2 The physics of the violin

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Introduction

A study of the physics of the violin gives a fascinating insight into how the instrument converts the player's intricate motions into musical sounds. Practising musicians are often blissfully unaware of the ways in which their instruments function, but a basic understanding of the mechanics involved can be of great benefit when teaching, selecting instruments or dealing with minor problems. It also brings a little more objectivity to a subject otherwise clouded with myth, mystique and superstition.

The twentieth century has witnessed a great increase in the scientific evaluation and development of a wide range of musical instruments. Occasionally, investigations are designed specifically to improve the performance of instruments or to achieve greater control during their manufacture. Some of these studies have been successful. More usually, they are carried out purely for the sake of curiosity – a desire to seek a rational explanation of an observed phenomenon. The researcher now has a wide range of powerful analytical techniques at his disposal. For example, he can use sensitive electronic instrumentation, high-speed computers and even lasers to probe the tiny vibrations of the violin. Although these physical studies have demonstrated the basic action of the violin and unravelled a few of its 'mysteries', they are still far from answering those tantalising questions relating to the finer details of violin tone. Once we begin to involve the *subjective* evaluation of instruments, we may raise many psychological questions concerning the relationship between the instrument and the player and also about the perception of music. An instrument must provide a perfect vehicle for musical expression. It must 'feel' right and respond to the nuances of the player. The sound quality must appeal to both the player and the audience in a wide variety of acoustical environments, and it must have a tonal range suitable for the performance of different styles of music. It must also be visually attractive. These are not purely physical aspects of the instrument. To make substantial further progress in our *objective* understanding of the finest instruments requires the combined efforts of physical scientists, psychologists, musicians and makers.

The acoustical function of the violin[1]

Sound is produced when a vibrating surface interacts with the surrounding air. As the surface moves backwards and forwards, it decreases and increases the local air pressure. These pressure variations travel rapidly away from the source as sound waves, which spread out filling the space around the listener. The primary source of vibrations in a violin is the bowed or plucked string, but it produces virtually no sound on its own because its surface area is too small to drive the air. The body of the violin is designed to act as a mediator between the string and the air. The vibrating string creates a time-varying force at the bridge which causes the whole body to vibrate in sympathy. The sound we hear comes from the tiny vibrations induced in the wooden structure. Amplification is achieved mechanically through resonance of the violin body, and the large, lightweight plates (the table and back) making up the instrument form efficient sound radiators, not unlike the cones of loudspeakers.

The driving force created by the string can be measured with a transducer on the bridge. The force of interest is not the considerable static down-loading of the strings (typically about 10 kg weight) but the small, rapid variations caused by the vibrating string as it swings to and fro. The form of the force signal depends on the method of excitation. A bowed string always produces a 'saw-tooth' waveform, as shown in Fig. 22a. This results from a cyclic slip-stick motion created by the frictional forces which exist between the string and the bow. The motion involves periods where the bow and the string move together slowly (sticking) and periods in which the string slips rapidly in the opposite direction. The rosin provides the friction which drives this process and must be present on both the string and the bow hair for correct action.

A waveform of the sound radiated by a violin is shown in Fig. 22b. This appears to have little in common with the force signal, though close inspection shows that both waves have the same period (the repeat time of the waveform). The shape and perceived tone-quality of the waveform are related to its harmonic content. This can be determined from the spectrum, which shows the relative amplitudes of the individual harmonics making up the signal. The spectrum of the sound wave shows that although the body responds to all harmonics, it does not do so equally, radiating some more efficiently than others. This spectral transformation, or filtering effect, is a function of the construction of the instrument and varies considerably from one violin to another, giving each instrument a unique tone.

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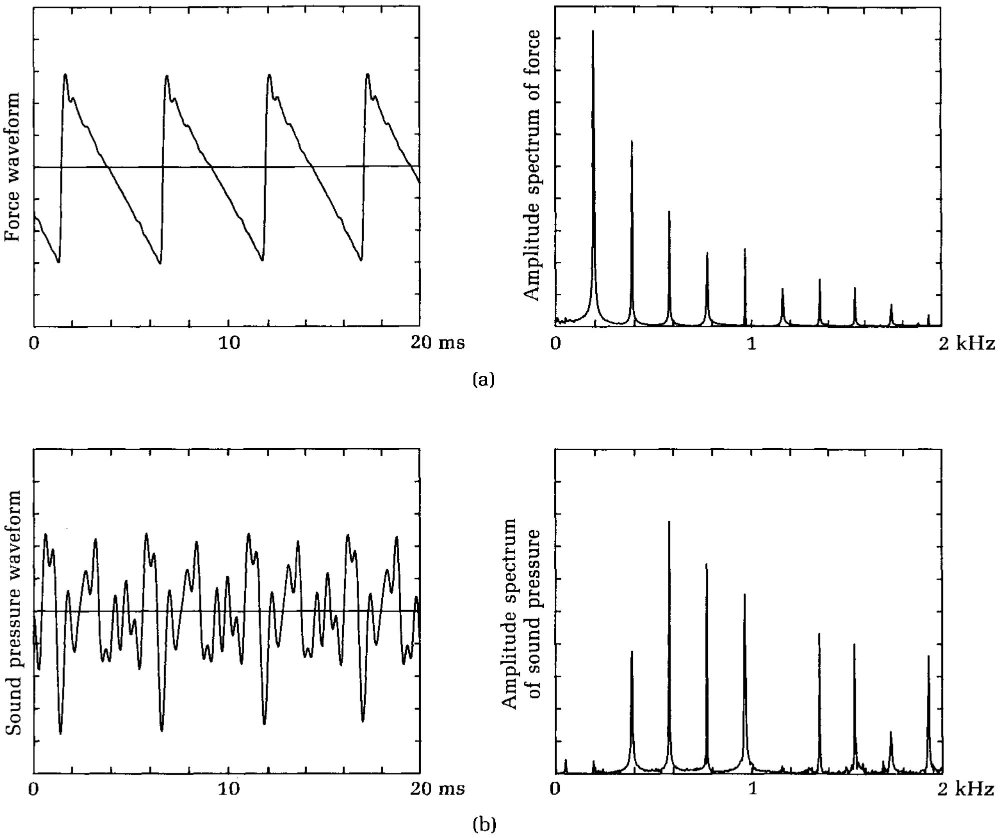


Fig. 22 The waveforms and spectra of (a) the force exerted by a bowed string at the bridge, and (b) the sound radiated by the violin playing the same note (open G string). The two waveforms have the same period (0.005 seconds or 5 ms), but the spectra show that they have different harmonic content.

String vibrations and the player

A casual observation of the vibrations of a bowed string fails to reveal the complexity of its motion. 'Snapshots' taken at different times show that the string is bent into two straight sections (Fig. 23a). The 'kink' between these sections travels at a uniform rate around a cyclic path plotting out the envelope of the motion. The envelope is all we see of the string's motion without special equipment. When the kink is on the far side of the bow, the string 'sticks' and moves slowly with the bow, but when it lies between the bow and bridge, the string slips quickly in the opposite direction. This slip-stick cycle is repeated over and over. The time taken for the kink to complete one cycle is the period of the motion and governs the perceived pitch of the sound it produces; the longer the period, the lower the pitch. The inverse of the period gives the number of cycles per

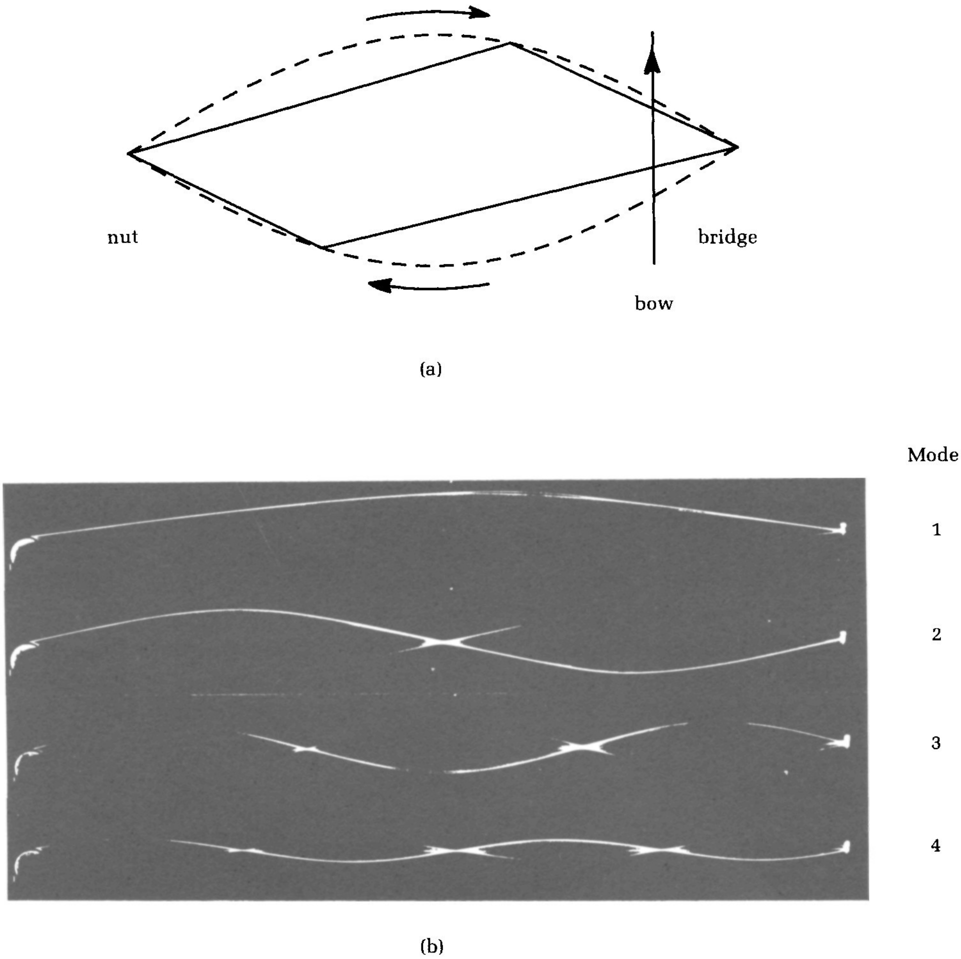
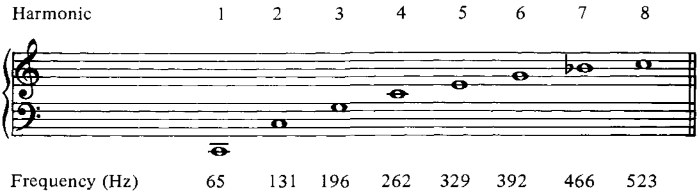


Fig. 23 (a) Schematic representation of the motion of a bowed string arrested at two different times during its cycle. The kink in the string draws out the envelope of the vibration (dotted line). The displacement of the string at any arbitrary instant can be synthesised by adding, in the correct proportions, the simple string displacements shown in (b). The latter are photographs of a real string vibrating in its individual modes of vibration. The string now flaps up and down between the extremities of its motion, always retaining the same mode shape.

second or the *frequency* of the oscillations, measured in Hz (Hertz) or kHz (thousands of Hertz).

It is instructive to view the motion of the string in an alternative way, as a summation of more basic vibrations of the string. The first four modes of vibration of a string are shown in Fig. 23b. These 'simple' vibrations can be used to synthesise more complex motions, such as those produced by bowing or plucking, by adding modal vibrations of appropriate amplitudes (this is the information we see in the spectrum of the string vibrations). The frequency of the motion of the string in its

Ex. 1 The first eight harmonics of the harmonic series based on C. The approximate frequency associated with each note is shown below the stave.



fundamental mode (mode 1) is the same as the frequency of the bowed-string vibrations. The frequencies of higher modes are harmonically related to the fundamental frequency; that is, they are integer multiples of the fundamental. Played individually as a sequence, sounds corresponding to these frequencies form the harmonic series (Ex. 1). The technical use of the term 'harmonic' is no accident. The blending properties of sounds whose frequencies are related by low-order integers form the very basis of musical harmony and are what give rise to the harmonious sounds of stringed instruments. In the violin, the action of the bow is to excite all the string's modes simultaneously, locking them together into a single harmonic entity.

Each of the higher modes of vibration has one or more stationary or *nodal* points at rational positions along the string. The player exploits these nodal points to play harmonics (in the musical sense). Normally, all modes can co-exist, but if new boundary conditions are imposed on the string, some modes can be eliminated to alter its pitch. Suppose, for example, that the player touches the string at its mid point, then only those modes which have nodes at this point will sound. These are the even-numbered modes; when sounded together they create a new harmonic series based on a note one octave higher. The pitch of the sound thus rises by an octave.

The pitch of a string is governed by its vibrating length, mass and tension. A 6 per cent change in the length produces a pitch change of one semitone. Because of this geometric relationship, notes get 'closer' together in higher positions. Increases in tension give a higher pitch, while increases in mass give a lower pitch. For practical reasons, tension and mass must be traded off against each other. To maintain reasonable consistency in tension across the four strings, the mass must increase on the lower strings, each being roughly double that of its neighbour. High-mass strings are normally made by overwinding heavy wire on a flexible core, since thick plain strings have a high bending stiffness which reduces harmonicity of the higher modes. This leads to poor sound in plucked or struck strings (it is a particular problem in the higher notes of pianos). In the bowed string, where the bow excites strictly harmonic frequencies, inharmonicity has a significant effect on the spectral content of the sounds. High-tension strings give greater sound output, but materials must have sufficient breaking strain to bear the higher tension. Technological innovations have introduced materials with higher breaking strains, allowing the use of heavier, more powerful strings (the most obvious example being the change from gut to steel). The materials and construction used in the manufacture of strings affect their dynamics, altering the harmonic content of the vibrations and the rate at which vibrations are set up and die away, all of which influence the sound-quality of the instrument.

For steady bowing, the player must carefully control the bow's speed and its down-bearing force on the string (the 'bow pressure'). The bow's speed does not affect the period of the string's vibrations, but it does control the amplitude (loudness). For stable oscillations the bow force must lie between a maximum and minimum value, each dependent upon the proximity of the bow to the bridge and the bow's speed. If the bow force is too low, the string tends to slip two or three times per cycle, producing whistles or accentuating certain string harmonics and giving a 'ghostly' sound. At the other extreme, the tone becomes raucous or 'gritty' – the sort of sound which gives *sforzando* playing its biting edge. The bow hair now holds on to the kink for too long, releasing it at imprecise times, which is heard both as a noise component in the sound and a flattening of the pitch of the string. This latter effect is most noticeable near the bridge, where higher bow force is necessary for steady playing. Similar random fluctuations are present in all steady bowing, and although not harmonious, this noise is an accepted and essential part of the violin sound.

Music is, of course, not dominated by 'steady' playing but by starting and stopping and changing notes. The stable vibrations discussed above are the result of bending waves on the string travelling backwards and forwards, reflected from the two end stops and interacting with the bow. These waves take time to establish themselves. This transient part of the note can be an unpredictable period for the violinist. Instruments which 'speak' easily are those in which stable oscillations are set up quickly and uniformly. Factors which affect the transient are the mobility of the bridge, the physical characteristics of the player's left-hand fingertips, the construction of the strings and the bow control. Changes of strings or modifications to the bridge and soundpost can often help to improve troublesome notes on an instrument.

Plucking the string sets up fundamentally different types of vibration, in which the driving force measured at the bridge looks more rectangular. The precise shape of the waveform depends on the excitation point on the string, having significantly greater high-frequency content for plucking positions near the bridge. Similar effects also occur in the bowed string but to a much lesser extent. Because energy is not continually supplied to the plucked string, its vibrations begin to decay immediately. The decay rates of each harmonic are not the same but depend on how efficiently the energy at that frequency is transmitted to the air by the body or absorbed by the finger in a stopped string.

Body vibrations

For a given set of strings, player and playing conditions, the form of the force at the bridge would be virtually the same irrespective of the instrument on which the strings were mounted. The same cannot be said for the sounds produced by different instruments. Although the body responds to each of the harmonic motions of the vibrating string, it does not respond equally, and it alters the proportion of the harmonics in the radiated sound. It thus 'colours' the sound. The variable response is produced by mechanical resonances of the body. In other words, it has modes of vibrations, just like the string. The difference is, however, that the vibrations are now spread over the entire body, and because of the complexity of the violin's shape and structure, the frequencies at which they occur are no longer harmonically related.

Fig. 24 shows a response curve made on a good-quality violin. It was produced by electronically driving the instrument with an oscillating force of constant amplitude in the frequency range 100 Hz to 20 kHz. This represents a range which starts one octave below the bottom note of the violin and extends to the upper limit of human hearing. The curve shows the amplitude of the velocity (speed) of the motion induced in the body, or its mobility, as seen by the strings. The main response occurs in the range 300 Hz to 5 kHz, in which the relative mobility varies over a range of about 100:1. Each of the peaks on the curve represents a resonance of the instrument. String harmonics which coincide with these peaks are strongly present in the radiated sound. At each resonance frequency, the centre frequency of each peak, the instrument vibrates predominantly in one of its modes of vibration. Off resonance, the body vibrates in a combination of its modes. The strength, or height, of each resonance peak is governed partly by the proximity of the bridge to nodes of the body vibrations (see Fig. 25) and also by the damping of the mode, which is a measure of the energy radiated as sound or converted into heat by the body. A different response curve is obtained for every possible combination of driving and observation points. Other forms of response curves showing the sound radiation as a function of frequency tend to be more complex because of the directional character of the radiation from many of the modes.

Every instrument will produce a unique set of response curves, and for this reason they can be regarded as the instrument's 'fingerprint'. There are, however, some common features among them. The overall shapes of the curves, though variable, have a pattern which identifies them as belonging to a violin rather than a viola or cello. With experience it is

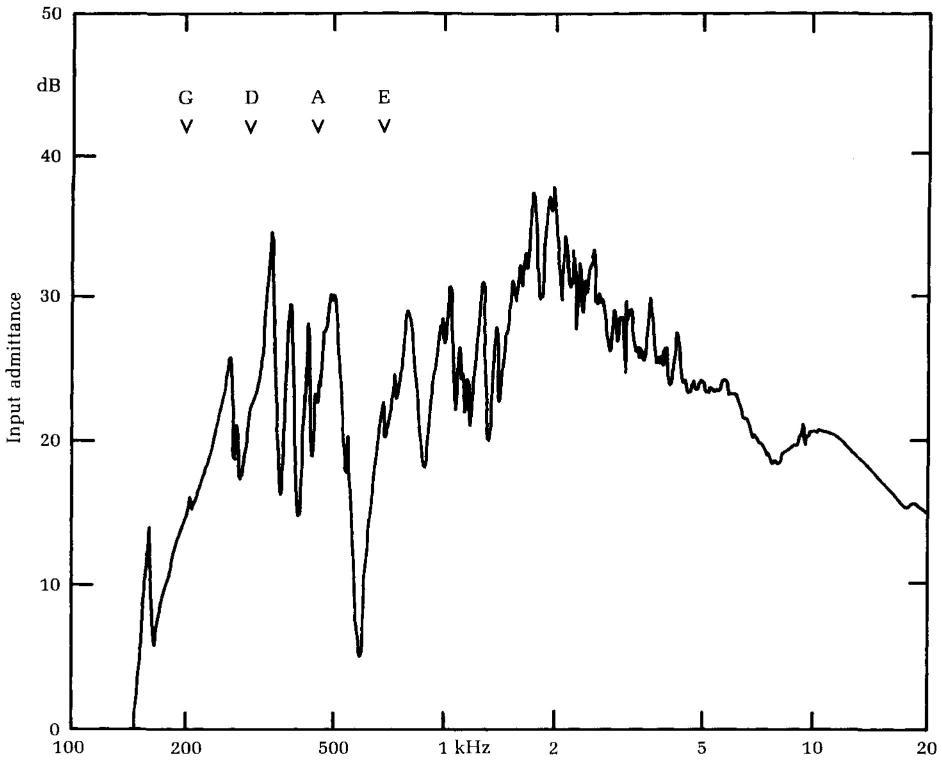


Fig. 24 A violin response curve showing the input admittance (velocity amplitude per unit driving force) of the body as a function of frequency. The vertical scale is expressed in decibels (dB). A change of 20 dB represents a tenfold increase in the amplitude of the body's motion.

possible to distinguish between good and bad instruments. The overall shape is sometimes referred to as a formant, a term derived from the analysis of speech and vowel sounds. Thus the curve can give an indication of the general sound quality, whether it is 'nasal' or has an 'ee' or 'u' sound. Good violins tend to have strong resonances which lie near to the frequencies of the open D and A strings (293 Hz and 440 Hz respectively). Like other aspects of the instrument's acoustics, this resonance placement is not necessarily an optimum design, but it is where from experience one *expects* to find strong resonances.[2] Undoubtedly the placement of many of the higher resonances is equally important but these modes are not so readily controlled by the maker.

The large variations in mobility across the playing range might be expected to produce an instrument with wildly fluctuating loudness. This is not the case, however. Fig. 24 was obtained by driving the violin with a signal equivalent to a single harmonic of the string (a signal known as a sine-wave). The saw-tooth waveform generated by the bowed string includes higher harmonics, and a good instrument is engineered such that at least one of the note's principal harmonics (one of the lower two or three) is strongly present in the sound emitted by the violin. For example, the fundamental component of the open G string (196 Hz) always falls in a region of weak response of the body and is virtually absent in the spectrum of the radiated sound (see Fig. 22b, in which even the second harmonic is rather poorly represented). Lack of fundamental does not alter the pitch of the note because the higher harmonics are still present, but the note tends to sound less 'full' than notes a few semitones higher when the first resonance of the body is able to give it support. Because of the complexities of the response curves, no two notes on the same instrument have the same harmonic content. Even the small modulations in frequency induced by vibrato vary the harmonic content, adding greatly to the richness of the overall sound. Surprisingly, listeners have little difficulty in associating sounds with a particular instrument, even when it is part of a larger ensemble. The perception of instrument tone does not merely involve the analysis of the steady-state part of the note. There are important perceptual clues in the transient parts of notes which are characteristic of an individual instrument and help the listener to identify the origin of the sound.

Fig. 25 shows a small selection of some of the modes of vibration of a violin. These particular modes are strong radiators of sound, both to the player and beyond. The low-frequency modes involve motion of the whole violin body and there is strong co-operation between the wooden plates and the air inside the cavity. At the first strong resonance, usually to be found around the second position on the G string, the net motion is that the whole body swells and contracts. Fig. 25a shows the motion of the table. The main activity occurs roughly along the line of the bass-bar, and the right-hand rib is also in motion. A node sweeps down the full length of the plate traversing the soundpost and treble foot of the bridge. The back exhibits similar motion at this frequency. Sound is created not only by the motion of the two plates but also by the air being squeezed resonantly in and out of the f-holes. The frequency of this mode is controlled to a large extent by the volume of the air cavity and the area of the f-holes. This is the same sort of resonance which can be produced by blowing across the top of a wine bottle, but in the violin the walls are flexible and the air motion is excited by vibrations of the walls. The coupling between the plates and air cavity extends the response of the instrument at low frequencies, without which the bottom octave would be weak. When the driving frequency is raised to about that of the open A string, the body exhibits similar motion except that the two plates tend to swing in the same direction so that the body as a whole bends like a thick sandwich and both ribs vibrate actively. An interesting observation is the degree of asymmetry of these two modes, primarily caused by the presence of the soundpost and bass-bar. At progressively higher frequencies the modes become more complex, breaking into a number of smaller

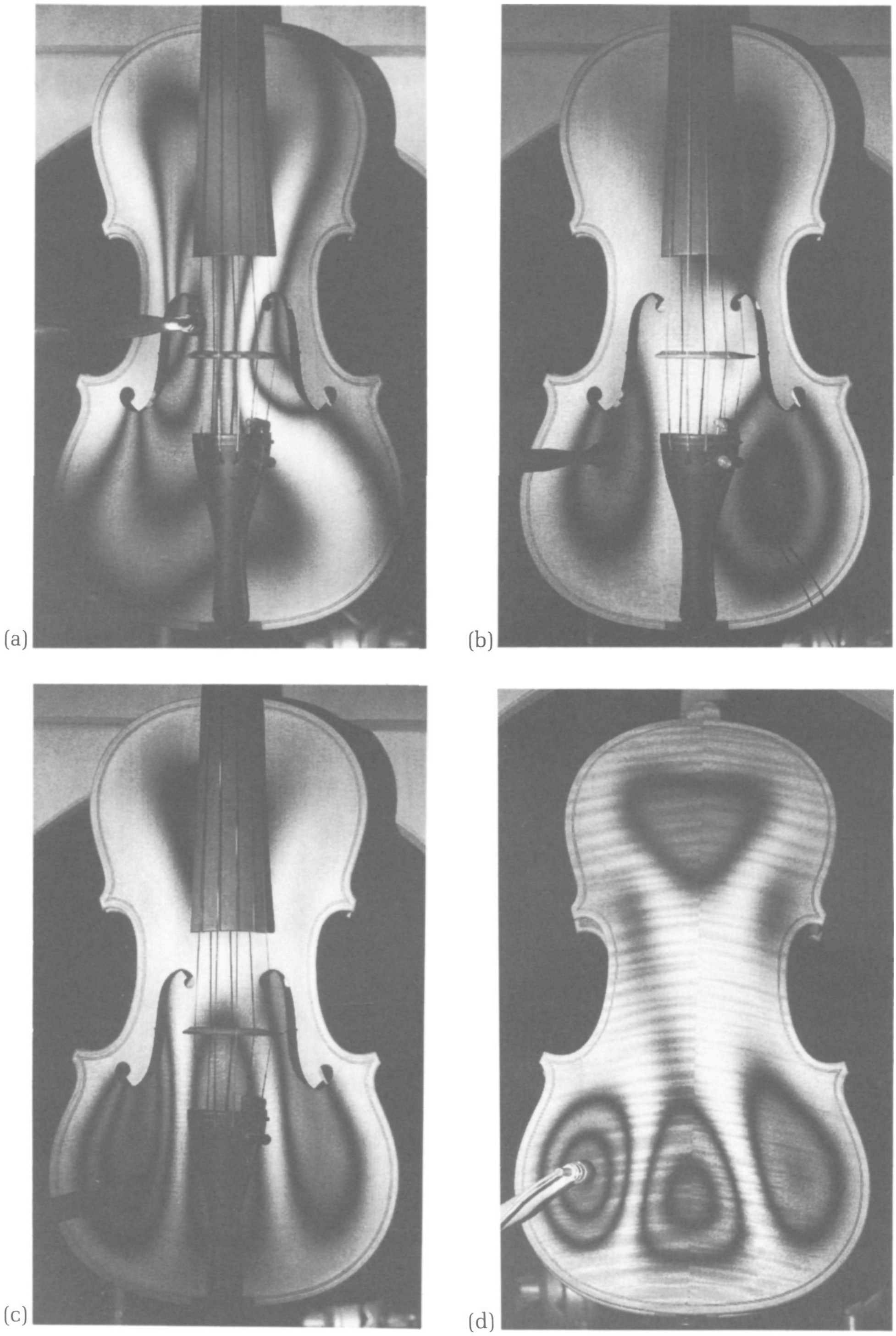


Fig. 25 Modes of vibration of a violin body visualised by means of an optical technique called holographic interferometry. The light and dark bands overlying the images are ‘contour maps’ of the vibration amplitude (the brightest bands are nodal lines – see also Fig. 27). Mode frequencies in this violin were (a) 272 Hz, (b) 755 Hz, (c) 1255 Hz and (d) 1288 Hz.

vibrating regions separated by nodal lines, not unlike two-dimensional versions of string modes. In Fig. 25b the motion in the lower bout has separated into two regions, resulting in a rocking motion about a nodal line which now runs almost up the centre of the plate. Fig. 25c shows the next mode, in which the vibrations have separated into three regions. The two outer regions now swing in the opposite direction to the patch under the tailpiece. Note how the f-holes relieve the bending in the central area of the plate giving greater flexibility to the bridge region. This progression continues with division occurring both along and across the plates. The higher modes are generally confined to one or other of the plates.[3] A similar set of motions exist on the back (e.g. Fig. 25d), though equivalent modes tend to occur at slightly different frequencies. The vibrations of the back plate are excited primarily by energy which flows from the bridge and table via the ribs. The majority of the sound we hear is produced directly by these flexures of the plates or of the instrument as a whole.

There are other categories of low-frequency body motion which involve simple bending or twisting of the body, neck and fingerboard. These tend to be poor radiators, though they can colour the sound heard locally by the player and may, via feedback, influence the overall performance of the instrument. Neck vibrations can also influence the player through tactile response.[4] In effect, there is virtually no part of the instrument which is not involved in sound production on the violin.

The precise features of the modes shown in Fig. 25 are, of course, unique to that instrument. There is, however, considerable similarity of mode shapes and their hierarchy among violins. The differences lie in the subtle variations of the positions of nodal lines relative to the bridge and the frequencies and damping of the modes. As in the string, the modes of vibration are created by waves, which now spread out and flow around the entire body, becoming partially reflected and transmitted at any boundaries, such as the intersection between the ribs and belly. These waves travel fastest along the length of the instrument because the wood is stiffest in this direction. The waves themselves are not influenced directly by details of the grain pattern of the wood. Instead, the wave propagation is governed by the general mass and stiffness distribution of the plates and by the instrument's dimensions. The stiffness distribution is very sensitive to the particular arching of the plate and the material properties of the wood. The sound quality of an instrument is thus closely linked to its construction.

The bridge and soundpost

The bridge and soundpost play a particularly important role in the lower playing range of the violin. For obvious practical reasons, the player must bow the strings of a violin from side to side. Unfortunately, the

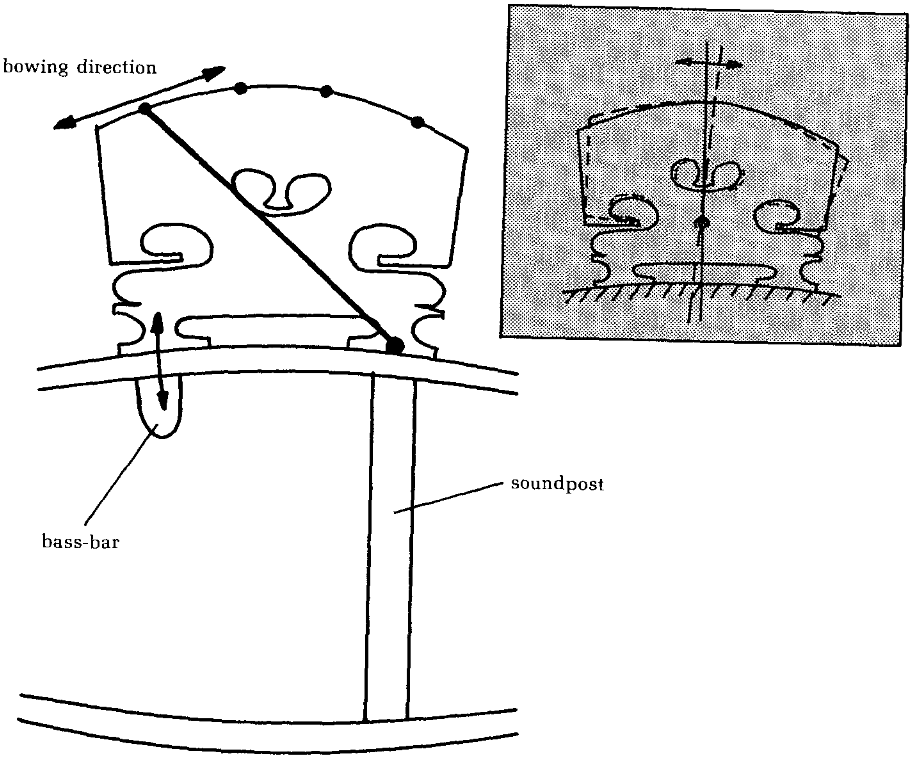


Fig. 26 At low frequencies, the violin bridge acts like a lever, with the soundpost acting as a fulcrum, converting the sideways motion of the string into an up-and-down motion at the plate. Note the different mechanical advantage of each string. At higher frequencies (inset) the bridge can no longer be considered to be rigid and exhibits resonances of its own.

body is least responsive to forces exerted in this direction, being most readily excited by forces perpendicular to the plate. What the soundpost does, at low frequencies at least, is to induce a node in the vicinity of the bridge foot, creating a fulcrum at that point. This can be seen in all the body modes in Fig. 25. The bridge, which is virtually rigid at these frequencies, then acts like a lever, swinging about this fulcrum, converting the sideways motion of the bowed string into an up-and-down motion at the other bridge foot (Fig. 26). At mid-range frequencies, the table and back co-operate more readily and allow the soundpost to move up and down, destroying the nodal line near the bridge foot. The lever action of the bridge then breaks down. Above 2 kHz, the bridge itself begins to exhibit strong resonances, which help to boost the sound power radiated by the instrument. The broad peak seen at 2 kHz in Fig. 24 is caused by a bridge resonance. As in the case of the body, the density and stiffness of the wood and the precise way in which it is cut and shaped determine the resonance frequencies.

Because the bridge and soundpost are easy to manipulate, they can be used to fine-tune the sound or playing qualities of the completed instrument. From the previous discussion, it is clear that changes to the internal position of the soundpost will affect the mechanical action of the violin as a whole. Bridge resonances can also be adjusted, being particularly sensitive to wood removal from between the 'ears' or from the 'legs'. The drastic effects of the mute can also be understood. First, it adds mass to the instrument at the driving point, making it harder to drive and reducing the sound output. Secondly, it substantially lowers the resonance frequencies of the bridge, altering the filtering effect of the bridge–body structure.

The body has thus far been described very much as the servant of the string. This is true except at strong resonances of the body. The motion at the bridge then becomes very large, and the string no longer has a node at this point, which upsets the usual vibrations and can lead to intolerant or troublesome notes. In the extreme it creates a cyclic stutter known as a wolf-note, common in cellos but also found occasionally in violins. Wolf-notes can be subdued by using lower-tension strings or using an 'eliminator', which tunes some other part of the structure to the same frequency as the wolf, absorbing energy and helping to keep the bowed string under control.

Construction and tone

The violin combines the best in fine engineering, visual artistry and sound-quality. The arched plates provide maximum strength for the body to bear the considerable down-bearing force of the strings, whilst retaining sufficient flexibility to allow the instrument to vibrate in response to the bowed string. The instrument's shape is functional, but its functionality is never allowed to interfere with its perfect classical form. The design is not rigidly fixed, but invites an individualistic approach by the maker, so that the violin has undergone a continual, subtle development to cater for the specific needs of the day.[5]

It may seem strange that in our advanced technological age we cannot emulate the sound of the instruments of past masters. From an acoustical point of view, copying implies reproducing the vibrational modes of an instrument. Size-for-size copies do not work because the frequencies, shapes and damping of the body modes are determined not only by the dimensions and construction of the instrument but also by the mechanical properties of the wood. Mechanical properties vary considerably from sample to sample because of differences in growth or because of the way the timber is cut. The very best wood is split from the tree, ensuring that the wood fibres run parallel to the surface of the plate and that the wood is quartered, i.e. the grain runs vertically through the plate. These two conditions ensure maximum stiffness both along and across the grain. Even small deviations from the quarter can substantially reduce the cross-grain stiffness of the wood, which then has to be compensated for by an increase in the plate's thickness or arching with a consequential reduction in sound power. The influence of long-term changes in the mechanical properties of wood is an additional, unknown factor. In an effort to maintain consistency or to achieve a predetermined tone-quality, the maker has to modify the dimensions and design of an instrument to compensate for differences in the quality of the wood. All but the very best of makers perform this task with a high degree of uncertainty.

Quality control by the maker starts at the earliest stages in construction. The choice of wood is made carefully according to empirical and traditional rules. The table is made from spruce or pine. This type of wood combines great strength and stiffness with low density, which are important structurally and acoustically. Low internal friction in the material ensures that energy losses within the plate itself are minimised. The back and ribs are made from maple, which is a less obvious choice (and is undoubtedly selected more for appearance than acoustical reasons). The maker's work then proceeds with the carving of the plates. These are the most important vibrating parts of the instrument. Good makers can tell when they are correctly dimensioned and rely little on modifications to the near-finished instrument. They are able to respond to the 'feel' of the plates and adjust them through experience.

A common method for testing plates is tap toning. The plates are thinned gradually until they produce certain notes when held and tapped at special places. The maker is actually making measurements of the modes of vibration of the free plates. Ideally, the plate is held at a node and tapped at an antinode (a point of maximum vibration), thereby isolating an individual mode. The well-defined pitch produced by the plate then corresponds to the resonance frequency of that mode. The duration of the sound gives an indication of the damping. With practice five or six modes can be isolated in this way.

It is not clear how the maker uses information about the free-plate modes. Through experience, each maker develops his own set of empirical tuning rules for the free plates, which is one of the reasons why propagating his art is so difficult. But since the best makers produce consistently good instruments, it seems reasonable to conclude that there are *measurable* properties of the free plates which give some indication of the quality of the finished instrument.

The first serious scientific work to determine tuning rules for violin plates was undertaken in the nineteenth century by Félix Savart (1791–1841). He was fortunate in being able to test plates removed from many fine instruments (including Stradivari and Guarneri violins), loaned to him by the great French luthier J. B. Vuillaume. He concluded that in good instruments the most dominant tap-tone of the free back plate (now

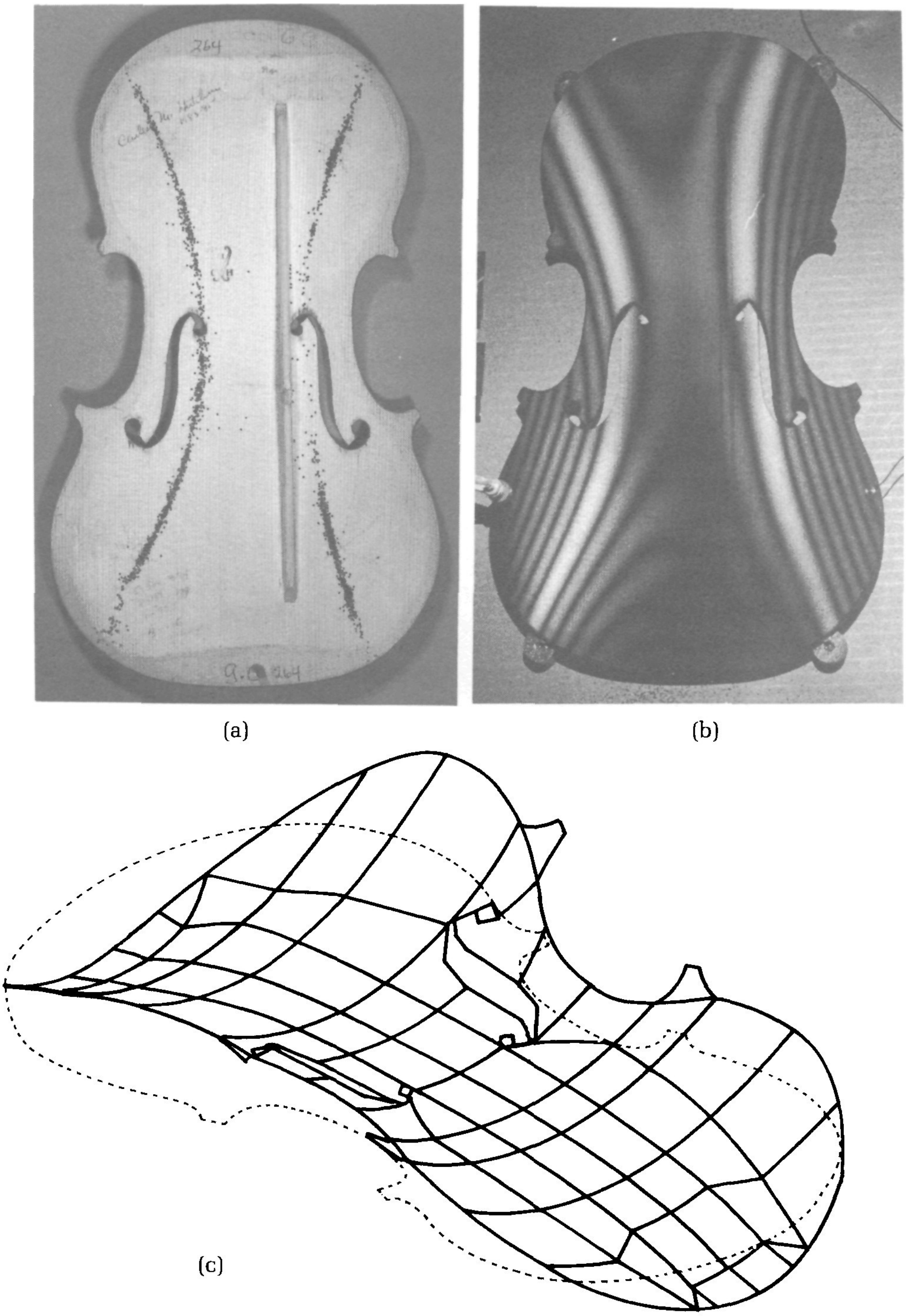


Fig. 27 The second mode of vibration of a free violin plate visualised by (a) a Chladni pattern; (b) holographic interferometry; and (c) numerical calculations. The black lines in (a) show the positions of the nodal lines. The light and dark bands in (b) are equivalent to contour lines showing the bending across the plate (the two bright bands are the nodal lines). (c) Computer-generated plot showing the bending of the plate during its vibration cycle. The dotted line shows the outline of the stationary plate. The motion is grossly exaggerated.

known to be the fifth mode) was always a semitone to a tone higher in pitch than in the free table. More recently, Carleen Hutchins has developed tuning rules for free violin plates which help her to achieve consistency in the quality of finished instruments.[6] Besides tuning the frequencies of a number of modes, she adjusts the plates to obtain particular nodal configurations. The positions of the nodes are identified by means of Chladni patterns (Fig. 27a). The plate is excited electronically at one of its resonance frequencies, by suspending it over a loudspeaker for example. It is then dusted uniformly with sand or coloured aluminium flake, which bounces off the vibrating parts and collects along the nodal lines. Chladni patterns are one of the most vivid demonstrations of the vibrations of violin plates. They can highlight asymmetries in the vibrations, which often occur because of inconsistencies in thickness, arching, or material properties. Manipulating the frequencies *and* the shape of *several* modes is extremely difficult. The technique is so sensitive that the plates are tuned after varnishing to account for the small but significant changes which the surface coatings induce in the stiffness and mass distributions of the plate. It is clear from Hutchins's descriptions that these methods do not make the maker's task any easier – they simply define the goals more objectively.

Free-plate tuning alone is not sufficient to produce a good violin. The problem is that the modes of vibration of the free plates bear little relation to the modes of the finished instrument; the rib structure, the neck and the internal air cavity are also important in determining the dynamical properties of the completed body. Modifications to seemingly unimportant components such as the top-, bottom- or corner-blocks or the linings can be expected to induce perceptual changes in the tone quality of an instrument. Plate-tuning rules work for individual makers because they tend to build the rest of the instrument in a consistent way. Recent work in computer modelling of violin vibrations is helping to cast light on this otherwise intractable problem.

The relationships between the construction of musical instruments and their tone qualities will remain an extremely difficult problem at the forefront of physics and psychology; this is, of course, one of the attractions of the problem to all concerned with the violin. The physical differences between the 'best' instruments are undoubtedly extremely small, but nevertheless clearly perceived by the accomplished player. Thus although physical studies have created an accurate picture of the mechanical function of the violin, in itself a most valuable contribution, the only true test for quality is to play on the instrument.