Violin Acoustics

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The acoustics of thin-walled shallow boxes – a tale of coupled oscillators.

Introduction

This article describes how sound is excited by the violin and how the quality of its sound is related to the vibrations and acoustic properties of the body shell of the instrument.

The violin and the closely related viola, cello, and double bass are shallow, thin-walled, boxlike shell structures with orthotropic, guitar-shaped, doubly-arched plates, as illustrated in **Figure 1**. They therefore share very similar acoustical properties reflecting their similar shapes and symmetries. Violin acoustics is just a special example of the acoustics of any shallow boxlike structure.

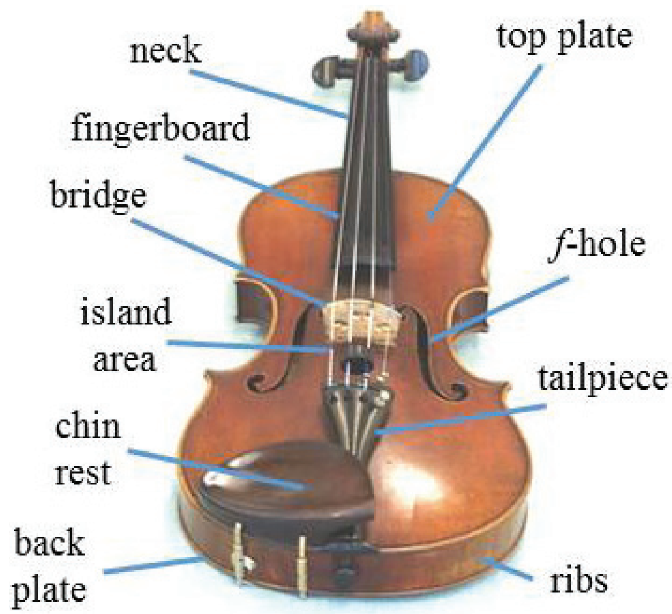


Figure 1. *A 19th century French violin with component parts labeled.*

The earliest known extant violin, now in the National Music Museum in Vermillion, was made by Andrea Amati (ca. 1505-1577), widely recognized for introducing the violin in its present largely unchanged form. It was made in Cremona in Northern Italy, which became the home of several generations of famous violin makers including Antonio Stradivari (1644-1737) and Guarneri del Gesù (1698-1744). Their violins still remain the instruments of choice of almost all top international soloists. They fetch extraordinary high prices; the "Vieuxtemps" 1741 violin by Guarnerius was reputably recently sold for around $18M.

In contrast, the highest auction price for a violin by a living maker was $130K in 2003 for a violin made by the Brooklyn maker Sam Zygmuntowicz, only recently surpassed in 2014 for a violin jointly made by the Ann Arbor, MI, makers Joseph Curtin and Greg Alf, which fetched $134 K. At the other end of the spectrum, a mass-produced student violin can be bought for around $100, with bow, case, and a cake of rosin included!

Can we tell the difference in the measured acoustic properties of instruments of such vastly different prices? Can we discover the acoustic secret, if any, of the old Cremonese master violins? Can a knowledge and understanding of the acoustical properties of the old violins help modern makers match the sounds of such violins? These are the major challenges for acousticians.

Despite the continuing reluctance of many violin makers to accept the intrusion of science into the traditional art of violin making, it is surely no coincidence that outstanding makers like Zygmuntowicz and Curtin have also played prominent roles in advancing our knowledge and understanding of the sounds of fine Italian instruments and their acoustic properties.

Today, as a result of strong collaborations involving violin makers, museum curators, players, owners, dealers, and acousticians, we have a wealth of information on the acoustical properties of nearly 100 classic Italian violins including many Stradivari and Guarneri violins, as well as many fine modern instruments, important knowledge that was missing until the last few years.

Such information establishes a "benchmark" for modern makers, if their instruments are to consistently match the sounds of the early Cremonese makers. Simple acoustic measurements in their workshops during the making of their instruments can help them achieve this.

Interestingly, Claudia Fritz and her collaborators (Fritz et al., 2014) recently conducted a rigorously designed psychoacoustic investigation of six fine Italian and six modern violins, which involved comparative listening tests and parallel vibroacoustic characterization. The outcome was that without visual clues even top international soloists were unable to reliably distinguish the old instruments from the new despite their huge disparity in value. This confirmed similar conclusions from a previous investigation involving a smaller number of instruments (Fritz et al., 2012).

The concept of a "Stradivari secret" known only to the classic Italian makers to account for the outstanding sound of many of their instruments is now largely discredited, not in the least because the sound of the instruments we listen to today are very different from when they were originally made. This is because they were "modernized" in various subtle ways in the 19th century by the use of metal-covered rather than pure-gut strings, a lengthened neck, a different standard tuning pitch, a modern bridge, and being played with a modern bow. This was in response to the need for instruments that could respond to the increasingly virtuosic demands of the player and project strongly over the sound of the larger orchestras and concert halls of the day.

Radiated Sound

In many ways, the acoustics of the violin is closely analogous to that of a loudspeaker mounted in a bass-reflex cabinet enclosure as described in many acoustics textbooks (e.g., Kinsler et al., 1982). The thin-walled body shell of the violin radiates sound directly just like a loudspeaker cone. The shell vibrations also produce pressure fluctuations inside the hollow body, which excite the Helmholtz *f*-hole resonance, the highly localized flow of air bouncing in and out of the *f*-holes cut in the top plate. The Helmholtz resonance frequency is determined by the size and geometry of the *f*-holes and compressibility of the air inside the body shell. This is similar to the induced vibrations of air through the open hole in a bass-reflex loudspeaker cabinet. In both cases, this significantly boosts the sound radiated at low frequencies, where radiation from the higher frequency body shell or loudspeaker cone resonances would otherwise have fallen off very rapidly.

Contrary to what many players believe, negligible sound is radiated by the vibrating string because its diameter is much smaller than the acoustic wavelength at all audio frequencies of interest. Nevertheless, the bowed string clearly provides the important driving force producing the sound of the instrument just like the electrical current exciting a loudspeaker cone. The quality of the radiated sound is therefore only as good as the player controlling the quality of the bowed string input!

Sound is excited by transverse "Helmholtz" bowed-string waves excited on the string, which exert a force with a sawtooth waveform on the supporting bridge as described below. Because of the offset soundpost wedged between the top and back plates, the transverse bowed-string forces the bridge to bounce up and down and rock asymmetrically backward and forward in its own plane on the island area between the *f*-holes cut into the top plate, as illustrated in **Figure 2**. The bridge and island area act as an acoustic transformer coupling energy from the vibrating string into the vibrating modes of the lower and upper bouts of both the top and back plates of the body shell.

The radiated sound is then strongly dependent on the coupling of the vibrating strings to the radiating

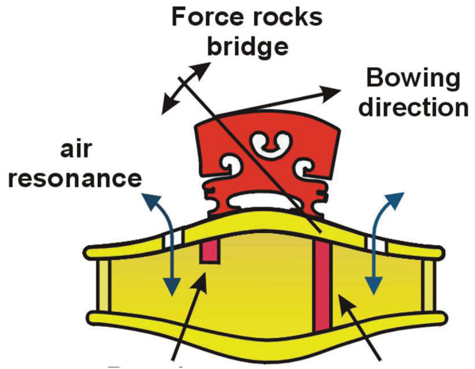


Figure 2. A schematic representation of the excitation of the vibrational modes of the body shell and Helmholtz f-hole resonance by the bowed string via the asymmetric rocking of the bridge.

modes of the body shell, which are only weakly perturbed by their coupling to other attached parts of the violin such as the neck, fingerboard, tailpiece supporting the strings, and even the player holding the instrument.

String Vibrations

Hermann von Helmholtz (1821-1894) was the first to both observe and explain the transverse vibrations of the bowed string. His measurements and their interpretation were described in *The Sensation of Tone* (Helmholtz, 1863), which laid the foundation for the discipline of psychoacoustics and our understanding of the perception of sound. Although a strongly bowed string appears to be vibrating as a simple half-wavelength sinusoidal standing wave, what we observe is only the time-averaged parabolic envelope of the much more interesting Helmholtz wave.

For an ideally flexible string with rigid end supports, Helmholtz showed that the waveform consists of two straight sections of the tensioned string rotating in opposite direction about its ends, with a propagating "kink" or discontinuity in the slope at their moving point of intersection. The kink traverses backward and forward at the speed of transverse waves, $\sqrt{T/\mu}$, reversing its sign on reflection at both ends, where T is the tension and μ is the mass per unit length of the string. The Helmholtz wave is therefore periodic with the same repetition frequency or pitch as the fundamental sinusoidal mode of vibration.

Such a wave can be considered as the Fourier sum of the sinusoidal eigenstates of an ideal string with rigid end supports, with "harmonic" partials ($f_n = nf_1$), and amplitudes varying as $1/n$, where n is an integer and f_1 is the frequency of the fundamental component. On an ideal string, such a wave would propagate without damping or change in shape.

In practice, the Helmholtz string vibrations are excited and controlled in amplitude by the high nonlinear frictional "slip-stick" forces between the moving bow hair and string similar to the forces giving rise to the squeal of car tires under heavy breaking. **Video 1** (http://goo.gl/UtNOI4) (Wolfe, 2016) illustrates the bowed waveform as it sticks to and then slips past the steadily moving bow.

To produce sound, the string vibrations clearly have to transfer energy to the radiating shell modes via the asymmetrically rocking bridge. As a result, each mode of the string contributing to the component partials of the Helmholtz wave will be selectively damped and changed in frequency by its coupling to the individual shell modes (Gough, 1981). Nevertheless, provided the coupling of the lowest partials is not too strong, the highly nonlinear, slipstick, frictional forces between the string and rosined bow can still excite a repetitive Helmholtz wave. Cremer (1984) showed that the kink is then broadened with additional ripples that are also excited by secondary reflections of the kink at the point of contact between string and bow.

If the fundamental string mode contributing to the Helmholtz wave is too strongly coupled to a prominent body resonance, even the highly nonlinear frictional force between bow and string is unable to sustain a repetitive wave at the intended pitch. The pitch then rises an octave or leads to a warbling or croaking sound, the infamous "wolfnote," which frequently haunts even the finest instruments, especially on fine cellos. This is an extreme example of the way the string-shell mode coupling affects the "playability" of an instrument (Woodhouse, 2014, Sect. 5), which is almost as important to the player as its sound.

The excitation and properties of Helmholtz waves on the bowed string are so important that Cremer (1984) devotes almost half his seminal monograph on *The Physics of the Violin* to a discussion of string vibrations. In Cambridge, UK, McIntyre and Woodhouse (1979) developed elegant computer simulations to investigate the physics involved, with more recent advances described by Woodhouse (2014, Sect. 2) in his recent comprehensive review of violin acoustics.

Major advances in our understanding of how the player and the properties of the bow determine the time evolution and shape of the circulating kink, hence the sound of the bowed string, were made by the late Knutt Guettler (2010), a virtuoso soloist and teacher of the double bass. The rapid excitation of regular Helmholtz waves on short, low-pitched,

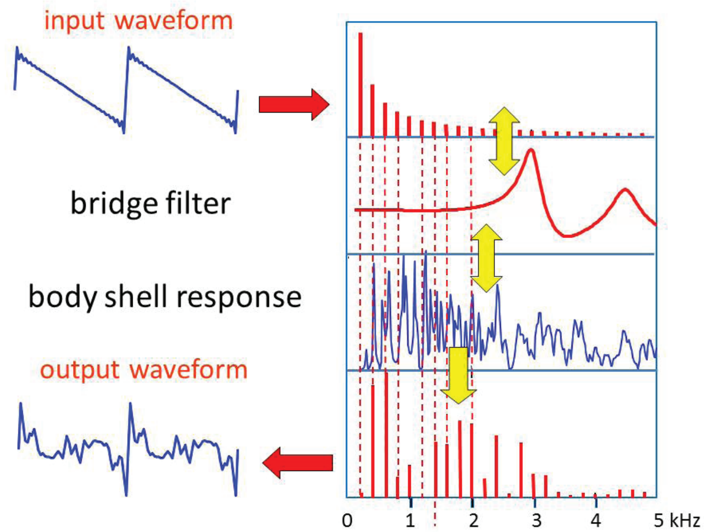


Figure 3. The transformation of the bowed string input waveform into the radiated sound by the bridge and body shell resonances for one selected note. Vertical dashed lines: Frequencies of the bowed string partials.

bowed notes on the double bass is vitally important; otherwise, the note is over before it has even started! The ability to achieve a clean start to a bowed note is one of the skills of a really good player on any bowed instrument (Guettler and Askenfelt, 1997). This involves controlling the acceleration of the bow following contact with the string as well its velocity, position, and downward force. This is one of the most important factors differentiating the skills of a top soloist from those of a good amateur player, let alone a beginner.

The short audio extract (**Audio 1**, http://goo.gl/UtNOI4) of the sound produced by the piezoelectrically measured bowed string force acting on the bridge (Woodhouse, 2014) illustrates both the already violin-like sound of the driving force and the skill of an expert performer in controlling its subtle inflections of both amplitude and pitch.

Excitation of Body Shell Modes

The radiated sound of the violin is therefore determined by the overlap of the comb of harmonic partials excited by the Helmholtz wave on the bowed string and the multiplicity of resonant radiating body shell modes, with the bridge acting as an acoustic filter between, as illustrated schematically in **Figure 3**.

The isolated bridge resting on a rigid platform has two important in-plane resonances at around 3 kHz and 6 kHz, rotation of its upper half about its waist and bouncing up and down on its two feet. When mounted on the island area of the top plate, such resonances are strongly damped by their coupling to the body shell modes.

As many as 40 harmonic partials can be observed in the sound of the lowest bowed open string on a cello! The time-varying strengths of each of these partials, modified in amplitude by the player and the multiresonant acoustic filter response of the instrument, will then be processed within the cochlea of the ear and the highly sophisticated audio processes that take place in the brain. The resulting complexity of the signals reaching the brain ultimately determines the listener's perception of the quality of an instrument as played by a particular player.

Because of the multiresonant response of the violin, the waveform and spectrum of the radiated sound is very different from that of the input Helmholtz sawtooth force at the bridge, as illustrated by the computer simulation in **Figure 3**. It also varies wildly from note to note, and even within an individual note, when played with vibrato. Yet the sound of the violin perceived by the player and listener remains remarkably uniform, other than slight changes when bowing on different strings. This paradox suggests that the quality of an instrument cannot be determined simply by the frequencies and strengths of the individual resonances excited. This has encouraged the view that the frequency-averaged formant structure is perhaps the most important generic feature, with both the overall intensity and balance of sound radiated in the upper and lower frequency ranges being important.

However, if a single period of the recorded waveform of the recorded sound of a violin is selected and repeated indefinitely, the sound is like that of any crude Fourier synthesizer and nothing like a violin (**Audio 2**, http://goo.gl/UtNOI4). This suggests that the fluctuations in frequency, amplitude, and timbre, even within a single bowed note, strongly affect the perceived quality of a violin's sound. The "complexity" of the sound arises from the strongly frequency- and directional-dependent fluctuations in spectral content or timbre, the use of vibrato, noise associated with the finite width of the bow hair in contact with the string, frictional forces, and the superposition of reflections from the surrounding walls (Meyer, 1992). All such factors provide a continuously changing input to the ear. This allows the brain to focus on the instrument being played, which may be just as important as the overall intensity of the perceived sound in determining an instrument's "projection." Averaging the frequency response would clearly reduce the complexity of the radiated sound, hence interest to the listener.

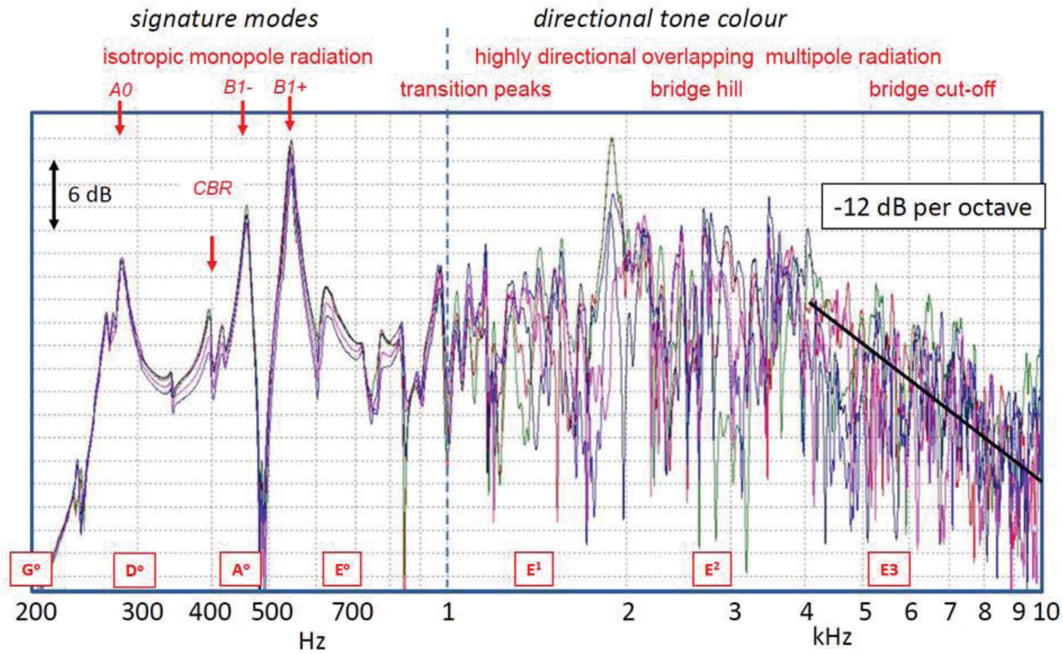


Figure 4. RSuperimposed spectra of the radiated sound pressure measured in the bridge plane at 0°, ± 30° and ± 60° in front of the top plate of the Willemotte 1734 Stradivari violin. Red boxes: Frequencies of the open G0 to E0 strings and the first three octaves of the open E-string, E1 to E3. Data courtesy of Curtin, personal communication.

The Acoustic Spectrum

Unlike loudspeakers designed to have as flat a frequency response as possible, the spectrum of the violin fluctuates wildly, with many strong peaks and troughs reflecting the relatively weakly damped, multiresonant responses of the instrument. This will vary markedly in detail from one instrument to the next, even between different Stradivari and Guarneri violins, giving each instrument its individual sound quality.

Figure 4 shows the radiated sound measured by Curtin in five different directions for the Willemotte 1734 Stradivari violin investigated in the Strad 3-dimensional project (Zygmuntowicz and Bissinger, 2009). The acoustic response was measured by tapping the bass-side top corner of the bridge in a direction parallel to the plates. This simulates the component of the bowed string force in the same direction. The fast Fourier transform (FFT) of the recorded sound has been normalized to that of the force of the light impact hammer exciting the violin modes. To simplify the acoustic response, the strings were damped, although string resonances can make a significant contribution to the quality of the radiated sound (Gough, 2005).

The observed resonances are those of the independent *normal* modes of the freely supported instrument, which have individual resonant responses just like a single damped mass-spring oscillator. They describe the coupled *component* mode vibrations of the body shell, the air inside the cavity, and all attached structures such as the neck, fingerboard, tailpiece, and strings (Gough, 2015b). To avoid potential confusion between the uncoupled *normal* and coupled *component* modes, capital letters will be used for the former (*A0, CBR, B1–, B1+,…*) and small letters for the latter (*f-hole, cbr, breathing, bending, …*).

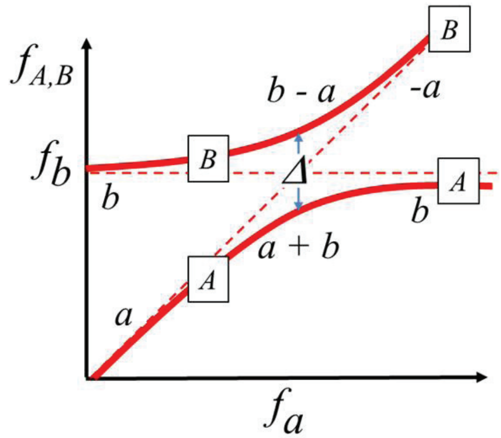
The "coupled oscillators" text box illustrates how the coupling between coupled component modes result in the veering and splitting of the frequencies of the resultant normal modes describing the in- and out-of-phase vibrations of the component modes.

The radiated sound is the sum of the radiated sound from each of the excited *normal* modes. For typical *Q*-values (25-50), the amplitude and width of each resonant peak is damping limited over about a semitone or two of its resonant frequency. Because of the logarithmic sensitivity of the ear, each mode still contributes significantly to the perceived sound well away from its resonance, where its response is determined by its springiness and effective mass below and above its resonant frequencies.

The effective mass of the individual shell modes can be determined from the measured mobility or admittance (induced velocity/applied force) in the direction of the force at the point of excitation. For a given mode, the lighter the plates, the stronger the radiated sound. Curtin (2006) has suggested that one of the reasons for the general decline in quality of violins from around 1750 onward was the use of somewhat heavier plates than those of the Italian masters.

The radiated frequency response can be divided into three overlapping regions.

(1) A *signature* mode range over the first two octaves up to around 1,000 Hz, where there are a relatively small number of well-defined resonant modes such as the *A0, B1–, and B1+* modes indicated. Their resonant frequencies and intensities provide



Coupled Oscillators

Consider two coupled crossing-frequency *component* modes *a* and *b*. For simplicity, assume that some external constraint increases the frequency of mode *a*, which in the absence of coupling leaves the frequency of mode *b* unchanged, as illustrated in **Figure 5**, dashed lines. As soon as the coupling is "switched on," two uncoupled *normal* modes *A* and *B* are formed (solid lines) describing the in- and out-ofphase coupled vibrations of the *a* and *b component* modes. Well away from the crossing frequency (coincidence), the *normal* modes retain their characteristic *component* mode forms with only a small contribution from the other mode. However, as coincidence is approached, the normal modes acquire an increasing contribution from the other mode. This results in the illustrated veering in opposite directions of the *normal* mode frequencies away from those of the otherwise uncoupled *component* modes. At coincidence, the *normal* mode frequencies are split by an amount (Δ) determined by the coupling strength, with the two component modes vibrating with equal energy in either the same or opposite phases. Well above coincidence, the *normal* mode *A* continues to acquire an increasing *component b* mode character at the expense of mode *a*. Similarly, on passing through coincidence the character of *normal* mode *B* changes from *b* to *a*, as illustrated.

The vibrational modes of the violin can be considered as independent *normal* modes, with resonant responses identical to those of a simple harmonic oscillator, describing the coupled modes of the *component* modes of vibration of the top and back plates, the ribs, the cavity air modes, the neck and fingerboard assembly and their resonance, the tailpiece, and strings.

Figure 5. A schematic representation of the veering and splitting of normal mode frequencies describing the coupling of two component oscillators or vibrational modes.

an *acoustic fingerprint* for individual violins. They act as monopole sound sources radiating uniformly in all directions. Additional weak *CBR, A1*, and other higher frequency modes are also often observed but usually only contribute weakly to the radiated sound.

(2) A *transitional* frequency range from around 800-1,500 Hz, where there is a cluster of quite strong resonances that cannot so easily be characterized without detailed modal analysis measurements and analysis, such as those made by Bissinger (2008a,b) and Stoppani (2013). At these frequencies and above, the modes act as additional multipole sources, with the radiated sound fluctuating strongly with both frequency and direction. This results in what Weinreich (1997) refers to as *directional tone color*, with the intensity of partials or the quality of sound of bowed notes varying rapidly with both direction and frequency.

(3) A *high-frequency* range extending to well above 4 kHz, below which there is often a rather broad peak around 2-3 kHz, originally referred to as the bridge hill (BH) feature, although no longer considered a property of the bridge alone. The density of the overlapping damped resonances makes it increasingly difficult to identify individual resonances. Above around 3 kHz, there is a relatively rapid roll-off in the frequency response of around 12 dB/octave, as indicated by the solid line with slope −2. This is because the bridge acts like a strongly damped resonant input filter coupling the string vibrations to the radiating modes of the body shell.

The relative contributions and acoustic importance of the signature and higher frequency components to the sound of a violin are highlighted in **Audio 3**, http://goo.gl/UtNOI4, which illustrates the unfiltered recorded sound of a violin, then when the hard cut-off filters are applied first above and then below 1 kHz, and then with the their combined sounds repeated.

In the high-frequency range, a statistical approach arguably provides a more useful way of describing the acoustic response, with a relatively broad, formantlike frequency response, with superimposed fluctuations in amplitude dependent on mode spacing and damping (Woodhouse and Langley, 2012 , Sect. 3.3).

At a casual glance, all fine Italian violins and many later and modern instruments have very similar acoustic responses to those shown in **Figure 3**. Yet players can still recognize large differences in the sounds of even the finest Stradivari and Guarneri violins. Puzzlingly, it is currently still difficult to identify which specific features of the acoustic response correlate strongly with differences in perceived quality – other than at low and high frequencies.

At low frequencies, Dunnewald (1991) and Bissinger (2008a) found that poor violins usually have a very weak sound output, whereas at high frequencies, the response of all violins is strongly influenced by the vibrating mass of the bridge. This is easily demonstrated by adding a mute to the top of the bridge, with the increased mass increasing its high-frequency cut-off filtering action. This leads to a "softer," "warmer," and less intense sound, even for bowed notes played on the lower strings, which still involve important contributions from the higher frequency partials. The bridge mass and design can therefore strongly influence the sound of an instrument.

At low frequencies, the bowing forces cause the bridge to rock backward and forward on the island area. The resulting asymmetric rocking then allows components of the bowing force in the rocking direction to excite both antisymmetric and symmetric volume-changing modes. In particular, it enables the vibrating strings to excite a single, volume-changing, *breathing* mode primarily responsible directly and indirectly for almost all the sound radiated at frequencies in the *signature* mode frequency range (Gough, 2015b).

In addition to radiating sound directly, the *b1– breathing* mode excites the *a0* Helmholtz *f*-hole resonance. The coupling between the *component a0* and breathing modes results in a pair of *A0* and *B1 normal* modes describing their in- and out-of-phase vibrations.

Once the frequencies of the *A0* and *B1* modes are known, their monopole source strengths are automatically fixed. This follows from what is colloquially known as the "toothpaste effect" or zero-frequency sum rule (Weinreich, 1985). Well below the *a0* resonance, any inward flow of air into the cavity induced by the cavity wall vibrations will be matched by an equal outward flow through the *f*-holes. Because the source strengths of the coupled *f*-hole and *breathing* modes have to cancel at low frequencies, their contribution to the radiated sound is automatically determined throughout the signature mode frequency range, apart from the very small frequency range around their resonances when damping becomes important.

In practice, the strongly radiating *breathing* mode is also weakly coupled to the nonradiating *bending* mode of the body shell, illustrated to the right of the plot in **Figure 6**. This is a consequence of the different elastic properties of the arched top and back plates. When the shell breathes, the arched plate edges of the two plates move inward and outward by different amounts. This induces a bending of the body shell like the bending of a bimetallic strip induced by the differential expansion of the dissimilar metals. This is the origin of the coupling between the *b1– breathing* and *b1+ bending component* modes of the body shell. This results in the pair of *B1–* and *B1+* modes, with relative radiating strengths determined by the amplitude of the component *breathing* mode in each (Gough, 2015b). Such a model describes the dominant features of the typical low frequency acoustic response illustrated in **Figure 4**.

The introduction of the offset soundpost results in a localized decrease and asymmetry of the shell-mode shapes across the island area between the *f*-holes. This and coupling to the *f*-hole mode result in a large increase in the component *breathing* mode frequency, increasing its coupling to the component *bending* mode. It also accounts for the asymmetric rocking of the bridge, enabling horizontal components of the bowing forces to excite the strongly radiating *breathing* component of any its coupled modes.

The soundpost and enclosed air also induce coupling of the *breathing* modes to the other nonradiating body shell modes and to the vibrational modes of all attached components like the neck, fingerboard, tailpiece, and strings. This is responsible for the additional weakly radiating *normal* modes appearing as substructure in the acoustic response, as in **Figure 4**.

Modeling Violin Modes

A successful physical model for the resonant modes of the fully assembled violin needs to describe the relationship between the modes of the assembled body shell and those of the individual plates before assembly and to show how the body shell modes are affected by their coupling to the cavity air modes within the shell walls, by the offset soundpost wedged between the top and back plates, the strings, and all other attached components like the neck, fingerboard, tailpiece, strings, and even the player.

Such a model is described in two recently published papers on the vibrations of both the individual plates and the assembled shell (Gough, 2015a,b). COMSOL 3.5 Shell Structure finite-element software has been used to compute the modes of a slightly simplified model of the violin to dem-

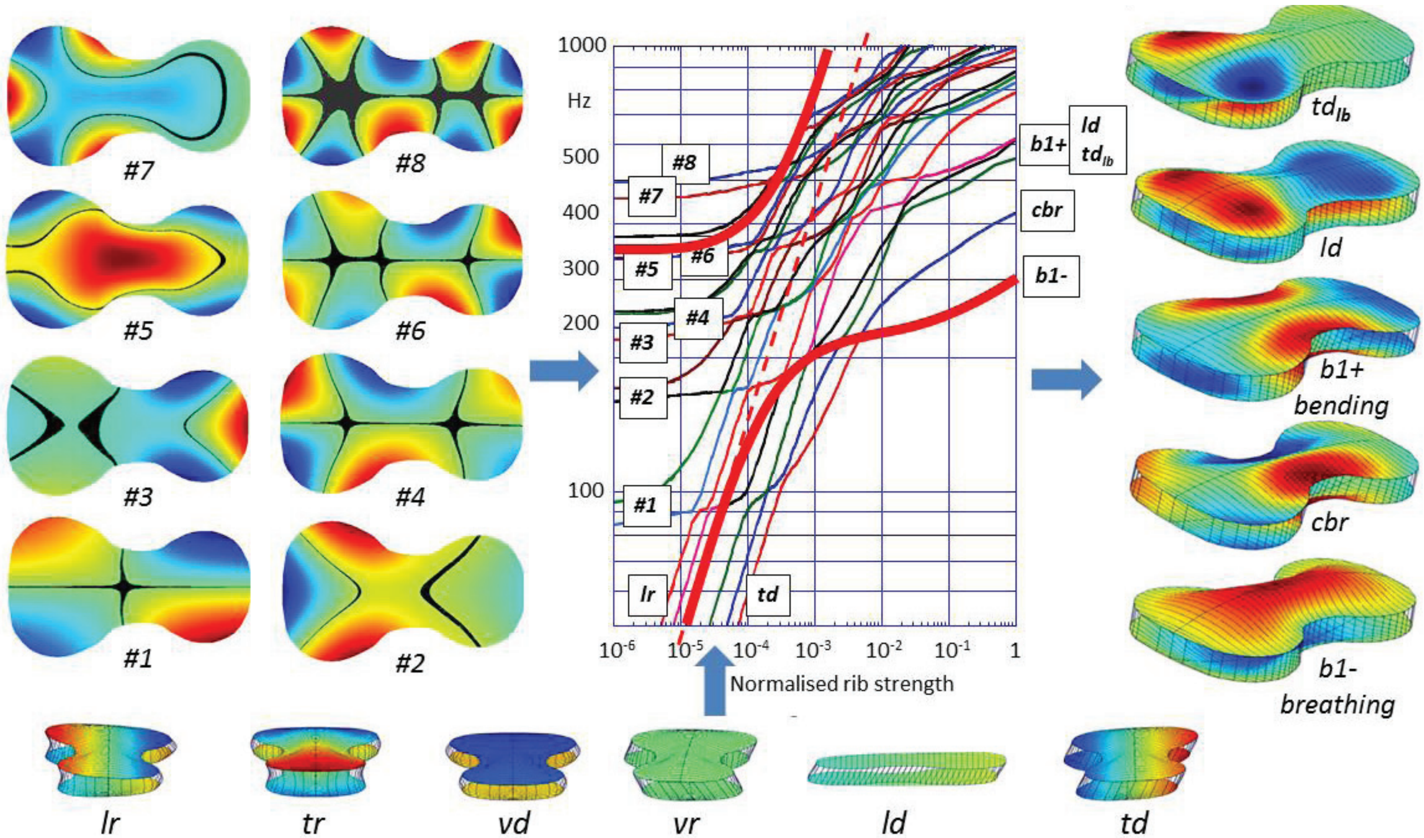


Figure 6. Transformation of the modes of the freely supported top and back plates into those of the assembled empty shell as a function of normalized rib strength varied over six orders of magnitude.

onstrate and understand how the coupling between all its component parts influences the vibrational modes and their influence on the radiated sound. This has involved varying the influence of each component over a very wide range as an aid to understanding the nature of and effect of the coupling.

To give a flavor of this approach, **Figure 6** illustrates the transformation of the initially freely supported individual plates into the modes of the empty body shell as the rib coupling strength is varied over six orders of magnitude from close to zero to a typical normal value. The highlighted curves illustrate how the important radiating *breathing* mode of the body shell is transformed from the *component #5* plate mode and its extremely strong interaction with the rising frequency *bouncing* mode of the rigid plates that are constrained by the extensional springlike and bending of the ribs.

There are many perhaps surprising and interesting features that such computations reveal, which are described in the downloadable supplementary text *Modelling Violin Modes* (http://acousticstoday.org/supplementary-text-violin-acoustics-colin-e-gough/), which also gives suggestions for additional background reading. Here, I simply invite those interested to view **Video 2, Video 3,** and **Video 4** which illustrate the 3-dimensional vibrations of the *A0, CBR, B1−, B1+*, and higher frequency dipole modes computed first in vacuum, then with coupling to the air inside the cavity via the Helmholtz *f*-hole resonance, and finally with the offset soundpost added.

Such computations validate and quantify a model for the violin and related instruments treating their modes as those of a thin-walled, guitar-shaped, shallow-box shell structure, with doubly-arched plates coupled together by the ribs, cavity air modes, soundpost, and coupling to the vibrational modes of the neck-fingerboard assembly, the tailpiece, and strings. This model can be understood by standard coupled oscillator theory and, I believe, accounts for all known vibrational and acoustic properties of the violin and related instruments.

Acknowledgments

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Biosketch

Colin Gough is an Emeritus Professor of Physics at the University of Birmingham, Birmingham, UK, where he researched the quantum wave mechanical, ultrasonic, and microwave properties of both normal and high-temperature superconductors. As a "weekend" professional violinist, musical acoustics has always been an added interest, publishing papers on various aspects of violin acoustics, teaching, and supervising courses and projects for undergraduate physics students. In recent years, he has been on the staff of the annual Oberlin Violin Acoustics Workshops. He contributed chapters on *Musical Acoustics* and *The Electric Guitar and Violin* for Springer's *Handbook of Acoustics* and *The Science of String Instruments*, respectively.

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