Science and the Stradivarius Violin

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1 Introduction

Stradivari violins are among the most sought-after musical instruments in the world. But is there a secret that makes the Stradivarius sound so outstandingly good? Can modern violins match the wonderful tonal quality of this great Italian instrument? Is there really a lost secret that sets Stradivarius violins apart from the best instruments made today?

After more than a hundred years of vigorous debate, this question remains unanswered, provoking strongly held, but often divergent, views amongst players, violin makers and scientists alike. The greatest violinists of modern times certainly believe it to be true and almost all perform on violins by Stradivarius or Guarnerius or one of their illustrious contemporaries. However, there are exceptions, as an increasingly large number of really outstanding modern instruments are now being made.

Violins by the great Italian makers are, of course, beautiful works of art in their own right, and are coveted by collectors as well as by players. Particularly outstanding violins have changed hands for many millions of pounds. In contrast, a really fine modern instrument may cost a few tens of thousands of pounds, while factory-made violins for beginners can be bought for well under £100 - including case and bow!

Do such large differences in price really reflect such differences in quality? If so, can we identify the differences in acoustical terms? Might such information help makers in their continuing quest to match the quality of the great Cremonese violins of the past?

For the researcher, answering such questions remains a major unsolved challenge that is at least 150 years old. The 3D-Strad project constitutes a major step towards such understanding, as it has provided the first detailed picture of the way that three outstanding Cremonese violins by Stradivarius and Guarnerius vibrate and produce their wonderful sounds.

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* *This is a revised and updated version of an article first published in 2000 in Physics World, which with Tom Rossing's book on Percussion Instruments was awarded the 2001 Prize for Science Writing by Professionals from the Acoustical Society of America.*

The violin and other instruments of the violin family are the most highly developed and most sophisticated of all stringed instruments. The violin first appeared in Northern Italy around 1550, in a form that has remained essentially unchanged ever since. The famous Cremonese violin-making families of Amati, Stradivari and Guarneri formed a continuous line of succession that flourished from just after 1550 to around 1750, with skills being handed down from father to son and from master to apprentice. The popular belief is that their unsurpassed skills, together with the magical Stradivarius secret, were lost by the start of the 19th century.

Every violin, whether a Stradivarius or the cheapest factory-made copy, has a distinctive 'voice' of its own. Just as any musician can immediately recognize the difference between Domingo and Pavarotti singing the same operatic aria, so a skilled violinist can distinguish between the sounds of individual Stradivari or Guarneri violins, though the differences are often far less obvious to the general listener. The challenge for scientists is to characterize such differences by physical measurements. Over the last century and a half, many famous physicists of the past have been intrigued by the workings of the violin, with Helmholtz, Savart, Rayleigh and Raman all making major contributions to our modern day understanding of the instrument.

It is important to recognize that the sound of the great Italian instruments that we hear today is very different from the sound they would have made in Stradivari's time. Almost all Cremonese instruments underwent extensive restoration and 'improvement' in the 19th century. You need only listen to 'authentic' baroque chamber ensembles, in which most top performers play on fine Italian instruments restored to their former state, to recognize the vast difference in tone quality between these restored originals and the more familiar 'modernised' Cremonese violins we hear in the concert hall today.

Prominent among the 19th-century violin restorers was the French maker Vuillaume, whose copy of a Guarnerius violin is shown in figure 1a. Vuillaume worked closely with Felix Savart, best known today for the Biot-Savart law in electromagnetism, to enhance the tone of early instruments. Vuillaume, Savart and others wanted to produce more powerful and brilliant sounding instruments that could stand out in the larger orchestras and concert halls of the day. Improvements in instrument design were also introduced to support the technical demands of great violin virtuosi like Paganini.

2 Back to basics: the components of a violin

To understand the factors that determine the quality of sound produced by particular instruments, we must first recall how the violin works (figure 1b). Sound is produced by drawing a bow across one or more of the four stretched strings. The string tensions are adjusted by tuning pegs at one end of the string, so that their fundamental frequencies are about 200, 300, 440 and 660 Hz - which correspond to the notes G, D, A and E. However, the strings alone themselves produce almost no sound.

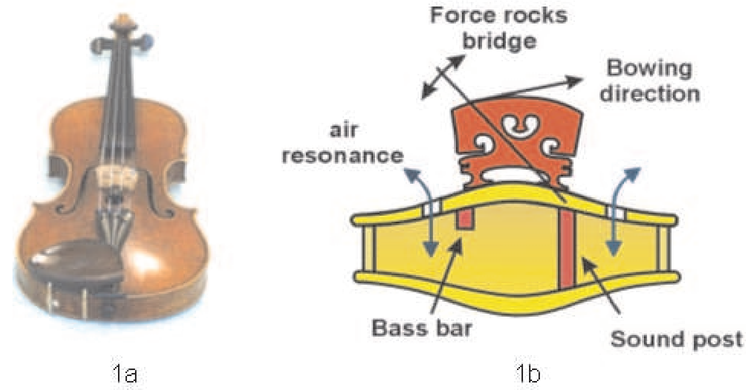

Figure 1: *Vuillaume copy of Guarneri violin with a schematic cross-section illustrating the rocking action of the bridge on the central island area between the f-holes, inducing breathing modes of the shell walls and exciting the Helmholtz resonance of the air within the cavity.*

To produce sound, energy from the vibrating string is transferred to the main body of the instrument - the so-called sound box. The plates of the violin then act rather like loudspeaker cones, which vibrate and radiate sound.

The strings are supported by the bridge, which defines the effective vibrating length of the string and also acts as a mechanical transformer. The bridge converts the transverse forces of the strings into the vibrational modes of the sound box. Because the bridge has its own resonant modes, it plays a key role in the overall tone of the instrument, particularly for the higher frequency components of the bowed sound - even for the lowest notes on the G-string.

The front plate of the violin is carved from two solid wedges of fine-grained spruce joined along the centre. Maple is usually used for the back plate and sides. Two expertly carved and elegantly shaped ‘f-holes’ are cut into the front plate. The carving of the f-holes often helps to identify the maker of a valuable instrument - never rely on the inside label to authenticate a violin, the label may well have been faked as well!

The f-holes play a number of important acoustic roles. By breaking up the area of the front plate, they affect its vibrational modes at all frequencies. Most importantly, they boost the sound output at low frequencies. This occurs through the ‘Helmholtz air resonance’, in which air bounces backwards and forwards through the f-holes. The resonant frequency is largely determined by the area of the f-holes and the volume of the violin. It is the only resonance with a frequency that is almost entirely fixed by the geometry of the instrument. What is more important than the resonant frequency is the strength with which the resonance can be excited, which depends on the coupling between the body vibrations and the volume of air within the instrument.

Early in the 16th century it was discovered that the output of stringed instruments could be increased by wedging a solid rod - the 'sound post' - between the back and front plates, close to the foot of the bridge on the E-string side. At low frequencies, the force exerted by the bowed strings causes the bridge to rock about this position, causing the other side of the plate to vibrate with a larger amplitude. This increases the radiating volume of the violin and produces a much stronger sound.

The violin also has a 'bass bar' glued underneath the top plate. This encourages the upper and lower bouts to vibrate together to enhance the volume changing ('breathing mode') vibrations, which are largely responsible for most of the radiated sound below around 700 Hz. The bass bar and sound post were both made bigger in the 19th century to strengthen the instrument and to increase the sound output.

3 How strings vibrate

In the 19th century the German physicist Hermann von Helmholtz showed that, when a violin string is bowed, it vibrates in a way that is completely different from the sinusoidal standing waves familiar to all physicists. Although the string vibrates back and forth parallel to the bowing direction, Helmholtz showed that other transverse vibrations of the string could also be excited, made up of straight-line sections. These are separated by 'kinks' that travel back and forth along the string and are reflected at the ends. The kinks move with the normal transverse-wave velocity, $c = (T/m)^{1/2}$, where T is the tension and m the mass per unit length of the string. The bowing action excites a Helmholtz mode with a single kink separating two straight sections (figure 2). The waveform repeats itself when the kink has traveled twice the length L of the string to return to the same position, with a period $2L/c$.

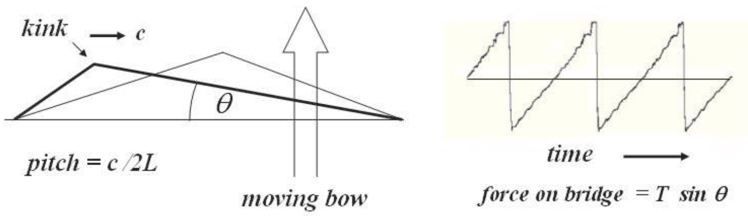

Figure 2: *Schematic representation of the excitation and propagation of Helmholtz waves on the violin string and the resulting transverse force acting on the bridge. The more solid line represents the transverse string displacements at a particular moment of time and the lighter line the displacements a little while later.*

When the kink is between the bow and the fingered end of the string, the string moves at the same speed and in the same direction as the bow. Only a small force is needed to lock the two motions together. This is known as the 'sticking regime'. But as soon as the kink moves past the bow - on its way to the bridge and back - the string slips past the bow and starts moving in the opposite direction. This is known as the 'slipping regime'.

Although the sliding friction is relatively small in the slipping regime, energy is continuously transferred from the strings to the vibrational modes of the instrument at the bridge. Each time the kink reflects back from the bridge and passes underneath the bow, the bow has to replace the lost energy. It therefore exerts a short impulse on the string forcing it to move again at the same velocity as the bow.

The 'slip-stick' mechanism of string excitation relies on sliding friction being significantly smaller than sticking friction. The Helmholtz wave generates a transverse force $Tsin\theta$ on the bridge, where θ is the angle of the string at the bridge. This force increases linearly with time, but its amplitude reverses suddenly each time the kink is reflected at the bridge. This results in a sawtooth force on the bridge, with a rich harmonic content that falls off relatively slowly as $1/N$, where N is the N-th partial. In recent years, the rather more complicated physics of the bow-string interaction has been extensively studied by Jim Woodhouse and colleagues at Cambridge University and the distinguished bass player and acoustician Knut Guettler in Sweden.

It is important to recognize that the Helmholtz wave is a free mode of vibration of the string. The player simply has to apply just the right amount of pressure to excite and maintain the waveform without destroying it. The lack of such skill is one of the main reasons why the sound produced by a beginner is so excruciating. Conversely, the intensity, quality and subtlety of sound produced by great violinists is mainly due to the fact that they can control the Helmholtz waveform with the bow for both the loudest and quietest of sounds. The quality of sound produced by any violin therefore depends as much on the bowing skill of the violinist as on the physical properties. One of the reasons that the great Cremonese violins sound so exciting is because we usually hear them played by the world's greatest players!

4 How the violin makes its sound

The sawtooth force generated on the top of the bridge by a bowed string is the input signal that forces the violin to vibrate and radiate sound - rather like the electrical input to a loudspeaker, albeit with a much more complicated frequency response. The input sawtooth waveform has a rich harmonic content, consisting of numerous Fourier components.

Since the violin is a linear system, the same Fourier components or 'partials' appear in the sound of the violin. The amplitude of each partial in the radiated sound is determined by the response of the instrument at that particular frequency. This is largely determined by the mechanical resonances of the bridge and by the body of the instrument. These resonances are illustrated schematically in figure 3, where typical responses have been mathematically modeled to simulate their influence on the sound produced.

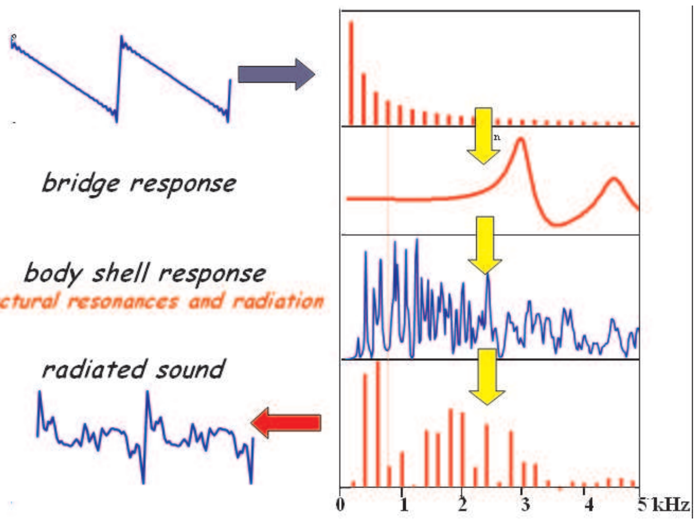

Figure 3: *Filtering action of bridge, body and room resonances determining the spectrum of the radiated sound from the bowed string, with a sawtooth force on the bridge.*

At low frequencies the bridge simply acts as a mechanical lever, with a response that is independent of frequency. However, between 2 and 2.5 kHz the bowing action excites a resonance of the bridge sitting on the central island area between the f-holes, with the top of the bridge rocking about its narrowed waist section. This boosts the intensity of any partials in this frequency range, where the ear is particularly sensitive, and gives greater brightness and carrying power to the sound. Another resonance occurs at about 4.5 kHz in which the bridge bounces up and down on its two feet. Between these two resonances there is a strong dip in the transfer of force to the body. This dip decreases the amplitude of the partials at these frequencies, which the ear associates with an unpleasant shrillness in musical quality.

The force exerted by the bridge on the top plate produces an acoustic output that can be modeled mathematically. The output increases dramatically whenever the exciting force involves frequency components that coincide with one of the many vibrational modes of the instrument. Indeed, the violin is rather like a loudspeaker with a highly non-uniform frequency response that peaks every time a resonance is excited.

In practice, quite small changes in the arching, thickness and mass of the individual plates can result in big changes in the resonant frequencies of the violin, which is why no two instruments ever sound exactly alike. The multi-resonant response leads to dramatic variations in the amplitudes and spectra of bowed notes played on any stringed instrument.

Such factors must unconsciously have guided the radical redesign of the bridge in the 19th century. Violinists often place an additional mass (the mute) on the top of the bridge, effectively lowering the frequency of the 'bridge resonance'. This results in a much quieter and 'warmer' sound, used as a special effect. It is therefore surprising that so few players - and sometimes even violin makers - recognize the major importance of the bridge and supporting island area in determining the overall tone quality of an instrument. The island area is important because its compliance affects the resonances of the bridge, while it also provides the pathway to transfer vibrational energy from the bridge to the upper and lower bouts of the violin. The pathway to the back plates is provided by the supporting side ribs and sound post.

One of the reasons for the excellent tone of the very best violins is the attention that top players and dealers give to the violin set-up - rather like the way in which a car engine is tuned to get the best performance. Violinists will, for example, carefully adjust the bridge to suit a particular instrument - or even select a different bridge altogether and will make the minutest changes to the position of the soundpost, to suit the sound required by the player. The sound quality of many modern violins could undoubtedly be improved by taking just as much care in selecting and adjusting the bridge and soundpost, as the care taken in graduating (varying the thicknesses) the individual plates.

The transfer of energy from the vibrating string to the acoustically radiating structural modes is clearly essential for the instrument to produce any sound. However, this coupling must not be too strong, otherwise the instrument becomes difficult to play and the player has to work hard to maintain the Helmholtz wave. Indeed, a complete breakdown can occur when a string resonance coincides with a particularly strongly coupled and lightly damped structural resonance.

When this happens the sound suddenly changes from a smooth tone to a quasi-periodic, uncontrollable, grunting sound - the 'wolf-note'. Players, particularly on the cello, where the lever action of the high bridge makes their instruments more prone to wolf-notes, can sometimes minimize this problem by wedging a duster against the top plate to dampen the vibrational modes, or by placing a resonating mass, the 'wolf-note adjuster', on one of the strings on the far side of the bridge. However, unless this also involves additional damping, this may only move the wolf-note to a less frequently played note, minimising the problem rather than eliminating it altogether .

The Helmholtz motion of the string and the wolf-note problem were extensively studied by the distinguished Indian physicist Chandrasekhara Raman in the early years of the 20th century. His results were published in a series of elegant theoretical and experimental papers soon after he founded the Indian Academy of Sciences, long before his work on optics that earned him the Nobel Prize for Physics in 1930.

5 The role of resonances

The existence of so many resonances at almost random frequencies means that there is simply no such thing as a 'typical' waveform or spectrum for the sound of a violin or any other instrument of the violin family. Indeed, there is just as much variation between the individual notes on a single instrument as there is between the same note played on different instruments. This implies that the perceived tone of a violin must be related to the overall acoustic parameters of the instrument, rather than to the frequencies of particular resonances.

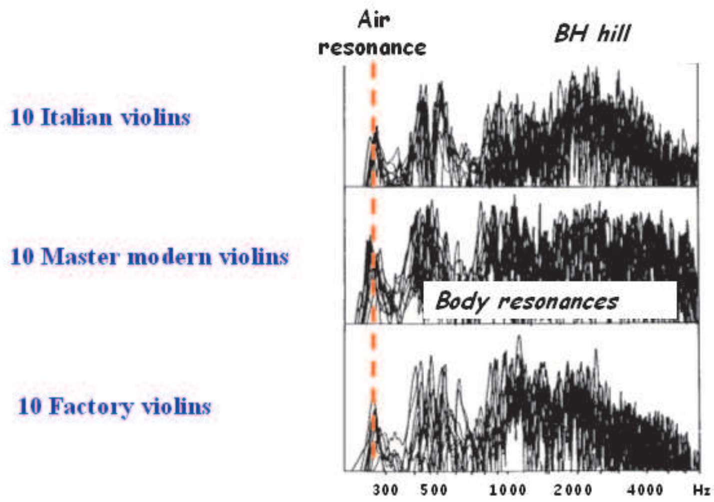

Figure 4: *Overlays of the frequency response of the sound output of 10 fine Italian, 10 fine modern and 10 factory-made violins measured by Dünnwald.*

An interesting attempt to look for such global properties was made by the German violin maker Heinrich Dünnwald. He overlaid on a single plot the sound spectrum produced by 10 Italian violins, 10 fine modern copies and 10 factory-made violins, when excited by an electromagnetic driver on one side of the bridge (figure 4).

The three prominent low frequency peaks in the sound of the old Italian instruments are referred to as the 'signature modes'. The lowest is the Helmholtz air resonance, while the upper two are prominent volume changing 'breathing' vibrational modes of the shell of the instrument found in all instruments, the lowest two body modes to radiate sound efficiently. These modes are frequently referred to as bending modes. Although pure bending modes would be very inefficient radiators of sound at low frequencies, such modes appear to be strongly excited in combination with the strongly radiating breathing modes. At higher frequencies, the radiating body modes are rather randomly distributed over the whole spectrum, though their envelope will clearly make large differences to the resulting sound quality.

The old Italian instruments were characterised by breathing body modes at relatively well-defined frequencies, whereas there was much more variation in their frequencies for both the modern and factory-made instruments. The old Italian instruments also exhibited a broad peak in output at around 3 kHz, which is associated with the vibrations of the bridge and island area on which the bridge sits. Above this so-called BH (Bridge-Hill) feature, the sound output falls off rather rapidly on the old Italian instruments and on the factory made violins, which lack a prominent BH feature, but the output remained rather high on average for the modern master violins. The factory made violins had rather poor outputs at both low and high frequencies, which undoubtedly contributes to their rather poor quality sound. The particular modern master violins used in these measurements therefore appear to have had (on average) a rather too strong output at high frequencies and too much variation in frequencies of the signature modes to consistently reproduce the low frequency sounds of the Italian master violins. However, the German violin maker Martin Schleske has had considerable success in reproducing the sounds of fine Italian instruments by 'tonal matching', achieved by thicknessing the plates of his instruments to reproduce as closely as possible the same acoustic output as the copied instrument.

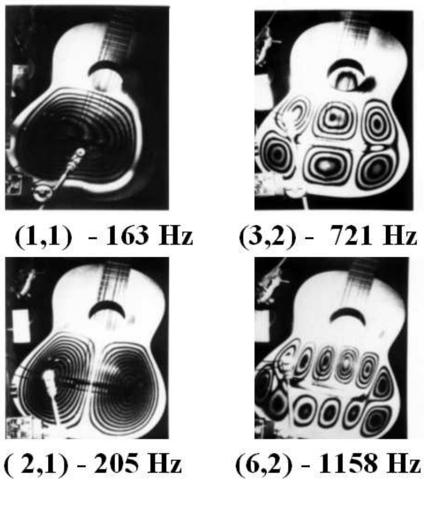

Figure 5: T*ime-averaged interference holograms of the front plate of a guitar showing flexural waves on a guitar front plate excited by a magnetic driver. The lines are contours of equal amplitude vibration, just like the contours of peaks and valleys on a geographical map, with opposite sign vibrations in adjacent regions with nodes running between them.*

Although such measurements give the frequencies of important acoustic resonances, they tell us nothing about the way a violin actually vibrates. A powerful technique for investigating such vibrations is time-averaged interference holography, in which interference between laser light reflecting off the vibrating surface of an instrument and light from the original beam produces an image showing contours of equal amplitude vibration on the excited surfaces. Bernard Richardson, at Cardiff in the UK, has made a number of such studies on the guitar and violin. Some particularly beautiful examples showing typical modal patterns of flexural waves on the front plate of a guitar are shown in figure 5. Similar flexural waves of the front and top plates of the violin are responsible for the radiated sound. However, it is not quite so easy to obtain similar high-quality images for the violin because of its smaller size and strongly arched surfaces. Furthermore, the off-set sound post and to a lesser extent the bass bar destroy the symmetry of the wave patterns, resulting in modal waveforms that are much more difficult to analyse and interpret.

Nevertheless, the holographic images of waves on the front plate of the guitar show that flexural waves on the similar thin plates of the violin will vibrate rather like waves on a string. The supporting ribs restrict the vibrations around the edges to form 2-dimensional standing waves on the plates. Unlike string vibrations, flexural waves are dispersive and travel with a velocity and resulting standing wave frequencies that increase linearly with plate thickness and inversely with the square of the linear dimensions of the plate. Other complicating factors that affect the standing wave frequencies are the anisotropy and density of the plates, which will vary from one species and piece of wood to another, and the arching and variations in plate thicknesses, which are under the makers control.

Another powerful approach towards understanding the vibrations of the violin is modal analysis, which provides very similar information to that obtained from holography. The violin is lightly struck with a calibrated hammer at several positions on the surface of the instrument and the transient response at a chosen point is measured with a light accelerometer. Alternatively, the instrument can be tapped at a fixed position and the induced vibrations measured over the surface of the instrument. These responses can then analysed to give the resonant frequencies and structural modes of vibration of the whole instrument.

This technique was pioneered as a teaching tool for students at the famous Mittenwald school of violin making in Germany and was used by Ken Marshall in America to provide the first detailed measurements of the complex vibrational modes of the whole body - including the neck, fingerboard and tailpiece, all of which are involved in the vibrations of the violin. Marshall showed that the way the violin is held by the player had relatively little effect on the resonant frequencies of the violin, other than to increase the damping of particular resonances.

Such measurements have been revolutionised in the last decade by George Bissinger at the University of East Carolina, who has used laser interferometry to analyse the structural vibrations and radiated sound of many instruments of varying quality, in response to an impulse at the bridge. Such measurements should, in principle, completely characterise the sound of the violin for any given bowing force at the bridge. The programme culminated in the 3D-Strad Project, undertaken in collaboration with a large team including the distinguished violin maker Sam Zygmuntowicz, Fan Tao from D'Addario Strings and Joseph Regh from the Violin Society of America, who helped fund the project. This involved the use of a state-of-art 3D-laser spectrometer from Polytec, to study the vibrational modes of three great Cremonese instruments - the *Titian 1715* and *Willemotte 1734* Strads and *Plowden 1735* del Gesu Guarneri violin. Such measurements and accompanying 3-D scans of the plate thicknesses will be published in a forthcoming CD, which will also include detailed supplementary information on all three instruments.

In addition, a wealth of information on the acoustical properties of well over 20 other great Italian instruments has been generated by 'tap-tone' measurements. One simply taps the bridge with a calibrated light hammer and records the sound at several positions around the violin. An elegant measuring rig for such measurements has been developed by Joseph Curtin for use in the violin maker's workshop and at violin making exhibitions and events. We are therefore in a far stronger position than ever before, to compare the acoustical properties of modern violins with those of the very greatest Italian masters.

Unsurprisingly, the differences between instruments are quite subtle, other than the obvious requirements that any good instrument must have - a powerful output in the lowest octave, which is strongly affected by the strength with which the Helmholtz resonance of the air within the cavity can be excited, and a strong ringing quality in the higher registers.

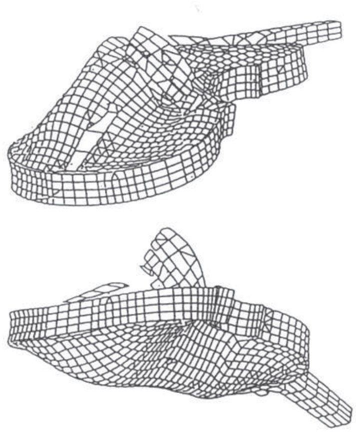

Figure 6: *The highly exaggerated computed vibrations of the strongly radiating B1 mode of a violin calculated using finite element analysis by Knott in 1987. Note the vibrations of all parts of the instrument, the asymmetric volume changing vibrations of the the violin shell and the flexing of the supporting ribs.*

Bissinger's measurements provide detailed information on both the frequencies and mode shapes of the violin's resonant modes. Similar information can be obtained by finite-element analysis, which involves modeling the violin plates and all its associated parts as a set of masses connected by springs. With the emergence of fast desk top computers and powerful dedicated software, it is nowadays relatively straightforward to evaluate the resonant modes and associated vibrations of the whole structure, illustrated in figure 6 by an example from the very first such computation by George Knott, as a student research project with the American Navy in California. The thicknesses and physical parameters of the plates can be changed at will and varied over a much wider range than would ever be physically possible. This provides a great deal of insight into the nature and acoustic importance of the various modes excited. It is now possible, in principle, to construct a 'virtual' violin and to predict all its vibrational and radiating acoustic properties. This could provide a potential tool for future violin makers wanting to improve the sounds of their instruments - but only once we have learned how to correlate the acoustical properties with our subjective assessment of 'quality' in a measurable way.

6 How to make a good violin

So how do skilled violin makers optimize the tone of an instrument during the construction process? They begin by selecting a wood of the highest possible quality for the front and back plates, which they test by tapping with a hammer to judge how well it 'rings'.

The next important step is to skilfully carve the plates out of the solid wood, taking great care to optimise the degree of arching and variations in thickness. The craftsman has to learn how to adjust the thickness and arching of the plates to produce a fine-sounding instrument. Traditional makers optimized these properties by testing the 'feel' of the plates when they are flexed, and by the sounds produced when the are tapped at different positions with the knuckles. This is the traditional equivalent of nodal analysis, with the violin maker's ears and brain providing the acoustical input and interpretative computing power.

However, in the last 50 years or so, a group of violin makers has emerged with a more overtly scientific approach. A notable pioneer in this field was Carleen Hutchins, the American doyenne of violin acoustics. Now well over 90 years old, she was a co-founder of the Catgut Society of America in 1958, together with Frederick Saunders, well known to physicists through 'Russell-Saunders coupling' in atomic physics, John Schelling, a former director of radio research at Bell Labs, and Bob Fryxell a research Chemist with the GEC company. The range of disciplines involved in studying the violin remains one of the principal attractions of violin research today. The society, whose role has now been taken over by the Violin Society of America, brought together violin makers and scientists from across the world, with the common aim of advancing our understanding of violin acoustics and developing scientific methods to help makers improve the quality of their instruments.

One common practice adopted by many violin makers has been to replace the traditional flexing and tapping of plates by continuous monitoring the flexural free-plate frequencies and shapes during the graduation process. This is achieve by suspending the plates horizontally above a large loudspeaker. Acoustic resonances excited by the loudspeaker can readily be identified by sprinkling glitter onto the surface of the plates. When a resonance is excited, the glitter bounces up and down, and moves towards the nodal lines (figure 7). The makers aim is to interactively thin or 'tune' the first few free-plate resonances to specified frequencies and nodal patterns, believed from previous practice to be important for the production of a fine sounding instrument. Note that, despite the much more complicated arched shape of the arched violin plate, the vibrational mode shapes are very similar to those of a freely supported square flat plate.

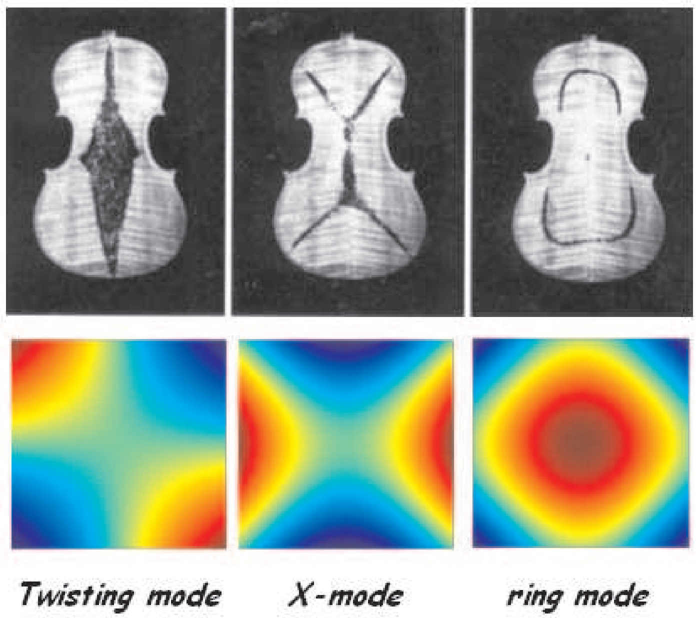

Figure 7: *Glitter patterns for modes #1, #2 and #5 of a 'well-tuned' back plate by Carleen Hutchins, and a comparison with the equivalent modes of an isotropic square plate, with blue and red illustrating vibrations in opposite phase and green indicating nodal lines.*

Unfortunately, there are very few examples of such measurements for the front and back plates of fine Italian instruments - the owners are naturally reluctant to allow their violins to be taken apart for the sake of science. The few early measurements on the free plates of early Italian instruments, made as long ago as the mid-nineteenth century by Felix Savart and much later by Saunders in the 1950's, suggested that early Italian makers may have matched the resonant modes of the front and back plates close together. The later measurements also suggested that the resonant frequencies might have been tuned to give ringing sounds - like those of a fine bell- by tuning modes #2 and #5 (Figure 7) to be an octave apart. This would reflect the prevailing Renaissance view of numbers with simple harmonic ratios pervading and reflecting the 'perfection' of all aspects of science and nature. However, as we now know, life is rarely that simple.

Nevertheless, the 'scientific' school of violin makers could reasonably claim that this might have been the lost Stradivarius secret. However, no historical evidence survives to support the case. Furthermore, Joseph Curtin's more recent measurements of the modal frequencies of a number of front plates of fine Cremonese instruments, failed to provide any convincing evidence to support plate tuning. Although many first-class modern violins have been based on these principles, there is little evidence to suggest that they are any better than many fine modern instruments made using more traditional methods.

Neither traditional craftsmanship nor scientific methods can hope to control the detailed resonant structure of an instrument in the acoustically important range above 1 kHz. Even the tiniest changes in the thickness of the plates will significantly affect the specific resonances in this frequency range, as will the inevitable variations in the properties of the wood. Furthermore, the frequencies and distribution of the resonant modes of the violin depend on the exact position of the sound post, which imposes an additional constraint on the modes that can be excited. Top players regularly return their instruments to violin makers, who move the sound post and adjust the bridge in an effort to optimize the sound. This means that there is no unique set of vibrational characteristics for any particular instrument - not even a Stradivarius!

Another factor that affects the quality of a violin is the internal damping of the wood. This strongly affects the multi-resonant response of the instrument and the overall background at high frequencies. In particular, the difference between the peaks and troughs of the resonant response is determined by the quality-factor of the resonances. This largely depends on internal losses within the wood when it vibrates. At low frequencies, only a small fraction of the energy is lost by acoustic radiation, though the acoustic efficiency increases at higher frequencies.

It has recently been suggested that the Stradivarius secret could possibly be explained by the period of global cooling that gripped Europe from the mid-1400s until the mid-1800s, slowing tree growth and providing unusually dense wood for master violin makers in 18th century Italy. In recent years a lot of new evidence on growth rates and the exact age of the wood used by the master Cremonese makers has emerged through the science of dendrichronology - a method of dating wood via the spacing patterns of growth rings.

7 The sound of the violin

The strongly peaked frequency response of the violin has a dramatic influence on the sound produced when vibrato is used. This involves the cyclic rocking backwards and forwards of the the finger stopping the string, periodically changing the pitch of the note. Because the response has such strong peaks and troughs, any change in pitch also produces cyclic variations in the overall amplitude, waveform and spectral content of the sound (see figure 8).

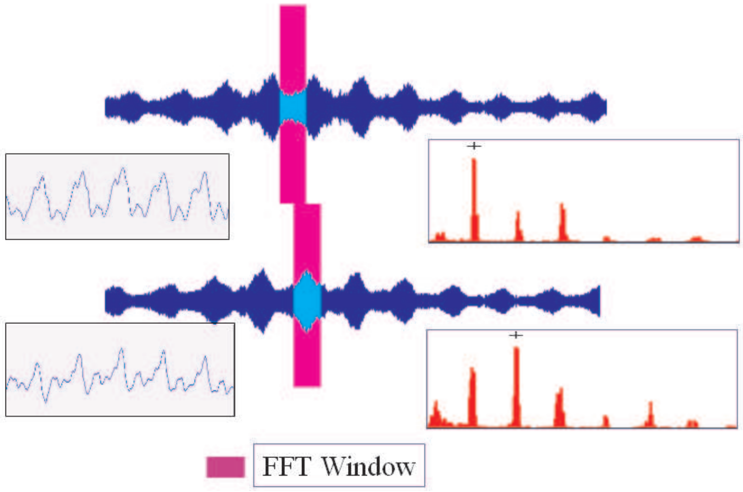

Figure 8: *The wave envelope and successive snapshots of the varying waveforms and FFT spectra of the open-D note played on the G-string with vibrato on the ex-Milstein Strad by Tasmin Little.*

Vibrato is commonly used nowadays because it captures and holds the attention of the listener, enabling the solo violin to be heard even when accompanied by a large orchestra. It would have been considered far less important when Stradivari was alive because vibrato was then used largely for special theatrical effect. The violin was generally expected to blend in with other instruments rather than to have a prominent soloistic character. Vibrato adds a certain ‘lustre’ and interest to the quality of sound produced because the ear is particularly sensitive to changes in the waveform. In a recent radio broadcast, for example, the English violinist Tasmin Little demonstrated the marvelous tone of the Stradivarius violin used by Nathan Milstein, one of the finest violinists of recent times. After playing just a few notes on the violin, she described the tone as

> *wonderfully exciting, almost deafening, very vibrant. It is alive. It has an incredible ring under my ear. It is amazing.*

There can be little doubt that Little's subjective assessment can be directly related to the extremely large changes in amplitude, waveform and spectral content associated with the use of vibrato, which gives 'life and vibrancy' to the sound - especially on the illustrated note D on the G-string (figure 8), which is close to both the Helmholtz air resonance and sympathetic resonant vibrations of the unstopped (open) D-string.

However, vibrato alone is not sufficient to characterise the sound of a violin, which is completely different from that of a synthesised sound with the same but unchanging amplitude and spectrum. Almost certainly both the inherent and player-controlled variations and fluctuations in amplitude of the bowed string, resulting from fluctuations in pressure, position and speed, plus irregularities in the bow-slip mechanism, at the start, middle and end of notes, help to distinguish the sound of the violin and other members of the violin family from any other real or synthesised musical instrument. The way in which the violin responds to such fluctuations is therefore likely to play an important role in the player's and listener's assessment of the quality of individual violins.

To achieve the observed dramatic changes in amplitude from the use of vibrato, the individual resonances of the instrument have to be strongly peaked, which requires high-quality wood with low internal damping. Because wood absorbs moisture from the air, increasing the damping, the sound and responsiveness of an instrument will therefore change with temperature and humidity.

The choice of high-quality wood for making instruments has always been recognized by violin makers, and well-seasoned wood is generally recommended. However, by measuring the pattern of growth-rings in the wood of a Stradivarius, we know that the Italian violin makers sometimes used planks of wood that had only been seasoned for a relatively small number of years. However, such wood is now 300 years old, and the intrinsic internal damping will almost certainly have decreased with time, as the internal organic structure has dried out.

The age of the wood may therefore automatically contribute to the perceived quality of the older instruments. This may also explain why the quality of a modern instrument appears to change in its first few years. Surprisingly, many players still believe that their instruments improve because they are loved and played in tune by a good player, which would be very difficult to justify on any rational scientific basis! However, it is certainly true that the sound of a violin improves with the player's age, as they themselves change, as they learn to adjust their playing technique - and ears - to optimise the sound of any newly acquired instrument.

Many other theories have been put forward to account for the Stradivarius secret. The most popular for well over a century has been that the varnish had some sort of 'magic' composition. However, the main function of the varnish is to protect the instrument from dirt and to stop it absorbing moisture from the player's hands. The varnish also imparts great aesthetic value to the instrument, with its translucent coating highlighting the beautiful grain structure of the wood below.

Moreover, the varnish is probably little different from that used by many furniture makers when Stradivari was alive and is similar to the varnish used by makers of the lute and other early stringed instruments a century before the violin emerged, when there was no great need to keep the composition of the varnish a secret. Claire Barlow and co-workers at Cambridge University, for example, have used electron microscopy to identify many of the important ingredients of the varnish itself, and the materials that are used to smooth the surface before the varnish is applied. It turns out that most of the ingredients could have been bought from the pharmacist shop next to Stradivari's workshop. Apart from the possibility that the varnish was contaminated with the wings of passing insects and debris from the workshop floor, there is no convincing evidence to support the idea of a secret formula!

Indeed, ultraviolet photography has revealed that many fine-sounding Italian violins have lost almost all their original varnish, and many were extensively revarnished during the 19th century and later. The composition of the varnish is therefore unlikely to be the long-lost secret, although too thick a varnish would certainly increase the damping and therefore sully the tone.

Other researchers, notably in recent times the biochemist and violin maker Joseph Nagyvary from the University of Texas, have claimed that the secret was to soak the wood in water or other chemicals, to leach out supposedly harmful constituents of the wood before it was seasoned. Although this would be consistent with an older suggestion that the masts and oars of recently sunk Venetian war galleys were often used by early Italian makers, the scientific and historical evidence to support this view remains tenuous.

8 Concluding remarks

Over the last 150 years, physicists have made considerable progress in understanding the way the violin works. In the 19th century the 'modernized' Stradivarius violin emerged with an 'enhanced' tone as a result of scientifically guided 'improvements' by the leading violin restorers of the day. However, Stradivari would be amazed to find that the modern musical world credits him with such a secret. After all, how could he possibly have had the clairvoyance to foresee that his instruments, despite being extensively modified in the 19th century, would produce the sound in the large concert hall that we value so highly today? Indeed, such sounds would have been totally alien to the musical tastes of his time!

Science has not provided any convincing evidence for the existence or otherwise of any measurable property that would set the Cremonese instruments apart from the finest violins made by skilled craftsman today. Indeed, a few leading soloists already play on modern instruments. Nevertheless, all but a few of the top soloists - and, not surprisingly, violin dealers with a vested interest in maintaining the Cremonese legend - remain utterly convinced of the inherent superior quality of the early Italian instruments.

Maybe there is an essential aspect of violin quality that we are still failing to recognize. Many violinists claim they can distinguish an instrument with a fine 'Italian Cremonese' sound from one with, say, a more 'French' tone, such as my Vuillaume violin. But we still do not know how to characterize such properties in meaningful physical terms. What we need is more research, with high-quality violinists working alongside psycho-acousticians, scientists and sympathetic violin makers, to make further progress in solving this challenging and fascinating problem. Such a programme involving Jim Woodhouse and his distinguished colleagues in the Departments of Music and Psychology is currently being conducted at Cambridge University in the UK.

Hopefully such research will take us a further step forward towards our ultimate goal of understanding in physical terms, why the the sound of great instruments by the likes of Stradivarius and Guarnarius and their Italian contemporaries really do produce a superior sound to those of most, but certainly not all, modern instruments.

8.1 Suggested further reading

- A H Benade (1976) *Fundamentals of Musical Acoustics* (Oxford University Press)

  Non-mathematical, but full of penetrating insights.

- L Cremer (1984) *The Physics of the Violin* (MIT Press, Cambridge, Massachusetts) translation J S Allen

  A detailed mathematical account of the essential physics of violin acoustics by one of the modern pioneers of violin research.

- N H Fletcher and T D Rossing (1998) *The Physics of Musical Instruments* 2nd edn. (Springer, New York)

  An authoritative book describing much of the relevant background to both stringed instruments and musical acoustics in general

- C E Gough (2007)*Musical Acoustics: Stringed instruments in Handbook of Acoustics* (Springer, New York)

  An up-to date review of the acoustics of the violin and other stringed instruments, with many audio examples.

- C Hutchins and V Benade (ed) (1997) *Research Papers in Violin Acoustics 1975-93 vols 1 and 2* (The Acoustical Society of America, New York)

  A comprehensive collection of many of the most important research papers on violin acoustics published in the last part of the last century. The volumes also include excellent summaries and overviews of all aspects of violin acoustics.

- M E McIntyre and J Woodhouse (1981) On the fundamentals of bowed string dynamics, Acustica 43 93

8.2 Recommended web sites for anyone wishing to learn more practical details about violin acoustics

- Martin Schleske, Violin maker and acoustician, Munich http://www.schleske.de/en/geigenbauer.html
- Erik Jansson at KTH, Stockholm. Acoustics for violin and guitar makers. http://www.speech.kth.se/music/acviguit4/
- American Physical Society, Fiddle Physics, with useful links to other web sites http://www.physicscentral.com/explore/action/fiddle-research.cfm

8.3 About the author

Colin Gough is an Emeritus Professor (i.e. retired but continuing to research the acoustics of the violin family) in the School of Physics and Astronomy, University of Birmingham, where he led a large interdisciplinary research programme on high temperature superconductors. In addition to teaching undergraduate courses and supervising research projects on Musical Acoustics, he led the university's Haywood string quartet for almost 30 years, and other local orchestras and chamber ensembles.