischen Holzdicke, Schwingungsform, Körperamplitude und Klang eines Geigenkörpers. *Elek. Nachr. Tech.*, **14** (4), 119-134.

Meyer, J. (1985).The musicians subjective impression of sound on the concert platform. *Catgut Acoust. Soc. Newsletter* **43**, 26-29.

Meyer, J. (1995). “Akustik und musikalische Aufführungspraxis,” 3rd ed. Erwin Bochinsky, Frankfurt/M.

Mikisaburo, O. (1984). “Antonio Stradivari in Japan.” Gakken, Tokyo, pp.135, 178.

Minnaert, M. and Vlam, C.C. (1937). The vibrations of the violin bridge. *Physica* 4, 361-372.

Möckel, Otto. (1930). “Die Kunst des Geigenbaus, Zweite neubearbeitete und ergänzte Auflage von Fritz Winckel.” (1954). Bernh. Friedr. Voigt, Berlin.

Molin, N.-E. and A. O. Wählin (1990) Transient wave response of the violin body. *J. Acoust. Soc. Am.*, **88**, 2479-2481.

Moral, J.A. and E.V. Jansson (1982). Eigenmodes, Input Admittance, and the Function of the Violin. *Acustica* **50** (5), 329-337.

Morset, L. H., A. Krokstad and O. J. Lokberg (1998). A Computer-based Method for Quality Control of Violins using Impulse Excitation. *Proceedings of the ISMA 1998*. 23-28.

N.N. (1999). French Connection: French Luthier Jean Auray. In *Double Bassist*, Nr. 10, Orpheus Publications, Harrow, Middlesex, 54-57.

Planyavsky, A. (1984). “Geschichte des Kontrabasses,” 2nd ed. Hans Schneider, Tutzing.

Raman, C. V. (1918). On the mechanical theory of the vibrations of bowed strings and of musical instruments of the violin family, with experimental verification of the results. Bull. 15, The Indian Association for the Cultivation of Science.

Roederer, J. G. (1973). “Physiologische und psychologische Grundlagen der Musik.” Springer-Verlag, New York.

Rosenblum, M. (1984). The Viola d'amore. In Sadie, S. (Ed.), *The New Grove Dictionary of Musical Instruments*, Macmillan Pub. Ltd. London, pp. 760-763.

Rosengard, D. (1992). "Cremonese Double Basses." Ed. Turris, Cremona.

Rossing, T. D. and N. H. Fletcher (1998). "The Physics of Musical Instruments." Springer, New York.

Rossing, T. D. (2001). Musical Acoustics in the 2nd and 3rd Millennia. *Proceedings of the ISMA 2001*. 7-26.

Rudert, G. (1991). Violone Kontrabass: Eine Gegenberstellung zweier 16-Fuß-Streichinstrumenten. (wissenschaftliche Hausarbeit), IWK, Univ. f. Musik u. darst. Kunst Wien.

Sacconi, S. F. und J. von Stietencron (1997). "Die Geheimnisse Stradivaris." Erwin Bochisky, Frankfurt am Main.

Sadie, J. A. (1984). The Baryton. In Sadie, S. (Ed.), *The New Grove Dictionary of Musical Instruments*, Macmillan Pub. Ltd. London, pp. 163–166.

Saunders, F. A. (1937). The mechanical action of violins, *J. Acoust. Soc. Am.,* **9**, 91-98.

Saunders, F. A. (1945). The mechanical action of instruments of the violin family. *J. Acoust. Soc. Am.,* **17**, 169-186.

Savart, F. (1840). "Des instruments de musique." Translated by D.A. Fletcher, in Hutchins (1976), 15-18.

Schelling, J.C. (1963). The violin as a circuit. *J. Acoust. Soc. Am.,* **35**, 326-338.

Schleske, M. (1992a). Modalanalyse im Geigenbau - Vom praktischen Nutzen physikalischer Forschung im Musikinstrumentebau. Teil I: Grundlagen. *Das Musik Instrument*, **41,** 2/3, 98-106.

Schleske, M. (1992b). Modalanalyse im Geigenbau. Teil II: Zur grundsätzlichen Funktion der Geige. Wie schwingt der Geigenkorpus? *Das Musik Instrument*, **41,** 6, 10-14.

Schleske, M. (1992c). Modalanalyse im Geigenbau. Teil III: Praktische Konsequenzen. *Das Musik Instrument*, **41,** 7, 58-61.

Schleske, M. (2001). Empirical Tools in Contemporary Violin Making: Part I. Analysis of Design, Materials, Varnish, and Normal Modes. *J. Catgut Acoust. Soc*. **4** (5) (Series 2), 50-64.

Schleske, M. (2002). Empirical Tools in Contemporary Violin Making: Part II. Psychoacoustic Analysis and Use of Acoustical Tools. *J. Catgut Acoust. Soc*. **4** (6) (Series 2), 43-61.

Simpson, Christopher (1965). "The Division-Viol." (Facsimile of the original, 1665), J. Curwen & Sons, London, 1-2.

Slatford, R. (1984). The Double Bass. In Sadie, S. (Ed.), *The New Grove Dictionary of Musical Instruments,* Macmillan Pub. Ltd. London.

Sundberg, J. (1989). The Science of Musical Sound, 3rd ed. English translation by Acedemic Press, San Diego (2001).

Terhardt, E. (1972). “Zur Tonhöhenwahrnemung von Klängen, Teil 1 & 2.” *Acustica*, **26** (4), 173-199.

Terhardt, E., G. Stoll and M. Seewann (1982). Pitch of complex signals according to virtual-pitch theory: Tests, examples and predictions. *J. Acoust. Soc. Am.*, **71** (3), 671-688.

Traeger, C. (1988). Tuning flat backs, in *J. Catgut Acoust. Soc*. **3** (2) (Series 2), 40-44.

Traeger, C. (1996). The setup and repair of the bass violin for optimum sound. *J. Catgut Acoust. Soc*. **3** (2) (Series 2), 40-44.

Tro, J., O. Kr. Petterson und U. K. Kristiansen (1983). Sound radiation from a double bass visualized by intensity vectors., *Catgut Acoust. Soc. Newsletter*, **40**, 7-9.

Veit, I. (1996). “Technische Akustik: Grundlagen der physikalischen, physiologischen und Elekroakustik.” 5. Auflage. Vogel-Buchverlag, Würzburg.

Wall, E. (1985). Preliminary Studies of Flat-Backed Basses, in *Catgut Acoust. Soc. Newsletter* **44**, 28-33.

Wang, L. M (1999). Radiation Mechanisms from Bowed Violins. Doctoral dissertation, Penn. State U.

Wang, L. M., and C. B. Burroughs (2001). Acoustic radiation from bowed violins. *J. Acoust. Soc. Am.*, **110** (1): 543-555.

Warneke, F. (1909). “Ad infinitum: Der Kontrabass.” Im Verlage des Verfassers, Hamburg.

White, A. C. (1893/1934). “The Double Bass.” London.

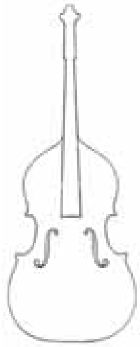
Woodfield, I. (1984). “The Early History of the Viol.” University Press, Cambridge.

Woodfield, I. und L. Robinson, (1984). The Viol. In Sadie, S. (Ed.), *The New Grove Dictionary of Musical Instruments*, Macmillan Pub. Ltd. London, 736-753.

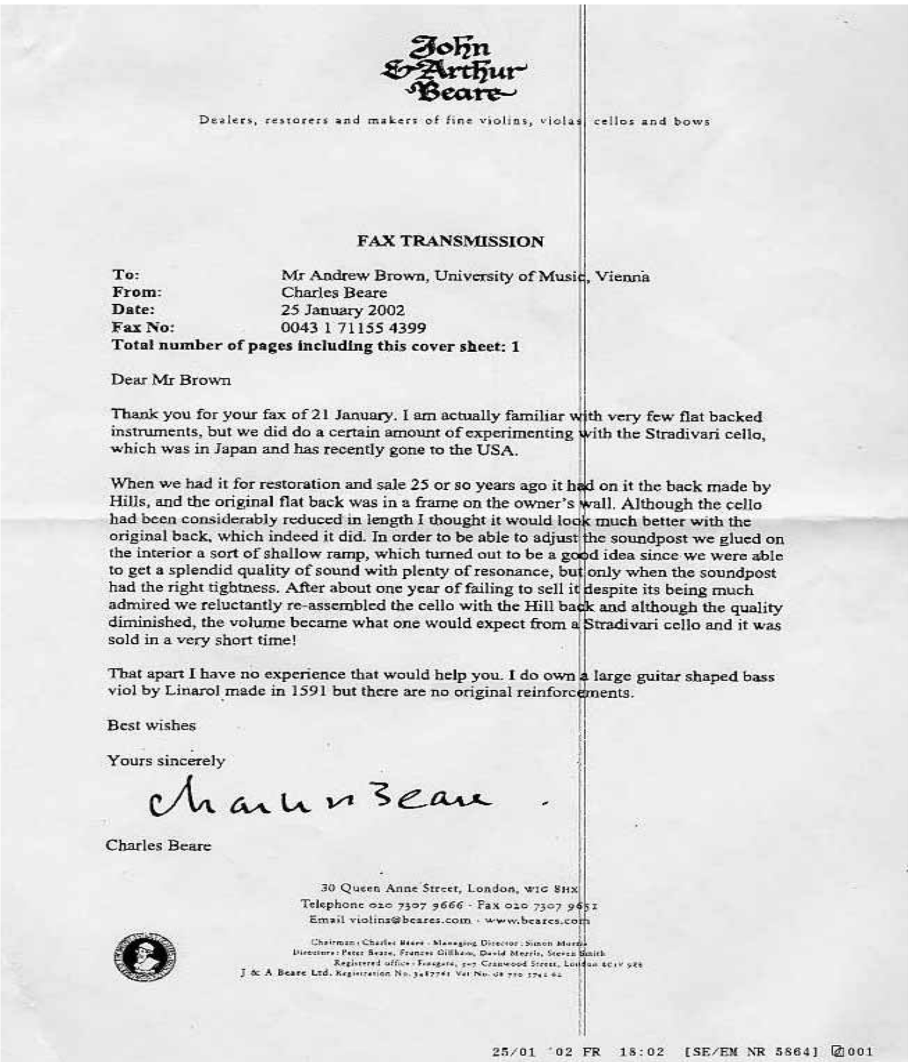
Zipser, L. and H. Franke (2003). Refractoscopic visualization of sound in musical instruments. *Proceedings of SMAC 03*, Stockholm, Sweden. 763-766.

Zopf, S. and A. Brown (2001). Input admittance measurements and their relationship to the sound characteristics of violins and violas. *Proceedings of the ISMA 2001*. 137-140.

9 Appendix



9.1 Letter from Charles Beare



John & Arthur Beare

Dealers, restorers and makers of fine violins, violas, cellos and bows

FAX TRANSMISSION

To: Mr Andrew Brown, University of Music, Vienna
From: Charles Beare
Date: 25 January 2002
Fax No: 0043 1 71155 4399
Total number of pages including this cover sheet: 1

Dear Mr Brown

Thank you for your fax of 21 January. I am actually familiar with very few flat backed instruments, but we did do a certain amount of experimenting with the Stradivari cello, which was in Japan and has recently gone to the USA.

When we had it for restoration and sale 25 or so years ago it had on it the back made by Hills, and the original flat back was in a frame on the owner's wall. Although the cello had been considerably reduced in length I thought it would look much better with the original back, which indeed it did. In order to be able to adjust the soundpost we glued on the interior a sort of shallow ramp, which turned out to be a good idea since we were able to get a splendid quality of sound with plenty of resonance, but only when the soundpost had the right tightness. After about one year of failing to sell it despite its being much admired we reluctantly re-assembled the cello with the Hill back and although the quality diminished, the volume became what one would expect from a Stradivari cello and it was sold in a very short time!

That apart I have no experience that would help you. I do own a large guitar shaped bass viol by Linarol made in 1591 but there are no original reinforcements.

Best wishes

Yours sincerely

Charles Beare

Charles Beare

30 Queen Anne Street, London, W1G 8HX
Telephone 020 7307 9666 · Fax 020 7307 9651
Email violins@beares.com · www.beares.com

Chairman: Charles Beare · Managing Director: Simon Morris
Directors: Peter Beare, Frances Gillham, David Morris, Steven Smith
Registered office: Fengate, 5-7 Cranwood Street, London EC1V 9EE
J & A Beare Ltd.

25/01 '02 FR 18:02 [SE/EM NR 5864] 001

Fig. 9.1. Letter (Fax) concerning the history and sound of a flat-backed cello by Antonio Stradivari, 25 January, 2002

9.2 Frequency Response Set-up Details

The following (overly) detailed procedure for frequency response measurements is included for future reference:

The technical equipment is adjusted and prepared: the sweep signal from a wav. File is called up; the Duke's preamp is turned on, with channels 1-5 set to +30 dB. The sixth channel for the accelerometer signal is set to +0 dB. The ADAT eight track digital recorder is turned on and a SuperVHS cassette with a sampling rate of 44,100 Hz (or 48,000) is inserted, and the recording button engaged. The B&K "Flasche" is set for the reference signal. The Uher amp is set to "6".

The settings of the bridge and soundpost on the instrument are checked. The strings are dampened by three pieces of foam rubber mounted between the strings and fingerboard. The endpin is removed and the instrument is mounted on the artificial endpin of the stone plate. The position of the microphones is checked in the height and distance to the instrument. The accelerometer is mounted with natural beeswax on the bass side of the bridge next to the driving point. The shaker is then brought to the correct height and the needle is positioned with the correct tension approximately 4 mm from the forward edge of the bridge. A test run will be made to check for overdriving the sixth channel during the sweep. The door of the anechoic chamber is closed. The start position on the audiotape is logged in the recording protocol. The recording is completed, most ordinarily with a second back-up run. The door is then opened again, the instrument rotated 180°, and the process repeated. After the successful capture of the data onto audiotape, the channels are recorded in pairs onto the hard disk for storage and later analysis. The data are then ready for analysis with S_Tools and other analysis software.

9.3 Listening Test Materials

9.3.1 Listening Test 1

Hörtest 03.05.03 *Listening Test 03 May, 2003*

A) Erwartungen / *Expectations*: Was für einen Klang erwarten Sie von einem Instrument mit einem flachen Boden im Vergleich mit einem gewölbten Boden?
What kind of sound would you expect from an instrument with a flat back compared to one with a round back?

B) Jetzt werden die zwei Testinstrumente immer eins nach dem anderen gespielt. Manchmal können die Instrumente in einer anderen Reihenfolge gespielt werden. Von Ihren Erwartungen ausgehend, bitte versuchen Sie die Instrumente in den betreffenden Spalten einzuordnen.
Now, each of the two test instruments will be played one after the other. The order in which the instruments are played may be changed. Based on your expectations, please try to order each instrument in the appropriate rows.

Beispiel / *Example Nr.*	Flach / *Flat*	Gewölbt/ *Round*	Kommentar / *Comment*
1.			
2.			
3.			
4.			
5.			
6.			
7.			
8.			
9.			
10.			
11.			
12.			
13.			
14.			
15.			
16.			
17.			
18.			
19.			
20.			
21.			
22.			
23.			
24.			
25.			
26.			
27.			
28.			

Fig. 9.2. Listening Test 1 Questionnaire

9.3.2 Listening Test 2

Name oder Psysdonym: ____________________ *Datum:* ____/____ 2003

Bitte um Ihre Angaben:

□ Ich bin keine MusikerIn □ Ich bin Hobby-MusikerIn □ Ich bin MusikstudentIn □ Ich bin Profi-MusikerIn.

Ich spiele folgendes Instrument: □ Kontrabass, oder □ ein anderes Instrument.

□ Das ist mein erster Durchlauf dieses Tests

□ Das ist mein _______ ter Durchlauf dieses Tests.

Sie hören jetzt je Ziffer drei kurze Audioausschnitte. Zwei davon stammen vom gleichen Instrument. Entweder der erste Ausschnitt ODER der zweite Ausschnitt stammt vom gleichen Instrument wie der dritte Ausschnitt. Bitte beurteilen Sie ob der erste Ausschnitt *a* oder der zweite Ausschnitt *b* mit dem Instrument des dritten Ausschnitts zusammenpasst.

Beispiele kommen mit einem Abstand von 5 Sekunden. Wiederholung von einzelnen Beispielen ist nicht möglich. Dafür sind mehrere Durchgänge des Tests erwünscht. Es folgt nun ein Probebeispiel:

Probe:	□ a b a	□ a b b

„Richtige" Antwort: □ a b a

1.	□ a b a	□ a b b
2.	□ a b a	□ a b b
3.	□ a b a	□ a b b
4.	□ a b a	□ a b b
5.	□ a b a	□ a b b
6.	□ a b a	□ a b b
7.	□ a b a	□ a b b
8.	□ a b a	□ a b b
9.	□ a b a	□ a b b
10.	□ a b a	□ a b b
11.	□ a b a	□ a b b
12.	□ a b a	□ a b b
13.	□ a b a	□ a b b
14.	□ a b a	□ a b b
15.	□ a b a	□ a b b
16.	□ a b a	□ a b b
17.	□ a b a	□ a b b
18.	□ a b a	□ a b b

Danke für Ihre Interesse und Hilfe!

Fig. 9.3. Listening Test 2 Questionnaire

Listening Test Key 12.12.03

Track 01: Length: 00:04.00, Pause frames: 150, Filters: 1, Name: 'EfbrbrbNFsynth.WAV'.
Track 02: Length: 00:04.00, Pause frames: 150, Filters: 1, Name: 'ErbfbrbFFsynth.WAV'.
Track 03: Length: 00:09.15, Pause frames: 150, Filters: 1, Name: 'EfbrbfbNF.WAV'.
Track 04: Length: 00:08.46, Pause frames: 150, Filters: 1, Name: 'EfbrbfbFF.WAV'.
Track 05: Length: 00:04.00, Pause frames: 150, Filters: 1, Name: 'CfbrbrbNFsynth.WAV'.
Track 06: Length: 00:04.00, Pause frames: 150, Filters: 1, Name: 'CrbfbrbFFsynth.WAV'.
Track 07: Length: 00:09.24, Pause frames: 150, Filters: 1, Name: 'CrbfbfbNF.WAV'.
Track 08: Length: 00:08.73, Pause frames: 150, Filters: 1, Name: 'CrbfbrbFF.WAV'.
Track 09: Length: 00:07.14, Pause frames: 150, Filters: 1, Name: 'DfbrbrbNF.WAV'.
Track 10: Length: 00:07.14, Pause frames: 150, Filters: 1, Name: 'DfbrbrbFF.WAV'.
Track 11: Length: 00:04.00, Pause frames: 150, Filters: 1, Name: 'AfbrbfbNFsynth.WAV'.
Track 12: Length: 00:04.00, Pause frames: 150, Filters: 1, Name: 'ArbfbrbFFsynth.WAV'.
Track 13: Length: 00:06.31, Pause frames: 150, Filters: 1, Name: 'ArbfbrbNF.WAV'.
Track 14: Length: 00:07.05, Pause frames: 150, Filters: 1, Name: 'AfbrbfbFF.WAV'.
Track 15: Length: 00:07.49, Pause frames: 150, Filters: 1, Name: 'WrbfbrbNF.WAV'.
Track 16: Length: 00:07.31, Pause frames: 150, Filters: 1, Name: 'WrbfbfbFF.WAV'.
Track 17: Length: 00:06.17, Pause frames: 150, Filters: 1, Name: 'FisrbfbrbNF.WAV'.
Track 18: Length: 00:06.19, Pause frames: 150, Filters: 1, Name: 'FisrbfbfbFF.WAV'.
Track 19: Length: 00:06.20, Pause frames: 150, Filters: 1, Name: 'EfbrbrbNFsynth.WAV'.
Total size: 02:39.58

Fig. 9.4. Listening Test 2 Key: Track number and file name. (Track 19 is the test sample, played before Tracks 1–18 during the test)

9.3.3 Informal Listening Tests

It may be appropriate to include some comments made during informal tests during the project. When making informal blind tests, it was interesting to observe listeners became typically more confused as time went on. Initial confidence that the difference in sound is easily audible soon melted into confusion, and no one could successfully and consistently differentiate between one model and the other. This is also reflected in the first listening survey answers and comments on tape.

The flat-backed cello was used for preliminary tests and played among other standard round-backed cellos. Both the author and the professional player found the quality of the flatback's tone to be very good in comparison with the others, and certainly "cello-like" in character. The player's comment was, however, that it was difficult to modulate the timbre while bowing. The instrument had different dynamic levels, and was even quite loud, but not the colors that this player is used to making. It is the opinion of the author that the flatback design makes a real difference concerning this aspect due to the great differences in the frequency response of the braces, especially under the soundpost. It is possible that the gamba bowing techniques are especially suited to accommodate this quality. It also seems to be a typical violin instrument trait that the rounded back allows the player to "dig in" to the string more before the tone quality becomes unpleasant-the player has more dynamic and timbre range which he or she can control in a much different way than with a flat-backed instrument. While this may seem obvious to proponents of either the viol or violin, bassists don't seem to differentiate between the two types in their playing techniques. This all remains to be studied in detail.

One more anecdote in connection with the listening tests: in the initial phases of this project, colleagues at the laboratory were asked spontaneously whether any differences were audible between a few recordings of Pfb and Prb made in the anechoic chamber. There seemed to be some agreement that the timbre was different. The best comment, though, described the tone of one instrument as sounding "rounder" (*"runder"*) while the second sounded "flatter" (*"flächig"*)! The listener heard this quite clearly, even though he had no visual information and no idea which instrument was being played! In fact, the "round" sounding instrument was Prb, and the "flat" sounding instrument was Pfb.

9.4 Documentation of all response curves

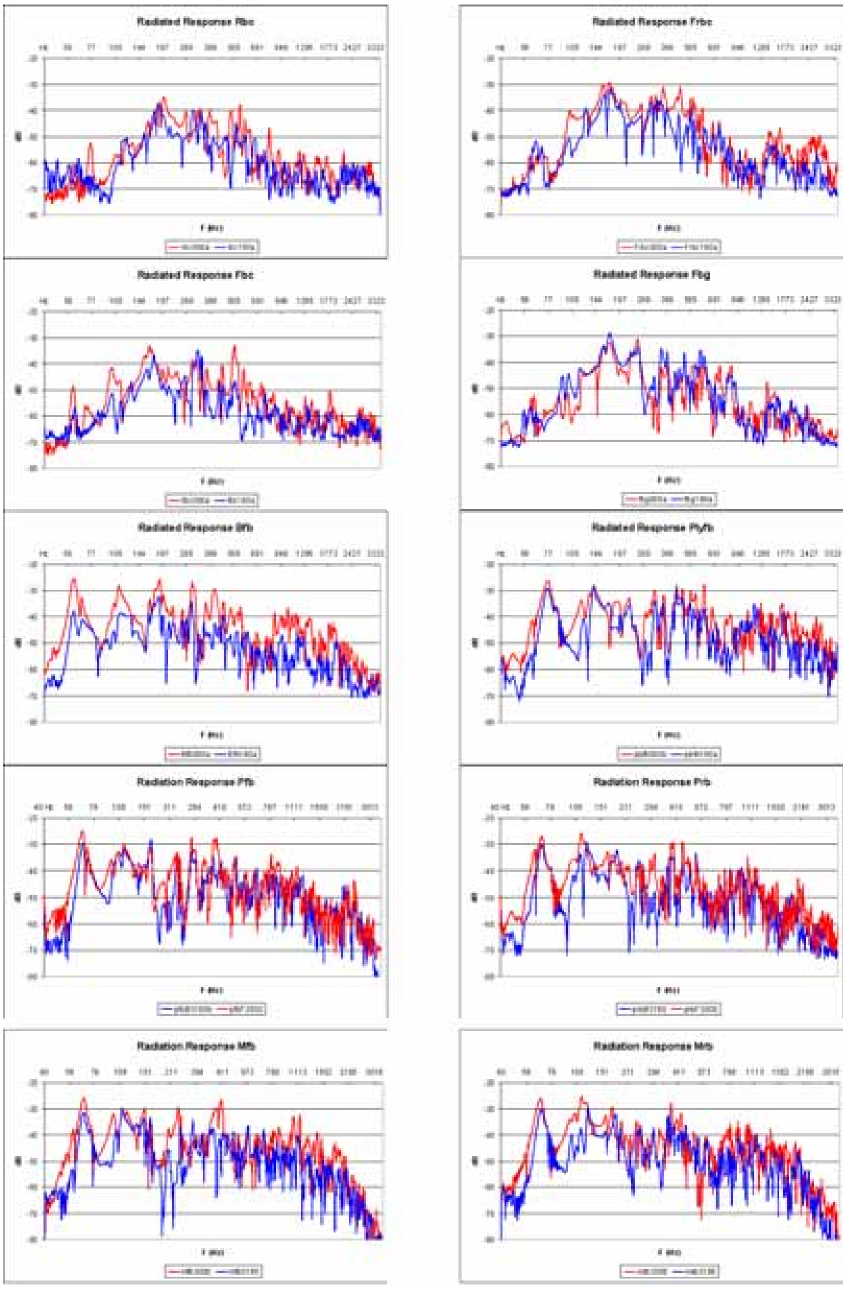


Fig. 9.5. Radiation response at 0° (red) and 180° (blue) of Rbc, Frbc, Fbc, Fbg, Bfb, Plyfb, Pfb, Prb, Mfb and Mrb. For a list and description of the instruments see Table 5.1 on page 58.

9.5 Documentation of all input admittance curves

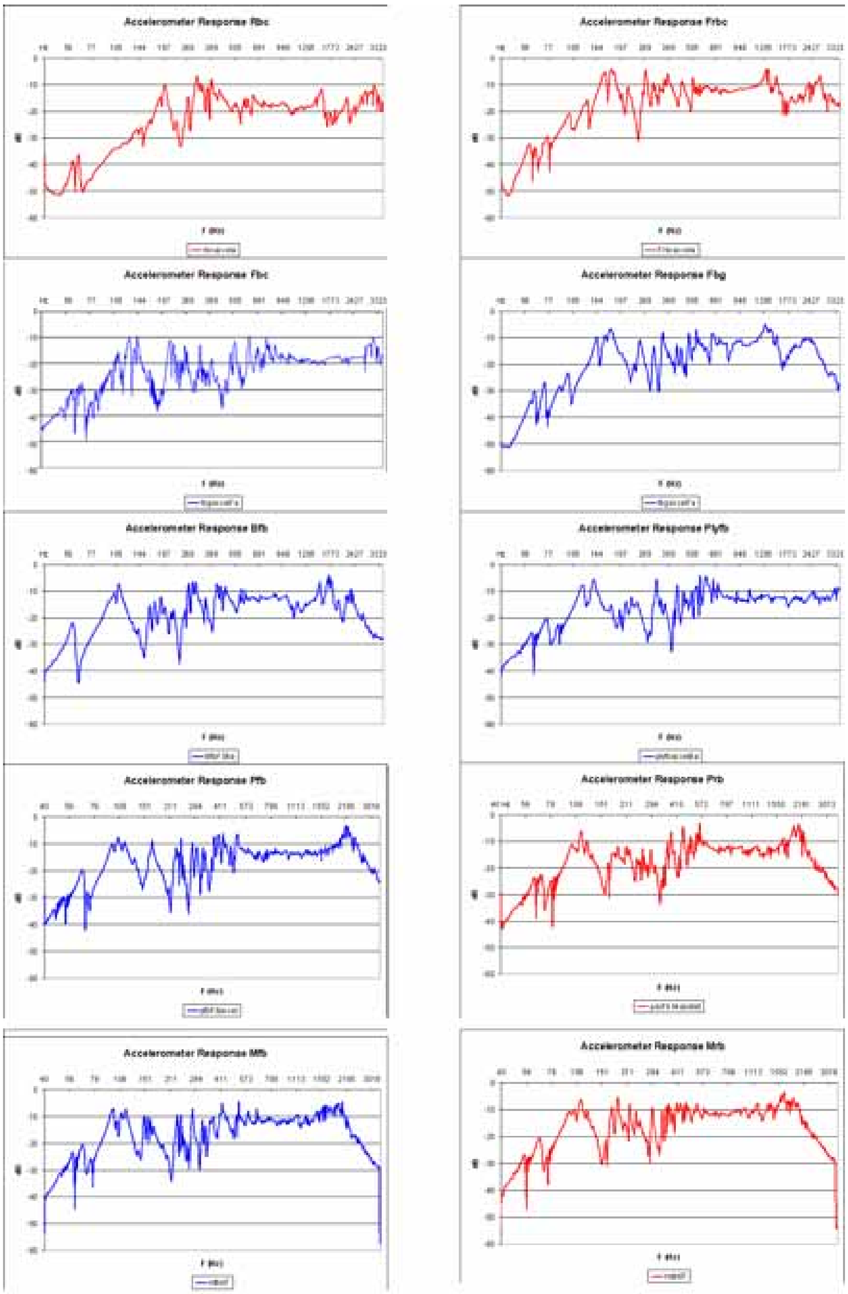
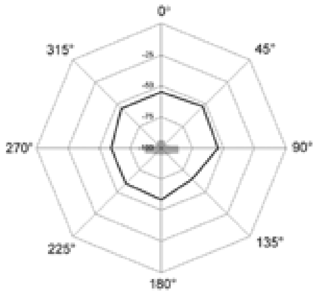


Fig. 9.6. Input admittance curves of Rbc, Frbc, Fbc, Fbg, Bfb, Plyfb, Pfb, Prb, Mfb and Mrb. Flat-backed instruments are blue, round-backed instruments red. For a list and description of the instruments see Table 5.1 on page 58.

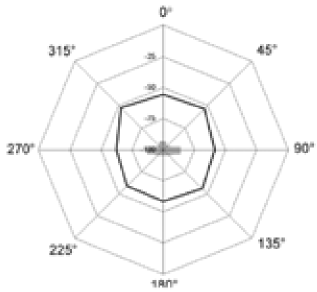
9.6 Documentation of Directivity: Pfb, Prb, Mfb and Mrb

On the following pages are diagrams of radiated sound energy in eight directions of four basses. The scale is from 0 dB to -100 dB in 25 dB increments, and the front of the bass is at the top (0°). A larger print for orientation can be found in Chapter 6 (see Fig. 6.4 on page 77). Note that diagrams of the frequency bands appear in groups of four, clockwise from the upper left: Pfb, Prb, Mrb and Mfb. The raw audio data and the source Excel files are found on the accompanying DVD-ROM, along with the graphics saved as multi-layered Adobe Photoshop .psd files.

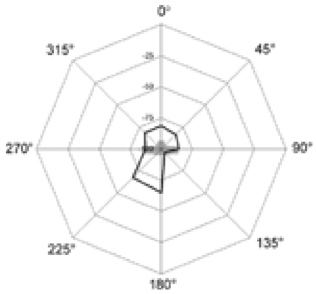
pfb 40 Hz



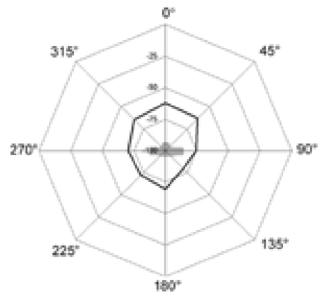
prb 40 Hz



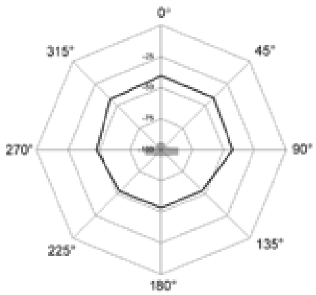
mfb 40 Hz



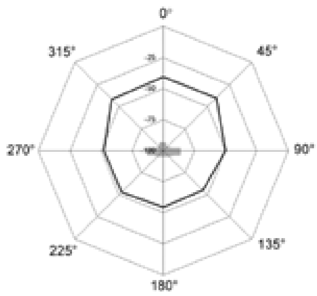
mrb 40 Hz



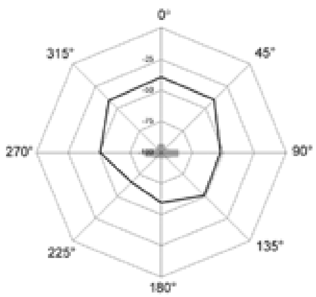
pfb 60 Hz



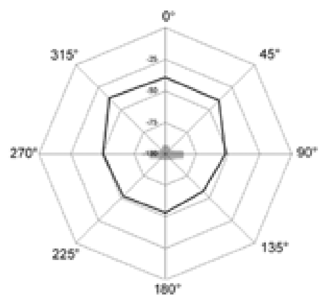
prb 60 Hz



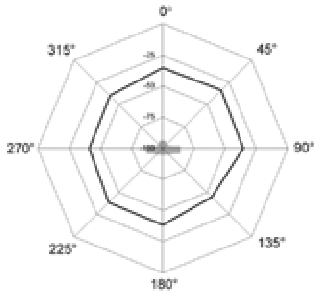
mfb 60 Hz



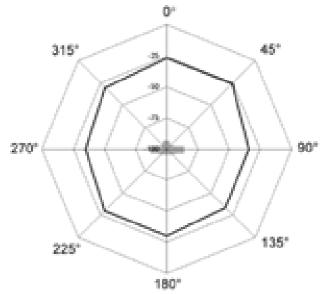
mrb 60 Hz



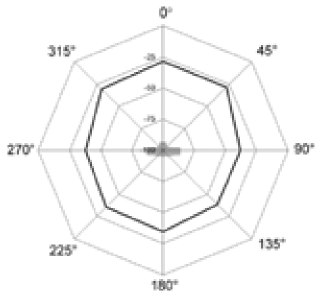
pfb 70 Hz



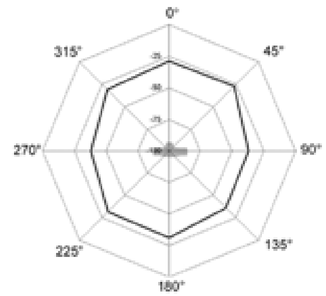
prb 70 Hz



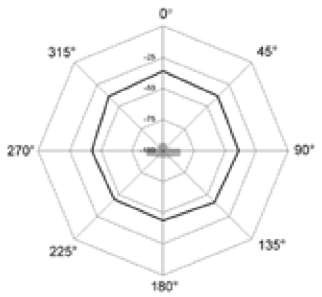
mfb 70 Hz



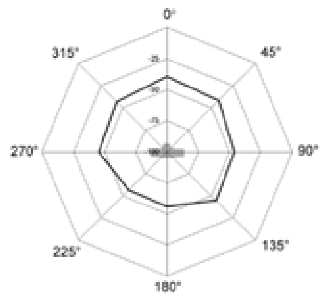
mrb 70 Hz



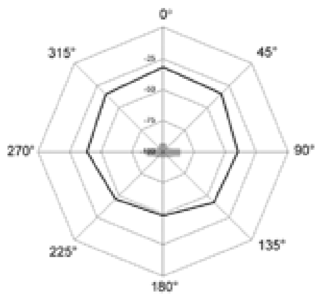
pfb 100 Hz



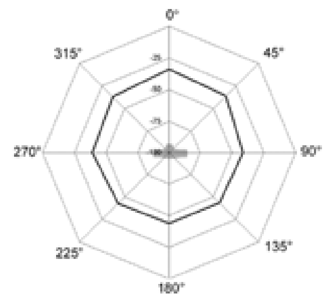
prb 100 Hz



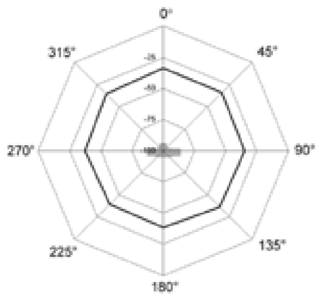
mfb 100 Hz



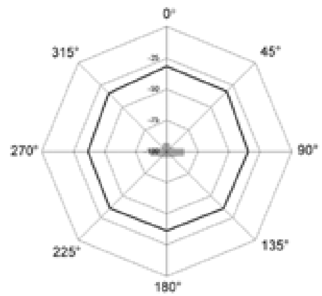
mrb 100 Hz



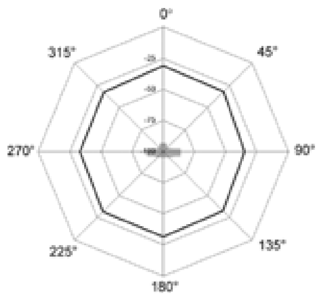
pfb 115 Hz



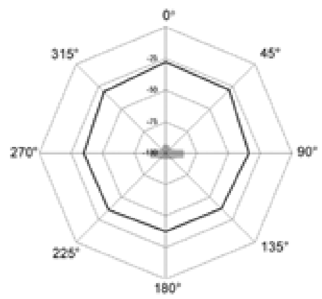
prb 115 Hz



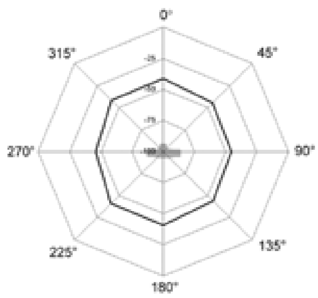
mfb 115 Hz



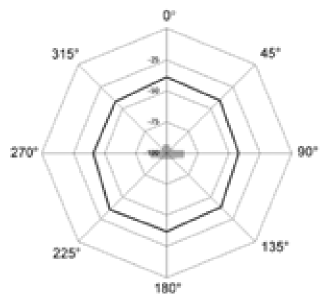
mrb 115 Hz



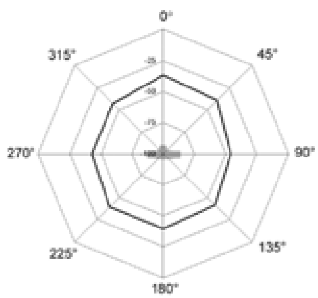
pfb 140 Hz



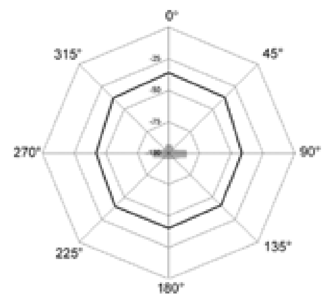
prb 140 Hz

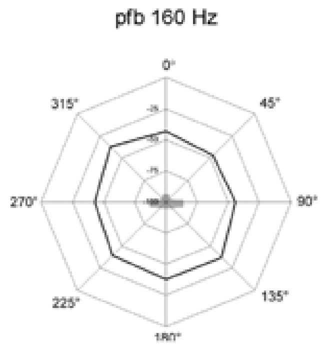


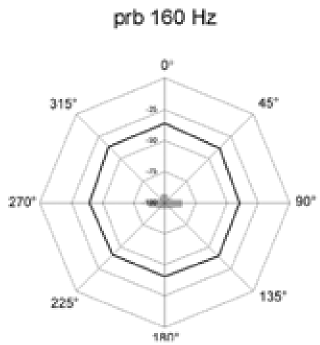
mfb 140 Hz

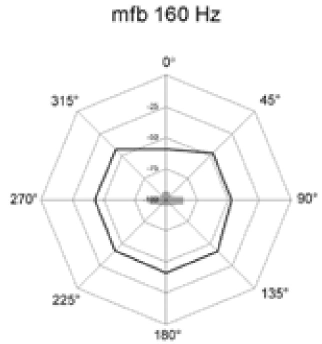


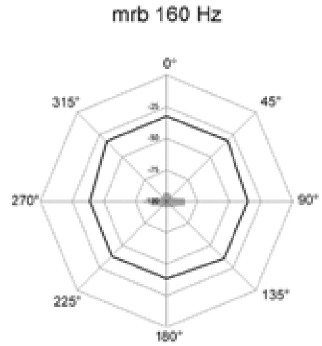
mrb 140 Hz

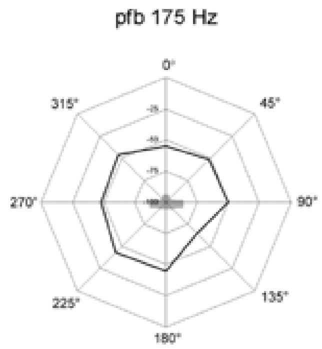


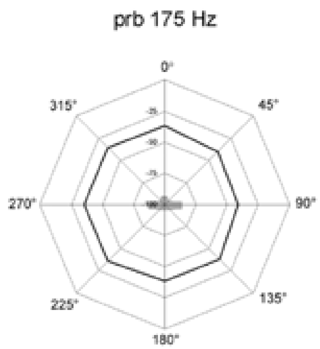

pfb 160 Hz
0°
45°
90°
135°
180°
225°
270°
315°

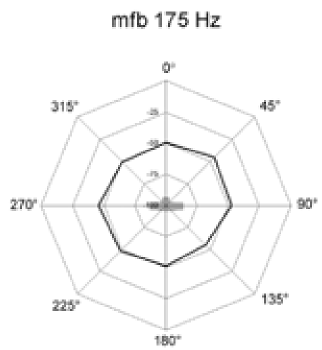

prb 160 Hz
0°
45°
90°
135°
180°
225°
270°
315°

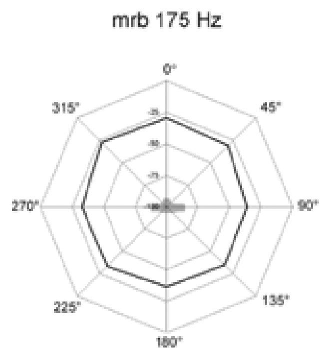

mfb 160 Hz
0°
45°
90°
135°
180°
225°
270°
315°


mrb 160 Hz
0°
45°
90°
135°
180°
225°
270°
315°

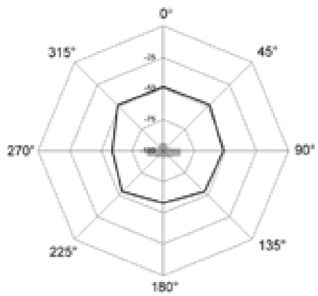

pfb 175 Hz
0°
45°
90°
135°
180°
225°
270°
315°


prb 175 Hz
0°
45°
90°
135°
180°
225°
270°
315°

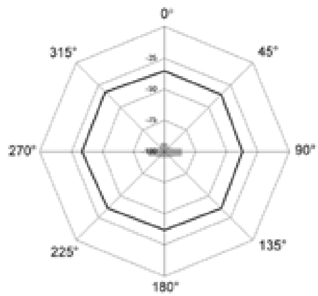

mfb 175 Hz
0°
45°
90°
135°
180°
225°
270°
315°


mrb 175 Hz
0°
45°
90°
135°
180°
225°
270°
315°

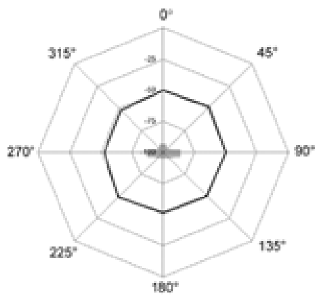
pfb 185 Hz



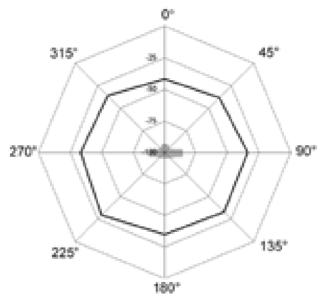
prb 185 Hz



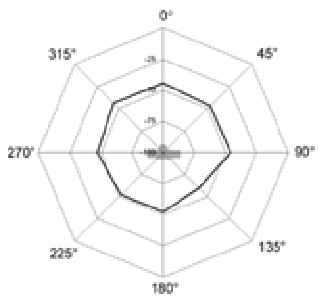
mfb 185 Hz



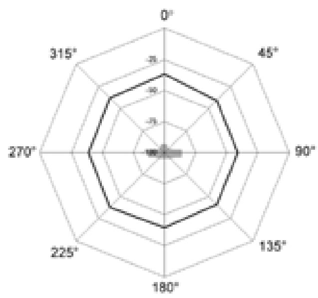
mrb 185 Hz



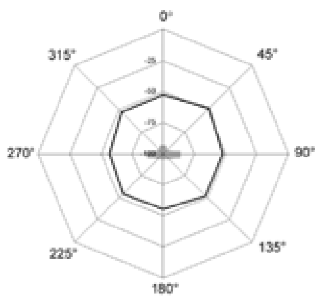
pfb 200 Hz



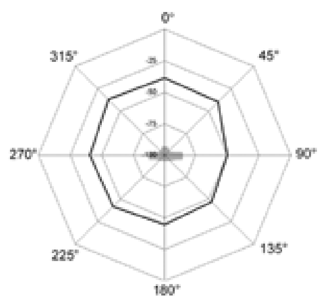
prb 200 Hz



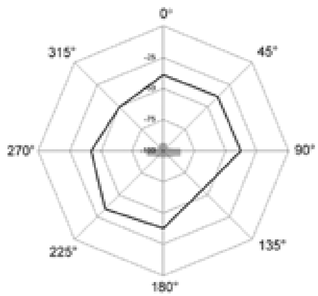
mfb 200 Hz



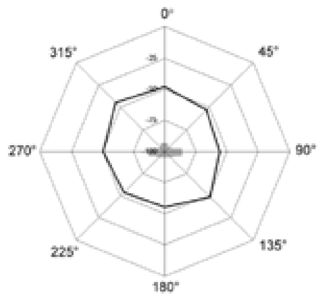
mrb 200 Hz



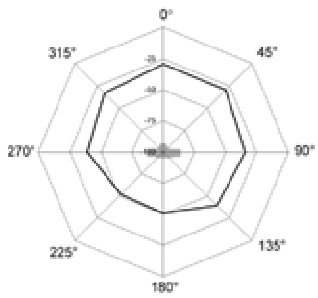
pfb 235 Hz



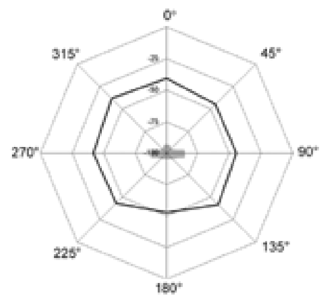
prb 235 Hz



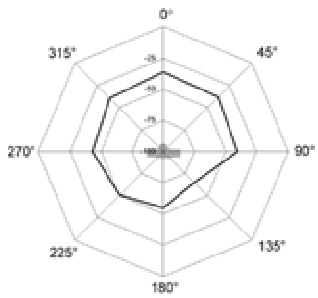
mfb 235 Hz



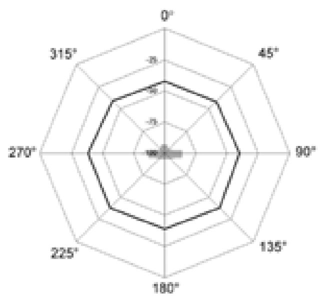
mrb 235 Hz



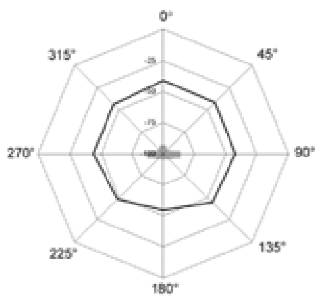
pfb 250 Hz



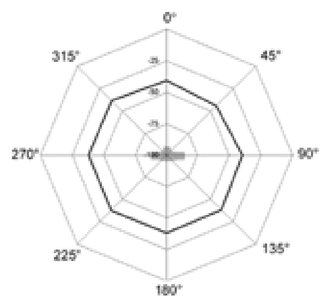
prb 250 Hz



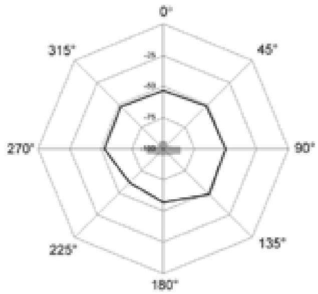
mfb 250 Hz



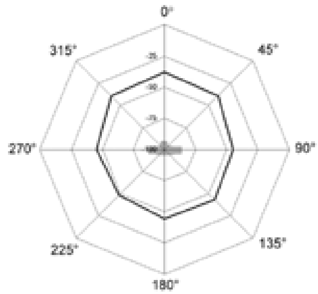
mrb 250 Hz



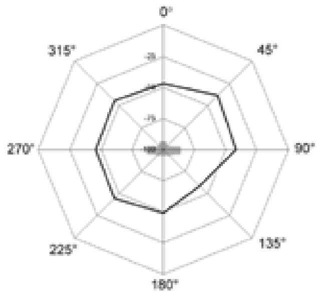
pfb 270 Hz



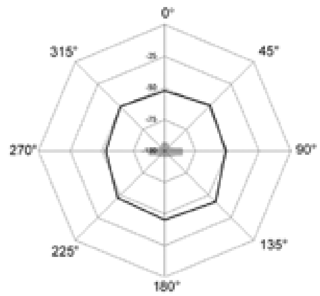
prb 270 Hz



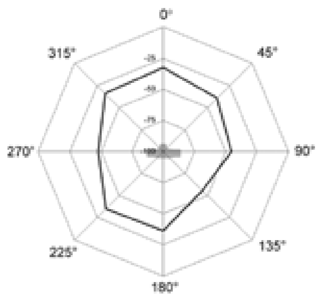
mfb 270 Hz



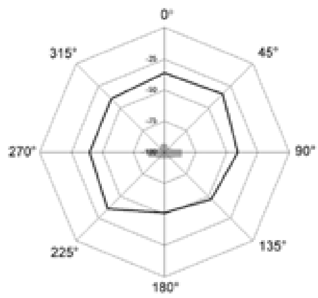
mrb 270 Hz



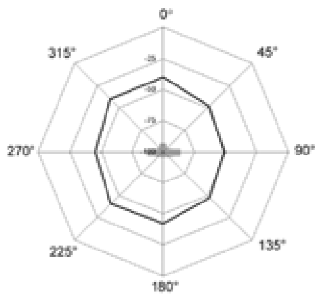
pfb 300 Hz



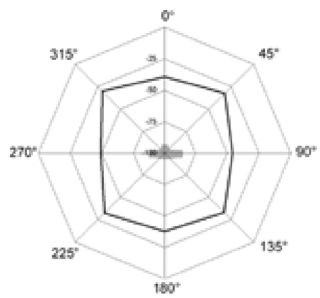
prb 300 Hz



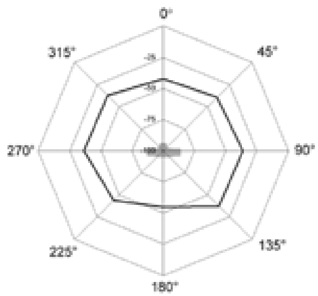
mfb 300 Hz



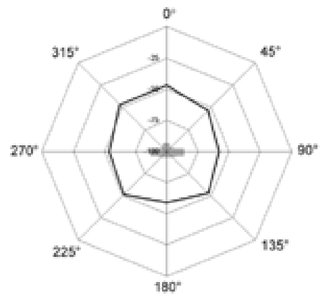
mrb 300 Hz



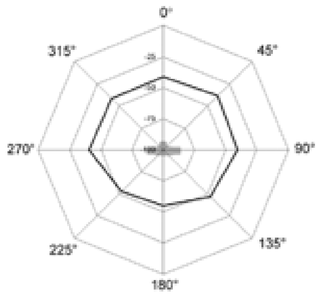
pfb 330 Hz



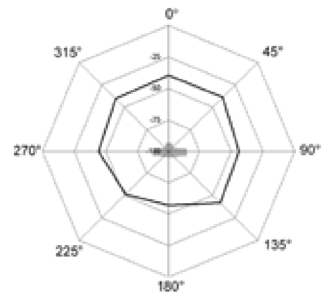
prb 330 Hz



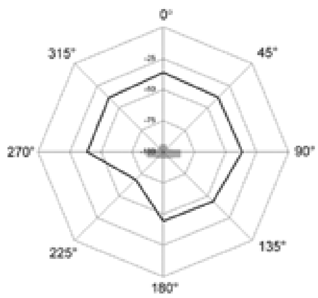
mfb 330 Hz



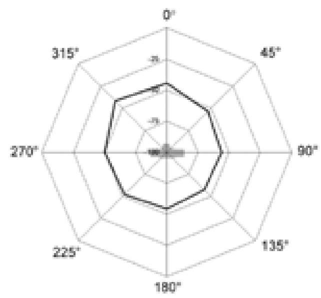
mrb 330 Hz



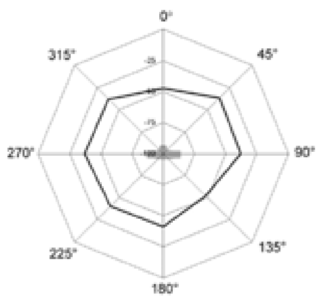
pfb 350 Hz



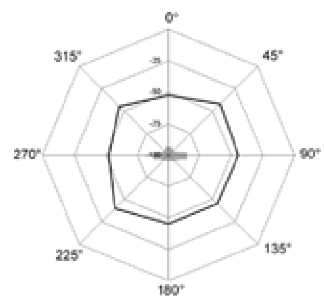
prb 350 Hz



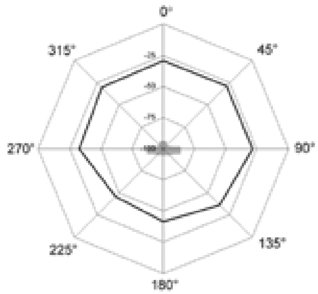
mfb 350 Hz



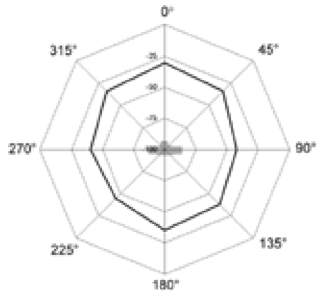
mrb 350 Hz



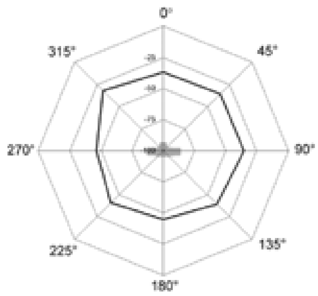
pfb 400 Hz



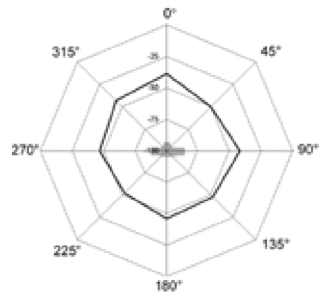
prb 400 Hz



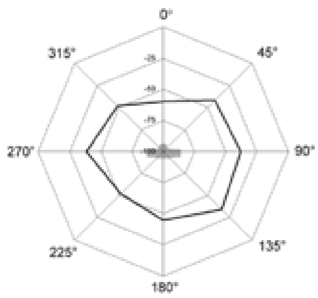
mfb 400 Hz



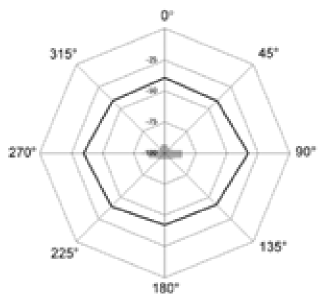
mrb 400 Hz



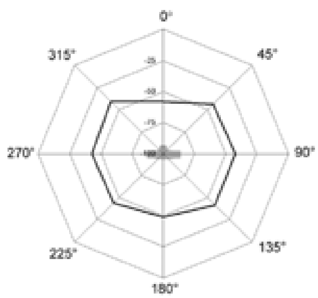
pfb 500 Hz



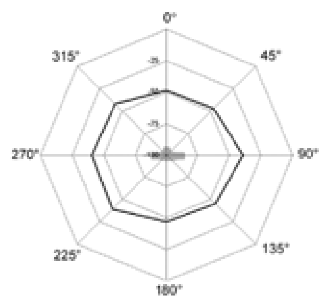
prb 500 Hz



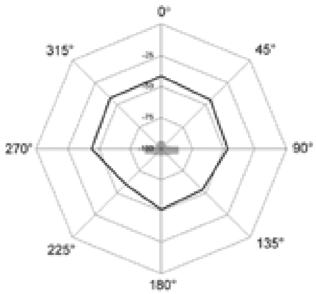
mfb 500 Hz



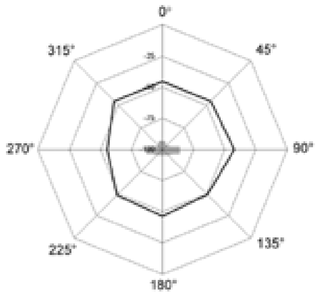
mrb 500 Hz



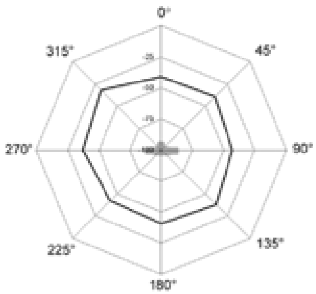
pfb 600 Hz



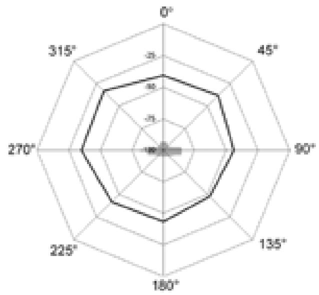
prb 600 Hz



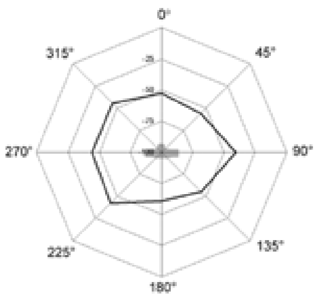
mfb 600 Hz



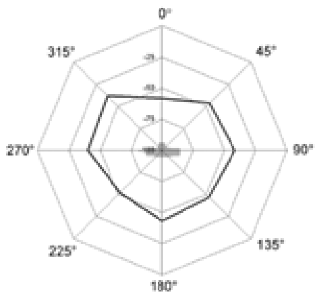
mrb 600 Hz



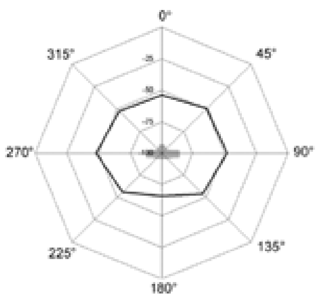
prb 700 Hz



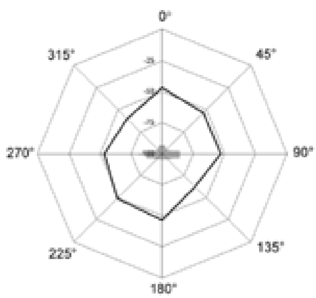
pfb 700 Hz



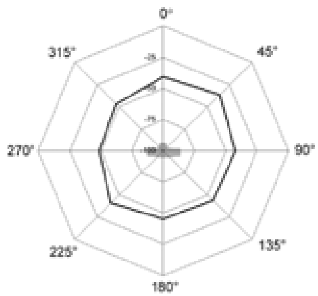
mrb 700 Hz



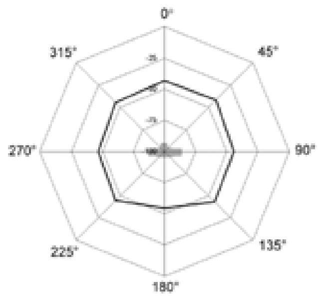
mfb 700 Hz



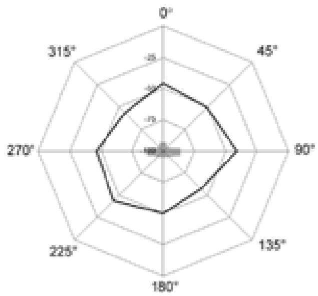
pfb 800 Hz



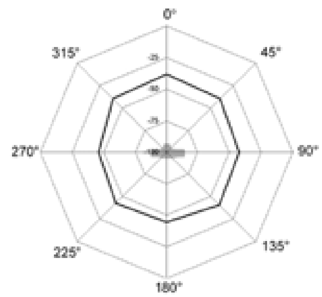
prb 800 Hz



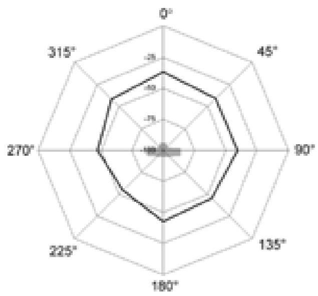
mfb 800 Hz



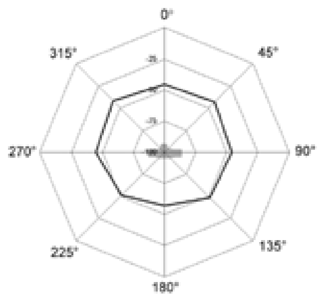
mrb 800 Hz



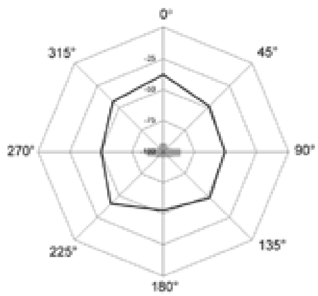
pfb 900 Hz



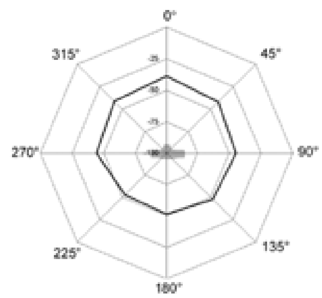
prb 900 Hz



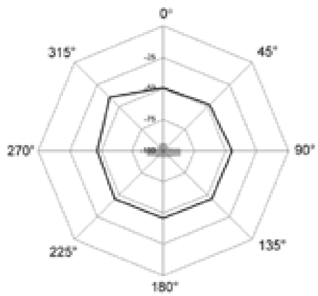
mfb 900 Hz



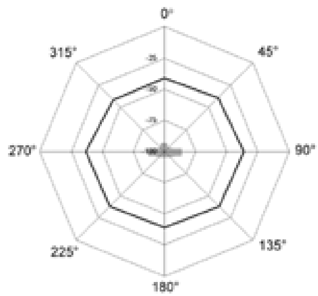
mrb 900 Hz



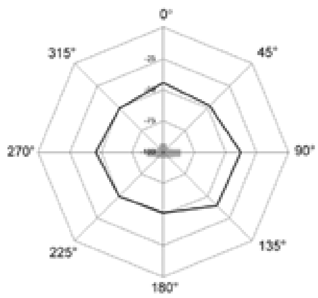
pfb 1000 Hz



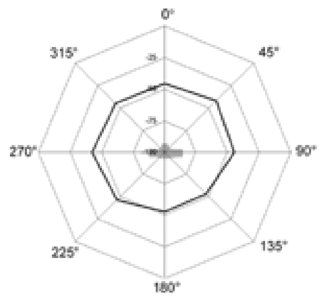
prb 1000 Hz



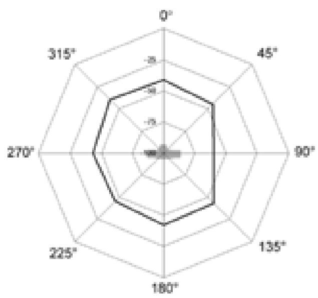
mfb 1000 Hz



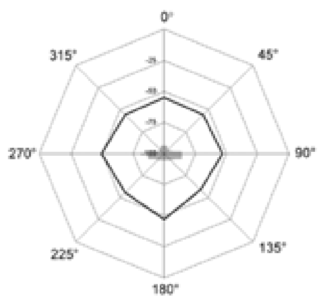
mrb 1000 Hz



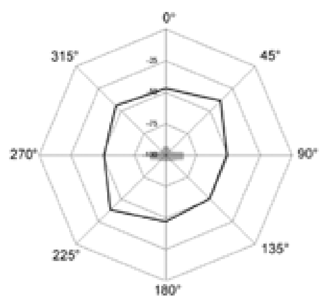
prb 1250 Hz



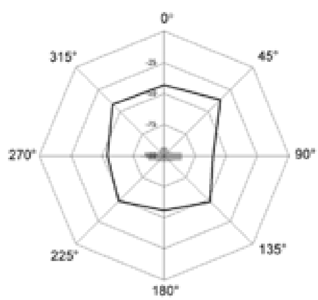
pfb 1250 Hz

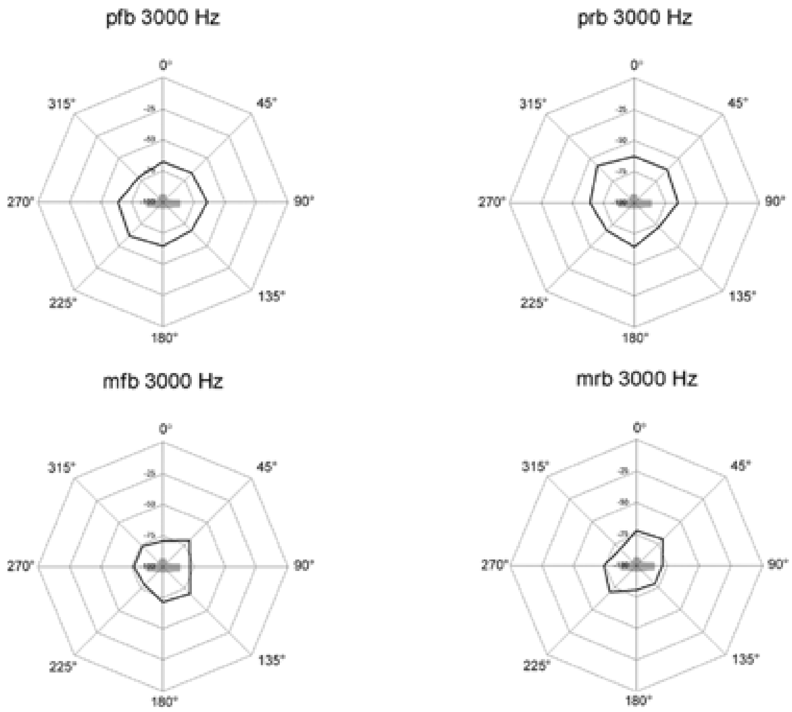


mrb 1250 Hz



mfb 1250 Hz



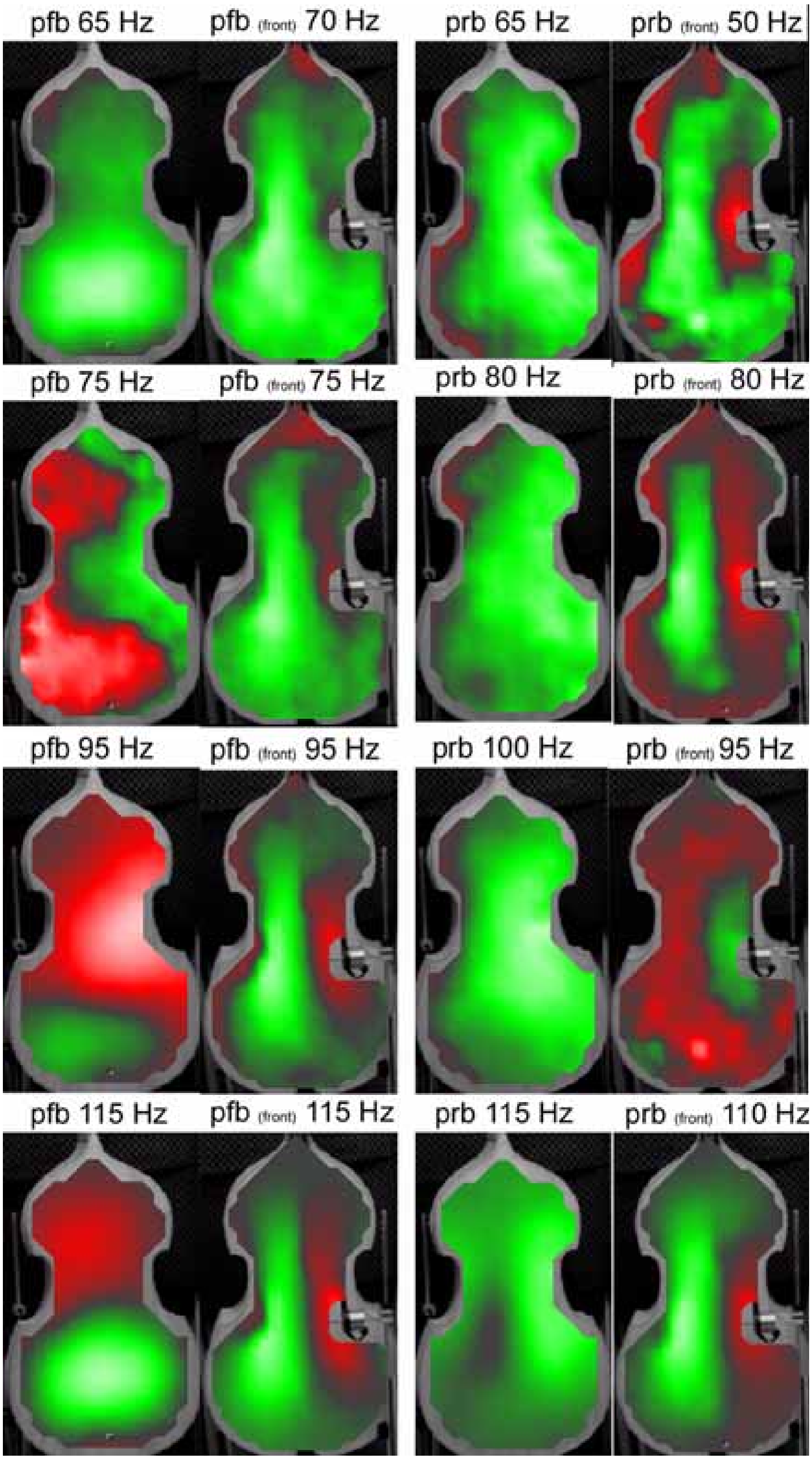

pfb 3000 Hz
prb 3000 Hz
mfb 3000 Hz
mrb 3000 Hz
0°
45°
90°
135°
180°
225°
270°
315°

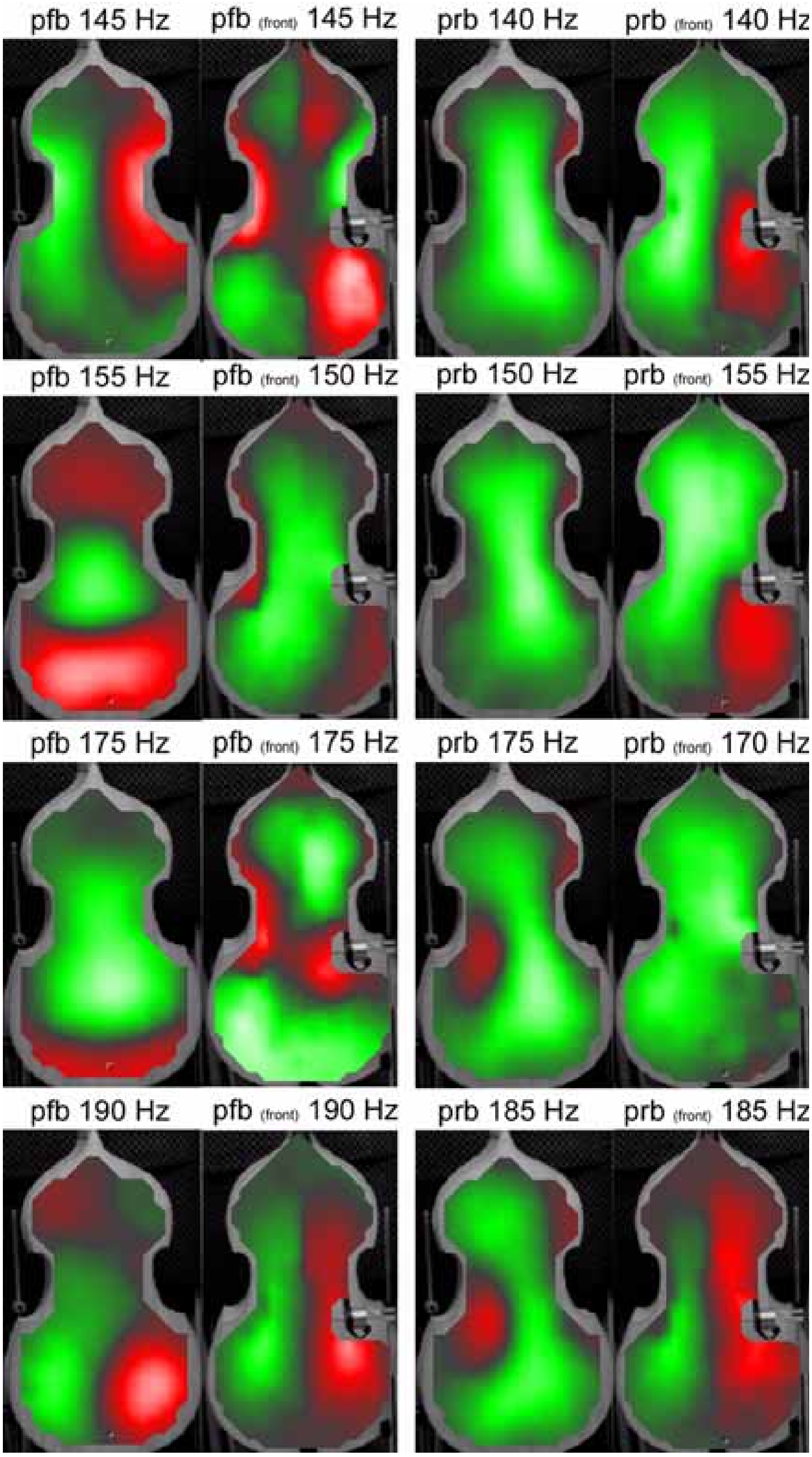
9.7 Documentation of operational deflection patterns gained by laser vibrometry analysis

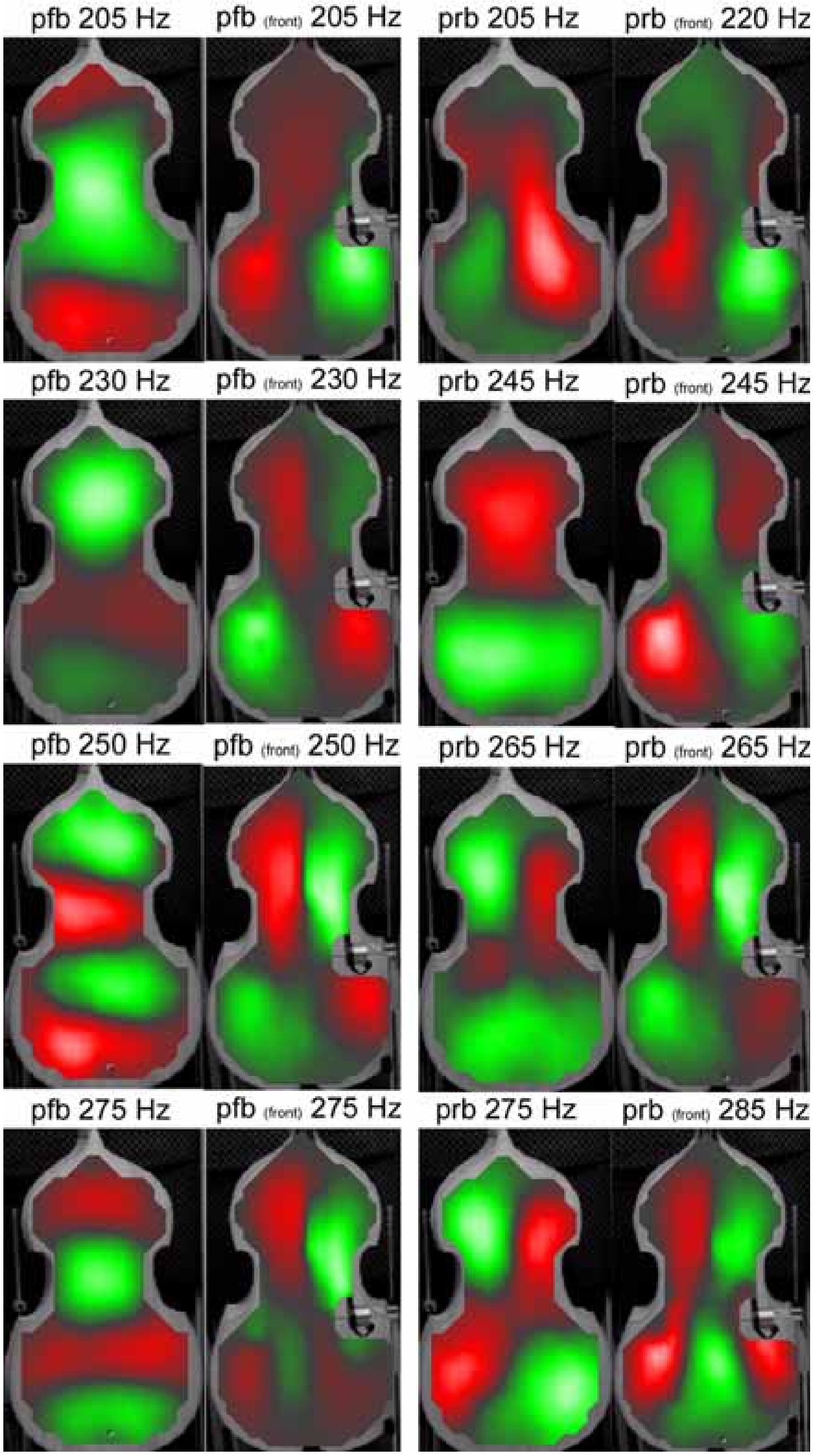
The following pages contain a documentation of operational deflection patterns of basses Pfb and Prb. Measurement points above the fingerboard and tailpiece were invalidated for the analysis. The frequency resolution is 5 Hz, but frequency analysis in the diagrams may vary up to 10 Hz because limited access to the Polytec equipment precluded later corrections/ alterations to previously selected frequency bands.

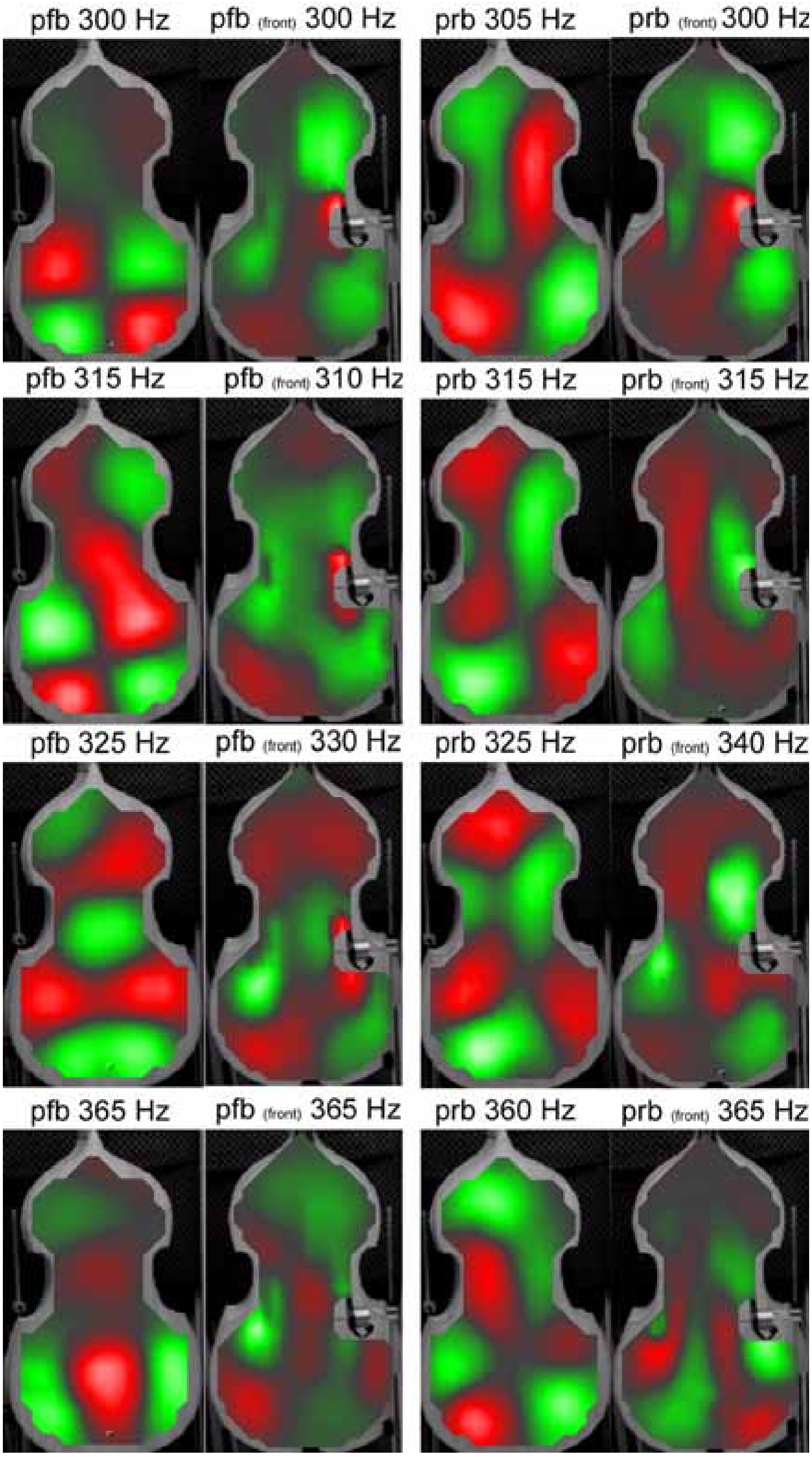
Note that the diagram groups appear in two columns, the order of a diagram group is from left to right: Pfb back, Pfb front, Prb back and Prb front. Frequency ranges are ordered in rows from lowest to highest in each column.

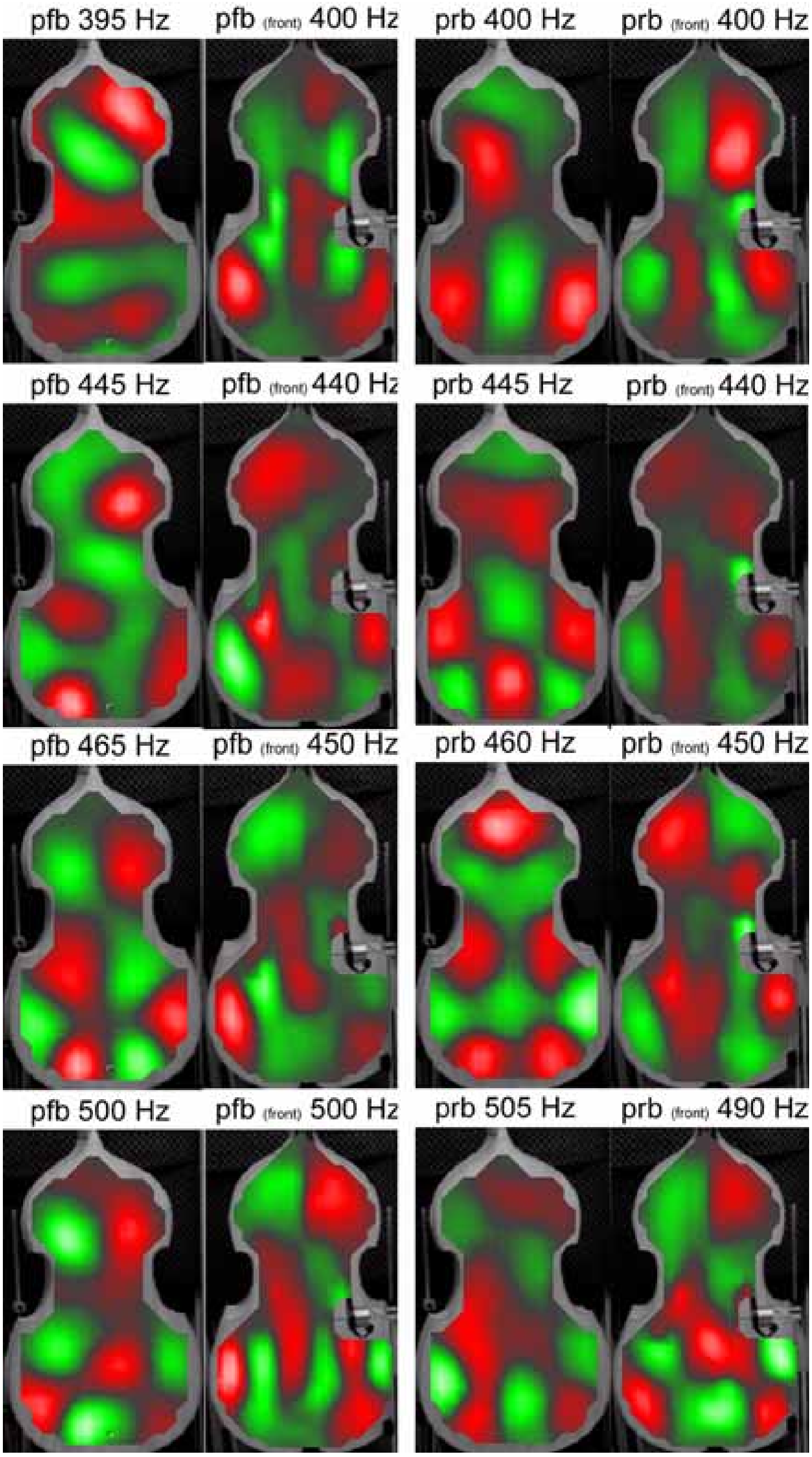
The original diagrams are printed in green/red, instead of black/white, because the modal patterns appear thus most clearly. These diagrams may lose quality if printed in grey tones. The included DVD ROM contains the original measurements in .psv format, which requires the original Polytec software to read, and the graphics in multi-layered Adobe Photoshop 7 .psd files.

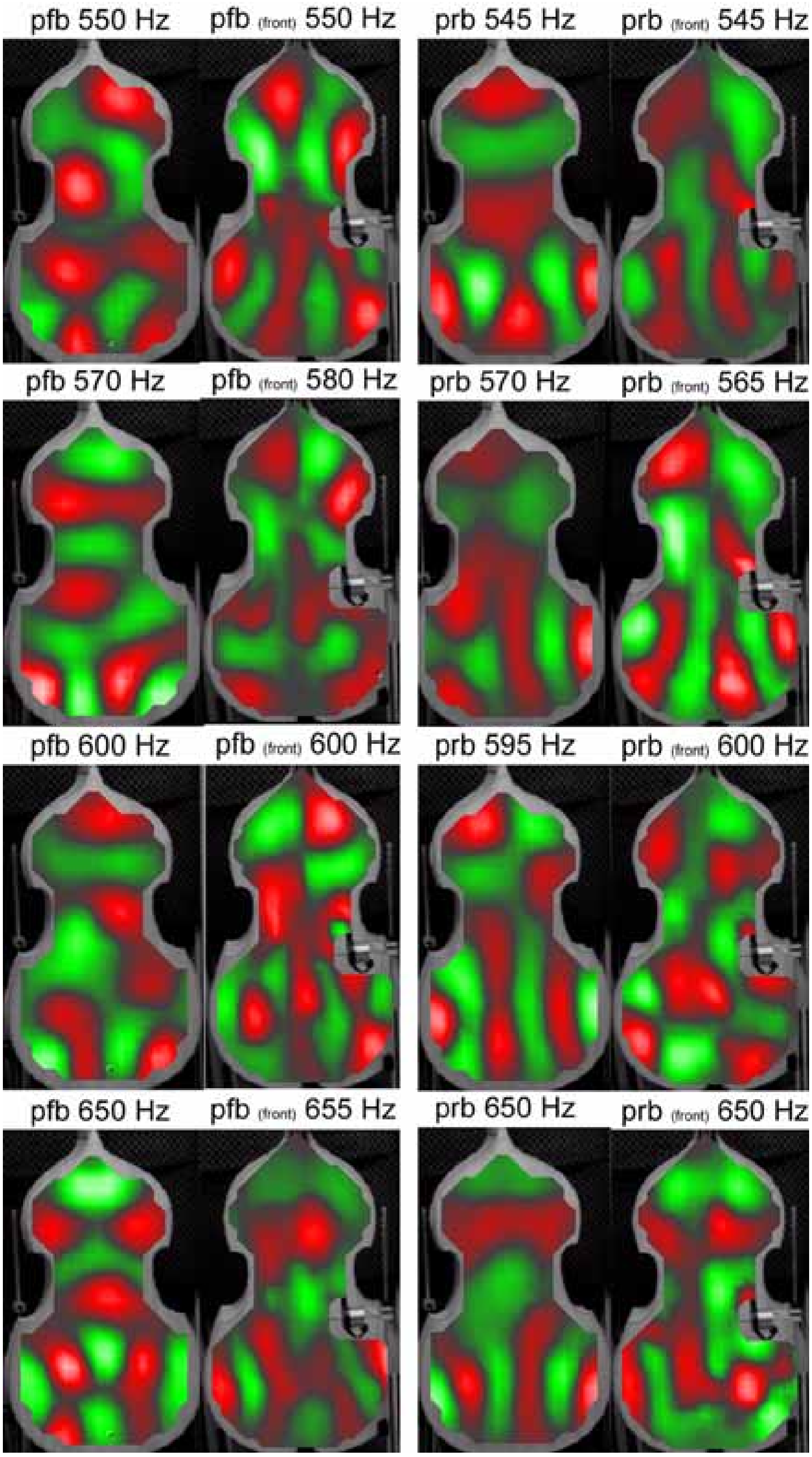

pfb 65 Hz
pfb (front) 70 Hz
prb 65 Hz
prb (front) 50 Hz
pfb 75 Hz
pfb (front) 75 Hz
prb 80 Hz
prb (front) 80 Hz
pfb 95 Hz
pfb (front) 95 Hz
prb 100 Hz
prb (front) 95 Hz
pfb 115 Hz
pfb (front) 115 Hz
prb 115 Hz
prb (front) 110 Hz

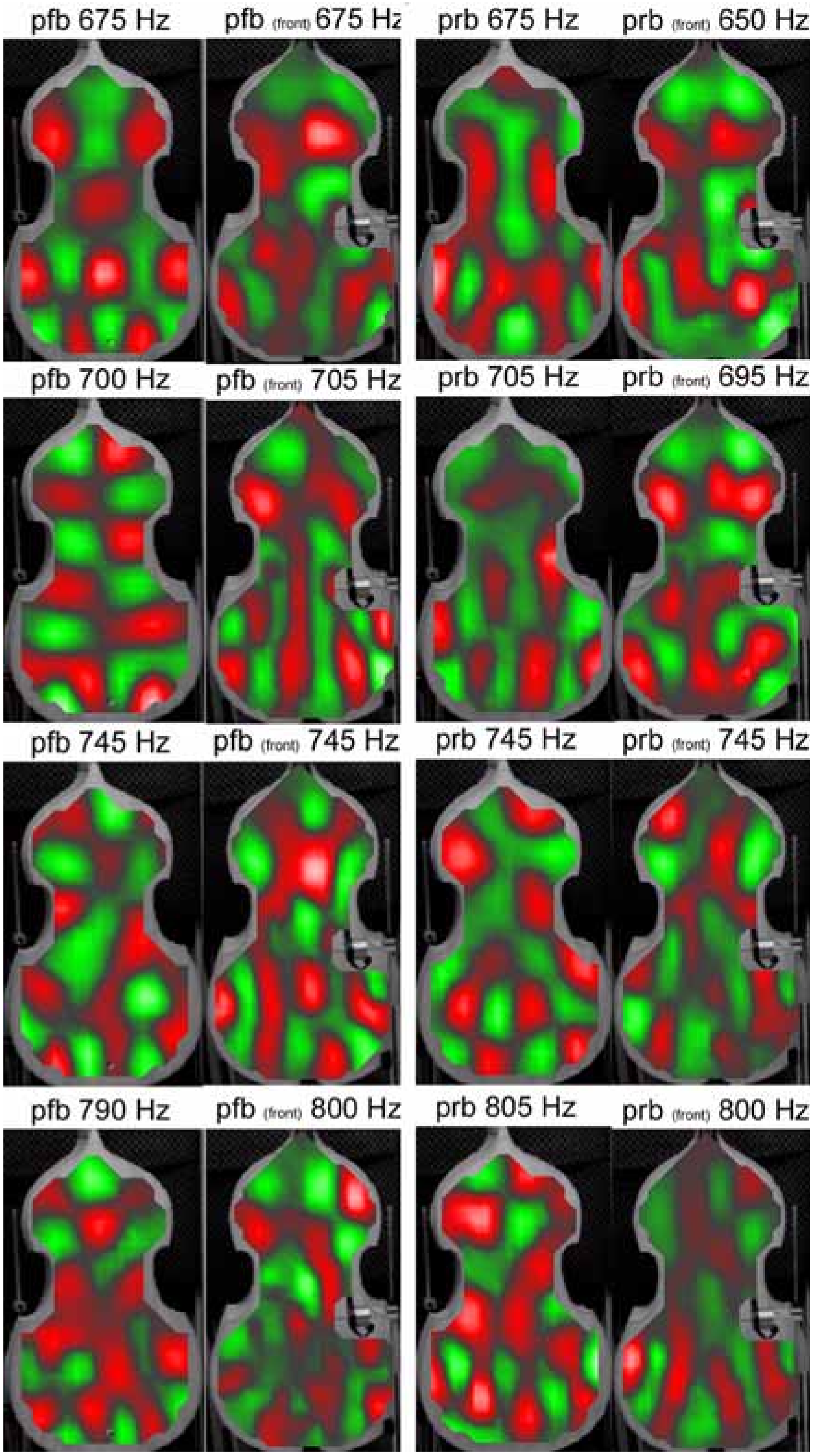

pfb 145 Hz
pfb (front) 145 Hz
prb 140 Hz
prb (front) 140 Hz
pfb 155 Hz
pfb (front) 150 Hz
prb 150 Hz
prb (front) 155 Hz
pfb 175 Hz
pfb (front) 175 Hz
prb 175 Hz
prb (front) 170 Hz
pfb 190 Hz
pfb (front) 190 Hz
prb 185 Hz
prb (front) 185 Hz

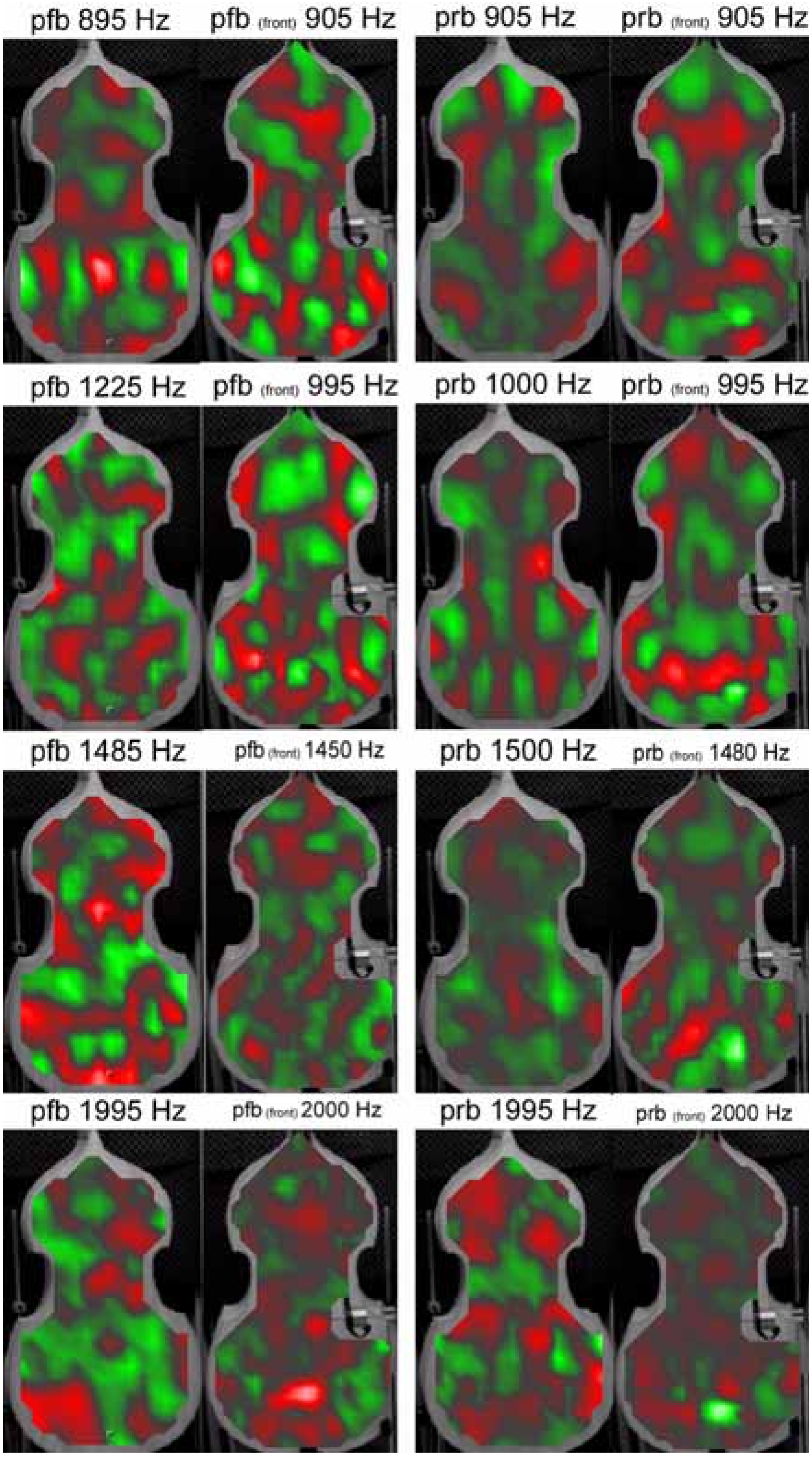

pfb 205 Hz
pfb (front) 205 Hz
prb 205 Hz
prb (front) 220 Hz
pfb 230 Hz
pfb (front) 230 Hz
prb 245 Hz
prb (front) 245 Hz
pfb 250 Hz
pfb (front) 250 Hz
prb 265 Hz
prb (front) 265 Hz
pfb 275 Hz
pfb (front) 275 Hz
prb 275 Hz
prb (front) 285 Hz


pfb 300 Hz
pfb (front) 300 Hz
prb 305 Hz
prb (front) 300 Hz
pfb 315 Hz
pfb (front) 310 Hz
prb 315 Hz
prb (front) 315 Hz
pfb 325 Hz
pfb (front) 330 Hz
prb 325 Hz
prb (front) 340 Hz
pfb 365 Hz
pfb (front) 365 Hz
prb 360 Hz
prb (front) 365 Hz


pfb 395 Hz
pfb (front) 400 Hz
prb 400 Hz
prb (front) 400 Hz
pfb 445 Hz
pfb (front) 440 Hz
prb 445 Hz
prb (front) 440 Hz
pfb 465 Hz
pfb (front) 450 Hz
prb 460 Hz
prb (front) 450 Hz
pfb 500 Hz
pfb (front) 500 Hz
prb 505 Hz
prb (front) 490 Hz


pfb 550 Hz
pfb (front) 550 Hz
prb 545 Hz
prb (front) 545 Hz
pfb 570 Hz
pfb (front) 580 Hz
prb 570 Hz
prb (front) 565 Hz
pfb 600 Hz
pfb (front) 600 Hz
prb 595 Hz
prb (front) 600 Hz
pfb 650 Hz
pfb (front) 655 Hz
prb 650 Hz
prb (front) 650 Hz


pfb 675 Hz
pfb (front) 675 Hz
prb 675 Hz
prb (front) 650 Hz
pfb 700 Hz
pfb (front) 705 Hz
prb 705 Hz
prb (front) 695 Hz
pfb 745 Hz
pfb (front) 745 Hz
prb 745 Hz
prb (front) 745 Hz
pfb 790 Hz
pfb (front) 800 Hz
prb 805 Hz
prb (front) 800 Hz


pfb 895 Hz
pfb (front) 905 Hz
prb 905 Hz
prb (front) 905 Hz
pfb 1225 Hz
pfb (front) 995 Hz
prb 1000 Hz
prb (front) 995 Hz
pfb 1485 Hz
pfb (front) 1450 Hz
prb 1500 Hz
prb (front) 1480 Hz
pfb 1995 Hz
pfb (front) 2000 Hz
prb 1995 Hz
prb (front) 2000 Hz

9.8 DVD ROM Contents

9.8.1 Dissertation Text

9.8.2 Audio Data

9.8.3 Excel Tables

9.8.4 Laser Vibrometry Data

9.8.5 Listening Tests

9.8.6 Pictures

9.8.7 VIAS Data

9.9 Curriculum Vitae

Name: Andrew William Brown
Date of Birth: 11 January, 1969
Birthplace: Prince George's County, Maryland, U.S.A.
Citizenship: U.S.A.

School Education:
1975–1977: District Heights Elementary School, Maryland
1977–1981: Marlton Elementary School, Maryland
1981–1983: James Madison Junior High School, Maryland
1983–1987: Eleanor Roosevelt High School Science and Technology Center, Maryland

Academic Education:
1987–1991: Studies at the Benjamin T. Rome School of Music, Catholic University of America, Washington, D.C. Bachelor of Music in Double Bass Performance, Magna cum laude, 1991.

1991–1999: Studies with Ludwig Streicher and Josef Niederhammer at the University of Music and Performing Arts Vienna, Austria, with the degree *Magister Artium, Konzertfach Kontrabass*, 1999

2001–2004: Doctor of Philosophy studies, *Musical Acoustics*, at the University of Music and Performing Arts Vienna in cooperation with the University of Vienna, Austria

Professional experience:
1991–present: Free-lance double bassist, bass-guitarist, guitarist and vocalist

1991–present: Private teacher of double bass, bass-guitar, guitar and piano students

1997–2002: Part-time employment as a luthier at a violin shop in Vienna

1999-2002: Employed by the University of Music and Performing Arts Vienna as a research assistant specializing in stringed instruments, as well as text editing and translation into English

2004: Guest teacher at the University of Music and Performing Arts Vienna of the seminar "Acoustics of Stringed Instruments"