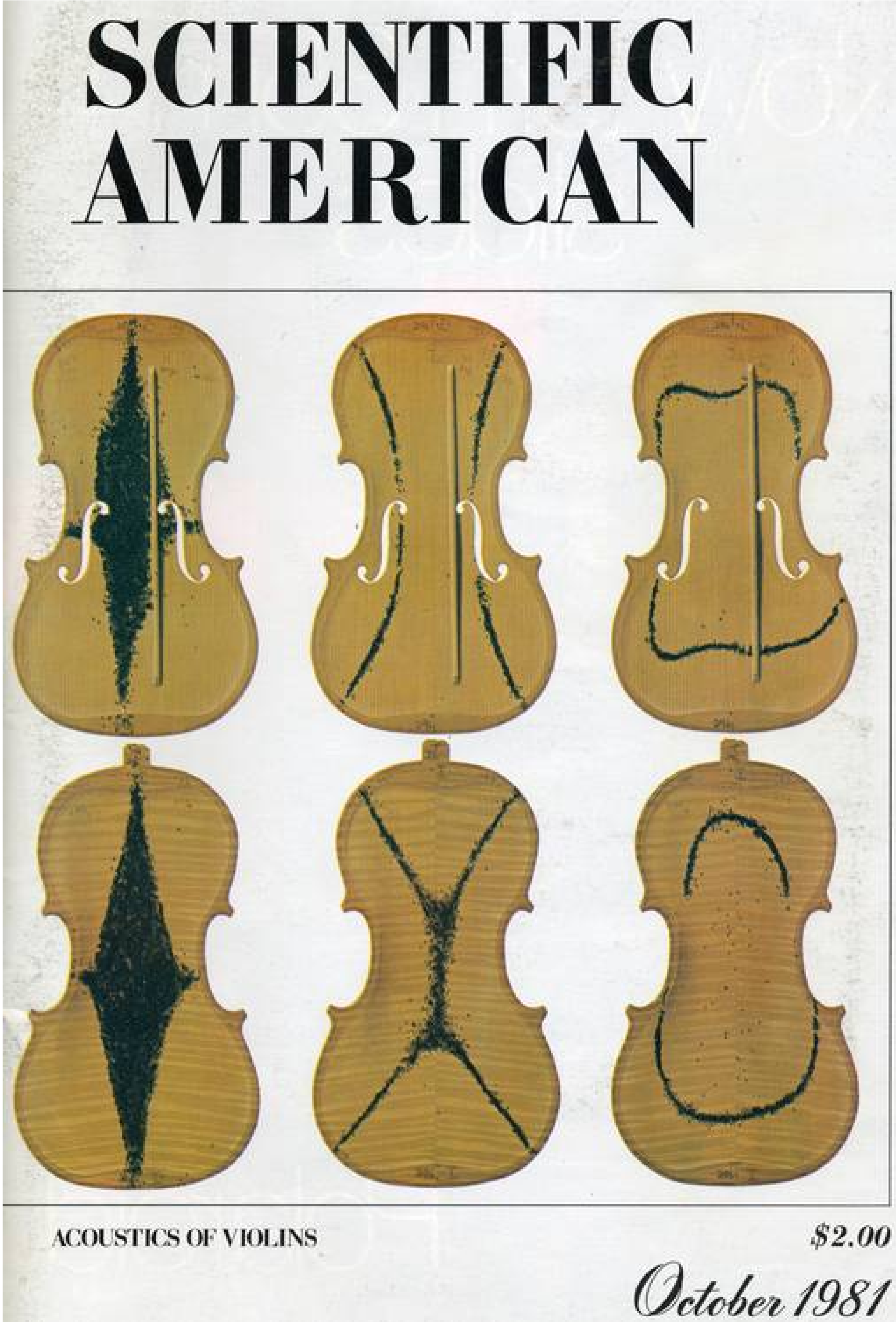
Scientific American Oct 1981, Vol. 245, No.4, page 170 ff.
"The Acoustics of Violin Plates", by Carleen Maley Hutchins.

The vibrations of the top and back plates are tested to find out how to make superior violins.



THE COVER

The painting on the cover shows tests of the vibrational properties of an unattached top and back plate of a violin *(see "The Acoustics of Violin Plates," by Carleen Maley Hutchins, page 170).* In the test the plate is mounted inside upward over a loudspeaker and particles of aluminum flake are sprinkled on it. The plate rests on four soft foam pads, each adjusted to support it at a nodal, or non-vibrating, point. The loudspeaker is centered under an antinode for the vibrational mode being tested. In response to a single-frequency sound from the loudspeaker the particles begin to bounce. Since the antinodal areas move vigorously, the particles are bounced quickly into the nodal areas, giving rise to a pattern that is characteristic of the particular mode. The modes are designated as mode 1, mode 2 and so on, beginning with the mode of lowest frequency. In the painting one sees from left to right the patterns of modes 1, 2 and 5 on each plate. The top plate is made from two pieces of spruce, the bottom one from two pieces of curly maple. The insides of the plates are left "in the white," that is, without sealer or varnish, and therefore display the natural color of the wood.

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The Acoustics of Violin plates

Modern tests of the vibrational properties of the unassembled top and back plates of a violin reveal something of what violinmakers do by "feel" and lead to the making of consistently good violins.

by Carleen Maley Hutchins.

One of the great mysteries of music is how the renowned violinmakers of past centuries, apparently having had no more than a practical knowledge of the physics and acoustics of their instrument, could turn out violins that are still cherished today for the beauty of their sound. For some 30 years a small but worldwide group of us in an organization named the Catgut Acoustical Society have applied modern methods to the study of the physics and acoustics of violins and other stringed instruments. I described the early stages of the work in these pages nearly 20 years ago *[see "The Physics of Violins," by Carleen Maley Hutchins; SCIENTIFIC AMERICAN, November, 1962].* Now the work has progressed to the point where a good deal can be said about the properties of the top and back plates (the "belly" and the "back") of a violin before they are assembled into an instrument. Moreover, it is possible on the basis of these findings to construct violins and other members of the violin family with consistently fine tone and playing qualities.

The two plates are carved traditionally from solid blocks of wood, the top plate from two adjacent pieces of straight-grain spruce *(Picea abies)* joined down the middle, and the back plate from either a single piece or joined pieces of maple *(Acer platanoides)* that usually have a "flame," or curl, across the grain of the wood. Yet because of the variations in wood, even between two adjacent pieces from the same tree, it is not possible to reproduce measurement for measurement the parts of a fine-sounding violin and so to create an instrument with the tone and playing qualities of the original. The way to duplicate a fine violin lies not in geometrical measurements alone but must include measurements related to the vibrational properties of the wood.

The long-term investigation described here draws heavily on the experience of violinmakers and provides some new answers to a question asked in 1830 by Felix Savart, a physician and physicist: "What sounds ought the top and back of a violin have before they are joined?" Through the generosity of the eminent French luthier Jean Baptiste Vuillaume, Savart was able to test the disassembled top and back plates of a dozen or so violins that had been made by Antonio Stradivari and Giuseppe Guarnieri. (Imagine!) He applied a measuring machine he had devised, together with a technique worked out by his friend Ernst F. F. Chladni. By the Chladni method the eigenmodes, or normal mode patterns of vibration, of a horizontally mounted flat plate can be demonstrated by sprinkling the plate with a fine powder and causing the plate to vibrate. At certain frequencies (the eigenfrequencies) the vibration bounces the powder into the nonvibrating nodal areas, thereby outlining the nodal and antinodal configurations of the plate at its specific resonance frequencies. These plate resonances, or normal modes, are created by the physical properties of stiffness and mass, which cause standing-wave patterns to be formed in response to vibration at discrete frequencies unique to each plate. In answer to Savart's question he reported: "We have found that the sound varies in good violins between C# 3 [the 3 indicates the octave] and *D* 3 for the belly, and for the back between D 3 and D # 3, so that there is always a difference between them of a half or a whole tone[1]."

Over the years other investigators have made vibrational measurements of violin plates, both free and in the assembled violin, and have assessed the resulting tonal characteristics. Particularly notable is the work of the acoustician and violinmaker Hermann F. Meinel in Berlin during the 1930's, which documents the correlation between the thickness of the plates and the vibrational modes, the volume of sound and the timbre of sound. Meinel also recognized the limits of constructing violins on an empirical basis and noted the effects of the properties of the wood, the arching of the plates and the varnish. He explored the possibility of improving a particular violin in a given frequency range by removing wood from a specific area, following the work of Hermann Backhaus, but concluded that improvement does not always result because it depends on the physical state of the violin. This early work highlights a basic problem in violinmaking: a small change that will markedly improve one instrument may adversely affect another owing to the widely varying configuration of the vibrational modes and the stiffnesses throughout the plates.

[1] Note that this is the C#3 to D#3 of the mid 1800's, which was lower than today's pitch.

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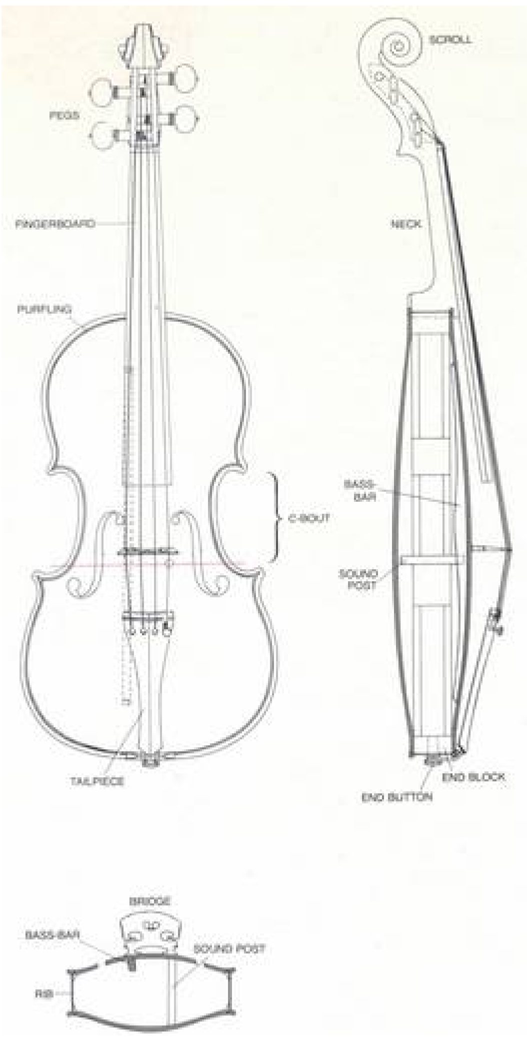
In 1950 the Harvard physicist Frederick A. Saunders and I began a collaborative study aimed at verifying Savart's findings and at developing other vibrational measurements that relate the unique bending characteristics of each pair of free top and back plates to the particular tone and playing qualities of the assembled instrument. By 1960 the results of some 200 tests on violins and violas in the course of construction had confirmed Savart's main finding: the instrument has good musical qualities when the principal plate tone of the top and of the back are from a tone to a semitone apart. Violinmakers call the principal plate tone the tap tone because it is the principal tone heard when the plate is tapped. Our findings showed in addition that the actual frequencies can vary considerably and that the top plate's tap tone can be higher than the back's or vice versa and still result in an instrument with good tone.

These observations did not go far enough toward explaining our finding that when the pairs of free plates were assembled, the resulting instruments did not always possess the expected tone and playing qualities. Every now and then an instrument proved without apparent reason to be much better than the others or worse. Seeking to explain these inconsistent results, I have continued the research since Saunders' death in 1963, building and testing 160 more instruments of the violin family. (The family includes the traditional violin, viola, cello and bass. Some new and revised instruments, developed with the test methods described here, make up the "violin octet," all designated as violins: treble, soprano, mezzo, alto, tenor, baritone, small bass and contrabass.) I have examined the instruments not only by the Chladni method but also by such new techniques as hologram interferometry and real-time analysis. It cannot be emphasized too strongly that before one can apply such methods one must learn the violinmaker's craft, so that the basic instrument is built according to the principles of fine violinmaking. I learned violinmaking in the 1950's under the tutelage first of Karl A. Berger and then of Simone F. Sacconi with Rembert Wurlitzer's encouragement. It was eight years of slow, painstaking work.

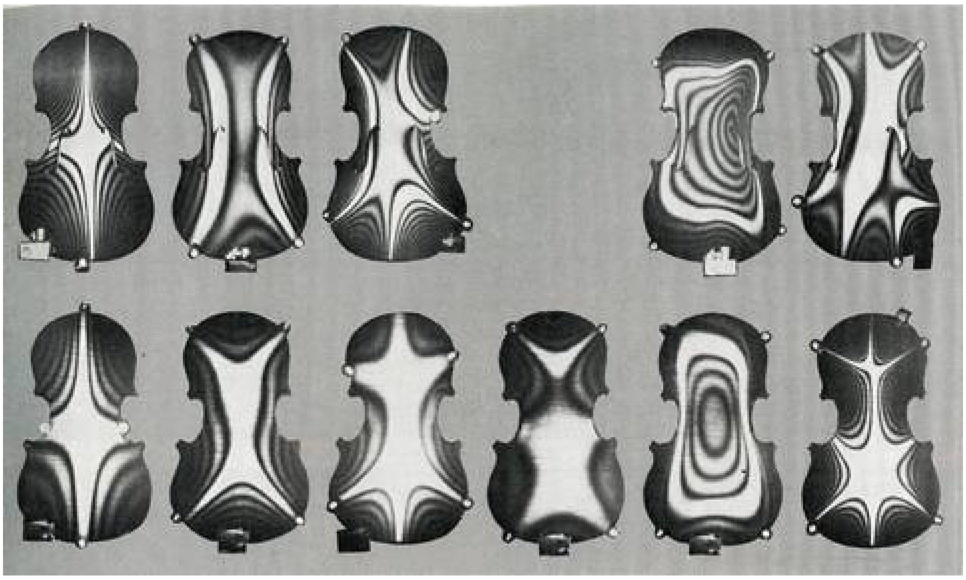


COMPONENTS OF A VIOLIN are depicted in views from the top, in cross section and from the side. The colored line in the view of the top shows the location of the cross section. Except for size and proportions the components of a violin, a viola and a cello are much the same.

The vibrational properties of each finished top and back plate are the result of the life history of that particular piece of wood. (The care and lore a violinmaker brings to the selection of a suitable tree are a story in themselves.) Tradition also calls for long seasoning of the flitches (log-size pieces of wood of appropriate length split or sawed longitudinally in "quartered" sections from the trunk) in stacks in outdoor sheds, spruce for from five to 10 years and maple somewhat longer. Some makers maintain that the wood should be seasoned for at least 50 years. This judgment may be supported by the suggestion of several wood technologists that the ratio of crystalline areas to amorphous areas in the cell structure of wood seems to increase as the wood seasons. This concept fits nicely into violinmaking traditions, because amorphous material absorbs and loses water readily but crystalline material does not. Perhaps the relation helps to explain why many older instruments are less susceptible to changes in moisture than new ones.

What physical properties of top and back wood, so carefully selected by the violinmaker, are most important to the sound of a fine instrument? Technical workers in this area generally agree on five; elasticity along and across the grain; shear; internal friction (damping) resulting in the dissipation of energy; density, and the velocity of sound in the wood.

The most important aspects of elasticity are the values of Young's modulus along and across the grain. Young's modulus is a measure of the material's resistance to local bending and stretching; it is the ratio of the local force applied per unit area to the resulting relative change in length. Shear is a measure of resistance to angular distortion of the kind one sees when the top of a thick book lying on a flat surface is pushed sideways, shifting the upper surface with respect to the lower one.



***VIBRATIONAL PATTERNS** of a pair of unattached top and back plates for a violin (the top complete with f-holes and bass-bar) are made visible by hologram interferometry. Starting with the mode of lowest frequency, they are designated mode 1, mode 2 and so on. The upper row of interferograms shows the mode shapes at the particular frequencies where they occur in this top plate: respectively 80, 147, 222 304 and 349 Hertz. (Mode 4 is missing.) The lower row shows the first six modes in the back plate at 116, 167, 222, 230, 349 and 403 hertz. Many other resonance modes occur at higher frequencies. In all the instruments of the violin family the configuration of the lower resonance modes is quite consistent, but the frequencies differ depending on the dimensions, mass and stiffness of the plate.*

Internal friction or damping is a measure of the ratio of energy dissipated to energy stored elastically. It can be expressed in several ways. One is by the decay time, or the time during which vibration persists after excitation is cut off; a violinmaker listens for a long decay time in the tap tone as he tunes a violin plate. Another is by the width of the frequency interval within which there is a response to continuous excitation as the frequency is varied about a resonance. Damping is often expressed as the "quality factor," or Q The higher the Q value, the lower the damping.

Density is weight per unit volume and is found by multiplying the length, width and thickness of a rectangular strip of wood and dividing the product into the weight of the strip. Velocity is found by dividing Young's modulus by the density and taking the square root. One of the desirable characteristics of spruce for the soundboard of a musical instrument is its high ratio of stiffness to density, reflecting a high sound velocity.

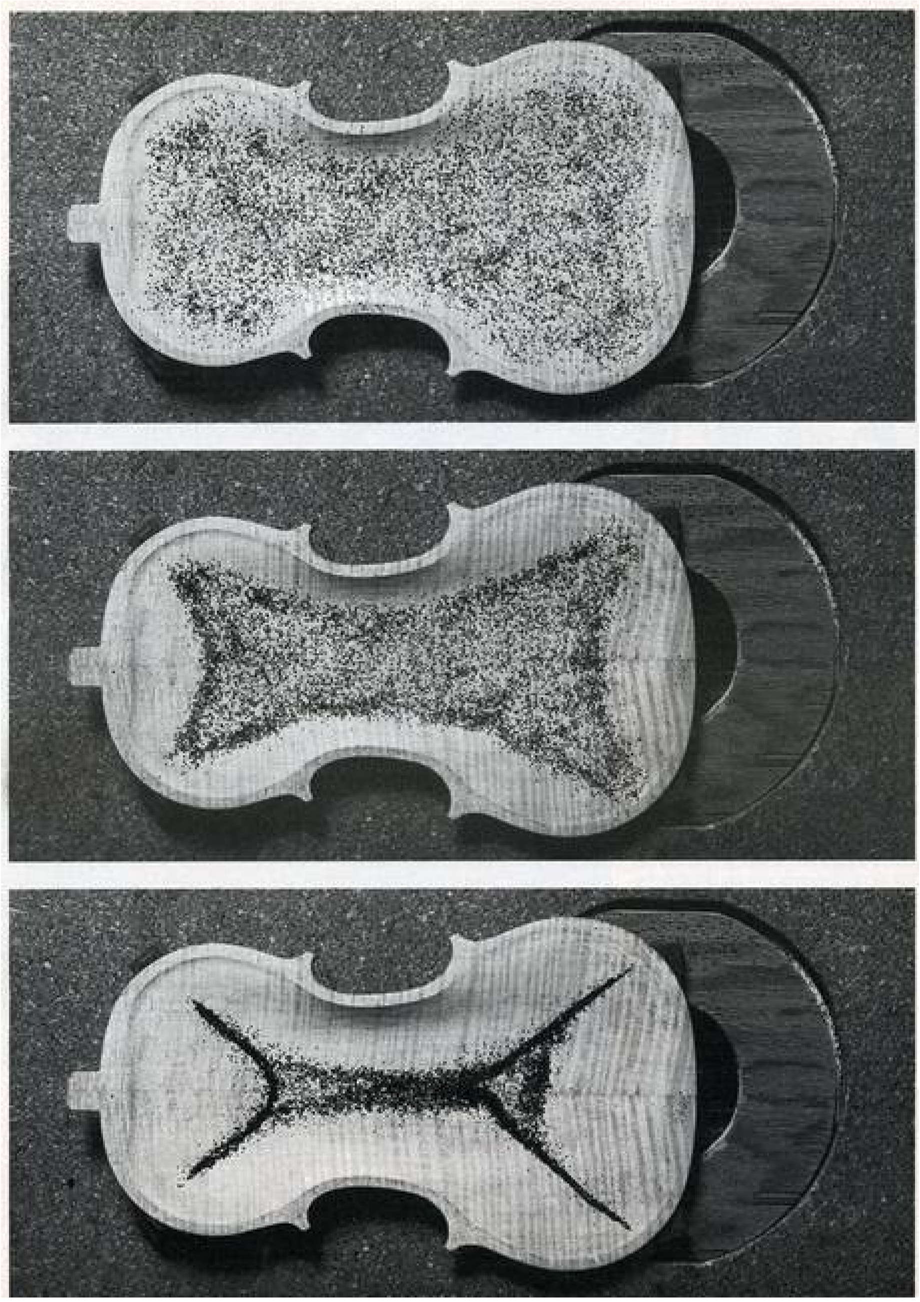
Two main problems arise in the scientific investigation of violin plates. First, what physical mechanisms are activated in free top and back plates as they are flexed, held and tapped? Second, can measurement of these mechanisms and their component factors yield practi-cal information about the resulting tone and playing qualities when a given pair of plates is assembled into a finished instrument?

In our effort to find answers to these questions we have explored the plate mechanisms and made several thousand comparisons of the eigenmodes of free plates with the tone and playing qualities of the instrument assembled from each pair of plates. The main characteristics of the eigenmodes are easily made visible by our modified Chladni technique. A free plate is placed horizontally over a loudspeaker, with the inside of the plate facing upward like a dish. A sine-wave signal (a single-frequency signal) is directed through the speaker, sweeping across the frequency range of interest and causing powder sprinkled on the plate to assume characteristic patterns at discrete frequencies that are unique to each plate.

An even clearer understanding of the configurations of the modes emerged when lasers made it possible to apply hologram interferometry to violin plates. This line of experimentation was first pursued with free violin plates in the late 1960's by Karl A. Stetson, who made interferograms showing the bending modes (some with amplitudes of only a few micrometers) as the plates were vibrated at their discrete frequencies of resonance.

By each method the mode shapes for instruments of the violin family are found to follow a similar sequence in all sizes of free plates. They have therefore been designated mode 1, mode 2 and so on, starting with the mode of the lowest frequency. Although the mode shapes are similar throughout the violin family, the frequencies at which they occur are unique to each plate. In general the larger the plate, the lower the mode frequency, but even between plates of the same size there is considerable variation in the mode frequencies.

The modes that have so far been found to be most important in tuning violin plates are 1, 2 and 5. Mode 1 entails a twisting of the plate, with one corner up and the other down in opposite phase. Thus when a violinmaker holds a plate at



each end, twisting it between his hands to feel its "resistance," he is actually sensing the main stiffness characteristics of mode 1.

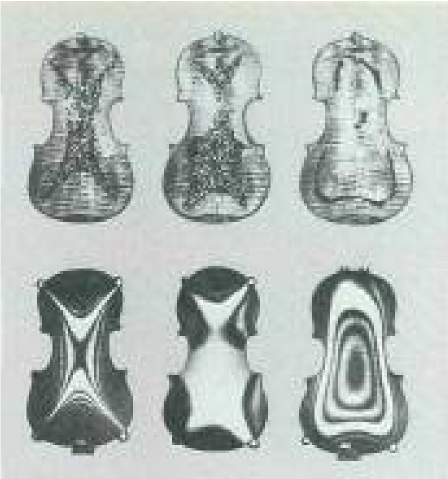
***CHLADNI METHOD** of displaying the eigenmodes of a free (unattached) violin plate is demonstrated in the author's workshop. In the photographs on the opposite page the plate, a violin back, is mounted inside upward on four soft foam pads over a loudspeaker. Each pad is adjusted to support the plate at a nodal (nonvibrating) point and the speaker is centered under an antinode for the mode being tested. Particles of thin aluminum flake or some other powder are sprinkled on the plate (fop). When the plate mode resonates in response to the appropriate single-frequency sound from the speaker, the particles begin to bounce (middle). The vigorous bending motion of the antinodal areas bounces the particles into the nonvibrating nodal areas of the plate, thereby outlining the nodal and antinodal configurations characteristic of that particular mode. In these photographs one sees the development of a mode-2 pattern (bottom). The technique, a modified version of a testing method devised in the 18th century by Ernst F, F, Chladni, was also used to make the patterns of modes 1, 2 and 5 shown on the cover.*

When a maker holds one end of a plate in both hands with thumbs on top and fingers spread out underneath across the wood, squeezing it and bending it slightly to assess the cross-grain stiffness of first one end and then the other, he is comparing the relative stiffness of mode 2 in the two ends. Some makers achieve essentially the same result by laying a plate arch side up (the plates are arched outward in the finished instrument) on a flat surface and putting a shallow dish of water first on the upper area of the plate and then on the lower area, pushing gently on the plate to compare how much the water in the dish moves in each case.

When a luthier holds a plate around the two ends in his fingertips and pushes down in the middle with his thumbs, he is actually checking the principal stiffness of mode 5. The same test can be made by holding the plate around the edges and gently pressing the top of the arch against a flat surface to feel the bending.

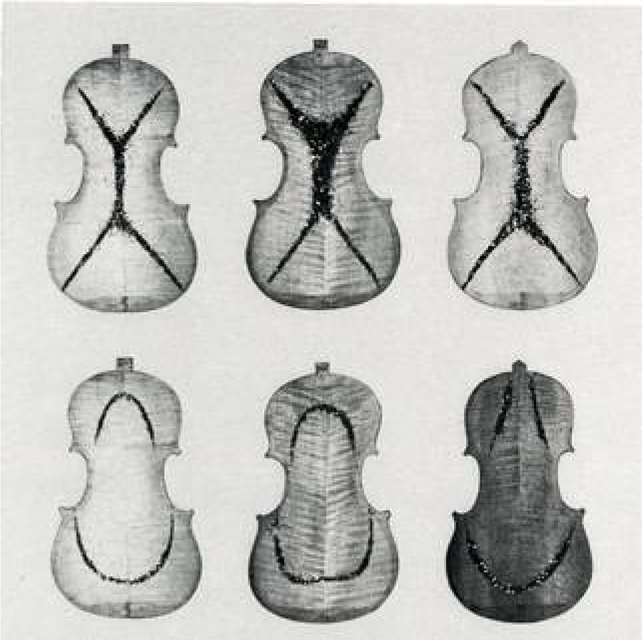
Holding the plate at the midpoint of one end and tapping with the soft part of a finger around the upper and lower edges will activate the sound of mode 1 quite clearly, because the holding point is a node and the curves of the upper and lower edges are antinodes for that mode. Holding at one of the four points where the nodal lines of mode 2 intersect the edges and tapping on the antinodal area near the midline of either end of the plate activates primarily mode 2. Holding at a point along the nearly oval nodal line of mode 5 and tapping in the centre of the plate causes the sound of mode 5 to predominate.

All the modes, however, contribute in greater or lesser degree to the sound heard when the plate is tapped, depending on the place of excitation and the effect of holding. For example, when a violinmaker holds a plate between thumb and forefinger near one end just off the midline and taps it in the centre, listening for a clear and full ring, he often finds it necessary to move his holding point a bit to attain optimum sound. The best holding point is at the crossing of the nodal lines of modes 2 and 5; then tapping in the centre activates primarily mode 5 and tapping at the lower or upper end of the plate activates primarily tapping place, being particularly clear if modes 2 and 5 are an octave apart. In a plate that is not well tuned it is often difficult to identify by ear the pitch of the sound that predominates. These variations can help to explain why there are so many different interpretations among violinmakers of the sounds in a violin plate and so many views of what to do about them.

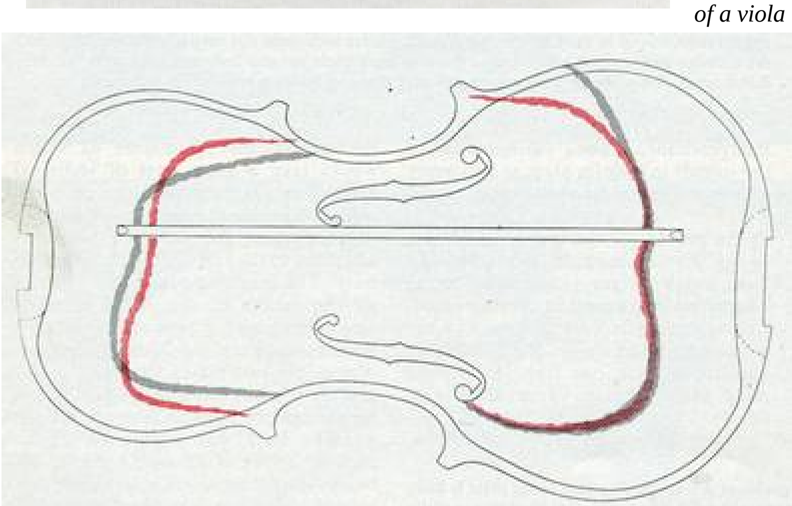


The process of tracing the evolution of the eigenmode characteristics from a pair of free violin plates to the assembled instrument in playing condition is extremely complicated and not yet clearly understood. The theoretical analysis of even one free violin plate must take account of at least nine parameters, the calculation of which would take a great deal of technical skill, to say nothing of more time and money than are currently available.

TWO TECHNIQUES for demonstrating the eigenmodes of a free violin plate are compared. In the photographs at the top the Chladni patterns of a back plate are shown at frequencies of 165, 225 and 357 hertz. Laser interferograms of the same plate at a different relative humidity are shown in the photographs at the bottom at frequencies of 165, 222 and 348 hertz. The nodal patterns, which show in the interferograms as wide white areas, are indicated by the quite similar dark shapes in the Chladni patterns. The laser technique not only is more sensitive than the Chladni one to small vibrations of a top or back plate but also indicates motion in the anti-nodal areas of a plate by the narrow and dark lines of the characteristic interference fringes.



WELL-TUNED AND POORLY TUNED PLATES are revealed by means of the Chladni technique. Each pair of photographs, top and bottom, shows modes 2 and 5 respectively of a violin back plate. In the plate at the left both modes are well tuned. In the plate at the center the nodal areas of mode 2 are too wide in the upper section, indicating that the entire upper area of the plate is too stiff. In the plate at the right the nodal areas of mode 5 extend straight to the upper edge instead of closing into a ring shape. This usually happens when the plates are too thick through the upper section of the center between the C-bouts and inside the upper corner.



EFFECT OF VARNISH on the outer surface of the detached top plate of a viola is evident from the change in the Chladni pattern of mode 5 on its inner surface. The colored lines show the pattern of mode 5 in the tuned plate before assembly, when it already had sealer and two coats of varnish on it. The gray lines show the pattern in the detached plate after the viola had been completely finished (with a total of seven coats of oil varnish) and had been played for two years. Varnish and sealer help to protect the wood and reduce somewhat the effects of varying humidity, but they also change the tonal characteristics of the instrument. The tonal characteristics continue to change over a period of approximately two years as the varnish hardens.

In the assembled violin the two plates are glued to the ribs (sides) of the instrument. The resulting edge constraints alter the modes of the plates in many ways. Moreover, a new set of coupled resonances is created from the interaction of the two plates through the ribs and the sound post (a pencil-size rod of spruce held by friction between the top and the back and positioned almost under the foot of the treble side of the bridge). Additional resonances are created by couplings between the wood of the box and the modes of vibration of the air mass within the box.

To discover the effect of various freeplate mode characteristics on these complicated constraints and couplings we have employed the long, slow process of making violin-family instruments of all sizes. One carefully selects the wood, forms it into plates, tunes the eigenmodes of the plates, assembles the instrument, evaluates it and then in many cases takes the plates off, retunes them and reassembles the instrument, repeating the technical and musical evaluations.

The possibility of testing the free plates of a fine concert violin always looms large as a way to obtain information on the free-plate eigenmodes that are coupled into such instruments. It is highly desirable to test the top and back plates at the same time because of changes in the wood with changes in temperature and relative humidity, but obtaining the detached top and back plates of a fine violin simultaneously is almost impossible. Even in an extensive repair job a violinmaker seldom removes both top and back unless the instrument is in very bad condition.

Through the kindness of two violinmakers, however, we have been able to test the free-plate pairs of two concert violins, a Stradivarius of 1713 and a Guarnerius del Gesu of 1737, with comparison tests after the instruments were reassembled. Considerable information was gained from these two violins, but in each case the repairs were so extensive that gaining any knowledge of their original condition was out of the question. Moreover, in view of the changes that have been made in violins built before 1800 in order to increase their tonal output (longer neck, increased fingerboard angle, higher bridge and appropriately heavier bass-bar, with invariably some scraping of the inside of the top plate) there is little chance of ascertaining what their original makers intended.

In the course of our studies we have tested (in playing condition) many fine modern instruments as well as early ones, thanks to the interest and cooperation of their owners. In this way we have accumulated a body of knowledge based on more than 800 tests of all types of instruments of the violin family with a wide variety of musical potential. For example, the response curve of a famous Guarnerius del Gesu violin made in 1731 and that of a violin recently constructed on a Stradivarius pattern show quite similar characteristics. The curves reflect a decrease in amplitude of the resonances through the 1.5-kilohertz range and an increase in the range from two to three kilohertz. This characteristic has been reported by Meinel and others as being typical of the response curves of some of the most musically desirable violins.

Our tuning process for free plates starts with a pair of nearly finished top and back plates for an instrument of the violin family. The outside archings are planed and scraped to their final contours. For the top plate the f-holes are cut and the bass-bar is installed (but not shaped); the purfling (the three strips of black and white wood inlaid around the edges of the two plates) is glued in, and the edges are finished. It has also been found desirable for the sealer, or filler, and at least two coats of varnish to have been on the outside of each plate for several months.

As the violinmaker planes and scrapes away the wood from the inside of a pair of violin plates so that the top is from three to four millimeters thick and the back from three to six millimeters thick, he begins to flex each plate in his fingers, holding it and tapping it in various ways. He feels the stiffnesses of the wood and listens for certain sounds as he continues to thin the wood in different areas a few tenths of a millimeter at a time. The process of learning the proper feel of the wood and the sounds to listen for in the two free plates is crucial to the art of fine violinmaking; years of experience are needed to become good at it. .

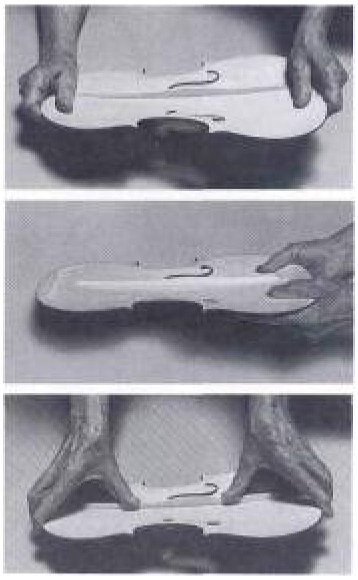
As an aid to understanding what the violinmaker feels and hears in his beautifully carved plates our tests of free plates explore modes 1, 2 and 5, mainly with the Chladni-pattern method. In a given pair of top and back plates each mode is checked for frequency, amplitude, Q and the conformation of its nodal pattern, with adjustments of the frequencies of the three modes to certain relations as far as is possible in each plate and between the two plates. We test the finished instrument by means of the response curve, the loudness curve and comments by players.

Five findings stand out in our results.

- First, an instrument of good quality results when mode 5 has a relatively large amplitude and its frequency in the top plate lies within a tone of the frequency in the back plate. If the frequency of mode 5 in the top is higher than that in the back, the tone quality is usually "brighter." If this relation is reversed, the tone is somewhat "darker."
- Second, smooth, easy playing characteristics result when the frequency of mode 2 in the top plate lies within 1.4 percent (about five hertz in violin and viola plates) of that of mode 2 in the back plate.

- Third, if mode 5 is at the same frequency in a pair of top and back plates, the frequency of mode 2 in the top should be within 1.4 percent of that in the back, otherwise the resulting instrument is hard to play and has a harsh, gritty tone.
- Fourth, violins of exceptional quality have resulted when modes 2 and 5 are placed approximately an octave apart in each plate and at corresponding frequencies with high amplitudes in both plates.
- Fifth, a further refinement is to place the frequency of mode 1 in the top plate an octave below that of mode 2, so that modes 1, 2 and 5 are in a harmonic series. It is possible but difficult to adjust the frequency of mode 1 to this relation in the top plate; the adjustment cannot be made in the back plate because of the different structures of the two plates.

It is easier to state these conclusions than it is to achieve them in the actual tuning of plates. Many problems arise in attaining optimum eigenmode and eigenfrequency relations. The problems are largely related to four factors: the selective thinning of the plate to adjust for desired mode characteristics; the effects of the coatings (the sealer and the varnish); changes in relative humidity and temperature, and certain physical properties of the wood selected for the top and back plates.



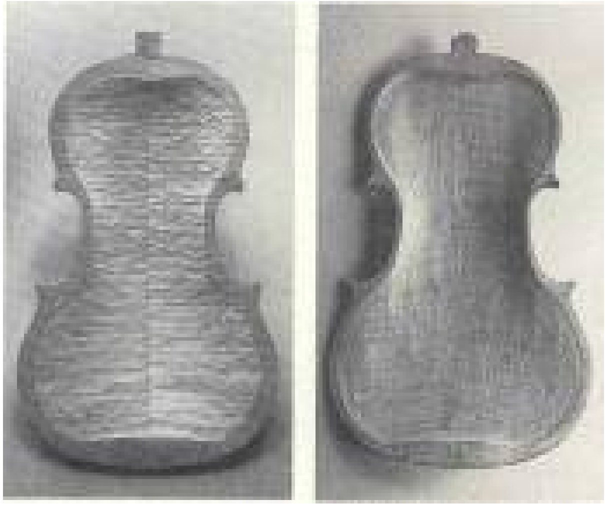
MANUAL TESTING for the characteristics of wood that give rise to modes 1, 2 and 5 entails a flexing of the plate in various ways by the violinmaker. When the maker holds the plate at each end and twists one corner up and the other down several times {lop}, he is testing for the stiffnesses that produce mode 1. When be holds one end of the plate in both hands with his thumbs on the top and his fingers spread out underneath (middle), squeezing and bending the wood slightly across first one end and then the other, he is checking and comparing some of the stiffncss characteristics of mode 2 in the upper and lower areas. When he holds the plate in his fingertips and pushes down in the middle with his thumbs {bottom), he is checking some of the bending characteristics of mode 5. The hands in these photographs are the author's.

Shaving the surface of a wood plate clearly reduces both mass and stiffness and also alters the plate's capacity for absorbing energy. Thus the frequency and shape of a given mode can be adjusted selectively to a limited extent by thinning the plate a few tenths of a millimetre at a time on the inside of the arch when it is within a millimetre or so of its final thickness. The general rule is that removing wood from a region of pronounced bending of a particular mode will tend to lower its frequency; removal from an area of little bending will raise the frequency. Thinning the wood in an area of pronounced bending reduces stiffness more than mass, so that the frequency goes down. Removing wood from an area of little bending reduces mass more than stiffness, so that the frequency goes up.

The bending areas (areas of strong curvature of motion) of a violin plate can be identified on the interferograms by lines that change from close to wider spacing. The process is somewhat like reading a topographical map where the curved slope of a hill is indicated by contour lines of equal elevation that become more closely spaced as the slope gets steeper. A straight slope is indicated by lines of equal spacing. In the interferograms the evenly spaced lines of the interference fringes indicate translation, or motion without pronounced curvature, just as the two ends of a seesaw move up and down without bending.

Hence removing wood a few tenths of a millimeter at a time from a crescent-shaped area around the two ends of the plate beginning just inside each corner will tend to lower the frequency of mode 5 more than it does that of mode 2. Removing wood from the center of the plate, reducing mass where the amplitude of motion of mode 5 is high, will tend to raise the frequency of the mode slightly. On the other hand, thinning the wood through the center of the upper and lower areas of a plate tends to lower the frequency of mode 2 because they are usually the bending areas for mode 2. Since the effective stiffnesses of a particular mode in one plate are not necessarily the same as those in another, it is important to assess them by the violinmaker's methods of feeling the bending areas as well as by observing the characteristics of the nodal patterns.

The sealer and the varnish influence plate tuning because they add mass, stiffen the outermost fibers of the wood and increase the damping. The lower the Young's modulus of the bare wood is, the more pronounced the increases in stiffness and damping are with added coatings. The effects are somewhat different for spruce and maple, with the result that the addition of sealer and varnish tends to detune



CARVING INSIDE OF PLATE after the outside archings have been shaped is the means by which the violinmaker achieves the desired acoustical characteristics. At the left a back plate for a violin is shown at an early stage of carving; at the right a different plate is shown in a nearly finished state. The marks were made by toothed planes. The plate is now ready for final scraping and acoustical testing by the Chladni method. A finished top plate for a violin usually varies in thickness from two to 3.5 millimeters, a back plate from two to six millimeters.

the modes of the top plate considerably more than those of the back plate. Daniel W. Haines has reported that sealer and varnish increase Young's modulus and damping in cross-grain spruce much more than they do in cross-grain maple, with an associated rise in frequencies. Maple is two and a half times stiffer in cross grain than spruce.

Our tests indicate that sealer and varnish can indeed be detrimental to the sound of an instrument but that precautionary measures can be taken in the tuning of the free plates. For example, if the aim is to match the frequency of mode 2 in the top and back plates of a violin or a viola, mode 2 in the top should be left from 5 to 10 hertz lower before varnishing than it is in the back. Thus the varnish can help the sound of the instrument. If, however, the frequency of mode 2 in the top plate matches or is higher than that in the back plate when the plates are "in the white" (before varnishing), the discrepancy will be even greater after the addition of the coatings, and the instrument will probably have a harsh, gritty playing quality.

Violinmakers often say that a violin sounds better in the white than it does after it is varnished, and many of them have learned to compensate for the effect. Louis Condax, who experimented with sealers and varnishes for years, reported that when he removed the varnish from a violin that had a "harsh, gritty, tight sound," the instrument "came to life." The late John C. Schelleng showed that the acoustical properties of varnish coatings continue to change over a period of more than two years, which is doubtless one of the reasons it takes a newly varnished violin several years to settle into its true playing qualities.

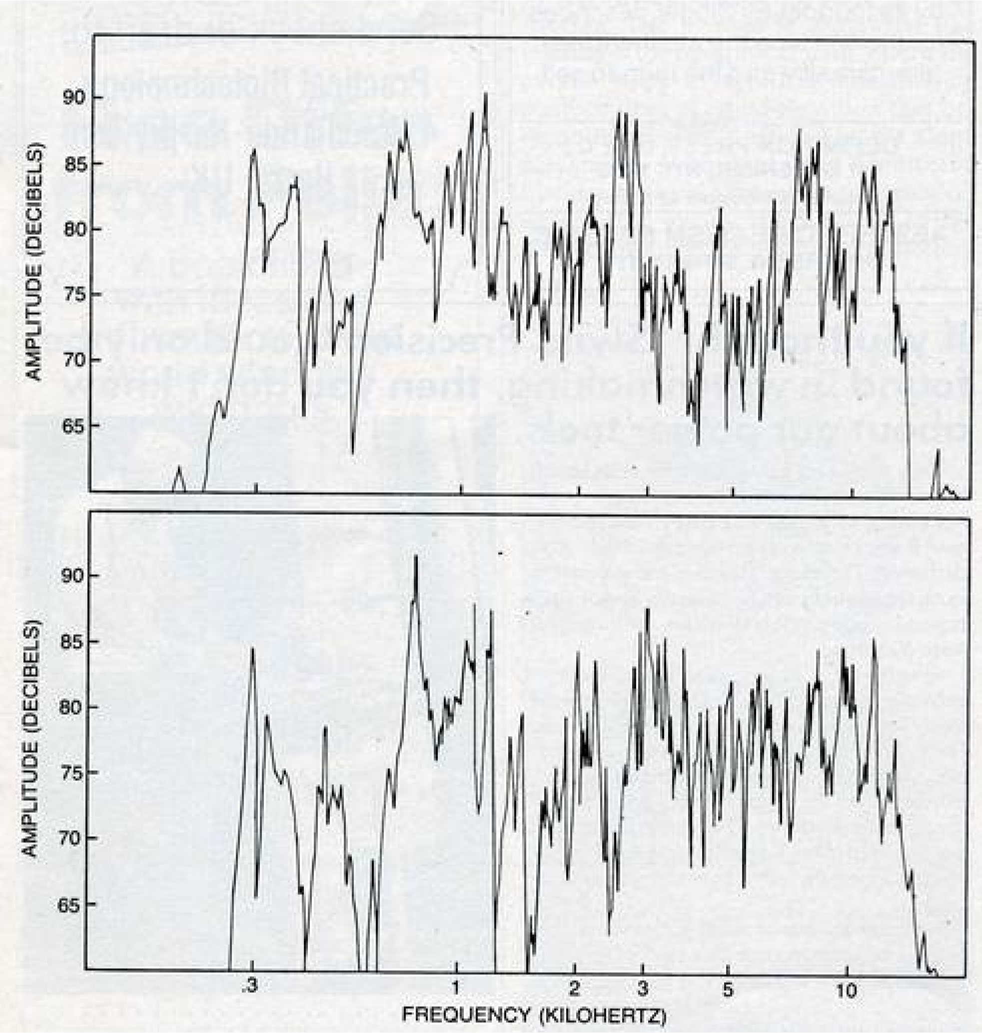
Violinmakers have long been troubled by the complaints of players whose instruments begin to sound dull and unresponsive in hot, humid summer weather and those whose instruments get harsh and gritty in the dry, heated houses of the Temperate Zone in winter. Adjustments of the bridge and the sound post can help to mitigate these problems, but a given instrument will generally sound best under the conditions of temperature and relative humidity in which it was made.

Wood is a hygroscopic material, taking on water and losing it readily in response to ambient conditions. The coatings of sealer and varnish on the outer surfaces of the violin help to retard this process somewhat, but to our knowledge there is no satisfactory treatment of the bare inner surfaces that is not detrimental to the tonal qualities of the instrument.

Experiments done in recent years by Robert E. Fryxell indicate that wood of various ages (as well as varnished and unvarnished violin plates) absorbs moisture quite slowly over a period of several months but loses it in a few hours, with maple slightly more absorbent than spruce. He also found that plates coated with sealer and varnish showed appreciably more stability than those in the white. Rex P. Thompson in Australia has found that the frequencies of mode 5 in a pair of varnished (for two years) and tuned plates varied as much as 18 hertz in the back and 23 hertz in the top over the range from 15 to 79 percent relative humidity. At a constant relative humidity the difference did not exceed five hertz. He also found that at a constant relative humidity of 50 percent the variations in frequency were only about 1 percent at temperatures from 15 to 25 degrees Celsius (59 to 77 degrees Fahrenheit). He concludes that for precise plate tuning either the temperature and humidity should be controlled or the humidity should be at 50 percent if the temperature cannot be controlled.

Our study has entailed work with many kinds of wood and many sizes of violin plate. We have found that carefully selected spruce of both European and American varieties can be employed successfully in making top plates. It is important, however, that the cross-grain stiffness be high enough to help maintain the desirable relation of an octave between modes 2 and 5. Various species of American maple have been tuned effectively by the Chladni method to make back plates for instruments with excellent tone and playing qualities. We have also found that other species of wood with characteristics fairly close to those of maple (pear, apple, cherry, sycamore and teak) can serve effectively for violin and viola backs, although the resulting tone qualities differ slightly from one instrument to another depending mostly on the high-frequency properties of the wood.

In the light of the understanding that our group and others have gained of the enormous number of variables encompassed in the making of a fine concert violin it is even harder than before to comprehend how the early luthiers managed to build instruments that were sophisticated and beautiful in both tone and appearance. The work I have described indicates that it is most desirable (but often quite difficult) to have the free-plate modes 1, 2 and 5 of a finished violin top lie in a harmonic series, with mode 5 having a large amplitude and a frequency near 370 hertz, and to have the frequencies of modes 2 and 5 in the top plate match those in the back. The shape, arching contours and thickness distributions of the top and back plates are crucial in achieving these relations. Moreover, the physical characteristics of the wood must lie within a narrow range of variables, and many other components of expert violinmaking must be held to close tolerances. In these conditions, and with the application of the Chladni method to aid in the determination of desirable eigenmode and eigenfrequency relations in each pair of unassembled top and back plates, violins and other members of the violin family can be made with consistently fine tone and playing qualities.



RESPONSE CURVES of a famous Guarnerius del Gesu violin made in 1731 and a violin made by the author in 1979 are compared. The curves reflect the same test procedure: a constant-current sine wave to the bridge, with the response of the violin (hung on rubber bands) picked up by a microphone 14 inches away in a fairly non-reverberant room. The upper curve is from the Guarnerius, the lower one from the modern instrument, which was made according to the plate-tuning principles described in this article. Note the decrease in the amplitude of the resonances through the 1.5-kilohertz range and the marked increase in amplitude from two to three kilohertz. This characteristic has been reported by Hermann F. Meinel and other investigators as typical of the responses of some of the most musically desirable violins.

Although the knowledge of certain characteristic relations in the eigenmodes and eigenfrequencies of free violin plates makes possible the construction of consistently fine instruments, it does not explain what happens to those modes *when the plate pairs are* assembled into the extremely complex vibratory system of the completed violin. In an analytical sense, however, the eigenmodes and eigenfrequencies of the parts fully define those parts. Therefore one can hope for the eventual recognition of a thread of generic information that will link the known vibratory characteristics of the free plates to the vibratory char acteristics of the completed instrument.

Any structure such as a violin can be considered as essentially an arrangement of materials with its own characteristics of geometry, stiffness, mass and dissipation of energy. The assembly of the various parts into a completed instrument creates an additional set of potentially recognizable properties, namely the eigenmodes and eigenfrequencies of the instrument itself, each mode with its associated damping. Even though the process is a highly complex one, the eigenmodes of the parts can be regarded as elements that will ultimately determine the eigenmodes of the whole. The *challenge this investigation presents for* future investigators is: Can the tools and methods of measuring and analyzing vibrations be applied to a study of how the characteristics of free violin plates affect the vibrations of the coupled top and back plates and the enclosed air mass of the violin body as they respond to the forces generated by the bowed violin string?

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