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MAGISTERARBEIT

SOUND POWER OF MODERN AND HISTORICAL ORCHESTRAL INSTRUMENTS

PART I: STRING INSTRUMENTS

VORGELEGT VON

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[redacted]

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Die selbstständige und eigenständige Anfertigung dieser Magisterarbeit versichere ich an Eides statt.

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Part I: String instruments

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Along with obvious differences in timbre between orchestral instruments of modern and historical construction, it has been generally assumed that the ability of a higher projection, typically ascribed to modern instruments, is correlated to an increase of the instruments' sound power. In order to verify this hypothesis, sound pressure-calibrated recordings of a large number of modern and historical orchestral instruments were collected by means of the enveloping surface method in a full-anechoic chamber. Sustained single notes and diatonic scales in different dynamic levels, played by professional musicians, were recorded over the entire pitch range. Both the maximum and minimum attainable sound power was determined. Intermediate dynamic levels were subsequently calculated from the data obtained. No systematic differences were found for all examined bowed string instruments between those of modern or historical construction. Together with the results for brass and wood wind instruments, an empirically-based estimation of the sound power of modern and historical orchestras and ensembles is enabled.

I. INTRODUCTION

The distinct sound characteristics of musical instruments of the 18th and 19th century, compared to modern orchestral instruments, are an essential element of a historically informed performance practice of music such as the works of the Viennesse Classics. Although the use of instruments of historical construction, whether originals or individual replicas, is widely integrated in today's concert life, there is so far hardly any data available, documenting the acoustical differences to modern instruments. As a consequence, it is still generally assumed, that the ability of a higher projection, typically ascribed to modern instruments, can be attributed essentially to changes in construction, resulting both in spectral differences as well as in an increase of sound power. Examples for such speculations, which in the case of bowed string instruments, generally apply concretely to the violin, can be abundantly found in statements by researchers, violin makers, and musicians alike. As an example, Curtin[1] points out, that the sound characteristics of the violin have changed so drastically within the past few centuries, „that a violinist equipped with a Baroque bow and an instrument straight from Stradivari's work-bench would find most of the standard repertoire unplayable – and in a typical concert setting, scarcely audible". Boyden[2] furthermore notes in his essay on the history of the violin, that while the sound quality of instruments may be expressed only with difficulty in words, the tone of historical compared to modern instruments can however be described as "smaller", "less brilliant", "sweeter", and "less metallic". According to Boyden, this could be attributed mainly to lighter bows, different string patterns and less string tension.

Direct references, which mention the sound of especially valuable orchestral instruments as "screaming out",[3] can also be found in historical sources of the 18th century. Although such statements must of course be seen within the context of their times, they do however prove, that already in the last few centuries an increase in projection and assertiveness must have been regarded as a quality criterion of instruments. However, it still remains scientifically unaccounted, whether such clearly perceivable differences in sound are solely due to changes in the overtone spectrum[4] or are also ascribable to the parameter of sound power, so far hardly investigated. The present investigation should therefore show whether such links may be attributed to systematic changes of the sound power of historical and modern orchestral instruments and show not leastly, in as far the projection and assertiveness, ascribed to modern instruments, can be encountered in the values of the sound power. In order to acquire a comprehensive set of data on their total dynamic range, an extensive measurement series by means of the enveloping surface method in a full-anechoic chamber has been realized for all instruments of the classic-romantic symphony orchestra and for various development stages of instrument making. The first part of the documentation, encompassing all string instruments of the violin family (violin, viola, violoncello, and double bass) is presented in continuation. An empirically-based estimation of the overall sound power of orchestras and ensembles from different periods is enabled by a further inclusion of the results obtained for brass and wood wind instruments.[5]

II. STATE OF RESEARCH

Although considerable research has in general been done on various acoustical aspects of musical instruments, scientific contributions on the radiated sound pressure or sound power have so far been limited to modern instruments. Fundamental research in this field has been conducted in the nineteen-eighties by Meyer,[6,7] undertaking the only consistent series of sound power measurements according to the reverberant room method with a reference sound source. Several earlier investigations, carried out since the 1960s, indicate some systematic difficulties und have been partially performed under unclearly defined environmental conditions. According to Meyer, one of the first investigations in relation to the dynamic behavior of musical instruments has been carried out by Clarke and Luce,[8] who measured unweighted sound pressure levels of the most common orchestral instruments in an anechoic chamber. Another research project of Burghauser and Spelda[9] provides information on weighted sound pressure levels of a variety of modern orchestral instruments, measured from an "average listening distance" in a broadcasting studio. Further investigations by Bouhuys[10] refer exclusively to weighted sound pressure levels of wind instruments, collected both in environments of partially known and unknown volumes and reverberation times. Due to the fact, that none of these investigations have been performed under metrologically standardized and valid conditions in an either anechoic or reverberant measurement environment, a conversion in sound power values of such direction-dependent and potentially error-prone data appears to be feasible only through compromise. In view of a comparison with his own data, Meyer however undertakes the attempt to convert the results of all three aforementioned investigations into sound power levels by applying corresponding factors of correction.[11] In this manner the first empirical comparison of different sets of data regarding the dynamic behavior of modern orchestral instruments has been enabled. Published in 1990, this documentation still represents the de facto standard and reference literature in the field until today.[11]

Regarding the measuring programs of both Clark and Luce as well as Burghauser and Spelda, Meyer also faces another difficulty, concerning the dynamic playing instructions for the musicians. While both investigations determine the values for the maximum and minimum limits (*ff* and *pp*) and deduce from these the highest possible dynamic range, they also provide measured level values for a playing mode that is felt by the musician as the medium volume level ("*mf*"). According to Meyer it however appears to be obvious, that such values represents results which are reliable only with certain limitations and can vary strongly from musician to musician. This is essentially due to the fact that these values refer to the rather subjective assessment and way of interpretation of the musician, who not lastly plays under unfamiliar acoustical conditions. Meyer therefore provides with his own measurements only the limits of the playable range for single notes and faster played scales and establishes furthermore an arithmetical process for the determination of a so-called mean forte sound power level L_{wf}.[11] This matter is further discussed in Section V, where the results of the present investigation are presented.

III. PRINCIPLES OF SOUND PRODUCTION IN BOWED STRING INSTRUMENTS AND MODIFICATIONS SINCE THE 18TH CENTURY

Unlike wind instruments, whose sound character is primarily defined by the resonance effects of the enclosed air column and hence by clear dimensions such as the pipe diameter or the mouthpiece,[12] the specific sound of bowed string instruments is determined by a rather complex interaction between multiple components. Besides the resonant characteristics of the body, the sound quality is a result of the material properties and workmanship of the bow, the strings and not at least of the string-body coupling components such as the bridge and the soundpost. As a consequence, the sound spectra of bowed string instruments in general show a much higher variety than other orchestral instruments. This section provides a brief overview of the most important aspects of sound production in bowed string instruments. In addition some modifications in construction in the course of the 18th century are mentioned along with their possible impact on the sound characteristics. As acoustical research has clearly focused on the violin, the following depictions refer for the most part to this instrument. None the less, most results may be transferred to the lower and larger variants of the violin family. Nonetheless, specific properties of instruments are discussed if necessary, or references are given for further reading.

A. Principles of sound production in bowed string instruments

In order to provide an insight into the mechanisms involved in sound production, it appears appropriate to explore the acoustics of bowed string instruments in terms of their components, such as the string and its interaction with the bow, the string-body coupling parts and the resonance body. Thus the basic principle of sound production can substantially be described in terms of several successive steps. Initially the string gets excited by means of a stroking bow. Several bow parameters further determine the resulting energy of the vibrations which are subsequently transferred to the top and back plates of an instrument via the bridge and sound post. Ultimately, the body acts as an effective sound radiator with frequency determinant resonance zones. In the following section, these different steps are discussed in further detail so as to subsequently consider partial aspects of instrumental construction which may be determinant for the different sound characteristics of modern and historical instruments.

1. String excitation

When applied to an instrument, the bow exerts both a frictional force acting sideways and a downwards striking force which causes a triangular motion to the string with a rotative action of sticking and slipping. This excitation principle can basically be described by way of a Helmholtz solution to the wave equation.[13] Thus the motion of a bowed string can be represented as two straight lines with a sharp kink at the point of intersection, which travels back and forth along the string. An entire cycle of a so-called Helmholtz string motion consists of the stick-to-slip and slip-to-stick transitions, as a consequence of which the terms of capture and release are also common. During the major part of such a cycle, in which the string and bow move at roughly the same velocity, the string gets pulled aside by the bow until the resisting force against the displacement, that resulted from the tension of the string, is high enough in order to slip back. The string can be caught again by the hairs of the bow, when its natural oscillation heads in the same direction of the bow's stroke. These self-excited relaxation oscillations, caused by dry frictions between solid sliding bodies are further discussed by Cremer,[14] who provides a comprehensive insight into the theoretical physics of bowed string instruments. FIG. 1 shows an idealized Helmholtz motion of a string during its vibration cycle and the displacement at the point of contact with the bow. As the traveling kink of such a cycle can be discerned only with difficulty by the eye, the observation of a bowed string results in the perception of a parabolic envelope. The arrows inserted in FIG. 1 which demarcate the direction of movement of the bow and of the kink, change as a consequence of the bow direction. At the point of release, the kink has just traversed the bow. At (b) the kink has approached the bridge, from which it further bounces back down the string in (c), (d), and (e), until it arrives at the nut in (f) and is again reflected. As the required time for one full cycle depends both on the length and wave velocity of a string, the vibration frequency remains quite constant under varying bowing conditions.[15] As can be further derived from FIG. 1, the amplitude of the Helmholtz bowed waveform vibration depends both on the position as well as on the velocity of the striking bow. Due to the independence of the kink around its curved path regarding its position and velocity, the amplitude of a vibration can therefore be increased both through a faster bow stroke as well as by bowing closer towards the bridge. The principal basics of sound production can be graphically explained with the aid of these although simplified models of the Helmholtz-motion. However, it should be noted, that several sub-aspects such as how such waves are exactly excited and maintained by the frictional forces between the bow and the string are not taken into account.[16] In order to better comprehend the detailed mechanics of the strongly nonlinear coupling process between the bow and the string, the Helmholtz model has been further investigated and extended by a variety of investigations such as those by Woodhouse and Galuzzo,[17] McIntyre and Schumacher,[18] and most recently by Berdahl.[19]

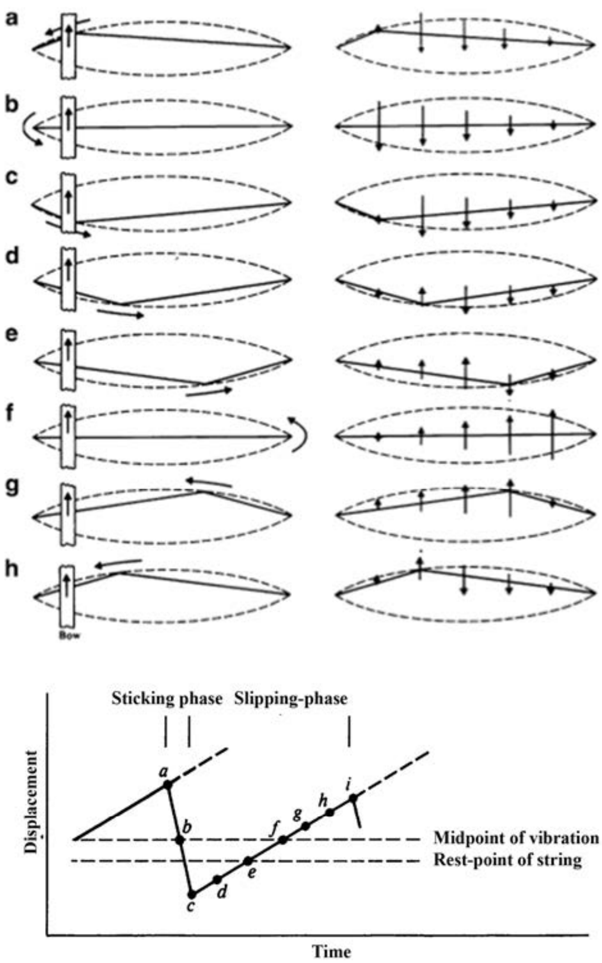

FIG. 1. Exemplary motion of a bowed string at consecutive steps (a-h) according to the Helmholtz model. On the upper side, the profile of a string viewed during bowing (left) and the velocity of the string at various points in the vibration cycle (right) is indicated. The displacement of a string at the point of contact with the bow is shown below with the respective steps from a-h (reproduced from Rossing and Hanson[15]).

2. Bowing parameters

The interaction between the bow and string has for many years been an object of extensive research and may be considered to be well understood at the present time.[17] The production of an appropriate musical tone requires a subtle coordination of several bowing parameters, as it has been formalized for steady notes by Schelleng[20] and for initial transients by Guettler.[13] The playable combinations of these parameters are further dependent on properties of the respective string and also of the instrument, providing the musician with a broad range of continuous control over the sound quality, such as loudness and brightness.[21] The vibration of the string is governed by three bowing parameters, namely bow velocity, bow force and bow-bridge distance. Saunders[22] investigated the effect of these parameters on bowed string waveforms and showed, that for a given combination of bow velocity and bow-bridge distance there is a certain range of force required in order to maintain the Helmholtz motion, as described above. Schelleng[20] derived explicit qualitative criteria for the minimum and the maximum bow force as a function of relative bow-bridge distance and bow velocity. The so-called Schelleng diagram for an open A-string of the violoncello with a constant and typical bow velocity of 20 cm/s is shown in FIG. 2, applying a log-log representation.

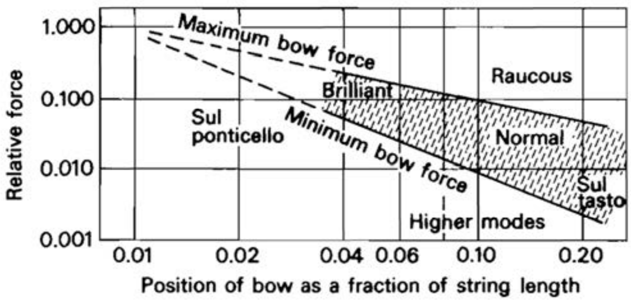

FIG. 2. Schelleng diagram, indicating the playable bow force range for different bow-bridge distances for a violoncello open A-string with a constant bow velocity of 20 cm/s (Schelleng[20]).

As the Schelleng diagram clearly implies, bowing close to the bridge (*sul ponticello*) results in a loud and more brilliant tone and requires considerable bowing force whereas bowing further from the bridge (*sul tasto*) produces a less bright tone. Due to the logarithmic scaling the diagram could lead to the assumption that the range of bow force to be applied decreases when bowing closer to the bridge. However in absolute values the force range rather increases as the distance from the bridge becomes smaller. Considering both the proportionality between bow velocity and bow force as well as the fact that the Schelleng diagram presents the Helmholtz system with regard to normalized bow-force values for a given bow velocity, the force-position coordinate shifts upwards when lowering the bow velocity while retaining the bow force unchanged. This results in a more brilliant tone character as long as the Helmholtz requirements are met.[23] Schonderwaldt et al.[24] has further proved that the maximum bow-force limit for a Helmholtz motion corresponds well to Schelleng's equation, whereas the minimum bow force is autonomous from the bow velocity. It has been further found that the breakdown of Helmholtz motion at low bow forces involves a mechanism related to ripple and corner rounding which was not taken into account in Schelleng's derivation of minimum bow force. If maximum bow force is exceeded, periodic breakdown of the Helmholtz motion leads to a weakening of the fundamental frequency and several overtones resulting in a squawking sound.[25] Consequently, a string can be excited over quite a wide range of distances from the bridge, bow velocities, and pressures. This however does not apply for sections very close and very distant from the bridge.[26] Nevertheless bowing within the range of a proper Helmholtz range results in the most sought after sound and is what musicians usually make an effort to attain.

3. String-body interaction

As the vibrating string itself is incapable of radiating an appreciable intensity of sound, the energy has to be transferred via the bridge to larger resonating surfaces, such as the body of an instrument. The bridge thus acts as an efficient string-to-corpus conduit. It also vitally influences the sound coloration and loudness of an instrument by means of its material and geometric characteristics. In contrast to the rather robust and low bridges of plucked and struck stringed instruments, the high and fragile bridges of string instruments of the violin family have a major impact on transmitting mainly transverse forces of the string into normal forces on the body through their feet. Bridges are usually made of maple and taper in thickness in the upward direction. The upper part is detached from the lower portion by a well-defined waist, providing conditions for a resonance. By these cuts in the sides of a bridge, all flexural motion is filtered out, allowing only transverse rocking motion to reach the top plate of an instrument.[27] Thus, the waist is acting as a spring, while the upper part constitutes an oscillating mass. Various studies of bridge motion and its important impedance converter role have been published over the years, providing specific spring-mass models in order to describe the vibrational modes. For example, Reinicke[28] showed that the main bridge resonance of a violin, which is the bridge's first and lowest in-plane mode, is usually found around 3 kHz and evokes a rotational side-to-side rocking of the top part of the bridge about its waist. Besides some other in- and out-of-plane resonances within the frequency range of relevance, a second in-plane mode at about 6 kHz affects an up-and-downward bouncing of the bridges top on its feet. This results in forces via the legs perpendicular to the supporting surface. As soon as a bridge is mounted on an instrument, most of the bridges modes disperse into those of the body. Below about 600 Hz, the bridge behaves as an effectively rigid element, while motions of the bass bridge foot are prevalent. By undergoing a variety of bendings with increasing frequencies, the treble foot turns into the motion's center until both feet can dominate at still higher frequencies.[16] The first and second in-plane modes and their respective frequencies for modern violin and cello bridges are shown in FIG. 3. The arrows indicate the directions of the bowed outer and middle strings. Due to the longer legs of the violoncello bridge, both twisting modes at around 1kHz and 2 kHz apply a couple on the upper top plate.

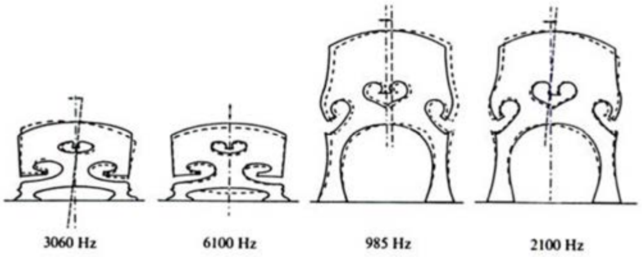

FIG. 3. First and second vibrational modes of a violin (left) and violoncello (right) (Reinicke[28]).

Further investigations on the influence of the lowest bridge resonance have been carried out, focusing particularly on the so called *Bridge Hill* feature of a violin.[29,30] This broad peak in driving point mobility is widely associated with a corresponding reversal in phase in the vicinity of 2-3 kHz in the violin and viola, 1-2.5 kHz in the violoncello, and 500-1000 Hz in the double bass. Beside the fact that not all stringed instruments exhibit this phenomenon, the precise source mechanism remains somewhat unclear until today.[31] However, recent studies have shown, that this feature arises not solely from isolated bridge motions at some rocking mode frequency but is rather due to local corpus motions at the bridge-foot position.[32] This might however be enhanced by the effective masses, Q-values and resonant frequencies of the bridge itself. Due to the uncertainty about the connection between the bridge and the top plate, the feature is sometimes also labeled as *BH*, being a combination of *Body Hill* and *Bridge Hill*.[33] As the *BH* is commonly associated with brilliance and projection in the sound, McLennan[34] suggests to designate it rather as a "Bridge Formant", in line with the feature developed by singers to enable them to stand out against an orchestra.[27] Further indications of the *BH* feature may also be noted in Dünnwald's[4] measurements of a large number of modern and historical violins of different origin (see FIG. 10). The impact of the aforementioned bridge parameters on the sound spectrum is subsequently discussed in the section entitled "String-body coupling components", indicating that such a highly valued sound as that of the Cremonese violin may be precisely controlled by adjustments of the mass, size and fitting of the bridge.

Beside the bridge, two further component parts are considered to play a major role in determining the acoustical response of any string instrument of the violin family. The The soundpost, located and slightly displaced under the treble foot of the bridge, is wedged between both plates. Additionally, a corresponding bass bar on the bass foot side of the bridge is glued along much of the top plate's inner length. Both parts are made of spruce and originate a structural asymmetry into the instrument's otherwise-symmetrical arrangement. Thus, an acoustical "short-circuiting", that would significantly reduce low frequency radiation can be prevented.[1] Moreover an additional mechanical constraint is provided by the soundpost in particular, preventing the top plate from collapsing under the large downward string force. The major acoustical task of the sound post however lies in an effective coupling of induced vibrations from the bridge or top plate to the back plate of an instrument. Due to this connection, the pivot motion of the bridge's treble foot appears to be considerably restricted, in contrast to the bass foot of the bridge, which moves more freely up and down.[16] The acoustical function of the soundpost and its influence on the vibrational behavior of an instrument has been a central research topic in recent years. Mc Lennan[35,36] investigated specifically its effect on plate nodal line positions, its interactions with the sides and the transmission of force to the back. Saldner et al.[37] looked into the changes and behavior of some of the most important signature modes of an instrument (see section below), occurring when the soundpost has been relocated or completely removed. The same phenomenon has also been investigated by Bissinger,[38] who found not only a drastic decrease in the radiation efficiency when the soundpost has been removed, but also considerable alterations of the main mode shapes, as will be discussed in the following section.

4. Vibration modes of the instrument body

Bowing a stringed instrument excites an additive response of a variety of damped normal modes. This primarily includes the mutual interactions of both plates and ribs that make up the body of an instrument. In addition, other components, such as the neck and the fingerboard, which vibrate in either torsion or bending, are involved as well and may be clearly felt by the player.[34] The interaction and performance of all these parts is ultimately considered to constitute the overall vibrating system of an instrument, consisting of both individual resonance peaks and broader resonant ranges. In order to analyze the frequencies of vibrational modes and nodal line patterns of plates, both in themselves and in the assembled violin, a series of techniques, such as the modal analysis, the finite-element analysis and laser holography has been established with the latter being essentially the modern-day equivalent of Chladni plate measurements.[16] Another common method to investigate the characteristic eigenmodes is to measure the frequency response of force admittance at the position of the string support. Thus, details regarding the frequencies, the damping and the effective masses of the normal modes of vibration can be obtained. With regard to the violin, Bissinger[39] accounts for a total of around 100 identifiable structural modes below approx. 4 kHz, although it is stated, that not all of these involve a major change to the overall sound radiation. However, since a lot of such apparently subsidiary modes evoke considerable bridge motion, they still cause resonant features in the input admittance. This not only in return leads to inharmonicity and damping of the string resonances, but also has an effect on the playability of particular notes on the instrument.[14]

FIG. 4 shows examples of typical input admittance curves on the body-mounted bridge of six different violins. The arrows on the left hand side expose the position of the Helmholtz air resonance, as is discussed in further detail below. Although such measurements provide less information on specific properties of normal modes, they still lay down a distinctive fingerprint for an instrument by highlighting the amount of resonant modes that may be excited. Not least, efforts have been made to construct string instruments of the violin family with almost analogical admittance characteristics, requiring that similar wood, with identical geometric measurements and vibrational properties, is used.[16]

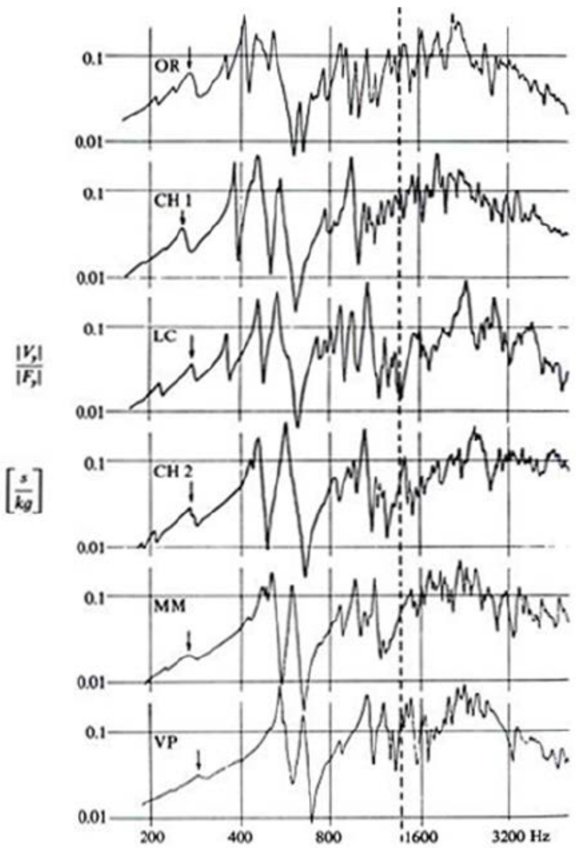

FIG. 4. Mechanical admittances (mobilites) measured at the bridge of six different violins (Cremer [14]).

At frequencies below 200 Hz, the violin acts in a way that is not directly related to sound generation, although component parts such as the tailpiece are known to show modes even below the lowest violin note (~196 Hz). With a rise of frequency, top and back plate resonances define the body vibrations of a violin, emerging in a central playing range between 200 Hz and 1 kHz. Above this range, the bridge makes an important contribution, while both plates are separated into smaller areas, radiating in a more directional way.[33,37] As Schelleng[40] has shown, the spectral composition of a single note is mainly based on combinations of an air subsystem (cavity modes) and a mechanical subsystem (body modes). It has been further stated by Hutchins,[41] that numerous interactions of both subsystems based on the frequency relations of the lowest cavity modes and the three body modes below 1 kHz are crucial to the sound and playing qualities of any string instrument of the violin family. In order to describe the eigenmodes, which contribute to the excited vibrations of an assembled instrument, different systems of terminology have been established over the years. FIG. 5 provides an overview of equivalent mode nomenclatures. In continuation, reference is made to the nomenclature of Jansson,[42] who designates all body modes with regard to their most distinctive feature: A for air modes, C for body or corpus modes, and T for particular top plate modes. The body mode designated with an N for "Neck", merits specific importance, as is discussed in further detail below.

~ Hz	Jansson	Hutchins	Curtin/Rossing
190	C_1	B-1	B_1
280	**A_0**	**A_0**	**A_0**
300	N	B_0	B_2
385	C_2		C_1
460	**T_1**	**B_1^-**	**C_2**
485	A_1	A_1	A_1
530	**C_3**	**B_1^+**	**C_3**
650	C_4		C_4

FIG. 5. Equivalent mode nomenclatures according to different investigators[1,41,42] for the most important resonant modes of a violin below 1 kHz. The highlighted modes represent the most distinctive "signature modes" of any bowed string instrument.

Virtually all modern and historical bowed string instruments take advantage of the main air resonance or f-hole resonance A_0 in order to enhance the power of low notes. This is determined by the volume of the body and the size of the f-holes. In the case of a violin, A_0 usually lies in the frequency range of 270-90 Hz, while the lowest strongly excited body resonance occurs around 450Hz (T_1). The strong peak of A_0, which is also known as the *Helmholtz resonance*, involves the lowest characteristic mode of vibration inside the body cavity as a result of the movement of a significant amount of air in and out of the f-holes cut into the top plate.[43] A_1 typically lies in the field of 480 Hz and is substantially defined by the inner length of the body. Besides A_0 and A_1, some higher air resonances, when excitation is induced by the bridge, occasionally do not appear as peaks. Due to their direct interaction with concurrent body modes, their energy is absorbed, often resulting in a trough.[44] It has been further shown, that the plate thickness and arching of the instruments body may have a considerable effect on the distribution of these lowest air modes.[45] This matter is further described in the section entitled "Resonance body". It may also be remarked, that according to Curtin,[46] research of the past years such as those of Dünnwald[4] have correlated relatively high A_0 amplitudes with old Italian instruments, suggesting that A_0 levels are an indicator of overall quality. In Curtins opinion, this phenomenon can however not be generalized, as Stradivari violins for example confound this notion. The two lowest body modes C_1 and N are described by Curtin as modes with beam-like bending motions of the violin body.[1] Compared with one of the strongest radiating body modes T_1, both C_1 and N may be considered as rather nonradiating modes. The so-called *Neck-Fingerboard mode* N however has a special significance, as it tends to be close in frequency to A_0. It has been reported that by adjusting the frequency of N to correspond with that of A_0, both the radiation in the A_0-N-range and the ease of playing may be enhanced.[41] According to Hutchins the frequency of N can primarily be altered by modifying the mass and stiffness of the neck-fingerboard combination. Additionally, the mass of other parts, such as the chinrest, the pegs and the scroll, may also contribute to the final frequency. C_2 is a rather weakly radiating corpus mode near 400 Hz. This symmetrical mode is sometimes also labeled as CBR (C-bout cross-section) and is considered, due to its shear-like-top-back motion and out-of-phase f-hole volume flows, as one of the most prominent mechanical modes.[47,48] The *main top plate resonance* T_1 is generally considered as one of the strongest radiating modes of the violin, showing a pronounced peak in the range of 440-570 Hz. It is also known as W for *main wood* or P_1 for *peak.*[22]. According to Hutchins,[41] T_1 may be considered as the result of a combination of the A_1 and C_3 modes. Finally, two further salient corpus resonances, that increase the response characteristics of a violin in the central playing range, can be found in the frequency range between 530 and 650 Hz. C_3 is a strong mode with relatively high sound radiation, resulting in a peak that has also been labeled as P2. C_4 constitutes a nearly symmetrical mode with rather less radiation in comparison with C_3.[1] The changes in tone and playing qualities of a violin related to an alteration of the A_1-C_3 range are further discussed by Hutchins.[41] The conclusion is, inter alia, that narrowing this range results in a lower overall radiation efficiency of an instrument, but in a wider frequency band. Although this is said to make an instrument easier to play, a lack of power should also be taken into consideration.

In summarizing, it can be stated that among all the above mentioned modes, A_0, T_1, C_3 represent the most distinctive resonance elements in the main frequency range of any bowed string instrument. Owing to the individual interaction properties of different components, these main resonances may slightly vary in their magnitude and frequency. None the less, these can be identified with regard to almost every instrument. As a result, these signature modes are considered to be an important quality criterion and to provide a decisive contribution to the spectral sound characteristics of an instrument. FIG. 6 shows the admittance curves of a violin, a violoncello, and a double bass, indicating the different manifestations of the main mode frequencies for the different representatives of the violin family. In comparison with the violin, the frequency scaling for the violoncello is displaced downwards by one octave and for the double bass by two octaves. This reflects the larger sizes of the lower instruments and, not lastly, enables also a direct comparison of the resonance peaks. This comparison shows clearly that the violoncello and the double bass are not simply enlarged variants of the violin. While the higher modes T_1, C_3, and C_4 of the violin are separated and spread out over nearly one octave, in the case of both lower instruments, they are gathered in one main peak, showing a particularly pronounced T_1 mode.

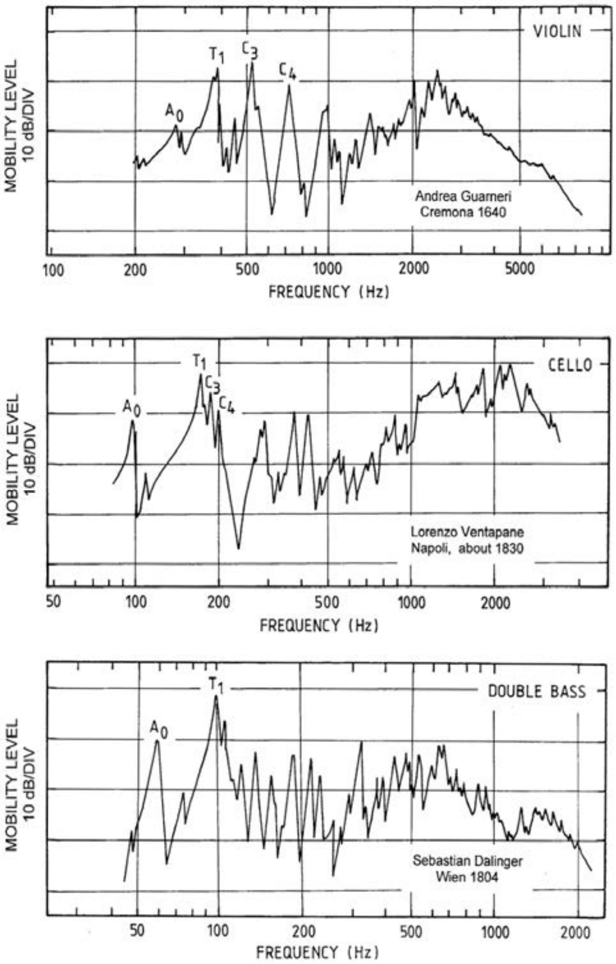

FIG. 6. Admittance curves of a violin (top), a violoncello (middle) and a double bass (bottom), indicating the different manifestations of the main mode frequencies for instruments of different sizes (Askenfeldt[49]). The frequency scaling for the violoncello is displaced downwards by one octave and for the double bass by two octaves.

Such differences in the acoustical scaling of instruments of varying size can be comprehended by means of a comparison of the mode frequencies with the tuning of those instruments. By way of an example, in the case of the violoncello, the strings vibrate at one third of the frequency of those of a violin, while however the relative size of the body is twice rather than three times as large. In consequence the bodies of the lower instruments, as those of the cello or double bass, should be larger in order to be in accordance with the acoustical scaling of the violin.[49,50]

In passing it should be mentioned that efforts have been made by Hutchins and Schelleng to create such acoustically scaled sets of bowed string instruments.[51] This so-called "new violin family" is an octet of string instruments with extraordinarily large sizes, which constitutes the first example of the use of physical scaling laws to design instruments with the same basic signature modes of a conventional violin.[47,52] Without dealing with this approach in further detail, reference shall however be made to the remarks of Askenfelt.[49] He points out the extent to which such an acoustical scaling is desirable from an aesthetical point of view. Accordingly, one argument that would favor this is that all instruments would blend very well, forming a consort sound. Owing to the furthermore associated loss of specific mode distributions of different instruments, the same argument may however be employed against scaling as a design criterion. What remains uncontested is the fact that different string instruments, regarding today's concert practice, are scaled anything but acoustically.

B. Construction forms and modifications of bowed string instruments since the 18th century

Although the general form of bowed string instruments, as we know them today, may be widely considered to be established since the time of the golden period of Cremonese violin-making, partial contrasts regarding the sound characteristics of historical and modern instruments can be recognized. As a result of a new repertoire and the aesthetical ideals of a particular period, such differences may be attributed especially to the corresponding demands on the instruments, which at all times were subject to a resulting process of adaption in their construction. However, as the physical principles of sound production remained constant over time, a critical appreciation of the individual components and their differentiated material characteristics may be revealing. Thus it can be basically ascertained, in an representative way, where and to what extent these modifications come to bear.

In the course of an examination of the evolution of the individual components, it becomes evident that the flexibility of the adaption to an appropriate sound ideal can be different between components. Thus the more easily alterable parts, such as the strings or bows, show a close affinity with the prevailing historical style and its means of expression.[53] Further obvious differences result from the examination of the fixed elements of the instruments setup. Thus the *Baroque* configurations of almost all bowed string instruments since the beginning of the 19th century were successively changed to a *Romantic* or modern setup.[34] Alterations in this respect concern the forming and positioning of the neck and fingerboard, and the increased size and weight of the main string-body coupling components such as the bridg, the soundpost and the bass bar. Contrary to this, the basic form of the resonance body may be considered as almost unaltered from the 16th century until the present time. None the less the resonance body also offers reason for a consideration of rather subtile differences regarding material and geometrical properties of the front and back plates. Here different formings of instruments from one and the same period, which can be attributed directly to their application in a certain context, may be recognized especially well.[53] Thus in the 18th century one can already encounter recommendations given to exercising musicians to have two distinctive instruments for specific purposes of employment.[54] These can be distinguished, apart from a certain choice of strings and bow, on the basis of their method of construction especially with regard to arching designs and the thickness of the wood of the resonance body. Filigree and highly arched instruments in the manner of Amati, as a consequence of their rather soft and sonorous qualities, seemed to be suitable for the interpretation of solo- and chamber music. Stradivaris rather flat and robust method of body construction is on the other hand considered to be the ideal typical precondition for orchestral instruments with "penetrating" sound qualities.[53] Not least for this reason instruments according to the method of construction of Stradivari's seem until the present day to possess validity of reference regarding their ability of assertion and projection.

On the basis of this comparison it becomes evident, that in the course of the analysis of acoustical characteristics one may only conditionally assume a paradigmatic prototype of a historical instrument. Especially in view of period orchestral instruments, the difficulty occurs that these have only seldomly been preserved in their unmodified condition, but were rather regularly subjected to modernization in the sense of an adaption to the prevailing sound ideal. Not lastly such instruments were exposed to a regular and frequent application of more intense demands. Thus in the case of those instruments, substantial modifications have to be tolerated and taken into account, as especially working parts subject to wear had to be inevitably replaced over time. Although these modifications may affect the sound in a considerable way, such altered orchestral instruments are none the less usually described as originals, even though the faithful restoration is not always feasible.[55] Despite these difficulties regarding a comparison of instruments from different times, the most important aspects of the historical development may be rationally explained on the basis of a reference to the previously discussed principles of sound production. As a consequence, a compact summary is presented below, considering the large field of instrument making traditions as of around 1700. On this basis, concrete clues regarding the possible changes in sound and, not least, also in the dynamic behavior of bowed string instruments may be found.

1. Strings

Strings being the actual generator of sound, one might assume to find comprehensive information on the physical properties of such an obvious important element, which has one of the most fundamental impacts on the sound characteristics, articulation and feel of any of the stringed instruments. In fact, quite the opposite is the case, leaving strings and especially those, which have been used in the past centuries, one of the less documented components of the instrument. While at the present time, different string material such as steel and several polyamides can be found, it is generally assumed, that all strings, until the beginning of the 20th century have been exclusively made of plain or metal-wound gut. As even the gut strings nowadays used for period instruments have been developed on the basis of an industrialized process, there is a general lack of information on the response characteristics and modulation behavior of original strings that allows the estimation of their contribution to an often striven for “original sound”.[53] However, according to recent insights, the rather irrepressible desire for utmost authenticity with regard to a genuine stringing has, within the last decades, apparently led to misunderstandings regarding the reinterpretation of old musical practice. For example, the often mentioned cause for the “thinner” and “nasal” sound characteristics of gut-strung period instruments has been associated with strings that are thinner and lighter than is the practice nowadays.[56] By taking some basic mechanical properties of different string types, such as the important aspect of tensioning into account, this concept of a “typical Baroque stringing” may however be considered as almost certainly non-existent before the second half of the 20th century.[57] As a result, regarding an informed contemporary application, it seems evident that there is more to take into consideration than just replacing metal strings with thin and loose tensioned gut variants. Some of the crucial aspects of original stringing shall therefore be touched upon in continuation.

In order to obtain a better understanding how mechanical properties of a string affect the acoustic response of an instrument, a brief initial look at the physical aspects of strings appears to be appropriate. A multiresonator system such as the string may be approximately described by taking into account the main parameters of mass per unit length, the playing tension (stiffness) and elasticity.[25] Due to the determination of the fundamental vibrational frequency and the string length by the tuning and construction of an instrument, the only alterable variables are given by the tension and the mass per unit length. From this it follows, that a constant ratio between those variables is essential in order to maintain the fundamental frequency required. As a consequence of this correlation, the specific weight of a string constitutes the most common unit of measurement for practical applications. The significance of weight is further underlined, if one considers the fact, that the specific vibration sensitivity of a string is given by the inverse proportionality of its weight and can therefore also be derived from the mass per unit length. Useful information on the mechanical behavior of a certain string material may also be attained by considering the parameter of density, that determines the amount of energy which is transferred into the body of an instrument.[23] With a density of 7.700 kg/m^3, steel shows a value six times higher than gut, which in contrast has a comparatively low density of 1.300 kg/m^3.[33] As a consequence, a gut string requires 2,5 times the thickness in order to provide the same tension as a steel string for the same pitch. With regard to a representative comparison of the specific vibrational sensitivities of equally tuned steel and gut strings with the same thicknesses, a loss by 16 dB is indicated in the case of the gut type, with the corresponding decrease of the sound level by 16 dB respectively.

With these fundamental facts in mind, the rather intuitive approach of gut string manufacturing within the last few centuries may be understand more readily. Although until today there still is uncertainty on the precise construction details of gut strings, the basic traditional production process may be described by a simple procedure. Lengths of the strong membrane material of the intestines of sheep is threaded between two hooks and twisted on one end until the resulting string attains a cylindrical shape. After a subsequent drying and optional polishing process the plain gut string has received its final form. This is evidently a simplified representation, as may be appreciated by the investigations of Peruffo,[56] who provides an overview of practical gut string manufacturing techniques in the 18th and 19th century. According to Peruffo, the treatment of the gut material with several substances such as alkaline solutions before and after the twisting process seems to be of importance in order to increase the elastic properties of a string. Further developments towards more flexibility has been achieved both by putting as much twist as possible on a string as well as by spinning two or more such highly twisted strings together in a so-called rope construction. *Catlines* or simply *cat guts* have been other designations for such types of roped-gut strings. Both of those highly twisted types were held in great esteem for their elastic properties. As elasticity can be understood as a measure of change in tension and hence pitch range for a given change in length,[25] the development of such strings seems to be of importance in view of more efficient mid and low-range strings. In consideration of the above, it can therefore be held as a principle tendency that more harmonics emerge with an increase in elasticity of the string material.[58] Due to the aforementioned fact, that the gauge and the mass have a profound effect on the pitch range of a string, further ways of production approaches aimed at designing appropriate types for each register can be found over the years. As an example, Peruffo[56] points to a common string-making method in order to increase the specific weight of the gut in lower bass strings. Allegedly, the chemical treatment by means of heavy mineral salts enabled the production of thinner yet more sonorous types of strings, which visually distinguish themselves by their brown or dark red color, compared to the typical yellowish coloration of natural gut strings.

As has been shown above, the thickness of a string increases with length towards mid and low-range registers and thus also changes the spectral characteristics in a considerable way. According to Segermann,[58] there is a certain point where the thickness of a plain or roped-gut string reaches a limit, resulting in a rather dull sounding quality due to a lack of overtones. As a consequence, the change to another material or construction type with more elasticity in terms of its weight seems to be indicated. Although it has been documented that an all-gut stringing was used until well into the second half of the 19th century,[58] the invention of metal-wound plain gut strings may be considered as an important turning point in the history of both music and instrument-making. By closely wrapping a gut string with a round metal wire of silver or (silver-plated) copper, the density is considerably increased, which consequently facilitates the construction of thinner and thus more manageable lower strings.[57] This fast-spreading innovation, which is said to have emerged in the second half of the 17th century may therefore be seen as path-breaking both from a practical and also from an aesthetical point of view. On the one hand, those metal-wound strings, were initially used on the lowest strings of bass instruments for mainly physiological reasons, enabling a more convenient way of playing. Peruffo[56] even describes these new strings as directly responsible for the swift abandonment of "the awkward bass-violins" in favor of the emerging violoncello. On the other hand it goes without saying that such changes in stringing must also have paved the way for a new repertoire, providing composers and musicians with new aesthetic possibilities. This leads to the second aspect of also stringing treble instruments, such as the violin with metal-wound gut strings as of that time. Without going into physical details, Segermann[58] points out that for example a metal-wound violin G-string provides a "more focused" sound compared to an all-gut type, which must in all probability be a result of its richer harmonic spectrum. It is further stated by Segermann,[59] that while "compressing the range of different tone colors available across the instrument", such metal-wound strings provided the player with more smoothness and quicker response characteristics. Besides these qualitative assessments, a general lack of research information in this field impedes a further analysis of the modulation behavior of these types of period strings. Such strings have moreover mostly not been preserved. This difficulty is further compounded by the fact, that innovations in string manufacturing in the 20th century are said to have profoundly altered the design of wound strings for the violin family. Most notably, the metal-round windings were successively replaced by metal-flat-ribbon windings, providing an expanded contact area with the bow. Besides new core materials, such as steel rope and synthetics, a thin layer of plastic floss or ribbon has been implemented between the core and winding, not least in order to improve the tuning stability.[58]

Summarizing an overview of typical string patterns for a certain period, the chronological sequence for a violin may be classified by means of the following examples: While an all-gut setup with a plain gut E, a plain gut or high-twist A, a high-twist or roped-gut D and a roped-gut G has been used until well into the second half of the 18th century, the roped-gut G has been widely replaced by a metal-wound G at the end of the 18th century. In the 19th century, a combination of a plain gut E and A, a high-twist D and a G with (silver-plated) copper may be seen as a typical string pattern. With regards to changes in the 20th century, both the emergence of steel strings for E and A as well as the replacement of the high-twist gut D with aluminum winding seem to be general tendencies, which, together with the aforementioned alterations to wound strings, still applies today.

If one relates the aforementioned physical correlations to the recommendations of influential didactical papers of the 18th century, it becomes clear that the initially mentioned concept of a "typical Baroque stringing" with thin gauges and loose bow tensions, especially in the case of the lower strings of larger instruments, cannot apply in principle. Thus both Quantz[60] as also Mozart[61] demand in the middle of the 18th century different types of stringing, dependent upon the purpose of use of the instrument. Thus especially orchestral musicians were advised to string their instruments with massive and thicker strings in order to distinguish themselves with "a strong and manly bowing stroke"[61] from the softer sound characteristics of solo- and chamber music instruments. Since, as has been previously described, thicker strings are in principle accompanied by higher tensions, the level of string tension constitutes one of the most cardinal differences between historical and modern string patterns. According to Segermann[58], two basic systems of stringing may be considered to have generally coexisted as of around the middle of the 18th century, The system, originally most widely dispersed throughout Europe, is represented by the so-called principle of equal tension, which has all of the strings at approximately the same tension. Segermann defines all string patterns as equal, as long as the tension of each string deviated from the average of the pattern by no more than 10%.[62] The stringing principle of progressively changing tension, which has widely been maintained until today became established around 1800 with the new development and rapid spreading of the metal-wound gut strings.[56] This system can also be seen in a direct relation to further modifications to the instrument setup, such as the altered string-body coupling components.

It has never the less been reported that the system of equal tension was still in use with all-gut stringing and with the lower metal-wound strings throughout the whole 19th century.[63] Not least, there is some indication that this system is increasingly gaining recognition also in the context of today's historically informed interpretation of the early classical orchestral repertoire.[53]

On the basis of the previously mentioned recommendations regarding thicker and more robust string material in connection with orchestral instruments, it can be assumed that both Mozart and also Quantz have been proponents of the equal tension stringing principle. As has been shown, clearly higher tensions for all strings, in comparison with the presently utilized modern system, result in view of the practical application of the equal tension system due to the systematically increased thickness of the lower strings.[57] Whether the four strings of an instrument are at exactly the same tension or deviate slightly from each other, one main advantage often mentioned, is, of an equally strung system from the players perspective, the equal "feel" of each string in so far as that the same force at the identical relative positions of the string presses down each string to the same extent.[58] According to Webber, the resistance of the strings under bow and fingers is also much greater. This poses further questions regarding playing techniques, such as the interaction with the bow.[57]

Not least, unambiguous tendencies which may be of significance within the context of a historically informed performance practice result in view of the differences between both string tension principles. The equal tension system may generally be considered to have a balancing effect on the overall sound characteristics of an instrument in terms of the perception of loudness. This may be ascribed to the increased tension of the thicker lower strings, which are said to allow a higher "volume of sound" to be drawn from the instrument.[57] Consequently, compared to the progressively changing tension system, the instrument shows a more equalized leveling, rather than having an emphasis towards the treble. With an extension of the playable pitch range in the course of time, highlighting the upper range becomes increasingly desirable, not least due to the demands of new repertoire. This seems to be another main reason for the establishment of the progressively changing tension system in the 19th century. As Segermann points out, a further benefit of this system may be seen in the decreasing difference between adjoining strings regarding the maximum energy one can apply to a string with a bow.[58] Consequently, this enables the player to move more conveniently from string to string at maximum loudness.

2. Bows

Even though the central role of the bow is considered to be one of the most deciding determinants regarding the generation of sound, it has, until this day not been possible, to explain scientifically what causes one bow model to sound different compared to another. This particularly applies to the historical bow models, whose physical characteristics are even less sufficiently documented However, conclusions can be drawn from the varying playing characteristics of original bows, which closely interact with the string material and the playing technique, regarding the conception of tone and articulations at the time.[53] With regard to the evolution of the bow, one can, in general, proceed from a rather uneven development until the end of the 18th century. Thus Boyden describes the different configurations of various bows as unstandardized in length, design and weight, hence also resulting in quality differences.[64] Köpp in essence traces this multiplicity back to the fact that bows, in comparison with other components of an instrument, such as the resonance body with its mounted parts, could be more easily and sensitively adapted to the necessities of a period.[53] Thus the more robust string gauges of an orchestral instrument required a correspondingly heavier bow with stronger hair. To the contrary a markedly longer bow model has for instance been preferred for virtuoso solo- or sonata playing to meet the requirements for broader articulations of phrases and legato.[34,53]

While the evolution of bowed string instruments since the 18th century can be generally traced back to the craft of the Cremonese violin makers, the development of the modern bow, as we know it today, can be essentially seen as a French contribution, consequence of the establishment of a new profession of bowyers around 1750. Thus the probably most renowned bowyer Francois Tourte develops a bow around 1785 with standardized characteristics and component parts which maintain validity of reference until the present day.[64] Besides Tourtes' pioneering technique of hot-bending of bow sticks, the use of pernambucco wood and a screw for adjusting the hair tension, the reversed camber and the standardized length of the stick, the hatched head and a fixed width of the bow hair belong additionally to the key features of the so-called modern bow. Compared to the varied set of earlier bows, the Tourte bow is often considered to offer the musician an increased dynamic range along with a more intense and powerful tone.[34] This can be traced back to the altered distributions of weight and to the concave cambered bow stick which enables a more rapid increase in the bow force and thus a more direct impact on the string. With the earlier concave or straight cambered models, more movement, and thus time has been necessary in order to achieve a corresponding bow force.[23]

Further differences in the construction of period bows are evident in the course of a detailed observation of the individual components, whose interaction constitute the characteristic playing attributes of each model and affect the acoustical response of an instrument. Thus in the course of time not only the bending and length of the bows, but also their weight increase in a noticeable way. Furthermore the center of gravity is displaced along the length of the bow, in function of the form and mass of the head and the frog. This may have a significant influence on the possibilities of articulations. Historical bows can be assigned relatively easily to a specific period and purpose in consideration of the elaborations of the head and frog as well the shape of the stick. FIG. 7 shows four bows from the 18th century. The two upper bows may be considered to be rather typically earlier and the lower two rather later models. The upper-most bow is a slightly convex-curved bow with a fixed clip-in frog mechanic and a swan bill, as was typically used in the orchestra of the 18th century. The second bow from the top represents a rather extraordinary prestige-model with a straight stick and a pike's head, having also a movable ivory frog in the form of a pandurina. This bow is also denoted as a so-called Stradivari bow. The second bow from the bottom is an original Tourte bow with the above described properties of a concave stick and a hatched head, while the bow at the bottom represents an English transitional model and may be seen as a direct precursor of the Tourte bow.[64]

The earlier shorter bow, widely used in orchestral practice as late as the end of the 18th century, is equipped with a so-called clip-in frog mechanic. The hair of the bow has been tensed only by means of the frog which was notched into a dent at the lower end of the stick. Consequently the fixed tension of the bow could be changed only slightly by the introduction of additional material between the frog and the beginning of the hair. Constructionally necessitated, the basic tension of such a frog had to be relatively high to avoid the frog popping out of its anchorage. According to Köpp[53] the denomination „frog" goes back to this circumstance, as a rise in humidity and the consequential decrease in tension of the bow hair, favored this occurrence. Although the novel and initially costly bows with screw mechanics have been utilized by soloists and virtuosos since approximately 1750, it can be taken as granted, that only bows with clip-in frog mechanics have been available to orchestral musicians until the beginning of the 19th century.[53] Studies, which assign a "stronger sound" and more precise response characteristics to bows with clip-in frog mechanics, substantiate that this had also aesthetical reasons in consideration of a specific sound-ideal.[65] On the contrary a bow with a screw mechanic allowed a great increase in the "flexibility" and "plasticity" of a sound.[66] This may have accommodated the rather muted sound ideal of the sentimentality (*Empfindsamkeit*) of the early classical period, especially within the context of chamber music. The cause for such judgments regarding the differences in acoustic response between both types of bows may be most readily discerned on the basis of the different principles of construction of both types. In the case of the bow with a screw, the mechanism suspends the coupling between the wood of the bow and the hair at the lower end. In the state of tension the frog is thus pulled away from the stick of the bow so that, as a consequence, only the front-most end is in direct contact with the stick of the bow. To the contrary, the bow with the clip-in frog mechanic constitutes a closed system with a characteristic natural oscillation, the frog being in close contact over its total upper side with the bow stick.[53]

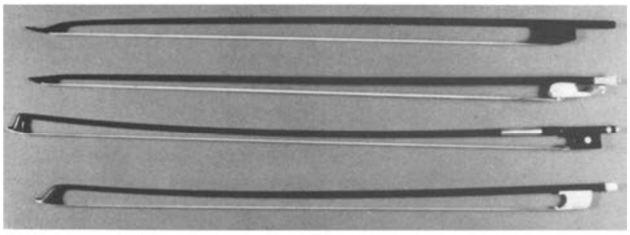

FIG. 7. Two early 18th-century bows (top) and two bows of the later 18th-century (bottom) showing different configurations of the stick curvature, head forms and different frog-mechanics. The second bow from the bottom represents the modern Tourte-bow model (Boyden[64]).

Whilst at the latest since the time of Tourte, Pernambucco wood represents the first choice for the majority of all bows, the so-called Snakewood has previously been the dominating wood in bow construction. The preference for both tropical woods can be explained on the basis of their wood characteristics of especial elasticity and density. Thus both types of wood have the same Young's modulus, whilst Snakewood indicates an even greater density.[23] The characteristics of high specific mass, in conjunction with distinctive long grain can be considered to be the main reasons for the former preference of Snakewood. Longer and also thinner bow sticks could thereby be realized, without having to accept a loss of elasticity and strength.[65] As a consequence of these wood characteristics, bows made from Snakewood were seldom slackend, as they have been less exposed or even not at all, to the danger of deformation. Reiners also indicates that bows with the clip-in frog mechanic could be played, as a consequence of their construction, with a substantially higher tension.[66]

Apart from such differences in construction, the different playing characteristics of bows on the basis of the three previously described main bow parameters and the characteristics of their interaction with the respective string material may be described. According to Köpp,[53] it is possible, especially with slow strokes, not only to realize a greater spectrum of bow velocity with historical gut strings, but also to broaden the scope of possible bow pressures. As already established by Mozart,[61] especially the velocity of the bow can exercise an influence upon the sound intensity and thus represents an important element regarding historical bows and string material, most notable in the shaping of long notes. The expanded possibilities in the spectrum of the bow pressure furthermore result in technical playing conditions regarding historical variants which on the one hand enable manifold articulation nuances on the string,[60] but on the other hand allow jumping bow strokes only on rare occasions. The third bow parameter, namely the bow bridge distance, becomes especially important in view of the more heavy plain gut strings with their clearly more inert mass characteristics. Thus the occurrence of an inherently high share of side noise on the lower strings could be deliberately counteracted through a determined choice in the point of contact. The width of the bow hair, which has changed over the years, also seems to have a direct relation to the control of the inevitable amount of side noise. Therefore a bow as typically used in the orchestra of the 18th century was strung with relatively few hairs (typically 60-80 hairs) to thus reduce the higher amount of side noise on the rather rough surface of gut strings. While 100-120 strong hairs have already been utilized for a Tourte bow in the middle of the 19th century the quantity of hair of the present bow models is typically around 200 hairs[53]. Recent investigations have shown that a decrease in the width of the bow hair can also have an effect on the string spectrum for higher harmonics. Especially a gain in particular harmonics of 3-6 dB above harmonic 20 has been reported.[67] Although this effect has been investigated in view of the tilting effect of the playing technique of a modern bow on a modern string, there are strong indications that the lesser hair width of historical bows has a favorable impact on the radiation of higher frequency components.

A further discussion of the constructural changes of period bows and their impact on various playing characteristics can be found in the work of Boyden,[64] who also indicates that the obvious differences in construction and the developments are often directly traceable to the requirements and needs of renowned virtuosos and soloists. This allows the explanation of why bows before Tourte's time have been named rather after their famous players such as Corelli or Tartini and not after their actual manufacturers. Even the Tourte bow has been sometimes denoted after the renowned violinist Viotti, who is said to have been one of the first employed of this model and to have contributed to its further development. Another such example which constitutes an important step towards the modern Tourte bow, is the so-called Cramer bow.[64] Without going into further constructional details, this bow may be seen, due to its distinct playing characteristics, as ideally suited for the interpretation of the early Classical repertoire. This model goes back to the German violinist and conductor Wilhem Cramer, who has been one of the leading performing musicians of the so-called *Mannheim School.* This association of musicians and composers is not only considered as an influencing innovator leading to the Classical and Romantic styles, but is also known for an innovative use of dynamic effects in the orchestra, such as the so-called *Mannheim Rocket* and the *Mannheim Roller*.[68] As a consequence, it might be conjectured, that due to its playing characteristics, the Cramer bow model has made a considerable contribution to the specific sound aesthetics of this period.

3. String-body coupling components

Compared to the actual sound producing parts of an instrument, such as the strings and the body, the most obvious alterations as part of the modernization process during the 18th century can be identified if one considers the string-body coupling components such as the bridge, the neck, the fingerboard, and of course the sound post and the bass bar. In general, all changes which have been made regarding these parts have been seen often in a correlation with the need for both an increased projection and playability of an instrument, required by composers and musicians of the appropriate period.[34] In the case of the violin, Babitz[69] investigated the key trends in the evolution of these component parts as of around 1600 and sketched his findings in an illustration, shown in FIG. 8.

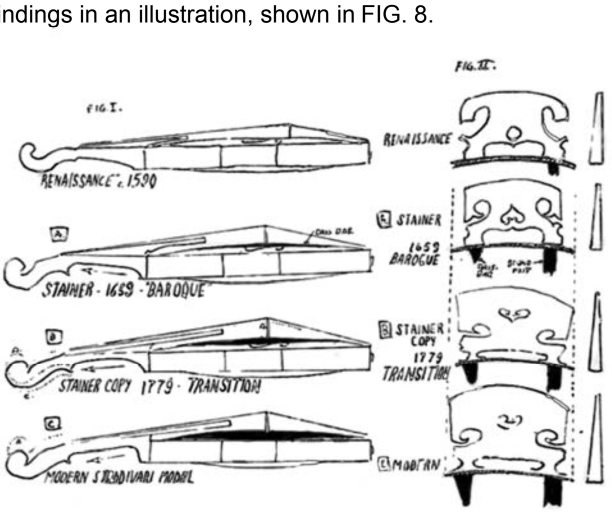

FIG. 8. Alterations of several string-body coupling components from the Renaissance to the modern setup (Babitz[69]).

A first remarkable alteration can be seen regarding the neck-fingerboard combination. While the neck of the early *Baroque* model tilts slightly upwards, a tendency towards a downwardly turned angle is indicated in the *Transition* model. This involves an adjustment by eliminating the wedge between the neck and fingerboard which originally assisted in holding the instrument while playing in the first position.[34] Together with the emergence of the chinrest by the beginning of the 19th century, these modifications allowed for a more flexible movement in higher positions along the extended fingerboard. In order to compensate for the altered angle of these components, an increase of the relative proportions of the bridge as well as the sound post and bass bar has been necessary, not at least in order to withstand the resultant higher force acting vertically through the bridge. Besides a greater height and thickness, the bridges curvature furthermore becomes more pronounced and indicates some differences regarding its structural design. Babitz particularly emphasizes the “high eyes” and the square feet of the baroque bridge, which totally differ from the “low eyes” and broad, splayed feet of the later bridges.[69]

Considering these various configurations, it seems evident, that the often mentioned evolution towards a perceived increase of the power of an instrument could have been precisely controlled by the structural adjustment and fitting of all the above described component parts. As a proven example, raising the height and size of the bridge can be considered as a practice of violin making established for a long time in order to enhance the brightness and projection and of an instrument.[70] This technique can be comprehended by means of a theory of Cremer,[14] who found that the mobility at the indents of the strings tends to increase as the square of the ratio of bridge-height to bridge-foot spacing. As a consequence, the acoustical output for a given string force is often said to increase with higher bridges, while maintaining the foot-spacing unchanged. Another widely applied process which is commonly known as bridge tuning among violin makers may be practically reproduced by a simple experiment. Raising the effective mass by either narrowing the waist or adding a light mass (or mute) on top of the bridge, results in a softer tone and a distinct decrease of the resonant frequency and consequently lower high-frequency components in the spectrum of the sound. Increasing the in-plane stiffness of the bridge by inserting tiny wedges between the wings to restrain the rocking motion of the top of the bridge increases the resonance frequency and thus the brightness of the perceived sound characteristics of an instrument.[16] Scientific investigations considering this phenomenon may be found by investigators such as the likes of Hutchins,[70] Jansson et al.,[71] Rodgers and Masino[72] and Curtin,[73] who provide in-depth theoretical and practical insights into this matter. FIG. 9 illustrates the degree of this correlation by showing a force transfer function of a violin bridge for an added mass of 1.5 g and additional stiffness through inserted wedges between the wings of the bridge.

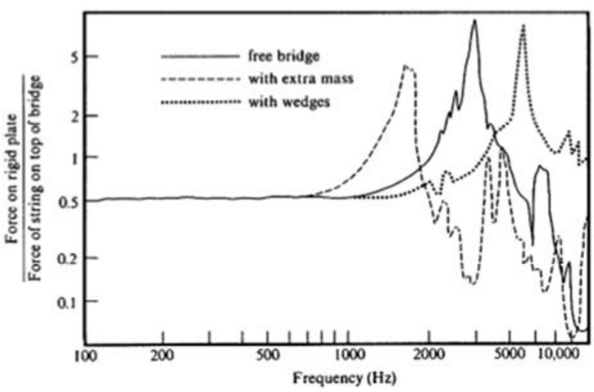

FIG. 9. Exemplary representation of the bridge tuning process: Force transfer function of the bridge with additional mass (1.5 g) and additional stiffness of the bridge (Reinicke [28]).

Besides these verifiable facts of the bridge-tuning process, the aforementioned BH feature constitutes another phenomenon, which has often been attributed to the first in-plane resonance of the instrument’s bridge. Although there is still some uncertainty about the definite cause, it seems rather likely, that quite a complex interaction between the bridge, the top plate and not least, the sound post is accountable for this feature.[34] Jannson further points out, that in the case of “good violins” the resulting broad hill in the 2-3 kHz range is the particular result of two forces acting in opposite directions at the bridge feet.[32] Thus, according to Jansson, the BH peak may be specifically adjusted to a certain extent both in terms of frequency and level by modifying the distance between the bridges feet. Considering Dünnwalds[4] superimposed admittance measurements of a great amount of high-quality Italian, modern master and factory violins in FIG. 10, a remarkable lack of the BH for all examined modern master violins is clearly indicated. According to Gough this may be attributed to a wider variation in bridge resonances and effective masses of bridge and plate resonances.[16] Although it still needs to be explored, if this may be regarded as a general and systematic tendency, the presence of such a pronounced acoustical resonance band constitutes without any doubt a considerable aesthetic criterion regarding the specific sound characteristic of an instrument. Since the BH feature arises in the most sensitive frequency region of the human auditory system, it might also be of particular importance in terms of the perception of loudness.

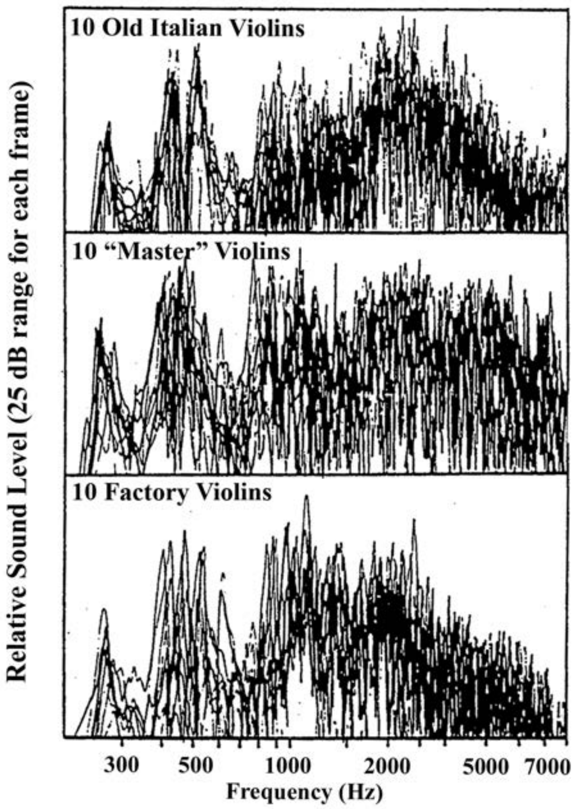

FIG. 10. Superimposed admittance measurements of 10 distinctive old Italian (top), modern master (middle), and factory violins (bottom) as a function of a constant sinusoidal input force at the top of the bridge (reproduced from Dünnwald[4]).

By taking a closer look inside the instruments body it is indicated, that the geometrical dimension of the soundpost has altered over the last few centuries as well. Compared to the modern setup, the generally lighter and smaller versions in period instruments are widely considered to have a profound impact on the specific sound characteristics of such variants. As it has been described before, the key function of the soundpost lies mainly in an effective coupling of the initiated vibrations from the bridge onto the top and back plates of the instrument.[16] This may be seen as the main reason, why already early in the Renaissance period the soundpost has been introduced to string instruments of the violin family in order primarily to increase the radiation efficiency of both the fundamentals and some further important body resonances.[34,37,38] To provide an example, it has been stated by Jansson,[74] that the installation of a soundpost considerably increases especially the markedness of some of the aforementioned signature modes, such as most notably A_0, T_1 and C_3. As the soundpost itself does not show any resonances within the main pitch range of an instrument, an almost truly rigid behavior may be assumed. Therefore it seems evident, that the material quality of its wood plays only a tangential role.[75] Assuming an ideally tailored length, positioning and mass, the longitudinal stiffness in compression may thus be regarded as the most crucial physical parameter which is mainly defined by the grain structure of the wood and its dimensions.[34] As it has been shown in the course of an experimental investigation by McLennan,[35] the power of particularly the lower registers may be considerably increased by raising the stiffness of the soundpost. This is simply achieved by expanding the diameter or by using stiffer wood, which has been a common practice in the course of the development of more powerful sounding instruments. Considering the bass bar, both its acoustical properties and evolution appear to have fallen into a research shadow thrown by the other aforementioned string-body coupling parts. However, it can be deduced from the investigations of Babitz that this component has been nonexistent in early bowed string instruments and after being initially implemented, constantly increased in size (see FIG. 8). Besides the principal purpose of providing mechanical constraint and structural asymmetry into the instrument's otherwise symmetrical arrangement, it still remains uncertain though, to what extent the installation and modification of the bass bar also plays a role regarding an alteration of certain top plate modes. While on the one hand the introduction of a bass bar has been considered as hardly affecting the behavior of top plate modes in general,[25] Bynum[50] on the other hand refers to a practice of violin making, which increases and spreads especially the T_1 and C_3 mode by using, inter alia, lighter and smaller bass bars. This matter is further discussed in Section V, as it might be assumed, that this phenomenon is indicated in the course of a comparison of the examined violoncellos, at least to a certain extent.

4. Resonance body

Compared with the great variation in size and form of the different bowed string instruments during the Renaissance period,[76] no significant alterations in this regard are noted thereafter. With the center bouts established, the plates arched and no variation of the position of the f-holes, the instruments' shell hardly changes in shape.[34] Although this could lead to the assumption that the resonance body has a rather secondary influence on the sound ideal of a certain period, it is still advisable to take into account both its geometrical and material properties as vitally defining the vibrational characteristics. Wood is generally considered as a highly anisotropic material with distinct mechanical properties involving vibrations of the complex three-dimensional shape of the instrument body perpendicular and parallel to the grain. The top and back plates are usually made of different types of wood with different thicknesses and arching, causing highly dissimilar wavelengths of flexural vibrations for typical vibrational modes.[16] Top plates are traditionally carved from two adjacent pieces of quarter-cut spruce, although sometimes pine or fir is used as well. Spruce is considered to be a softwood, typified by a dense grained formation with prominent annual rings of large thin-walled cells, separated by dense thick-walled cells, providing a profound stiffness along the grain and flexibility across the grain. Other parts of the instrument such as the back plate, ribs, neck and scroll are usually made of maple, a hardwood with a less obvious grain structure. Further hardwoods such as sycamore, poplar and willow have been used as well, particularly for instruments of the lower registers, while the use of pearwood and some harder fruitwood became increasingly rather rare.[77]

The extent to which the material properties of wood contribute individually to the formation of sound qualities has been the subject of both a variety of scientific investigations as well as the substance of empirical knowledge of violin-making practice over an extended period. Although mass, stiffness and damping are the essential determinants which define the resonant behavior of an instrument, the following material properties are also known to be of importance: elastic moduli along and across the grain, shear, density, internal friction coefficients as well as the velocity of sound in the wood.[40,78] In addition, Schleske[79] particularly emphasizes the relevance of the local orientation of the grains and rays of wood. These he considers to be even more crucial than for example the consequence of modifying the variation of plate thickness. This is said to be mainly due to the fact, that the orientation of grain and rays relative to the arching determines what fraction of the maximum available sound velocity will be attained in the two directions of the arching, longitudinal and cross. An example regarding the investigation in wood densities of classical Cremonese and modern violins, using Computed Tomographic scans, can be found in Stoel and Borman.[80,81] Although no remarkable dissimilarity could be determined between the median densities of modern and historical instruments, the density difference between wood grains of early and late growth has been proved to be considerably smaller in classical violins, both in the case of the top and back plates. These divergences in density differentials are said to possibly reflect similar changes in stiffness distributions, which could directly impact vibrational efficacy or indirectly modify sound radiation via altered damping characteristics.

The physical evidences of the common methods of traditional violin-making indicate that the damping characteristics of an instrument can be substantially influenced by the specific treatment and distribution of plate thickness. Once the basic form of a plate is established and the inner surface is carved out, some important adjustments of the plate thickness are made before the instrument is assembled. This procedure is widely known as plate tuning. By tapping a single plate with a finger on several positions of the instrument's body, the quality of a specific frequency, damping and mode shape of one or several vibration modes can be evaluated allowing for further fine-tuning operations to achieve what has been described as a "clear and full ring".[25] Mc Intryne[82] especially points out that sometimes a difference can be heard even as a result of removing just 0,1 mm of wood from a few square centimeters of plate of some 3-5 mm thickness.[78] Contrary to the widespread opinion among today's violin makers and researchers, that these "ringing times" of the top and back plates of a high-quality instrument should be as long as possible, Curtin found, that original plates of old instruments seem to be more profoundly damped compared to their modern counterparts.[83] Skudrzyk[84] further investigated this phenomenon and found that old wood has remarkably low damping characteristics at low frequencies and an even stronger damping effect than modern wood at higher frequencies. Thus he arrives at the rather remarkable conclusion that because of the low damping properties at low frequencies, old violins usually have even more carrying power than modern violins. Meinel[85] experimentally investigated the mode shapes and amplitudes of vibration through the procedure of narrowing both plates of a violin. As a result, a distinct decrease of the initially predominating natural frequencies has been noted, the fundamental increasingly becoming the strongest partial throughout the thinning process. Allegedly, this accounts for a more strident and bright sound for thicker and more robustly built instruments, compared to instruments with thinner plates, which tend to have a rather muffled sounding character.

Already in 1774, Löhlein[54] directly correlated the physical and geometrical properties of the body of the violin with markedly different sound characteristics, which he discusses in a highly subjective way regarding aesthetic and stylistic preferences of those times. According to Löhlein, the violins of Stradivari are robust instruments, more "penetrating" in their sound, often with ticker plates and relatively weakly marked archings of the body. He alleges that due to their "solid", "penetrant", and "oboe-like" tone, those variants were suitable for their use in the orchestra. For "delicate" ears however these instruments were somewhat "insulting" and have thus not been preferred by all contemporaries. Reference was further made to the by far more marked archings of the body of Amati violins which enabled these, in comparison with others, to "always sound as full and gentle as a flute". As a consequence, those variants should be preferred for solo and chamber music playing. Beside the fact that the body's arching constitutes an obvious aspect of the artistry of an instruments shape, virtually all renowned violin makers are said to have experimented with the parameters of arching and plate thickness throughout their period of creativity in order both to adjust the overall quality of the sound as well as for constructional reasons. Higher arched front and back plates are widely regarded as providing a bowed string instrument with an improved amount of stiffness and structural rigidity without at the same time increasing thickness and adding mass.[25] Most importantly however, arching is considered to have a crucial significance for the inrease of mainly the lowest flexural plate modes of an instrument. According to a rather theoretical approach by Gough,[16] a duplication of the respective mode frequencies can be achieved when the height of the arch is a little more than twice the shell thickness

By applying a simplified version of Dünnwalds[4] timbre parameters for "Old Italian Violin Sound", Buen[86] compared the spectral sound characteristics of 15 Stradivarius and 15 Guarnerius del Gesú violins. As a result, it has been stated, inter alia, that instruments with thinner plates and higher arching generally show higher values for some distinctive spectral ranges and thus sound "more Italian" while also sounding "less loud". Buen has further shown in detail that a lower border and average thickness of the back plate correlates specifically with nasal components and a marked low frequency parameter. On the other hand thinner top plates show signs of being most influential on higher parameters, associated with clarity and brilliance.[86] Using the example of the *Violon du Diablé* of Guaneri del Gesù, shown in FIG. 11, Buen however clearly points out, that in the case of such specifications one may only speak of tendencies which can neither be generalized nor reduced to any of the parameters discussed above. According to Buen, this very famous model from the Golden Period of violin-making shows both high values of all timbre parameters while at the same time having also a remarkably high sound output. In conclusion one cannot in consequence detect a systematic change or evolution of the resonance body of bowed string instruments since the golden period of Cremonese violin-making.

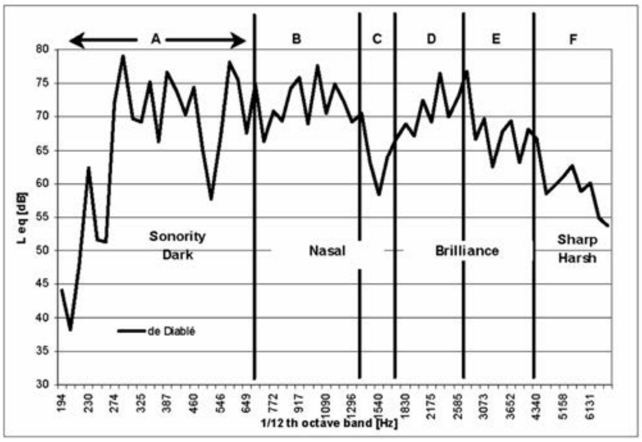

FIG. 11. Long- ime-average spectrum of a highly projective old Italian master instrument (Le Violon du Diablé by Guarneri del Gesù from 1734) with frequency regions of the Dünnwald parameters[4] and typical terms in order to characterize the timbre in words (measured by Dünnwald,[4] reproduced by Buen[86]).

IV. METHODS

In order to investigate the sound power of musical instruments, two different procedures among conventional engineering methods appear to be appropriate. Unlike Meyer, who investigated with a reference sound source in accordance to the reverberant room method,[6,7] the enveloping surface method in a full-anechoic chamber is utilized in the subsequently described investigation, consistent with the ISO 3745 standard for sound power measurement under free-field conditions.[87] By means of a spherical microphone array, time-averaged sound pressure levels are measured at a total of 32 discrete points, surrounding the instrument from all directions. The resulting individual levels are energetically averaged locally over an imaginary spherical enveloping surface and from this an unweighted sound power level is determined. The utilized method proves to be more robust compared to other procedures for the determination of the sound power, having, as systematically determined, the lowest interval of measurement uncertainty. This is documented in DIN EN ISO 3740, Table 2,[88] as the maximum value of the standard deviation of reproducibility. For instance, compared to measurements in a reverberation room, the range of measurement uncertainty may be reduced by up to 2 dB when applying the enveloping surface method in a full-anechoic chamber according to accuracy class 1.

A. Measurement Environment

All instruments were recorded using a spherical microphone array with a diameter of approximately 4.20 m. The arrangement chosen was a truncated icosahedron (soccer ball shape) with regularly distributed microphones at each center of a surface.[89] All requirements defined in DIN ISO 3745 regarding the measurement conditions were principally met, the only difference being the total number of microphones. Instead of using the recommended quantity in sets of 20 units in a clearly defined order (in accordance to Appendix C), a total of 32 units were used. This increase in the number of measurement points has been necessitated by the requirement of a simultaneous acquisition of the directivities of all orchestral instruments.[90] Nevertheless the measurement results of the sound power were fully compatible with those applicable to a test series following the DIN standard. All measurement criteria for precision method 1 were met.

Number	x/r	y/r	z/r
1	1,02	0,74	1,66
2	-0,39	1,20	1,66
3	-1,27	0,00	1,66
4	-0,39	-1,20	1,66
5	1,02	-0,74	1,66
6	1,66	1,20	0,39
7	-0,63	1,95	0,39
8	-2,05	0,00	0,39
9	-0,63	-1,95	0,39
10	1,66	-1,20	0,39
11	0,63	1,95	-0,39
12	-1,66	1,20	-0,39
13	-1,66	-1,20	-0,39
14	0,63	-1,95	-0,39
15	2,05	0,00	-0,39
16	0,39	1,20	-1,66
17	-1,02	0,74	-1,66
18	-1,02	-0,74	-1,66
19	0,39	-1,20	-1,66
20	1,27	0,00	-1,66
21	0,00	0,00	2,09
22	1,86	0,00	0,93
23	0,58	1,77	0,93
24	-1,51	1,10	0,93
25	-1,51	-1,10	0,93
26	0,58	-1,77	0,93
27	-0,58	1,77	-0,93
28	-1,86	0,00	-0,93
29	-0,58	-1,77	-0,93
30	1,51	-1,10	-0,93
31	1,51	1,10	-0,93
32	0,00	0,00	-2,09

FIG. 12. Microphone positions of the spherical 32-channel array for sound power measurement in accordance to the enveloping surface method (the origin of ordinates is located in the assumed acoustical center of the sound source).

With a free volume of 1070 m^3 and proven to be anechoic at frequencies above 63 Hz, the full-anechoic chamber at TU Berlin meets all requirements regarding consistent data acquisition. All pitch ranges of the examined string instruments, with the exception of the lowest notes of the double bass, whose pitch range reaches approximately 40 Hz, lie well above this lower limit frequency. Determined by the measurement method applied, one can however be confident of a high probability that the values obtained have not been affected by eigenmodes of the full-anechoic chamber. In order to align the assumed acoustical main source of the instruments with the geometric center of the array, musicians were placed on a movable and vertically adjustable chair. In order to ensure a most consistent sampling of each examined instrument, musicians were asked to perform in a playing position that remained as constant as possible. Since the acoustical center of each instrument can only be assumed, a small trade-off may be needed in certain cases. This however concerns mainly instruments of large dimensions such as the double bass. FIG. 13 shows the measurement environment in the full-anechoic chamber at TU Berlin with a spherical 32-channel microphone array.

FIG. 13. Sound power measurement according to the enveloping surface method in the full-anechoic chamber of the TU Berlin.

B. Recording Setup

Sound pressure levels were recorded with 32 pre-polarized, back-electret condenser microphone capsules of the type Sennheiser KE 4-211-2, mounted at each node of the spherical grid. These pressure transducers have a reasonably flat frequency response while showing a relatively high equivalent noise level.[91] This however is considered to have no influence on the measurement accuracy. All microphones were supplied with a phantom voltage of 48 V by a total of four 8-channel pre-amplifiers of the type RME OctaMic. All 32 channels were optically connected via ADAT with audio interfaces of the type RME Digiface and RME Multiface and subsequently recorded on a desktop PC running Steinberg Nuendo at 24 bit/44.1 kHz. The sensitivity and magnitude responses of the channels were calibrated in situ by means of a class-A-device at a reference level of 94 dB at 1 kHz. A free-field calibration measurement of the microphones shows a significant comb-filter effect in the sensitivity above 2 kHz, caused by the joints connecting the sticks to the microphone enclosures. This influence was simulated by the use of the Boundary-Element-Method[90] and taken into account by the evaluation of the sound power levels of all instruments.

C. Musicians and Instruments

Beside a variety of wind and other orchestral instruments, a total of eight modern and historical string instruments of the violin family have been recorded. Due to the great scope of the measurement series, only one representative of each instrument could be considered. Thus, the highest demands are made regarding the suitability of the specific instrument and the capabilities of the musicians. This has been achieved by exclusively recruiting professional orchestral musicians. All historical instruments were played by experts of the *Akademie für Alte Musik Berlin*, a renowned and specialized ensemble of the historically informed performance practice. All modern instruments were made available by members of the *Deutsches Sinfonieorchester Berlin* or other professional orchestras from Berlin. Thus it can be assumed that only highly skilled and experienced musicians with instruments of an extraordinarily high-standard were chosen.

	Historical	**Modern**
Violin	Neil Kristóv Értz 1998 Replica after Guaneri del Gesù 430 Hz	Leandro Bisiach da Milano 1902 Original 443 Hz
Viola	Christoph Leihdolff 1745 Original 430 Hz	Felix Scheit 1995 Original 442 Hz
Violoncello	Tilman Muthesius 2007 Replica after Matteu Gofriller 430 Hz	A bert Roth 1934 Original 443 Hz
Double Bass	Italian Instrument ~ 1900 Original 430 Hz	German Instrument ~ 1900 Original 443 Hz

FIG. 14. Overview of all examined bowed string instruments of modern and historical construction with addi ional information on their origin and tuning frequency.

All original instruments are well-preserved, built in the 18^{th} or 19^{th} century or are faithful replicas, all equipped with a combination of wound and plain gut strings. Original bows of the period were also used as appropriate. For example in the case of the historical violoncello a bow from the prestigious bowyer John Kew Dodd from 1830 could be made available. All modern instruments are tuned to a pitch of ~ 443 Hz, whereas all historical instruments are tuned to ~ 430 Hz, which represents a typical tuning for the time around 1800. FIG. 14 shows a survey of all evaluated bowed string instruments, including specific information on their origin and tuning frequency.

D. Measuring Series

Initially, the primary objective of the investigation has been the determination of sound power levels with regard to dynamic extreme values, covering the entire playable range of each instrument in chromatic scaling. To this end each single note has been repeatedly recorded at least three times, both at its dynamic maximum and minimum range. Musicians were instructed to perform both in fortissimo (*ff*) by playing “as loud as possible without letting the sound become unaesthetic or distorted“ as well as pianissimo (*pp*) by playing “as silent as possible without losing the sound”. In the evaluation, the unweighted sound power level of the loudest and softest tone over a time-averaged steady-state amount has been subsequently determined. The musical terms of *ff* and *pp* are used throughout the entire process of measuring and analyzing in order to describe the maximum and minimum attainable sound power level of an instrument. The background to this decision is that in the Classical period of musical history both *ff* represented the greatest possible and *pp* the least possible volume.[6] Further dynamic markings such as *fff* and *ppp* emerged only in the Romantic period and do not imply an extension but only a more discrete graduation of the entire dynamic range. All musicians were further asked to play without vibrato for a minimum duration of 3 seconds per single note. This has been necessary so that a sufficient duration of the steady-state amount could be extracted from the subsequent process of analysis. The same playing instructions were given for an additional recording of a diatonic scale with tied tones “in a comfortable position over two octaves“. The tempo should be rather “fluent“, in order to record a total of approximately 4-5 tones per second. The time-averaged sound power level covering the total range of the scale was determined on the basis of several recorded playings. Accordingly an average value for the most important pitch range, both at *ff* and *pp,* of the respective instrument could be attained. Consequently, in addition to the extreme values, a realistic example of the sound power of a musical phrase, where tones are played in a musical context, has been obtained.

E. Analysis

The process of analysis regarding an evaluation of the data obtained can be subdivided into essentially two parts. Before the captured recordings could be calculated in a largely automated process, a comprehensive manual pre-selection procedure of the raw material was first required. As within the framework of the performed measurement series, a variety of modern and historical brass and woodwind instruments have been considered as well,[5] a total amount of data of about 300 GB had to be evaluated. Thus a number of about 15.000 recorded single notes result in the course of an approximated summation of measurements of about forty instruments each having a pitch range of three to five octaves. In both dynamic levels, these were initially audited and sorted manually in consideration of their aesthetical quality and thus their suitability regarding representative measurement results. The most suitable variations for each of these single notes were subsequently marked both at their starting and ending points as well as the on- and offset of the steady state amount, which in the case of all examined instruments has a duration of at least 630 ms. This manual pre-selection and editing procedure has been done with the help of the Reaper digital audio workstation (v. 3.7x), which is applicable not only for a batch export of multichannel recordings but also for the integration of additional third party extensions. Thus the appropriate marker positions could be transferred as numerical sample values in a text file by means of the so-called *SWS extension*, especially requested to be expanded for the investigation. The resulting text files provide the basis for a subsequent determination of the specific variant with the highest or lowest sound power level over the time-averaged steady-state amount of each single note. This second step of the process of analysis could be largely automated in its execution with the assistance of Matlab. A linear phase Butterworth band-pass filter of 4^{th} order (63 Hz- 20kHz) has moreover been implemented in this process. This however, does not apply to the data of instruments with pitch ranges below the lower limiting frequencies, such as the double bass. Further information on the Matlab scripting details is provided in the second part of the documentation of this measurement series, in which the examined wood wind and brass instruments are presented.[92]

V. RESULTS

Before a closer look is taken at each of the evaluated instruments, FIG. 15 provides an overall survey, presenting the key findings of the investigation. The right hand side shows the maximum and minimum sound power levels achieved in each case, considering the time-averaged steady-state amount of all captured single notes in chromatic scaling over the entire pitch range. The total scope of the attainable dynamic range, which is maximally feasible due to especially strong and soft variants of individual sustained notes can be calculated on this basis. On the left hand side, the sound power levels of a fluently played diatonic scale with tied notes are indicated, both at *ff* and *pp*, time-averaged over a range of two octaves. These values consistently show a constrained dynamic range regarding all examined instruments. This may be ascribed both to the altered transient response of faster played and tied scale notes[93] as well as to the circumstance, that the playable dynamic range is in part dependent upon the pitch. Consequently, these scales represent a dynamic range more oriented towards a common playing practice, in comparison with pronounced extreme values of single notes with a longer duration. As may be ascertained from all instruments evaluated, the exhibited dynamic limits cannot be considered as typical, if the sound power is to be described on the basis of a single numerical value. For this purpose, following an example of Meyer,[11] a so-called mean forte sound power level L_{wf} has been determined. This value, distanced one quarter from the absolute maximum, is a result of the division of the total dynamic range in four equal parts, and of the corresponding allocation of a dynamic value to each of these parts, that is to say *pp*, *p*, *mf*, *f*, and ff. According to Meyer, a calculated determination of such intermediate values proves itself to be more reliable, compared with a direct measurement of intermediate dynamic levels, as occurred in the case of earlier measurements.[8,9] This must be essentially ascribed to the fact, that the scope of variation in the interpretation of what, for instance, exactly constitutes an *mf*, can be relatively large for different musicians.[11] As this margin of variation can be considered to be the least in the case of extreme values, only these have been employed in the calculation of the mean forte sound power levels.

	Scales [dB]		Single Notes [dB]		
	L_{wff}	L_{wpp}	L_{wff}	L_{wpp}	L_{wf}
Historic Violin	90	75	95	56	85
Modern Violin	88	75	95	52	84
Historic Viola	88	70	94	57	85
Modern Viola	91	77	97	58	87
Historic Violoncello	93	73	102	57	91
Modern Violoncello	98	90	97	63	89
Historic Doublebass	90	80	100	66	91
Modern Doublebass	89	65	100	65	92

FIG. 15. Dynamic range of all examined modern and historical bowed string instruments. Both the measured maximum and minimum sound power level for the time-averaged steady-state amount of single notes and a fast played scale as well as a calculated mean forte sound power level L_{wf} is shown.

In spite of the evident disparity in forms of construction, different string patterns and bow models of modern and historical instruments, only slight differences can be determined, especially in view of the maximum sound power levels of all evaluated instruments. In view of the violin and the double bass, identical *ff*-values result for single notes. In addition, the historical violoncello, for which the highest sound power levels in the *ff* are measured both for single notes as also for the diatonic scale, proves itself to be the most powerful examined bowed string instrument. These results appear to be especially representative as from a metrological point of view, the details of sound power for the *ff* are generally considered to be the most reproducible.[7] To the contrary, the fluctuations in the minimum *pp*-values may on the other hand result to be somewhat greater. This tendency may be ascribed to the fact, that the lower playable dynamic range is to a greater extent dependent upon the manner of interpretation of the individual musician, who performs not least under unfamiliar acoustical conditions. This can be especially discerned regarding both the modern violoncello and the historical double bass, where the *pp*-values of the scale result to be comparatively high. None the less, as is for instance the case with the scales of the modern and historical violin, now and then identical sound power values may result in the *pp*-values as well. By examining the calculated mean forte sound power levels, balanced results are also indicated, both within the modern and historical variants as well as between all considered instruments in general. Thus in this case, as well as in the case of the maximal values of the single notes, a slight tendency towards somewhat higher levels regarding the lower instruments can be discerned. This is mainly due to the larger size of bass stringed instruments, which are particularly capable of radiating a higher amount of energy in their lower playing range.[12] Considering a detailed analysis of the individual instruments, the data obtained for each of these instruments are presented in FIG. 16, FIG. 17,

FIG. 18, and FIG. 19. The dynamic range that reaches from the softest note in the *pp* to the loudest note in the *ff* is shown, indicating the maximum and minimum possibilities of effective sound power with regard to all captured single notes. As is evident from all variants evaluated, there are specific notes in both dynamic levels, which show an equally high or low response characteristic. This can be attributed to the great number of resonance modes of the instrument body. In view of all bowed string instruments, these zones are defined in frequency, and do not shift as is the case according to the played pitch with brass instruments.[12] As a consequence, the resulting sound power may occasionally vary to a considerable degree tone by tone. This phenomenon is illustrated, inter alia, in further detail below.

A. Violin

In the course of a comparison of the sound power levels of the examined violins, it is initially noticed, that the individual total dynamic ranges are only slightly different, due to the somewhat lower *pp*-values of the modern violin. On the other hand, both instruments attain an even identical sound power level of 95 dB in the *ff*. The total dynamics of both variants can therefore be considered to be relatively balanced, not least on the basis of the aforementioned fact, that the formation of the *pp*-values may be decisively dependent upon the musician's individual way of playing. Furthermore, concerning both instruments, the frequency dependent energy distribution is seen to be largely independent of both dynamic levels. This is the case especially in respect to the historical violin, which moreover indicates a homogenous dispersion of all sound power levels over the entire pitch range. However, considering the modern instrument, a slight tendency can be recognized towards a decrease of the values in the upper frequency ranges as becomes most evident in the *pp*. These tendencies are also apparent in view of the individual resonance characteristics of both instruments. Thus the historical violin reaches its highest sound power level in both dynamic levels in a frequency range slightly under 1 kHz at 930 Hz (A#5). On the contrary, with regard to the modern violin, the maximum values in both dynamic levels are more likely to be located in the lower and medium frequency range and obviously coincide with the previously described signature modes of a violin. This is especially evident, with respect to the maximum value, which can be seen in direct connection with the cavity resonance A_0, measured to be about 270 Hz in both dynamic levels (C4-C#4). Besides A_0, the main top plate or main wood resonance T_1 manifests itself especially clearly in the *ff*-range of the modern violin around 415 Hz for the note G#4. In the case of the historical violin, this is noticeable, if at all, in a marginal increase of the *pp*-value for A#4. In view of both instruments, the corpus modes C_3 and C_4 show rather strong peaks at around C5 and E5. While the C_4 mode has been previously described as a nearly symmetrical mode with rather less radiation in comparison to C_3, the historical variant indicates an even higher sound power level at C_4.

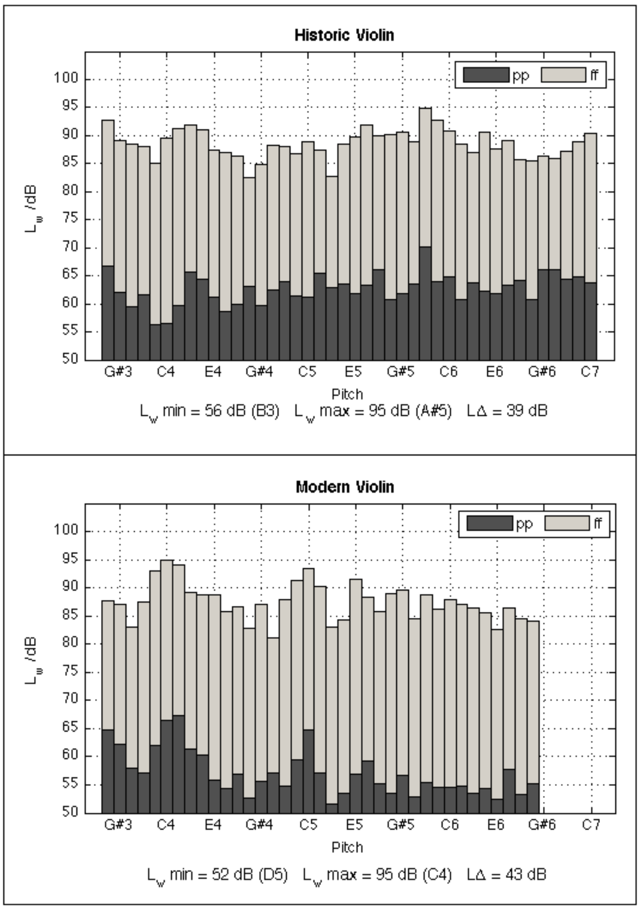

FIG. 16. Dynamic range of a violin of historical (top) and modern (bottom) construction method, indicating unweighted sound power levels in chromatic scaling.

It is further remarkable, that all recognizable main resonant modes of the historical violin, compared to the modern violin, are located at least half a note higher. A_0 is also shifted upwards with a maximum at D4, independent of the dynamical level. It can be seen on the basis of these connections, that the practical dynamic range of an instrument is largely constrained in part by pronounced resonance modes in the *pp*-range. The example of the modern violin clearly demonstrates this phenomenon by means of A_0 and C_3 which, in the case of the appropriate notes (C4/C#4 and C5), inhibit extreme *pp*-values.

Regarding the dynamic ranges within a dynamic level, a value of 12 dB results in the case of the historical violin for all values measured in the *ff*-level. The maximum difference between adjacent notes is up to 6 dB. This may be noted both at the transition from D5 to D#5 and also from A5 to A#5. The differences are even slightly more pronounced in the *pp*-level. Besides a dynamic range of 14 dB, the transition from D5 to D#5 also shows itself as the most drastic with a difference of 7 dB. In the case of the modern violin, the maximum dynamic range within the *ff* (14 dB) and the *pp* (16 dB) is only slightly expanded. Here the differences in values between adjacent single notes are even more important due to the marked main resonances. Thus the sound power level, after the protruding peak of C_3 at C5 (approx. 520 Hz), decreases both in the *ff* and also in the *pp*, over an intermediate note by more than 10 dB, which leads in the pp to the lowest sound power value of all examined bowed string instruments (D5 = 52 dB).

In passing, a remarkable phenomenon of the historical violin, which may also be encountered with respect to the historical violoncello, should be pointed out. In each case a significantly higher sound power level in comparison with the modern instruments can be observed regarding the lowest note which inevitably is played on the open string. This note, with a value of 93 dB, represents, regarding the historical violin, one of the three notes with the highest sound power level within the entire *ff*-range. In view of the historical violoncello, this note even proves to be the highest sound power value of all measured instruments, uniquely passing the 100 dB-level. Given that in general the share of the fundamental in the sound power spectrum drops considerably for all bowed string instruments below the cavity resonance,[12] it seems reasonable to rather assume the cause for this in a differentiated formation of the overlying partials. It is confirmed on the basis of a spot-checked spectral analysis, that for both instruments specifically the third partial is solely responsible for this peak.

Considering the historical violoncello, this partial stands out at 192 Hz with a level difference of more than 15 dB to the adjacent partials. Although this matter shall not be discussed more profoundly herein, an important insight becomes evident at this point regarding the continued interpretation of the attained values. While the different design of the historical and modern variants have, but only in individual cases a rather negligible effect on the sound power values, systematic differences could more likely be made out by means of a comprehensive investigation of the spectral energy distribution.

B. Viola

In the comparison of the violas, similar to the violins, also no obvious systematical differences are discernible. Although the modern variant in isolated cases achieves somewhat higher sound power levels, none the less the *pp*- and *ff*-values remain comparable in both instruments. Besides almost identical minimum values for both instruments, the absolute dynamic range of the modern variant is only insignificantly expanded by somewhat more pronounced resonance modes. Taking into consideration both violas, it is also evident that, especially in the lower and middle range of playing, the frequency-related energy distribution is largely independent from the dynamic levels. Merely the dynamic range of the modern viola decreases towards the higher regions. This is mainly due to a consequence of a rise of the *pp*-values throughout the whole range, while the *ff*-values decrease almost constantly at about G5 (800 Hz).

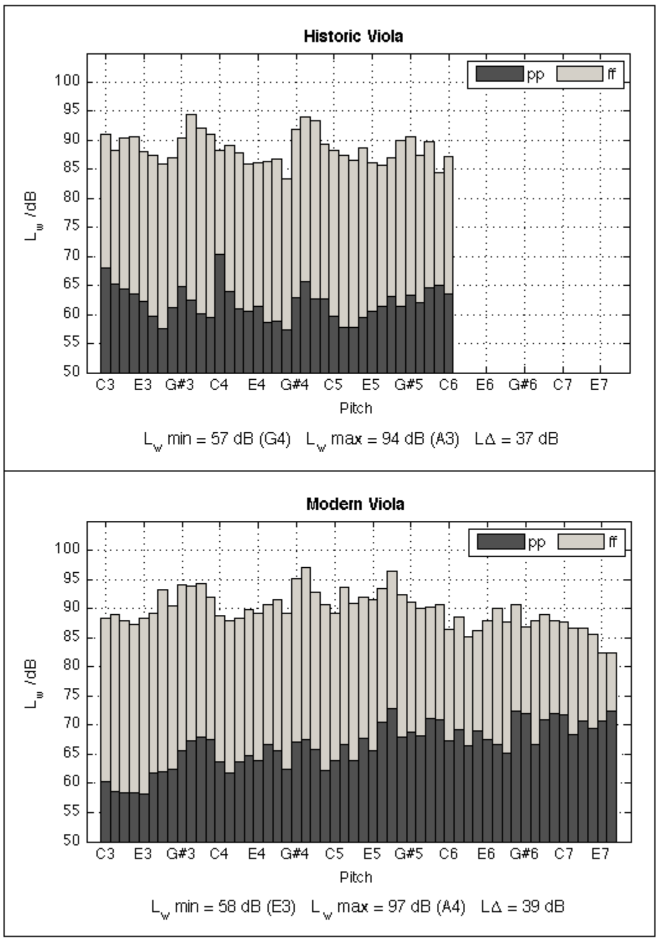

FIG. 17. Dynamic range of a viola of historical (top) and modern (bottom) construction method, indicating unweighted sound power levels in chromatic scaling.

Contrary to the violins, one can recognize that even identic notes in the case of both instruments may be equally well formed. This becomes evident especially in the cavity resonance A_0 around A3 about 220 Hz, where the historical viola reaches its maximum sound power level of 94 dB. As occurred regarding the violins, the T_1 mode is also scarcely marked and only notable in the modern viola in the range of F4-F#4. On the contrary, the pronounced C_3 mode, in which the modern viola reaches its maximum level in the *ff*, is encountered one octave above the cavity resonance at A4 in all dynamic levels. Taking into consideration the maximum level differences of both instruments within the individual dynamic levels, the same dimensions are indicated as is the case with the violins. The historical viola with 11 dB (*ff*) and 8 dB (*pp*) shows a slightly lesser margin in comparison with the modern viola. Here the difference in both dynamic levels is 15 dB in each case.

Furthermore notable is the circumstance, that for both instruments the maximum level difference between adjacent single notes in the *ff* occurs in exactly the same pitch range. Of not lesser importance, the differences of 5 dB (modern) and 8 dB (historical) between G4 and G#4 are approximately equal to the corresponding level differences of the evaluated violins. As expected, also in the *pp*-range somewhat greater differences between adjoining single notes are evident with 10 dB from B3 to C4 for the historical viola and 7 dB from F#6 to G#6 for the modern viola.

C. Violoncello

Taking into consideration the sound power levels of both violoncellos, it is immediately recognizable that, at least in the case examined, the historical method of construction produces markedly higher *ff*-values, in comparison with the modern variant. Here one encounters in the lower range not just one but several tones around 100 dB. In addition, the open C-string, with a maximum value of 102 dB, represents the single note with the highest sound power level measured of all examined bowed string instruments. Furthermore it appears remarkable that not only the highest, but also the lowest sound power levels are attained for the historical model. As a consequence the dynamic range, in this case, increases by almost 10 dB compared to the modern violoncello.

As can be clearly seen, especially as regarding the historical variant, the violoncello, owing to its size, is capable of radiating noticeably more sound energy than smaller instruments, such as the violin. This becomes notable mainly in the area of the cavity resonance A_0 around 100 Hz, where the historical variant reaches sound power levels in the range of 100 dB with regard to both notes G2 and G#2. In the *pp*-range the resonance maximum is slightly displaced towards the tone F2, which, with a value of 74 dB and a level difference to the adjacent notes of almost 10 dB, stands out significantly and represents the loudest note in the entire dynamic level. However, in the case of the modern violoncello, the A_0 mode in the sound power level of the *ff*-range is less distinctive. Here one encounters in view of the A_0 mode a broader resonance peak around E2-G#2 primarily in the *pp*-range, which at least at this dynamic level represents one of the maximum sound power levels. At higher frequencies however, the larger corpus plates of the violoncello are said to vibrate in a much differentiated way, which may often result in an acoustical short circuit between adjoining areas and hence in a tendential decrease of the overall sound power level.[12] This is noticeable in view of the modern violoncello, whose acquired pitch range surpasses that of the historical violoncello by more than one octave. In this case the level difference between adjoining notes in the *pp*-range is especially significant despite the rather balanced relations within the *ff*-range, with spans of up to 10 dB. Furthermore a typical tendency in violoncellos towards a decrease of the sound power level in the higher pitch range is indicated in both dynamic levels beyond approx. G4.

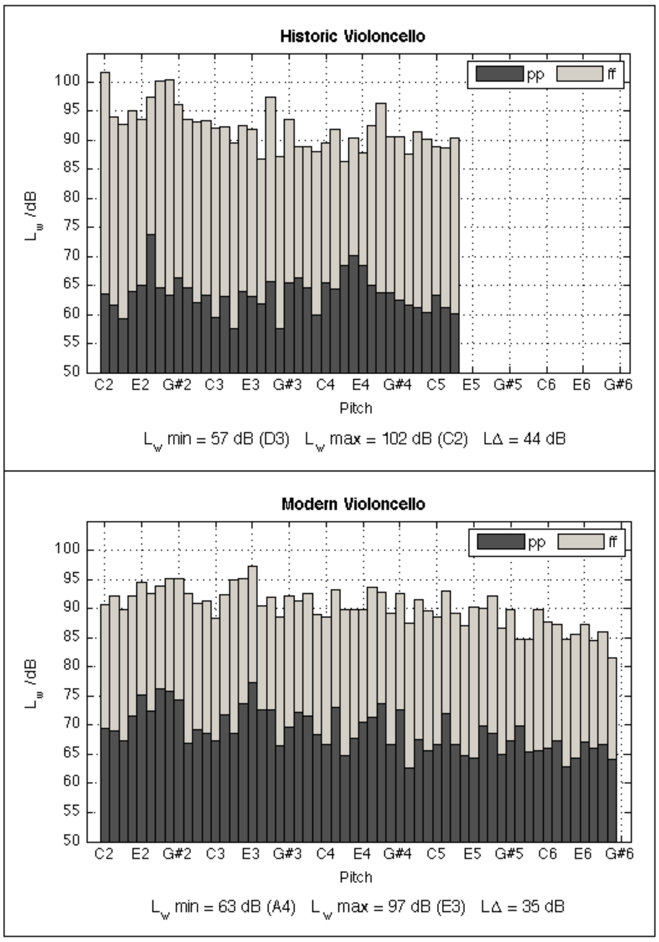

FIG. 18. Dynamic range of a violoncello of historical (top) and modern (bottom) construction method, indicating unweighted sound power levels in chromatic scaling.

While both of the violins' signature modes T_1 and C_3 are separated from each other in the violin by approximately one octave, with regard to the violoncello, due to its construction, these may be found closer to each other and often make up a broad resonance peak around 140-190 Hz. [50] This phenomenon is distinctive in the modern violoncello in the range of C#3 to F#3. In both dynamic levels the maximum sound power level of 97 dB in the *ff*-range and 77 dB in the *pp*-range have been measured for the tone E3 (approx. 175 Hz). Considering the historical violoncello however, a minor increase in the tones D#3-F#3 becomes apparent in the *pp*-range while in the *ff*-range at F3 with 86 dB, one of the weakest *ff*-levels of the instrument can be observed. On the basis of the drastic level increase of more than 10 dB in the case of the directly subsequent higher note F#3, a pronounced T_1 peak with a level of 97 dB, frequencially displaced upwards, may be assumed. According to Bynum[50] such differences in the distinctness of the T_1 and C_3 peaks can selectively be influenced by certain construction methods of individual components of the violoncello. Reportedly, slightly more pronounced curvatures of the corpus, lighter bass bars and the thinning of the plates at the edges cause an increase and spread in frequency of both modes in the spectrum between 165 and 220 Hz. Therefore it appears to be possible to interpret the historical violoncellos' broader peak in the *ff*-range of the tone G#3 and the distinct increase of the respective frequency bands in the *pp*-range, as a C_3 mode that is displaced upwards and clearly separated from T_1. As it has been shown that the bass bar has increased in size over time, it appears justified to attribute such prominent forms of resonance modes to the different methods of construction of the historical and modern violoncello, at last to a certain extent.

D. Double bass

In comparison with the rather "standardized" design of high-pitched instruments, such as the violin, the double bass even today shows a greater variety of different shapes and sizes [49]. This gives reason, in view of a comparison of both instruments, to expect higher deviations in the radiated sound power. That however is not confirmed by both evaluated variants. Quite to the contrary, a well-balanced relation can be found for both instruments regarding the maximum sound power level as well as the dynamic range in general. Even though a larger pitch range has been recorded of the modern variant, only the lower range up to E3 is considered in the evaluation for reasons of a better comparability with the historical instrument. Consequently, similar values of 100 dB in the *ff* and 65-66 dB in the *pp* result regarding both double basses in a quasi-identical dynamic range of maximally 35 dB. The maximum values attained in the *ff*-range have approximately the same order of magnitude as those of the violoncello and, concerning both variants, fall in the lower main resonance ranges A_0 (55 Hz) and T_1 (110 Hz), typical for the double bass. In the case of the historical instrument, the main wood resonance peak of T_1 at G#2 (around approx. 100 Hz) proves to be the strongest single note in both dynamic levels. Furthermore, in comparison with the modern variant, with the exception of a level drop at E2 (82 Hz) (with a level difference of more than 6 dB) a pronounced *ff*-range with on the average somewhat higher values of approximately 93 dB is recognizable. Regarding both dynamic levels, the modern double bass however reaches its maximum sound power levels in the lower range around A1, after which the measured values decrease with a rise of the pitch. On a side note it should be taken into account that the lowest notes E1-B1 (40-63 Hz) of the double bass fall somewhat below the limiting frequency of the measurement room. As a consequence, under certain circumstances no optimal free-field conditions may be assumed in this particular frequency range. As determined by the measurement method applied, one can however assume a high probability that the values obtained have not been affected by eigenmodes of the full-anechoic chamber. Not least, this is also underscored by the fact, that Meyer[11] quotes identical maximum and minimum single note values of 66 dB (*pp*) and 100 dB (*ff*) for the modern double bass.

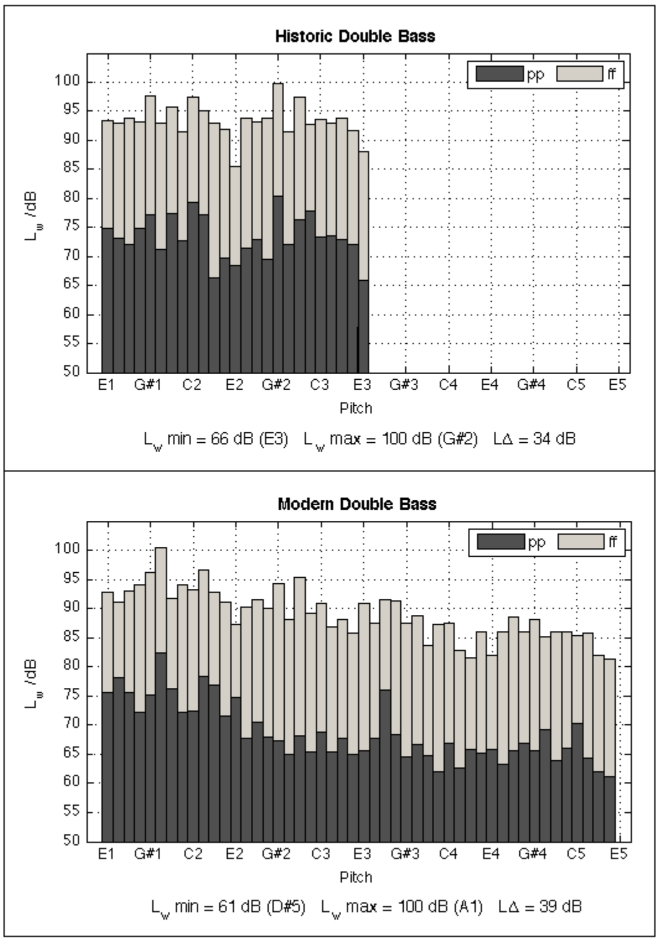

FIG. 19. Dynamic range of a double bass of historical (top) and modern (bottom) construction method, indicating unweighted sound power levels in chromatic scaling.

VI. DISCUSSION

Besides an introduction to the basic principles of sound production of bowed string instruments and modifications in their construction since about the 18th century, this paper presents the results of a measurement series of the sound power of modern and historical instruments according to the enveloping surface method in a full-anechoic chamber. Both the maximum (*ff*) and minimum (*pp*) attainable sound power for single notes and diatonic scales has been determined. A mean forte sound power level (Lwf) has moreover been subsequently calculated for all examined instruments. As a first result, a high degree of consistency emerges by comparing the data obtained for the modern string instruments with those collected by Meyer.[11] This is particularly true for the maximum sound power levels in the *ff*-range, which, for example, in the case of the double bass prove to be identical and also deviate only slightly regarding all other instruments. To the contrary, some indicated fluctuations in the minimum *pp*-values may be attributed to the influence of the measurement environment, which in any case constitutes quite unfamiliar acoustical conditions for many musicians. It is therefore assumed, that the interpretation of a given playing instruction such as “as soft as possible without losing the sound” may differ depending on the measurement method chosen in an anechoic chamber or a reverberation room. On the other hand, the playing instruction for the maximum level “as loud as possible without letting the sound become unaesthetic or distorted“ proves to be of rather motorical than musical nature. As a consequence, the maximum levels obtained may be regarded as substantially given by the physiology of the player and his instrument rather than being affected by varying interaction behaviors towards the environmental conditions. From this it follows, that from a metrological point of view, data on the maximum sound power in the *ff* are generally considered to be the most reproducible and thus the most representative. It is therefore all the more surprising, that especially these data obtained in the present investigation do not indicate any systematical differences in the sound power of bowed string instruments of historical construction with their lighter bows and plain or metal-wound gut strings, in comparison with the modern instruments, with steel strings and heavier bows. For example, both in the case of the violin and the double bass, in the *ff* identical maximum values are attained. This is a notable result, as one would have expected, that the higher projection, usually ascribed to instruments of modern construction correlates with an increase in sound power. Quite to the contrary, with regard to the violoncello, even higher values were determined for the historical instrument.

In reference to the initial question, whether a historical ensemble is actually louder or softer, compared to a modern one, a representative total sound power level can be calculated by adding the mean forte sound power levels L_{wf} of all instruments. Regarding a string quartet with modern instruments, a mean forte sound power level of 92 dB results in this way, while the corresponding level of an ensemble with historical instruments turns out to be even somewhat higher at 93 dB. Including data obtained for wood- and brass instruments,[5] the total sound power level of an entire orchestra can be calculated applying the same method. On the basis of an ideal-typical orchestration of

Beethoven’s era,[94] the extrapolation of a mean forte sound power level shows only a slight difference of 110,9 dB for an orchestra with modern instruments, in comparison with 110,2 dB for an orchestra with historical instruments. As a consequence, a historical change of the sound characteristics of instruments and larger ensembles can, at least with regard to bowed string instruments, be correlated only with variances in the spectral properties. A comparison of modern string instruments initially realized only in an representative way[95] indicates, without exception, a higher contribution of the fundamental and very high partials in comparison with the spectrum of instruments of historical construction. These in turn are more likely to have their main spectral emphasis in the middle range and the fundamental only seldom appears to be the strongest partial. These facts give grounds for further investigations to be realized in the near future on the basis of the sets of data obtained.

At this point the objection would seem to be somewhat justified that only limited criteria can be elaborated on the basis of the evaluation of only one representative of each instrument in conjunction with a specific musician. In the course of the interpretation of the data it must therefore be considered that it should be regarded as a matter of course that no claim is made to accurately predict the original sound of an instrument in any individual case. Especially with regard to the historically informed use of old instruments, too many individual possibilities such as the stringing or the choice of a specific bow remain. Not least, such use can occasionally even diverge deliberately from the original point of reference. The primary objective of the investigation can rather be found in the documentation of the present status of the historically informed performance practice with regard to acoustics, so as to offer for the first time important indications for a consistent means of comparison of the range of instruments of our times. What however remains evident is the fact that the loss in the amplification of spatial acoustics due to the enlargement of concert halls and the increase in audience[96] is compensated only in a minor way by the development of instrument-making. Ultimately, even when the perception of dynamics is by far not solely dependent upon the radiated sound power, it can nevertheless be assumed that the reception at the time of Beethoven of an ensemble playing in one of the historical venues of lesser spatial volume[96] resulted in a considerably louder overall impression.

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