SOUND GENERATION

IN

WINDS
STRINGS
COMPUTERS

Papers by Benade, Chowning, Hutchins,
Jansson, Alonso Moral given at seminars
of The Committee for the Acoustics of Music

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P R E F A C E

On May 19 and November 10 1979, the Committee for Music Acoustics of the Royal Swedish Academy of Music arranged two full day seminars at the Royal Institute of Technology (KTH). The seminars were devoted to wind and bowed instrument acoustics with A.H. Benade and C.M. Hutchins as the main talkers. They were arranged in cooperation with the Center for Speech Communication Research and Music Acoustics, KTH. All contributions presented at the seminars are now published in this book except for the final panel discussion at the wind instrument seminar with A.H. Benade, J.M. Chowning, E. Jansson, S. Berger and C. Carp as participants. This book is the fourth seminar proceedings published by the Committee. As previously, the sound illustrations are collected in a grammophone record.

A practical result of the bowed instrument seminar might be mentioned. A full setup of Hutchins´ new violin family instruments was purchased by and are kept for musical use at the Stockholm Music Museum.

The editing work has been done by Erik Jansson and myself. The examples of music played on the new violin family was edited by Semmy Lazaroff and the grammophone record was produced by Lennart Fahlén. Printable copies of all papers except Benade´s were prepared by Marianne Beskow of the Music Academy, and Sven Wilson of the same Academy is responsible for the layout.

KTH, September 1980

Johan Sundberg

President of the Committee for Music Acoustics

COMPUTER SYNTHESIS OF THE SINGING VOICE

by

John M. Chowning

Center for Computer Research in Music and Acoustics

Department of Music

Stanford University

Stanford, California

Introduction

The work represented here demonstrates above all that acceptable synthesis of a sung tone demands careful attention to rather simple characteristic details of the real target tone which are *largely independent of the synthesis technique*. While the particular spectral content of a wave may be achieved by a variety of synthesis techniques, "naturalness" depends upon the temporal characteristics of very basic descriptors such as pitch and loudness, and spectral changes during the attack-decay portions of the tone. Although frequency modulation (FM) synthesis has been used to simulate some orchestral instrument tones (Schottstaedt 1977, Morrill 1977), the singing voice seems to remain the province of synthesis models borrowed from speech research (Sundberg 1978, Moorer 1979). The purpose of this paper is to show a strategy for the use of FM in the synthesis of two cases of the singing voice 1) a soprano, and 2) an un-naturally low male voice we might call basso *profondissimo!*

In as much as the basis concepts underlying FM synthesis are by now well-known (Chowning 1973) and the synthesis program which was used, MUSIC 10, is not unlike many others in general use (Mathews 1970), detailed descriptions will not be presented here.

Frequency Modulation Tone Synthesis

The fundamental FM algorithm is based upon the output of a modulating oscillator which adds to the frequency term of a carrier oscillator thereby producing a complex waveform. This is expressed in the equation

$$e = A \sin(2\pi f_c t + I \sin 2\pi f_m t) \qquad \text{eq. 1}$$

where

e = the instantaneous amplitude of the carrier
A = the peak amplitude of the carrier
f_c = the carrier frequency
f_m = the modulating frequency
I = the modulation index

The ratio of the carrier and modulating frequencies, f_c/f_m, determines the relative interval of the component frequencies in the modulated carrier signal while the modulation index determines the amplitudes of the components and the overall bandwidth of the signal. The modulation index is the ratio of the depth of modulation or peak deviation to the modulating frequency. Of particular interest in the application of FM to voice synthesis presented below are ratios of frequencies where

$$f_c = Nf_m \text{ and } 1 \leqq N \quad \text{and where } N \text{ is an integer.}$$

The spectra resulting from this class of ratios are such that the frequency components form the harmonic series with f_m as the fundamental.

There are a number of useful extensions of this basic algorithm, 1) summing the outputs of two or more of the basic algorithm in parallel, 2) one carrier oscillator and two or more modulating oscillator in parallel, 3) one carrier oscillator and two or more modulating oscillators in series and 4) two or more carrier oscillators and one modulating oscillator, to name some of the basic types of extensions. It is the last of these which is appropriate to voice synthesis.

General Characteristics of Natural Soprano Tones

Spectral representations of the attack, quasi steady-state, and decay portions of recorded soprano tones show that for most vowel timbres and through the greater part of the range

1) there is a weighting of the spectral energy around the low order harmonics with the fundamental as the strongest

harmonic, thus supporting the theory that in female singing the lowest formant tracks the pitch period (Sundberg 1978),

2) there are one or more secondary peaks in the spectrum, depending on the vowel and fundamental pitch, which correspond to resonances of the vocal tract or upper formants.

3) the formants are not necessarily at constant frequencies independent of the fundamental pitch, but rather follow formant trajectories which may either ascend or descend, depending on the vowel, as a function of the fundamental frequency (Sundberg, 1978),

4) the upper formants decrease in energy more rapidly than does the lowest formant when a tone is sung at decreasing loudnessess,

5) only the lowest formant is prominent at the amplitude threshholds of the attack and decay protions, while the upper formants only become pronounced as the overall amplitude of the signal approaches the quasi steady-state,

6) there is a small but discernable fluctuation of the pitch period even in the singing condition without vibrato.

FM Model for Synthesized Singing Voice - Soprano

For the simplest FM model of sung soprano tones two formants are included, the lowest formant and the most dominant of the upper formants. Therefore, one oscillator can be used to modulate two carrier oscillators. The frequencies of the modulating oscillator and the first carrier are always set to the frequency of the pitch of the tone, while the frequency of the second carrier oscillator is set at that *harmonic* frequency closest to the 2nd formant frequency. In this model the various parameters, or terms, of the FM equation are computed from the basic musical descriptors of overall amplitude and fundamental pitch frequency and from a set of tables which form the data base for the terms at selected pitches through the soprano range. In this sense, then, it is an adaptive algorithm since all of the computation is based upon the following two "performance" variables.

Amp = overall amplitude of the signal, where $0 \leq Amp \leq 1.0$,
Pitch =fundamental pitch frequency,
where G_3(195.9 Hz) $\leq Pitch \leq G_6$(1568 Hz).

The modulating signal is defined to be

$$M = \sin 2\pi f_m t \qquad \text{eq.2}$$

where

M = the instantaneous frequency deviation of the modulating signal

f_m = the modulating frequency ≐ *Pitch*

The signal resulting from the sum of the two modulated carriers is

$$e = Amp^{.5} A_1 t \sin(2\pi f_{c1} t + I_1 M) + Amp^{1.5} A_2 t \sin(2\pi f_{c2} t + I_2 M) \qquad \text{eq.3}$$

, where

e = the instantaneous amplitude of the sum of the two modulated carrier signals

A_2 = the relative amplitude of the second carrier, $0.0 \leq A_2 \leq 1.0$,

A_1 = the relative amplitude of the first carrier ≐ $1.0 - A_2$

f_{c1} = the first carrier frequency = *Pitch*

f_{c2} = the second carrier frequency = Nf_m, where N is an integer

I_1 = the modulation index for the first carrier

I_2 = the modulation index for the second carrier

The data base used for the computation of the amplitudes, indices of modulation, and the second carrier frequency is in the form of tables, where there is a set of four tables for each vowel as represented in Tables 1-4. The data is stored for the frequencies of pitches.

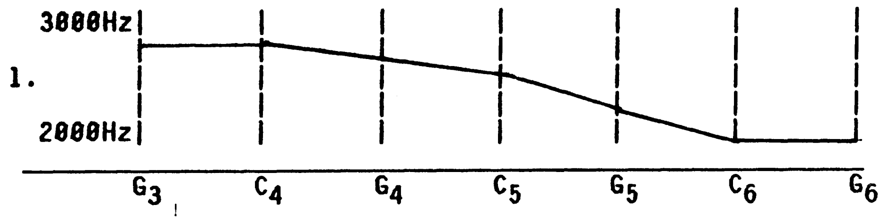
$$G_3 \; C_4 \; G_4 \; C_5 \; G_5 \; C_6 \; G_6$$

and the data for the intervening pitches is computed by linear interpolation. Thus, for the frequency of the second carrier, $f_{c2} = Nf_m$, the integer N is determined by taking the integer part of the following division after rounding

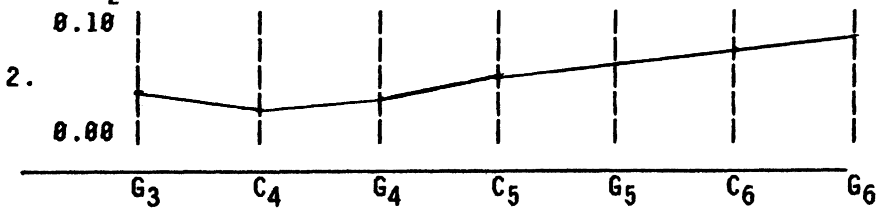
$$\frac{\text{(upper formant frequency)}}{Pitch} + 0.5$$

where the upper formant frequency is computed from Table 1. as a function of *Pitch*. The values for the amplitude and indices of modulation are computed directly from the tables

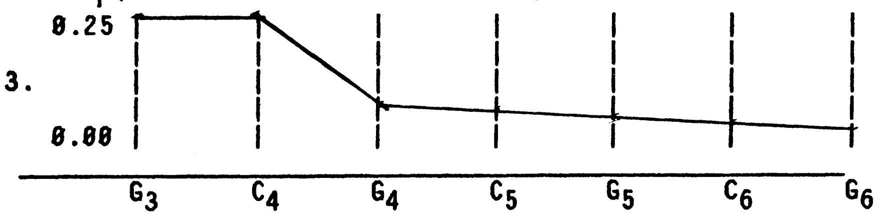
Upper formant frequency (from which f_{c2} is computed)



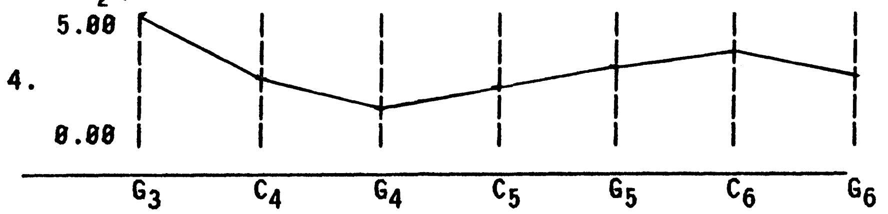
A_2 (contribution of second carrier)



I_1 (Modulation index for first carrier)



I_2 (Modulation index for second carrier)



Tables 1. - 4. for the vowel"e"(as in "he")

In eq. 3, it should be noted that the relative contribution of the two carriers varies with the overall loudness of the tone. With decreasing values of Amp, the amplitude of the second carrier decreases relative to the first because of the different exponents, 1.5 and .5 respectively. This is a very important property of this model since without this scaling, tones at decreasing loudness sound to be increasing in distance from the listener rather than softer at the source, i.e. rather than *sung more softly*. This suggests that there may be a non-linear relationship between the energy entering the vocal tract and its distribution among the formans.

For the same reason, the rapid increase and decrease of energy in the vocal tract during the attack and decay portion of the tone, the amplitude envelope for the second carrier (formant), A_2t is less prominent that the first A_1t, as shown in Fig. 1.

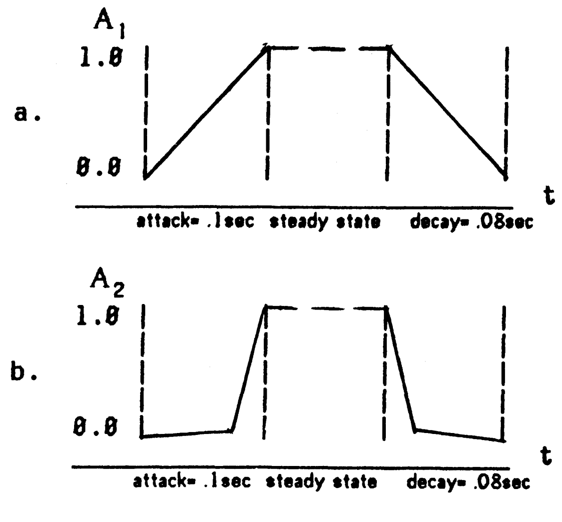


Figure 1.

Finally, a small amount of periodic and random vibrato is applied in equal amounts to the frequency terms in eq. 3, according to the relation.

$$\text{vibrato percent deviation} = 0.2\log_2 \mathit{Pitch}$$

at a frequency which ranges from 5Hz to 6.5Hz according to the fundamental frequency range of G_3 to G_6. Additionally, a slight portamento or pitch glide is included during the attack portion of the tone.

All of the sound examples were synthesized using the above model except for the first tone of sound example 1.

Sound example 1:

The first tone is a recording of a soprano while the second tone is synthesized with an attempt to approximate the spectrum, portamento, and vibrato of the recorded voice.

Sound example 2:

Six voices in polyphonic texture 1.

Sound example 3:

Six voices in polyphonic texture 2.

Sound example 4:

Voices in close harmonic voicing.

Sound example 5:

Four pitches for vowel "a" as in "father".
(a) second formant computed from table as a fundtion of pitch
(b) second formant at constant harmonic, i.e. transposed spectrum.
Four pitches for vowel "e" as in "he".
(a) as above
(b) as above

Sound example 6:
Example of linear and non-linear amplitude scaling for *Amp* values of 1.0, 0,5, 0.25, 0.125, 0.062
(a) Linear scaling. (From eq. 3, *Amp* without exponents)
(b) Non-linear scaling. (From eq. 3, *Amp* with exponents)

Sound examples 7:

The importance of periodic and random vibrato in the perception of vocal tones is demonstrated by presenting first the fundamental alone, then by adding the harmonics and finally by adding vibrato. It is striking that the tone only "fuses" and becomes a unitary percept with the addition of the pitch fluctuation, thus *the spectral envelope does not make a voice!*

(a) at 400 Hz
(b) at 500 Hz
(c) at 600 Hz
(d) a,b, and c together with independent vibrato parameters

FM Model for Synthesized Singing Voice - Bassc *profondissimo*

A sung bass tone is rich in harmonics and therefore strikingly different from soprano tones. The model, therefore, must be extended in order to accomodate a large bandwidth spectrum and additional formants. The range of pitches chosen for this particular bass tone is

$$C_1 \leq \mathit{Pitch} \leq C_3$$

To eq. 3 is added an additional carrier and another modulating oscillator is added in series. The modulating signal is now defined to be

$$M = \sin\left(2\pi f_{m1} t + K \sin 2\pi f_{m2} t\right) \qquad \text{eq. 4}$$

where

M = the instantaneous frequency deviation of the modulating signal
f_{m1} = the first modulating frequency = *Pitch*
f_{m2} = the second modulating frequency = *Pitch* x 3
K = modulation index =

$$4.0 + (2.0-4.0) \times \left[(\mathit{Pitch} - C_1)/(C_3-C_1)\right]$$

The signal resulting from the sum of the three modulated carriers is

$$e = \mathit{Amp}^{.5}\left[A_1 t \sin(2\pi f_{c1} t + I_1 M)\right] + \mathit{Amp}^{1.5}\left[A_2 t \sin(2\pi f_{c2} t + I_2 M)\right] + \mathit{Amp}^{1.5}\left[A_3 t \sin(2\pi f_{c3} t + I_2 M)\right] \qquad \text{eq. 5}$$

The effect of modulating the frequency of the modulating oscillator is to produce a complex modulating wave, which when applied to a carrier oscillator produces a spectrum having greater bandwidth (Le Brun, 1977). As seen above, K decreases from 4 to 2 with an increase of *Pitch*, resulting in a corresponding decrease in the bandwidth of the individual formants.

In the synthesis of the bass tones the two upper formant frequencies are constant for all pitches, while the lowest formant tracks the pitch period as in the case of the soprano synthesis. The unusually large amount of energy in the low formant suggests tones produced by a basso literally "bigger than life". The indices and relative amplitudes are again determined through tables. Except for a slower vibrato frequency all parameters are treated as in the model for soprano tones.

Sound example 8:

Two examples of basso *profondissimo* in polyphonic textures

Conclusions

Although the research presented here is in the beginning stages, it serves to show that a non-linear synthesis technique can be used to synthesize interesting, if not natural sounding, vocal tones and serves in confirming previous research results in regard to formant trajectories for the soprano voice. It suggests, as well, two areas for future research, 1) the physical correlates to performance dynamics (loudness), and 2) a more precised understanding of the effect of microfrequency fluctuation on perceptual fusion.

Acknowledgements: The author wishes to express his gratitude to Jean-Claude Risset and IRCAM, Paris for the support of this work, to Johan Sundberg for his encouragement and sharing of his extensive knowledge of the singing voice, to Gerald Bennett and Xavier Rodet for their helpful comments, and a special indebtedness to Michael NcNabb, who first revealed the significance of random pitch fluctuation in vocal tone synthesis.

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WIND INSTRUMENTS AND MUSIC ACOUSTICS

by

Arthur Benade

Department of Physics
Case Western Reserve University
Cleveland, Ohio

INTRODUCTION

This set of three lectures concerns itself with sound production by wind instruments, on their radiation properties into the room, and on the behavior of their sounds as they progress via the room and the auditory system to the listener's brain. We can schematize the lectures and also the path of a musically interesting signal in the following way:

PLAYER ⟶ INSTRUMENT ⟶ ROOM ⟶ LISTENER

When we look at our subject matter a little more closely, we find that it organizes itself in a very curious, even impossible-seeming, way as shown in Fig. 1.

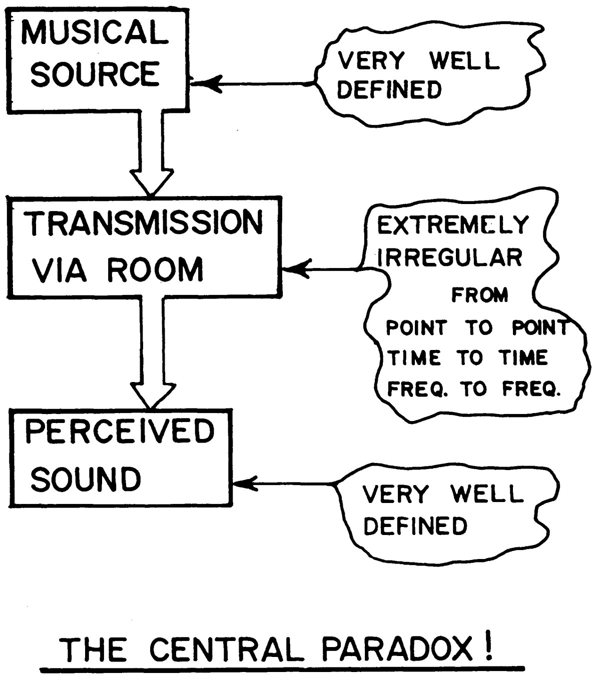


Fig. 1

From the point of view of this picture, the first lecture concerns itself with the mechanisms whereby the instrument generates its sound and with some of the reasons why this generated sound is exceedingly stable (far more so than is commonly recognized). I will discuss certain properties of the air column which govern the instrument as a self-sustained oscillating system and which are also important controllers of its sound-emitting properties. Once we get past the preliminaries of defining some terms and outlining some basic behavior, Lecture I becomes very much a preparation for Lecture II. In essence, the first two lectures present an account of our recently evolved and quite detailed understanding of the properties of wind instruments themselves, an understanding that is sufficiently advanced that every week brings one or more performers or instrument makers to my laboratory for assistance with the making or playing of real instruments.

Interesting as these things are in themselves, however, they have a much deeper implication. We should therefore consider the first two lectures as providing the instrumental background for Lecture III, where the deeper implication is discussed. This has to do with the resolution of the Central Paradox referred to in Figure 1. Lecture III opens with a brief account of the theory and measurement of the wave-statistical behavior of sounds in rooms (an area which also has developed into a well-understood part of scientific and engineering acoustics). We will learn in an unequivocal detail that two- to thirtyfold random fluctuations are common in the transmission of any given component of sound from one point to another in a room. In a manner of speaking, Lecture III starts out by appearing to prove that the passage of musical sound through a room to the listener's ears would make such a mess of the signal that the listener could make little sense of it. The major portion of Lecture III is devoted to a demonstration of the fact that the human auditory system does not merely surmount the difficulties posed by the room irregularities but that, on the contrary, it uses certain aspects of the room behavior to give itself a "picture" of the sound source that is far more quick, detailed, and accurate than it could ever get from listening out-of-doors or in an anechoic chamber.

LECTURE I. SOUND PRODUCTION IN WIND INSTRUMENTS

A. Musical requirements for a good instrument

Because wind instruments are the property and prime concern of musicians, we should open our discussion of their behavior with a quick summary of what is required in a good instrument. Such a summary is the following, expressed in musicians' language.

1. It must "sing"; i.e. respond clearly, be pitch stable, have controllable dynamics, and it must carry well.
2. It should have a reasonable pattern of intonation, with basic pitch flexibility for proper use in ensemble work.
3. It needs to have an acceptable tone color, suitable for the music and adapted to the local (national?) taste.

We will glance at the meaning of some of the requirements and inquire briefly into some of their acoustical implications before settling down to our analysis of oscillation mechanisms. Musicians over the past two-and-a-half centuries have shown great unanimity concerning these requirements (provided you ask your questions properly!). Let us take them up one by one, noticing that they are listed using progressively weaker versions of the imperative form. First of all, the instrument must "sing." I use this short word as a catch-all to represent a family of closely related virtues: The player must be able to start and stop the notes he plays cleanly and neatly with any desired articulation and without danger of squeaks or coughs; an instrument that sings will also have its own well-defined pitch for each note, a pitch to which it will return if the player does not pull it elsewhere; furthermore, it has a good range of easily controlled dynamics that can be varied without loss of tone color. A similar set of virtues is to be found in a well-designed automobile, which will straighten itself out of a curve when one lets go of the steering wheel, which accelerates and decelerates smoothly, and which takes corners well regardless of how rough the road may be.

This is a good time to define a useful technical term--resistance. This word is already commonly employed by many musicians (at least in America) to describe informally the ideas that I am about to state formally. Their usage of the word means that the basic idea is already recognized to be significant and also that the word already has reasonably clear connotations. It is important to recognize, however, that this new usage has nothing whatsoever to do with the ways in which scientists and engineers ordinarily make use of the word resistance.

An instrument has large (or good) resistance if the player must make relatively large muscular changes (in blowing pressure, embouchure tension, etc.) to produce relatively small changes in such aspects of the instrumental sound as pitch, loudness, etc. However, this is not to be construed as implying that a highly resistant instrument has a narrow range of response to the controlling muscles. To the contrary, it should have a wide range of dynamics (etc.) under control of an even wider range of muscular variation.

The virtues of large resistance as defined here are manifold, and a few examples will suffice to make some of them clear. The small tremors or unsteadinesses of a nervous player will be made less apparent to his audience on an instrument with good resistance than on one with lesser resistance. He can also so-to-speak keep himself brave by "leaning into" his instrument with no fear of its choking up or squealing. The skilled and steady player, on the other hand, is able to use finely graduated variations of his controlling muscle tensions to produce the subtlest nuances in his music, again without fear of a disruptive blurting or fading. For both players, an entry after a few bars of rest is less hazardous if he can be sure that a slight misplacement of his embouchure on the reed will not produce much change in its accustomed behavior. We must recognize that none of these claimed virtues would be important if the listener were not able to perceive and appreciate all this fine-grained control!

There is one more aspect to the ability of a good instrument to sing: its tone should "carry" well. The musician's concept of carrying power has been much misunderstood, particularly by physicists and psychoacousticians. I will not try to define it rigorously here or to describe the nature of a sound that carries well (though we will return to this question in the third lecture). For the present it will suffice to point out the easily verifiable fact that for a given level of loudness (or of dB level), certain instruments will be heard and followed by the ear better than others in the presence of the complications of an orchestral sound. Let me present an extreme example. If a woodwind plays with a string orchestra it will be heard whenever it is actually playing. If, on the other hand, a violin is immersed in a wind band, it will never be heard at all even if the sound levels of all the instruments are kept the same (as a matter of fact, most instruments play at about the same level). It is not at all a criticism of the violin to point out that in the context of a wind group its tone carries very poorly, whereas the woodwind sound carries extremely well in the context of a string orchestra. We find that one piece of advice must always be given to a player after his instrument has been reworked to sing as well as possible in all other ways: he must learn to play it at a lower dynamic level than he has been accustomed to heretofore, otherwise he will unbalance the ensemble. I had the unpleasant experience of hearing the beautiful clear voice of one of my modified clarinets all the way through Beethoven's Fourth Symphony--its thoughtless player did not understand that sometimes one is to hear the clarinet among the other voices and that at other times it, for instance, is supposed to melt in with the violas to make a nice composite sound with them.

The second (and somewhat weaker) requirement for a good instrument is for it to have a reasonable intonation pattern. What does this mean today? Strict equal temperament is used only on the pipe organ, and a close cousin to it on the piano, the harpsichord, and other keyboard instruments. All other instruments can have their playing pitches shifted up and down by note to best fit into the changing chords. Even when playing with a keyboard instrument, the wind player or violinst departs from equal temperament in his responsible efforts to best fit in with the sounds coming from his colleague's instrument. As a practical matter today it is proper to build wind instruments so that their unmodified pitches match the equal-tempered scale, despite the fact that no wind musician plays serious music with this sort of tuning. However, as a statistical matter, the pitches needed for each note lie in a trimodal distribution placed so that the central group cluster about the equal-temperament pitches, while the upper and lower groups cluster about pitches some 12 or 15 cents above and below this. A player wants his instrument's natural tendencies to lie in the middle of the range it must cover, allowing him to pull it sharper or flatter as needed, without excessive loss of tone color or of the other aspects of response.

We come now to the last and least explicit requirement--the instrument should have "suitable" tone color. This is a matter of national and cultural taste and also of historical authenticity. It is premature for us to go into the question of tone color suitability here. However, we can usefully notice that suitable tone color for the clarinet in the Berlin Philharmonic is quite different from what is considered correct in the Paris Conservatory orchestra.

So far everything has been described and discussed in musicians' language. Before we launch ourselves into an investigation of the ways in which these musical properties depend on the physical structure of an instrument or on the way a listener functions in a concert hall, I should say explicitly that there are straightforward connections between the physical properties of a wind instrument that join to make it play well in all respects. Furthermore we can recognize and exploit the fact that the musicians' needs impose relatively few contradictory demands upon the properly skilled instrument designer. It is surprising to recognize how extremely well the traditional instruments have evolved to meet their players' needs, despite all the nonsense you can read about irrational ad hoc air-column and tone-hole systems. Very few of the critics have been able to even match the constructions of the makers they criticize. On the other hand, we must remember that wind instruments are complex enough that many aspects of their behavior have appeared heretofore inexplicable when looked at upon the basis of elementary acoustical theory.

B. The maintenance of oscillations

We should take explicit note now of the fact that wind instruments are self-sustaining oscillators--meaning that they sound as long as the player blows. This is in contrast, for example, to the behavior of the piano, in which a struck string starts with a large supply of energy which it gradually passes to the room via the bridge and the soundboard, and so its vibration fades away to rest.

The oscillating air within the bore of a wind instrument also sends its energy out into the room for us to hear, but here the energy supply is replenished by an automatic mechanism--the reed. For this reason we should get a glimpse of the way in which this automatic mechanism functions under the guidance of the air column that controls it, after which we will be in a position to understand not only the way in which the basic characteristics of the instrument's sound are determined by its structure but also to see how these features of the structure must be mutually adjusted in order to make the instrument a good one from the point of view of the player.

An example of a simple self-sustained oscillator is a child on a swing whose back-and-forth motions are maintained by a series of properly timed pushes which must be provided from a supply of energy (which was laid in by the pusher at his last meal!). Because the correct timing of these pushes is determined by observation of the child's position, we may say that the system is kept in motion via the action of an "eyeball-operated force controller".

On our way to understanding the reed-and-air column system of a wind instrument as a self-sustained oscillator, we must digress briefly to review a little about the easily observed and readily understood oscillations of water in a trough, since these oscillations turn out to be the mathematically exact counterparts of the less easily observed motions of air in the tubular bore of a wind instrument. Figure 2 shows three of the possible ways in which water can slosh back and forth in a trough.

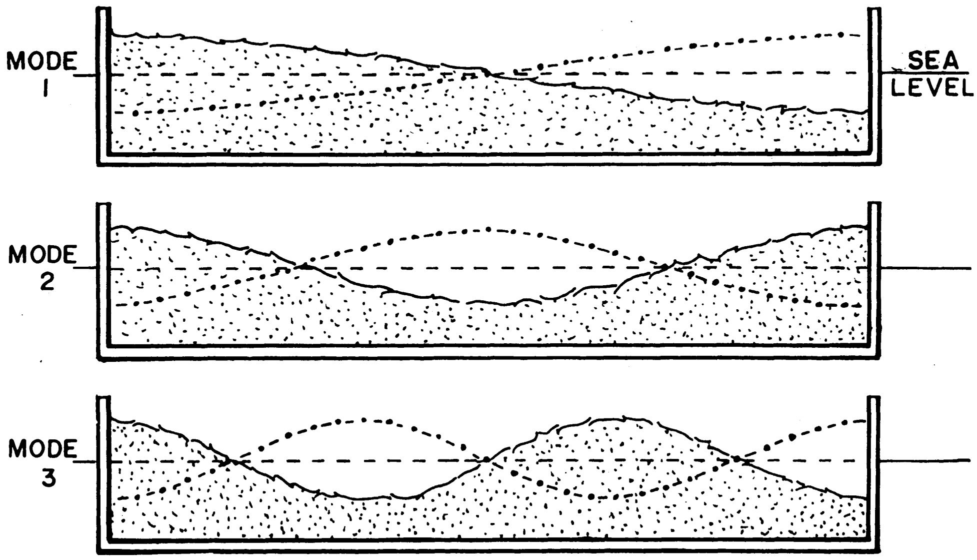


Fig. 2

The top part of the diagram shows the simplest mode of motion (call it mode 1). The water merely sloshes back and forth, piling up alternately at one end and then the other. This motion is strictly analogous to that of the child on a swing, whose mass moves back and forth from one extremity of the oscillation to the other. Clearly, I could put my opened hand into the water at the center of the trough and by suitably timed pushes could build up this simplest type of oscillation. The second type of motion possible for the water in this tub is shown in the middle part of Figure 2.

It is apparent that if I place my flattened hands symmetrically some distance out from the center of the tub, moving them alternately closer to one another or farther apart will set up and maintain an oscillation of the second type--provided once again that my eyeball-operated force controller supplies the stimuli at correctly timed instants during the motion. The lowest part of Figure 2 shows yet another mode of oscillation for water as it moves longitudinally in an elongated channel. Here again, properly timed pushes from my hands could be used to start and maintain the oscillation.

Before we turn away from our water trough, let us notice yet another way in which its oscillations can be maintained. We recognize that at the left-hand end of the water trough the water level goes up and down considerably in the course of any one of the modal oscillations. This means that we could excite any one of these oscillations by the vertical motion of my hand spread horizontally in the water at this end. All that is required is that this vertical motion be correctly timed to correspond to the sloshings of the desired mode. The important point here is that it is possible to "talk with" and thus excite any or all of the oscillatory modes by means of a stimulus device placed at one end of the trough.

So far I have said nothing at all about the frequencies of these various modes of oscillation in the water. As a matter of fact there is relatively little that can be said at this point. If the trough is very long, all the frequencies are low, but the exact number of oscillations that take place in each second depends as much on the variations of the cross section of the trough as it does on the length. Further than this, experiment quickly shows us that sloshings of the second type repeat themselves more often in unit time than do those of mode 1, while mode 3 oscillates yet faster. I wish to emphasize that in general mode 2 does not oscillate twice as fast as mode 1, nor mode 3 three times as fast. It is only for certain special shapes of trough that this particular sort of frequency orderliness manifests itself.

The elongated air columns of the various wind instruments show exactly analogous to-and-fro sloshings, and once again the air column shape determines the exact frequencies at which the various types of oscillatory motion take place. We have recognized that the water level rises and falls at the closed end of the trough. This is of course a consequence of the cyclic arrival and departure of water at this point. On the other hand, in the air column we have a rise and fall of pressure at the end as more or fewer air molecules squeeze themselves into this region in the course of their oscillations. We will find in the next paragraphs that it is this oscillatory variation of pressure at the end of a musical instrument air column that controls the excitation mechanism by means of which it is played.

Figure 3 shows our first musical instrument, a device which we can call a

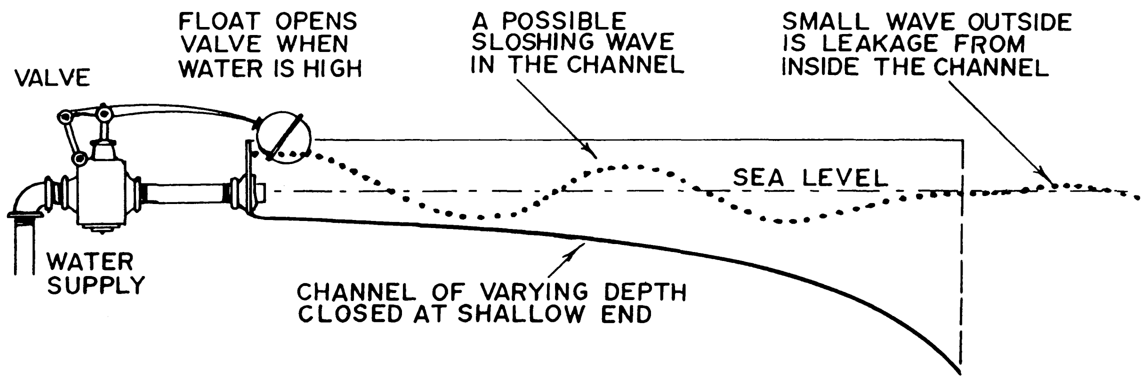


Fig. 3

water trumpet. In this machine we have a trough with a trumpetlike varying depth. A lever-mounted float is provided that opens and closes a valve in step with changes in the water level. The system of valve, float, and water channel can oscillate steadily in synchronism with any one of the natural sloshing modes of the water. This system is kept in operation through the services of a height-operated flow controller. When a strong sloshing motion is maintained inside the channel, a weakened version of it will leave the open to spread out over the sea--or into the concert hall for us to hear, if this is a wind instrument.

Every wind instrument consists of an air column fed at one end by some externally operating flow-control valve. In the clarinet or oboe it is the reed that serves as a little door that opens and shuts to admit puffs of air from the player's lungs under the control of sound-pressure variations that take place inside the reed-and-mouthpiece cavity. In the brass instruments the player's lips opened and closed by acoustic pressures present within the mouthpiece. In the flute family a jet of air from the player's mouth is steered alternately into and out of the mouth hole by the oscillating air within the air column itself. In short, we have a chicken-and-egg situation. In the reed woodwinds a series of air puffs is admitted into the air column by what we will call a pressure-operated flow controller in response to acoustic stimuli provided within the instrument's mouthpiece. On the other hand, these pressure variations in the mouthpiece are part of the air column's response to the stimulus provided by the entering puffs of air.

Because each response depends not only upon its particular stimulus but also upon the nature of the responding system, we must know something of of the dynamical behavior of the flow controller (i.e., the reed) and also of the air column to which it is attached. When one starts a note, a cycle of stimulus and response is set up in each half of the overall system that (in a good instrument) quickly settles down into a steady oscillation of the desired pitch, dynamic level, and tone color. Thus we must find properties for both air column and flow controller that are mutually able to negotiate the desired stable behavior.

C. Definitions of instrument categories

Before proceeding, we should make clear exactly what a wind instrument is. Table 1 summarizes the various definitions and distinguishing features of the different members of the family. I wish to emphasize that the defini-

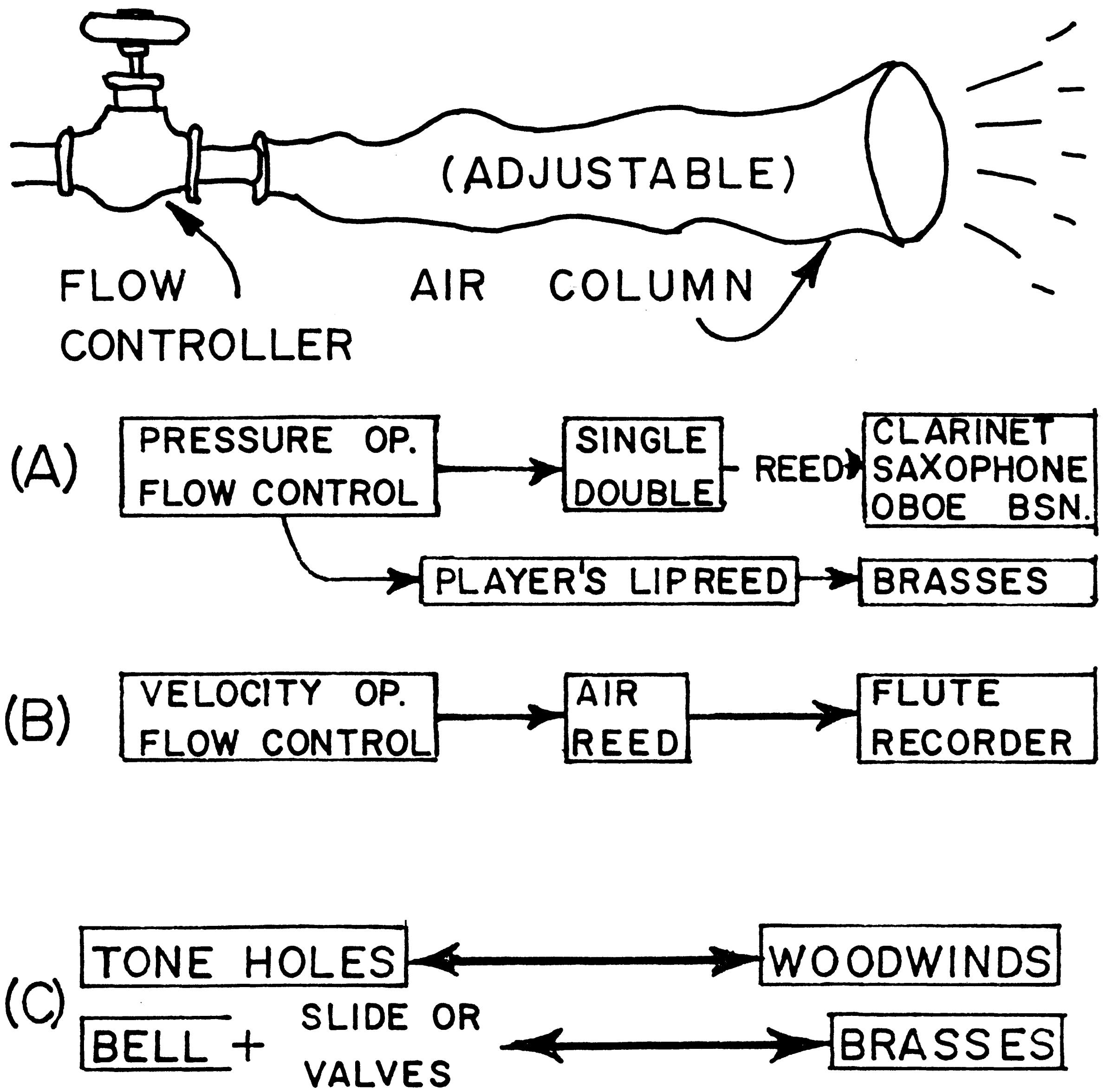


Table 1

tions and distinctions tabulated here are acoustically, musically, and perceptually definite. Practically all instruments can be classified in an unambiguous way. Thus it is clear that the renaissance cornetto is a true woodwind.

I will use a clarinet as the basis for essentially all my explanations and demonstrations partly because it is especially well adapted for this job and partly to avoid confusion caused by too many changing viewpoints. However, we discover that the clarinet shares practically all of its properties with the other reed woodwinds and much of its essential behavior with the brasses. I will return to the flute family at the end of Lecture II. It turns out that the behavior of this family of instruments parallels that of the reed instruments so closely that we will need to change only one or two technical words to adapt my entire discussion to the flutes.

D. Characterization of the air column and the reed

So far we have had a glimpse at the way in which a musical system can keep itself in oscillation and we have provided ourselves with a framework for classifying the various types of instruments. Our next task is to learn how one characterizes the acoustical properties of an air column and of its collaborating reed in a manner that permits us to understand what we hear of their sounds and to predict what they act like.

The upper part of Figure 4 looks like it has strayed from Lecture III and in a sense it has done so. However, it introduces us here to the way in which the response of a room (or an air column) can be measured. To begin, we take a sound source and a microphone and place them anywhere we like in the room. The excitation frequency of the source is then systematically varied from low to high as the response of the room is measured at the position of the microphone. Such an experiment typically provides us with an irregular response curve of the sort shown as part of the diagram. To be technically strict, this curve shows the pressure response at one point

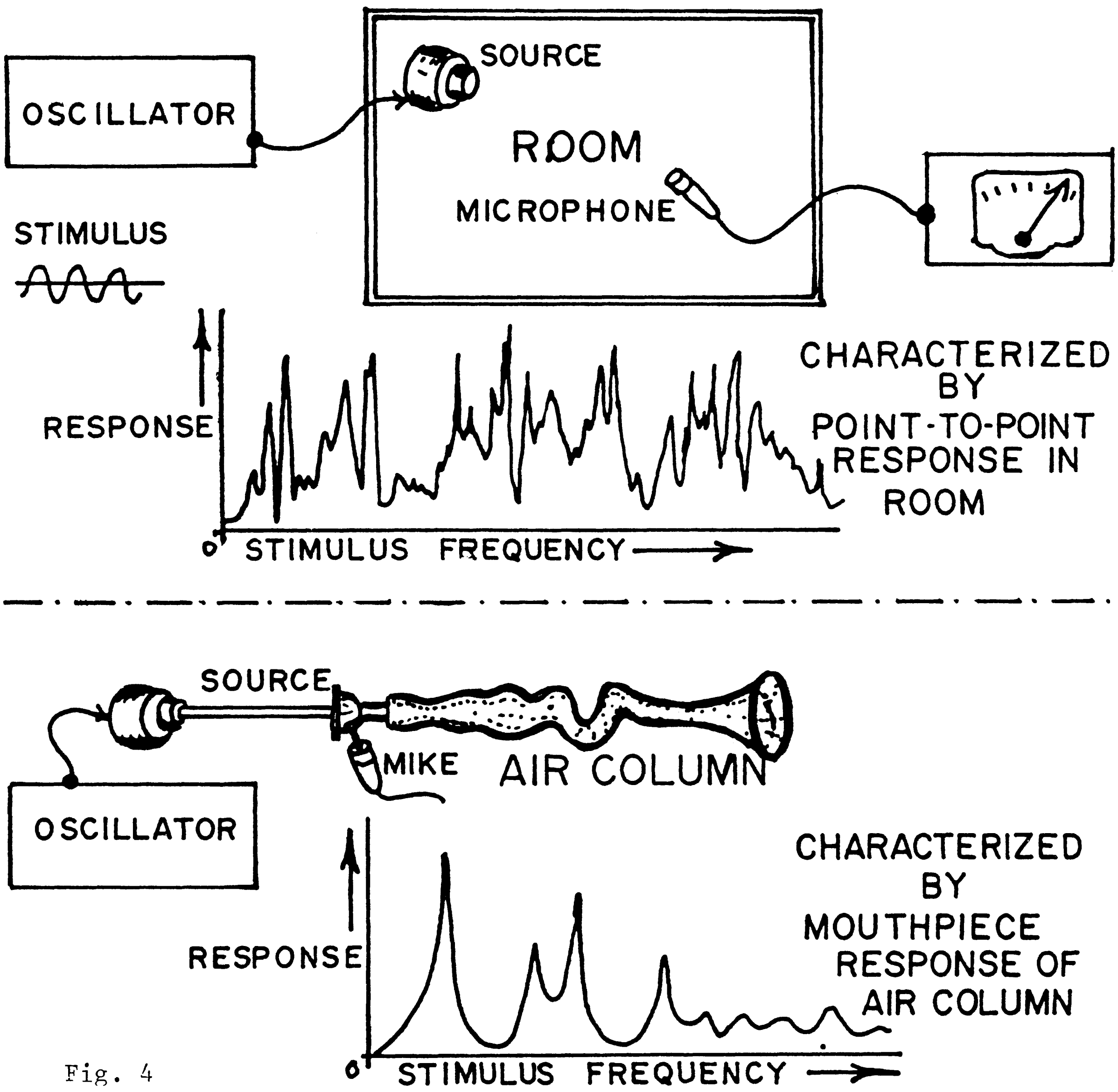

OSCILLATOR
SOURCE
ROOM
MICROPHONE
STIMULUS
RESPONSE
0
STIMULUS FREQUENCY
CHARACTERIZED BY POINT-TO-POINT RESPONSE IN ROOM
SOURCE
MIKE
AIR COLUMN
OSCILLATOR
RESPONSE
0
STIMULUS FREQUENCY
CHARACTERIZED BY MOUTHPIECE RESPONSE OF AIR COLUMN

Fig. 4

of the room arising from a constant-amplitude sinusoidal flow stimulus applied at another point. Such an experiment has meaning for room acoustics because our ears are primarily pressure sensitive and because most sound producers are ultimately of the flow-source type. The lower half of Figure 4 shows a variation of the basic experiment as it is adapted to the air column of a musical instrument. Here the source (which acts willy-nilly to inject air because it is driven by an electronic amplifier) is placed where the flow-controlling reed is normally found. The microphone is placed within the mouthpiece cavity, where it can measure the pressure response of the air column at exactly the point where pressure signals normally give instruction to the reed. The response curve obtained in such an experiment has strong peaks at the various natural frequencies of the air column. The location, height, and shape of these peaks serves to identify the air column. More important, such a response curve characterizes the air column in a way that lets us predict how it can interact with its reed. One can learn to read the curve like a book and to appreciate it as a good summary of the musical personality of the instrument it describes. We will make extensive use of the response curves of actual instruments throughout the remainder of these lectures.

The analogous experiments and summarizing curves for the reed itself are shown in Figure 5. The lower part of the diagram shows the experimental setup, and the upper part shows the data obtained from it. In essence one blows on a reed by means of an artificial embouchure, the reed and mouthpiece being attached to an air column filled with enough damping material that it cannot have any sloshing motions within it. The experiment consists of measuring the flow through the reed aperture as a function of the pressure difference between the "player's" mouth and the inside of the mouthpiece. When this pressure is low, the resulting flow is small. At first, flow rises as the pressure is increased (as shown in the upper part of the graph). Later on, the flow levels off and then begins to decrease as the pressure across the reed begins to push it closed, which decreases the aperture through which the air is flowing. This hump-shaped

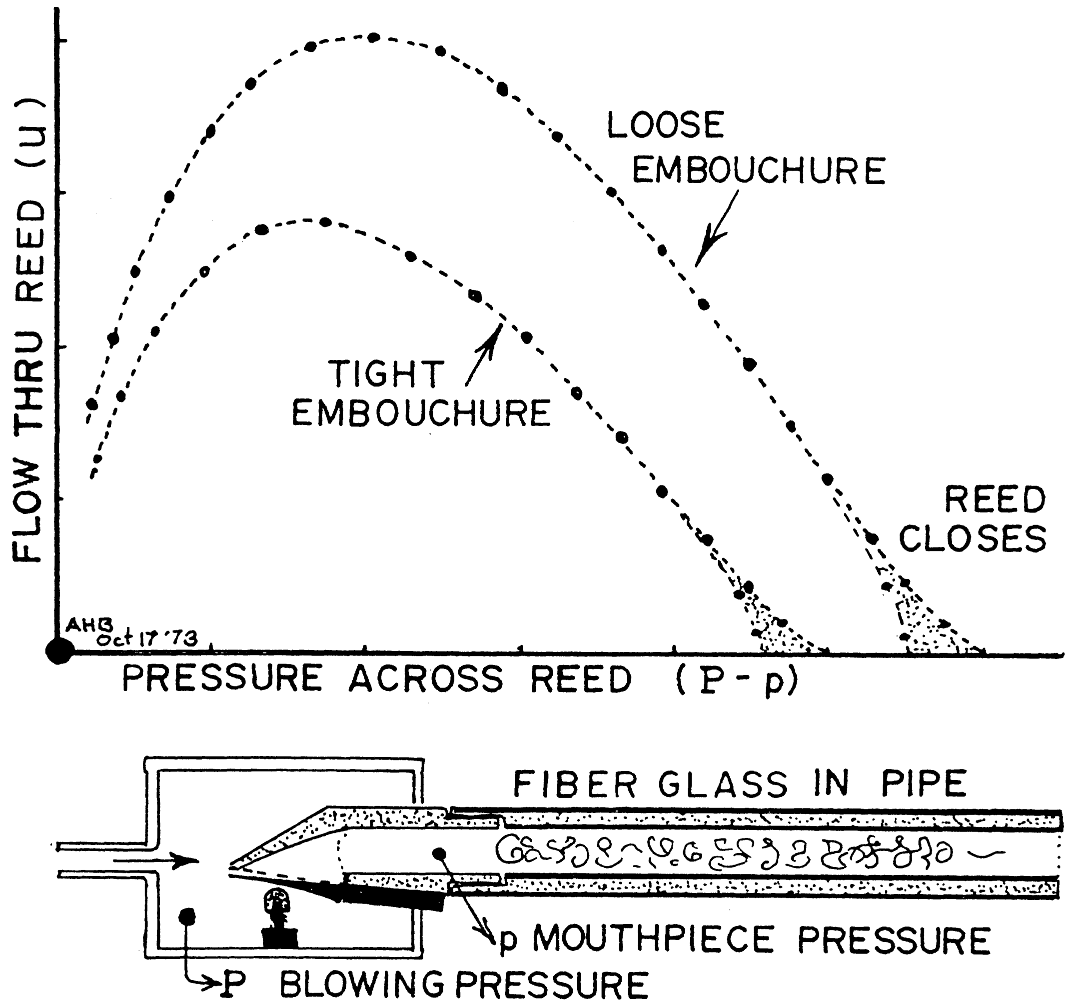


Fig. 5

curve relating flow through the reed to the driving pressure is typical of all the single-and double-reed instruments one meets in the orchestra. The detailed shape depends of course on whether we have a single reed or a double one, on the exact way in which it was made, and on the precise way in which it is acted on by the player's embouchure. We can recognize very easily that it is the presence of the downhill slope on the righthand side of these curves that makes them useful as musical flow controllers. In this region the general tendency of the player's steady blowing pressure is to close the reed, whereas a momentary increase in the mouthpiece pressure (in the course of an oscillation) acts to push the aperture wider and so permits the entry of more air. It is this increase of flow that is produced by an increase in mouthpiece pressure that maintains the oscillation, as we learned in the case of the water trumpet. By the way, Figure 5 shows two curves, from which we can recognize that the player has many choices in the way he gets the downhill part of the flow-control curve to have the proper slope and curvature. He can push the reed nearly closed by using a very tight embouchure and then blow gently or he can use less embouchure tension in conjunction with greater blowing pressure. We shall see that this freedom of choice is very important for the skilled player because it permits him to make yet another adjustment to the behavior of his reed without upsetting its flow-control properties.

E. Oscillations of a reed and air column

We are now in a position to put our two characterization curves (for the air column and for the reed) together in a way that summarizes the way in which the two parts of an instrument must work together. The tall curve of Figure 6 represents what one might measure for the pressure-response of a special air column constructed in such a way that it has only one natural sloshing mode. The peak represents the strongly excited pressure variations set up within the mouthpiece when the laboratory flow stimulus runs at a frequency approximately matched to that which is natural to ("preferred" by) the air column. The horizontal line labeled "breakeven" in the diagram is an abbreviated representation of the flow-control properties of the reed. It is used as follows. If the response peak of the air

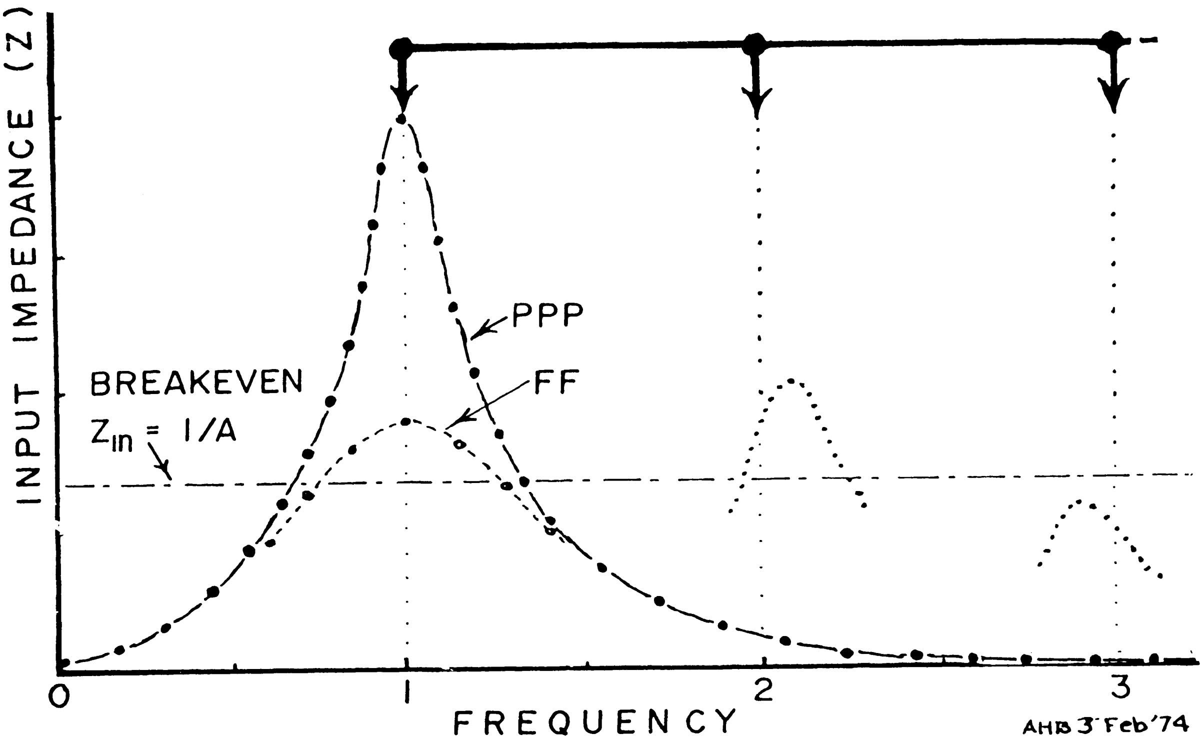


Fig. 6

column rises above this line, it means that the pressure response of the air column to a given flow stimulus is larger than the pressure stimulus required by the reed to produce this amount of flow. In other words, there is more than enough response from each part of the system to the stimulus provided by the other part to maintain an oscillation. Under these conditions we would expect the vigor of the oscillation to grow and grow until something explodes or otherwise changes, since more energy is fed into the system in each cycle of its oscillation than it can dissipate in friction and in radiation of sound.

In an actual air column (as I will demonstrate shortly) the oscillation does not grow indefinitely: two things begin to happen. First of all, as the oscillation grows, small turbulences begin to appear within the air column, especially at any bore discontinuities or tone holes. This newly added form of friction grows rapidly and has the effect of pulling down and broadening the response curve. If nothing else takes place, this means that the sound level grows and the response peak becomes less tall until its maximum point just kisses the breakeven line set by the reed. Thus turbulent losses set an upper limit beyond which the oscillation cannot grow, so producing a limit to the strength of sound a given device can generate.

There is also a second way in which the system can limit the amplitude of its oscillations. The reed does not just open and shut in a simple, proportional fashion. As a result, the flow pattern through it is not a straightforward copy of the pressure variations that give rise to it, except when the system is running at a pianissimo level. As one blows harder, the flow behavior changes and the air enters in little puffs that are properly timed by the pressure variation but which are not an exact copy of it. This means that (because the puffs form a regularly repeating sequence) the flow pattern is made up of the sum of a fundamental and a set of harmonic sinusoidal components. This is true even though the reed is being controlled by the sinusoidal oscillations of a single air column mode.

The presence of harmonic components is indicated in the diagram by the line with downward-pointing arrows. The leftmost arrow shows the location of the fundamental component, which is the one that is generated directly at the natural frequency of the, air column. The other two arrows show the locations of the second and third harmonics, which appear at twice and three times the "playing frequency". Notice that at both of the harmonic frequencies, the main response curve lie far below the breakeven line. This means that the air column and reed system cannot produce energy to help sustain the newly born components. On the contrary, they join together to become yet another way to steal energy from the main oscillation, and so to limit its amplitude. A musician trying to play a crescendo on our single-resonance prototype instrument finds that it is fairly easy to sound it at a pianissimo level. Here the turbulent losses are small and the harmonic generation process is negligible. However, as he increases his blowing pressure, turbulence places a rapidly growing drain on the system so that the loudness grows only a little when the player increases his effort a great deal. Furthermore, his greater effort produces increasing amounts of harmonic components which add to the drag upon his efforts. Ultimately the reed simply blows shut and the instrument falls silent.

Sound example 1 of the recording included in this report illustrates all phenomena outlined in the preceding paragraph. What you hear first is the normal sound of a healthy clarinet, complete with clear tone color and a reasonable dynamic range. Following this come the sounds produced by this same clarinet when it is fingered in a curious way that gives it a response curve of the single-peaked sort we have discussed so far. These sounds start out very soft and, as the player increases his efforts, become dirty and full of hissing noises. In each case, what is intended as a crescendo turns into a strangled little beep.

F. Cooperative effects

Suppose that instead of an air column whose response curve has only one peak we have one that is able to oscillate in two or more different modes, each of which manifests itself as a peak on the response curve. Such peaks are indicated by dotted lines in Figure 6. Notice that the peak belonging to mode two is tall enough to reach above the breakeven line belonging to the reed. This means that this mode also could collaborate with the reed to keep itself in oscillation. The third-mode peak does not extend above the breakeven line and, since it therefore cannot maintain its own oscillation, we will ignore it for the moment.

What happens when we blow on the reed of our revised instrument? First of all, at a pianissimo level we find that the tall first-mode peak takes precedence over everything else, and the oscillation starts at exactly the same frequency as before. This time, however, as one blows harder, the second harmonic component finds itself located at a point where the air column curve lies above the breakeven line. As a result it can support itself and even supply energy to the rest of the system instead of being a heavy drag on everything. Such an "instrument" allows you to blow very much harder without pressing the reed shut and produces a much more realistic sound complete with a true crescendo behavior. However, notice that, according to the figure response peak number 2 is not located at exactly the position along the frequency axis that would allow it to cooperate best with the second harmonic produced by the reed acting in conjunction with peak number 1. We use this observation as our introduction to one of the features that distinguishes a good instrument from a poor one. On an air column of the sort shown in Figure 6, an attempt to play a crescendo not only gives a rise in loudness, but also a rise in pitch. In a manner of speaking, peak number 2 says to peak number 1, "If you will consent to generating a sound whose fundamental is only a little higher than your frequency of maximum response, it will not reduce your efficiency very much. However, the second harmonic that you generate to go with this fundamental will lie somewhat higher, and so will fall closer to the frequency at which I interact best with the reed." Between the two response peaks a sort of political negotiation takes place which leads them to choose a basic oscillation frequency that maximizes the ability of both modes to produce energy through their interaction with the reed.

In general, then, several response peaks of an air column can cooperate in setting up what is called a regime of oscillation. The oscillation takes place at a fundamental frequency such that at this frequency and at its harmonics there is a maximum cooperation among the voting members of the regime. At the pianissimo level of playing we find that only the tallest peak has a vote, and during a crescendo the peaks lying near the successive harmonics gain influence one by one. If the air column shape is such that its natural frequencies are not quite in whole-number relationship, then one finds pitch drifts during crescendos and decrescendos and a general lack of every kind of playing stability. In short: to make an instrument sing, one must "align" the response peaks by carefully chosen adjustments of the air column, tone-hole, mouthpiece, and reed proportions.

G. Some practical implications

Every orchestration book warns the composer to beware of the almost unconquerable tendency of a clarinet to drift downward in pitch during a low-register crescendo. We can readily understand the reason for this: the frequency ratio between response peaks 1 and 2 is less than the whole number relationship (3-to-1) that would be desirable. This means that under loud playing conditions peak 2 is voting for a reduced pitch relative to the preferences of peak 1. During the decrescendo, peak 2 relinquishes its vote and the pitch rises to agree with the specifications laid down by peak 1.

Sound example 2 on the record shows peculiar and unfamiliar sounds produced by a clarinet whose response peaks are slightly rearranged so that the pitch drops rather than rises as the dynamic level is reduced. Experienced players find this clarinet very uncomfortable to play because their habitual actions, which have been highly developed to keep pitch changes to a minimum on their own instruments, only serve to accentuate the peculiar behavior of this instrument.

We have now met the cooperative behavior by means of which the sloshing modes of an air column govern the action of a pressure-operated reed in maintaining a musical oscillation. We have also met our first illustration of the implications of these phenomena for the practicing musician. Let us consolidate our understanding by using the measured response curve of an actual trumpet to predict and understand its behavior. Figure 7 shows the response curve for a first-class modern trumpet along with some diagrammatic indications of how the notes C_4 and G_4 are produced by regimes of different sets of response peaks. The regime for C_4 is based

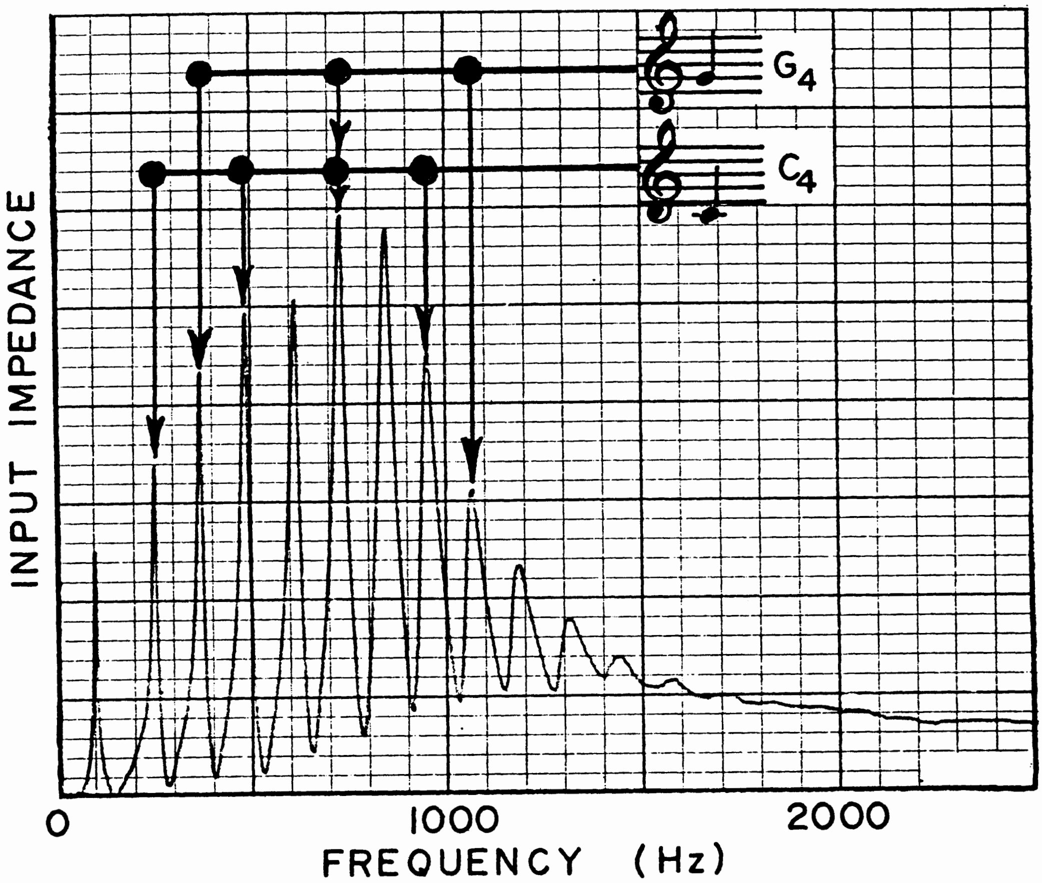


Fig. 7

on air-column peaks 2, 4, 6.... When the tone is sounded at a pianissimo level, it is unsteady because the not-very-tall peak has difficulty in stabilizing the accidental tremors of the player's lips which are rather massive in relation to the air which tries to control them. As the loudness level increases, the very tall peak 2 begins to get a vote; at once the sound stabilizes and fills out and, as the crescendo continues, the sound evolves into the full-throated blare that one expects from a fine brass instrument. The regime for G_4 a fifth above is based on mutual negotiations between peaks 3, 6, 9, ... Here the note is fairly steady even at a pianissimo level because the strongly responding (i.e., having a tall peak) mode 3 of the air column finds it easy to dominate the player's lip reed even when acting by itself. The tone stabilizes further as the crescendo continues, just as before. We see from all this why a trumpet player may be a little unhappy when asked to make a cold entry on a pianissimo C_4 but finds that a similar entry on a G_4 is no particular problem.

H. Role of the reed's own natural frequency

We have paid very close attention so far to the ways in which the natural frequencies of the air column affect the generation of musical sounds, and we have tacitly assumed the flow-controlling reed to be a simple springlike object to be pushed open and shut by the pressures that act upon it. This is true to a first approximation for the woodwind reeds, although I have already hinted at the usefulness of the player's ability to exchange embouchure tension for blowing pressure. Closer inspection reveals that the reed itself has a natural frequency of oscillation. When the reed is acted on by forces whose repetition frequency is relatively low, its motion is in step with those forces and is of magnitude determined almost completely by the springiness of the reed. In the neighborhood of the reed's natural frequency, a repetitive force produces a resonance behavior such that the excursions of the motion are very much larger than those observed with either low-frequency or high-frequency excitation. Furthermore we discover that when the excitation frequency is higher than the reed's own natural frequency, the resulting motion has rather startling behavior--the reed swings in an opposite sense from what is observed at low frequencies. Thus it runs toward a push and away from a pull!

The fact that a reed becomes especially sensitive to any instructions that may come from the air column at frequencies near its own natural frequency is important to the ultimate tonal behavior of both woodwinds and brasses. Furthermore, the reverse-phase behavior above resonance is absolutely necessary if the brass player's lips are to be able to function as a musical flow controller.

The brass player's analog to the reed flow-control curve of Figure 5 shows a continually rising graph. The harder one blows the wider the lip aperture becomes, and so the more the air flow. Looked at another way this says that an increase in the pressure within a brass instrument mouthpiece decreases the flow, exactly contrary to what happens with a woodwind reed. At first this would seem to say that the lip reed functions to kill off any oscillations that may be taking place within an air column. Resolution of the problem is very simple--the self-sustaining ability of a woodwind reed exists at frequencies below the reed's own frequency, whereas on the brasses it is always above (where the reverse-phase motion takes place).

Let us run through all this now using breakeven lines and air-column response curves. Figure 8 shows among other things the pressure-response curve for an air column similar to that used in producing the written note B_4 on a saxophone or oboe. We notice that it has only two tall peaks, above which is a squiggly region of slight response (whose existence will become progressively more important during the second lecture). This figure also shows a breakeven line for the reed, only this time it is not level. The height of this line falls progressively until it crosses the axis at the reed frequency. As one tries to drive the reed at frequencies progressively closer to its own resonance, its increased response means

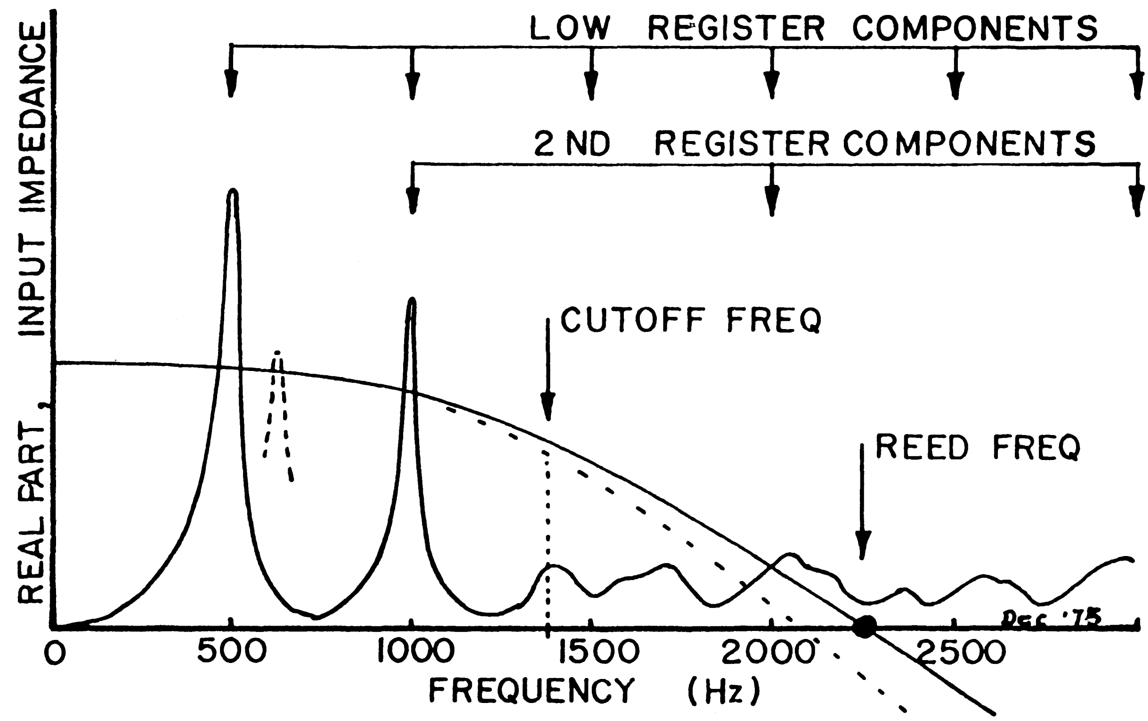


Fig. 8

that it can maintain oscillation by cooperating with progressively less tall air-column peaks. As the solid breakeven line is drawn in our figure, air column peaks 1 and 2 are tall enough to join a regime of oscillation. There is also a little region just above 2000 Hz where the air-column curve is above breakeven. However, this region is not in whole-number relation with the 500-, 1000-, 1500-Hz sequence of frequencies that will be generated by the regime of oscillation. As a result, this little region plays no role in the production of sound. Suppose now that the player slacks his embouchure a little, allowing (among other things) the reed's own frequency to fall enough that the breakeven line is like the one shown dotted. Now the air column response curve lies above the breakeven line at 2000 Hz, so that there is direct production of oscillatory energy not only at the 500- and 1000-Hz positions of the response peaks but also at the harmonically related frequency of 2000 Hz. The listener finds that the resulting tone is fuller and steadier. The player finds that this sort of playing--with his embouchure setting arranged to produce reed resonance cooperations at one or another of the harmonics of whatever note he is playing--not only makes him feel more secure about everything he is called upon to do but also that every aspect of what we have called the goodness of his instrument is enhanced by the additional cooperation that he has introduced into the various regimes.

Figure 9 shows a very similar set of curves, this time for a trumpet air

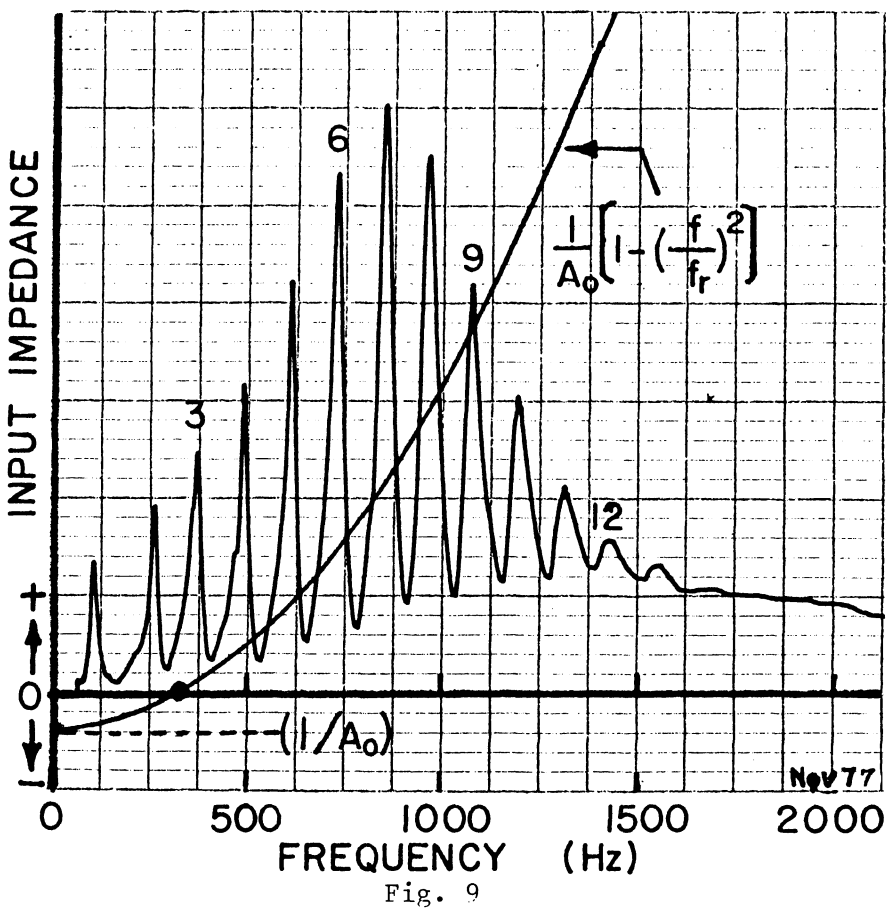


Fig. 9

column and the backwards-appearing breakeven line for the brass player's lip reed. The player has set his embouchure so that the lip-reed resonance lies just below peak 3 of the air column. As a result this peak takes primary responsibility in generating the tone. Peaks 6 and 9, which are at least somewhat taller than the sharply rising breakeven line, then join in the regime as needed. Notice that this figure gives us a closer look at the way in which the player and his trumpet generate the tone G_4. When the player wishes to play something like a bugle call, he simply moves the lip-reed resonance to approximately match the frequencies of the various air-column peaks that correspond to the notes that he wishes to play.

The brass player shifts from one note to another by changing the natural frequency of his lip reed. How then does the woodwind player change registers? Before we answer this question directly, let us digress to a byway of musical acoustics--sounds generated by an air column whose response peaks are not in a whole-number relationship. At first one might think that such sounds are not possible above a pianissimo level. Under heavier blowing the reed would be expected to blow shut. However, this does not happen if the player can arrange the reed resonance to lie at some frequency that can at least somewhat cooperate with one or another response peak. When this is done, a peculiar type of sound is generated. Some of the components of this sound lie in harmonic relation to one another; one might even find two or more <u>sets</u> of intertwined harmonic components, but one always finds a collection of additional components whose origin and relationship we will not discuss here. However, it is worthwhile to hear such a sound and to hear one version of it slowly evolve into another version as the player's embouchure gradually changes the reed frequency from one value to another. <u>Sound example 3</u> on the record provides such sounds, which are known to musicians as multiphonics.

I. Register changes and register holes

The last topic in this lecture on sound production by wind instruments has to do with the way in which a woodwind player changes registers--that is, how he changes the sound from one produced by the first air-column response peak acting on the reed with help from all the higher-frequency peaks to a sound in which the second peak takes major charge of the regime, using any assistance it can get from the higher-frequency air column. This changeover cannot have a trivial explanation because it requires a regime that includes many cooperating members to give up its authority to one with fewer participants. Sound example 4 a of the accompanying record shows how neatly and cleanly a properly constructed clarinet will jump from one register to the other a musical twelfth away. The top part of Figure 10 shows the actual response curve of a clarinet air column in its normal state--a tall first peak followed by several less tall peaks all arranged in a 1, 3, 5 frequency sequence. Superposed on this curve is the slightly modified curve associated with the air column response that occurs after the opening of a scientifically designed but non-standard register hole. This register hole was designed to have the major effect of making peak 1 less tall than peak 2 without altering the frequencies of any of the other peaks. Sound example 4 b of the record verifies that pianissimo playing on this air column gives the upper-register pitch, as we might expect for an air column whose peak 2 is the tallest. It is however possible to start the low-register tone by a fortissimo attack, exploiting all the normal cooperations of the low-register regime. Once the note is started, however, during a played diminuendo we find that the pitch makes a transition to the higher register (as demonstrated in sound example 4 c). This transition happens when the voting strength of the upper peaks becomes small enough that they can no longer support the weakened first peak against the efficacy of the taller peak 2 acting alone. We have here a register-hole design that is only useful for pianissimo playing, a design that is likely to produce unpredictable results at any other dynamic level.

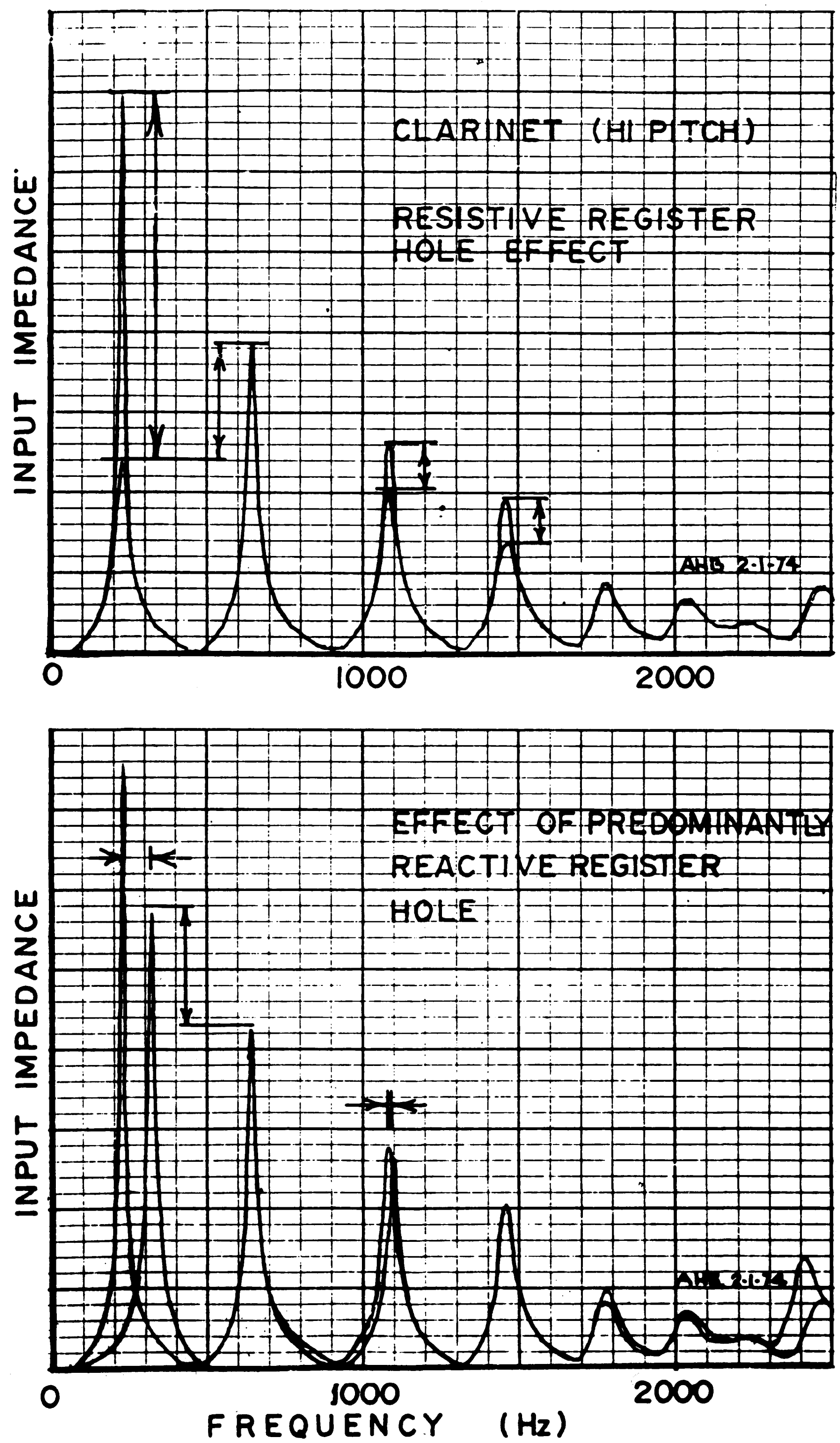

CLARINET (HI PITCH)
RESISTIVE REGISTER HOLE EFFECT
INPUT IMPEDANCE
AHB 2-1-74
0
1000
2000
EFFECT OF PREDOMINANTLY REACTIVE REGISTER HOLE
INPUT IMPEDANCE
AHB 2-1-74
0
1000
2000
FREQUENCY (Hz)

Fig. 10

The lower half of Figure 10 compares the normal response curve for this clarinet with the curve resulting from the use of yet another laboratory-type register hole. Here we see that, instead of making peak 1 less tall than peak 2 without altering its natural frequency, the register hole has left peak 1 quite tall but has displaced it upward to a carefully chosen frequency that has no whole-number relationship with the other peaks. Sound example 4 d of the recording shows us that when this particular clarinet is played fortissimo it runs steadily in its second register but, during a diminuendo, the pitch abruptly drops to an out-of-tune first-register note that is fed by the displaced but still tall first peak acting by itself. If I try to play a crescendo on this altered low-register note, the instrument will do one of two things: it will either choke up entirely as the higher harmonics generated by the reed encounter the anticooperating dips between the resonances, or it will cough and make a transition back up to the properly working second-register note. Here we have investigated the behavior of a register-hole design that functions reasonably well at the fortissimo level but which tends to misbehave at low levels and during changes in dynamics.

How then does the register-hole system of a real clarinet (or oboe, or saxophone) need to be designed? The answer is very simple--it must borrow its properties from both of the laboratory examples. A useful register hole must reduce the tallness of peak 1 sufficiently to assure proper operation at the softer playing levels. It must also displace the frequency of peak 1 to give it a position where the cooperative possibilities between it and the other peaks are destroyed, thus making certain that register changes are correctly obtained when the player is sounding his instrument at the louder levels of performance.

J. Conclusion of lecture I

This first lecture has been a very full one. Let us glance back over our path through it to see what all we have done. After considering the virtues that must be provided by any sort of good instrument, we took up the problem of how the oscillations of an air column are maintained by means of a pressure-operated flow controller (the reed). Next we became acquainted with the powerful effects of intermode cooperation, which allowed us to understand many aspects of the playing behavior of real instruments. In the next lecture we will learn a little about the nature of the sounds that are produced within a musical air column and then will take up a study of the way these are modified on their way out of the instrument into the room.

LECTURE II. SOUND RADIATION FROM INSTRUMENTS

We have seen so far many of the ways in which a set of natural frequencies belonging to an air column will cooperate with a reed in the task of converting the steady blowing of a player into musical sound. However we have not done more than glance at the nature of this generated sound. In other words, we have postponed until now almost all mention of the relative strengths of the harmonic components that make up this sound. The reasons for this postponement are twofold. Our attention was upon the large task of building up a basic understanding of the oscillation mechanism. Furthermore, certain details of the radiation processes that transfer (and modify) sound as it passes from the interior of the instrument into the room also play a part in controlling the nature of the produced sound within the instrument.

A. Properties of the internal spectrum

Our first task in this lecture will be to relate the shape of the air-column response curve to the sound spectrum that it will produce when working with a reed. For simplicity I will at the start confine my discussion to what happens in the pianissimo-to-mezzo-forte playing range of a single-reed woodwind. The corresponding range of a brass instrument behaves quite similarly. The double-reed instruments and the fortissimo range of single-reed instruments have a rather different behavior which I will only touch upon briefly before we look at the radiation behavior of all instruments.

We have already learned that in pianissimo playing the reed cooperates with the tallest air-column response peak to produce a very nearly "pure" sinusoidal oscillation. Putting it another way, the sound recipe measured within the mouthpiece has only a single ingredient and its frequency is very nearly that of the air-column peak. We have also learned that during a crescendo new ingredients are added to the recipe, one by one, their frequencies being whole-number multiples of the first-appearing (i.e., fundamental) component. Clearly, the relative strengths of these various components depend on the success with which the air column talks to the reed at the frequencies of these components. It will come as no surprise then for me to state that components will be strong or weak depending on the height of the air-column response curve measured at the frequencies of each component. Without going through the long and difficult mathematics that leads to it, let me set down here a simple but basically accurate formula relating the strengths of the various ingredients making up the sound:

$$p_n = p_1^n Z_n \times \text{[details having to do with reed complexities]}$$

This formula says among other things that if we refer everything to the strength p_1 of the fundamental component of the sound, the strength p_n of the nth harmonic will grow and shrink proportionally with p_1 raised to the nth power. Thus a doubling of the fundamental component increases the second harmonic fourfold ($2^2 = 4$), and the third harmonic ninefold ($2^3 = 8$). The symbol Z_n stands for the height of the response curve at the frequency of the nth harmonic ingredient of the tone, so that the formula tells us that (to present approximation) the strength of the ingredient is directly proportional to the corresponding value of Z.

We can gain somewhat more insight into the meaning of the formula if we consider what happens to the sound recipe as one plays a decrescendo from mezzo forte. At first the strong and weak components of the sound simply reflect the strong and weak responses of the air column at the frequencies of the components. If the player reduces his blowing pressure enough to make the fundamental component fall by 1/2, the second harmonic is reduced to $(1/2)^2 = (1/4)$ of its initial value, and the third harmonic by a factor $(1/2)^3 = (1/8)$. Continuing the decrescendo, by the time the fundamental component is reduced to 1/4 of its original value, the second and third harmonics are reduced to factors of 1/16 and 1/64. As the descrescendo continues, we find thus that the higher components become negligibly small before the lower ones. Conversely during a crescendo the lower components come in earliest and are followed by the higher components. One can very well say that one of the distinguishing features of the wind-instrument sound is the progressive "flowering" or "unfolding" of the tone color during a crescendo. As a matter of fact, something very similar to this flowering takes place every time a note is started or stopped. In other words, the components come in or go out as different members of the regime of oscillation take up or relinquish their influence.

B. Examples of the spectrum behavior

The Hungarian tarogato is an instrument that will serve us particularly well as an introduction to the use of our sound recipe formula and as a convenient illustration of some related aspects of the sound-production process. Before we look into its acoustical behavior we should learn in briefest terms just what sort of instrument this is. One of my musician friends described the tarogato in a wonderfully precise manner--"It is a wooden soprano saxophone with no bad habits; its tone is a cross between that of a saxophone and an English horn." Those of you who have struggled with or listened to a performer trying to overcome the nasty habits of a soprano saxophone will appreciate the first part of this characterization. The usefulness of the second part, that has to do with tone color will become apparent very shortly. While the tarogato is an unfamiliar instrument, it serves us well here in part because it shares its general behavior with all woodwinds and in part because it is an example of a really good conical instrument.

Figure 1 shows in its left half the measured response curve belonging to the G_4 fingering of the tarogato.

Notice that there are two tall response peaks and also that there is essentially no resonance behavior at all above about 1100 Hz. This shows that we may expect the sound recipe measured in the mouthpiece at forte level to

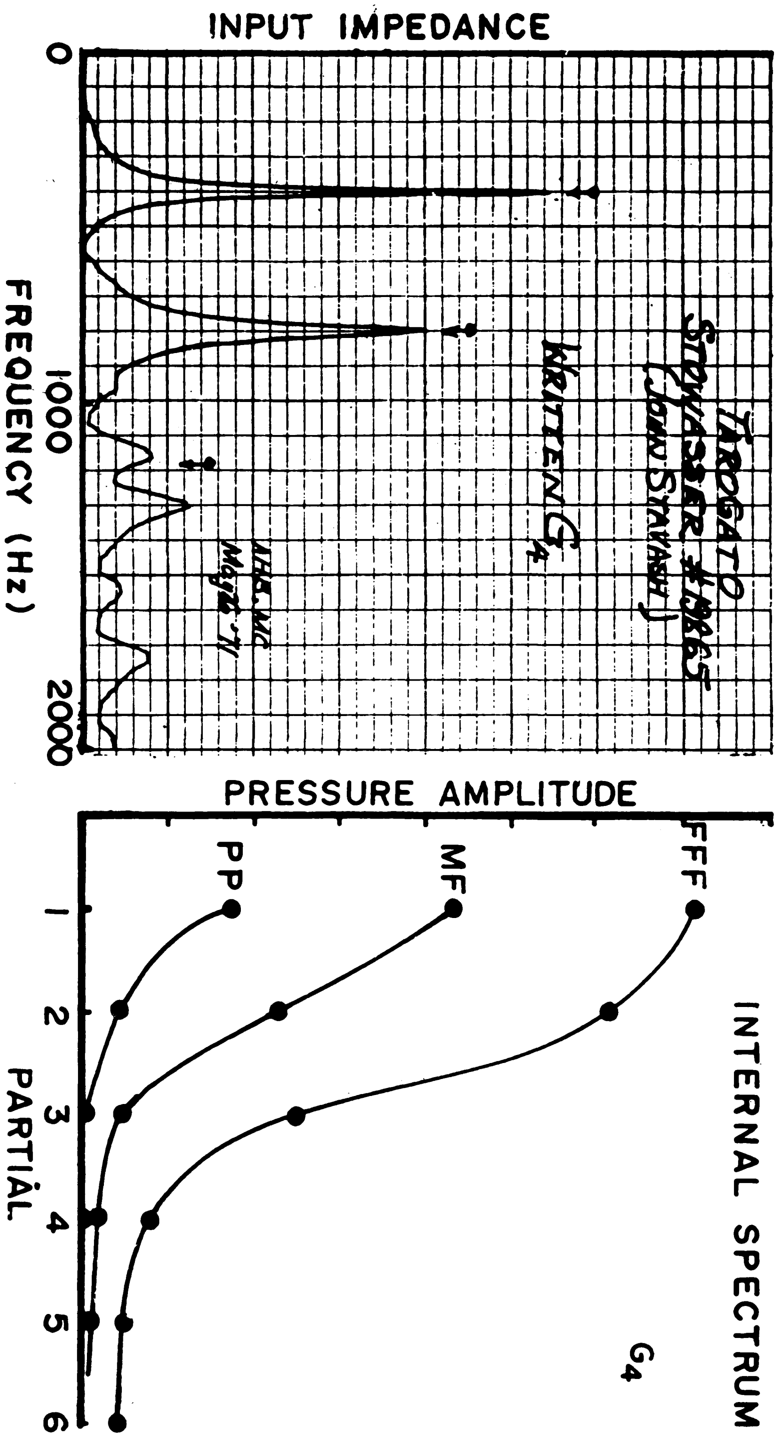
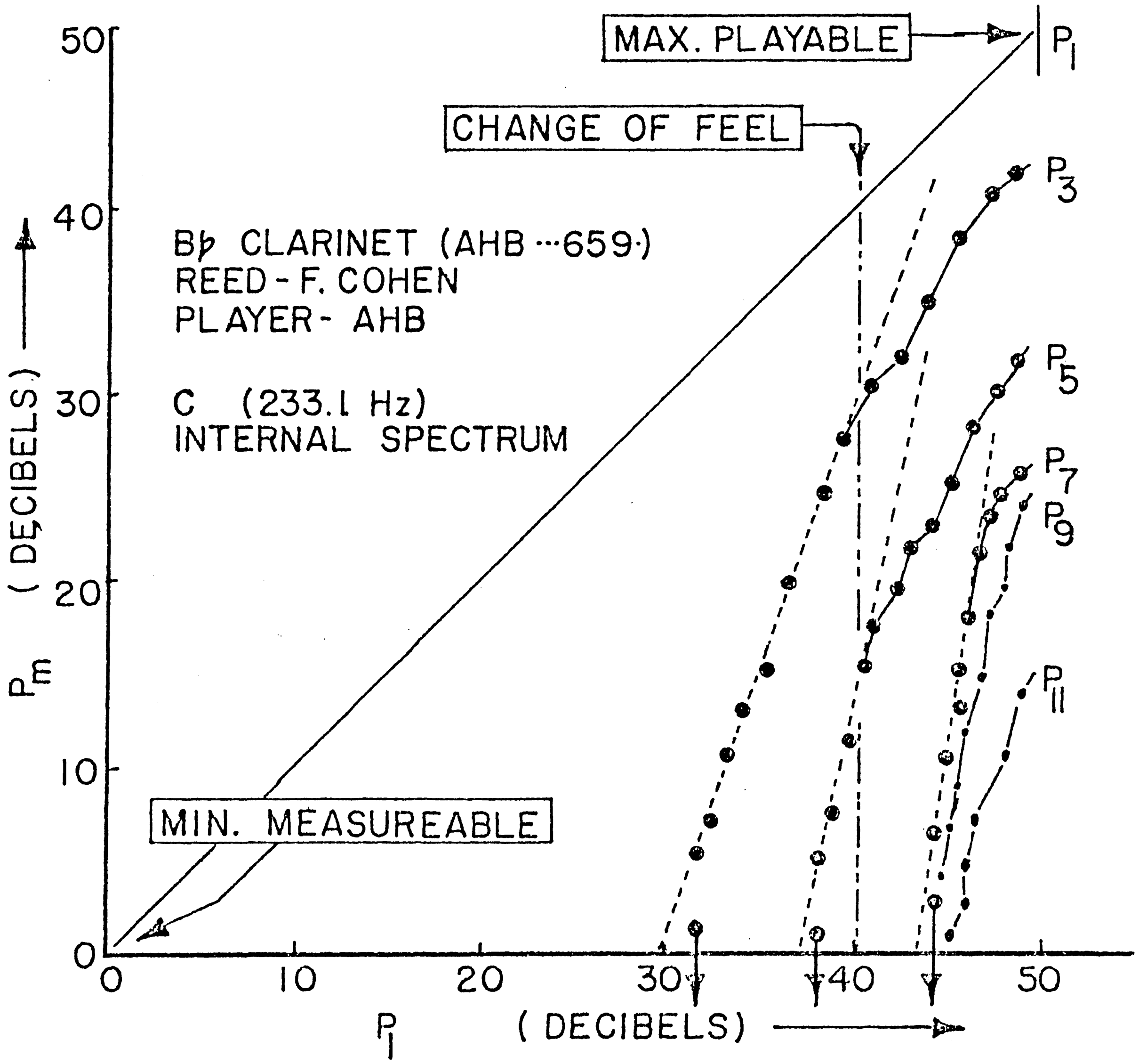

INPUT IMPEDANCE
0
1000
2000
FREQUENCY (Hz)
TAROGATO
STOWASSER #1965
(JOHN STAVASH)
WRITTEN G4
PRESSURE AMPLITUDE
INTERNAL SPECTRUM
G4
FFF
MF
PP
1
2
3
4
5
6
PARTIAL

Fig. 1

have strong first and second harmonics, with a fairly weak third harmonic, and very little in the way of higher-frequency components. The top curve in the right-hand part of the figure shows that the measured spectrum agrees very well with expectations based on our formula. When the blowing pressure is reduced enough that the fundamental component of the tone is reduced to 61 percent of its original value, the middle curve on the right side of Figure 1 shows that the second harmonic has fallen to 38 percent of its original strength. This is in almost precise agreement with the $(0.61)^2 = 0.37$ amplitude ratio predicted by our formula. Similarly the third harmonic is found to be reduced to 22 percent of its original amplitude in good agreement with the 23 percent given by the formula. The lowest curve of the righthand diagram shows equally good agreement with theory and serves us as an illustration of the fact that at low playing levels almost nothing remains of the tone beyond the fundamental component.

A convenient method of summarizing the variation with playing level of the sound spectrum within the mouthpiece of a single-reed instrument is to say that for every decibel change (up or down) in the level of the fundamental component we have a two-decibel change in the second harmonic, a three-decibel change in the third harmonic, etc. Figure 2 is based on this method of description of an experiment done on a clarinet.

Tape-recorded diminuendos and crescendos were analyzed by techniques similar to those used to get data for the righthand side of Figure 1. Measurements on successive crescendo-decrescendo sequences and measurements made on successive days proved to be extremely stable (within a decibel at corresponding dynamic levels). In Figure 2 we should take notice of a slanting line labeled P_1 which is devoid of data points and runs upward diagonally across the graph. This line represents (trivially) the dB change in the strength of the fundamental as referred to itself. Next on the right is a broken line with data points on it, labeled P_3. These points refer to



MAX. PLAYABLE
P1
CHANGE OF FEEL
P3
P5
P7
P9
P11
B♭ CLARINET (AHB ···659·)
REED - F. COHEN
PLAYER - AHB
C (233.1 Hz)
INTERNAL SPECTRUM
MIN. MEASUREABLE
Pm (DECIBELS)
P1 (DECIBELS)
0
10
20
30
40
50

Fig. 2

measurements of the third harmonic component of the tone. The line itself is drawn so as to slope upward at the theoretically predicted rate of 3 dB for every dB increase in the strength of the fundamental. Notice that the measured points lie almost precisely on the line up to a point marked "change of feel". Other lines rising at the rate of 5, 7, and 9 dB per dB are also shown along with data points marked P_5, P_7, and P_9 to show further evidence of the correctness of our formula.

I wish to emphasize that this formula comes directly from a mathematical analysis of the general behavior of an air column controlling a reed, and it has no "adjustable" features that could modify the predicted behavior we are studying. I have observed behavior in agreement with the formula not only for the clarinet and the tarogato but also for the trumpet and (under certain conditions) for the saxophone and the bassoon. The oboe shows entirely different behavior, as does the bassoon most of the time, along with the saxophone sometimes and even the clarinet, as we shall see.

C. The beating reed and its spectrum

I have gone to great pains here to demonstrate the straightforward and systematic behavior of most of the orchestral wind instruments as it concerns the change of sound spectrum measured within the mouthpiece. I have at the same time implied that, under certain conditions, the sound recipe of a wind instrument shows a different behavior. Let us turn out attention to the vertical line marked "change of feel" in Figure 2 as out introduction to what is going on.

When one plays softly on a single-reed instrument, the reed vibrates smoothly back and forth, opening and closing the aperture at its tip in the manner we discussed in Lecture I. As a crescendo develops, however, the amplitude of the reed motion grows until finally the tip of the reed actually strikes the tip of the mouthpiece and momentarily shuts off the air flow once in each cycle of its oscillation. If one blows harder and harder to further develop the crescendo, the reed spends an increasingly large portion of its time pressed against the facing. The air flow thus takes on more and more of the character of a series of abrupt puffs and less the character of a smoothly increasing and decreasing flow. The player can readily detect the instant in a crescendo when the reed begins to beat: not only does the reed "feel different" to his embouchure but also the sound he hears becomes distinctly different. This point is what is marked on the diagram, and it is clear from the altered trend of the data points that the entire behavior of the sound recipe changes once the playing level gets above this critical value.

Anyone else in the room can also hear the change of tone color that occurs when the reed first begins to "beat". The individual tapping noises from the reed's collision with the mouthpiece are readily heard when low notes on a bass clarinet are loudly played, as they are much of the time in the normal use of the saxophone. The bassoon also provides us a good illustration of the same effect produced by the beating together of the two parts of its reed. The oboe shows the same behavior, as does the clarinet, but here the tappings are not easily recognized for what they are until one knows what is going on.

There has been much controversy over many years as to whether the clarinet reed actually closes the mouthpiece tip or not. We can very easily resolve the controversy and also understand its origin. Particularly in German-speaking countries for many years it was customary to play the clarinet with reeds and mouthpieces proportioned so that in ordinary performance the reed never closed completely. It was considered bad technique to allow the characteristic sound of a beating reed to be heard (except perhaps under the most demanding circumstances of rapid playing at a high dynamic level).

In France, on the other hand, it has been customary to use reeds and mouthpieces designed to be used with a playing style that calls for the reed to beat almost continually. The tradition in other countries tends to lie between these two extremes, and the pervasiveness of the extreme forms in Germany and France is becoming progressively less. In general, musicians are tending toward equipment and playing techniques that permit them to vary their tone color across the range permitted by more or less vigorously beating reeds, and they can do this at nearly all dynamic levels. On the experimental side we can now readily understand how an observer will find one or another type of behavior, depending on the accidents of his country and the instrument he chooses to study. He can make very positive statements because he has never seen the full variety of behavior.

It is possible to give a rather general summary of the systematic behavior of the sound recipe generated by a <u>fully beating reed</u> to supplement the formula given earlier for the <u>non-beating reed</u>. One learns from the heart of vibration physics that regardless of any details of the excitation mechanism, if a reed permits air to flow through it for precisely 1/4th of the time of each cycle, then harmonics 4, 8, 12, 16, ... will be almost completely missing from the recipe. Similarly if the fractional time of flow is 1/6th, then harmonics 6, 12, 18, ... will be very weak, and so on. We learn also that the components lying most nearly at the midpoints between the zeros in the harmonic series will tend to be fairly strong. Furthermore, if the reed pops open for a time that is almost <u>but not quite</u> a simple fraction of the time of one cycle, then the corresponding components will be weak, though not quite as weak as before. All this comes from the mere existence of complete closure during part of the reed's cycle. The rest of the behavior of the recipe will depend more or less as before on the nature of the air-column response curve and thence on the detailed way in which the air flow grows and shrinks during each period when the reed is open.

Figure 3 shows a rather spectacular example of the sound spectrum produced by a strongly beating saxophone reed.

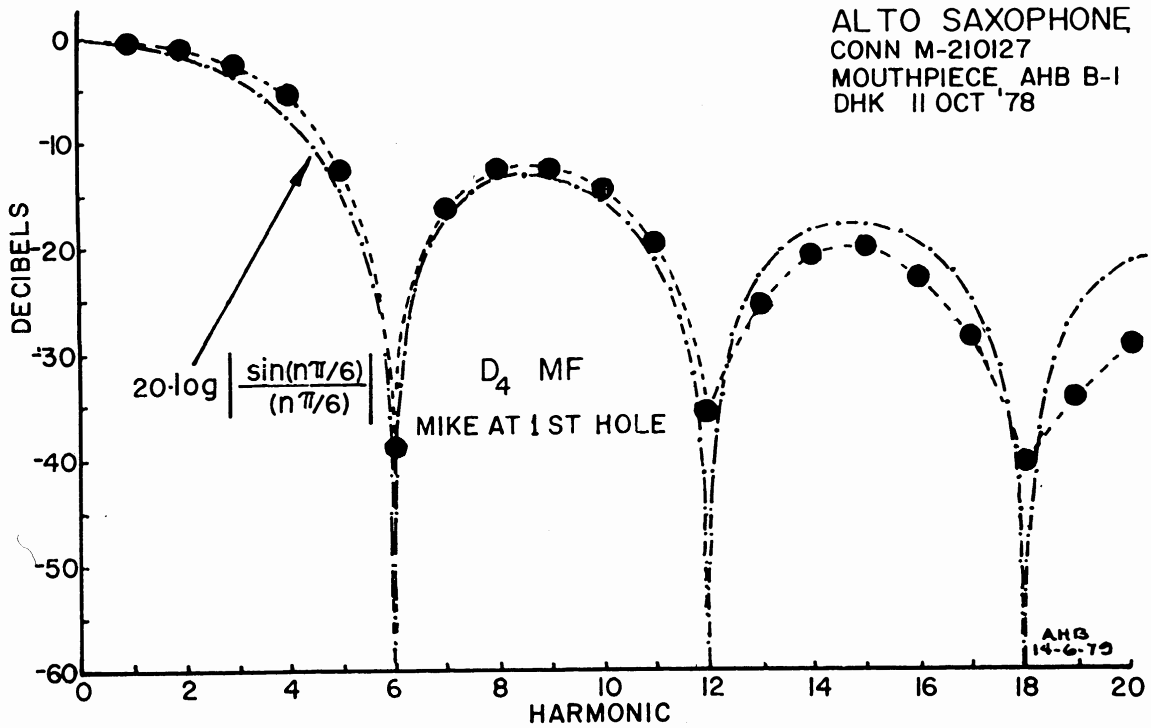


Fig. 3

By pure chance, the reed and mouthpiece profiles and the manner of blowing produced a valving action in which air could flow through the reed for exactly 1/6th of the time of each repetition, hence the weakness of components 6, 12, 18 ... in the recipe. Closer analysis shows that these components would be exactly zero except for the fact that the individual puffs of air do not begin and end in a precisely symmetrical fashion.

I should comment here that much of the formant structure traditionally attributed to woodwind spectra (to the extent that the measurements are correct at all) is in fact due to the rise and fall of the spectrum envelope produced by the beating reed. We recall that the strict usage of the word formant refers to the enhancement of certain portions of a sound spectrum that is associated with more or less invariable resonance or radiation maxima in the air column. It is worthwhile to look forward here to one of the conclusions we will reach in the course of this lecture. There is in fact almost no simple formant behavior to be recognized in the sound production of wind instruments.

D. Radiation behavior of tone holes and bells; the cutoff frequency

We are at last in a position to discuss the emission of sound from a musical air column. So far we have dealt exclusively with sound-pressure recipes of the sort that are measured within the mouthpiece, that is, at the very spot where the acoustic pressure variations of the air column carry out the job of instructing the reed about its duties as a valve. One way or another the sound produced within the air column communicates itself to the outside air, the relative strengths of the various components being modified along the way. We will refer to the description of this "outside" sound as the external spectrum to distinguish it from the internal spectrum measured within the mouthpiece. This of course implies the existence of some kind of spectrum transformation function which converts the internal spectrum to its external counterpart.

Theory and experiment agree that a long row of open tone holes spaced along the lower end of a tube (as at the lower end of a woodwind) is a very ineffective emitter of low-frequency sound. As a matter of fact, such sounds traveling down the tube toward the row of holes are almost totally reflected back, with only a minute fraction being able to leak out into the room. At somewhat higher frequencies, a somewhat greater fraction of the sound is radiated from the holes and (as a result) less is reflected back toward the source.

Suppose we carry out an experiment that measures the efficacy with which a row of holes emits sound into the room and measures also the remaining fraction of the sound that is reflected back up the tube. Beginning at low frequencies the radiation efficiency rises steadily to a certain sharply marked frequency (which we will for various reasons call the cutoff frequency f_c), above which very nearly all of the sound is emitted and essentially none is reflected. Similar experiments with a trumpet or trombone bell attached to the lower end of a long, cylindrical pipe show very similar results: weak emission and strong reflection at low frequencies; increased emission and reduced reflection as the frequency is raised toward a clearly definable cutoff frequency; and above this cutoff frequency, almost complete emission and negligible reflection. We can immediately surmise from these pieces of information that the spectrum transformation function rises steadily from a very small value at low frequencies to near unity at a cutoff frequency determined by the proportions of the open holes or of the bell. Let me put this another way: only a small fraction of the fundamental component generated within the mouthpiece of a musical instrument finds its way out into the room, a slightly greater fraction (whatever its internal strength may be) of the second harmonic is observable in the external spectrum, and so on. Components of the tone that are generated above the open tone-holes (or bell) cutoff frequency are strongly emitted into the room. An audio engineer might say that the tone-hole or bell-radiation device serves like a treble boost tone control. It has a rising characteristic to f_c and is flat thereafter.

In principle we know, by now, how to give a good approximation to the internal spectrum of a wind instrument played softly, fairly loudly, and very loudly. We have also just learned how, in principle, to convert the internal spectrum to the external one by use of our newly met transformation function. There is, however, a very interesting additional feature of the radiation behavior of a row of tone holes that must carry us back to the nature of the internal spectrum before we can take up several rather remarkable features of what the musician calls the tone color of a woodwind

Let us review for a moment. The player supplies a steady flow of air which is converted into a regular series of puffs by the back-and-forth motion of the reed. These puffs travel down the air column to the tone holes or bell, where they are modified because of the complicated way in which the radiation/reflection process takes place. The modified reflected puff comes back to push the reed open, thus starting the next round of the cycle. We know that this sequence of puffs is built up of the various harmonic components of the tone, and so we realize that the cooperative effects we studied in the first lecture can be thought of as being dependent on the strength and the timing of the return to the reed of each component from its round trip to the tone holes at the lower end of the instrument.

Because of the weak radiation of the fundamental component of the tone, it is strongly reflected and comes back to give the reed vigorous instructions on how to breed more of its kind. The second harmonic returns less strongly, and so breeds its replacement less successfully at the reed. Continuing this line of thought shows that any components that happen to be produced by the reed above the tone-hole cutoff frequency simply run down the bore and escape! They do not return to breed, and so to strengthen their tribe. All this can be summarized in very few words: the reed and air column do not directly collaborate to produce oscillatory energy above the cutoff frequency. Furthermore, low-frequency components are strongly regenerated, while higher components that lie below f_c are less strongly produced. All this we have already expressed in terms of the tallness of the air-column response curve peaks. Strongly reflected sounds are associated with tall peaks and so with strong <u>generation</u> of these components. Weak reflections give rise to less tall response peaks, and to weakly generated components of the tone. Above f_c there is essentially no reflection, and whatever is generated by the reed comes about as the result of all sorts of small-scale and one might say left-handed processes not otherwise associated with the main business of tone production.

Figure 4 contrasts the measured air-column response curve of a piece of clarinet tubing taken by itself and the curve obtained when the lower end is provided with an extension piece carrying a long row of open holes.

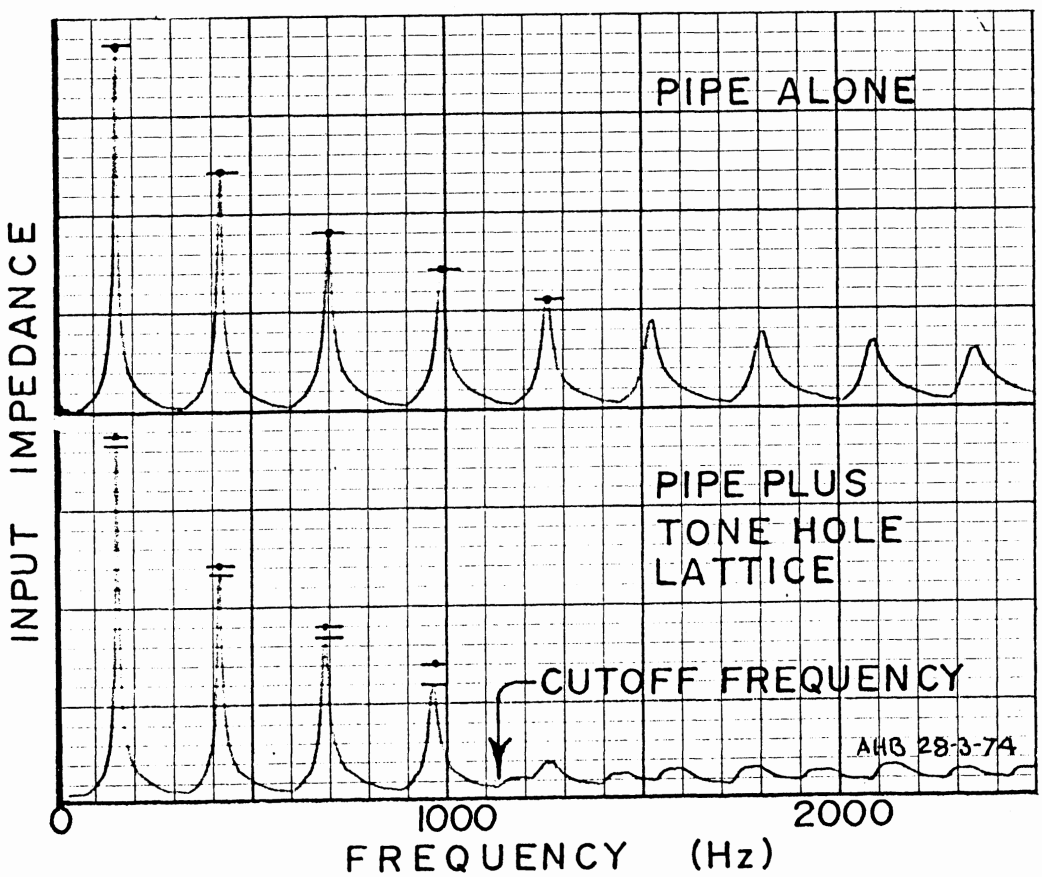


Fig. 4

The upper part of the figure shows a progression of equally spaced response peaks whose tallness falls away gradually because of the increasing frictional attenuation of the high-frequency waves. The lower figure shows that the tallness of the response peaks fall away more quickly in a pipe with tone holes and that above the cutoff frequency f_c there are essentially no response peaks. This is particularly clearcut laboratory example of the behavior you have already seen in Figures 8 and 10 of Lecture I and Figure 1 of Lecture II.

E. Tone-color implications of the cutoff frequency

We seem to have run into a kind of trap in our discussion of the sound spectra of woodwinds. Because of the behavior of reeds and tone holes we have deduced that components that are strongly produced within the instrument are weakly radiated. Similarly, the weakly produced components are strongly radiated. This seems at first to imply that the external spectrum of all woodwinds should be similar, because the effects of radiation and production efficiency will roughly counterbalance one another! To a first approximation, at least within the confines of a single family of woodwinds, this sameness of the measured external spectrum appears to be confirmed by laboratory measurement. However, I am about to describe to you evidence that shows that the musical ear (player and listener) is in fact extremely sensitive to effects associated with small changes in the cutoff frequency f_c.

Before going further let us glance a moment at how we can reconcile these apparently contradictory remarks. To begin with, data available so far on the external spectra have shown no sign of the effect of f_c. We must recognize however that this in itself proves very little because scientists who set out to measure external spectra have over the years paid almost no attention to the phenomena of sound propagation in the room or have misapplied its guidance. Secondly they have almost always neglected to take into account certain features of the radiation process (which we will not take up until Lecture III) whose existence and general nature has been at least talked about for nearly a century. Finally in this litany of inadequate performance, the scientist has not been sufficiently careful about specifying what he wants his player to do--he has not bothered to speak to him in musically intelligible terms and has not called on him to do things that are a part of the musician's professional skill. As a result, even cursory examination of published sound spectra show almost no agreement among observers or even between repetitions of the same test. To make matters worse, in most cases the musician has been blamed for his inability to hold a steady note or to repeat a set of tones one day after another.

While I am being extremely critical here of my fellow scientists, I should confess that until very recently, my awareness of what needed to be done was not matched by a knowledge of how to do it. As a result, caution and perhaps cowardice have kept me (till now) from even attempting to measure anything other than internal spectra, for which it is less difficult to obtain repeatable data.

I will now make a three-part assertion about the great musical significance of the tone-hole cutoff frequency and provide illustrations of their correctness and usefulness.

1. Other things being equal, on a properly aligned woodwind, lower tone-hole cutoff frequency is associated with darker tone color.
2. A considerable part of the characteristic sound of an instrument is determined by its tone-hole cutoff frequency.
3. Recognized similarities in the sounds of different types of instrument are often associated with the similarity of their tone-hole cutoff frequencies.

Figure 5 shows the air-column response curves measured on a specially constructed laboratory clarinet which will serve as a good introduction to our exploration of the relation between tone color and f_c.

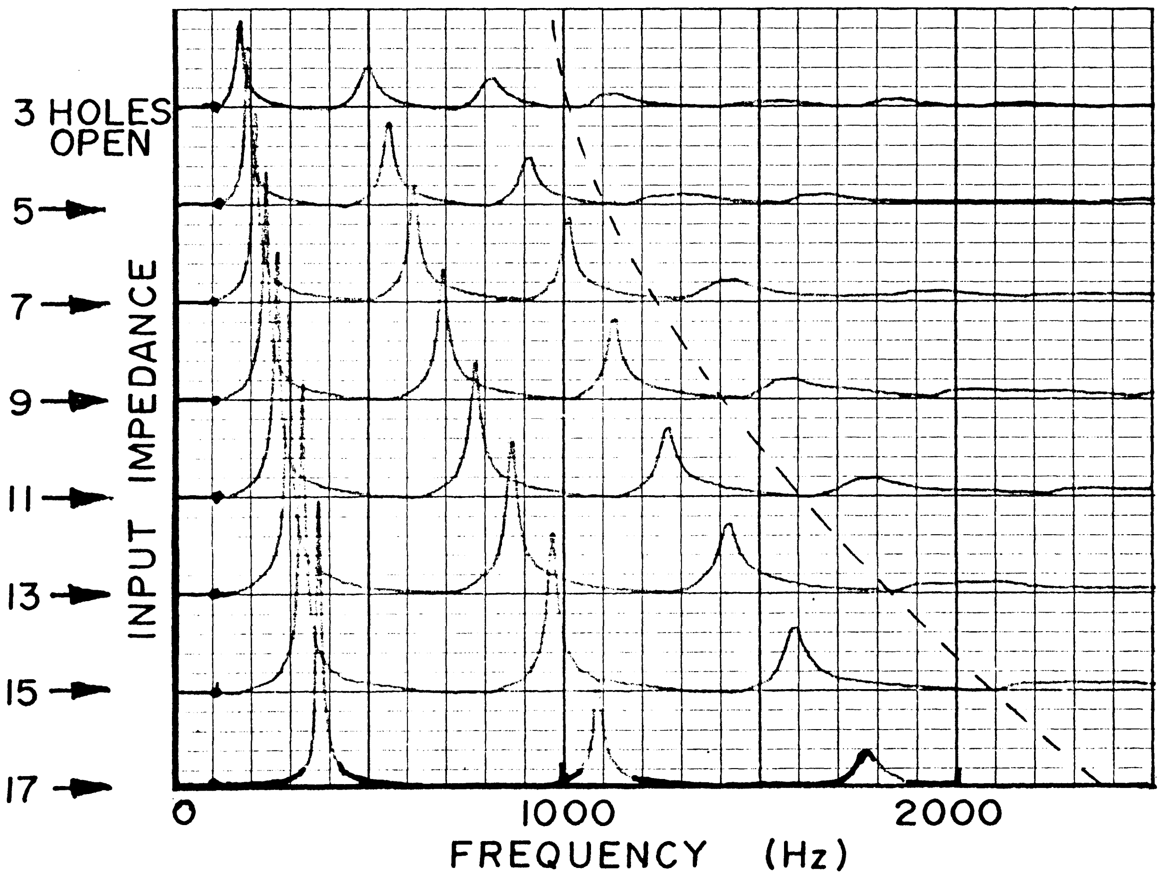


Fig. 5

The top curve shows the response curve for the tube when nearly all the holes are closed, so that it would sound one of the lower notes of its chalumeau register range. The successive curves traced below this one show the pattern of peaks and dips for the air column used in playing higher notes in the low-register scale, these notes being obtained by successively opening more tone holes.

Notice that the clarinet has been designed so that for each note there are fairly strong response peaks that can work together with the reed to produce the sound. A curving line down across the diagram shows for each curve the location of the cutoff frequency designed for that note. Above this line there are only weak, residual peaks and dips that do not play an active role in the oscillation.

A physicist looking at these response curves would at once recognize the reason why this instrument was named the isospectrum clarinet by its maker. Every note has essentially the same pattern of response peaks and dips as every other, and I should emphasize that the "alignment" of the response peaks for each note was carried out with great care to assure the best possible cooperations. According to what we have learned in part A of this lecture, the great similarity of air-column response pattern between notes will lead to the production (under any given conditions of blowing) of tones having different fundamental frequencies but with almost identical relationships between the strengths of the components of each of the various tones. Experiment shows that the designer's expectations are in fact borne out so far as the physical spectrum is concerned. Experiment shows further, however, that a musical listener invariably will describe the low notes of a chromatic scale of the chalumeau register of this instrument to be much darker than those of a normal clarinet, while the high notes are described as much brighter. In the neighborhood of C_4, however, the isospectrum clarinet has the familiar sound of a good conventional clarinet. I should tell you that the tone-hole cutoff frequency of the isospectrum clarinet was designed to match that of a normal B♭ instrument at the written note C_4 (in round numbers 1600 Hz). We will learn that f_c is roughly constant over the whole chalumeau register of a normal clarinet. On the isospectrum clarinet, f_c is therefore lower than normal at the low end of its scale and higher than normal at the top.

Sound example 5 on the record shows the auditory effects produced by the isospectrum clarinet and contrasts them with the behavior of a normal instrument. While it does not appear on the demonstration record, I can tell you that direct comparison of the new clarinet's lowest notes with those of similar pitch on an E♭ alto clarinet, or a comparison of its notes an octave higher (say E_4 to G_4) with those on an E♭ soprano instrument, show remarkable similarities. This is because the cutoff frequencies of these notes of the isospectrum clarinet closely match the cutoffs of these normal instruments.

The experiments described so far have all had to do with playing in the low register of an instrument. However, the second register of a woodwind is also played using the same set of tone holes (in conjunction of course with a register hole). Any tone-color effects associated with f_c in the low register will therefore have their second-register counterparts, as we will verify in the following paragraphs.

F. Experiments with two clarinets

Some years ago I took a pair of good quality B♭ clarinets and reworked their bores and tone holes in such a way that f_c of all the notes on one instrument was lowered by about 2 percent, while the other instrument was modified so that f_c was raised by a similar amount. Such modifications were a subtle business, since I wished to preserve their original good tuning and to arrange their inter-resonance alignments for best responsiveness. Playing rests agreed with laboratory measurements to show that by any standard the two clarinets were of top-flight artist grade. As a matter of fact, they have been borrowed from time to time by professional players wishing to exploit their especial virtues in public performance.

Having told you what fine instruments they are as individuals (they can also be played in duets with ease and comfort), it is time to describe the reactions of everyone who has heard them and everyone who has played them. Players with a primary interest in classical music--those who consider Mozart, Brahms, Schubert, Hindemith, or Bartok as their musical bread and butter--will invariably choose the lower-f_c instrument. While they admire its responsiveness and excellent tuning (features expected of any fine instrument), they are particularly taken with its dark, smooth tone--"almost like an A clarinet". These same players (or listeners) reject the raised-f_c instrument entirely, and frequently with considerable scorn. They claim it is too shrill, despite the fact that when pressed they agree that it is just as responsive and well tuned as its darker mate. One of my jazz-player friends, on the other hand, spoke about the low-f_c instrument: "You have a failure here--it has no tone, it is dead." He became very excited, on the other hand, about the raised-f_c instrument. He praised its bright, clear tone and insisted on taking it with him for that night's job and those in the succeeding week. When individuals of the two persuasions together confront both instruments, each confesses himself baffled by the other one's preferences, even when each is happy to acknowledge his friend's professional expertise!

We have here a spectacular example of the meaning of my remarks at the beginning of Lecture I about "suitable tone color". The classical player in America tends to want an instrument that is slightly darker-toned than he can readily obtain on the commercial market, but in a pinch he will accept his jazz-playing friend's brighter instrument on loan if his own instrument is in for repairs. In exactly similar fashion the jazz player wants a slightly brighter clarinet than he can buy, but will borrow a classically voiced instrument if he must. My two clarinets are, on the other hand, different enough that while each has its enthusiastic supporters, members of the opposite camp find them too different to be acceptable (even as musical instruments at all!).

G. Cutoff frequency influences on orchestral instruments

Having met two illustrations of the empirical relevance of the tone-hole cutoff frequency to the tone color of woodwinds, we can usefully look over the measured values of f_c over the scales of historically representative members of the clarinet, oboe, and bassoon families. Figure 6 shows such data for a number of clarinets.

A quick look at the plotted curves taken as a group shows that f_c falls only slightly in going from the top to the bottom of the range of tone

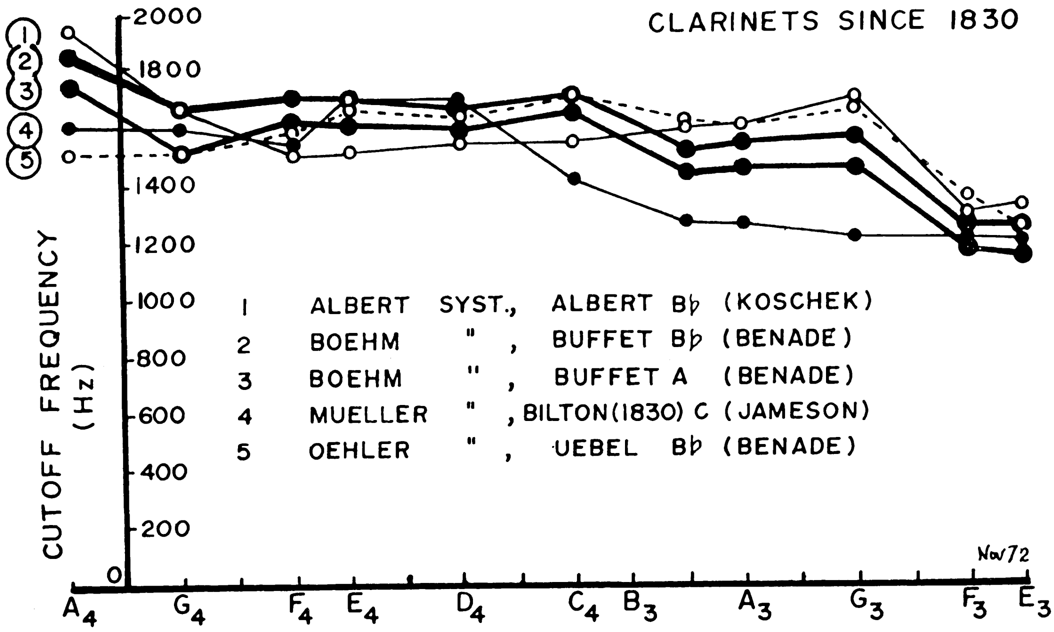


Fig. 6

holes. The upper heavy line (marked 2 on the diagram) is typical of modern Boehm-system B♭ clarinets. We can use this as our point of departure for our study of the other instruments presented here. For example, the lower heavy curve (no. 3) shows the trend of f_c for the matching Boehm-system A clarinet. Notice how parallel these two trend lines are, reflecting the fact that both instruments are of the same design.

Since f_c differs by about 6 percent between these two instruments, we can get a measure of the listener's sensitivity to small changes: my two modified clarinets each differ from the normal B♭ instrument by about one-third of the f_c difference between a normal B♭ and an A. Comparison of the raised, normal, and lowered f_c B♭ clarinets is readily done by playing before even a relatively inexperienced audience, with most of it able to place the instruments in correct order.

One of the clarinets shown in Figure 6 is a beautifully made and well-preserved C clarinet from Beethoven's time (no. 4). From the point of view of a player, the tone color of the upper-joint notes is found by actual trial to match a modern B♭ very well, whereas all but the bottom two of the lower-joint notes are distinctly darker even than today's A clarinet. Notice that these observations are entirely consistent with the trend of f_c for this instrument: "a member of the crowd" for the notes fingered in the left hand, and very low for the fingerings corresponding to the notes from C_4 down to $F_3\#$. We understand from this why it has become customary in today's orchestra to play classical C-clarinet parts on a B♭ instrument. We understand it even better when we recall that today's Boehm C clarinet ($f_c \simeq 1800$ Hz) is entirely too shrill for normal use. I have myself done major surgery on such an instrument and succeeded in combining excellent response and tuning with a greatly reduced f_c (close to 1700 Hz). The instrument has now lost the shrillness that is typical of its breed and has become a very pleasant instrument to play, but it is still too bright for acceptable performance of classical clarinet music.

We turn now to a glance at the oboe family, as presented in Figure 7. As

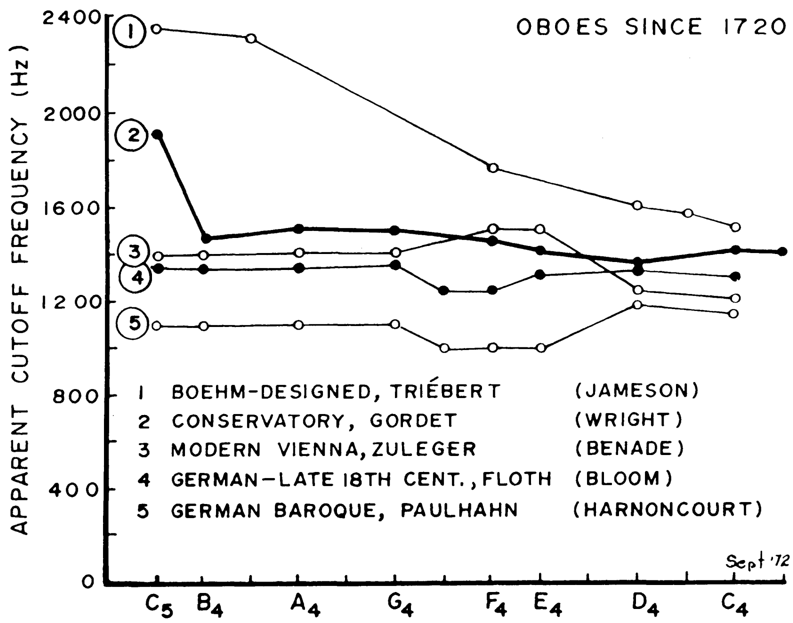


Fig. 7

before, a heavy line indicates the properties of our most familiar instrument, the Conservatory oboe. All instruments made today match this pattern extremely closely--recall the turmoil caused in the clarinet world by an unfamiliar 2 percent shift in f_c! We need only to point out that f_c is extremely constant across the entire scale, except at the fingering labeled C_5. It is well known that this C and its upper octave tend to be harsh and wild, and here we see the reason. I hasten to add that Triebert and his successors had very good reasons for permitting this anomaly and there would be many complaints from performers about the playability of the instrument if it were thoughtlessly regularized here.

The highest curve (no. 1) on Figure 7 is of an instrument made by Triebert himself to a design worked out by Theobald Boehm. Despite the fact that this oboe plays with a well-centered beautifully responsive tone and has very accurate tuning, it is musically useless. The tone is hopelessly bright and harsh, particularly in the upper-joint notes. Once again, the position and trend of our f_c line correlates exceedingly well with the musical attributes of the instrument. Despite the expert efforts of two of the best nineteenth-century craftsmen, this instrument fails because it does not include acceptable tone color among its many virtues.

The bottom line (no. 5) of data on Figure 7 is of particular interest to us for the light it casts on Assertion 3 about the effects of f_c on the identification of instruments. This curve shows the typical variation of f_c over the scale of Baroque instruments. We pause long enough to notice that in round numbers the characteristic value of f_c is 1100 Hz. I will also tell you that the modern English horn has a curve like that of today's oboe, except that it is moved down to lie close to 1100 Hz. No wonder that many people feel that the tone of a Baroque oboe is reminiscent of an English horn!

By the way, it is often said (I have written to this effect myself!) that the characteristic vowel sound ("aw") of an English horn is caused by the formant behavior of its pear-shaped bell. This is false for three reasons: (a) the bell on the instrument shows no formant behavior; (b) the spoken sound "aw" is associated with the position and strength of at least two, and better, three formants; and (c) replacement of the bell by a tubular extension with holes designed to give an 1100-Hz cutoff leaves the instrument with its characteristic voice unimpaired.

Before we leave the oboes I wish to hark back to my introductory remarks on the tarogato in section B of this lecture. There I said that the tone color of the instrument was reminiscent of the English horn. I also pointed out in connection with Figure 1 (without using these precise words) that the tarogato's f_c is close to 1100 Hz. By now the connection should be obvious--our ears have become familiar with a certain kind of sound by listening to the English horn.

The final set of data on cutoff frequencies applies to the family of bassoons. This is displayed in <u>Figure 8.</u>

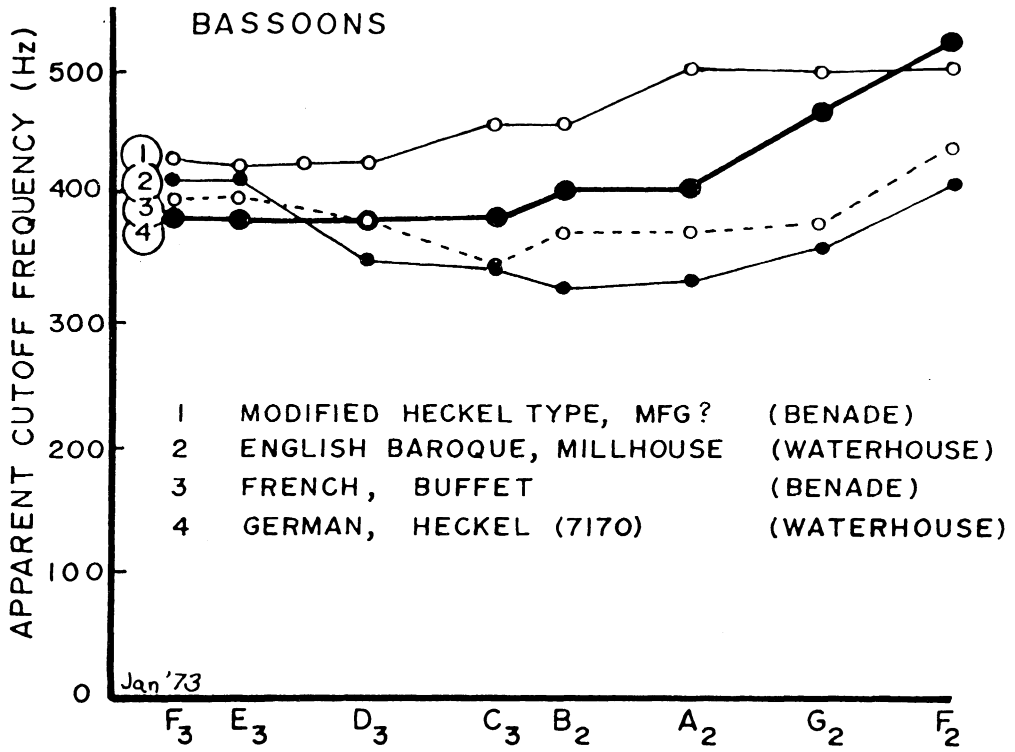


Fig. 8

As before, the familiar instrument, an excellent Heckel, is shown by means of a heavy line (no. 4). We notice that overall the cutoff frequencies of a modern French bassoon lie distinctly below those of its German counterpart, but not as low as its Baroque predecessor.
Curve 1, which refers to an instrument of the German type that I have modified somewhat, illustrates a very interesting point. Taken at face value, we would expect this instrument to have a somewhat brighter and more open sound than the other instruments--perhaps even to the point of musical unacceptability. When the modification process was first begun, the tone color was indeed on the bright side. Once the cooperating resonances of the air column had been worked into excellent alignment, however, the response became smoother and the sound lost the small coughs and croaks that are a familiar part of most bassoon sounds. People no longer feel that this instrument is excessively bright. It is in general important to note that whenever an instrument is carefully aligned, this smoothing-out takes place and the listener tends to describe the sound as becoming darker. Thus we have an additional way (to say nothing of effects having to do with reed and mouthpiece design) in which the tone of an instrument may be darkened, in this case without modifying its cutoff frequency.

I wish to emphasize in closing this part of the lecture that in all cases the carrying power of an instrument is increased when its cooperative effects are increased to the maximum extent. Once this has been done, the carrying power is essentially independent of the tone-color changes produced by altering the value of f_c. A harsh, bright instrument does not necessarily carry better than a dark-toned one.

H. A glance at the flute

Toward the beginning of Lecture I (sections B and C) I was very cavalier in passing over the flute with a remark that its oscillations are sustained with the help of a velocity-operated flow controller (in contrast to the pressure-operated controllers of reed woodwinds and brass instruments). I also promised that essentially everything about flutes can be obtained by simple modifications of the ideas that have already been discussed. Here at the end of Lecture II is the place where this promise should be made good.

The easy way to begin thinking about the flute's flow controller is to follow Helmholtz in calling it an air reed (this name is much more correct than was recognized for about 95 years!). Visualizing the action of an air reed begins with a trip into the garden. Suppose you are watering the flowers by means of a stream of water from a hose. If there is no wind, the water is projected directly along the direction of the nozzle. If the wind blows to the left, the stream of water is deflected to the left, and if it blows to the right, the water strikes the ground on a spot that is on the right-hand side of the place where the undisturbed jet would arrive. It goes without saying that the stronger the wind, the more the water jet is deflected.

Suppose we now replace the water jet by a jet of air directed by a flutist across the open neck of a bottle in such a way that it produces a hooting sound. The air in the neck of the bottle is so-to-speak bouncing up and down on the elasticity of the air contained within the bottle. This bouncing of the air in the neck is merely another way of saying that there is an oscillatory flow (a wind!) blowing in and out of the neck. This vertically moving oscillatory wind acting on the player's horizontal air jet deflects part of it alternately into the bottle and away from it into the room. Notice that the player's deflected ("steered") air jet always acts to augment the oscillatory flow belonging to the air column. It is this fact that enables the tone to be maintained.

The tones of a flute are generated by the deflection of the flow from the player in an amount proportional to the oscillatory velocity of the air blowing in and out of the embouchure hole. We can readily see that cooperative effects between various modes of air-column motion can stabilize and strengthen the oscillation process in ways that are exactly analogous to those found in the reed woodwinds and the brasses. The analogy can be extended somewhat farther when we learn that the player's adjustments to the angle of approach, the speed, and the dimensions of his air jet have consequences that prove to be closely similar to the reed players' games with reed profile, mouthpiece facing, and the natural frequency of the reed.

I have made a number of very rude remarks before about my fellow scientists, and unfortunately I must make yet another. There is a very commonly observed and scientifically interesting phenomenon called the edge tone. Generations of scientists have tried to force the flute's oscillatory action into the mold of the edge tone. This is wrong, in that the predictions of edge-tone theory are totally at variance with the daily experience of every flute player. For example, at normal blowing pressures the edge-tone frequencies for a flute are some ten to twenty times higher than the actual playing frequencies! It has been half a century since definitive experiments were carried out to confront the basic edge-tone and air-reed mechanisms with the facts of pipe-organ and flute tone production, but only in the last half dozen years has any sort of correct theory been developed for the flute family.

Let us take over the air-column characterization methods described in section D of Lecture I and adapt them to usefulness in the study of flutes. I dare not invest the extra half-dozen pages that it would take to do this properly, but perhaps we can get enough of an idea of what goes on that we can usefully proceed. Look back at Figure 2 of Lecture I and notice that when water sloshes back and forth in a duct, there are places of maximum depth variation between which there are regions where the water flows back and forth vigorously as it rushes to deplete the region on one side so as to fill up on the other. Figure 3 in the same lecture led us to recognize that what eventually became a pressure-operated valve must be located at a point in the duct where the pressure variations are a maximum. I am sure that you recognize that some sort of velocity-sensitive valve could readily be devised for insertion into the water trumpet at a point of large horizontal flow to sustain its oscillation in a new way.

With this informal preamble I hope you are willing to bridge a logical gap with me and simply accept the following assertions:
(a) Just as we found that a pressure-operated flow controller works at the peaks of the air-column response curve, so also do we find that a velocity-operated controller (an air reed) works at the dips of the response curve.
(b) Well-defined regimes of oscillation are set up with an air reed when the response dips are accurately aligned in harmonic sequence. Various good features result from this, exactly as in the cane reed and lip reed cases.
(c) The effects of cutoff frequency on the tone color of flute-type woodwinds are very parallel to those observed for the reed woodwinds.

Let us compare what happens when we replace the pressure-controlled reed and mouthpiece system of a clarinet by a suitably proportioned flute-type head joint. Referring to the upper part of Figure 4 of this lecture, let us imagine that the response peaks of that clarinetlike tube lie at 200, 600, 1000, and 1400 Hz (i.e., in a 1, 3, 5, 7 ... sequence). We already know that, as a clarinet, it will play a 200-Hz low-register note dominated by peak 1, with help from peaks 2, 3, and 4. When sounding in the second register, peak 2 takes charge (taking help from the higher peaks) and generates a tone whose frequency is 600 Hz, a musical twelfth above. All this is familiar--"The clarinet overblows a twelfth." Now put the flute head joint on, instead of the reed and mouthpiece. With this setup, the low register is dominated by dip 1 at 400 Hz (lying between peaks 1 and 2) with good help from the other dips located at 800 Hz (between peaks 2 and 3) and at 1200 Hz (between peaks 3 and 4). Thus the flute's low-register tone sounds an octave above that of a clarinet of the same size. To continue, the flute's second register is fed by dip 2 at 800 Hz and helped by a dip at 1600 Hz. Thus the flute's second register is running at double frequency and so sounds an octave above its own low register--"The flute overblows an octave."

Sound example 6 on the record illustrates all of these phenomena. The first part is there to simply remind you of the pitch, tone color, and overblowing behavior of my clarinet when played with its accustomed reed. The second part is very similar, using a flute-type head joint to replace the reed and mouthpiece. The third part is simply a silly little tune to convince you that my B♭ clarinet has been converted into a true flute simply by changing the type of flow controller at its top end. If you like, try to figure out why the pitch designation "E♭ soprano" is given to the flute incarnation of my instrument.

In closing, I will glance at the question of adjusting flute-type instruments and briefly describe their cutoff frequency behavior. Systematic procedures are known for adjusting flutes of both conical and cylindrical types; I have not only carried these out for numerous preexisting instruments (both old and new) but have also used the procedures as an adjunct to the design and construction of my own instruments. While I have made several excellent Baroque instruments, one that I am most proud of from a scientific point of view is a Boehm-system conical flute whose tone-hole cutoff frequency is chosen to match the normal Baroque value. Aside from its unfamiliar appearance, it is perfectly acceptable in an early-music ensemble, having tone color, response, and dynamic behavior that match its conventional ancestors. To the extent that mechanical couplings permit, it even has preserved many of the older fingerings, which are available for use whenever needed.

LECTURE III. INSTRUMENT SOUND IN A ROOM

At the beginning of Lecture I, I made a very strong point (which was developed throughout that lecture and the next one) that musical instruments produce exceedingly well-defined and stable sounds. I also was at some pains to point out that the path from instrument to ear in a room is a tortuous one, and I ended up with the inconsistent-seeming claim that the perception of musical sound is nevertheless well defined and stable. Evidence in support of this last claim has already begun to appear in sections E, F, and G of Lecture II, which are devoted to the musical implications of the tone-hole cutoff frequency in woodwinds. The present lecture will start by presenting several views of the magnitude of the time, space, and frequency irregularities in the point-to-point transmission of sound in a room, with musical examples given whenever possible. The next part will illustrate the means whereby the auditory system extracts precise and dependable information from the signals that come to it. Finally, I will present numerous anecdotal illustrations of the ways in which these means can influence the performance and recording of music.

A. Steady-state transmission in a room

To reemphasize the principal property of room transmission, let me encapsulate it as a clearly displayed assertion:

SOUND TRANSMISSION IN A ROOM IS EXTREMELY IRREGULAR!

Let us once again turn our attention to the prototype sound transmission experiment that is sketched in the upper part of Figure 4 of Lecture I. In this experiment, a loudspeaker source is placed at one point in a room and a microphone is located at another point. Starting at a low frequency, a sinusoidal signal of constant strength and slowly rising frequency is emitted by the source and a graph is plotted of the strength of the signal measured at the microphone. This is the sort of setup that was used in my laboratory to produce the extremely irregular room-transmission curves shown in the two parts of Figure 1:

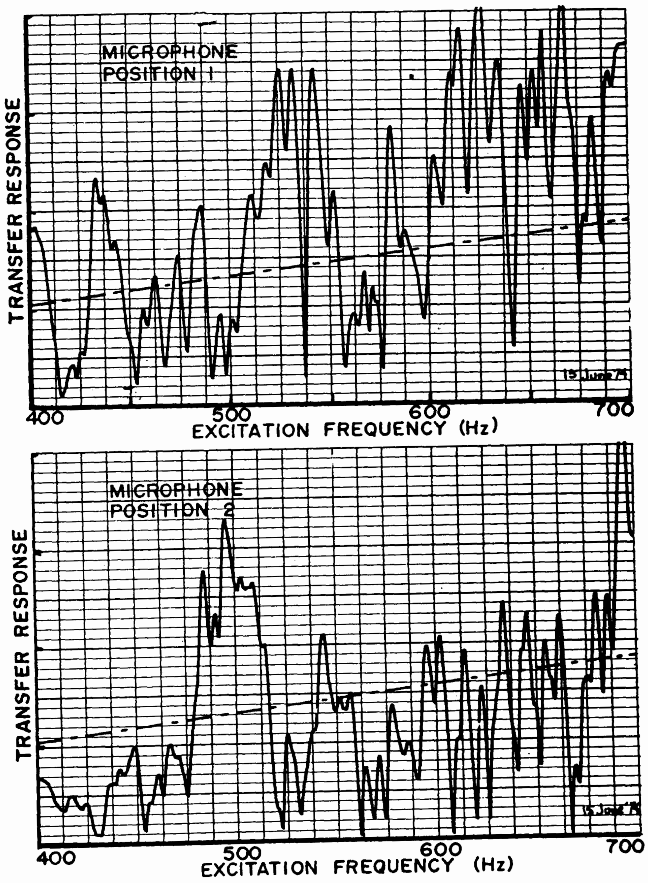


Fig. 1

Notice that the locations of the peaks and dips of response are quite different in the two graphs. The only difference between the experimental conditions for the two is that the microphone position differed somewhat. Already we see evidence of great turmoil in the signal path. As the frequency of a signal is varied, the transmission between two points fluctuates at random as much as thirtyfold! Furthermore, if we move either the source of the microphone, the pattern of irregularity is completely altered. Not only that, if anyone moves in the room, very considerable fluctuations are produced in the transmission even if the source and microphone positions remain fixed and the excitation frequency is left unchanged.

To help us appreciate what this seems to imply for the transmission of a musical sound, imagine for the moment that our source is emitting a sound whose components are all of equal amplitude, having frequencies of 400, 500, 600, and 700 Hz. You can see from the upper picture that the received signal at microphone position 1 has components whose strengths are 18, 8, 16, and 36 units. Similarly, at microphone position 2, the lower picture shows the observed strengths to be 7, 26, 16, and 31 units. No one would be able from such data alone to deduce the true nature of the source.

Suppose, however, that we could afford to have 50 or 100 microphones judiciously scattered about the room, and that we had obtained the transmission response curves for each one of these separately. Would we get any approximation to the true nature of the source by averaging all of the various curves? The answer is yes, if we collect enough data. For instance, we would need about 100 microphones if we wish to be 95 percent confident that the average lies within a few percent of the truth! For the particular source used in my room, the results of such an elaborate averaging procedure would be the sloping dashed line that runs across the middle of each graph. I must confess that I had a direct way to find out this fact, and did not need to actually carry out a very monotonous experiment!

B. Radiation to room from bell or tone holes

What we learn as we look further into how the brass-instrument bell and the woodwind tone-hole systems send their sounds into the room will give us even more reason to appreciate the need for careful averaging of room data. To begin, then, I will tell you that at low frequencies a trumpet bell sends its sounds out equally in all directions. The higher-frequency components of its tone tend to project somewhat more in the forward direction. Once we are above the bell's cutoff frequency (which we learned about in section D of Lecture II) the various components of the emitted sound are transmitted almost entirely in the forward direction. All this means that if we listen to a trumpet player outdoors (or in an absolutely echo-free room), standing behind him gives us an impression that lacks the high-frequency components of his tone; if we stand directly in front, the brassy blare that we hear is almost uncomfortably over-supplied with the higher components; listening from the side gives us a different but still unsatisfactory "view" of the sound. Put this another way: a tape recording made with the microphone in any one of these places will give a most unsatisfactory and implausible-sounding representation of the music and its player (remember, this is all being done in an echo-free environment!).

We can usefully extend our understanding of directional effects from a bell as they take place in a room by considering a certain experiment that we carried out two years ago. The origin of the experiment was my desire to find a simple way to circumvent the need for extensive room averaging when one desires to measure the sound output of a trumpet bell. The idea was to place a microphone directly outside of and very close to the bell so that, in a manner of speaking, all the sound would have to pass the microphone before it spread in complicated ways throughout the room. However, I expected at least some residue of the directional effects to remain, so that measurements were planned that would provide once and for all, a "calibration curve" relating what the bell microphone "heard" to what one obtains with a properly averaged set of microphones distributed throughout the room. The apparatus was set up as follows. A trumpet bell was used to replace the normal horn of a public-address system loudspeaker, which in turn was driven by the same electronic oscillator-amplifier apparatus that was used in the room-excitation experiments discussed earlier. One microphone was placed in the bell and a number of other ones were distributed about the room. In order to simplify the analysis of the data, the bell microphone was connected to an automatic circuit that would feed the loudspeaker with exactly the right amount of power that would maintain the signal constant at the bell microphone. This arrangement got rid of the complications of sound transmission through the bell itself. If now the bell microphone were a true measure of the sound in the room, the room microphones would produce a constant average-value signal as the frequency was varied from low to high. Similarly, any trend upward or downward in the frequency behavior of the room microphone data would be interpretable in terms of the angular distribution of sound from the bell. Figure 2 shows the result of this experiment.

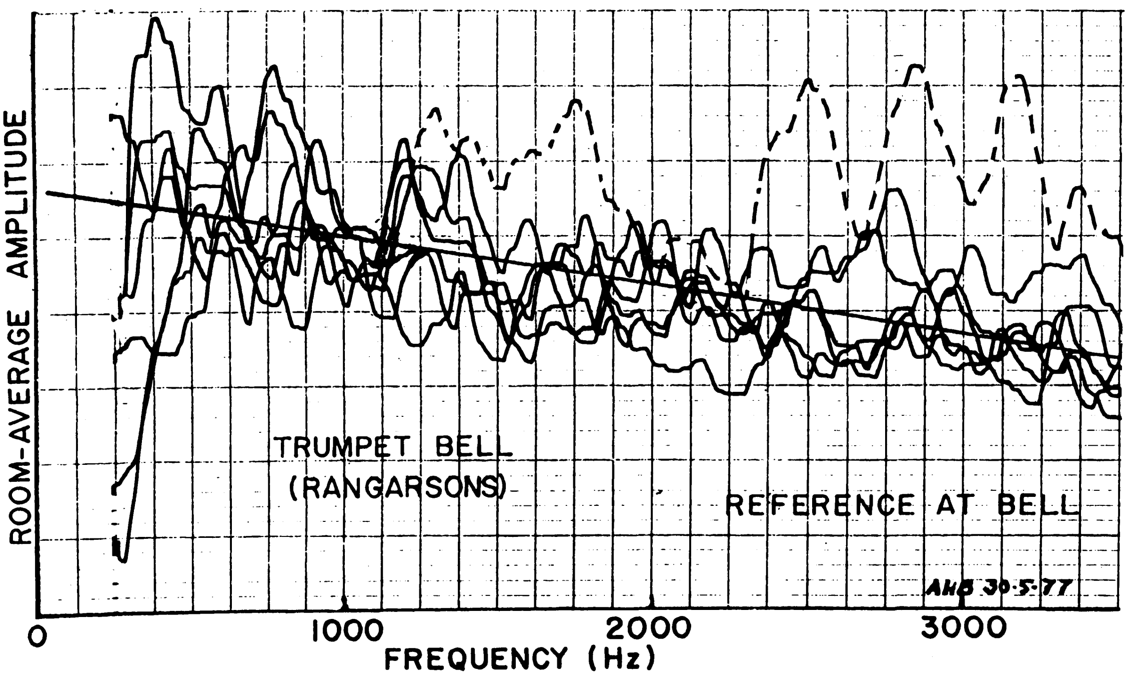


Fig. 2

Ignore the dotted curve, which has to do with an auxiliary test experiment, and pay attention to what goes on above 300 Hz, where the automatic control mechanism took hold firmly. Each of the wiggly curves shows the fluctuating signal received at one of the room microphone positions. The wiggliness of these curves is somewhat less than those of Figure 1 because the recording technique permitted me to "average out" the fluctuations to some degree by walking around the room during the slow sweep across the frequency range. Nevertheless, the variability of the data presented by each curve is sufficient to make clear the need for averaging several such traces. The sloping solid line drawn through the data shows such an average. The nature of this gently sloping line can be analyzed to show that the bell microphone does a pretty good job as a replacement for the room-averaging procedure, except that it tends to smoothly and continuously overestimate the strengths of the higher-frequency components.

A closely related experiment was carried out at the same time using a pipe provided with a row of tone holes as a replacement for the trumpet bell. The controlling microphone was placed this time immediately outside the tone hole closest to the driver. Figure 3 shows the data from this experiment.

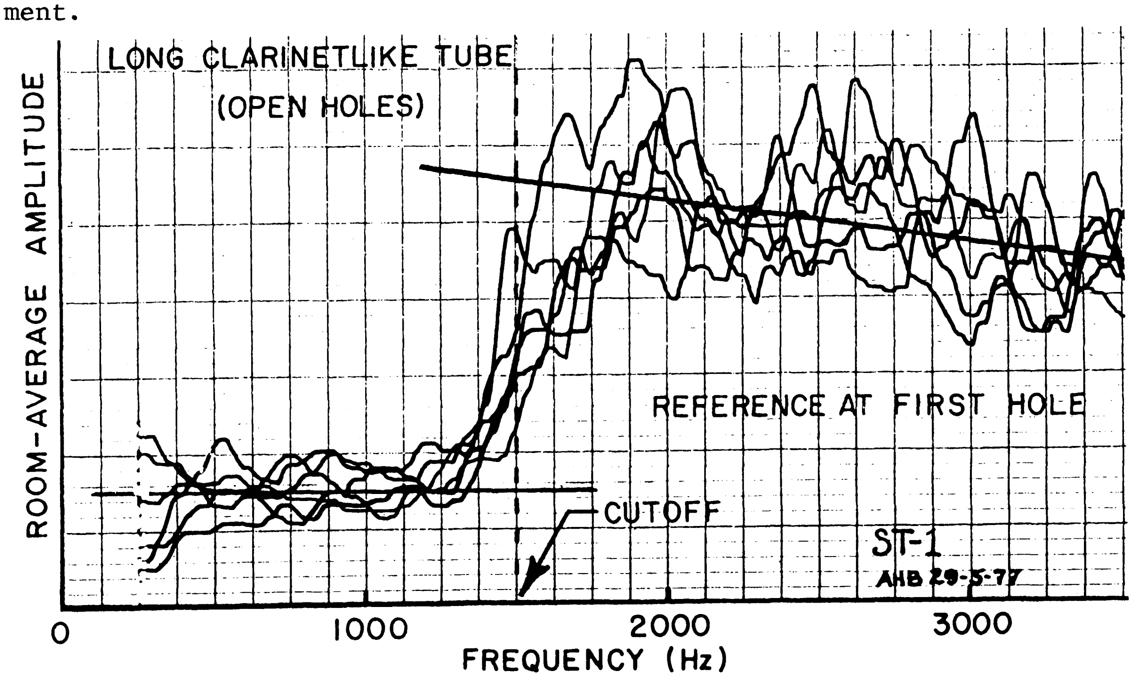


Fig. 3

We will not take time to analyze the extremely complicated way in which the sound distributes itself in the immediate neighborhood of the tone holes. However, we will take notice of the abrupt jog in all of the traces. This is one more evidence of the exceedingly powerful influence that the tone-hole cutoff frequency has on everything that has to do with woodwind sounds. Furthermore, the possibility of using a microphone near the highest open tone hole as a way to avoid doing a room average may be shown to be a risky procedure, one that is only suitable for a very limited set of purposes.

C. <u>A workable method for getting room-averaged spectra</u>

Here is a recently developed way of making an accurate determination of the room-averaged spectrum of an actual musical instrument. To begin with, the player is asked to play an alternating pair of notes, which has the effect of turning each one on and off. This assignment, not trivially chosen, gives the player something easy and familiar to do, which prevents him from trailing off, as he might with a sustained tone. Both the player and the carriers of two or more microphones (attached to a tape recorder) move slowly around in the room as they record. This moving around has several functions in the measurement. First of all, the microphones are presented successively with data from a large number of independent transmission paths. Secondly, the effect of the moving bodies of the player and the microphone-bearers can be shown to have a significant action of making the detected signal more random (in a room of any size, for instruments playing no lower than a clarinet). This significantly helps to "stir the statistical pot," whose fluctuations we are trying to eliminate. In a room average based on this type of data, the temporal response of the room to the turning on and turning off of the signal of interest further benefits the accuracy of the measurements.

When all these things are taken into account, one finds that a clarinetist playing half-second notes in alternation for the 35-seconds a lungful of air will provide his statistical analyzer with more than 75 pieces of good data even when only two of his friends are wandering about the room gently waving their microphones. The accuracy obtainable in the analyzed results from such data turn out to be barely adequate for detecting differences between individual instruments of the same type, but they are still unable to uncover finer details that the concertgoer's ear has no difficulty in detecting in an instant! Anyhow, we have met here a laboratory method for getting something well defined about the sound of a musical instrument, and we have also learned why it is by no means an easy matter to do so even when recent advances in the theory of room statistics are brought into use.

Let me belabor the room's transmission-irregularity problem one more time before we go on to our next topic. Every textbook on human speech has beautiful diagrams showing the spectral patterns of each vowel and consonant. The nature of these patterns is very stable and repeatable, and they reflect not only the type of sound that is being produced but also the speaker's regional pronunciation. The data upon which these diagrams are based are collected by using a microphone a few centimeters in front of the speaker's mouth, and it is easy to show that the listener has no difficulty in detecting the smallest changes in these patterns. Send these spoken sounds out to travel across a lecture hall--as I am doing in front of you now--and the room will certainly supply your individual ears with an enormous variety of sound recipes. Despite this, you understand my words and recognize my American accent. Perhaps some of you here can even deduce what part of the country gave me my accent and what were linguistic influences acting on it since childhood. We all know this can be done, but how?

D. The multiple reflection picture of sound in a room

As a first step to unraveling the mystery of how we hear so well in the face of the great irregularities of sound transmission in a room, we should consider an entirely different way of thinking about sound in the room. Up till now we have been thinking about the cumulative effects of responses of literally thousands of sloshing modes of the room, each one being excited to an amount determined by the position of the source and each detected contribution at the microphone determined by its position relative to the pressure nodes and antinodes of the mode in question. The other viewpoint (which is technically equivalent to the first one in absolutely every respect) considers the behavior of the room as a multiplicity of echoes that bounce the sound around the room when the source is turned on. As is true between many pairs of languages, one can say everything in each, but certain ideas can be expressed more clearly in one than in the other.

Suppose the source is abruptly turned on at a certain instant, and we follow the development of the sound at the microphone. The first intimation that the source has begun to emit sound comes to the microphone via the direct path from source to detector. The time for the traversal depends of course on the speed of sound and the distance traveled. The next arrival is a reflected sound which has traveled from the source to the nearest wall and thence to the microphone. This contribution is weaker than the first, in part because it has traveled farther and in part because of an absorption taking place during the reflection itself. Notice that because the second arrival has traveled farther than the first one, its individual oscillations are <u>not</u> in step with those of the first signal. Furthermore, the out-of-stepness depends on the random differences of travel time as this time relates to the time of each cycle of the oscillation. Depending on the accidents of distances between source, microphone, and wall, the second arrival may add to the first by arriving exactly in step with it; it may just as well tend to cancel it by arriving so that it is half a cycle out of step; or any intermediate behavior between simple addition and subtraction is equally likely to occur.

We realize that the reflections from the remaining three walls, the floor, and the ceiling are all going to provide their own sort of random arithmetic of the same sort, as will all the succeeding multiply reflected sounds. This means that the actual buildup of sound at the point of observation is of a completely irregular and random nature, both in the pattern of growth and in the final value of the accumulated signal (which is of course what we studied in section A of this lecture). When the source is shut off, an exactly similar process "unwinds" the sound at the microphone, as the multiply reflected and so delayed sounds cease making their contributions one by one.

The time during which the buildup or decay takes place is known conventionally as the reverberation time. Textbook discussions of the reverberation phenomenon tend to draw smooth growth-and-decay curves, but you will readily understand that these represent merely the average growth and decay pattern obtained by combining observations from many points in the room or from experiments using many different closely spaced excitation frequencies.

E. The paradox posed explicitly

You will recognize that I have managed once again to demonstrate the random behavior of sound in the room! This time we learn that not only does the steady sound have fluctuations from point to point, but also that each component of the sound from an instrument arrives at the listener's ear (over a period of about one or two seconds in most concert halls) in an almost entirely chaotic fashion. It looks like I have successfully proved that it is impossible to recognize instrumental tone colors or spoken vowels in a room. I seem also to have proved that the arrival habits of the sound are so messy that all details of articulation and of rhythm are obscured if they cover a time span of at least a second. We are face-to-face here with the fact that, on the one hand, physical science helps us to understand how sound comes to distribute itself chaotically in a room and, on the other hand, the most cursory experience of listening to music in rooms shows unambiguously that with practice we perceive its finest details with speed and precision. The psychoacoustician is the one who has to concern himself (along with us!) with the question of how the human nervous system manages to instantly deduce properties of the musical source from the auditory signals that it receives, signals that take hours to disentangle if we go at it by the customary methods of physicists and engineers.

F. The precedence effect and its generalization

We have come at last to where it is possible to outline the means whereby our auditory system exploits the sound signals which come to it. About twenty-five years ago, careful study established the general nature of a phenomenon (which was in fact first noticed a century earlier) that is known as the precedence effect. This auditory phenomenon has considerable usefulness in many practical situations where an engineer designs a loudspeaker system for a lecture hall or concert hall. I will not confine my discussion to the customary description of this effect in its simple form, but will rather set forth a generalized version expressed in terms most generally applicable to our present purposes.

IF TWO OR MORE REASONABLY SIMILAR SOUNDS COME TO THE EARS SPACED NO MORE THAN ABOUT 35 MILLISECONDS APART, THEY ARE PERCEIVED AS A SINGLE ENTITY.

(1) Each arriving sound adds to the listener's total "picture" of the composite sound.

(2) The position of the apparent source is that of the first arrival--everything is attributed to it.

Another way to look at this phenomenon relates directly to the fact that the first dozen or so reflections in a room or concert hall arrive at the listener's ear in a sequence that (in a properly designed halls) spaces them out no more than 35 or 40 milliseconds apart. We may metaphorically say that our ears "think about" and "understand" the information brought to them by these early echoes in the following way:

PRELIMINARY IDEA (perhaps incomplete)

----- PARTIAL CONFIRMATION (plus elaboration)

----------RECONFIRMATION (further elaboration)

---------------CONFIDENCE (detailed view)

In any room, reflection physics shows us that the successive reflections from a source come in fairly slowly at first, and then arrive at an ever-increasing rate as they become progressively weaker. Let us try a simple experiment to help us understand a little more about the way our ears function in a room. If I clap my hands together sharply as I stand in front of you in this lecture hall, most of you will hear a single slap followed almost immediately by a hissing sound that dies away quickly. Figure 4 will help us to see what is going on.

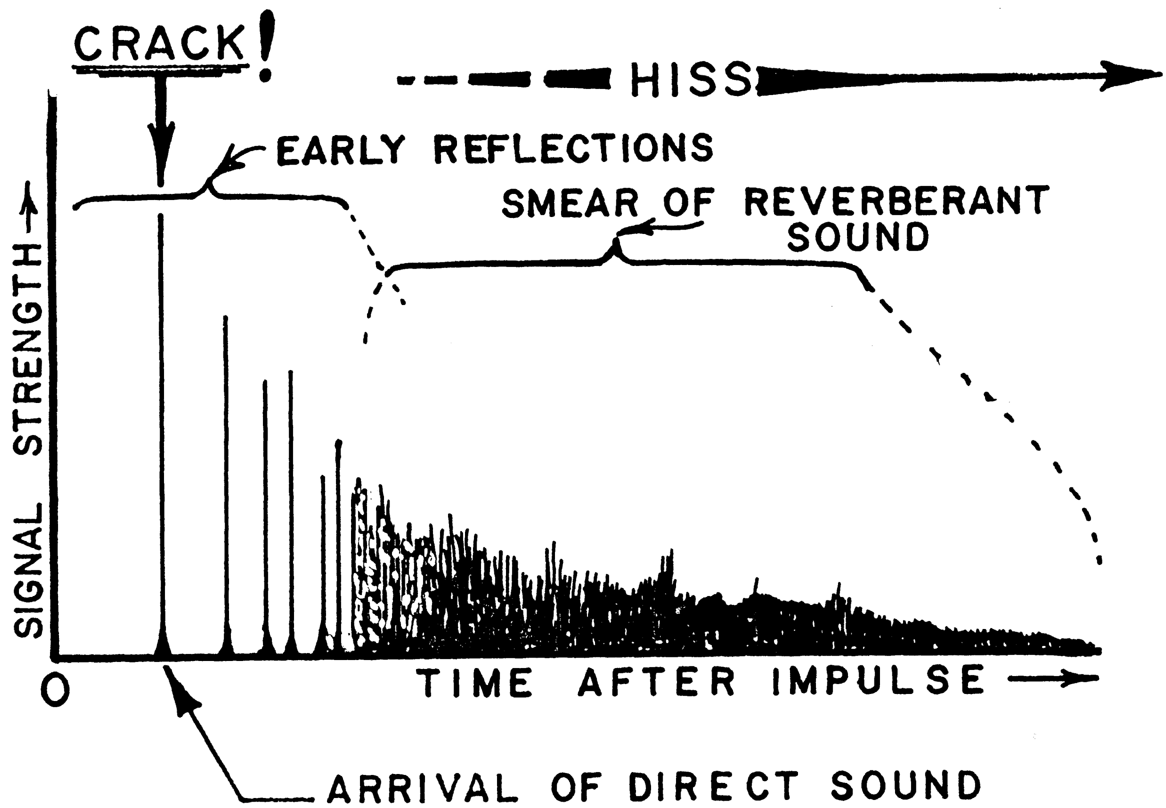


Fig. 4

This figure shows along a time scale the times of arrival of the various reflected impulses as well as of the initial slap that is directly transmitted from my hand to your ears. The generalized precedence effect helps us to recognize that the first few reflections are neurologically melted into the single clear "crack" that we hear at the beginning. The slight pause is then (at least in part) due to the fact that all of the information collected during the whole duration of the early reflection arrival is compiled into an event whose perceived time of occurrence is at the beginning of this interval! The hissing sound which we then hear dying away is simply our ears' way of organizing the rapidly arriving later reflections, which come too close together for them to be sorted out into anything more detailed than a decaying "smear" of sound. We should use our little experiment as providing yet another opportunity to elaborate or restate the summarizing statements about how we hear in a room:
(1) Early impulses spaced 10 to 40 milliseconds apart are heard together as a single clear and strong impulse whose time of occurence is associated with the time when the direct sound arrives.
(2) There may be a slight pause lasting for at least the length of time during which these early reflections have actually been coming in.
(3) The reverberant smear at later times gives a background to any later sounds. IT DOES NOT IMPROVE RECOGNITION OF THE IMPULSE.

I should say that items (1) and (2) above have hardly been studied in a way that directly explores their implications, despite their enormous importance for musical listening. Item (3), on the other hand, has, in my opinion, been given far too much importance in the design of music rooms. Perhaps it has received so much attention because of its recognition early in the development of acoustics, and because physics type of experiments concerning it are relatively easy to do (the related psychoacoustic experiments have been given serious attention only in recent years).

G. Implications for the concert hall

I would suggest that the practical implications of the generalized precedence effect for the design of concert halls might be the following:

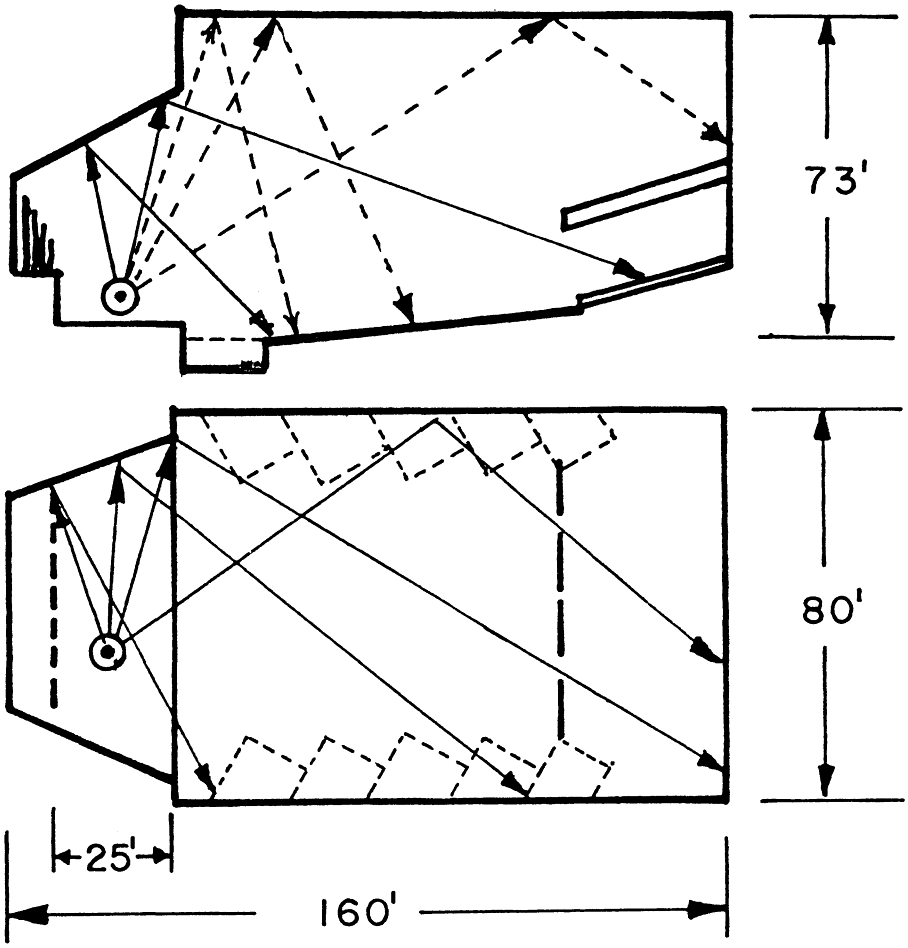
(1) Make sure that an adequate set of direct sounds plus early reflections are transmitted from one player to another on stage, to ensure confident and accurate ensemble playing by the musicians. The conductor cannot tune the players to one another or do more than lay down general policy during a performance on questions of rhythmic synchronization and dynamic balance. Without good communication on stage, no concert can be well played, and so no audience will be pleased.

(2) Make sure that direct sound and an adequate supply of early reflections are transmitted from all parts of the stage to all parts of the concert hall. Without good communication between players and audience, the listeners do not get a sufficiently clear idea of what is taking place on stage that they can appreciate it.

(3) Provide a suitable amount of reverberant sound for all participants of the occasion, since this forms part of the ambiance that builds up during the performance.

Musicians are well aware of the need for item (1) of my list, but the attention of architects and their acoustical consultants (as people who themselves tend to experience music only as passive consumers) has been focused almost entirely on items (2) and (3). In these matters many of them have built up a truly impressive skill.

Two or three years ago I was asked by musician friends at a certain American school of music to consult with them about their new and expensive concert hall. This hall, though designed by one of our leading acousticians, had proved disastrous from the point of view of the student musicians who attempted to play on its stage, and also from the point of view of those who wished to teach them the skills of ensemble playing. I attended a rehearsal and was struck by the sound of the orchestra, which was chaotic except when the trumpet or tympany would produce a loud and sharply marked pattern of pitch and rhythm. For one of two seconds following such activity, the students (who were really very talented) would pull themselves together, and one could even see the crisp, clean way in which each began to play, as well as hear the properly organized patterns of sound. Figure 5 shows the layout of this hall along with some lines of reflected sound to show how expertly its designer had provided for proper distribution of the sound from the stage to the main part of the hall.



STAGE – TO – AUDIENCE: EXCELLENT
ON STAGE: ALMOST IMPOSSIBLE

Fig. 5

A formal test of the success of this part of hall design is the so-called articulation test. In essence this test involves someone on stage who reads a list of carefully chosen words. Listeners placed throughout the hall then write down the words they recognize, and the percentage of correct words at any place in the hall is a measure of the clarity of transmission to that point. An articulation index of 75 percent or better elsewhere in a concert hall is considered perfectly acceptable. In our hall it was above 90 percent--a truly remarkable achievement. Nevertheless, this hall was a disaster, the reason being clearly shown when we tried to draw lines to indicate reflection paths between points on stage. There were almost none at all!

Let us contrast this unsuccessful (and necessarily anonymous) hall with an extremely successful one, which will let us see some of the ways in which good communication can be achieved on stage without detriment to the listeners in the hall. Figure 6 shows the hall in Troy, New York. Here

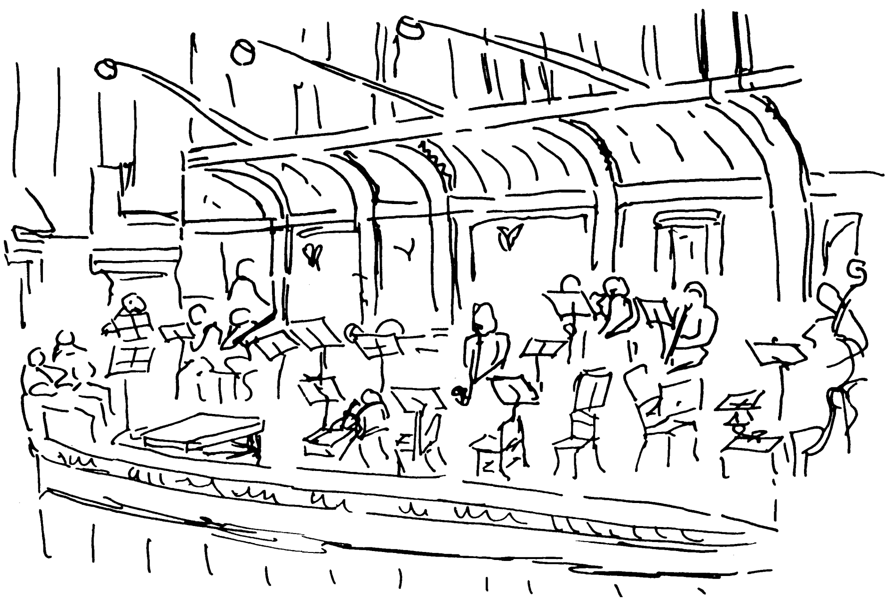


Fig. 6

my friends in the Cleveland Orchestra tell me they really enjoy playing. The pleasure is enough that some of them have been known to rearrange their free nights on tour for the privilege of playing there. Notice how the shallow stage, with its re-entrances, columns, and slightly projecting reflector overhead assures a wide variety of reflections for the players.

I will close this discussion of the implications of our hearing mechanisms for the design of concert stages with the showing of a drawing of a new hall in Denver, Colorado (Figure 7):

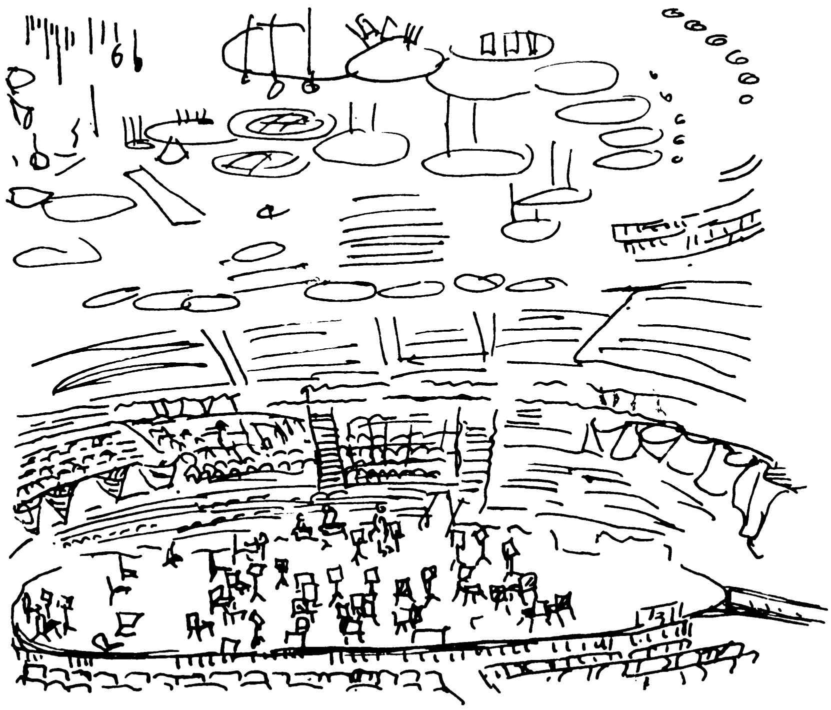


Fig. 7

This hall is an example of the currently fashionable theatre-in-the-round type of design that has terrible consequences for the musicians on stage. It has also very few advantages for a serious listener. The late George Szell had very bitter things to say about any attempt to perform music in places like this, and I have myself heard nothing but complaints from musicians with personal experience in them.

H. Recording and the "personality"of a wind instrument

While the business of playing properly in a concert hall and of hearing the music well enough to enjoy it is very interesting in its own right, our investigation of it has also prepared us to take the next steps toward an understanding of how we can get clear impressions of the musical personality of an instrument as we listen to it in a room. We are also ready to consider some of the problems one runs into when trying to capture some of this personality with a tape recorder.

We know that the auditory system collects its information by gathering and inter-comparing the data that come to it via the first few reflections (note that these early arrivals are those that have suffered only one or two reflections, so that the signals have run little risk of being mixed up or distorted by irregularities in the room!). To clarify how we hear by the instantaneous putting-together of several reflections, let us visualize what takes place in terms of the reflections we see in a room with mirrored walls. As you look at me, the direct view is of my face and the front side of my body. The reflection from the wall at my back shows what the back of my head looks like. Similarly, if you glance in the mirrors up or down and left or right, your eyes will be presented with information about my left and right ears along with both a bird's-eye and a worm's-eye view of me. Collection of all these data would of course take the visual machinery several seconds, whereas the auditory system can do the analogous job in only a few tens of milliseconds. For instance, when I play a clarinet, you are literally hearing me from above and below, front and back, left and right, all at the same time perceptually speaking!

Now consider what happens when an audio engineer insists on recording a musical instrument in a reflection-free room ("to avoid all the confusion with echoes")--he will give us an objective record of only one view of the instrument, and it will be no more complete than is the side view of an automobile shown in Figure 8.

THE PRECEDENCE EFFECT SOLVES A PROBLEM

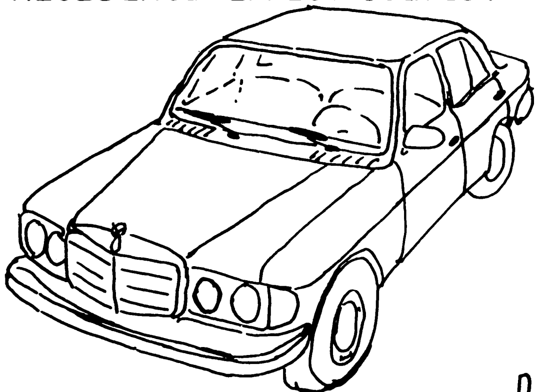


Fig. 8

THIS CAR HAS ONLY TWO WHEELS!

The fact that the recording "sounds like a clarinet" merely says that a partial view is sufficient for one to identify one's friends, but this proves nothing more than does the fact that you can all recognize that my picture is of a Mercedes. Have you ever seen a two-wheeled Mercedes? It is a manifestly absurd question, and no one would ever make a computer analysis of such a picture to extract an "objective description of the true nature of an automobile". Somehow, we are less sophisticated when we think consciously about the data processed by our ears.

Our brains can hold quite a vast collection of different pieces of incomplete information that has been gathered step by step. When enough is collected (and the amount needed depends on the seriousness of our purposes), we say "Aha, now I understand how all these pieces fit together!" Notice that this description of how our minds work fits not only our visual and auditory processes but also formal intellectual processes. As a matter of fact, over the grueling extent of three lectures I have been trying to make use of this ability of your minds. It is my hope that about now you are ready to say with me "Aha! A musical instrument does all its clever things (which I begin to understand), and it sends its signals out in all directions into the room. I collect these signals, each with its own story of the starting behavior, the steadiness of tone, the dynamic level, the pitch of the instrument, and put them together through the storage-and-compilation facilities of my brain, which does this by means of the generalized precedence effect." Then I am likely to say "Aha! This is a very fine oboe that is sounding, but I wish the player understood Mozart better"!

Once you have reached this stage of enlightenment, it is very easy for you to understand why it is that a properly aligned wind instrument, having all the virtues described at the beginning of Lecture I, automatically has the ability to carry well. In the real world one never gets all the auditory information one would like, but if the bulk of what one does get is consistent with the rest--in point of origin, commensurate rates of buildup of the various components, mutually consistent fluctuations of components during vibrato, and absence of random fluctuations of the source itself--then one has a very easy time in recognizing the well-defined voice of an instrument and of picking it out of a complex field of sound.

Up until now I have talked as though the entire collection of information about an instrument has to be completed in a handful of milliseconds. This is not true, particularly if the instrument is good enough that all its notes share their major characteristics, with no more change than a smooth trend to these characteristics as one plays a scale. We collect information over several seconds and form our opinions about tone color upon the basis of several notes. I think it is quite wrong to associate instrumental tone color with even the room-average spectrum (which is the physicist's clumsy way of collecting the information which his ears acquire in a flash). Tone color is a personality trait of the entire instrument, or at least a part of its playing range. It depends on many things besides spectrum and startup behavior, as I have hinted several times before.

I once startled a group of musicians with my apparent ability to completely transform the tone color of a certain woodwind during a few seconds while I turned my back upon the listeners. The explanation was simple. Before coming to them, I had arranged for the instrument to have a very bright, clear, and well-tuned F# in its otherwise consistently dark-toned scale. The first time I played a quick F major scale, and the second time in G major. My listeners did not have time to consciously detect the anomalous note in one scale, but they certainly were very much aware of the altered flavor of the whole passage!

I cannot possibly take time in this lecture to explain how you should seat yourselves at a recording session and how the microphones should be placed. Commercial recording practice tends to pay no attention to the need of the listener's ear to get a variety of samples of each player's sound. The use of "close miking", directional microphones, and the mixdown of several microphones placed near various parts of the ensemble are parts of a conscious plan to achieve what is called separation and definition. The fact that conventional records sell well mostly proves that the auditory system can learn to appreciate many things.

Suppose, however, that you wish to make what I describe to music students in my acoustics course at home as "audition tapes"--that is, tapes intended to convey a good idea of your sound effectively to another musician, whose auditory experience is like yours and like mine. Experience that has been accumulated chiefly in the practice room, living room, rehearsal studio, and concert hall (or laboratory) and has not primarily been strained through a multiplicity of equalizers and filters perhaps operated by people who have never heard music except through their earphones. How do you proceed? First, get a good grip on your ideas about early echoes and the accumulation of personality traits. Second, learn the general ways in which the various instruments (your own in particular) send out their high-, middle-, and low-frequency components. Third, recalling that all of these components do not have to be captured by every microphone at every instant, choose your seating and microphone placements to assure that a good sampling of all aspects of your sound is provided over any given half-dozen bars of music. Be sure to move around (sway, etc.) a fair amount as you play, to help display the different aspects of your tone to the microphones. (Incidentally, it is also a good idea to move a reasonable amount in live concerts, if this is not carried to excess.)

I will close this lecture with a brief example. Figure 9 is a diagram that should help you get an idea of how to think about recording a clarinet.

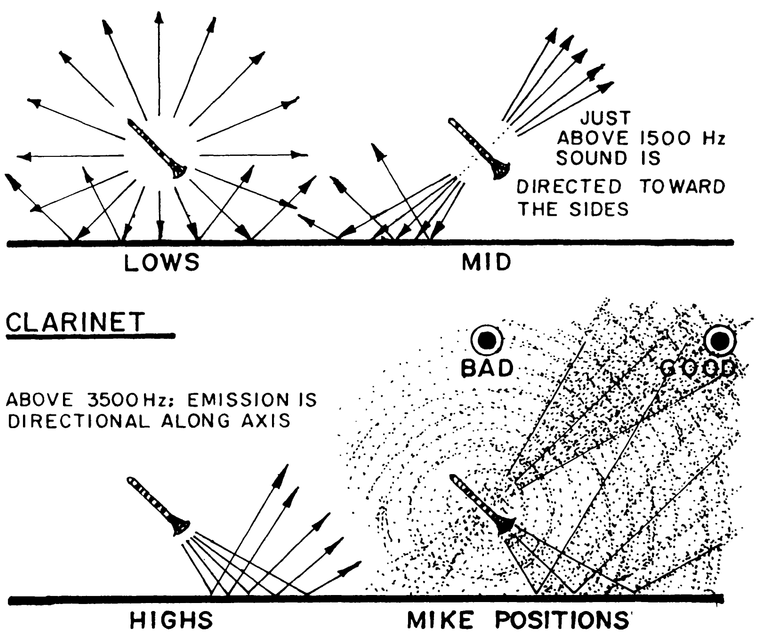


Fig. 9

The clarinet shares with all reed woodwinds (but not the flute!) an almost precisely uniform distribution of the low-frequency components of its tone. To be precise, all those components that lie below the everlastingly important tone-hole cutoff frequency are uniformly radiated. The clarinet and other reed woodwinds also share the property of spewing out the components lying just above f_c in a curious pancake-shaped pattern that extends all round at right angles to the axis of the instrument. For components of the tone that lie well above cutoff, the reed woodwinds project their sounds directly along the axis of the instrument, as though they were auditory shotguns. Placing the microphone directly above the player's head as indicated in the lower righthand part of the figure, would not give a very satisfactory sound, since essentially everything in the tone above 1600 Hz would be missing except what enters by way of late-arriving and therefore perceptually useless echoes from the hall ceiling. A microphone placed two meters in front of the clarinet at the player's waist level would also give a result that would not please him as a listener. Here the recording acquires an overdose of first-reflection high-frequency components from the floor, along with the normal share of the low-frequency parts of the tone. Another problem here is that the listener would be provided none of the just-above-cutoff aspects of the tone, since these pass right above the microphone. Finally, we can locate a general region in front of and somewhat above the player where (if the distance is right) the microphone will be supplied with a very practical, and <u>continually shifting</u> mixture of everything that is important to a musician listening to the record. It is this continual change in the details of the more or less complete supply of information that distinguishes this sort of recording from the dead-sounding results of electronic equalization combined with one of the other microphone positions.

All the way through these lectures we have threaded back and forth between formal science, the craftsman's skill, the musician's experience, and a general curiosity about how we hear and think about sounds. In recent years musical acoustics has come in age in three ways. First it has developed to the point that its practioners know enough that they are often surprised by what they notice in the world around them, and they have learned how to ask usefully for help from their musician friends. Second, musical acoustics has developed to the point where a musician or instrument maker finds things in it that are of practical use to him. Third, musical acoustics has progressed in a manner that raises new and exciting questions for future study both by physicists and psychologists. We will be coming around more and more to talk with you musicians, and to get your help! For these reasons it has been a particular pleasure for me to meet with all of you, in an institution where much of the finest work is being done in musical acoustics.

References:

For up-to-date bibliographies the reader is referred to A.H. Benade: Fundamentals of Musical Acoustics, New York 1976 and John Backus: The Acoustical Foundations of Music II New York, 1977.

In addition it may pay to look for the following names in recent indexes of journals as Acustica or Journal of the Acoustical Society of America: John Coltman, Neville Fletcher, Michael McIntyre, Cornelis Nederveen, Robert Schumacher, William Strong, Stephen Thompson.

B O W E D I N S T R U M E N T S

and

M U S I C A C O U S T I C S

Carleen M. Hutchins,
Catgut Acoustical Society,
Montclair, N.J., USA

I HISTORY OF VIOLIN RESEARCH

Early acousticians, who were primarily mathematicians, did not pay very much attention to musical instruments. A few of these men who contributed to the general foundations of musical acoustics were: Galileo Galilei (1564-1642), who described the phenomenon of sympathetic vibrations or resonance and the frequency of the pendulum based on its length; Marin Mersenne (1588-1648), who is credited with the first correct published account of the vibration of strings and their frequencies; Robert Hooke (1635-1703), who connected the frequency of vibration with pitch; Joseph Saveur (1653-1716), who laid the foundation for the concept of harmonic overtones, which later developed into the celebrated theorem of Fourier (1768-1830), based on the superposition principle, or the coexistence of small oscillations; J.L. Lagrange (1736-1813), who solved the problem of the vibrating string in elegant analytic fashion, and is known to have worked on the sounds of musical insturments in general; Ernst F.F. Chladni (1756-1824), who described a method of using sand sprinkled on solid flat elastic vibrating plates to show the nodal lines and antinodal areas.

Felix Savart (1791-1841) was apparently the only early acoustician who worked directly with musical instruments, and particularly with the instruments of the violin family. His "Memoire" (Savart, 1819) contains many interesting experimental findings on the soundpost, plate resonances, body resonances, air resonances, and a long description of the construction of a trapezoidal violin with flat plates which he made for experimental purposes, Fig. 1. (p.103). Savart worked with his friend Chladni on the vibrations of flat and arched violin plates. Perhaps his most famous results came from a study of the top and back plates of ten or more violins by the Cremona master luthiers, Antonio Stradivari, Joseph Guarneri, and others. The violins were loaned to him by the famous violin maker J.B. Vuillaume (1798-1875) of Paris, who allowed Savart to take the instrumentss apart for investigation! From this Savart found that the main vibration frequency, or tap tone, of the free back plate of these fine violins was always between a tone and a semi-tone higher than that of the free top plate. He also identified the air tone of the completed violin by the use of a device to blow a stream of air across the f-holes. Savart's identification of frequencies was based on a cog-wheel machine which

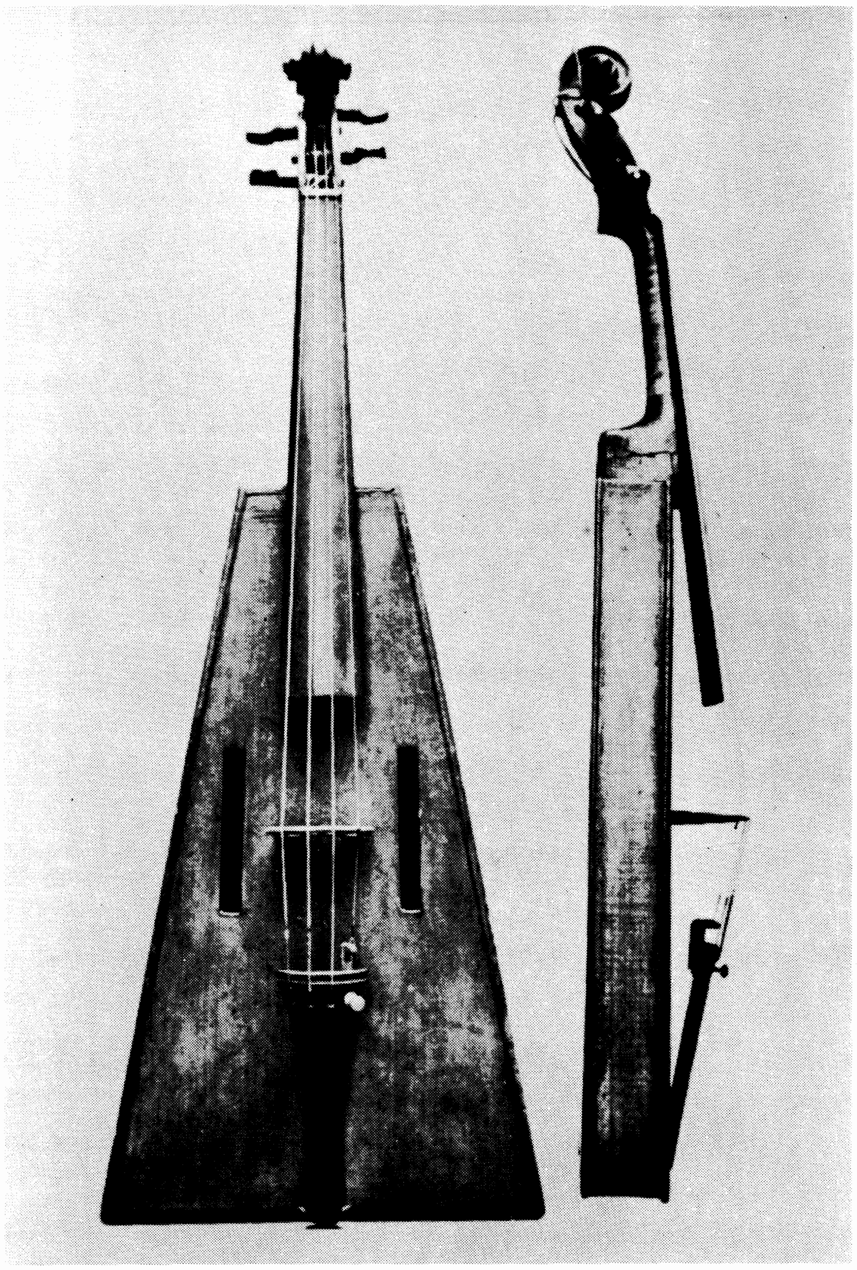


Fig. 1. A Savart´s trapezoidal violin.

he developed to give quite accurate results, Fig. 2.

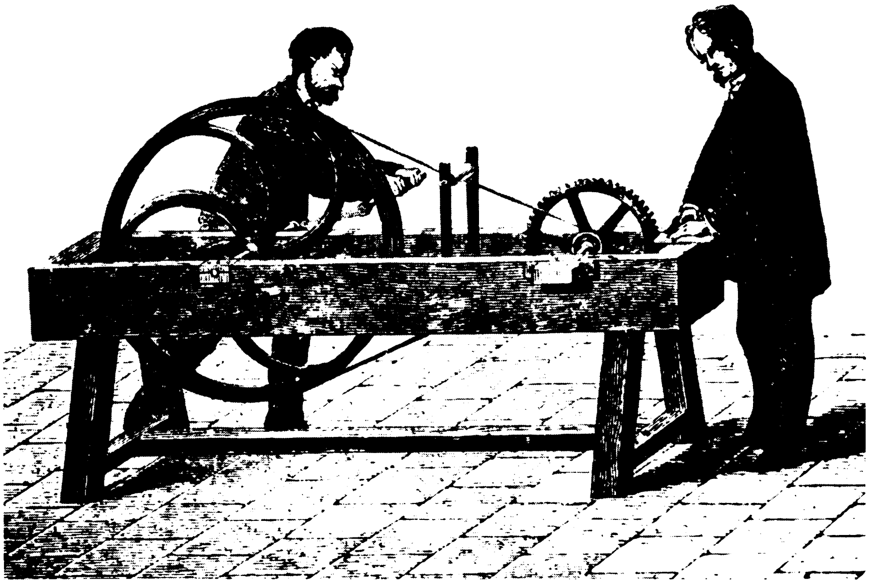


Fig. 2. Savart´s "frequency counter" of 1830.

There are various indications that Savart collaborated with Vuillaume on the development of new instruments such as a five string viola and the twelve foot octobasse, Fig.3.

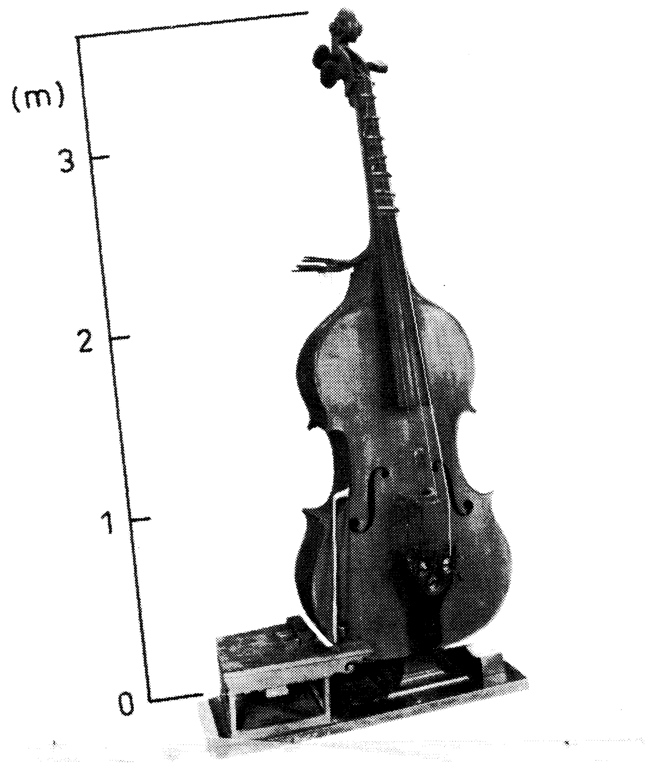


Fig. 3. Vuillaume´s octobasse

He even predicted the method that we have used recently in developing the instruments of the new violin family: "To make homologous dimensions (of a new instrument) proportional, and such that their relation be that of C natural (512 Hz in that day) to the new range and have plates giving sounds that differ by a tone." Savart, 1840. For example, in developing a new instrument to be tuned an octave below the violin, such as our tenor violin, dimensions should be such that the air resonance comes at approximately half 512 Hz or 256 Hz (128 Hz today). In the concluding paragraph of this "Memoire" Savart states exactly the position we are still in: "It is to be presumed that we have arrived at a time when the efforts of scientists and those of artists are going to unite to bring to perfection an art which for so long has been limited to blind routine." (Savart, 1819).An extensive bibliography of Savart´s research on the violin as well as on the acoustical properties of solids, liquids and gases can be found in a study by McKusick and Wiskind, (1959).

About the middle of the 19th century, Hermann L.F. Helmholtz (1821-1894), observed the harmonics of a complex tone in a variety of instrument sounds, including those of the violin, by means of a set of resonators tuned to certain frequencies (Helmholtz, 1862). These consisted of hollow metal or glass spheres of graduated sizes, each with two openings, one with sharp edges and the other funnel-shaped so that it could be fitted exactly into the ear canal with the aid of warm wax just as hearing aids are fitted today, Fig. 4.

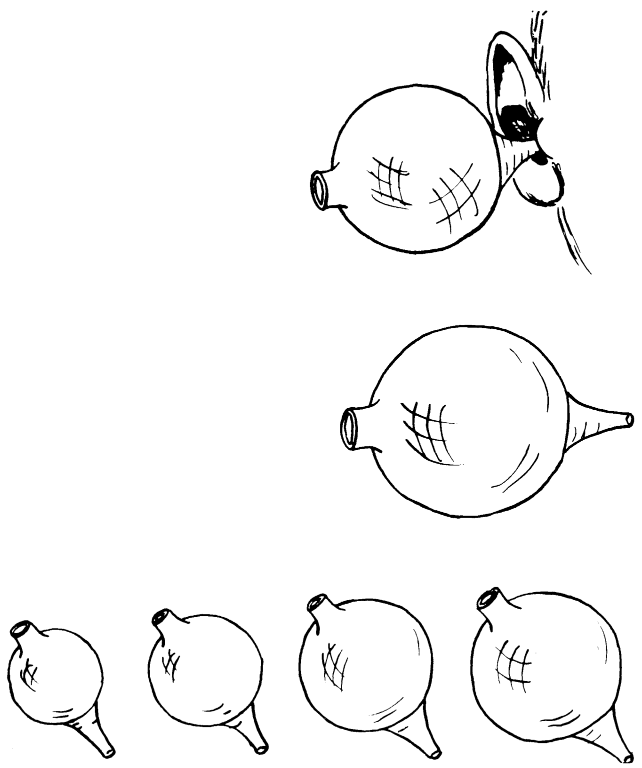


Fig. 4. Helmholtz´ resonators.

Listening through these resonators in sequence, the observer could hear clearly any partials that coincided with the frequency of a given resonator. This device had two drawbacks. Only one observer at a time could listen, and the range of pitch reinforcement by this resonators was too great for precise measurement of the component frequencies. In further analysis and sythesis of tones, he used a series of tuning forks activated by an electric switching device similar to a modern doorbell (Helmholtz, 1954, p. 121).

In 1874, Alfred Mayer of Stevens Institute of Technology, New Jersey, USA, described an apparatus whereby the effect of intervals of one cent (1/100 of a semitone in the equally tempered scale) could be made audible to a large audience. This consisted of a free reed pipe whose resonating chamber was connected by silk-cocoon fibres to eight tuning forks of different frequencies. (Helmholtz, 1954, p. 549).

With the aid of a vibration microscope proposed by the French physicist, Lissajous (1822-1880), Helmholtz studied the bow-string interaction and observed the vibrational form of individual points on the bowed string, the now famous Helmholtz saw-tooth waveform, with the result that he could calculate the motion of the whole string and the amplitude of its upper partial tones.

As far as we have been able to determine, Helmholtz was the first to recognize that the periodic impulse produced by the saw-tooth action of the rosined bow hairs on the rosined string sets up a regime of oscillation in which the upper partials are, to a large degree, maintained in simple harmonic relation to the fundamental.(For example,at A 440 Hz the bow hairs pick up and release the string 440 times each second.) This in contrast to the rectangular impulses of the plucked string in the guitar, harp or harpsicord, in which the stiffness of the string itself acts to raise the frequency of the higher partials, Fig. 5 (p. 108).

In the preface to his monumental work "Sensations of Tone" Helmholtz (1862) gives the essential clue to his approach to the whole wide range of his experiments with

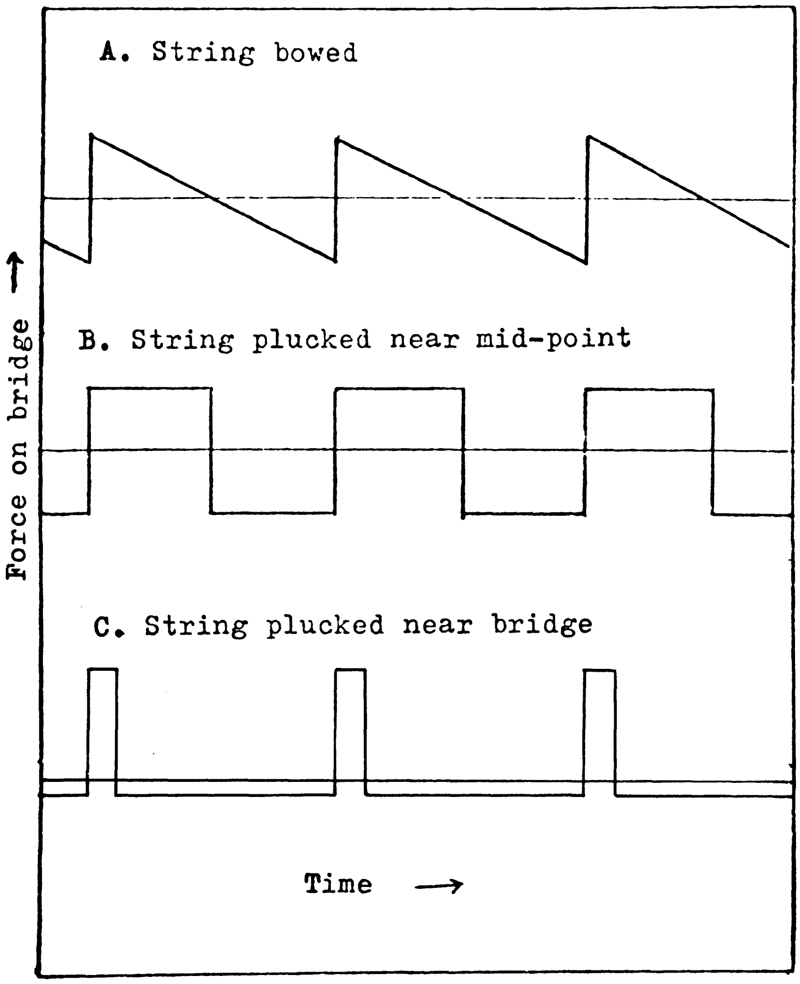


Fig. 5. Bowed versus plucked string-force curves (from Hutchins, 1977, after Schelleng).

sound and vibration. He is concerned with the effects of audible vibrations on the listener, not only the physical stimuli, but the physiological investigation of sensations as well as the psychological investigation of perceptions.

It was through the wide-ranging work of Helmholtz that Lord Rayleigh (John William Strutt, 1842-1919) became interested in sound. In the introduction to this "Theory of Sound" Rayleigh (1877) expresses a point of view quite similar to that of Helmholtz. But in his experimental and theoretical considerations he explores and formulates vibrational characteristics of many media to the extent that his work is the basis for much of the practical and theoretical acoustics of today. Rayleigh´s consideration of the vibrations of membranes, plates, shells and bells provides much of the background for our present understanding of the vibrations in the violin body, although there is much yet to be known. Rayleigh´s theories are basic to the work being done on the vibrations in various stringed instruments using hologram interferometry. He also developed electrical circuit analogies in connection with forced vibrations of acoustical resonators and other systems, a concept used by John C. Schelleng (1892-1979) in his pioneering study "The Violin as a Circuit (Schelleng, 1963).

In Russia during the 1890´s and 1900´s, Anatoli Ivanovich Leman studied and wrote on the violin. According to Nicholas Bessaraboff (1964) Leman was a "fine maker, a man of artistic talent, refined taste in music, and solid scientific training". His instruments can be compared in tonal qualities, elegance of outline, beauty of varnish and workmanship only with the best of Stradivari. His outstanding contribution is the "Acoustics of the Violin" (Leman, 1903).

During the first decades of the 20th century the characteristics of the bowed string were studied in great detail by Sir Chandrasekara Venkata Raman (1888-1970), who is best known for his work in spectroscopy and the discovery of the Raman effect for which he received the Nobel Prize in 1930. His string research followed that of Edwin H. Barton and Thomas F. Ebblewhite (1910) around 1910 in both England and India. In studying the bowed strings of the violin and the cello, Raman worked with techniques of hand bowing as well as with an automatic bowing device which kept the bow fixed and moved the violin to and fro with uniform speed, Fig. 6.

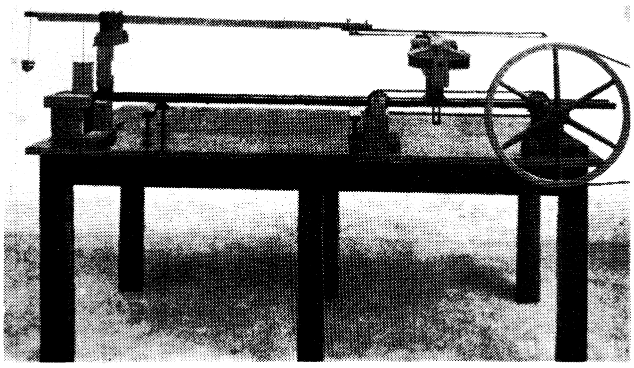


Fig. 6. A mechanical violin-player for acoustical experiments (from Raman, 1920-21).

Controlled adjustments in this apparatus made it possible to vary the action of the bow and to stimulate quite closely the hand bowing techniques of the violinist. With this it was possible to measure and observe the effects of bow speed, distance of the bow from the bridge, bowing force and various interrelations of these factors. Calculated and observed results both showed that minimum bowing force varied directly as the speed of the bow and inversely as the square of the distance of the bow from the bridge within normal bowing limits (Raman, 1920). Another study (Raman, 1918), is an extremely detailed consideration of different types of bowed string vibrations based on photographic records of both the string and the instrument body, particularly the cello, under vibration. Here he discusses characteristic string vibration curves in an effort to develop a dynamic theory consistent with observed vibrational modes in the string and its interaction with the bow. Much of Raman´s work was verified by Frederick A. Saunders (1875-1963) in his first major paper on violin acoustics (Saunders, 1937).

Raman´s findings and his interpretation of the so-called wolf note, found in most good cellos and some violas as well as a few violins, has provoked much discussion over the years, Fig. 7. This has been resolved by a combination of his findings with those of Schelleng´s as set forth by McIntyre and Woodhouse (1978).

Raman´s writings indicate that he had further plans for his research on violin strings, but no reports of this have been found. The explanation came in a very cordial letter to me in 1969 in which he said: "My studies on bowed string instruments represent my earliest activities as a man of science. They were mostly carried out between the years 1914 and 1918. My call to the Professorship at the Calcutta University in July 1917 and the intensification of my interest in optics inevitably called a halt to further studies of the violin family instruments."

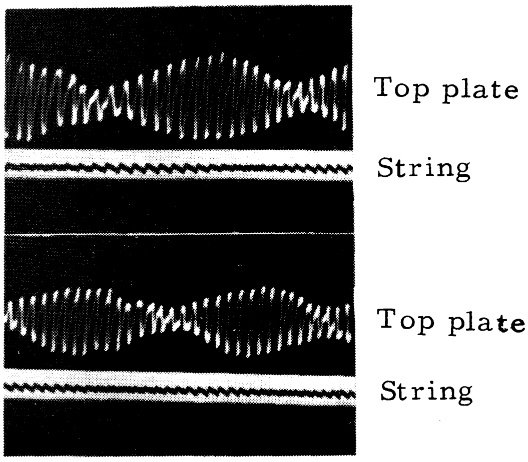


Fig. 7. Simultaneous vibration curves of belly and G-strings of violoncello at the "Wolf-note" pitch showing cyclical changes (from Raman, 1918).

In 1916 Dayton Miller (1866-1941) published his well known book "Science of Musical Sounds" (1916) in which he reported detailed studies of the harmonic structure of the tones of various orchestral instruments. Although Miller specialized in woodwinds, his experiments and comments on violin tones were outstanding. Over the years various devices had been developed to visualize sound waves, but none were as successful as Millers´s "phonodeik", the precursor of the oscilloscope, Fig. 8. With this apparatus, sound waves from the instrument being tested were collected in a horn (h) and directed to a very thin glass membrane (d). As this membrane vibrated, it twisted by means of a thin string, a tiny mirror (m) that reflected

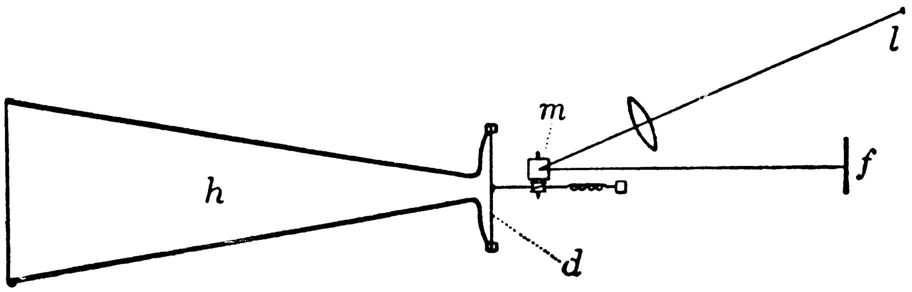


Fig. 8. Principle of Dayton C. Miller´s Phonodeik (from Miller, 1926).

a beam of light (e) onto a moving photographic film (f). There the complex waveform of the original sound wave was spread out and projected onto a graph in such a way that the number and intensity of the partials could be calculated with accuracy up to 10.000 Hz. Miller seems to have worked, however, only to 5000 Hz. From harmonic analyses of the four unstopped string tones of the violin, Miller found that: "For the lower sounds the fundamental is weak, as indeed it must be since these tones are lower than the fundamental resonance of the body of the violin; the tones from the three higher strings have strong fundamentals . ...
The tones from the three lower strings seem to be characterized by strong partials as high as the fifth, while the E string gives a strong third. In general the tone of the violin is characterized by the prominence of the third, fourth and fifth partials" (Miller, 1916).

With the advent of electronic equipment, such as the oscilloscope, the heterodyne analyzer and various types of recording devices, in the mid 1920´s, a whole new group of researches began to look more closely at the violin and the sounds coming from it. The first of these was Erwin Meyer (1899-1972), who made harmonic analyses of the sounds of various orchestral instrements, including the violin, viola and cello (Meyer & Buchmann, 1931). His work was followed by that of Hermann Backhaus (1885-1958) who worked in Germany for many years on the acoustics of the violin. His research on weak-current techniques during the 1920´s in the course of building microphones, amplifiers and analyzers made it possible to apply these research tools to violin research, using capacitance sampling and search tone analysis. His unique contribution was the first mapping of the vibrational modes of the arched top and back of the violin, vibrated with an automatic bowing device at main resonant frequencies. (Backhaus, 1930, 1931).

Hermann Meinel (1904-1977) studied with Backhaus from 1925 until the completion of his dissertation in 1935, and then went on to independent research on the violin. Meinel was not only an acoustical physicist, but also a master violin maker and trained musician. Thus he was able to make and test his instruments under various conditions of wood thicknesses and varnish, measuring the effect of progressively thinning the too-thick plates of several experimental violins on the vibratory mode patterns, frequency and amplitude of resonances, harmonic structures and musical evaluation of the sounds produced with an automatic bowing device, Fig. 9.

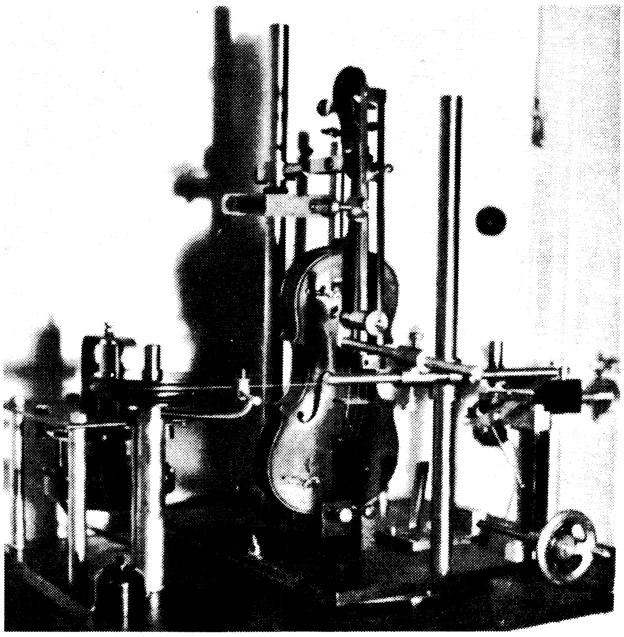


Fig. 9. Meinel's test equipment with automatic bowing device (courtesy of H. Meinel).

He also studied the properties of outstanding violins, effects of varnish, plate archings and properties of various woods for violin making, (Meinel, 1937, 1956, 1957).

Principal researcher on the violin in the USA for many years was Frederick A. Saunders, who is perhaps better known to physicists for his work in the Russel-Saunders coupling. Starting in 1933 at the Crufts Acoustical Laboratory of Harvard University, where he was then head of the physics department, Saunders continued his investigations on the violin family through the 1940s and 1950s at his home in South Hadley, Massachusetts. In his Crufts laboratory Saunders tested violins in a specially built corner, Fig. 10 (p.115) The recording microphone is in the upper left corner. The switch under his left foot controls a four second time sweep of the heterodyne analyser, which measures frequency and amplitude of the partials (harmonics). By means of this equip-

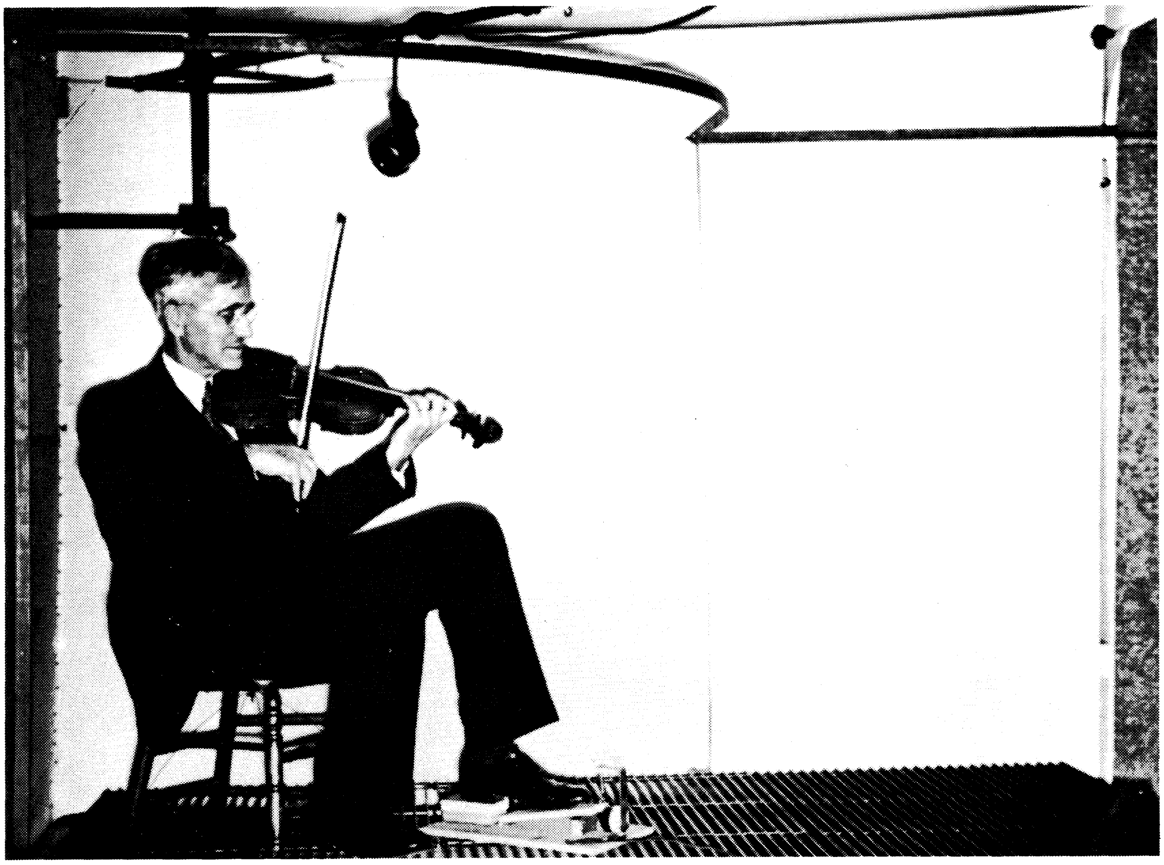


Fig. 10. Saunders´ test corner (courtesy of F.A. Saunders).

ment the spectra of Fig. 11 (p.116) where they have been called "harmonic patterns") were obtained. Such spectra were obtained for an octave of semitones played on each string. The amplitudes of the different partials were combined into an overall response curve. Such a response curve for three Stradivarious violin are shown in Fig. 12 (p.117) Saunders also used an automatic bowing device based on celluloid discs rotating against the violin in such a way that force and speed could be controlled and measured, Fig. 13 (p.118). His four major papers, published at about seven years intervals, cover every aspect of the instruments of the violin family he could think of to test (Saunders, 1937, 1946, 1953, Hutchins et al., 1960).When Henry Shaw, first treasurer of General Radio Co., got him into this work by asking Saunders if he could measure the differences bet-

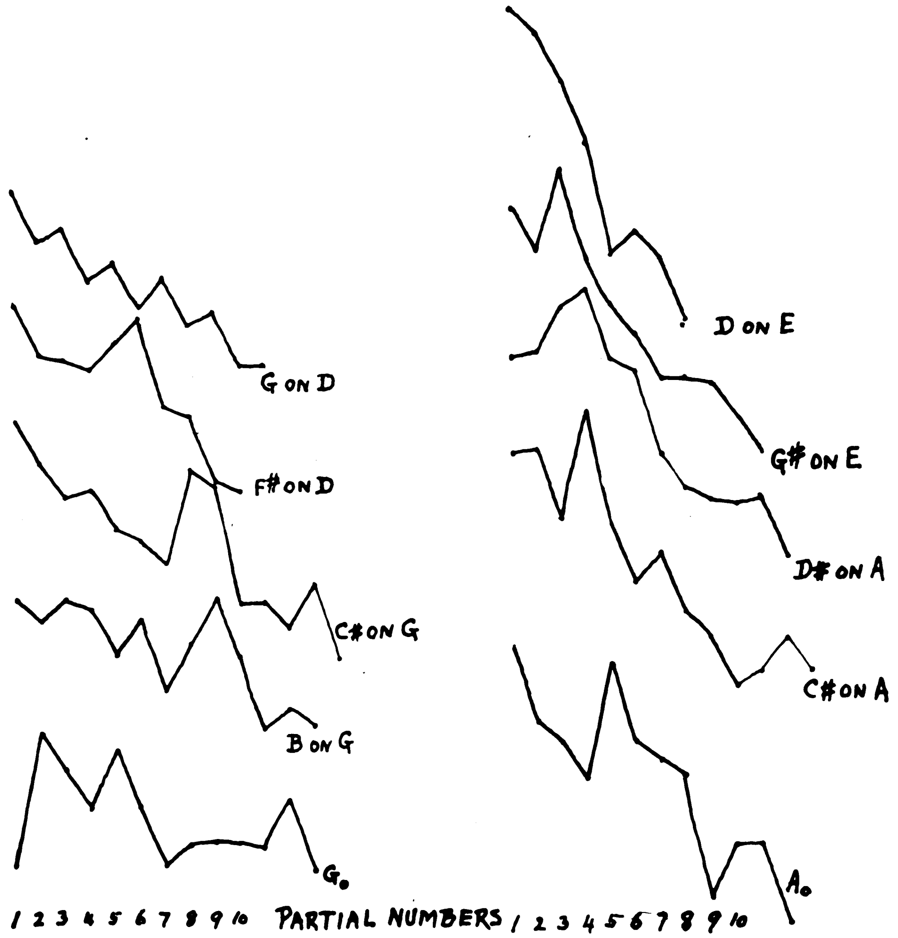


Fig. 11. "Harmonic patterns" of different tones from the same violin (i.e. partial strength as function of partial number (courtesy of F.A. Saunders).

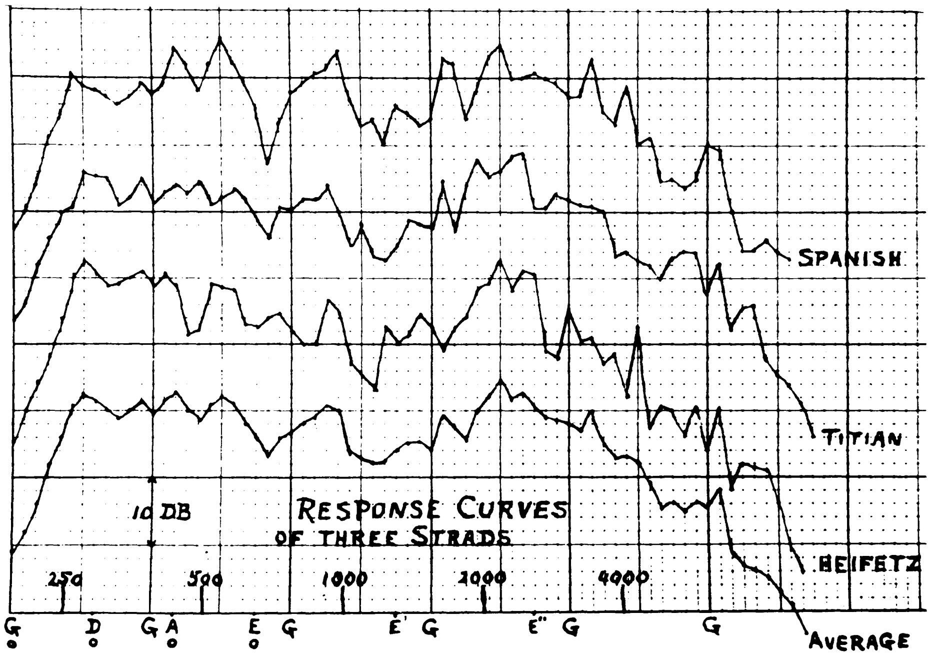


Fig. 12. Response curves of three Strads (courtesy of F.A. Saunders).

ween a fine early cello and a fine modern one, Saunders thought it would be easy. Toward the end of his career he was willing to say: "There is still no set of physical measurements that we can think of to separate clearly a fine early violin from a fine modern one". This statement was based on comparisons of many aspects of the physical properties of several hundred instruments that he had tested even though as a trained violin-viola player he knew there were differences.

During the 1930s to 1960s many violin researchers made response curves of violins with somewhat different test equipments, analysed harmonic content and measured various properties of wood and varnish. Gioacchino Pasqualini (b. 1902) in Rome is most famous for his investigations of wood properties together with I. Barducci (b. 1917) (Barducci-Pasqualini,1948), Fig. 14 (p.119). The test bar S is excited by the electrode E and the vibrations are measured by means of a special frequency modulation method. Rohloff (b. 1911) in Lübeck used his equipemnt, Fig. 15 (p.120) to measure the influence of radiation on violin properites by measuring electromagnetically the violin vibrations also in vacuum, Fig. 16 (p.121). Werner Lottermoser (b. 1909) developed at the Physikalisch-technische Bundesanstalt an electromagnetic driver for his investigations, Fig. 17 (p.122). Similar investigations were made in Japan by

Fig. 13. Saunders' automatic bowing device
(from F.A. Saunders, 1937).

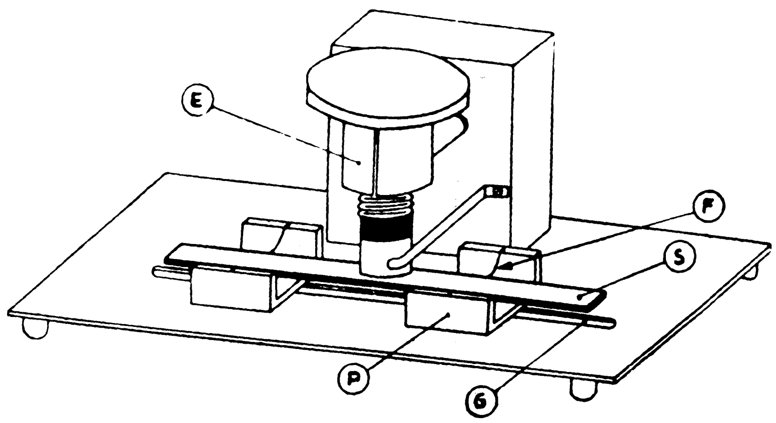


Fig. 14. Sketch of apparatus for testing wood properties (from Barducci & Pasqulini, 1948).

Hideo Itokowa (b. 1913). All these investigators made response curves of violins, analyzed harmonic content and measured various properties of wood and varnish. Their work has resulted in a large body of information in their published papers that is consolidated in the two BENCHMARK VOLUMES on violin acoustics (Hutchins, 1975, 1976).

In the late 1950s Frieder Eggers (b. 1920) at Göttingen did a continuous capacitive scanning of the amplitude and phase of the top and back of a cello, Fig. 18 (p. 123) (unfortunately a cheap student instrument). He also measured mechanical impedances which showed extreme values at different test points and frequencies (Eggers, 1959).

The vibrations of the violin bridge were studied in the early 1930s by M.G.J. Minnaert (1893-1970) and C.C. Vlam (b. 1916) at the University of Utrecht using an ingenious optical method of visualizing the various bending moments (Minnaert & Vlam, 1937). For many years this was the definitive work on the subject. Benjamin Bladier (b. 1908) at the Research Center in Marseilles has studied the responses of the cello bridge to mechanical excitation both on a block of concrete and on the instruments themselves. Bladier has also done extensive work on analyses of cello string vibrations as well as on room acoustics (Bladier, 1961, 1964). More recently, Walter Reinecke (b. 1939) investigated vibrations in violin and cello bridges using hologram interferometry (Reinicke 1973).

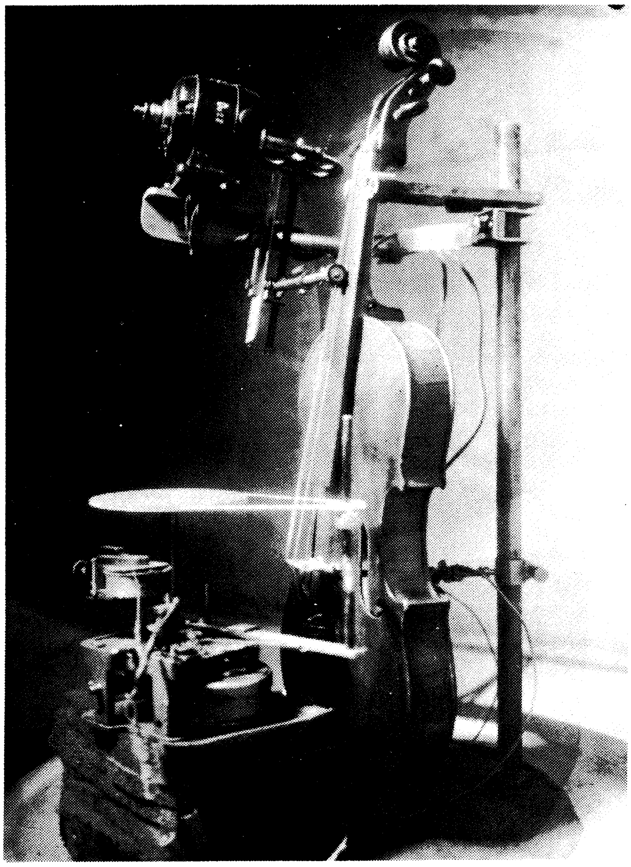


Fig. 15. Rohloff´s test equipment (courtesy of E. Rohloff).

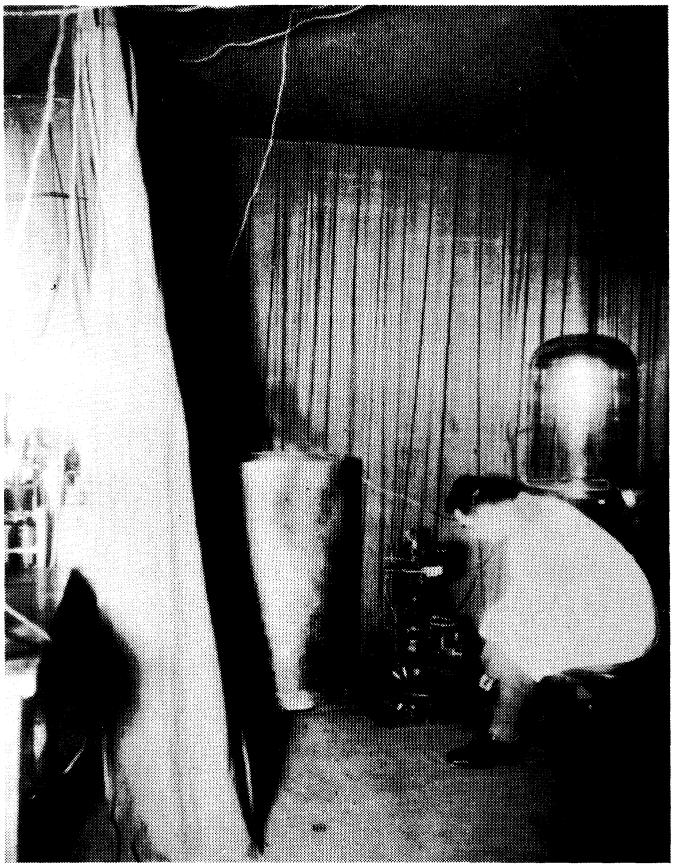


Fig. 16. Rohloff and his equipment set for measurement in vacuum (courtesy of E. Rohloff).

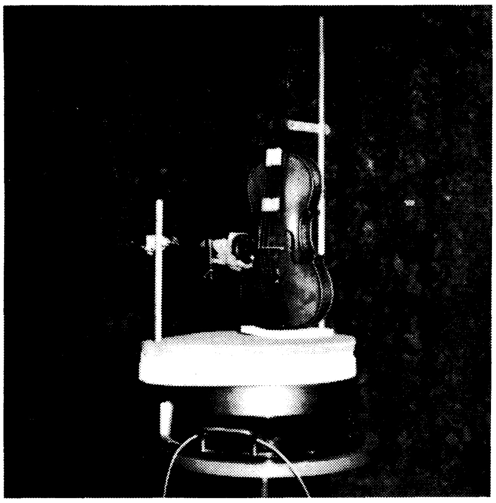


Fig. 17. Lottermoser´s electrodynamic system (courtesy of W. Lottermoser).

Carleen M. Hutchins (b. 1911) got into this in 1949 by offering to make some expendable violas for Saunders to cut up, Fig. 19 a and b (p. 124). After seven or eight years of making, testing, changing and retesting some 40 instruments under construction, Saunders asked me to work on the violin that he and Jascha Heifetz had used as their "standard of badness". This turned out so well that it was later named "Pygmalion". Corresponding so called loudness curves by Saunders are given in Fig. 20. In 1957 John C. Schelleng (1892-1979) joined Saunders´ group, which then consisted of

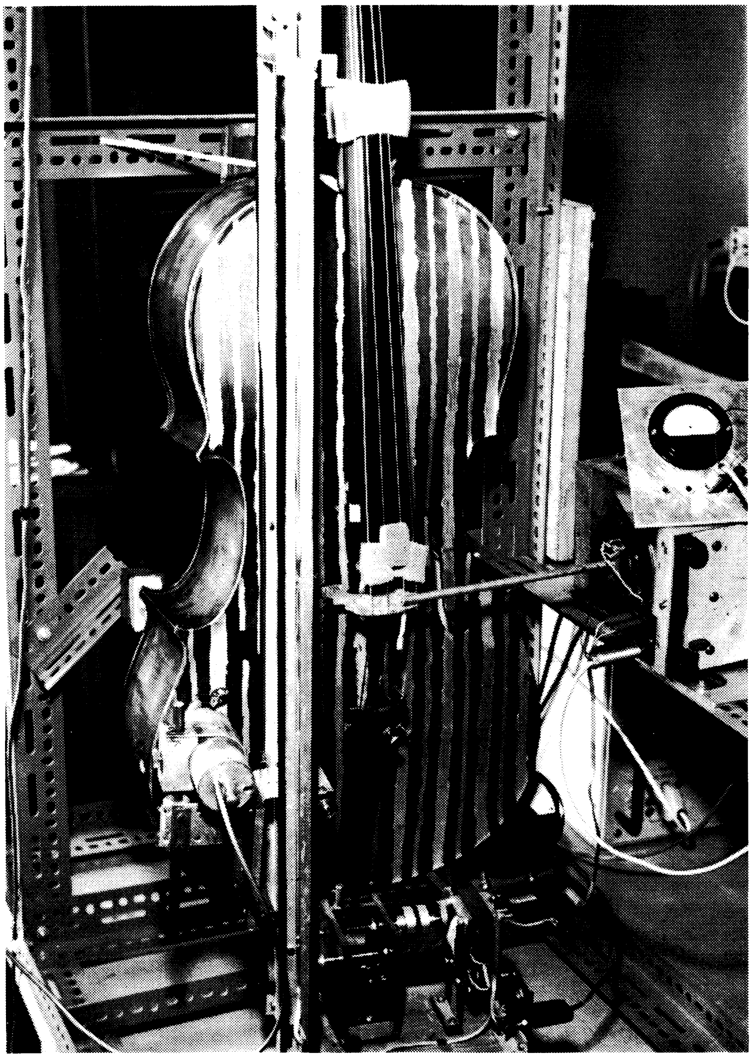
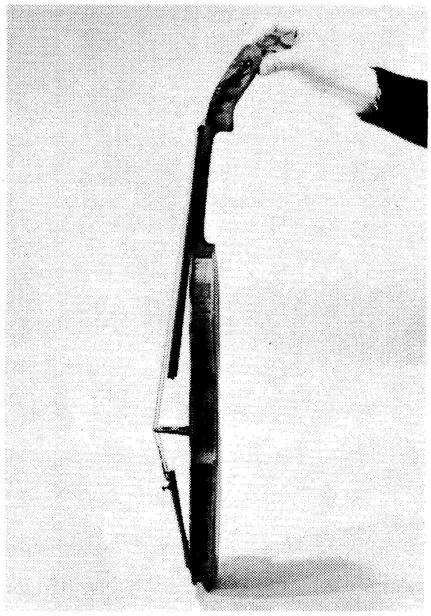


Fig. 18. Cello adpated for scanning of amplitude and phase (from F. Eggers, 1959).



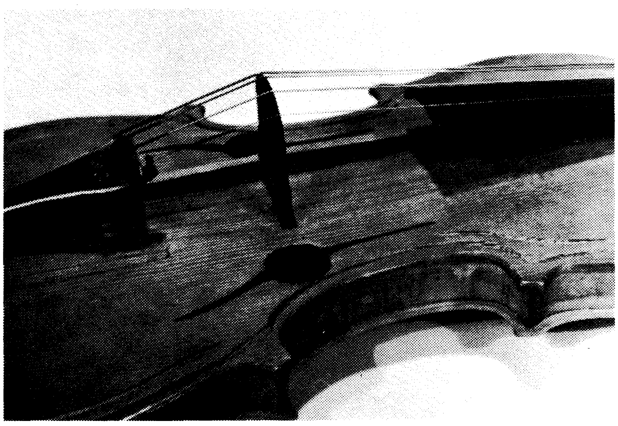


Fig. 19. One of Hutchins'& Saunders' expendable test violas.

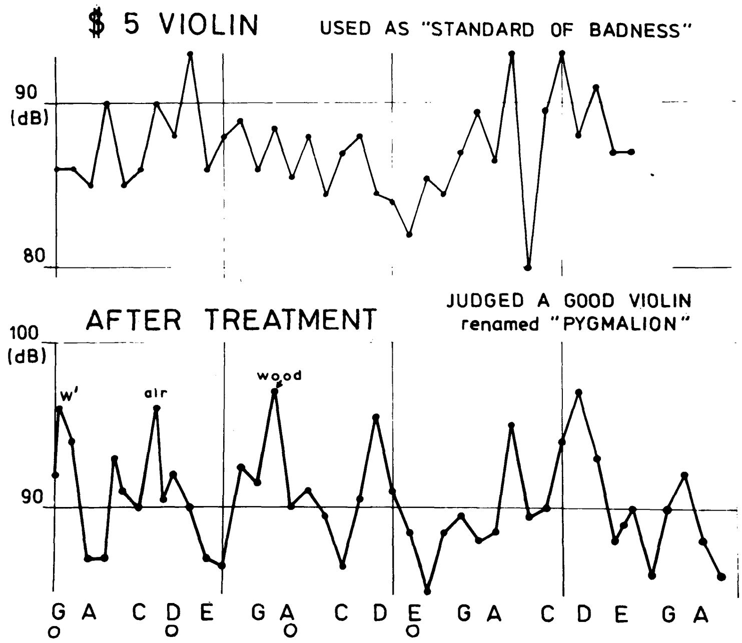


Fig. 20. Loudness curves for "standard of badness" changed into a good violin (courtesy of F.A. Saunders),

Hutchins, Robert Fryxell (b. 1923) and Alvin Hopping, an electronics engineer. At this time the group decided, jokingly, to call itself "The Catgut Acoustical Society", a name that has stuck to the organization that now includes over 700 members in 24 countries!

Schelleng has done some of the most defintive thinking of our time on the violin. In his monumental paper "The Violin as a Circuit" Schelleng applied elementary electrical circuit theory to predict the perforamnce of string-body vibrations, the importance of the first two resonances and the effects of wood properties (Schelleng, 1963). Five years later he published a theoretical and experimental investigation of the violin varnish (Schelleng, 1968). By the arrangement shown in Fig. 21 (p.126) he applied a magnetic field across the

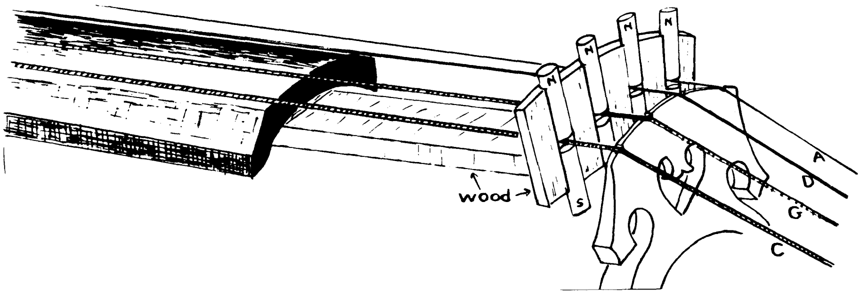


Fig. 21. Device for recording of string velocity and/or displacement (courtesy of J.C. Schelleng).

strings and could thereby record string vibrations as illustrated in Fig. 22 (Schelleng, 1973).

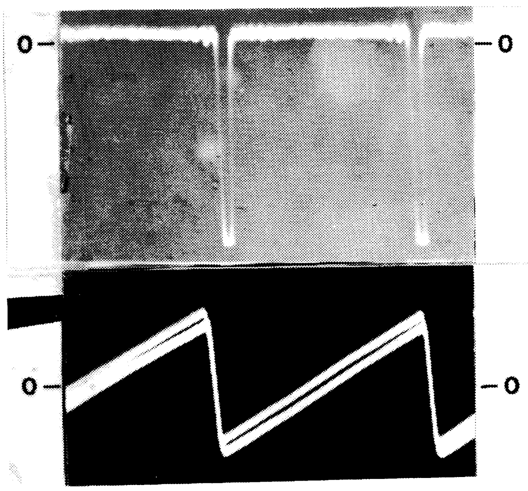


Fig. 22. Velocity and displacement at bow on a very flexible string (0.006 rocket wire) bow at 1/20 of the string length from the bridge (from J.C. Schelleng, 1973).

Furthermore he did the theoretical scaling for the development of the eight new instruments of the violin family as well as playing and testing them as they were made. His many articles in the Catgut Newsletter have provided insights into a wide variety of problems such as polarity of resonances, the function of the soundpost, and characteristics of violin wood including damping and shear.

During the 1960s Harvey Fletcher (b. 1884) and others at Brigham Young University made an extensive analysis and resynthesis of the tones of the violin, viola, cello and string bass (Fletcher & al. 1965). This was followed by a detailed study of violin vibrato, indicating that all of the harmonics have the same variation in frequency level from the note being played, but the intensity level of some harmonics increases while others decrease, see Fig. 8 (p.214)(Fletcher & Sanders 1967).

During the 1960s and 1970s at the Heinrich Hertz Institute of the Technical University, Berlin, Lothar Cremer (b. 1905) developed a very active research group of graduate students, several of whom worked on the problems of the violin. Their research included studies of interferograms of violin bodies (Reinicke & Cremer, 1970), see Fig. 23,(p. 128), as well as bridges (Reinicke, 1973), see Figs. 6 & 7 (p.158-159) and the sound radiation of the violin body (Cremer & Lehringer, 1973; Beldie, 1974). Together with Helmut Müller and Lazarus Cremer examined vibrations of the violin string (Cremer, 1971).

My own research since 1944 has been to study the various schools of violin making with the application of acoustically important features to actual construction in relating measurable parameters of the parts of over 200 instruments to the tone qualities in the finished instruments, particularly defining and analyzing the Eigenmodes, or tap tones, in the free top and back plates of violin family instruments of all sizes for good tone and playing qualities. This has led to a useful method for violin makers whereby Eigenmode parameters can be measured and controlled to produce good-excellent instruments every time, as well as to the application of the method combined with the principle of second harmonic reinforcement, for good tone and playing qualities in child size violas and violins down to 1/16 size. This research also made possible the successful development and construction of the eight new instruments of the violin family, which will be discussed later (Hutchins, 1967).

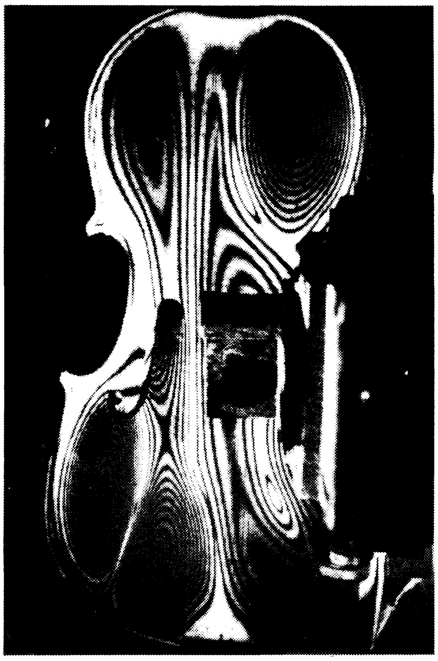


Fig. 23. Interferogram of violin top vibrations (from Cremer-Reinicke, 1970).

In 1967 Karl A. Stetson (b. 1937) suggested the use of hologram interferometry in visualizing the modes of violin plates and assembled instruments. His work provided, for the first time, a real understanding of the Eigenmodes of free violin plates (c.f. Fig. 1-3 p.166-170), and also to a limited extent, some of the Eigenmodes in assembled violins under various conditions. Erik Jansson (b. 1941), Nils Erik Molin (b. 1939) and Harry Sundin (b. 1939) in Stockholm demonstrated the use of hologram interferometry at various stages in the assembly of a violin (Jansson & al. 1970). Carl-Hugo Ågren (b. 1931) and Karl A. Stetson applied the method to plates of the treble viol (Ågren & Stetson, 1972). Further intensive work is now being done with interferograms of the violin body under vibration and on the spatial radiations resulting therefrom by Gabriel Weinreich at the University of Michigan (personal communication).

Jansson has provided, for the first time, a definitive study of the higher air modes inside the violin and guitar shaped cavities (Jansson, 1973); and with Johan Sundberg

(b. 1936) he has developed the Long-Time-Average-Spectra method of testing the output of musical instruments (Jansson & Sundberg, 1975).

Currently there is much work going on in violin research and musical acoustics in general, such as: the development by Daniel Haines of a synthetic material which reproduces the relevant properties of fine spruce and can be used for the soundboards of all stringed instruments (Haines & al. 1975 and Haines 1979) testing of the physical properties of many different kinds of wood to discover species with suitable properties for musical instruments; theoretical analysis and modeling of the action of the bowed string by Cremer, Lazarus, McIntyre and Woodhouse, Schumacher, Lavergren and others; the radiation distribution patterns of the output of various orchestral instruments, including the violin family, by Jurgen Meyer, who continues the work of Lottermoser in testing violins; coupling between the plates of the violin with air volume vibrations by Jansson; electronic simulation of violin and viola resonances by Kohut and Mathews, and by Sterling Gorrill.

An excellent detailed survey of this current activity and its possible meanings for the violin maker, player and the listener can be found in "The Acoustics of Stringed Musical Instruments", by M.E. McIntyre and J. Woodhouse, (1978).

II HOW TO MAKE A VIOLIN

When looking at a beautifully finished violin that can produce lovely music, one doesn´t often think of a tree. But to start to make a violin we need wood mainly from two types of trees, maple (Acer) and spruce (Picea). These are the two most convetionally used woods, spruce for the top of the violin and maple for the back, preferably what is known as curly or tiger striped maple. European species of spruce and maple have been used for several hundred years; so-called Norway spruce and Norway maple have special properites, as can be inferred from Fig. 1.

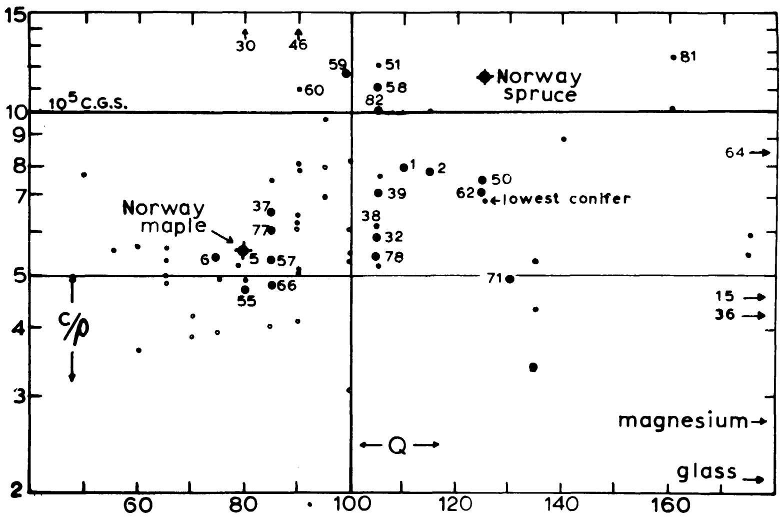


Fig. 1. Properties of tone wood. Vertical axis gives the ratio of c (velocity of sound along the grain) over ρ (density). Horizontal axis shows the Q factor which is the reciprocal of damping. The farther to the right the longer the duration or ring of sound or the decay time. (Chart developed by J.C. Schelleng 1963 from measurements of Barducci & Pasqualini,(1948).

We are finding that there are certain species of these two woods in America which do quite well in violin construction, although the grain, color and acoustic properties may be somewhat different from the European woods. All told, there are some 80 pieces of wood in the finished violin, all carefully shaped and held together with hide glue. Besides spruce and maple we use: ebony for the fingerboard, nut, saddle and pegs; willow or spruce for the blocks and linings; white poplar, and pear or walnut dyed black for the purfling strips (the inlay around the edges of the top and back plates).

Starting with a spruce log, it should be split first in half, then in quarters and then i a series of what is known as quarter cut fliches. A fliche is wider at the outside of the tree than in the center in its cross grain direction as shown in Fig. 2. For a violin a fliche should be about 16"

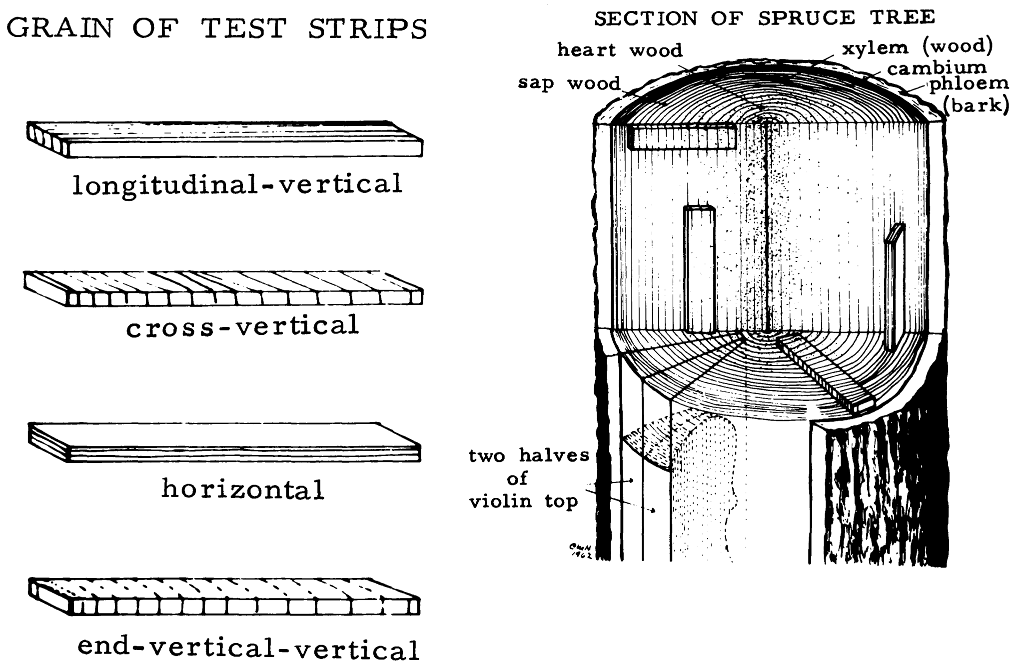


Fig. 2. Strips for measuring wood properties and section of spruce tree showing positions of strips and a fliche for a top plate.

(41 cm) long and 6 to 7" (15-18 cm) wide. This means it must come from a tree that is 15 to 16" (38-41 cm) in diameter, and preferably larger, for very often the heartwood in the center of the tree has undesirable grain characteristics and traces of knots from branches when the tree was small. The grain characteristics can also be distorted depending on how the tree has grown. Fig. 3 shows characteristics of tree growth that are

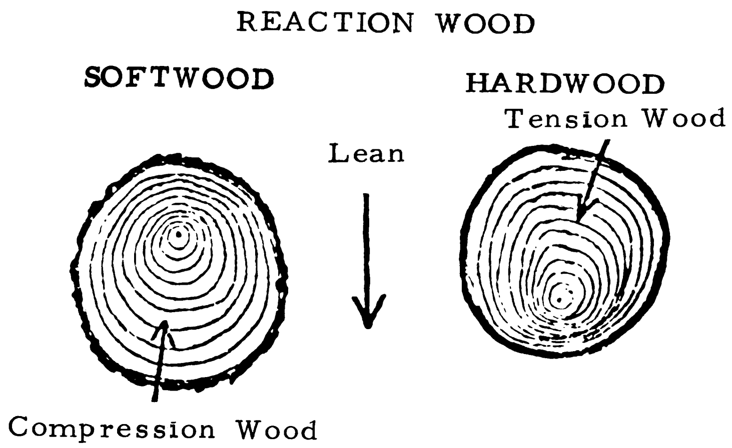


Fig. 3. Unsuitable tree growth: "Reaction wood".

not suitable for violins because the wood tends to be harder and less resonant than desirable. So-called "reaction-wood" is the result of extra stresses in a tree leaning away from the vertical, as is often seen on a steep hillside, and can be identified in the log by the off-center annual ring growth. In the softwoods, such as pine and spruce, this is known as "compression wood"; while in the hardwood, such as maple and oak, it is known as "tension wood", and is formed as shown in the diagram. Further more if the grains of the treee log are spiral or skewed the grains will not be parallel in the plate, Fig. 4 (p.133).

Proper seasoning of the wood is important. Tradition tells us that the fliches, once they are cut, should be stacked in an open shed where they will be protected from direct sun, rain and snow, but open to the elements. This air drying should continue for at least 3 to 5 years for the spruce and somewhat longer for the maple. Kiln drying is not desirable, but as far as I know there are no definitive tests on this.

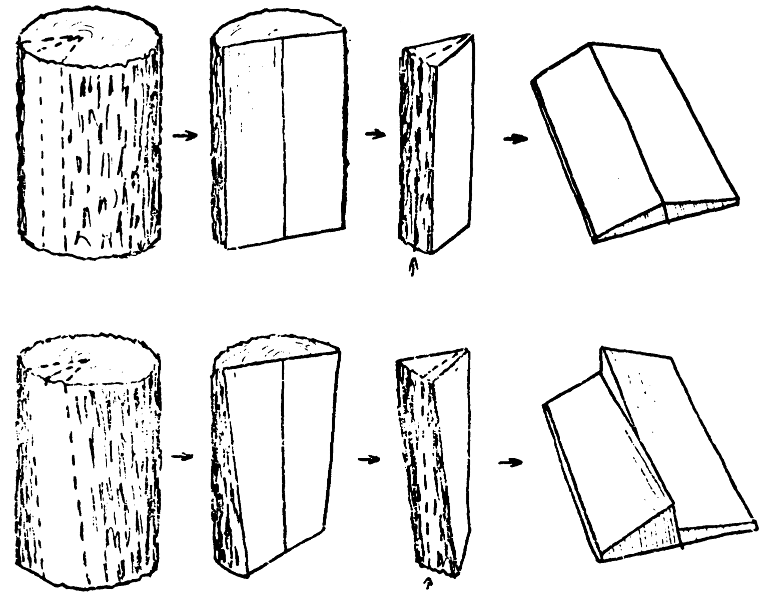


Fig. 4. Straight grain giving parallel fibres in a joined top and spiral or skewed grain giving a run-out and non-parallel fibres in a joined top. This type of join is known as "book join".

Once the wood is seasoned, a fliche of spruce is split or sawn lengthwise. The tow pieces are joined very carefully with a 24" (61 cm) hand jointer plane, shaving the two outside edges, which were next to the bark of the tree, so exactly, that they can be glued together in what is known as a book join c.f. Fig. 4 (p.133). Such a join will stay together, hopefully, for a hundred years or more. The same treatment is given the maple fliche for the back, except that it is seldom split because curly maple, particularly, does not split easily and straight. It is planed and joined in the same fashion as the top. Once the two plates are joined, the bottom surface of each is planed and sanded perfectly flat. At this stage the pattern for the outline of the instrument can be laid out on the wood and the outline rough cut, either with a bow saw or a band saw.

The next operation is to make the ribs, or sides of the violin. The wood for the ribs is cut from the same wood as the back so both the grain and the curl will match closely. The six pieces for the ribs are about 32 mm wide and are planed and scraped down to 1 mm thickness all over. It is best for tone production in violins and violas to keep the ribs an even

1 mm all over. This has come from many different sources, from violin makers, from players who have worked with connoisseurs, as well as from Rembert Wurlitzer, well known violin connoisseur and head of "Rembert Wurlitzer Violins" in New York City. He told me himself that they never got a violin or viola in the shop that needed improvement for tone but they always looked at the ribs first. If they were thicker than one millimeter they always thinned them down very carefully with scrapers from the inside.

There are two principle methods for assembling the ribs. Fig. 5 shows an inside form where the blocks are first glued into cuts in the form; glued lightly on one face so that later they can be cracked loose.

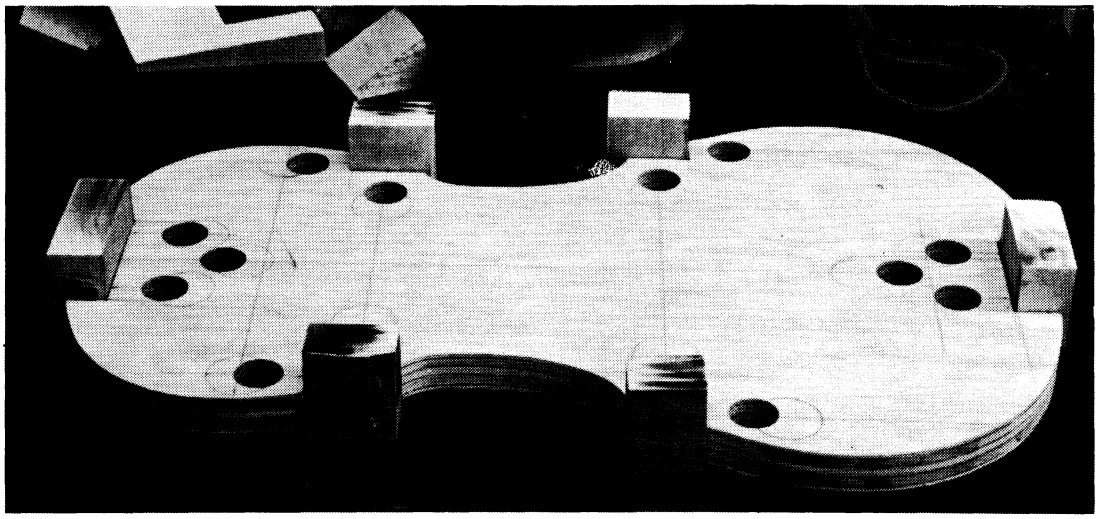


Fig. 5. Inside form (courtesy of G. Bissinger).

Both the form and the blocks must be carefully shaped to the outline for the inside of the ribs. Then the ribs are bent by gentle heat and moisture around a hot iron and shaped exactly to the form and blocks. Before the ribs are glued to the blocks the edges of the form are carefully covered with soap or tape. This is to prevent stray oozings of glue from sticking the ribs to the form which later must be cracked loose from the blocks and taken out. Then the ribs are carefully glued to the two end blocks and the four corner blocks. The ribs control the shape of the final instrument, so great care must be taken to have them smooth and evenly shaped all around, especially at the corners.

Another method for assembling the ribs is to use an outside form. When the ribs are bent to shape they can be fitted exactly into the mold where they are glued from the inside to the corner and end blocks.

The next step is to glue a set of thin lining strips of willow or spruce around the inside of the free edges of the ribs where they are not attached to the blocks, Fig. 6.

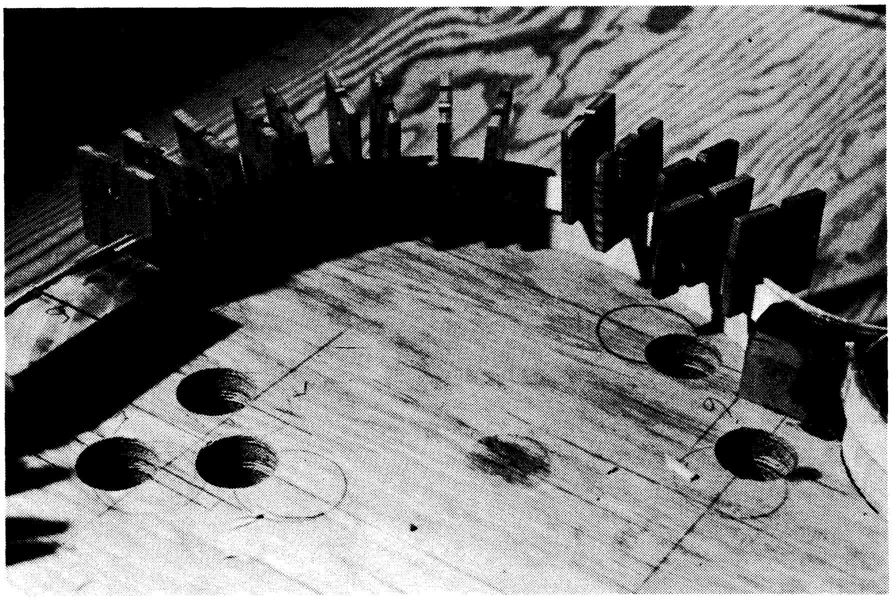


Fig. 6. Gluing of lining strings. Clamps are made of hard 1/8" plywood (courtesy of G. Bissinger).

For violins and violas, these strips are 2 mm thick and 8-10 mm wide. This means that the glueing surface for the attachment of the top and back plates will be 3 mm wide around the edges between the blocks. The lining strips are let into the blocks in the c-bouts, but are just butted against the blocks for the two ends. After the liners are glued in place they are bevelled off with a sharp knife to slope evenly to the ribs without a bump. Finally the upper and lower edges of the whole structure of ribs, blocks and liners is rubbed on a flat sanding board until they are exactly even all around both faces. The final shape of the ribs is shown in fig. 7 (p.137).

The carving of the arches is done with a chisel or sometimes with a router these days. Handwork is much simpler if one is making only one or two instruments, for it takes just about as long to tool up a router as it does to do the work by hand. The archings are cut very carefully. Sometimes they are cut using templates or marked by contour levels on the wood form a drill press such as shown in Fig. 8 (p.138). The experienced maker simply needs to look and "eye-ball" the shape of his arches, for he knows how to change the arches relative to the grain of the wood and various other subtleties that cannot be got from any sort of measurement technique. The arch of the top has a shape that is different from that of the back, mostly for accomodation of the f-holes and the center driving mechanism from the bridge. When the outside is planed and scraped to a glassy smooth surface, then the edges are ready to be finally shaped. Thereby, the overhang is exactly 3 1/2 mm beyond the edge of the ribs all around except for the corners. The corners need to be carefully cut mostly using templates because they are not exactly the same outline as the ribs. Fig. 9 (p. 139). Again, an experienced maker can do this by eye.

Once the outsides of edges are completely finished and smoothed evenly all around, then it is time to cut the groove for the inlay or purfling that goes around the edge. This purfling, according to Simone Sacconi, should sit half on the ribs and half on the liners. Since it is only about 1 1/2 mm thick, this means that the purfling groove is usually about 4 mm in from the edge. Purfling is made of three strips of wood, two black and one white. Some makers make their own, but it can be purchased in long straight

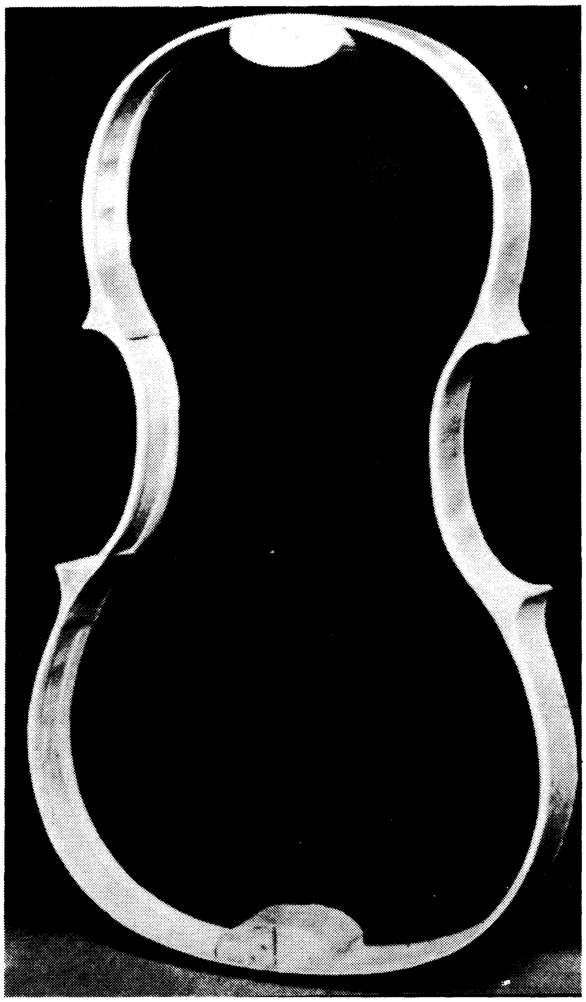


Fig. 7. Finished ribs with cleaned up blocks and linings (from Möckel & Winckel, 1967).

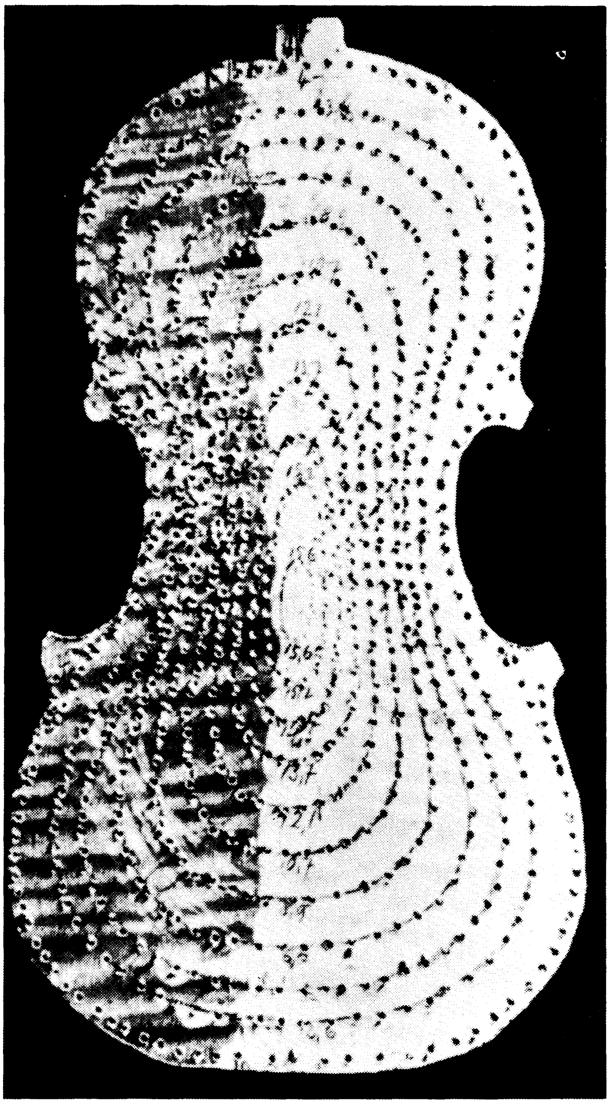


Fig. 8 Top surface of a roughly cut back with holes drilled at equal contour levels for arching contours (from Möckel & Winckel, 1967).

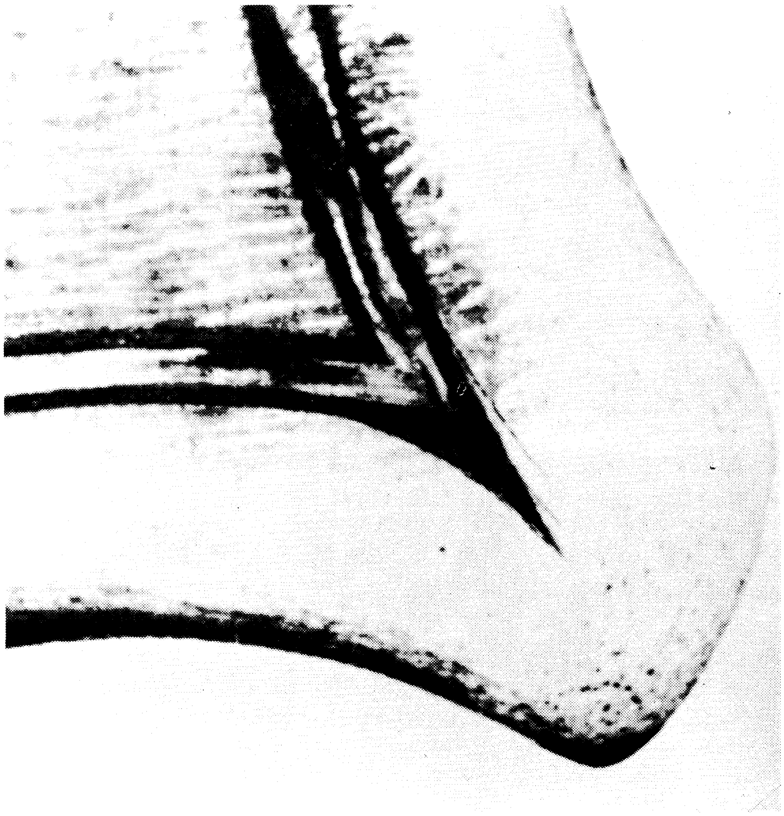


Fig. 9. Upper back plate corner of Stradivarius violin "Soil" 1714 (from Sacconi, 1972).

strips. These days sometimes it is made with fiber, two layers of black fiber on the outside and a layer of white wood in the middle. There are advantages to both the wood purfling and the fiber purfling, so the choice is up to the individual maker. The groove for the purfling is cut very carefully so as to leave the wood underneath the cut 1 1/2 mm thick only. This is thought to help in the final tone quality of the instrument, but has not been documented by physical tests as yet. One can observe, however, a fine hairline crack around the edge of an instrument that has been played for many years, indicating that the vibration of the playing has loosened the glue which holds the purfling in the groove. This creates a very thin edge to the vibrating plate which is a good acoustical feature and one which we think may be part of the process of seasoning or playing in of an instrument. When this crack forms around the edge it frees the center of the plates to vibrate more freely.

After the purfling is in, the shaping of the wood of the top is again part of the art of the violin maker. The little groove carefully made near the edge of top and back plate just over the purfling makes the edge itself rise from the purfling, giving the very nice effect of a bead around the edge of the instrument. Once the top and back are shaped on the outside completely, then it is time to gouge out the inside and thin down the wood to a delicate shell a few millimeters thick, Fig. 10 and 11, (pp. 141-142). The proper thinning, or graduation as it is called, of this wood is the heart of the sound production of the instrument. Very often the top plate is thinned to about 3 mm in the lower area, 3 1/2 between the f-holes and 2 1/2 mm in the upper area; while the back is usually left fairly thick in the center, say 5 or 6 mm , thinning out in progressively concentric contours to about 2 1/2 to 3 mm at the edges. It is never possible to indicate exactly how thick to make a given top or back plate because this depends on the quality of the wood, the arching that has been carved into the two plates, and the pattern of thicknesses that each maker chooses to put into a particular instrument. The end result of this is where our testing, using the so-called Eigenmode, or tap tone method, can aid in telling a maker when to stop thinning the wood. This whole process will be discussed later in "Tuning of Violin Plates" (p. 165).

When the top plate is graduated to slightly heavier than final thicknesses, the f-shaped holes are cut in the center of the plate, one on each side. Fig. 12 (p. 143). These must be cut and positioned accurately because the distance between the upper curves of the f-holes which controls the flexibility of the bridge platform is a critical part of the construction of an instrument. If this distance is too great, the rocking motion of the bridge is constrained and

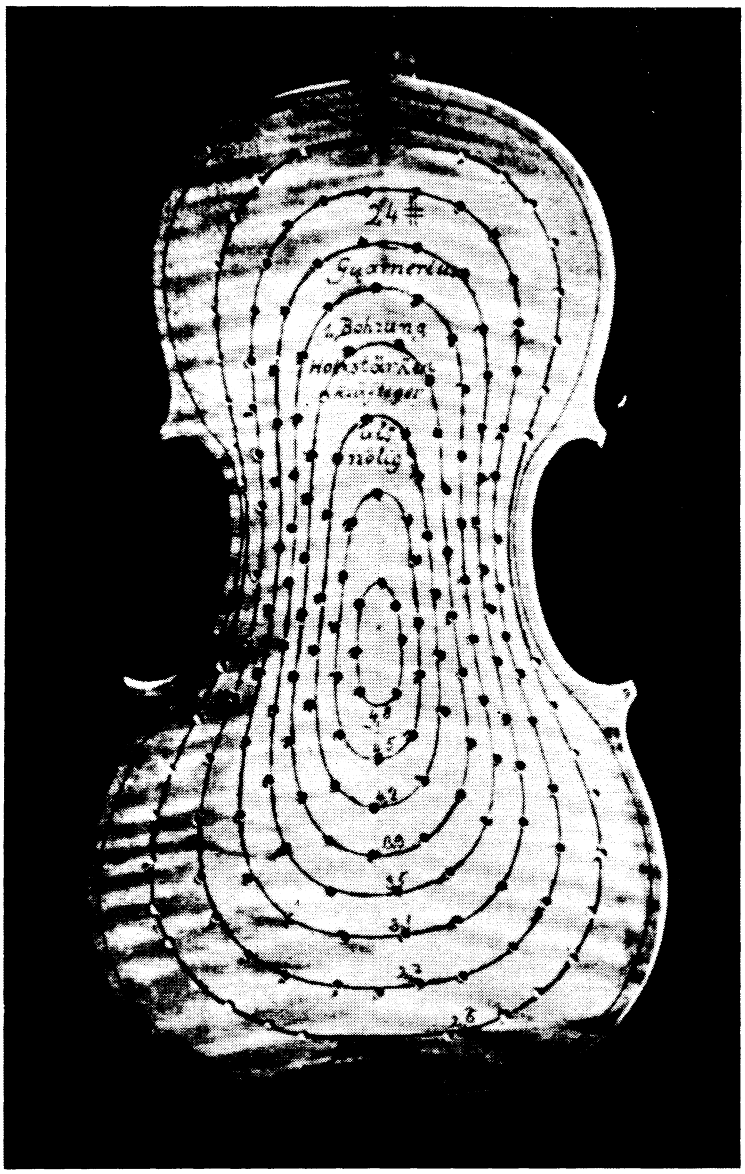


Fig. 10. Back with bore holes for "equal-depth contours" for inside work (from Möckel & Winkel, 1967).

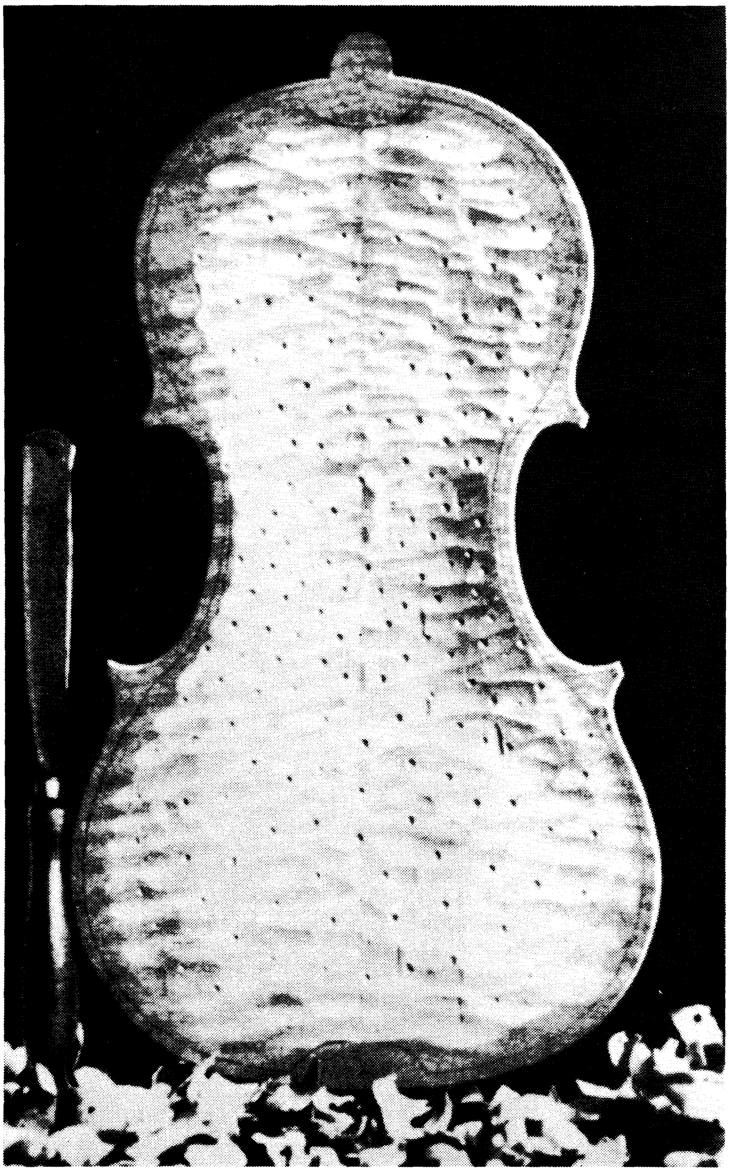


Fig. 11. First rough gouging of the drilled back (from Möckel & Winckel, 1967).

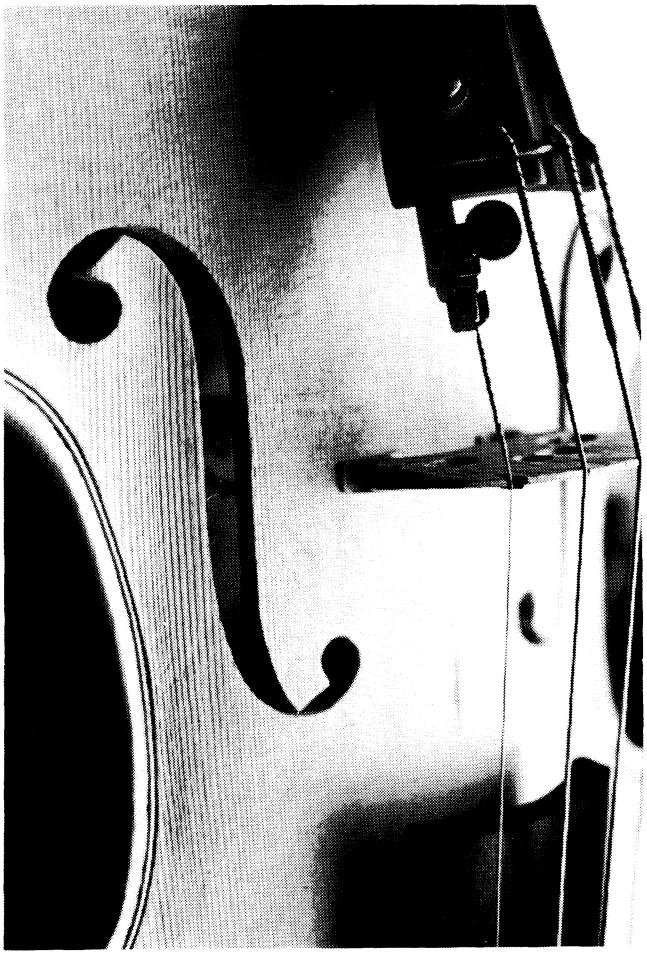


Fig. 12. Positions of bridge and f-holes (before cutting notches in the holes, (courtesy of G. Bissinger).

does not give the proper sound to the instrument. If it is too narrow, there is too much flexiblity and not enough response from the instrument to the bow of the player. The sides of the f-holes are cut with a knife very carefully and, according to tradition, left with sharp edges. Since the air moves in and out of the f-holes at the Helmholtz air resonance at an estimated 10 miles an hour (15 km/hour), there seems to be good reason for having the f-hole edges not quite as sharp as tradition would indicate. A light rubbing with sandpaper to smooth off the sharp edges was suggested by A.H. Benade from his experiments on the finger holes of recorders. Actually this smoothing effect of the edges of the f-holes occurs in the life of an instrument. When the maker is resetting a soundpost or doing some work through the f-holes, he is apt to scratch the edges a bit; then smooth them off and cover the edges with a bit of varnish. Thus there is less drag, less impedance, if you will, for the air as it moves in and out of the f-holes.

After the f-holes are cut it is time to put in the bass-bar, Fig. 13. This is a piece of selected spruce with a very

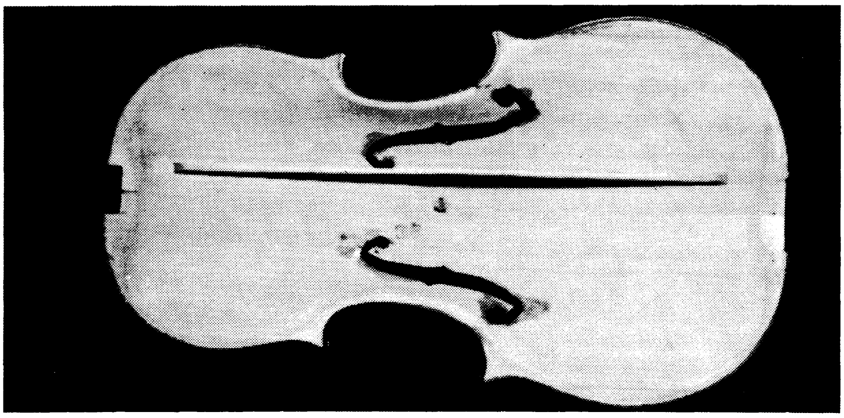


Fig. 13. Positions of bass bar and f-holes (with notches, courtesy of G. Bissinger).

straight grain usually matching the grain of the wood of the top. It is positioned lengthwise of top plate just inside the f-hole on the right as one looks at the inside of the violin plate, and it is angled to accomodate the relative size of the upper and lower areas. Actually the outside of the bar is approximately 1/9th of the width of each of the upper and lower bouts - from the center join of the plate.

This is an approximate measure because sometimes the exact 1/9 distance puts the bassbar across the upper hole of the f and that is not good. The bar should just come to the edge of the upper section of the right hand f-hole as one looks at it from the inside. The bar should be cut so that it´s grain is perpendicular to the surface of the top plate. In other words, it is essentially an extension of the grain in the wood of the top. Sometimes, in quickly made student instruments, this bar is simply a piece of the original top that is left carved in there, This is not the best way to do it however, for according to most violin making methods, the bar should be sprung in just a little so that the extra curvature tends to push the center part of the plate between the f-holes up without pulling the ends down. This is rather a critical operation, but if the bar is fitted first at one end and then at the other with the center left a bit high, it will tend to push the middle part of the plate up without pulling the ends down.

The final shaping or tuning of the bassbar is a very critical operation for the tone and the playing qualities of the violin. I have been experimenting with this for many years now to try to determine the optimum relation of first the bassbar to its own top plate and then to determine the relation that exists between the two plates - the back and the top free plate before they are put together. This will be discussed in more detail in a later chapter.

Once the two plates are completely finished and tuned, either by the skill of the experienced violin in feeling and tapping and flexing the two plates, or via the Eigenmode method, it is time to begin to assemble the parts. In the meantime a scroll is cut from a block of wood and carved to appropriate shape for the style of the violin under construction, fig. 14 (p. 146). This again involves the art of the violin maker, for here he can use his own discretion to a certain extent. There is a little more leeway in shaping the scroll, fig. 15 (p.147), than there is in the rest of the construction of the instrument because conventional methods are very precise and very demanding.

The next step is to glue the back onto the ribs with a fairly thick glue so that it will stay for quite a long time. I mention this because it is in contrast to the thin glue

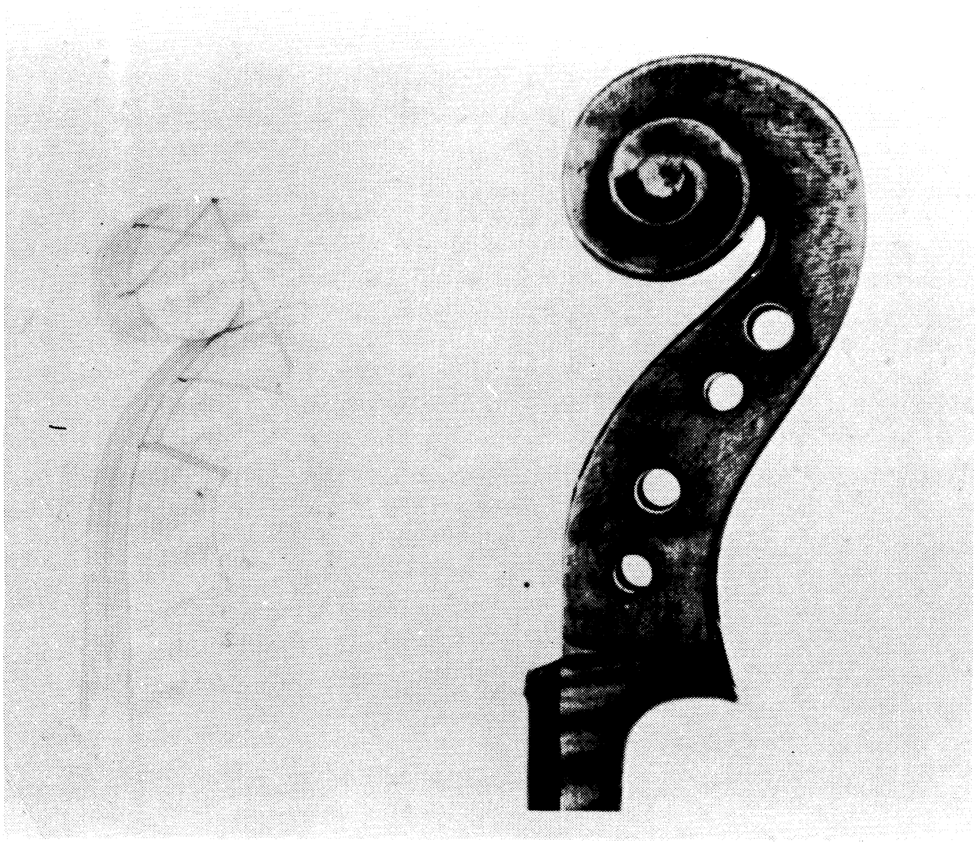


Fig. 14. Sawcuts for making a scroll (left) and scroll of the "Paganini" viola contraalto of Stradivari 1731 (right, Sacconi 1972).

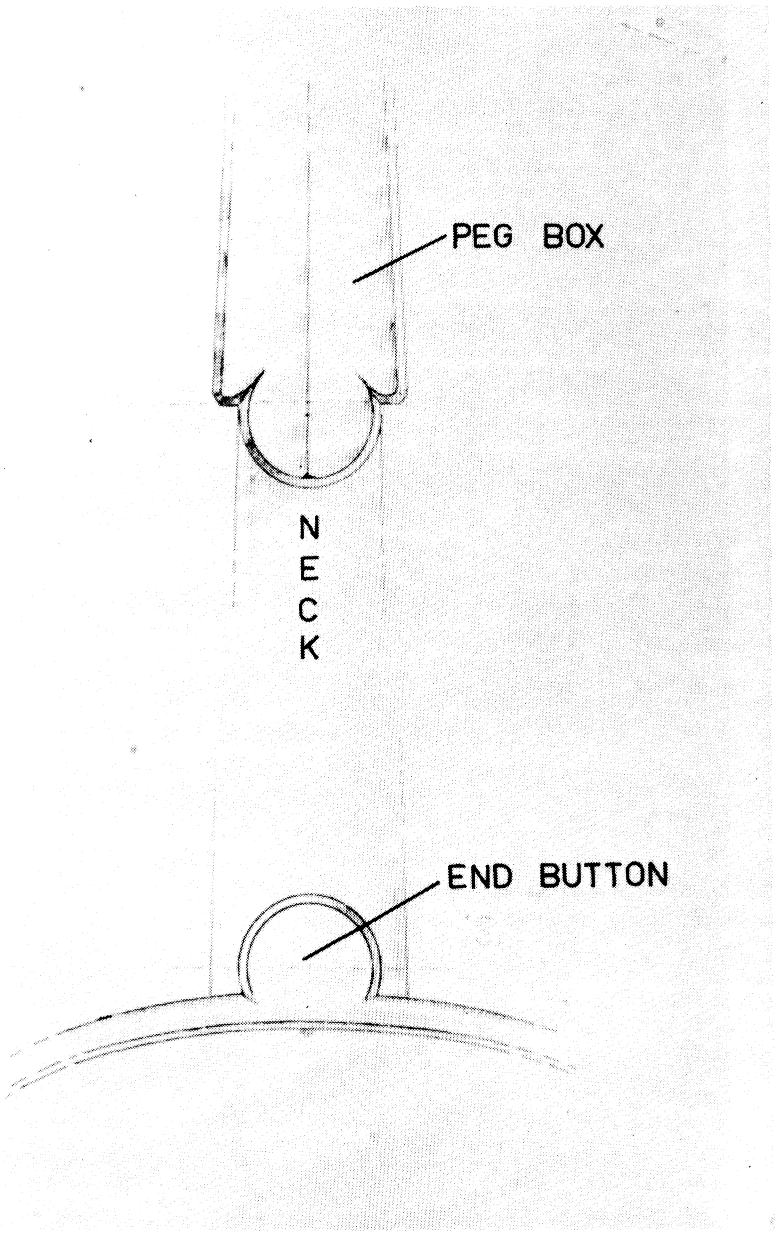


Fig. 15. Back of pegbox and end button showing the special design developed by Stradivari for his violas and cellos (Sacconi, 1972).

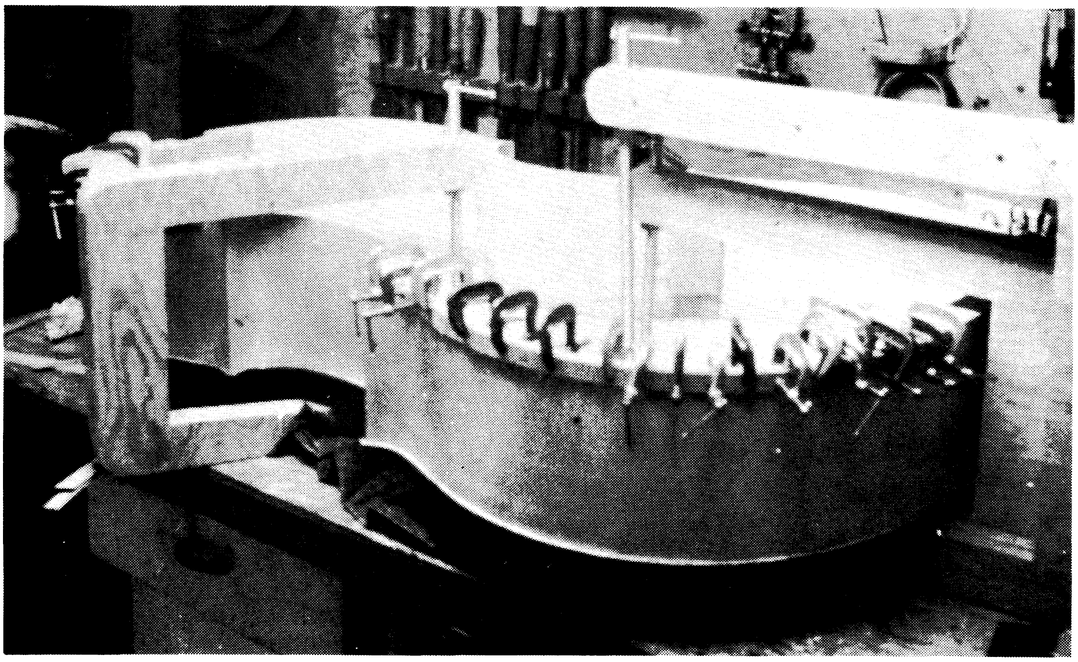


Fig. 16. Bass in clamps for gluing second set of lining strips.

used for gluing on the top. This must be emphasized very strongly because it is important that the top plate can be removed easily without breaking it up in order to repair damages which inevitably occur in the life of any instrument. When the back is glued on the ribs it is time to take out the form. This is cracked loose from the blocks where they were glued lightly to the form with spots of glue so that each block can be separated from the form without cracking the ribs. Sometimes this can be a very complicated process, especially if the glue has been put on too heavily when the blocks were set into the form. With the form out, it is time to clean up the inside of the box. Then a second set of lining strips is glued around the top edge (same dimensions as the other strips, i.e. 2 mm thick and 8-10 mm wide) carefully and then cut to taper off at an angle to the ribs, fig. 16, (p.148). This means that the gluing surface for the edges of the top of violins and violas are 3 mm wide. After the inside is cleaned up, the blocks are shaped, and the liners all smoothed out nicely, the maker puts in his label and glues on the top witha very light glue so that it can be taken off again. If the instrument should go through severe changes of moisture or temperature the edges will hopefully loosen rather than crack the wood of the top and back.

The next step is to cut the channel for the neck block into the upper end of the instrument. This channel is shaped so that the neck can fit into the upper block with practically a mortise and tenon joint. If it is well done, the neck should be able to be squeezed into the cut so firmly that one can string the instrument up to pitch without gluing the neck in. This, I understand, is one of the criteria for a well set neck at the Mittenwald School of Violin Making. The angle of the neck is important because it controls the height of the finger board above the top, which means the angle of the strings at the bridge, a critical factor for tone quality. After the neck is glued in and properly shaped for smooth action of the palyer´s hand, then the fingerboard is glued on. Some makers glue the fingerboard on the neck block before they put it in the channel, others put it on afterwards.

Then the fitting up process begins. The nut at the upper end of the fingerboard, where the strings go into the peg box, is a separate piece of ebony. It is glued on with little grooves filed into it so the strings stay in proper position and are the right height above the fingerboard. The pegs must be fitted into the sides of the peg box so that they turn easily. A saddle of ebony is put at the lower end of the top where the tail gut goes across, raising the end of the tailpiece just a little above the top of the violin surface so that it does not scratch it. The soundpost is made of carefully selected narrow grain spruce like a small pencil to fit as closely as possible just inside the instrument where it is set and held by friction nearly under one foot of the bridge. The sound post should be placed with the annual rings perpendicular to the grain of the top and back.

Finally the bridge is cut from a standard bridge blank, first fitting the two feet exactly to the curvature of the top plate where it will be positioned as indicated in Fig. 12 by the inner notch of the f-holes. The feet are cut down to be 1 mm thick at the edges. Then the top part is shaped to give the proper angle and spacing between string as well as height above the fingerboard, with the front face gently curved in two directions. The overall thickness of the bridge and the size of the various openings is a final adjustment, which in the hands of an experienced maker can greatly enhance the tone tone of an instrument. Since the bridge is the filter through which the vibrations from the strings must pass, the stiffnesses of its various parts control, to a large degree, the vibrations that reach the vibrating box of the violin. Once the pegs are properly fitted into the peg box and the strings put on and brought up to pitch, the violin is ready for playing. Further adjustment to bridge and soundpost are usually made as the maker and player listen for the sound qualities they want to hear. Research on bridge adjustments is currently being done in several laboratories and will be discussed in two later chapters.

III HOW THE VIOLIN WORKS

The sound of the tones coming from a violin depends on the tranfer of vibrations from the strings to sounding box to air, that is, if one ignores the acoustics of the room and the skill of the player. This disarmingly simple statement turns out to be extremely complicated as soon as an analysis of the various vibrating elements and the transfer functions are investigated. Fig. 1 gives a view inside the violin showing the position of soundpost and bassbar relative to the bridge feet (lower right); the contours of the back plate with soundpost set (not glued) in position; the ribs (edges) with corner blocks, end blocks and liners; the top plate with bassbar glued approximately under the string of lowest tuning; and the neck, scroll, fingerboard, tailpiece, bridge and strings.

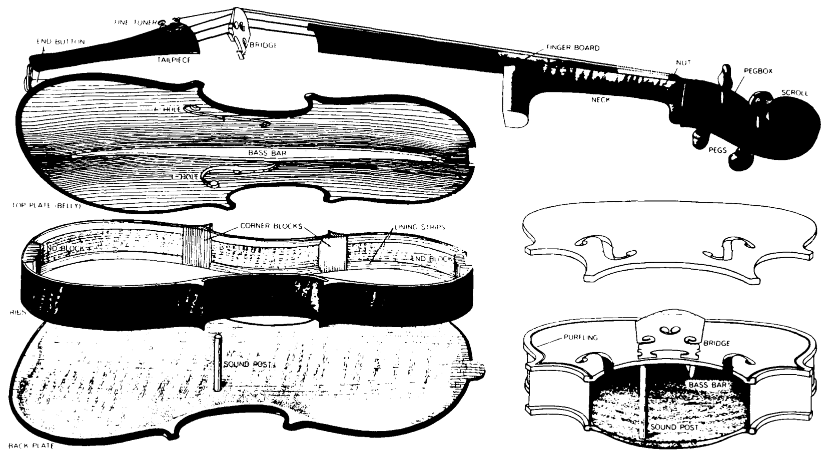


Fig. 1. Main parts of the violin. (From Hutchins: "The Physics of the violin". Copyright Nov. 1962 by Scient. American, pp. 78-93.)

The bowed string has been analyzed by researchers for nearly 100 years, and is still not completely understood. The vibrations of the bridge are slowly yielding information through the application of hologram interferometry to their bending moments. The vibrations of the violin body and their coupling to the enclosed air modes are under investigation in Stockholm by E. Jansson and others. There is still a no-man´s land between the body vibration modes as visualized by hologram interferometry and the actual radiation in the air around the instrument that brings the sounds to the ears of the listener.

The string itself provides the unique driving force for any stringed instrument, giving the player not only control of the violin under his fingers, but forcing him to solve certain problems in the quality of the sounds produced. As the bow is drawn across the string, the string appears to move back and forth in a lens shaped curve which is an optical illusion. Actually it takes the form of a broken straight line that could be seen in slow motion as a bend, or kink moving around the path of the string between the two ends. This can be demonstrated with a long thin coiled spring or a long piece of this rope held firmly at each end. A sharp blow downward near one end will send a kink shuttling back and forth between the two ends. It is this kink which traces the lens-shaped loop of Fig. 2 (p.153). In the figure eight successive positions of the kink are shown. In the action of the string under the bow this kink races around from nut to bridge at the frequency of the note being played. For example, at a A 440 Hz the kink makes 440 round trips in one second.

As the kink passes the bow it dislodges the string from the bow hair to which it has been clinging and reverses the string´s motion. The bow is thus freed from the string, not as a result of the gradual increase in stress between the rosined hair and the rosined string, but because the kink has turned it loose. The time of sticking is one of slow motion in one direction, followed by a quick snap back in the other upon release, thus giving the sawtooth waveforms of Fig. 3 (p.154). These are displacement waveforms that represent the motion of the bowed string as a function of time showing the up-bow and down-bow action as exact reversals.

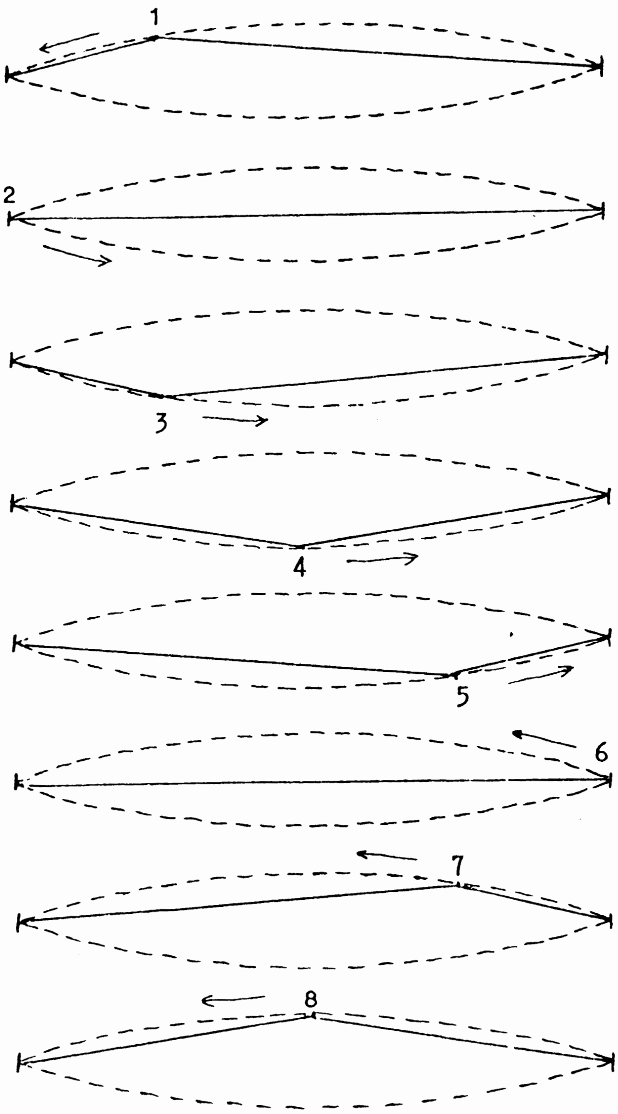


Fig. 2. Deformation of a bowed string at eight consecutive instants of time. The dashed contour represents the deformation envelope.

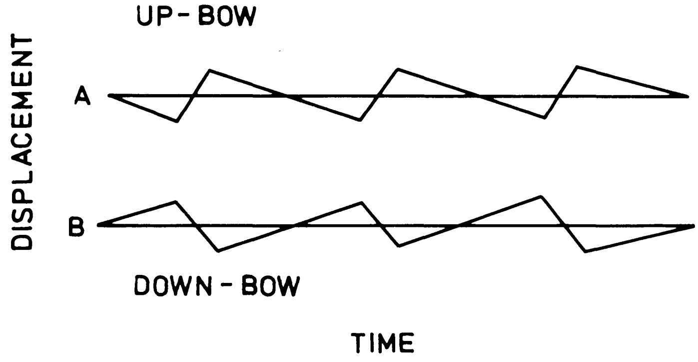


Fig. 3. Displacement waveforms representing the motion of the bowed string as a function of time showing the up-bow and down-bow as exact reversals (from Hutchins, 1977, after Schelleng).

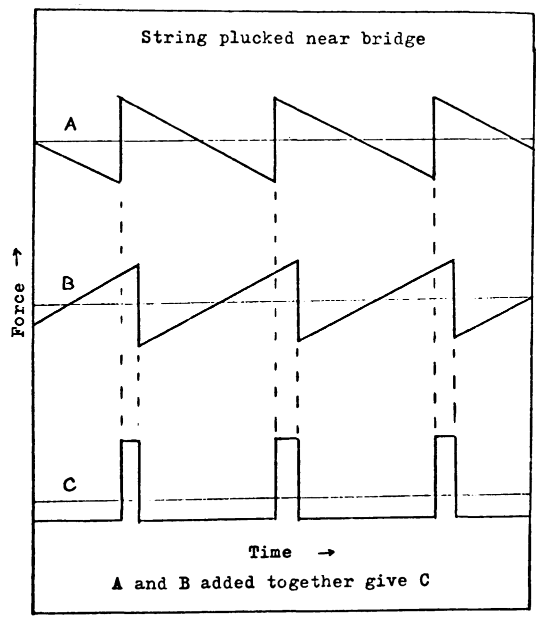


Fig. 4. Vibraton forces of the two partial waves (A and B) separately and of their sum (C) (from Hutchins, 1977, after Schelleng).

The farther the point of bowing from the two ends of the string, the more nearly equal are the two parts of the saw-tooth action. Effective bowing can occur, however, only near either end of the string.

If the action under the bow is truly repetitive, as it usually is, the frequencies of the string partials, which are all simultaneously present, are of necessity multiples of the fundamental frequency even though the string may have a little stiffness. Stiffness in a string causes the upper partials without the repetitive motion of the bow-string contact to be somewhat higher than the strict integral relationsship of 1-2-3-4-5-6 etc. Thus in the plucking of pizzicato, any stiffness in the string causes the higher partials to be sharper than simple, or integral multiples of the fundamental.

There are other important differences between the bowed and the plucked string. When the string is plucked, the pull of the finger creates a kink that divides the string into two sections, setting up two kinks or discontinuities travelling in opposite directions, one to the nut and one to the bridge. These are the same as the modes of motion of the up and down bow action in the bowed string, but in the plucked string they are both present at the same time. This sets up a force wave,(Fig. 4 p. 154) which drives the bridge. This force wave has a rectangular shape which depends entirely on the position of the plucking point along the string. The wave shape of force from the bowed string on the bridge is saw-tooth in form so that reversal is instantaneous regardless of the position of the bow on the string, Fig. 5 a (p. 156). If plucking occurs at the middle of the string the shape is of a square with minimal content of higher overtones, Fig. 5 b.

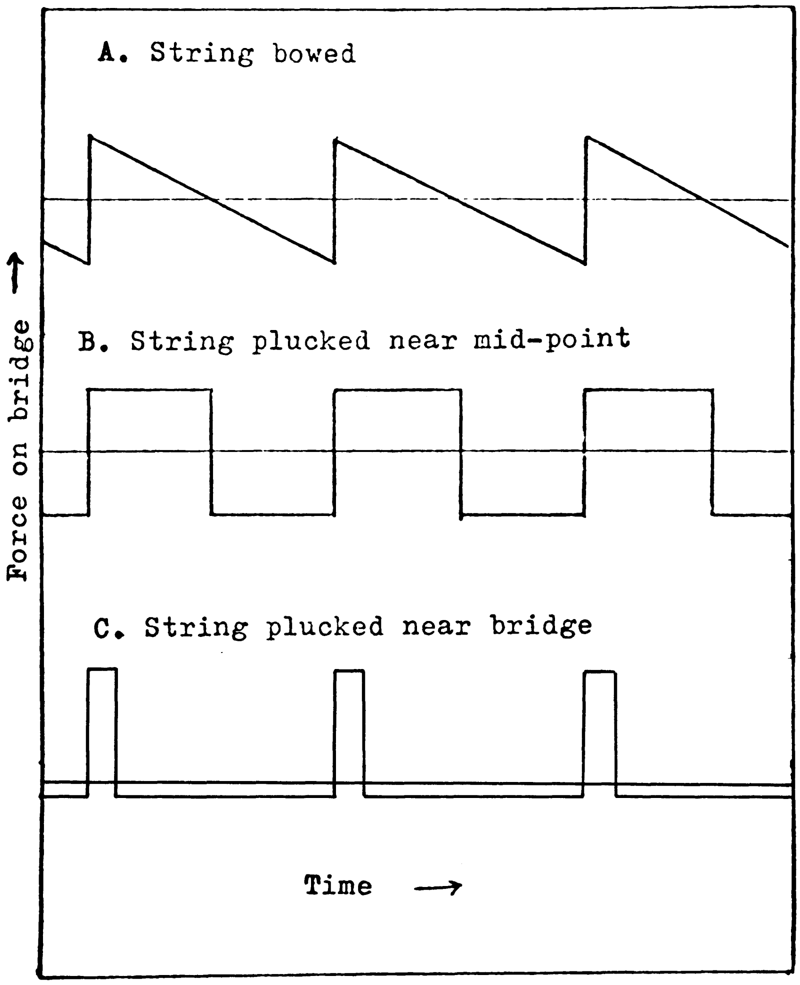


Fig. 5. Vibration forces on the bridge from different string excitations (from Hutchins, 1977, after Schelleng).

If the pluck is near one end of the string a sharp rectangular wave is produced that is rich in high frequency components, (Fig. 5 c, p.156). In this way a wider range of timbre is possible by changing the point of plucking than by changing the point of bowing. The actual change, however, is somewhat less than expected because, in plucking, the high frequency components tend to die out more rapidly than in bowing where they are maintained by the repetitive slip-stick action of the bow.

In spite of their frail structure, the instruments of the violin family are able to withstand the large tension of the strings, which in the violin itself totals around 50 to 60 pounds (25 to 30 kg) weight and in the cello over 100 pounds (50 kg). In the violin this combined string tension exerts a downward force through the bridge on the top plate from 16 to 20 pounds (8 to 10 kg) weight, and a correspondingly larger force on the cello. String tension is determined by the length, mass and frequency of the vibrating section of the string, and is independent of other factors. If a gut string and a steel one have the same mass per unit length, the tension will be identical.

The bending vibrations in the bridge itself have been studied in various ways over the past 50 years. A recent investigation by W. Reinicke (1973) using hologram interferometry on violin and cello bridges mounted on a firm support shows that there are bending moments, which together with the mass of bridge parts give Eigenmodes. In a violin bridge such Eigenmodes are found around 3000 Hz and 6000 Hz, and in a cello bridge around 985 Hz, 1450 Hz and 2100 Hz, Fig. 6 and 7 (pp.158-159). All three of these Eigenmodes in the cello bridge occur to some extent in its legs. Every good violin maker knows that taking even a little wood off the legs of a cello bridge can affect markedly the response of the instrument.

In addition to the vibrations within the bridge itself, the bowed string imparts a rocking motion to the bridge so that the forces which the two feet of the bridge exert downward are in push-pull relationship. Thus, when one foot of the bridge is pressing down the other moves up, i.e. in opposite phase.

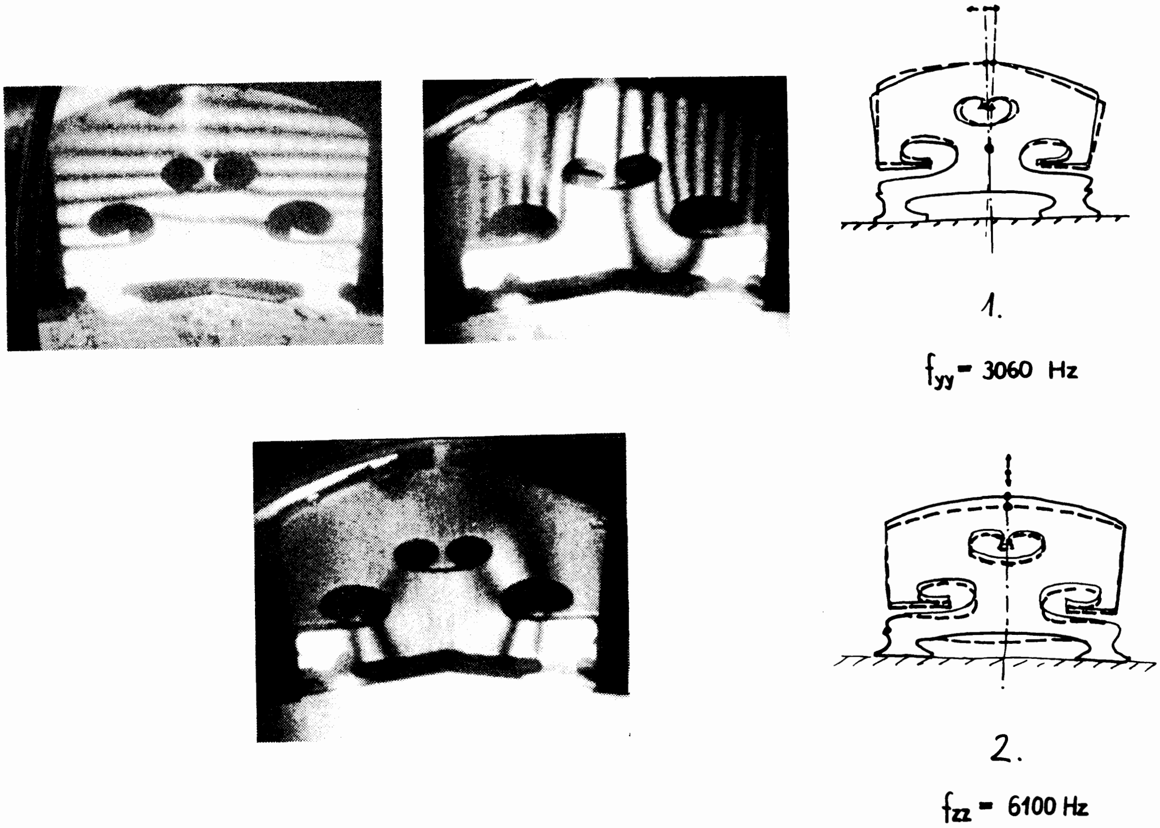


Fig. 6. Interferograms and interpreted Eigenmodes of a violin bridge (Reinicke, 1973).

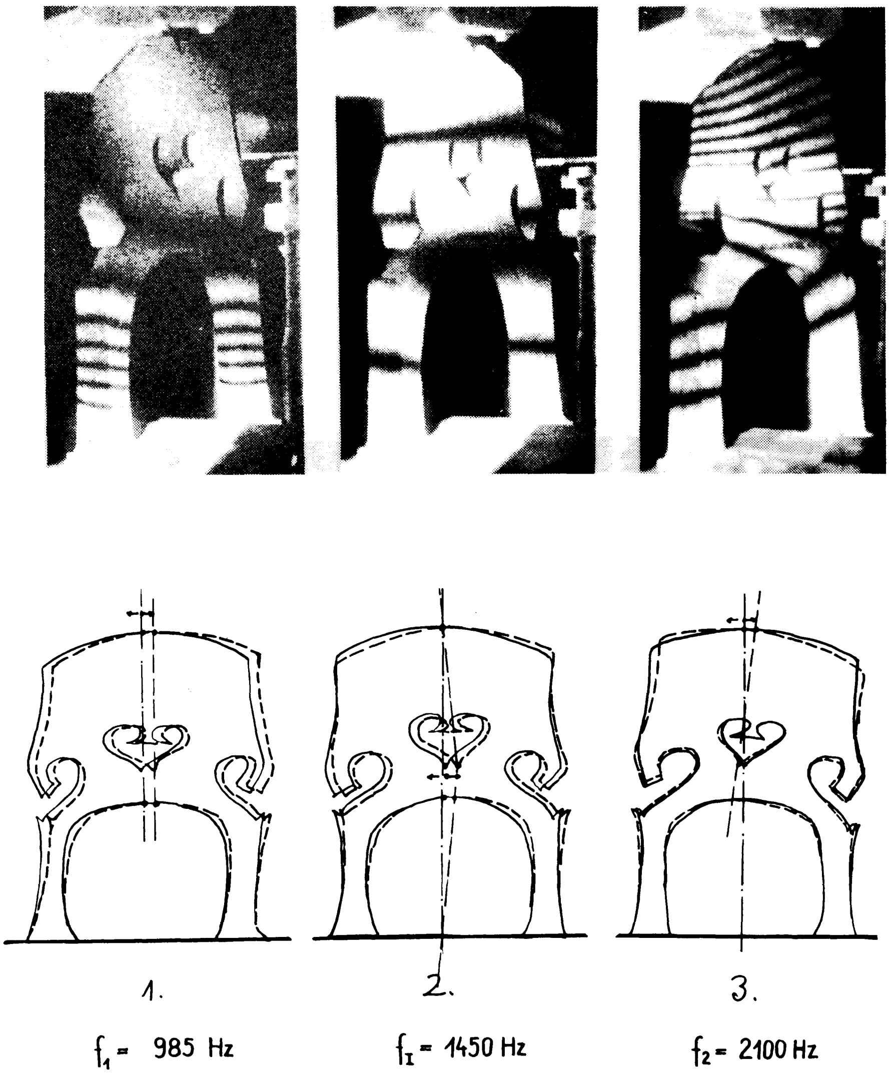


Fig. 7. Interferograms and interpreted Eigenmodes of a cello bridge (Reinicke, 1973).

The less active foot of the bridge rests nearly over the soundpost which tends to stiffen the top and back plates at that point, c.f. Fig. 1. Thus the soundpost acts somewhat like a fulcrum for the rocking motion of the bridge, particularly in the lower octaves. This rocking motion causes important changes in the violin body to occur in step with the left foot of the bridge. Under certain favorable conditions the top and back plates can move inward and outward respectively at a given moment. Then, almost the entire surface of the instrument cooperates to change the volume of the displaced air, thus resembling the surface of an expanding and contracting sphere at certain low frequencies.

The rocking motion of the bridge, in addition to being affected by the bassbar and soundpost, is constrained by the stiffness of the wood between the soundholes, or f-holes. These holes have two chief acoustical functions. First to reduce the stiffness of the floor on which the bridge stands. Second, to form a Helmholtz resonator. The f-shaped holes in instruments of the violin family are not only beautiful in design, but function to free the wood between them from a too rigid anchoring to the nearby ribs. At their upper openings the wood distance between the sound holes is about the same as the width of the outside of the bridge feet for a particular instrument. Together with the walls of the violin box, the soundholes function to form a Helmholtz resonator, or chamber which resonates to specific frequencies. In a resonating cavity with flexible walls, such as the box of the violin, it is not possible to calculate the frequency of the Helmholtz resonance based simply on the volume of air enclosed and the equivalent area of the f-holes. The flexibility or compliance of the walls must be taken into account. For example, the frequency of the Helmholtz resonance of a mezzo violin under construction was found at 227 Hz without the soundpost. With the stiffening effect of the insertion of the soundpost the frequency of this resonance went up to 282 Hz (Hutchins 1974).

Characteristically in instruments such as the violin, whose Helmholtz resonance supports a simple source, the Helmholtz mode is the lowest mode that produces actual radiation of any importance. The timbral impression tends to imply peaks at lower frequencies, when the string is bowed at lower fundamentals. However, this impression arises from resonance at harmonics, not the fundamental. The human ear acknowledges the harmonics, but mistakenly credits them to the fundamental. For example, the strong resonance near A 4 (440 Hz) in the violin reinforces the second harmonic when the G string is bowed at A 3 (220 Hz). Saunders' "Loudness Test" (Fig. 8, lower part) takes this subjective effect into account in that it imitates the subjective process: A scale is played on the violin. The resulting sound is picked up by a microphone and recorded by a sound level meter, which adds responses of harmonics to that of the fundamental. The result is that one

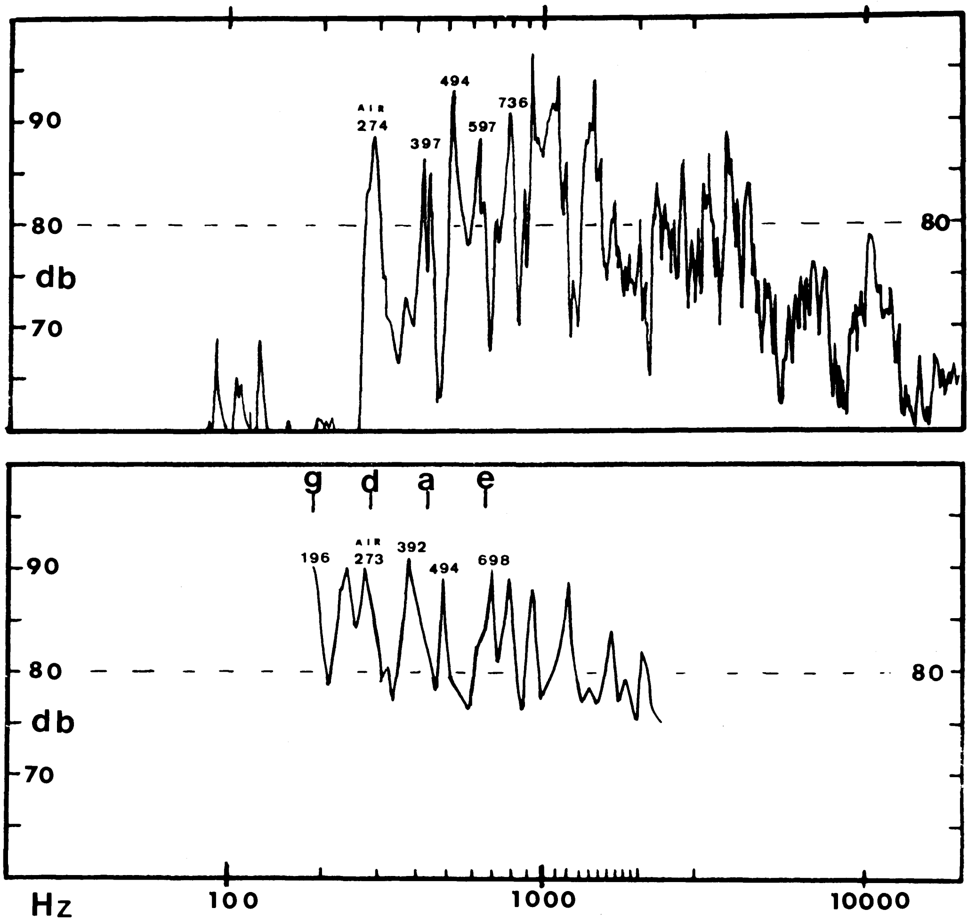


Fig. 8. Response curve of a violin obtained with sinusoidal excitation (upper part) and "Saunders Loudness curve" obtained with hand bowing (lower part).

plots the sum of these as a function of the played fundamental frequency. Narrow band tests made with sinusoidal vibration do not show this effect, as can be seen in Fig. 8 upper part. Thus all response curves made with a sweeping sinusoidal input show the Helmholtz air resonance as the lowest in frequency of the instruments of the violin family, as well as other bowed and plucked instruments, see Fig. 8 (p.159) upper part.

Various researchers from Felix Savart to the present have worked on the effect of the inner air on the tone of the violin. F.A. Saunders found traces of higher air modes but concluded that they are of little significance in the tonal behavior of the violin. He also worked on the idea that the inside air volume consists of two coupled cavities, but could not find enough strong evidence to support his theory. The general conclusion has been that the motion of the air through the f-holes at the frequency of the Helmholtz resonance is the predominating one, and energy in higher air modes is absorbed by the wood rather than radiated.

Recently E.V. Jansson has done a series of definitive experiments on a rigid wall violin-shaped box. They showed that below 2 kHz there are seven air modes above the Helmholtz. Fig. 9.

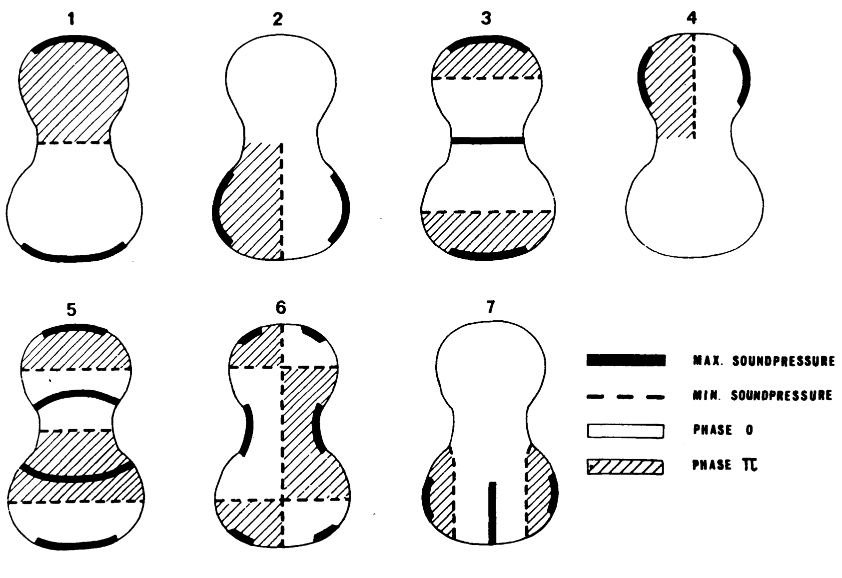


Fig. 9. Seven lowest Eigenmodes of a closed violin shaped cavity (Jansson, 1973).

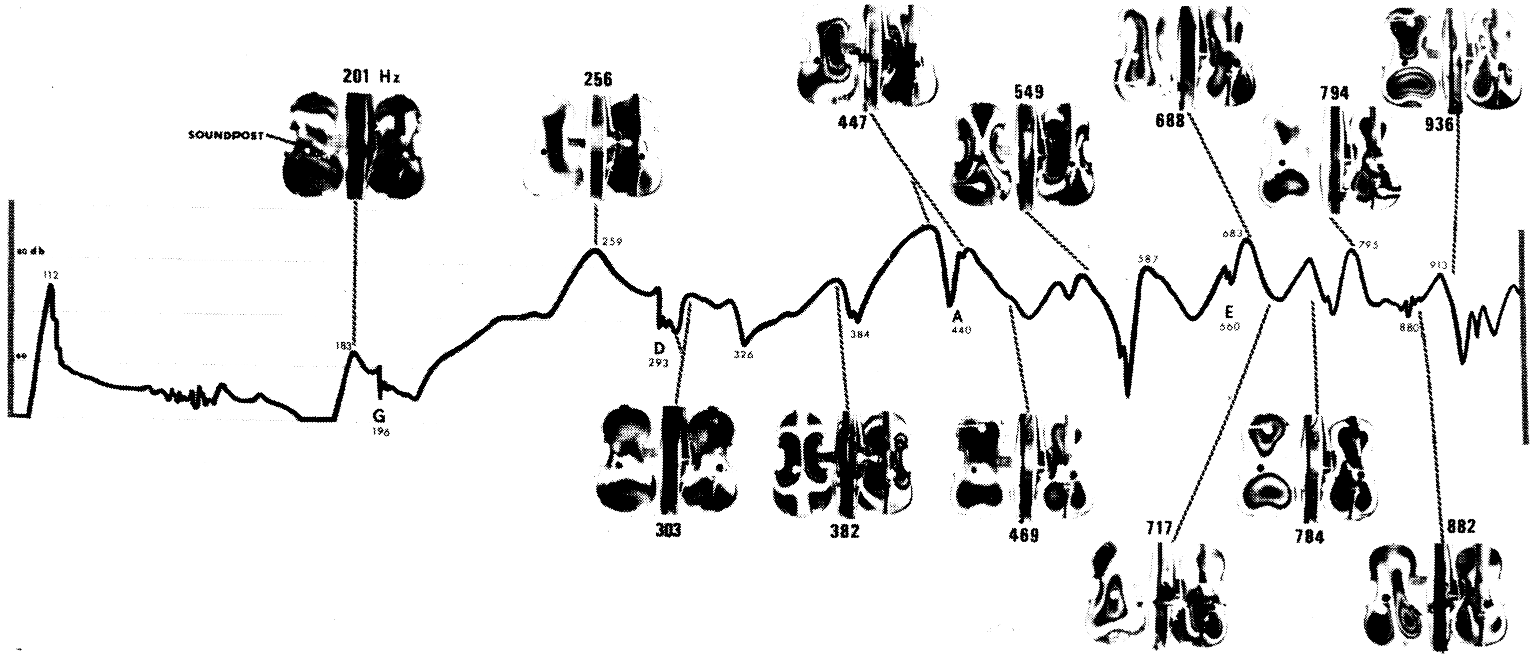


Fig. 10. Sine-response curve with driving coil on bridge and the microphone 36 cm off the top plate and interferograms at peaks of vibration of a complete violin. In the interferograms the violin is shown as normally seen with the bass bar to the left and the soundpost to the right in the top plate and the soundpost to the left in the back plate (SUS 180, response curve by Hutchins, and interferograms by Stetson & Taylor).

These air modes are affected to a greater or lesser degree by the f-holes, depending on the geometry of the f-holes and the box. He also concluded that the air volume acts essentially like two coupled cavities. Moreover, in a normal violin there is at least one higher air mode that is sufficiently coupled to wall vibrations that even though it does not radiate through the f-holes, its acoustical load on the vibrations of the violin body may be important.

The Eigenmodes of the violin body under certain conditions have been visualized by hologram interferometry both in Stockholm by E. Jansson, N.-E. Molin and H. Sundin and by K.A. Stetson and P.A. Taylor in Teddington, England. Fig. 10 (p. 163) shows one of Stetson´s studies compared with a response curve of the same violin made in my test laboratory. These vibration patterns indicate the motions in the wood of the instrument which couple more or less to the surrounding air in various ways, thus transmitting the sounds to our ears. Currently studies of such Eigenmodes of the vibrating violin and the resulting radiations, both phase and amplitude, are being studied by Weinreich at the University of Michigan.

The transfer of energy from bow-to-string-to-bridge-to violin-box- and enclosed air and thence to the surrounding air as acoustic radiation has been observed and measured in many ways for over 100 years. Yet the process is still not completely understood. It is a process that is less than 1 % efficient, with most of the energy imparted to the string from the bow dissipated in heat before it emerges as acoustic radiation in the air transmitting the lovely tones of the violin to the ears of the listener.

IV TUNING OF VIOLIN PLATES

Violin makers traditionally have worked to obtain a "good sound", sometimes described as a "clear full ring" or "tap tone" from the top and back plates of a violin before gluing them to the ribs of the finished instrument. Once the arching contours of both top and back plates are completed on the outside with the purfling installed and the edges correctly shaped, the violin maker begins to hold and tap the freee plate att different points, listening for various sounds. As the wood of the inside is gradually carved away with chisel, plane and scraper, certain sounds begin to predominate. Violin making practice has led to the establishment of average overall thickness contours, depending somewhat on wood quality, of the top and back plates toward which the maker works. The thicknesses of a nearly finished top plate might vary from 2 to 4 mm and those of a back plate from 2 to 6 mm. As a given plate approaches these thicknesses, the trained maker not only taps and listens for certain sounds, but flexes the wood in this hands, feeling for its various stiffness characteristics. The knowledge of the proper feel of the bending wood in his hands and the sounds to listen for are important skills for the trained violin maker, which take literally years to learn and are difficult to communicate to another person, for even a half-millimeter change in certain plate thicknesses can make the difference betweeen a fine sounding and a mediocre instrument.

Just what is the violin maker hearing and feeling as he taps and flexes the nearly finished violin plate? What are the physical characteristics of the bending vibrations in the beautifully carved shell-like piece of wood that he holds in his hands? How can the master violin maker´s instuitive knowledge be measured and what are the physical mechanisms that can make such a difference in the sounds of the finished violin?

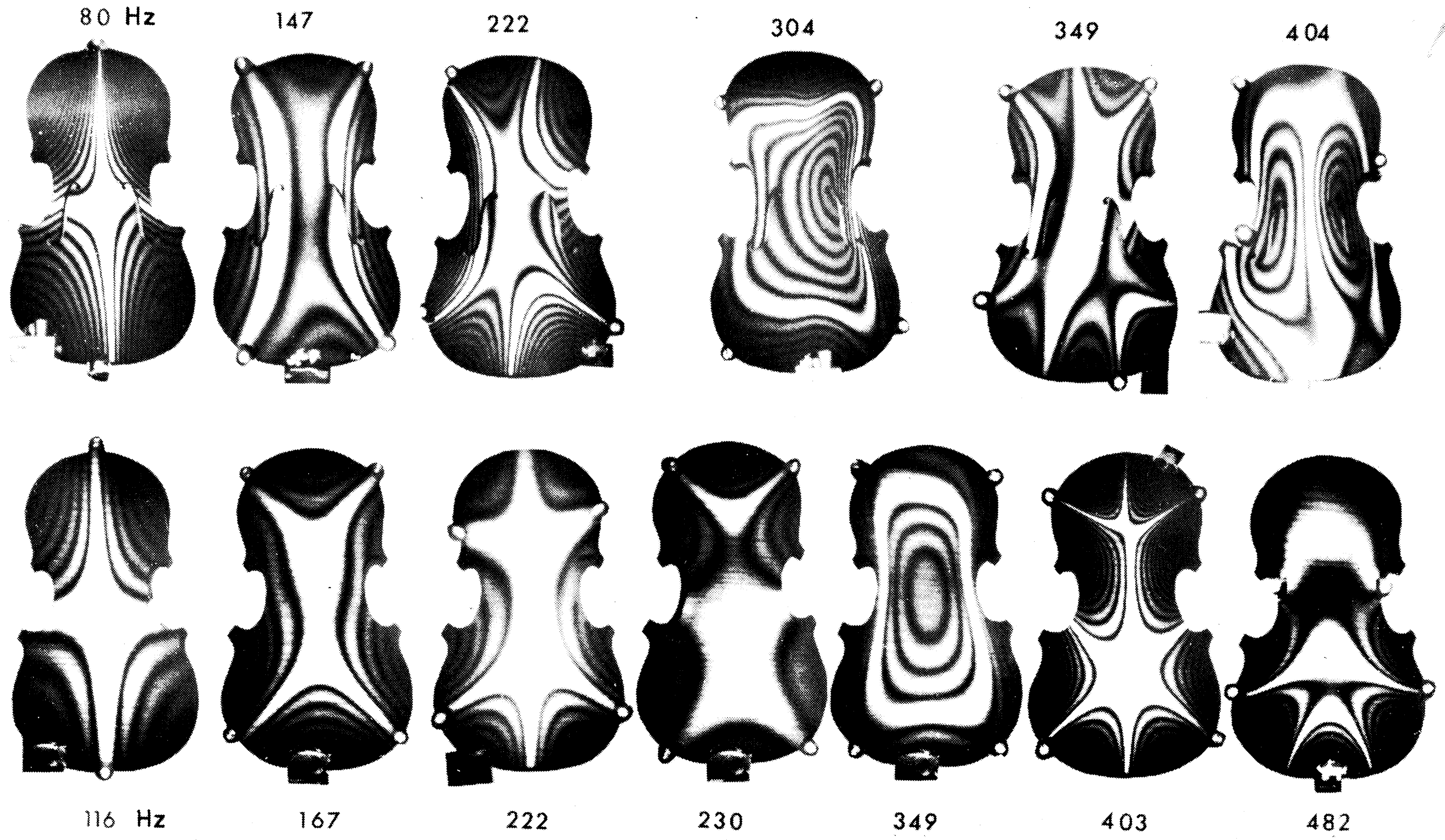


Fig. 1. Interferograms of two well tuned violin plates; top plate (upper row) and back plate (lower row, interferograms by courtesy of K.A. Stetson).

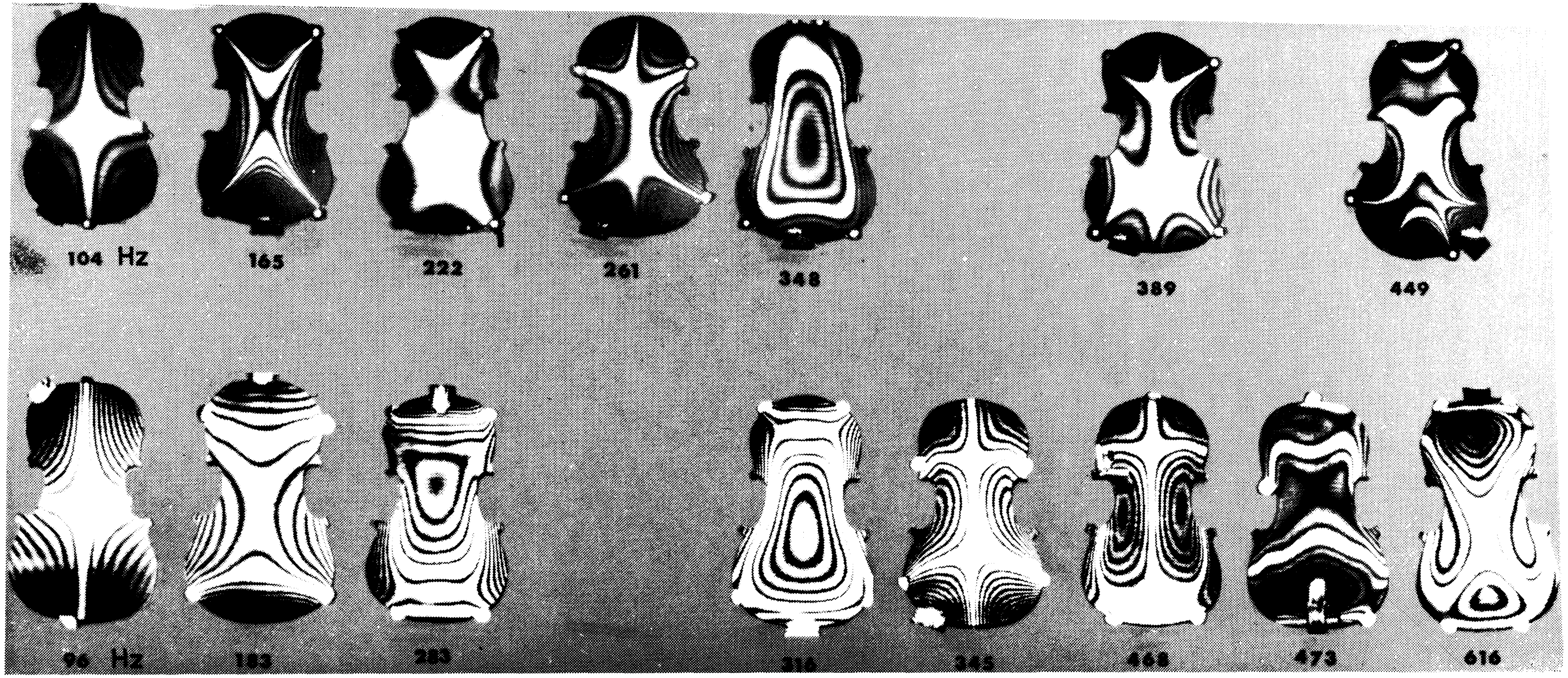


Fig. 2. Interferograms of Eigenmodes of a "free" back plate and of the back plate glued on ribs with no top plate (violin SUS 181, interferograms by K.A. Stetson).

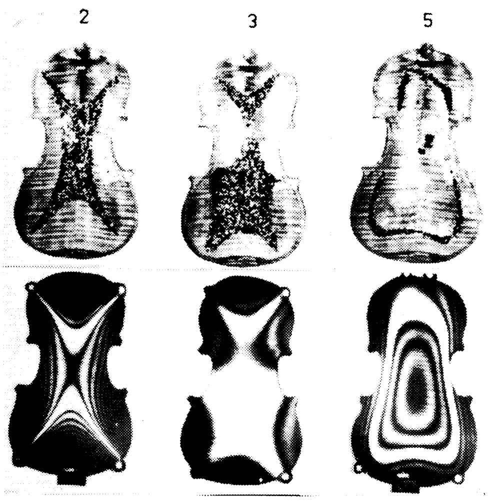


Fig. 3. Glitter patterns (upper row) and interferograms (lower row) of some modes of a free back plate (violin SUS 181, interferograms by courtesy of K.A. Stetson).

"cross mode" have been found to be the most helpful in measuring and judging the resonant characteristics of free violin type plates.

To get a pair of violin plates ready for tuning, the outside arches of both top and back should be completely finished, scraped smooth and the purfling installed but without f-holes. Also the inside gouging and planing should be done roughly to somewhat thicker dimensions than planned for final plate thicknesses. For example, a violin top plate could be brought to 4 mm all over and the back plate to 4 mm in the upper and lower areas and 6 mm between the C bouts. An experienced maker can work closer to final thicknesses than this, but at first it is safe to start this way.

Tuning the top plate

At this stage the violin top plate is mounted upside down like a dish over the speaker cone on the four soft foam pads, one near each corner. The inside surface is sprinkled with flake, the ring mode should be found somewhere between 350 to 450 Hz. The more even and the more ideal the realtions between the archings and the thickness graduations are, the clearer this mode will be. The glitter patterns should look like those in

Fig. 4 and 5. In Fig. 4 the patterns are shown of mode No 5 of ten different top plates, which vary in thickness, archheight and shape of arch. All ten plates have bassbars installed and tuned. The nodal lines are somewhat different because of the different characteristics of the plates. Notice that one plate has no f-holes. Fig. 5 shows the glitter patterns for mode No 2 of the same plates.

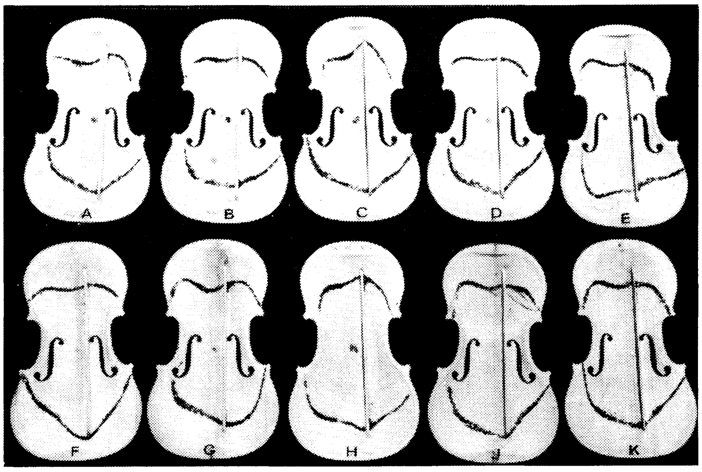


Fig. 4. Glitter patterns of mode No 5 (the ringmode) of 10 different but tuned free violin top plates (courtesy of G. Bissinger).

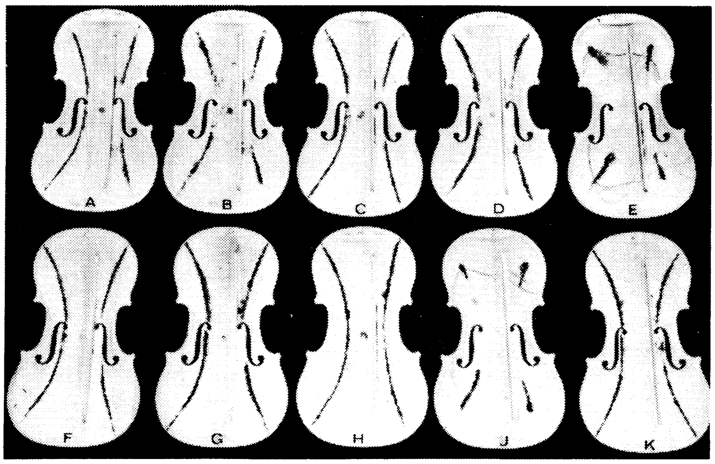


Fig. 5. Glitter patterns of mode No 2 of 10 different, but tuned violin top plates (the same plates as in fig. 7, courtesy of G. Bissinger).

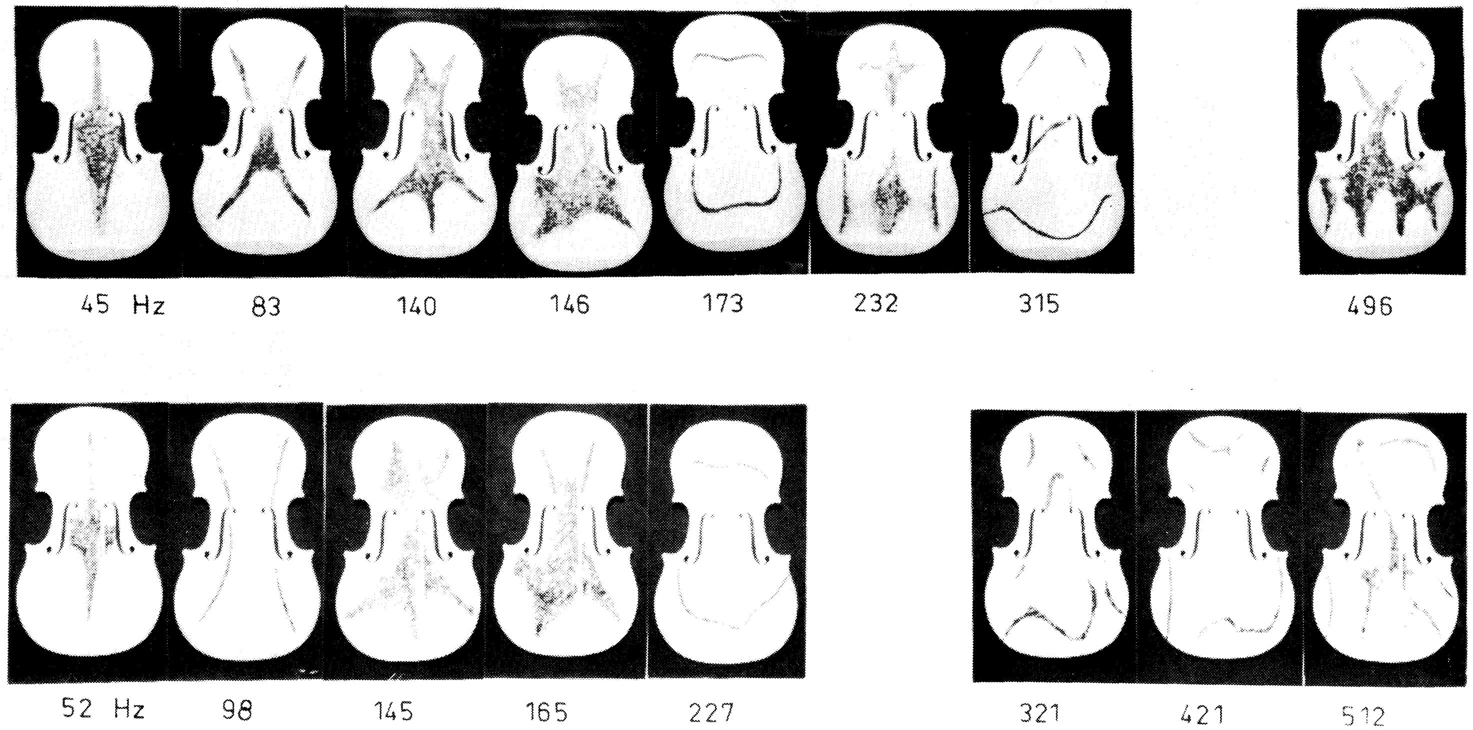


Fig. 6. Glitter patterns of tuned free 20" (51 cm) alto top plate without bassbar (upper row) and the same plate with tuned bassbar (lower row).

As the wood is brought down nearer to ideal thicknesses the frequency of this mode will decrease. The thinner the wood, the less stiff and the lower the frequency of its resonant modes.

In learning to use the method it is interesting to first thin the whole lower section, then the upper, and then the area between the C-bouts, testing and watching the mode shape change under varying stiffnesses in different parts of the plate. When the top plate has been brought to desired thicknesses, the frequency and shape of the ring mode should be recorded. The thicknesses preferred depend on wood quality but also on given violin making practice. Typical measures for the normal 14" (36 cm) violin are 2.5 mm all over the lower area, 2.0 all over the upper, and 3 to 3.5 between the C-bouts. The next step is to cut the f-holes and test again. Then the bassbar is intalled leaving its contours somewhat higher than final dimensions. The off-center bar completely upsets the nice symmetrical shape of the ring mode and raises its frequency. However, it is possible to get the ring mode back to near symmetry. This can be achieved by gradually shaping the bar, thinning it and lwoering its height in a series of stages, first the upper section, then the lower, then the middle. All the time the mode changes are repeatedly checked regarding both shape and amplitude, which is judged by the height of the bouncing particles.

Fig. 6 (p.172) compares glitter patterns before the bassbar has been glued to the top plate of an alto (upper series) and after the bassbar has been mounted and tuned (lower series. Note that the ring mode at 173 Hz is very symmetrical without bassbar. With the bassbar installed and shaped down, this mode can be brought back to near symmetry, with the nodal lines near the four corners. However, its frequency thereby changed from 173 Hz up to 227 Hz.

It there is no filler or varnish on the outside of the plate, particularly the top, where the cross-grain spruce is stiffened markedly by the coatings, it is well to leave the bassbar slightly higher than optimum to offset the subsequent stiffening effects of the coatings. "Optimum" in this case has been found to be when the nodal lines of the ring mode intersect the four corners of the plate as in Fig. 7.

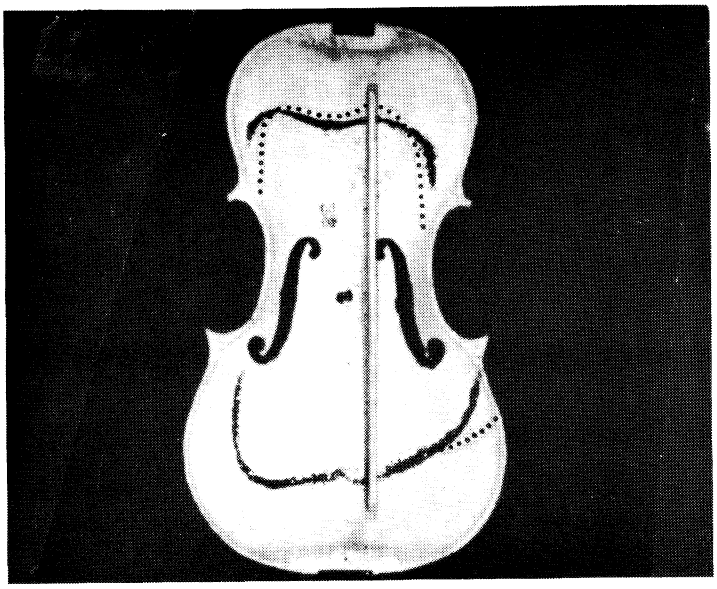


Fig. 7. Effect of varnish on mode No 5: before varnishing (dotted lines) and after varnishing the glitter pattern.

Coatings of both filler and varnish on the outside of the plates not only add mass, but considerably stiffness as well, depending on the quality of the varnish. Added stiffness tends to change the modes of top and back plates differentially. The crossgrain spruce of the top being the most flexible is most affected. Thus mode No 2 in the top plate increases in frequency, sometimes as much as 10 to 15 Hz, depending on the stiffness of the coatings and the crossgrain stiffness of the wood. Mode No 5 in the top plate usually increases only about 3 to 5 Hz, but will tend to get detuned because the wood of the plate is stiffened by the coatings, while the bassbar is not. The back plate, being somewhat thicker and less isotropic, is less affected for both modes No 2 and No 5 than the top plate. The effect of varnish is considerable as can be seen from the glitter patterns and frequency responses, see Fig. 8. (p. 175).

VARNISH

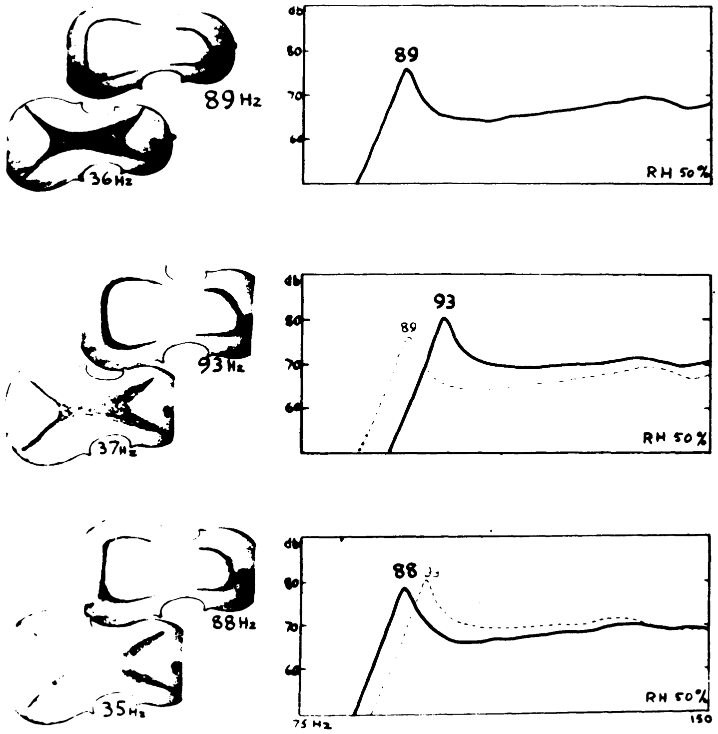


Fig. 8. Effect of varnish on modes No 5 and No 2 (EM 5 and 2),mass and frequency response of a bass back plate (relative humidity 50 %): with filter only, 1793 g, EM 5 at 89 Hz and EM 2 at 36 Hz (upper row), four coates of varnish, 1855 g before tuning EM 5 at 93 Hz and EM 2 at 37 Hz (middle row), and after retuning E 5 at 88 Hz and EM 2 at 35 Hz (lower row).

Thus we find it desirable to put filler and at least two coats of "tuning" varnish on the outside of both plates before final tuning. This then is rubbed back almost to the wood before final varnish is applied to the completed instrument.

Changes in relative humidity also affect the plate modes differentially. A pair of plates ready for final tuning should be kept together in as constant conditions of humidty and temperature as possible for at least a week, particularly if humidity is increasing.Fryxell (1965) has shown that moisture absorption by violin plates, whether coated on one side or not, will absorb moisture very slowly (over a period of many months) but will lose it quickly (within 48 hours). If the plates are in the process of humidity change, considerable internal stress is set up within the wood causing the modes to vary widely. Fig. 9 shows measurements made by Rex Thompson (1979) on a pair

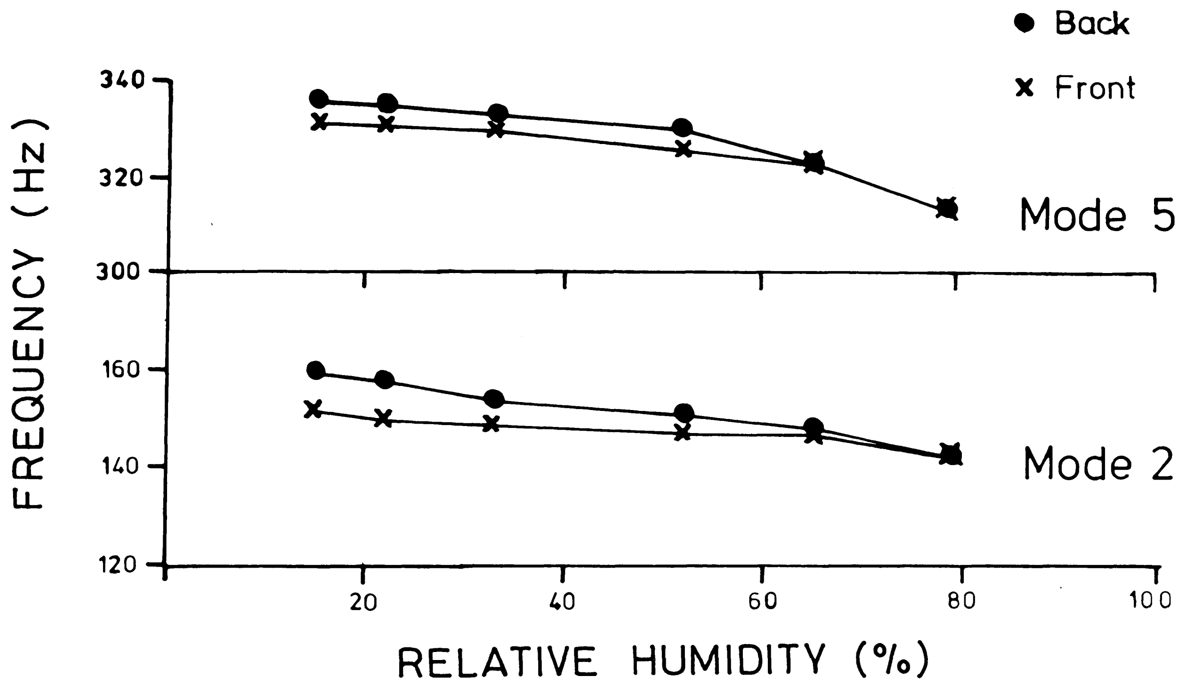


Fig. 9. Effect of humidity on the frequency of modes No 5 and No 2 for the two plates of Mezzo Violin SUS 108 (from Thompson & Hutchins, 1979).

of tuned mezzo violin plates that had had filler and varnish on for two years. The effect of changes in relative humdity is also considerable on vibration patterns and frequency responses, see Fig. 10.

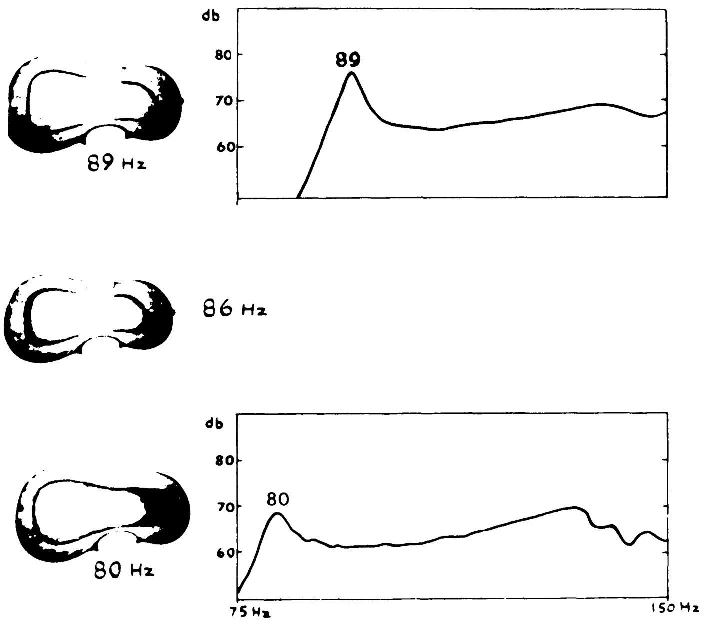


Fig. 10. Effect of relative humidity (RH) on mode No 5 mass and frequency response of a bass back plate: 50 % RH, 1793 g and 89 Hz (upper row), 70 % and 86 Hz (middle row), and 85 % RH, 1825 g and 80 Hz (lower row).

Listening and feeling

During all the process described above it is well to check the sound of the plate and the feel of it in one´s fingers. Notice when holding and tapping, that holding the plate on the nodal line (where the flakes pile up) and tapping in the center of an active area produce the best sounds. This is somewhat like mounting a seesaw in the middle and pushing at one end. One side goes up and the other down around the holding or nodal point.

Mode No 1, (see Fig. 1 p. 166 upper left), can be heard best by holding the plate on its center line and tapping the side of the upper or lower bout. Mode No 2 (Fig. 1 p. 166 upper second) sound best when the holding point is at an edge where one of its nodal lines intersects and the tapping done at the middle of the bottom or top edge. Mode No 5 (Fig. 1 p. 166 upper fourth) can be heard clearly by holding on its nodal line and tapping in the center of the plate, or around the edge.

If the plate is held where the nodal lines of both mode No 5 and No 2 intersect, the two sounds are heard clearly. This is usually the way the violin maker holds and taps the plate for that clear full ring. If modes No 5 and No 2 happen to be an octave apart a very clear full ring is heard. Whether or not this is an important relationship for good tone in the finished instrument has not yet been determined.

Violin makers also check the bending stiffness of the upper and lower plate areas by squeezing first one end and then the other cross-grain between the thumb and the fingers of both hands, in an effort to attain similar stiffnesses in the upper and lower plate areas. Some even lay the plate outside up on a flat surface and place a shallow dish of water on the outside of the arch first on the lower area at one end and then on the upper. By pushing gently on the arch and observing the motion of the water the relative stiffnesses of the lower and upper plate areas can be compared.

Mode No 2, the cross mode, is very useful in checking these relative stiffnesses of the upper and lower areas of a plate. The frequency of mode No 2 is usually somewhere near half that of mode No 5. In setting up to test for this mode, the four foam pads must be placed where the nodal lines intersect the edges, with the speaker under the antinodal area of one end or the other, NOT under the middle of the plate. The shape and activity of the upper and lower sections of this mode give an excellent indication of the realtive stiffnesses in the two plate areas. This is illustrated in Fig. 11.

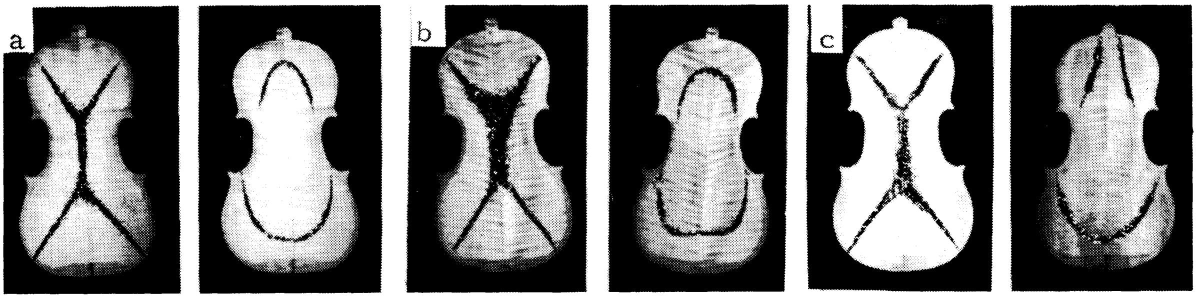


Fig. 11. Effects of vibration balance of free violin back plates on mode No 2 (left) and mode No 5 (right): a) plate graduations well balanced , b) too stiff upper area gives wide nodes of mode No 2 in upper area (middle pair), and c) too thick area between the C-bouts gives nodal lines too long and off the edge of mode No 5 in upper part (right pair).

Both good violin making practice and the use of this method for over ten years in the making of nearly 100 intruments indicate that the upper area of a given plate should be about 0.5 mm less in thickness than the lower to attain similar stiffnesses, since the lower plate area is usually larger than that of the upper. Only in the big viola pattern of Gasparo de Salo have the upper and lower area plate thicknesses turned out to be the same. But here the two areas are about the same size also. On the other hand in the Stradivarius viola pattern where the upper area is much smaller than the lower, the upper turns out to be nearly 1.0 mm less thick when the plate is well tuned.

Tuning the back plate

Once the top plate, complete with bassbar and f-holes, has been brought to "optimum" condition, then a similar process of thinning and testing for modes No 2 and No 5 is applied to the back plate. Here the important things to work for are a closed ring-shape for mode No 5 with high amplitude, and a balanced upper and lower mode shape for No 2. Also the frequency of mode No 5 in the back plate should be within a tone of mode No 5 in the finished top plate. The reason for finishing the top plate first is that it is easier to lower the frequency of the back plate than to adjust the frequency of the top plate with the bassbar in. Sometimes the nodal line of mode No 5 remains an off-sided oval, which is probably due to the tilt or skew of the wood grain in the two halves being different. This does not seem to affect the tone of the finished instrument adversely though. However, if the ring shape of mode No 5 is not closed in the upper area, careful checks should be made by means of mode No 2 to balance the stiffnesses.

Where to take off wood?

This is the greatest problem in the thinning and tuning process. To understand some of the mechanisms involved it is most helpful to look at the interferograms of a pair of violin plates. Fig. 1 shows the mode sequence of the first seven modes of a vibrating top and back plate. The top plate was "well tuned", included f-holes and bassbar and was measured free. Incidentally mode No 4 is missing in the top plate sequence.

In the interferograms, the nodal lines, or areas of no motion are indicated by large white sections,(while in the particle patterns they are black), as was mentioned above. It was also mentioned that the actively vibrating antinodal areas appear as a series of alternating dark and light bands which indicate the amount of vibration or bending at this frequency over the entire plate. The closer the lines, the greater the change of vibration between adjacent points. Bending occurs where the lines change from closer to wider spacing, indicating a curving of the plate. Equal spacing of the lines indicates a straight slope of vibration, for instance the up and down motion of a seesaw around its nodal point, i.e. translation.

But how does this indicate where to remove wood? If a lower frequency is desired for a certain mode, then the wood should be thinned in the areas of greatest bending for that mode. If a higher frequency, then wood should be removed from a non-bending area of that particular mode. Removal of mass (wood) raises frequency, while reduction of stiffness lowers frequency.

Reducing the thickness of a plate at any point reduces locally both stiffness and mass; however, the effect on frequency at which the plate as a whole vibrates depends on whether vibration at that point is (1) predominantly translation, (2) predominantly bending, or (3) some intermediate condition. In the first case, frequency increases with removal of wood, in the second it decreases, and in the third there might be either an increase or a decrease. Thus shaving wood from a predominantly bending area of a given mode will mainly decrease the stiffness and thus also lower the frequency of that mode; removal of wood from a nonbending area of a mode will mainly decrease the mass and thus increase frequency of that mode.

In actual practice removal of wood from the center between the C-bouts will raise the frequency of mode No 5, for there is practically no bedning in this area. Removal of wood from just inside the four corners will lower the frequency of mode No 5, for this is a bending area for mode No 5. It should be pointed out that the frequency decreases with removal of wood from a bending area (reduction of stiffness) considerably faster than it will increase with removal of wood from a non-bending area (reduction of mass) of a given mode.

When listening to the sounds as one holds and taps a free plate, the mechanism which is at work can be visualized by superposing, for example, the first five or six transparencies of the interferograms, one on another, of Fig. 1. A point source of excitation, such as tapping, will activate all modes to a greater or lesser degree, depending on relative modal activity and damping.- it being desirable to hold the plate loosely at the nodes. The sound heard as a result of this contains contributions from all modes in accord with the place of excitation and the effect of holding.

This can help to explain why there are many different interpretations among violin makers as to the sounds in a violin plate and what to do about them. Our work has been an effort to provide an understanidng of the basic mechanisms involved and to suggest ways of utilizing them in the construction of fine violins.

V THE NEW VIOLIN FAMILY

The application of modern technology to the violin family during the past 25 years by a group of dedicated scientists, engineers, musicologists, performing musicians, instrument makers, composers and interested laymen in the Catgut Acoustical Society has made possible the emergence of an new family of violins. The eight instruments that now constitute the new violin family have been constructed in the basis of mathematical design and electronic testing combined with classical violin making skills (Hutchins, 1967). They cover the range between the low tones of a seven foot (2.1 m) contrabass violin and the high tones of a tiny treble violin tuned an octave above the classical violin. Spaced at approximately halfoctave intervals over this range, Fig. 1 (p. 183) the new instruments are intended to create new sounds in the violin family as well as to augment but not replace the older string instruments in achieving a balance within a large symphony orchestra where the classical strings are in a critical position in having to compete with disproportionately stronger wind and percussion instruments. Although brass, woodwind, percussion and even keyboard instruments have been developed to produce more power and brilliance of tone, no comparable growth has, until now, taken place in the strings.

How the new instruments were developed

In 1958, during a long series of experiments to test the effect of moving violin and viola resonances up and down scale, the composer in residence at Bennington College, Henry Brant, and the cellist, Sterling Hunkins, proposed the development of eight violin-type instruments in a series of tunings and sizes to cover substantially the whole pitch range used in written music; these instruments would start with an oversize contrabass and to to a tiny instrument tuned an octave

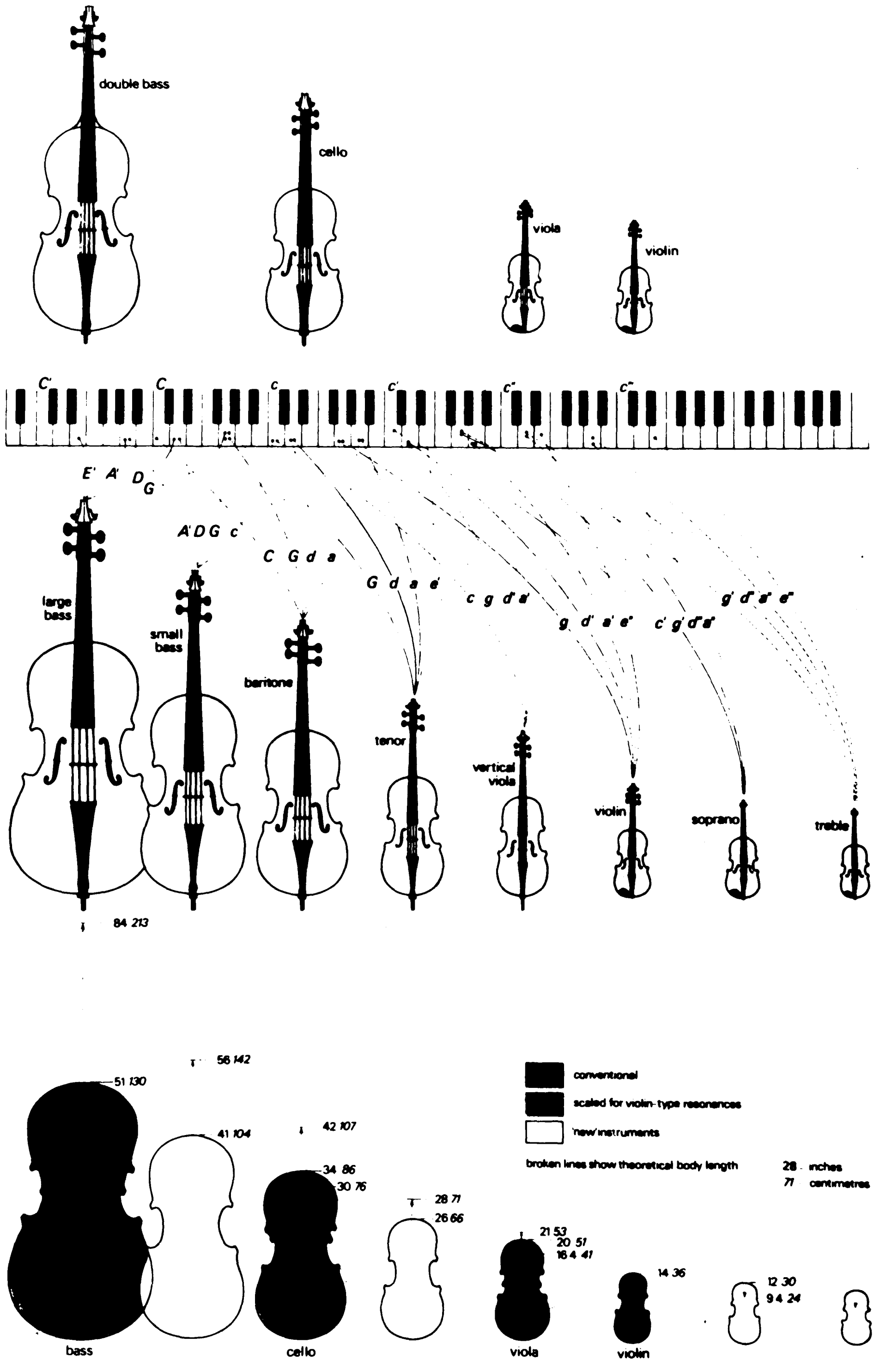


Fig. 1. The conventional and the new violin family.

above the violin. Their request was so closely related to our experimental work that after half an hour´s discussion, Frederick A. Saunders and I agreed that a serious attempt would be made to develop the set. The main problem would be to produce an instrument in each of the eight frequency ranges having the dynamics, the expressive qualities and overall power that are characteristic of the violin itself, in contrast to the conventional viola, cello and string bass.

From ten years experimentation the following four working guides were at hand:

1) location of the main body and main cavity resonances of several hundred conventional violins, violas and cellos tested by Saunders and others,
2) the desirable relation between main resonances of free top and back plates of a given instrument, developed from 400 tests on 35 violins and violas during their construction,
3) knowledge of how to change frequencies of main body and cavity resonances within certain limits (learned not only from many experiments of altering plate thicknesses, relative plate tunings and enclosed air volume but also from construction of experimental instruments with varying body lengths plate archings and rib heights) and of resultant resonance placements and effects on tone quality in the finished instruments,
4) observation that the main body resonance of a completed violin or viola is approximately seven semitones above the average of the main free-plate resonances, ususally one in the top and one in the back plate of agiven instrument. This observation came from electronic plate testing of free top and back plates of 45 violins and violas under construction. The change from two free plates to a pair of plates coupled at their eges through intricately constructed ribs and through an off-center soundpost, the whole under varying stresses and loading from fittings and string tension, is far too complicated to test directly or to calculate. Thus we have not yet been able to decipher this apparent shift of free-plate resonances to those of the finished instrument.

In developing the new instruments our main problem was finding a measurable physical characteristic of the violin itself that would set it apart from its cousins, the viola, cello and contrabass. The search for this controlling characteristic, unique to the violin, led us through several hundred response and "loudness curves" of violins, violas and cellos, Fig. 2.

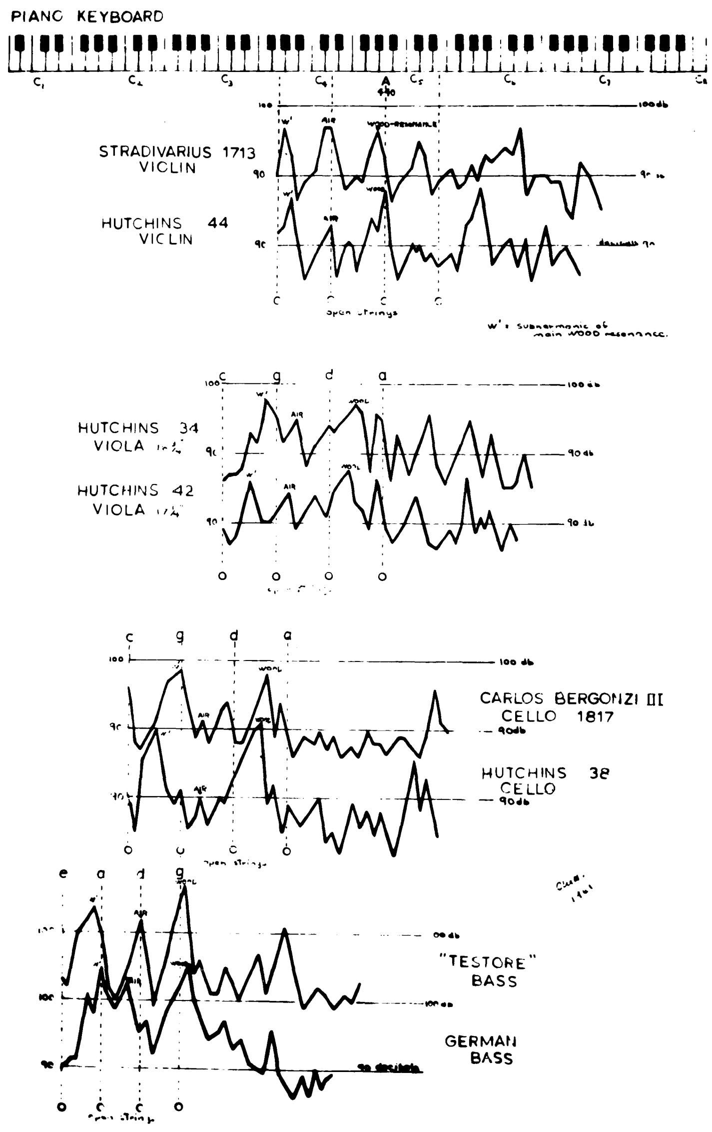


Fig. 2. Loudness curves of conventional instruments showing main wood and main air resonances.

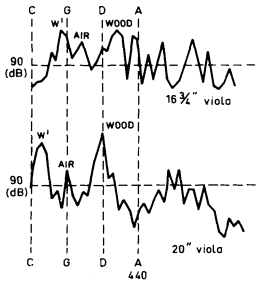


Fig. 3. Loudness curves showing relative placement of main wood (wood) and main air resonance (air) in a conventional 16 3/4" (42.5 cm) and a new 20" (50.8 cm) new viola.

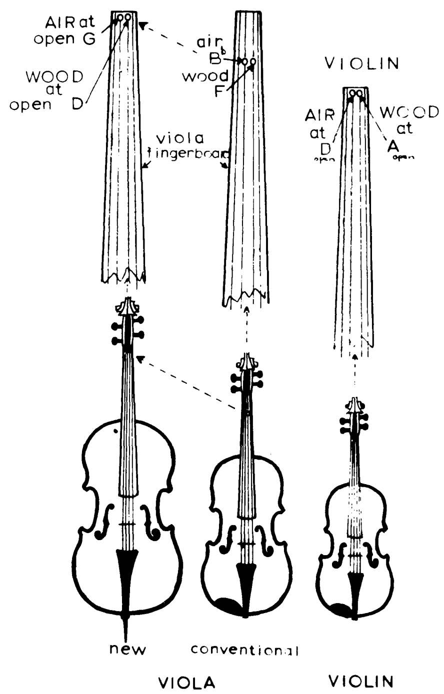


Fig. 4. Scaled dimensions give violin-type resonances to new 20" (50.8 cm) viola.

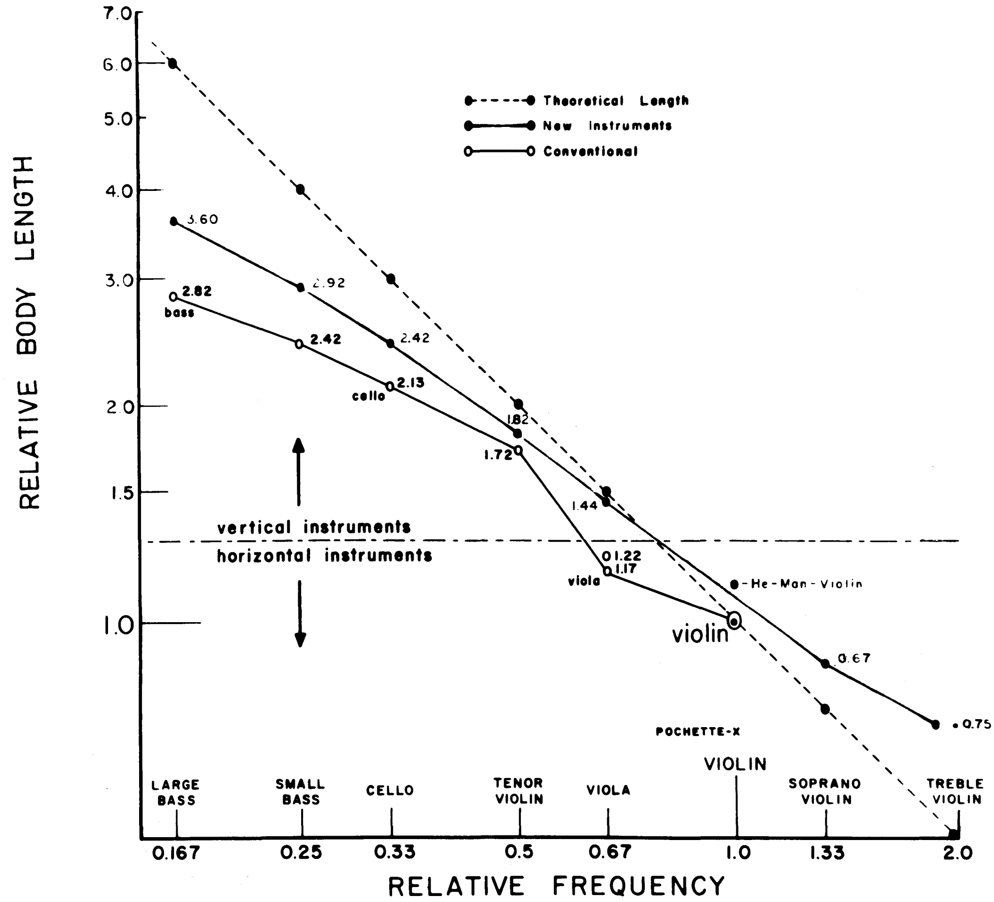


Fig. 5. Scaling to the violin.

The picture was at first confusing because many variations were found in the placement of the two main resonances. However, Saunder´s tests on Jascha Heifetz´s Guarnerius violin showed that the main body, or main wood resonance, was near the frequency of the unstopped A 440 Hz string and the main cavity or air resonance at the unstopped D 294 Hz string. Thus the two main resonances of this instrument were near the frequencies of its <u>two unstopped middle strings.</u>

Ten violins, selected on the basis that their two main resonances were within a whole tone of their two open middle strings, were found to be some of the most musically desirable instruments - Amatis, Stradivaris, Guarneris and several modern ones. In marked contrast to these were all violas and cellos tested, which characteristically had their main body and cavity resonances three to four semi-tones <u>above</u> the frequencies of their two open middle strings although they still had the same separation, approximately a musical fifth, between these two main resonances.

Using the principle exemplified by Heifetz´Guarnerius violin, of having the two main resonances at approximately the frequency of the two unstopped middle strings, we spent five years working first to adapt existing instruments where possible, and then to construct new ones where no reasonable approximation could be found, Fig. 3 and 4 (p. 186). Professional string players, composers, and a few expert violin makers including Rembert Wurlitzer were most helpful in criticising and suggsting ways in which the instruments could be made as playable and as musically effective as possible. A scaling theory for the new instruments was developed by John C.Schelleng which made it easier to predict how the wood and air resonances were going to fall in a given size instrument, Fig. 5 (p.187).

The big bass turned out to be seven feet from scroll to endpin, but we adjusted the playing relationships to that a 5'6" (1.7 m) player could manage it nicely. A 2 m tall bassist was not needed. At the other end of the family the treble violin had a body size not much greater than a large man´s hand, but was constructed with ribs made of aluminium so that four holes could safely by bored in the ribs without cracking them to raise the frequency of the cavity resonance to approximately D 586 Hz. (Subsequent treble violins have been made successfully with wooden ribs and the area around the holes lined with linen.) Without the holes, our calculation showed that the treble ribs would need to be only 3 mm high - a dangerous situation considering the amount of tension of the strings. New strings had to be developed for each of the new instruments and tested for suitable playing qualities. Carbon rocket wire, with a tensile strength twice that of conventional music wire was found for several of the new strings, particularly the top ones on the treble, soprano and tenor. The measurements and the scaling factors of the conventional and of the new violin family are given in table I (p. 190).

By 1965, with serveral interim musical trials, the new violin family was ready for its first public performance. Since then the eight new instruments have been transported more than ten thousand miles in the USA, Canada, England, Germany and Sweden, where they have been used by invitation in over 150 lectures and concert-demonstrations. Physicists and engineers are excited about the application of scientific research to creative art, and open-minded musicians and composers are challenged by dimensions in string sound that have never before been available. But as exciting and challenging as these new instruements seem to be, they should not be considered an end in themselves, but as one step in the controlled experimentation and development in instrument making to help meet the future needs of the bowed strings.

The musical potential

Frank Lewin, who has worked closely with the new instruments for some years has said:
"There are three ways in which the new instruments can be used: 1) to augment the capability of the strings in the symphony orchestra; 2) in ensemble, using various combinations of the new instruemnts as a body, either as a selfcontained group of strings, or blending and contrasting with conventional wind and percussion instruments or electric sources; 3) as solo instruments possessing certain distinctive characteristics and tone colors. I can see a temendous use, for example, for the contrabass violin with its wonderfully rich low range and strong pizzicato. I can imagine the powerful sound a group of these basses would contribute to the realization of a Mahler symphony. The same would be true of a group of bari-

Table I. Measurements and scaling factors for the conventional (underlinings) and the new violin families. The scaling factors are based on the violin as 1.00 (Catgut Acoustical Society, Inc. 1974).

Instrument			Length in cm			Relative Scaling Factors		
Name	Tuning	Hz	Overall	Body	String	Body length	Resonance placement	String tuning
TREBLE	G D A E	392 587 880 1319	48	28.6	26	.75	.50	.50
SOPRANO	C G D A	262 392 587 880	54-55	31.2	30	.89	.67	.67
MEZZO	G D A E	196 294 440 659	62-63	38.2	32.7	1.07	1.00	1.00
VIOLIN	G D A E	196 294 440 659	59-60	35.5	32.7	1.00	1.00	1.00
VIOLA	C G D A	132 196 294 440	70-71	43	37-38	1.17	1.33	1.50
ALTO	C G D A	132 196 294 440	82-83	50.8	43	1.44	1.50	1.50
TENOR	G D A E	98.0 147 220 330	107	65.4	60.8	1.82	2.00	2.00
CELLO	C G D A	65.4 98.0 147 220	124	75-76	68-69	2.13	2.67	3.00
BARITONE	C G D A	65.4 98.0 147 220	142	86.4	72	2.42	3.00	3.00
SMALL BASS	A D G C	55.0 73.4 98.0 131	171	104.2	92	2.92	4.00	4.00
BASS	E A D G	41.2 55.0 73.4 98.0	178-198	109-122	104-117	3.09-3.43	4.00	6.00
CONTRA-BASS	E A D G	41.2 55.0 73.4 98.0	213-214	130.0	110	3.60	6.00	6.00

tones and alto violins, as well as of the mezzo violins. In ensemble, the particular virtue of the new instruments, their ability to blend smoothly, can be exploited. Since there are no gaps in the overlapping ranges, each instrument can play in its best register without being called upon to fill in where other instruments are weak ... These new instruments are extremely effective in parts where the composer can explore the new colors they offer. I find these sounds exciting and have been able to use some of them in film recordings, especially the tenor and contrabass violins in solos. They produce sounds we do not get from conventional stringed instruments.

"Other properties that set these new instruments apart are the tremendous resonance and the powerful low ranges in both the alto and baritone violins. The C-string of the alto violin (viola) produces a sound I have never heard before in that range; the same is true of the C-string of the new baritone violin (cello). The beauty of sound produced by the new instruments speaks to the listener even when they are played at the extreme of their dynamic range".

"On the other hand, music of earlier periods, especially polyphonic vocal music, sounds beautiful when played on these instruments. The individual voices maintain their own colors in contrapunctal parts, yet blend into a homogeneous whole, similar to the effect of a good choir. This capacity for blending is reminiscent of the viols, yet since the new violins have a much greater dynamic range than either viols or the conventional strings now in use, full passages - especially chordal ones - suggest organ sonorities.

"The most exciting use for the new instruments is, of course, in new music composed specifically to exploit their particular character. The Catgut Acoustical Society is breaking ground here by commissioning new compositions and encouraging composers to experiment with the instruments. This is virgin territory, and offers wonderful opportunities to today´s composers.

<u>The mezzo violin</u>

In musical evaluations of the experimental members of the new violin family we found that even a fine concert violin did not have adequate power to match that of the other instruments, so we conceived the idea of developing a larger violin

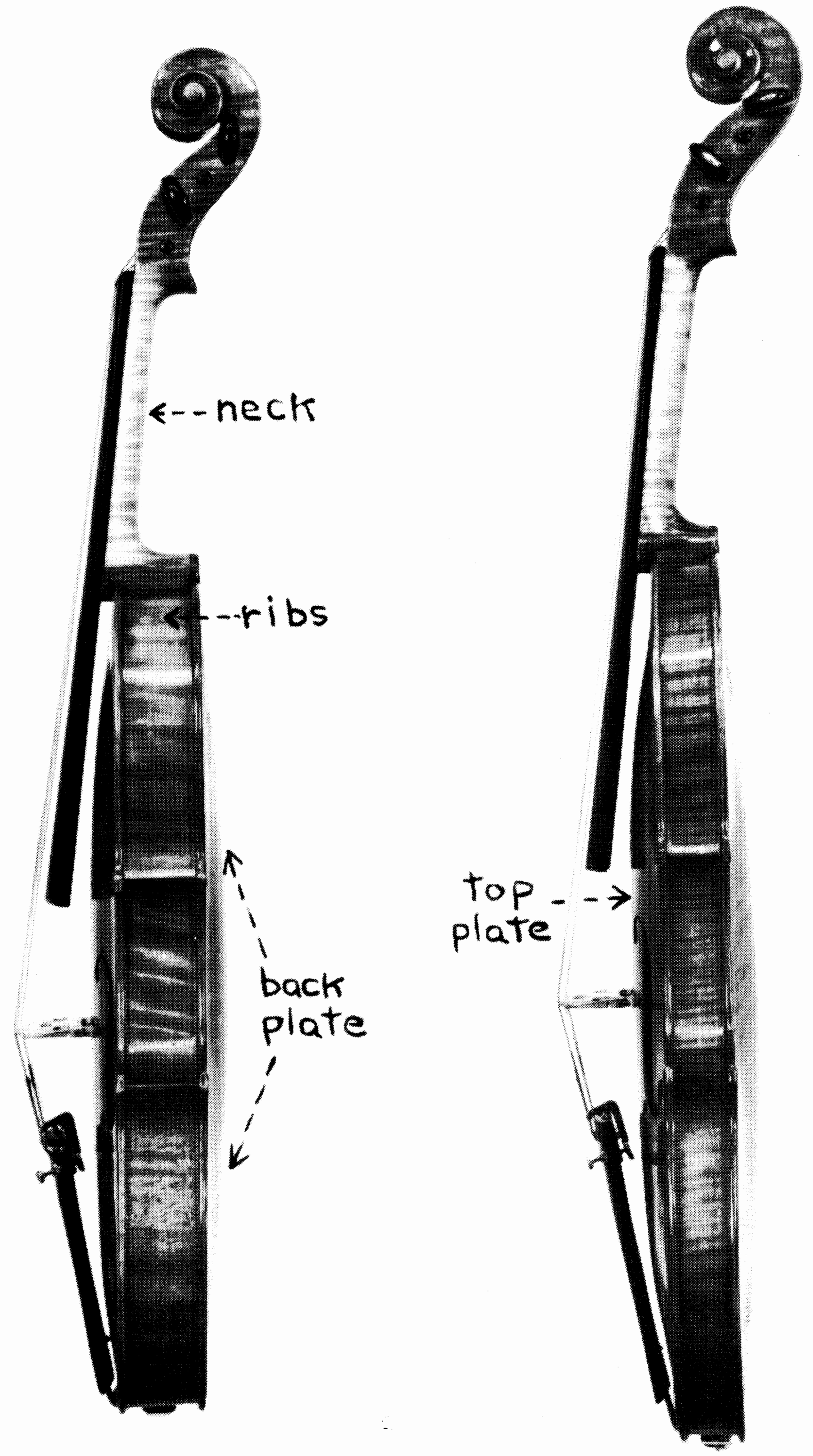


Fig. 6. Side views of conventional 14" (35,6 cm) violin and new 15" (38.1 cm) mezzo violin.

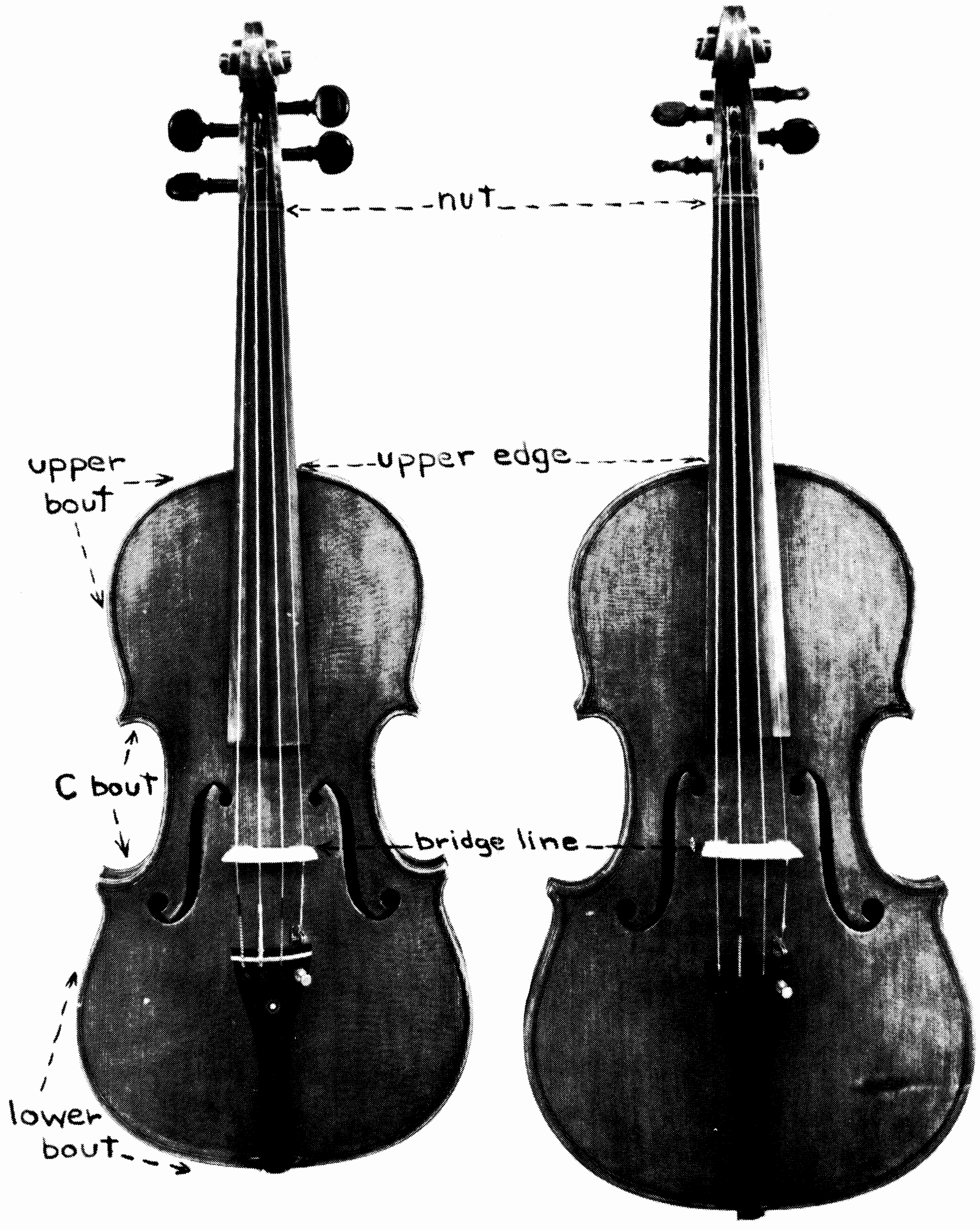


Fig. 7. Front views of conventional and new mezzo violin.

sicians are finding that its rich tone color and strong low range make it an ideal second violin in string quartets. One orchestral concert master who owns one reports that he has to play all the notes correctly for everyone can hear him in the orchestra.

Vertical viola - alto

The normal range for the body length of the viola is usually considered to be between 16 1/4" - 17 1/4" (40 and 44 cm) - longer than this is extra large, Fig. 8.

Fig. 8. Conventional 16 1/4" (41.3 cm) and 17 1/7" (43.8 cm) violas and 20" (50.8 cm) new vertical viola-alto (courtesy of J. Castronovo).

In developing the instrument in the viola range for the new violin family we worked according to the principle that the main (Helmholtz) air resonance and the main wood resonance should be in position similar to those in the normal violin relative to the frequency of open strings (Hutchins, 1962, 1967). This meant that the Helmholtz air resonance near B to B^b on the G string of the normal viola would have to be moved down to the open G string and the main wood resonance near F to F$^{\#}$ on the D string down to the open D string. To achieve this it was found experimentally that the body of our new instrument would have to be 51 cm long. Most violinists have found this to be too big to play under the chin, Fig. 8 (p. 196).

Fig. 9. William Berman with his 20" (51 cm) alto (courtesy of A. Montzka).

One professional, William Berman, who had been in the N.Y. Philharmonic and was teaching at the Oberlin Music Conservatory found the sound of the big viola so exciting and challenging that he taught himself to handle it with ease under the chin, even in the higher positions, fig. 9, (p. 197). The photograph shows how he plays the instrument which he has used exclusively for the past eight years, in symphony orchestras, recitals and string quartets with great success. Other violists are quite happy playing it vertically like a cello.

The tenor and baritone

In the early musical evaluations of the new violin family instruments it was found that the first tenor, adapted an experimental instrument in this range which had its two main resonances on the two open middle strings, did not seem to have the power and depth of tone of the other instruments. Thus a second, somewhat larger tenor was developed which had its main wood resonance close to the open second string, but the main air resonance several semitones below the frequency of the open D or third string. This made it more comparable to the first baritone, which also had its main wood resonance on the open second string, but the main air several semitones below the open third, or G string. This lowering of the main air, or Helmholtz resonance gave the full, rich, low sounds that the players and listeners seemed to prefer.

Here we were faced with possible changes in our original theory of the placement of the two main resonances, wood and Helmholtz air, on the two open middle strings. If the main wood resonance, largely controlled by the length of the instrument box, is kept within a semitone of the open second string, then can the Helmholtz air resonance be moved lower and still maintain desired tone and playing qualities? A third tenor, constructed with shallower ribs, but with the larger size body, seemed to bear out this idea.

During the musical evaluation of the new violin family in England, at the Royal College of Music in 1977-79, this increased sound in the lower range of these two instruments was found not to blend quite suitably with the other in-

instruments of the octet. So both a tenor and a baritone with somewhat shallower ribs were developed for comparison, 6.3 cm for the tenor and 8.5 cm for the baritone rib heights. Reports to date indicate that both instruments are quite satisfactory and have the desired tone qualities.

Other musicans, particularly cellists, have delighted in the full rich low tones in the tenor and baritone as they were originally designed. Michael Haran, principal cellist with the Israeli Symphony, feels that the baritone has all the power of the cello in the upper ranges and considerably more power and richness of tone on the two lower strings.

Thus it may be that the placement of the main wood resonance is more a controlling factor in maintaining tone qualities in violin family instruments than is the placement of the Helmholtz air resonance. Further work is being done to try to determine this.

The future

The new violin family represents the first time that a consistent theory of acoustics has been applied to a whole family of musical instruments. Whether or not it survives on a musically viable basis depends on the need for the sounds of the new instruments, both individually and as a group, in our musical culture today. Four main reasons for their survival seem to be emerging as they are demonstrated and played around the world: 1) Each instrument in its own right is more powerful than its counterpart (where there is one) in the conventional violin family and thus can be heard better in larger halls as well as in the full symphony orchestra; 2) The entire eight as a group provide the composer with a full range of balanced string sound on instruments that can be heard clearly on all four of their strings, somewhat like the diapason of the organ - sounds which can be used to enhance and blend with the characteristic sounds of the normal violin, viola and cello; 3) modern recording techniques are showing that the sounds of the new instruments are particularly suitable for high quality listening both as a group and in solo parts c.f. the sound example with six of the new instruments (more examples can be found on a LP-record, see references); 4) with the emergence of many small orchestras, the new instruments reduce the number of musicians needed on each part, as well as provide a medium with which to build small chamber groups using various numbers of all eight of the new violin family instruments.

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Music played on the family of new instruments can be found on the grammophone record in this book and also on an LP-record "Music for the New Violin Family" by Frank Lewin (Musical Heritage Society, Stereo No. 4102, 1979).

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FUNCTION AND FACTORS DETERMINING QUALITY OF THE VIOLIN

by

Erik V. Jansson

Department of Speech Communication
Royal Institute of Technology (KTH)
Stockholm

Introduction

In the first seminar within this series the present understanding of the acoustical facts, related to timbre and radiation was reviewed in general (Jansson, 1977 a,b). In the second seminar tone quality factors of violins were discussed more in detail, i.e. tone properties in relation to the hearing of player and listeners (Jansson and Gabrielsson, 1979). In the present paper function and quality factors will be discussed, i.e. relations between tone properties and the function of the violin.

In the present paper I shall thus try to present information to be used for the making of the violin. Data will be presented on the function of the violin in the frequency range above the first two resonances at 300 and 450 Hz. Thereafter a so called model will be set up. By means of this model it will be discussed how different parameters such as varnish, wood and plate thickness determine quality. The model and the predicted importance of the different parameters are a little speculative as we do not have all data necessary for a complete understanding. It will be clearly marked, however, where the borders are between true observations, interpretations and simplifications of the observations.

The tone production in a violin can schematically be described as in Fig. 1. The player moves the bow across

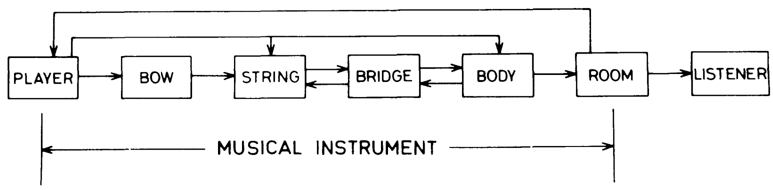


Fig. 1. Block diagram of the main production and monitoring chains of the violin tone from player to listener.

the strings, which thereby are set into vibration. The string vibrations result in vibratory forces on the bridge, which are transmitted through the bridge to the body and thereby set the body into vibration. The vibrations of the body affect the bridge vibrations and thus also the string vibrations. When a resonance in the body results in large bridge vibrations, a "wolf-note" can be produced. The bridge in itself works as a somewhat springy support for the strings. The bow-string-bridge-body phenomena are described more in detail in Hutchins article "How the violin works" p. 152.

The holding of the violin by the player may affect the vibration properties of the body. The body vibrations give the sounding tones in the room, which the player monitors by means of his hearing. The sounding tones pass through the room to the listener. The player affects the sound radiation (as a reflection and diffraction element) and the room affects the player's monitoring by means of his hearing. Therefore the player and the room may, in parts be included in the musical instrument, the violin, as marked in Fig. 1. In the next paragraphs the topic should be limited to the bridge and body.

A function model of the violin body

The model, which we shall present in this section, is restricted to the frequency range above the first two major resonances, i.e. above approx. 600 Hz.

As a starting point for our model we shall shortly review some data from an investigation by Jansson, Molin & Sundin (1970). First in this investigation the vibration properties of the top and back plates were measured with the plates separately glued to ribs fastened to a jigg without enclosing an airvolume. Measurements were made after the following major steps of construction: The top plate a) without and b) with f-holes, c) with bass bar and d) with a rigidly supported sound post; the back plate a) without and b) with a rigidly supported soundpost. Thereafter the vibration properties were measured of the top and the back plates assembled with ribs. Measurements were made separately of the top and the back plates after the following assembly steps before varnishing: assembled a) without and b) with fingerboard, and c) with devices for stringing and strings.

The properties were measured by means of an optical method, hologram interferometry. Before presenting results of the investigation, let me demonstrate how such results are interpreted by means of a simple example. The most informative vibration measures of a plate are its resonance frequencies, the sharpness of resonances and their vibration patterns. By means of hologram interferometery such vibration patterns can be made visible and can be photographed. Photographical records of vibration patterns, so called interferograms, of the first six resonances of a rectangular plate, clamped along its edges, are shown in Fig. 2.

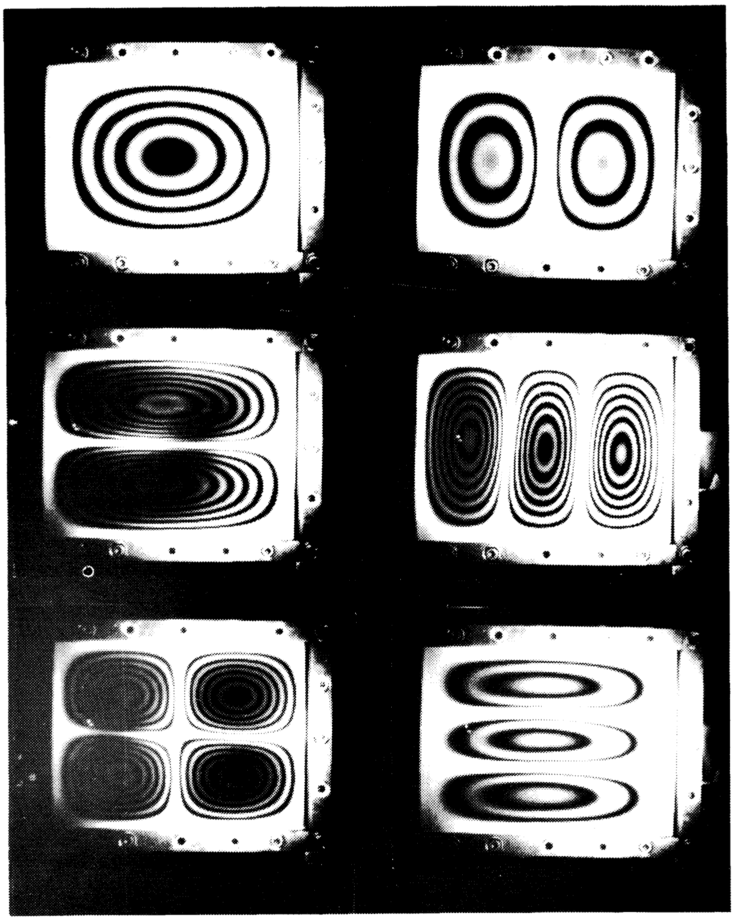


Fig. 2. Interferograms of the first six resonances of a rectangular plate clamped along its edges (from Molin & Ek, 1970).

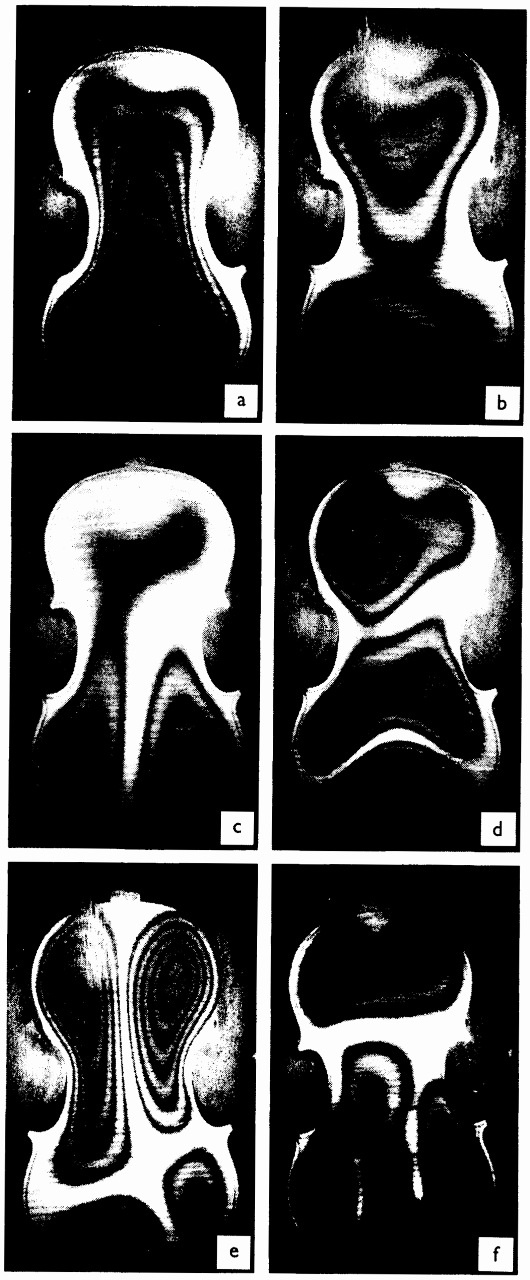


Fig. 3. Vibration patterns of the lowest six modes of a back plate on ribs a) 490 Hz, b) 660 Hz, c) 840 Hz, d) 910 Hz, e) 1030 Hz and f) 1120 Hz (from Jansson, Molin & Sundin, 1970).

such as this very soundpost must impose a nodal line passing through the point where this support is applied. This is also in agreement with the vibration patterns shown, i.e. still small vibrations in the bridge and sound post area.

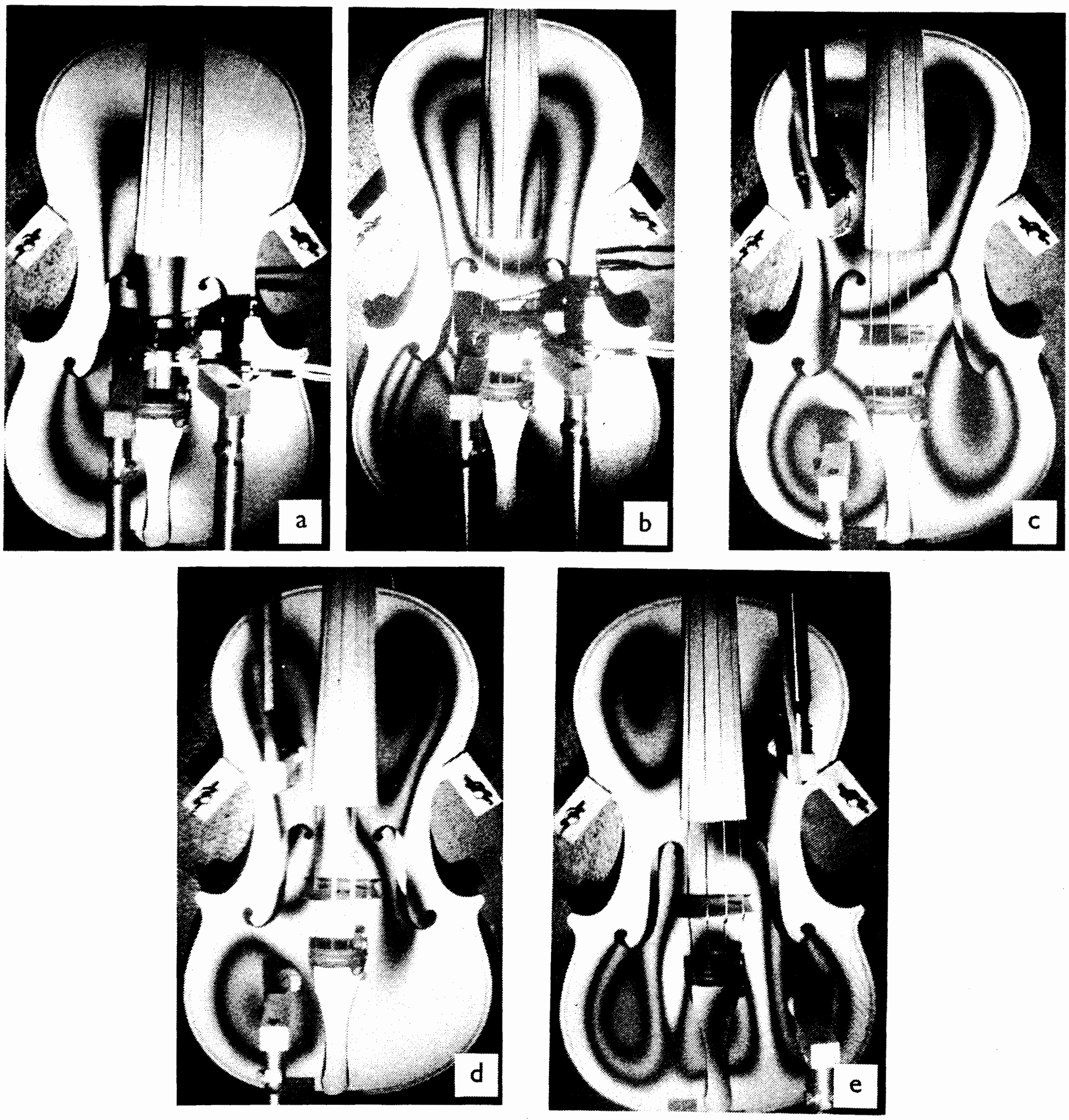


Fig. 5. Vibration patterns of the lowest five modes of a top plate in the violin assembled a) 480 Hz, b) 780 Hz, c) 830 Hz, d) 950 Hz and e) 1100 Hz (from Jansson, Molin & Sundin, 1970).

So far we have looked at the properties of the plates separately, which is a long way from the finished instrument. Let us first see what happens to the top plate after the violin body has been assembled. A comparison of the top plate vibrations in the assembled body Fig. 5 with

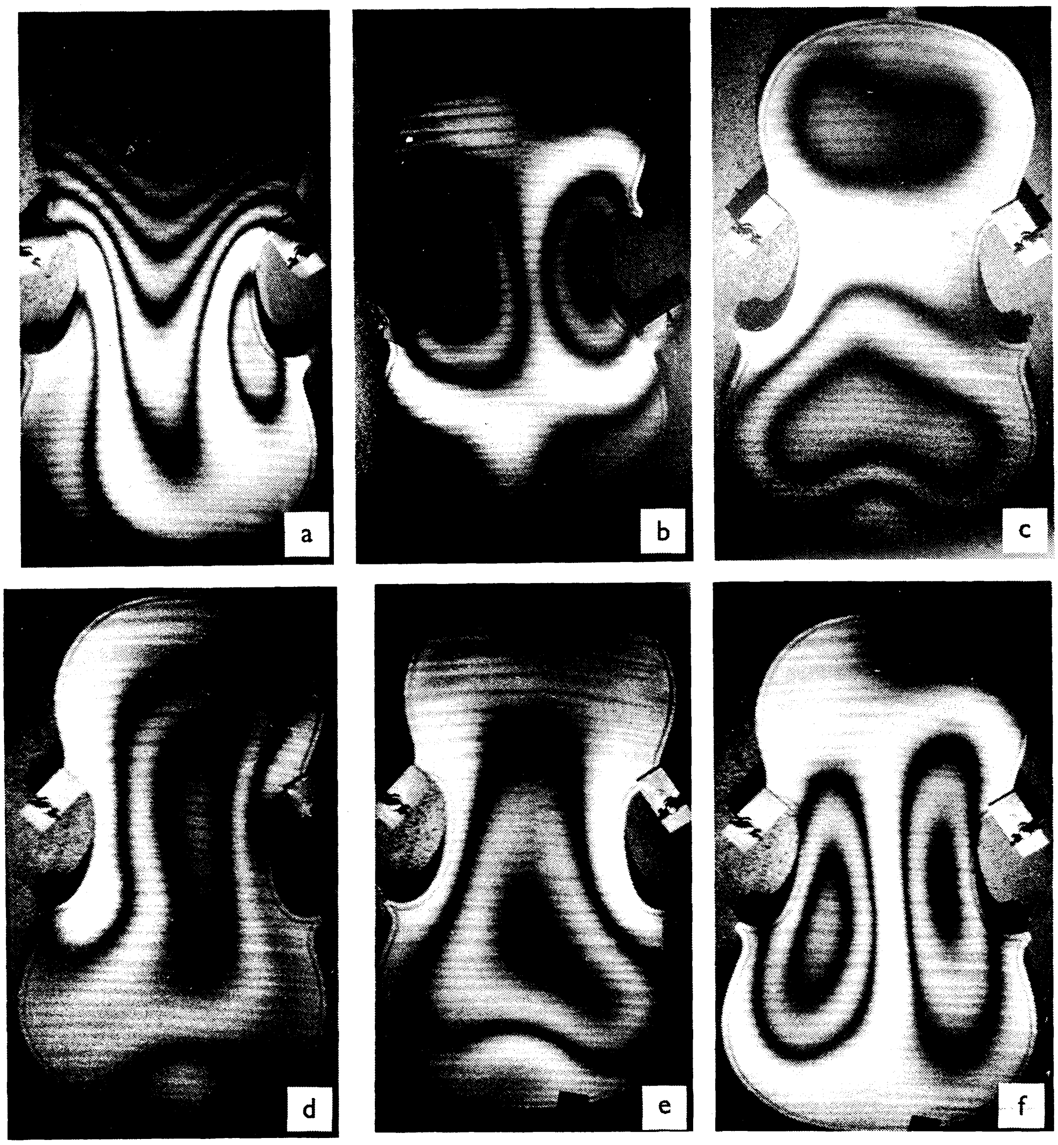


Fig. 6. Vibration patterns of eight modes of the back plate in the violin assembled a) 100 Hz, b) 340 Hz, c) 470 Hz, d) 505 Hz, 580 Hz, f) 770 Hz, g) 870 Hz and h) 970 Hz (from Jansson, Molin & Sundin, 1970

those of the top plate separately Fig. 4 shows that the vibration patterns are closely the same, i.e. there is still nothing mysterious about the vibration patterns and the vibrations in the bridge-sound post area are still small. A horizontal line through the bridge-soundpost area can therefore be regarded as a border between two areas with large vibrations, i.e. the upper and the lower part.

The first seven resonances of a violinshaped cavity are shown in Fig. 9,(p.162). The same patterns are found in the upper as in the lower parts, i.e. the violin cavity vibrations are like the top plate vibrations also divided in an upper and a lower part by a horizontal line through the bridge-soundpost area. The f-holes make the division even more pronounced as the air modes with sound pressure maximum in the bridge region are highly dampened.

But what about the back plate of the assembled violin body? Vibration patterns of the complete violin are shown in Fig. 6. (p. 211). The first four vibration patterns (Fig. 6) look quite different from those of Fig. 3-5. The black lines mapping the vibration amplitudes cross the edges of the back plate, i.e. the ribs and probably the whole violin is vibrating. The same applies to the higher vibration modes although less pronounced. No clear influence of the sound post can be found.

The vibration patterns shown were obtained with the violin clamped at specific positions in a jigg. Many experiments performed with the same clamping have revealed that these vibration patterns are representative for violins. The clamping does, however, affect the vibration patterns (c.f. Jansson, 1973). The vibration patterns later obtained by Stetson and Taylor for a violin held by thin rubber bands, show that the resonance vibrations are neither limited to the top nor to the back plate (Fig. 10 p.163). The resonance vibrations are found in both plates and the ribs at the same time. In playing, however, the violin is held by chin, shoulder and left hand, which gives conditions somewhere in between the rubber band holding and the clamping. (c.f. Fig. 3, p.233) For our model we therefore feel justified in assuming that Fig. 5 and 6 give a fair first approximation of the normally played violin.

From the data presented and the simplification motivated above we conclude that the following model describes the function of the violin for frequencies above the first two major resonances. The top plate is likely the main radiator of sound. It is divided into two "vibration" halves, an upper and a lower one, by a horizontal line in the bridge-soundpost area. The back plate and the ribs form a shell that supports the top plate. This means that if the back plate vibrates, then the whole body is vibrating.

Acoustical quality factors

The number of resonance in a violin is large, a magnitude of 20-40 below 5 kHz. This results in a rather uneven frequency response as illustrated in Fig. 7. Every resonance tends to give a peak if a glissando is played the fundamental (and the higher partials) will increase and decrease in accordance with the frequency response curve.

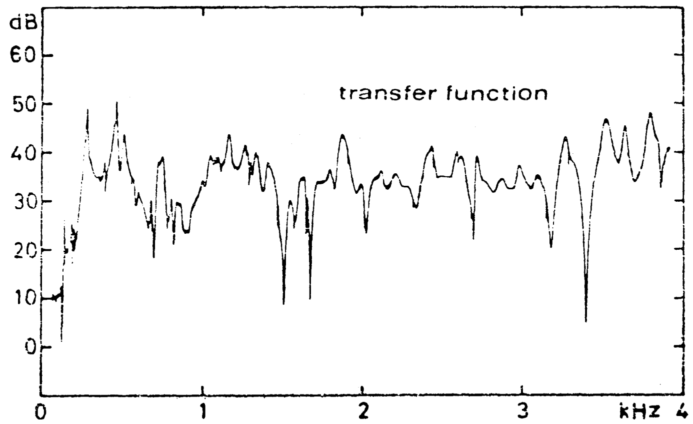


Fig. 7. Frequency response for a violin (from Jansson, Molin & Sundin, 1970).

This means that even in a good violin the tone spectrum will change from one tone to the other depending on the fundamental frequency. Thus no violin is acoustically even. Another consequence is that if a tone is played with a vibrato the different partials will vary differently. From Fig. 8 (p. 214) it can be seen that the intensity of the first, second and fourth partials varies little with time, i. e. they fall on flat parts of the frequency response. The third and fifth partials, however, vary considerably in

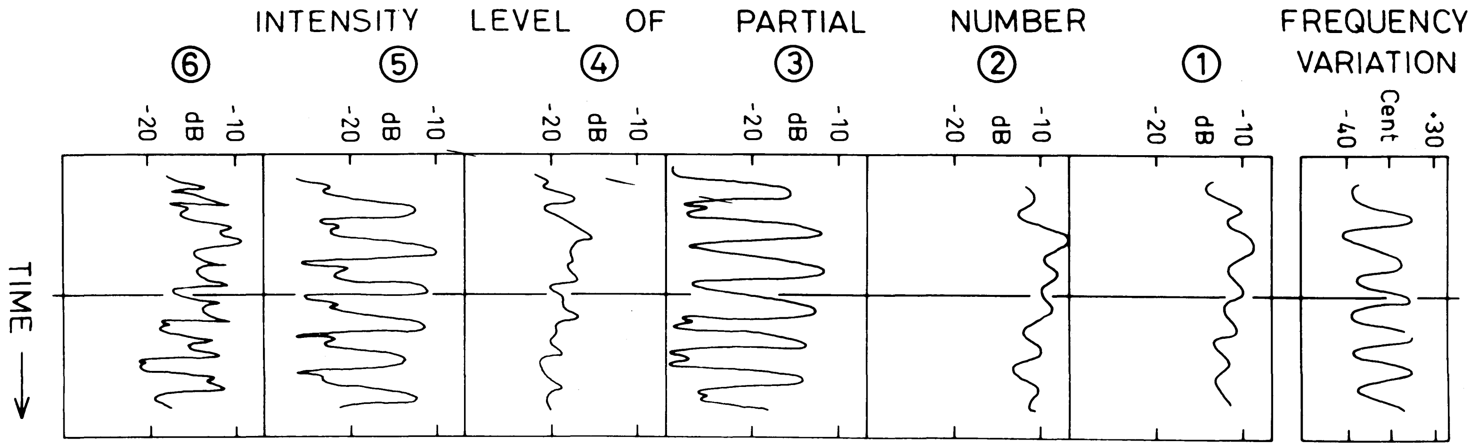


Fig. 8. Frequency variation and intensity level variations of six partials, approx 1 sec of played G_4-sharp 415 Hz tone, (after Fletcher and Sanders, 1967).

intensity. Note also that they vary in opposite phases, the fifth varies in phase and the third in opposite phase with the frequency variations (the vibrato). Thus the fifth partial is working on an uphill slope and the third on a downhill slope of the frequency response.

The influence of the peaks and dips in the frequency response on perceived tonal quality has been investigated by Mathews and Kohut (1973). The "string vibrations" were recorded on tape and replayed through an electronic filter approximating the peaks and dips of a violin frequency response. Furthermore the "string vibrations" were replayed with the frequency response set flat, and with extremely pronounced peaks and dips, Fig. 9.

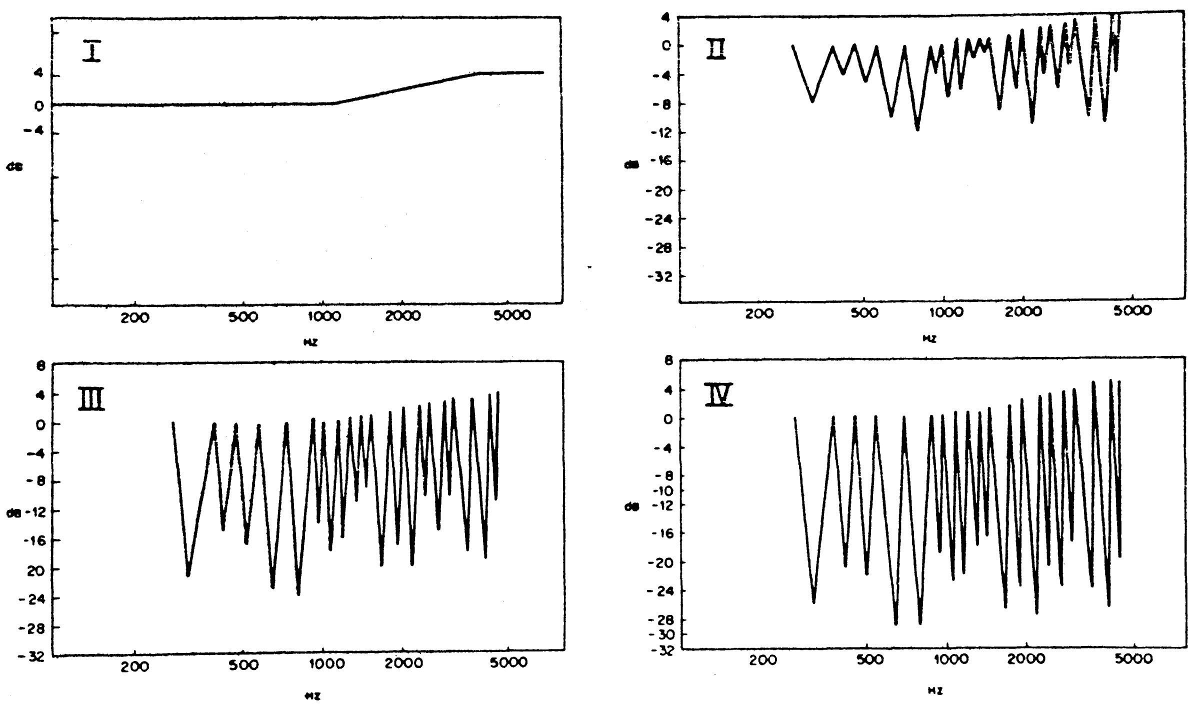


Fig. 9. Peak-to-dip curves for various Q´s of electronically simulated resonances of a violin (from Mathews and Kohult, 1973).

Thereby it was found that "Case No.I sounds harsh and unresponsive, Case No. II sounds the best and Case No. IV sounds nasal or pinched". A more detailed description as well as sound illustrations consisting of played test scales are found in Mathews (1977). The experiment proves that the detailed peakiness of the frequency response is important.

Our hearing can not resolve all spectral details of a played tone. Moreover, the frequency response curves contain too much information to be investigated in all details. Therefore it is common to average the over specific frequency ranges e.g. Jansson (1977 a). Played violin tones have been analysed with filters approximating properties of our hearing (so called critical bands of hearing giving a Bark pitch scale) see Gabrielsson and Jansson (1979).

A result of the last mentioned investigation is summarized by means of long-time-average-spectra of two groups of violins Fig. 10.

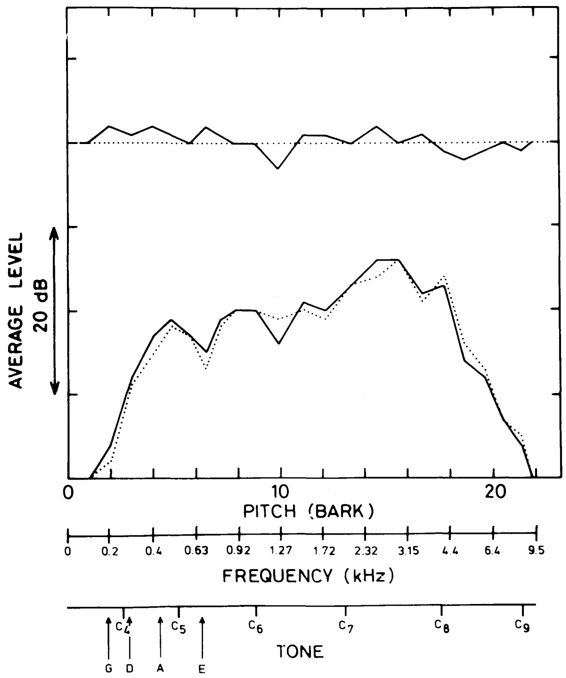


Fig. 10. Long-time-average-spectra of eight violins with high (——) and of seven violins with low (·····) tonal quality ratings (lower curves) and difference between the two curves (upper curve from Gabrielsson & Jansson, 1977).

The violins were borrowed from the Scandinavian Violinmakers Exhibition 1975. The violinsof this exhibition had previously been judged with respect to tonal quality and the two groups were selected to represent the highest and the lowest tone qualities. Fig. 10 shows that in spite of the coarse spectral averaging, the resulting spectra of the two groups are far from flat. The upper curve,showing the average difference, reveals that a high level is favourable for low and medium high Bark numbers (frequencies). On the other hand a low level is favourable at 10 Barksand high Bark numbers. Filtering experiment with played music has shown that different frequency regions influence the tone quality differently, Jansson and Gabrielsson (1979). In the high frequency regions (above 21 Barks)there are very weak partials and thus little influence on quality. In a medium frequency range (11-14 Barks) the tone components give clearness of starting transients and "carrying power", while sufficiently strong low frequency components are necessary for good tone quality.

From the abovepresented data we can draw the following conclusions regarding the frequency responses:

1) The broadband level, obtained by averaging in critical bands of hearing and
2) the peakiness i.e. the peak-to-dip ratio, are important and determine tonal qualities.

Function, model and acoustical qualities

Our model presented above indicates that two factors are crucial for the functions: 1) the balance between the upper and lower part with respect to the bridge-sound post region (affects the driving) and 2) the relationship between the properties of the top plate and those of the back plate (determining boundary conditionfor the vibrations of the top plate. It is difficult to relate these two factors to the frequency responses and to the long-time-average-spectra except in some general terms.

The peaks of the frequency response curves originate from resonances and their radiation properties. For instance, a certain number of higher resonances must be sufficiently excited in order to give a frequency response with favorable peakiness. For a top plate with its upper and lower parts well balanced with respect to the bridge region, such an excitation of higher resonances can probably be achieved by adjusting the position of the soundpost properly.

The peak-to-dip ratio, i,e, a measure of peak heights and dip depths, in the frequency response is determined to a large extent by the frictional losses in the whole violin. For instance the losses in glue joints between top plate and ribs can be made excessive, thus reducing the peak-to-dip ratio. Broad band levels, as those of the long-time-average-spectra, can at least to some extent be affected by "sympathetic" vibrations of the ribs and back plates. Such vibrations can "steal" vibratory energy from the top plate and thus reduce the top plate vibrations. The loss in vibratory energy may, however, be compensated for by means of increased radiation efficiency from the "sympathetic" vibrations. Much work seems still to be needed for a rational understanding of the involved phenomena.

Importance of wood properties, thickness and varnish

The violin maker can select wood with different properteis, he can work it to different shapes and thicknesses and he can varnish the instrument differently. In this section the magnitude of influence of these factors will be estimated and compared with experimental results.

In a paper on properties of varnish for violin, a simple model of the violin was developed, (Schelleng 1968). By means of this model the influence of varnish, material properties and thickness can be estimated.

The major properties of the wood along and across the grain can be measured by means of test bars as sketched in Fig. 11.

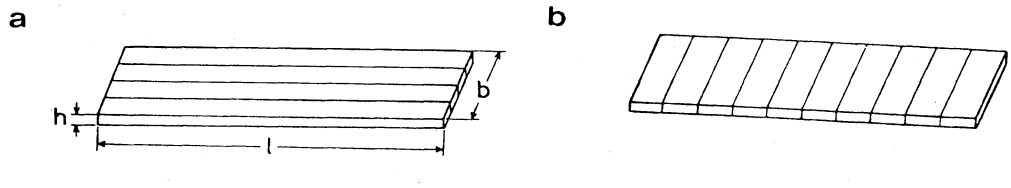


Fig. 11. Test bars a) cut along (index y) and b) cut across the grain (index x). The yearly rings are vertical in both cases.

Three measures for each bar are needed, for instance Young's modulus E (elasticity), the density ρ (weight per unit volume) and the internal friction. In an earlier investigation such measures were recorded for the top plates of 25 guitars, Jansson (1978). For practical reasons the threee measures were expressed as 1) density, 2) the ratio between elasticity and density CR(or to be exact $\sqrt{E/\rho^3}$), and 3) sharpness of the first resonance, Q. The results of the measurements are given in Fig. 12.

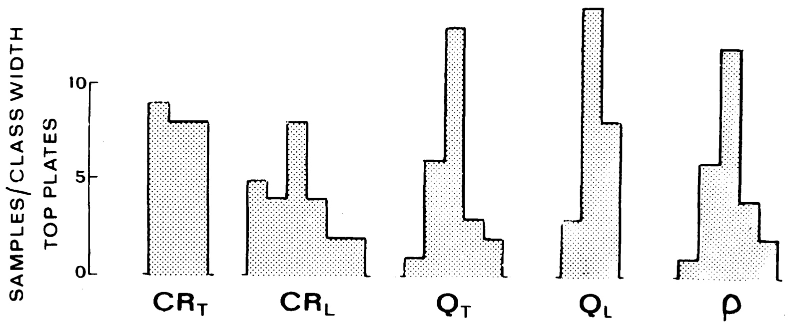


Fig. 12. Measured properties of test bars: (average)·CR_x = 3 m ^{4}/kg·sec (classwidth, i.e. width of the bars of the diagram, 30 %), CR_y = 13 m ^{4}/kg·sec (6 %), Q_x = 60 (10 %), Q_y = 135 (10 %) and 420 kg/m^3 (8%) (from Jansson, 1978).

Measures of the properties along the grains are indexed y and across the grains x. It can be seen that the variations in properties between different pieces of wood are considerable; ± 45 % for CR_x, ± 18 % for CR_y in the extreme cases; the standard deviations are 25 % and 10 % respectively.

The effects of these differences have been estimated by the mentioned simple model violin and are given in Table 1. (see p.220). From the table we should expect considerable differences between the 25 guitars made of this wood. The finished guitars turned out, however, to be rather similar in quality. Unfortunately only the differences between the guitars could only be measured in terms of variations in resonance frequencies. Instead of calculated ± 18 % differences, the measured ones were within ± 5 % only, i.e. considerably smaller. The magnitude of variations between the same resonances of different guitars were in agreement with expected larger crossgrain than longgrain variations.

Table 1: Estimated and measured shifts in broadband levels (BL), peak-to-dip ratios (PD) and resonance frequencies (RF).

a) Estimated shifts of measured variations in material properties

BL	± 1.5 dB
PD	± 1 dB
RF	± 18 %

b) Measured shifts from variations in material properties

RF 1	± 2.9 %
RF 2	± 4.0 %
RF 3	± 2.6 %

c) Estimated shifts of a 10 % increase in thickness

BL	- 1.5 dB
RF	+ 10 %

d) Estimated shifts of 20 g oil varnish

BL	-1 dB
PD	-3 dB
RF	+3 %

The effect of a 10 % change in thickness has also been estimated and is given in Table 1 (p.   ).

Effects of different extreme thickness are given in Fig. 13.

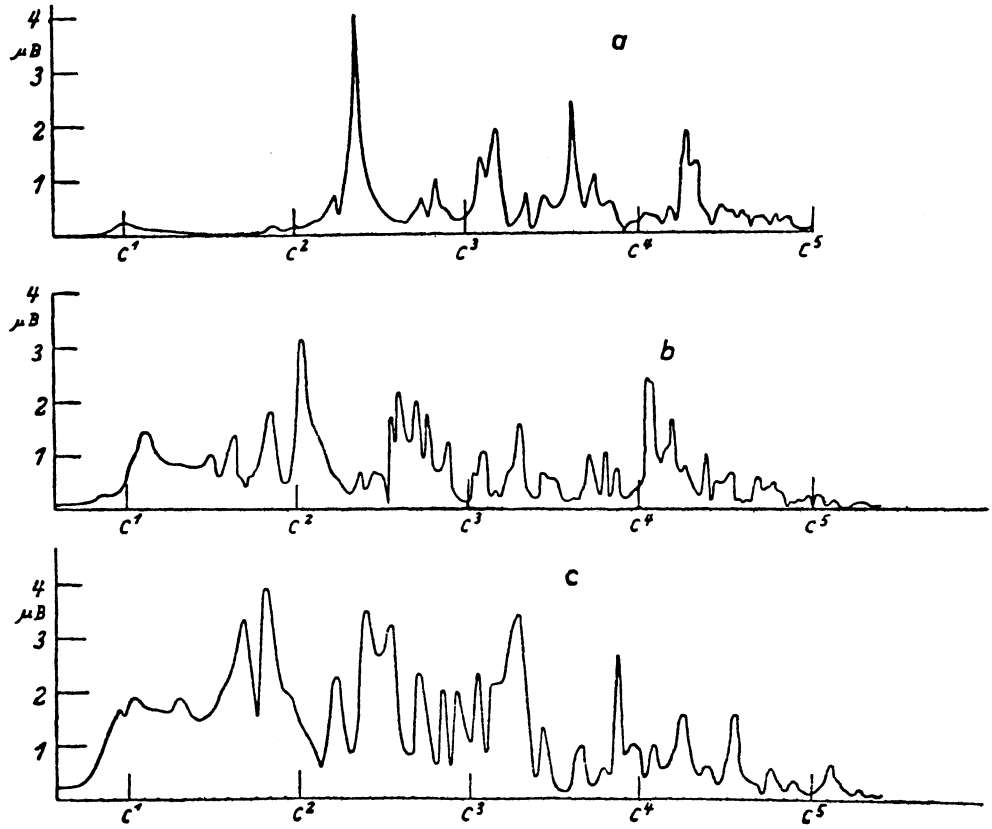


Fig. 13. Frequency responses for three different thicknesses: thicker than normal (upper), normal (middle) and thinner than normal (from Meinel, 1937).

The different frequency responses show large differences in three respects:

1) the broadband level increases with decreasing thickness for lower frequencies.

2) the peakiness is affected, as the number of pronounced peaks is increased, and

3) the frequencies of the resonance peaks are lowered (note the highest peak for comparison).

The changes are considerable especially the measured shifts.

The influence of a cover of 20 g oil varnish on a 400 g violin have been estimated after the theory, see Table 1 (p.). It should be noted that the crossgrain properties are more affected than the longgrain properties. The effect of varnish as measured by Meinel (1937) is given in Fig. 14.

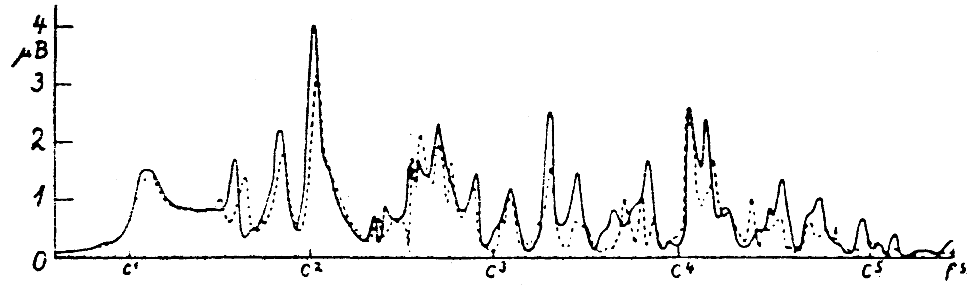


Fig. 14. Frequency responses before (_____) and after varnishing (....), (from Meinel, 1937).

A broadband level decrease of 1 dB corresponds to a 10 % decrease in the response curve of Fig. 14. Such a small difference is hard to detect in the response curve. It is also close to the limit of what the ear can detect. A 3 dB decrease in the peak-to-dip ratio corresponds to 1.5 dB, i.e. it corresponds to a 20 % decrease of peak heights in Fig.14. This prediction is in fair agreement with the measured shifts of peak heights. Fig. 14 indicates also a 5 to 10 % increase of the frequencies of the peaks in the lower frequency range, i.e. the estimates of frequency shifts are in fair agreement with measured results for the violin of the figure.

The results presented above indicate the following order of importance: 1) thickness, 2) material properties and 3) varnish. The investigated material does not support the common belief, that the varnish makes a Stradivarius. Other factors should indeed be more important.

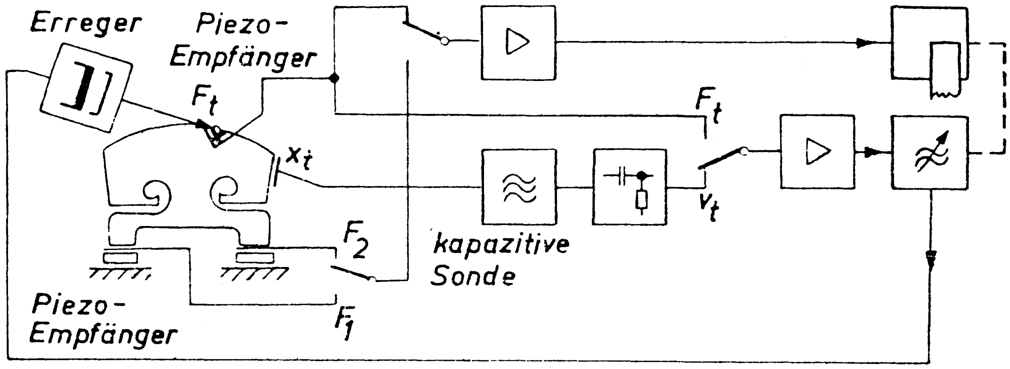
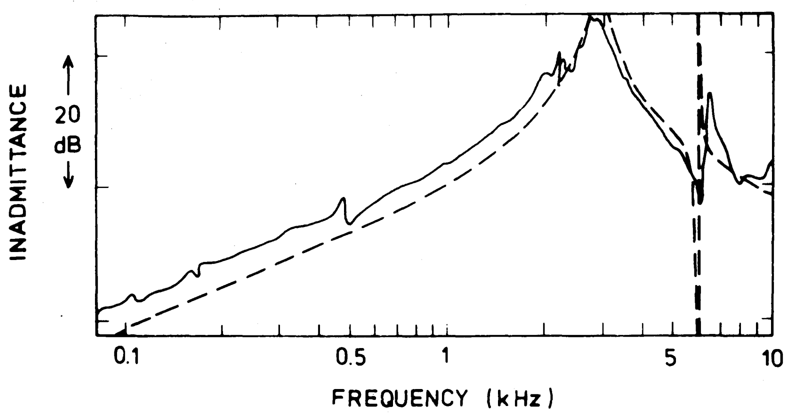


Fig. 15. Arrangement for measurements of bridge properties (from Reinicke, 1973).



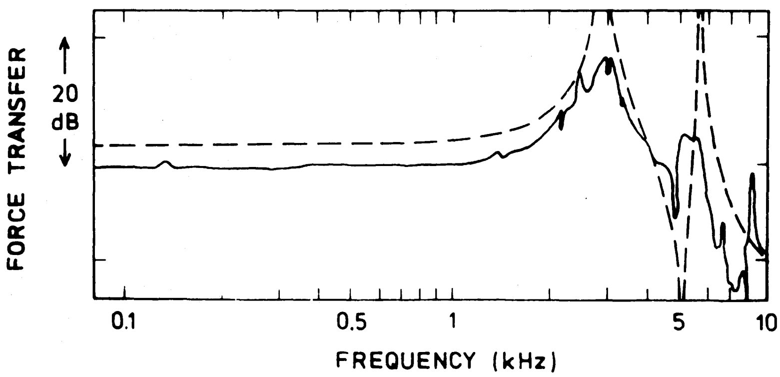


Fig. 16. Violin bridge properties, measured (———) and calculated (-----), (after Reinicke, 1937).

The bridge

Recently much attention has been directed towards the role of the violin bridge. In a doctor thesis, fundamental properties were recorded and explained by Reinicke (1972). Relations between driving force and resulting velocity of the bridge, c.f. Fig. 15 (p. 223), give a frequency response as in Fig. 16 (p. 223) The response is characterized by peaks at 3 and 6 kHz. The relation between driving force and resulting force at each of the violin feet gives a similar curve containing peaks at approximately the same frequencies. The two peaks result from two resonances: the first with the upper part of the bridge rocking at the "waist" and the second with the upper part vibrating up and down c.f. Fig. 6 (p.158).
Calculated frequency responses, assuming the two resonances, predict the measured responses reasonably well. c.f. the broken lines in Fig. 16. When the same experiments were made with cello bridges other pronounced resonances were found. The long legs of the cello bridge together with the upper part is the main vibrating parts, in contrast to the violin bridge where the "legs" are rigid. The third resonance of the cello bridge is, however, the same type as the first of the violin bridge c.f. Fig. 7 (p. 159).

The bridge will enhance the frequency components at its resonance frequencies. Fig. 17 gives an idea of the limits within which the resonance frequencies can be adjusted.

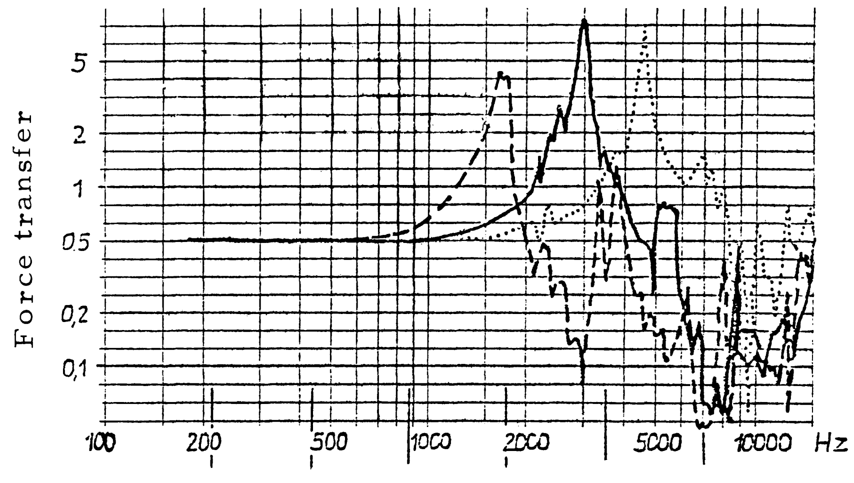


Fig. 17. Force transfer of a bridge normal (———) mass-loaded upper part (----) and with wedges in "cuts" (·····). Markings at frequencies of tones A (after Reinicke, 1973).

In the extreme cases shown here the first resonance is varied as much as ± 1.5 kHz and the second ± 2 kHz. It should be noted that the frequency range at 3 kHz seems to be of great importance for tone quality, c.f. singing formant,(Sundberg,1977).

Experiments have shown that the different steps of making give a moderate influence on broadband spectrum levels, Fig.18, (Müller, 1978).

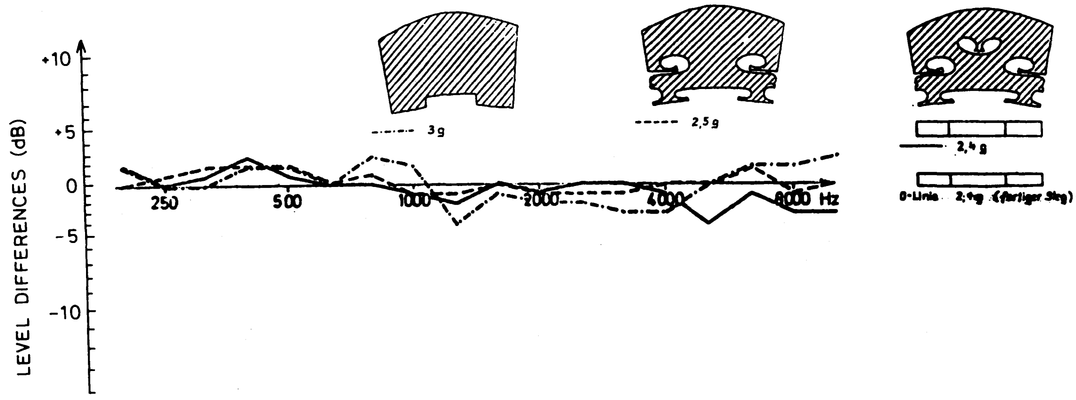


Fig. 18. Influence of bridge on radiated sound. Third octave band levels as function of status of bridge for white noise excitations (from Müller, 1978).

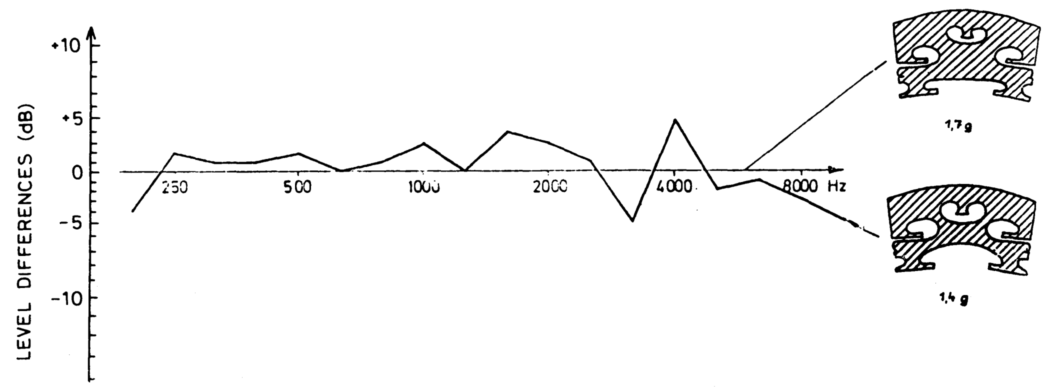


Fig. 19. Influence of the cutting of the bridge on radiated sound (As fig. 18, from Müller 1978).

The height and the shape of the arch give the largest effects, Fig. 19. But these effects of the bridge modifications are still small compared to those of the plate thicknesses, Fig. 20 (p. 226).

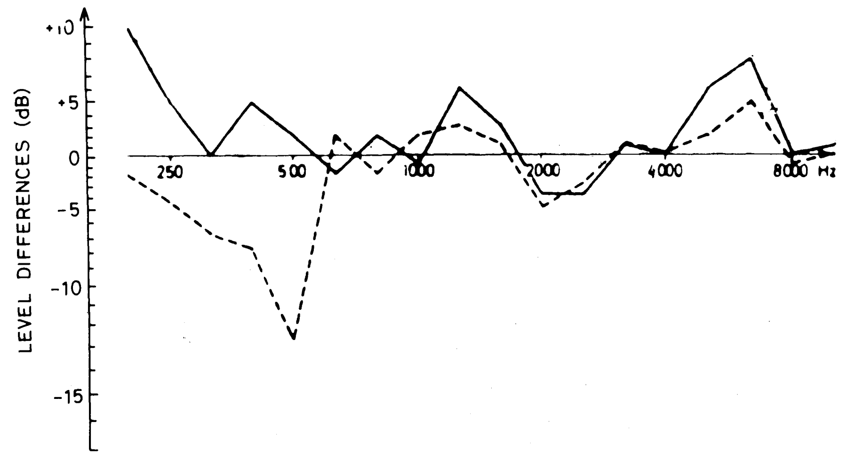


Fig. 20. Influence of wall thicknessess on radiated sound (as Fig. 18, from Müller, 1978).

Conclusions

The results of this study can be summarized in five points. Point 1, the first sentence and point 5 are a little speculative as no definite data can be found to verify them.

Point 1) The top plate is the main sound radiator. It is divided into two vibration halves, above and below the bridge.
Point 2) The spectral broadband levels i.e. the levels in critical bands of hearing are important to the tone quality.
Point 3) The peakiness of the frequency response (i.e. the peak to dip ratio) and the number of peaks are also relevant factors to tone quality.
Point 4) The spectral broadband levels are determined by the thickness, the material properties and the bridge.
Point 5) The peakiness of the response curve is mainly determined by a) the material properties (internal friction), b) the varnish and c) the vibration balance between the upper and lower parts of the top plate with a "fulcrum axis" in the bridge-soundpost region.

Finally I would like to state that a better understanding of what determines the tonal quality in physical terms is the information which presently is most needed. It is clear that tonal quality is not a so-called "onedimensional" property, i.e. a property that can be summarized in one number. It seems rather that for meaningful investigations of what determines the tonal quality, it has to be split up in several components. Such components as carrying power, sweetness etc. are more likely to correlate with specific physical parameters.

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RECENT VIOLIN RESEARCH AT KTH

by Erik V. Jansson & Jesús Alonso Moral

Department of Speech Communication
Royal Institute of Technology, (KTH),
Stockholm

Introduction

In this paper we shall report on work recently done and presently in progress. We shall first describe a method, which allows us to record the inadmittance. We shall describe how it is done and how it can be used. Secondly we shall present results from an investigation of violin top plates, which still is in progress. We can report on properties of free plates and a pilot study of a plate in an assembled body. Finally we shall present results from a detailed investigation of the function of the violin body in the frequency range of the main wood resonance.

Inadmittance

The characteristics of played tones of a violin are determined by how the vibrational forces of the strings are acting on the bridge and how these forces are accepted by the bridge. The forces set the violin body into vibration, which activates the surrounding air in the room into vibration. Thereby the tones are generated, which player and the listener hear. Fig. 16 (p. 223) shows that certain simple relationships exist between the bridge acceptance of driving forces, i.e. the inadmittance, and the force transfer through the bridge to the top plate. The relationship between inadmittance and sound radiation in a reverberation chamber (i.e. approx. sound power) has been studied by Beldie (1974), Fig. 1 (p. 230). For frequencies below 1 kHz the inadmittance curve and the soundradiation curve show a close resemblance, i.e. there seems to be fairly simple relationships between the input and the output as measured by Beldie. This kind of soundradiation measurements demands a specific room, a reverberation chamber and special driving signals. Thus it is fairly complicated to obtain these measures. The inadmittance on the

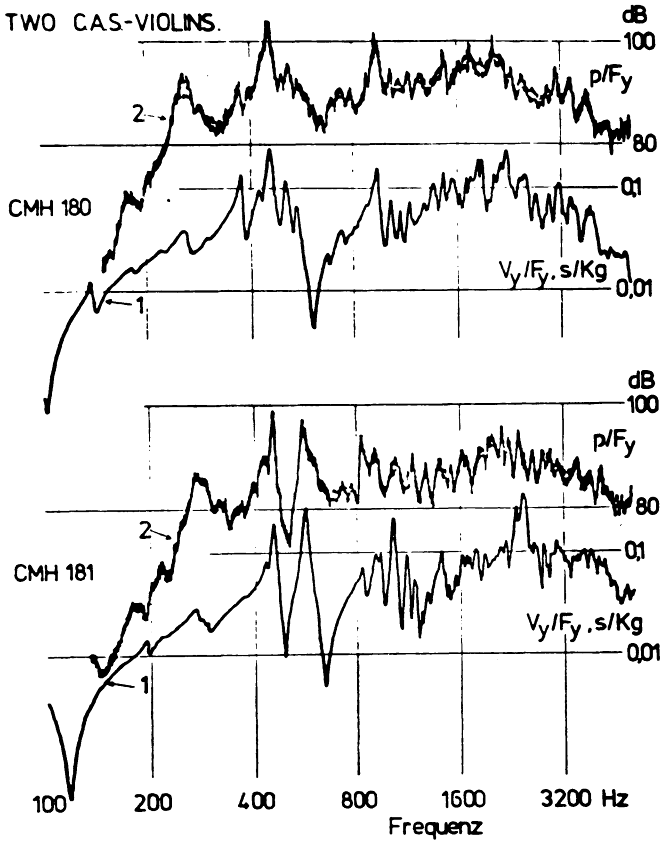


Fig. 1. Bridge inadmittance (1) and sound pressure in a reverberation chamber (2) for two violins Hutchins No 180 and 181, from Beldie, 1974).

other hand, is fairly simple to measure, especially with the technique we have developed at our laboratory. The inadmittance determines how the vibration forces are setting the violin body into vibration. The results of the two investigations by Reinicke and Beldie, just reviewed, show furthermore, that the inadmittance gives information on force transfer and the sound radiation properties. Thus, by means of simple measurements of inadmittance, valuable information can be obtained on the function of the violin, (e.g. internal frictional losses, frequencies of and number of resonances).

In 1975 one of the authors (EVJ), utilizing recently developed magnets, constructed a very simple driving system possessing ideal properties (low weight and no international losses) see Firth (1976a). Firth developed this construction further and made a complete "impedance head". Fig. 2.

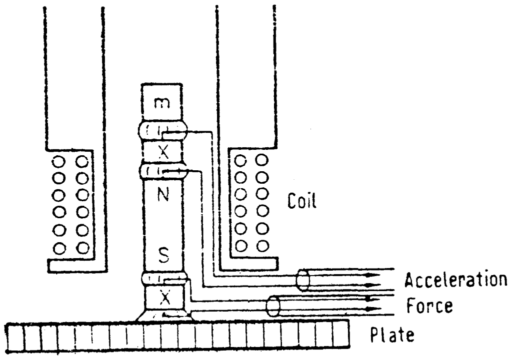


Fig. 2. Excitation and measurement transducer for inimpedance and inadmittance (from Firth, 1976 b).

We have found that with the magnet fastened to a miniature Brüel & Kjaer accelerometer, i.e. similar to the impedance head of Fig. 2 but without the force transducer, recordings of inadmittance are simple to make. This magnet-accelerometer-transducer is easily adapted to a large variety of measurements.

In the previous paper (p. 204) a simple model of function of the violin was presented. An uncertainty was, however which boundary conditions are given by normal holding of the violin. The demands raised by traditional hologram interferometry (i.e. either a rigid holding as the jigg used for interferograms in Fig. 5 (p. 210) or a loose holding combined with along stabilization time (as used for interferograms in Fig. 10, (p. 163), cannot be met when the violin is held normally as for playing. Radiation properties of a violin held in the three different manners described cannot be directly compared, because the radiation properties are influenced differently by a player, by a rigid jigg and be a frame with rubber bands. The inadmittance, however, can be measured with reasonable accuracy in normal violin holding

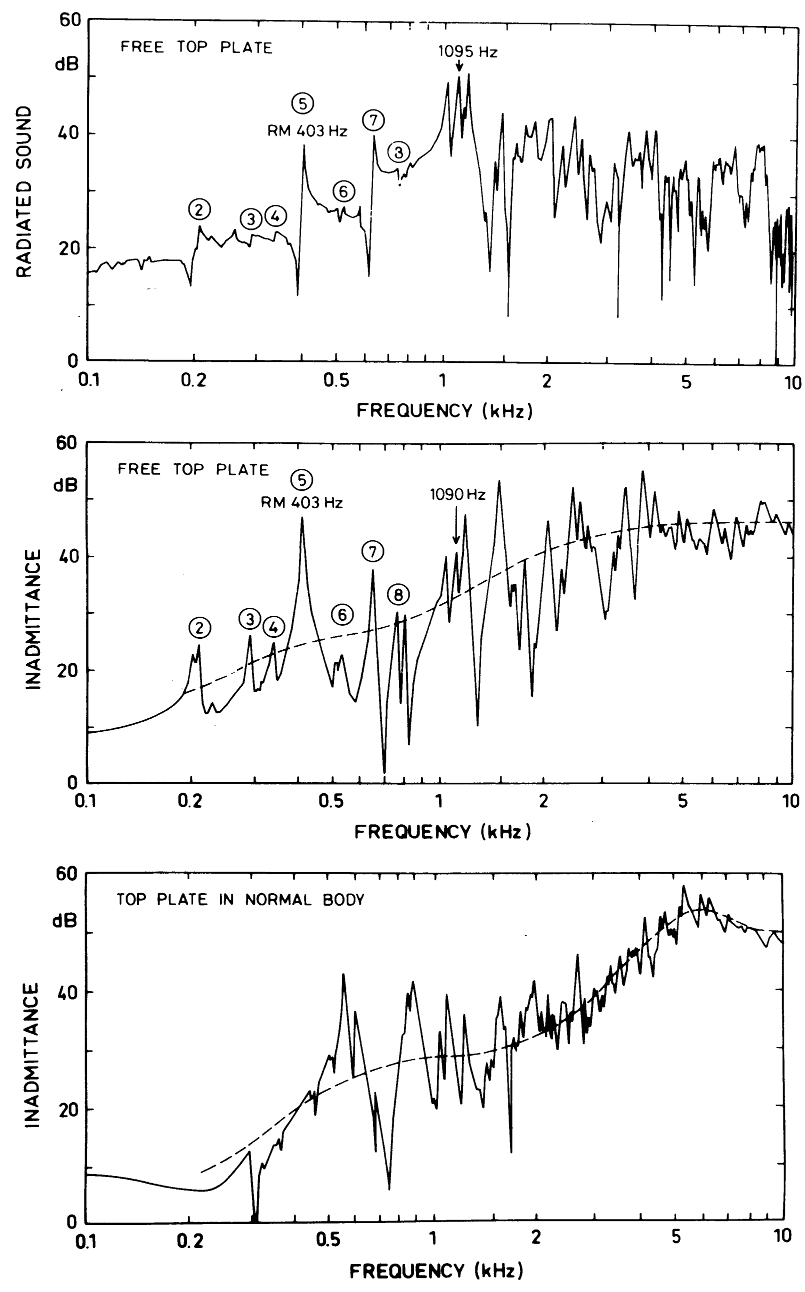


Fig. 4. Frequency responses of a violin top plate: sound pressure in an echoic chamber (upper) and inadmittance (middle) of the free plate, and inadmittance of the plate in assembled body.

Therefore it seems important to measure plate properties before and after assembly in order to provide a basis for understanding how properties of the plates in an assembled instrument can be predicted from the properties of the same plates with "free" boundaries.

Therefore we have started an investigation of free plate properties and the plate properties of the assembled instument. This work is made in cooperation with the Catgut Acoustical Society and Carleen M. Hutchins, who have designed and made 10 top plates with different thicknesses, arching etc. We have analysed the plate properties by means of traditional methods and our inadmittance method, previously described. An example of three different records of the same plate are shown in Fig. 4 (p.234). The upper diagram shows the sound pressure recorded at a distance of a plate length in an anechoic chamber. The middle diagram shows the inadmittance (acceleration/force) recorded simultaneously. The lower diagram shows the inadmittance obtained for the top plate assembled with ribs, back plate and soundpost. The same driving point, 16.5 cm from tailpiece end and the rubber-band-holding was identical in all three cases.

A comparison of the upper and middle curves reveals that the resonance peaks appear more clearly in the inadmittance curve c.f. especially the the numbered peaks below 1 kHz. This is in agreement with prediction based on electrical circuit theory. For higher frequencies, above approx. 2 kHz the two curves show a fair agreement except for very sharp dips in the upper curve. These dips derive from radiation properties.

A comparison of the middle and lower curves shows directly that the peak-to-dip ratio is lowered after the assembly. The number of peaks (higher than 3 dB) has decreased from 34 to 26. Estimated broadband levels in the two cases are not too different, somewhat higher on the free plate below 3 kHz but somewhat lower above 4 kHz.

The inadmittance is thus as earlier mentioned a very promising measure, it is fairly easy to obtain, it gives information which is easy to interpret and it is not affected by the position in and the properties of the measurement room. Thus it allows for a direct comparison of the middle and the lower curves.

From the detailed investigations of the ten free plates by one of the authors JAM the following results emerged.
1) The frequency of the ring mode (mode number 5) is proportional to the mass (weight) of the plate with a minor correction for differences in arching, Fig. 5. This result was interpreted as follows.

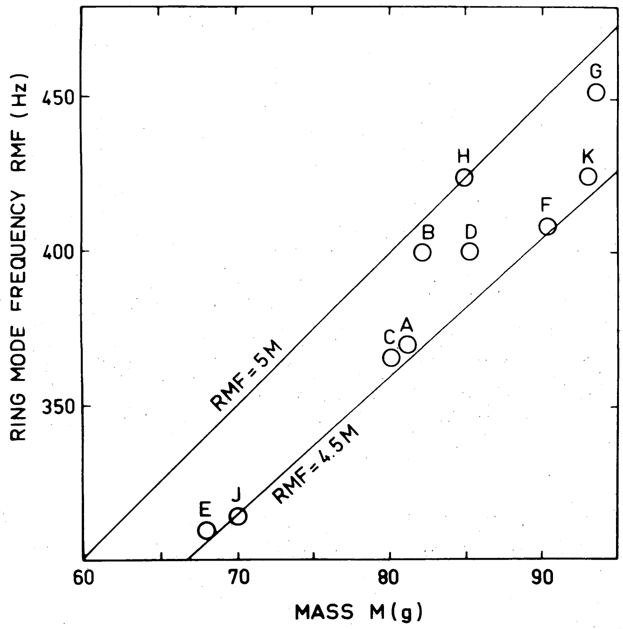


Fig. 5. Relation between ring mode frequency and mass of ten top plates (c.f. fig. 7, p.174).

According to theory the mass cannot be the main factor determining the ringmode frequency, because theory predicts it to be proportional to the inverse of the square root of the mass. However, if the density (specific weight) is approximately the same for the ten plates, then the thicknesses of all ten plates are proportional to masses of the plates and the ring mode frequencies are proportional to the thicknesses.
2) Six resonances below 1 kHz are found at the same frequencies if nomalized with respect to the ring mode frequency, i.e. the peaks numbered 2-7 in Fig. 4 (p. 234). Thus the peaks are found at approximately 0.5, 0.7, 1.0, 1.3, 1.6 and 1.8 times the ringmode frequency respectively.

3) A strong resonance is found at a frequency 2.7 times the ringmode frequency in the radiated sound.

4) The peak-to-dip ratio is approx. 20 dB and there are 34±4 peaks below 10 kHz with the selected driving position along the center line and 17.2 cm from the tailpiece end.
5) The average broadband levels above 500 Hz vary considerably between the different plates, ± 6 dB.

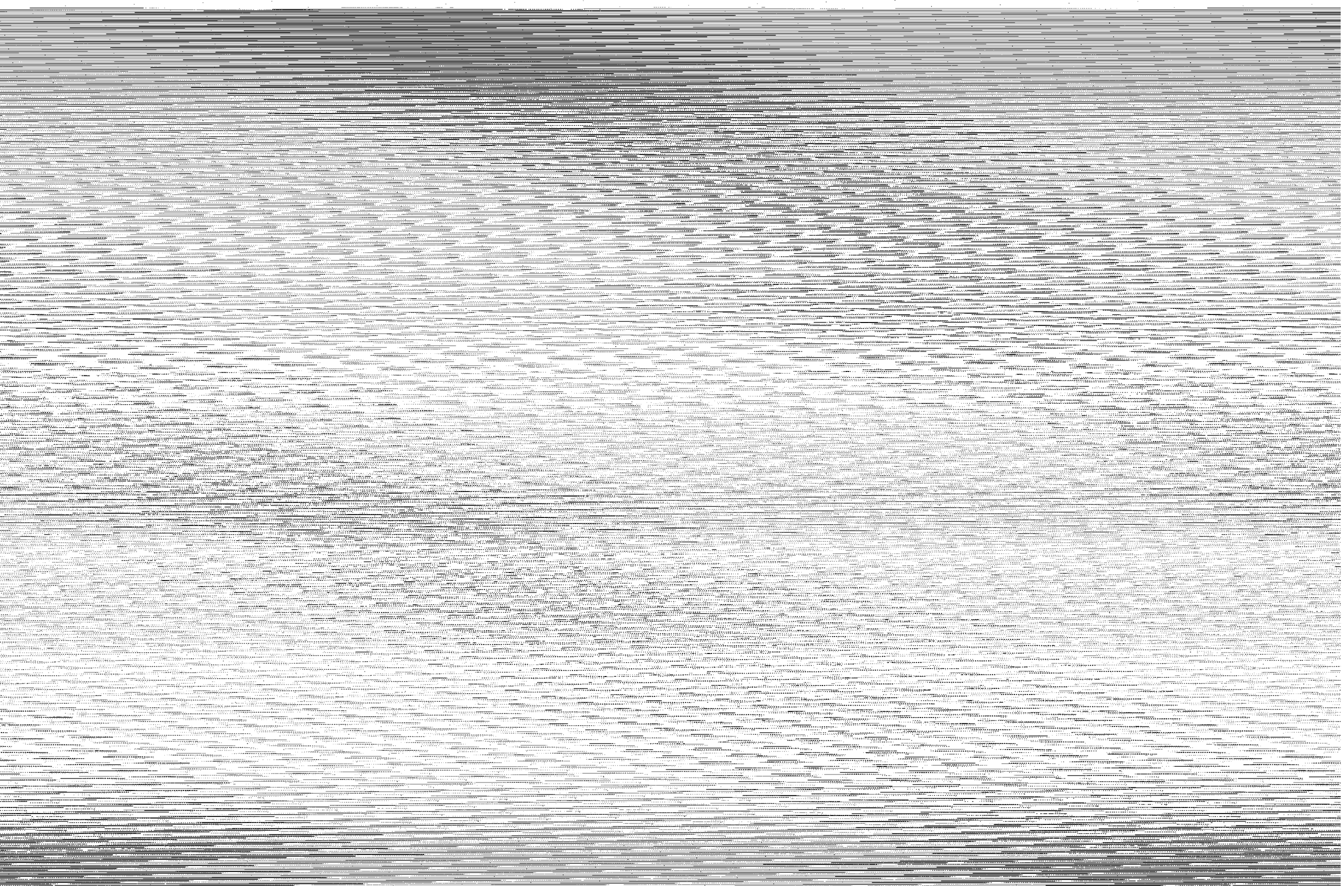
We have reasons to believe that the recorded parameters of the free plates will be found in the plates of the assembled violins, at least to some extent as illustrated in Fig. 4. Thus we should expect the differences betweeen the top plates affect quality parameters as broadband levels and peak-to-dip ratio according to results presented previously (p. 204).

The main wood frequency region

First top plate resonance

Experiments were made to obtain a better understanding of the function of the violin in the main wood frequency region and especially how this is affected by ribs, back plate and soundpost. The inadmittance was recorded in the top plate on the centerline and 16.5 cm from the tailpiece end in a normally assembled violin and with ribs and back replaced by heavy and rigid ones (solid wood 20 mm thick or more). In the normal assembly the main resonance in the top plate was found at 536 Hz. A vibration pattern of this mode, which we shall label T_1 is shown in Fig. 6 (p.238). An explanation of how the pattern is interpreted is given on p. 211 .

1) Rigid and heavy ribs increased the frequency to 616 Hz (+ 15 %).
2) Rigid and heavy back plate increased the frequency to 633 Hz, which corresponds to approx. + 15% shift after substracting the influence of other factors.
3) Removal of the air volume (back plate off and back side of ribs glued to a thick plate with a hole of the same size as the inner contour of the violin) resulted in a frequency decrease of less than 10 % (the experiment does not give the frequency directly as the gluing to the thick plate stiffens the ribs).



The experiments presented above indicated that the sound-post is the most important part. It is also known from violin making that it plays an important role. Therefore the effects of its position were recorded, Fig. 7.

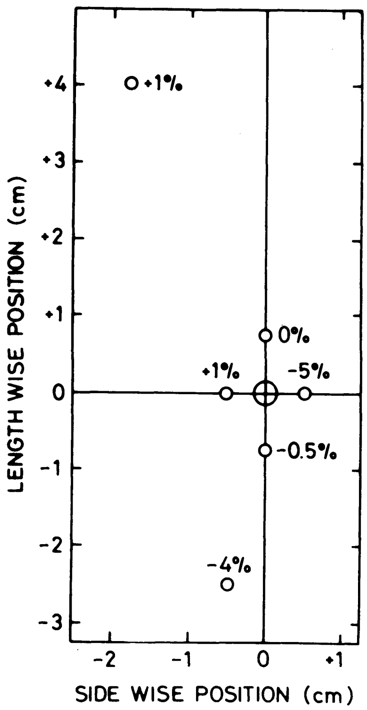


Fig. 7. Frequency shifts of the first top plate resonance for shifts of the soundpost position.

In the figure the different soundpost positions are marked with a circle, the bigger circle at origo representing the normal position. The percent number at the circles indicate the frequency shift for corresponding soundpost position. A comparison with the vibration pattern of Fig. 6 (p.) reveals that the recorded frequency shifts are in good agreement with our expectations, i.e. small for "length wise" shifts of the soundpost (as drawn in the figure) and larger for "side wise" shifts.

First top plate resonance and second air resonance

Let us examine a little more closely the frequency range of the main wood resonance. Previously it was found (Jansson, 1973) that all violins possess a strong air resonance at approx. 460 Hz, i.e. it falls in the frequency region of the main wood resonance. It has been shown that the air resonance and the main wood resonance (assumed to stem mainly from the first top plate resonance) can cooperate (Jansson & Sundin 1974). In this study the authors found other phenomena that could not be accounted for with reference to two resonances only. To improve our understanding at this point a detailed investigation was made with inadmittance measurements completed with mode tracings and airmode measurements.
Fig. 8 shows resonance frequencies in different states of assembly, starting with the ringmode frequencies for the free back (B) and top (T) plates on the upper line.

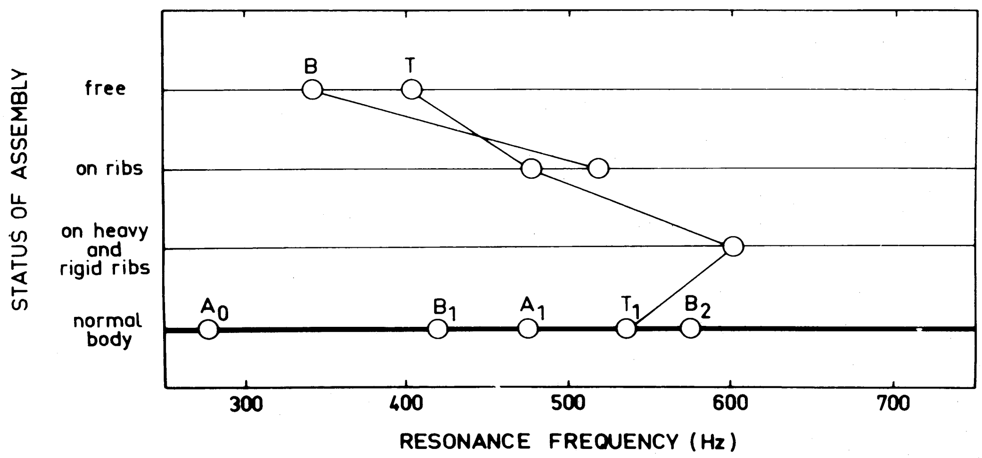


Fig. 8. Frequencies of the lowest resonances in a top (T and T_1) and a back plate (B) for different states of assembly, in a normal body with additional air resonances (A_o and A_1) and back or body resonances (B_1 and B_2).

With the two plates separately glued to the (normal) ribs, the first plate resonances are found at considerably higher frequencies, and gluing them to heavy-rigid ribs gives a still higher top plate resonance frequency. In the assembled instrument ("normal body") we find the first top plate resonance T_1 at a frequency higher than on "ribs" but lower than on "heavy-rigid" ribs, approx. halfway in between. Furthermore, there are the frequencies of two air resonances in assembly "normal body", the Helmholtz resonance A_o and the air resonance A_1, which are close to T_1. But in addition to this, two more resonances (B_1 and B_2) are found.

Four resonances in the main wood resonance frequency range

In the investigation mentioned above (by Jansson & Sundin 1974) of he main wood frequency region it was assumed that an analysis of modes A_1 and T_1 would suffice the two middle patterns of Fig. 9, but evidently the B_1 and B_2 modes may be important, the left and right patterns of Fig. 9.

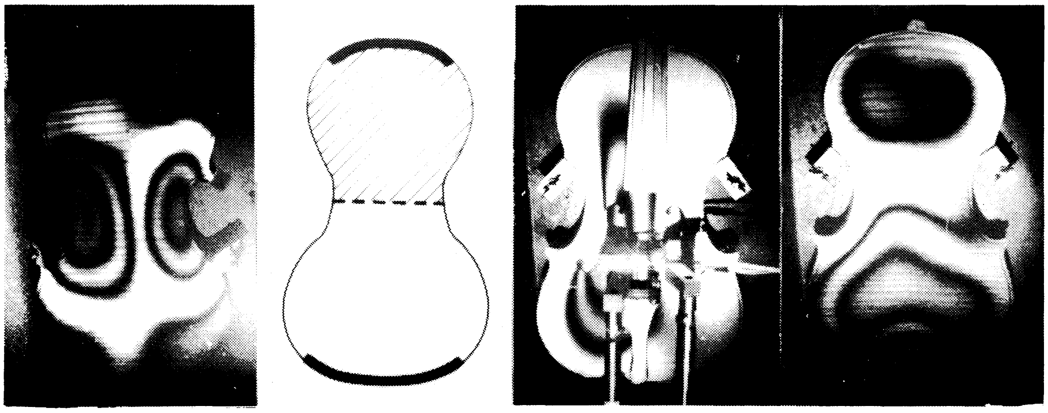


Fig. 9. Vibration patterns of the back or body modes (B_1 and B_2), first higher airmode (A_1) and first top plate mode (T_1).

Note that the B_1 and B_2 also can be found in the Stetson-Taylor interferograms Fig. 10 (p.163). Furthermore, the B_1 mode was recorded by Reinicke-Cremer(1970). Let us start to see what frequency shifts occur to all the five resonances under conditions of normal assembly and four coarse perturbations. Fig. 10.

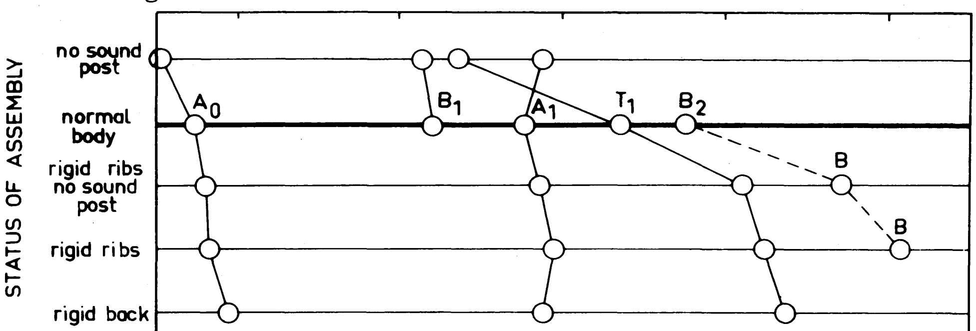


Fig. 10. Frequencies of the lowest resonances of a violin body in different states of assembly; air modes (A_o and A_1), back or body modes (B, B_1 and B_2) and first top plate resonance (T_1).

It is clearly shown in Fig. 10 that the resonance frequencies A_0 and A_1 are shifted moderately, but that those of B_1, T_1 and B_2 are shifted considerably. The B_1 and B_2 modes were not found within the range of measurements for the three lower states of assembly (the last one being selfevident).

So far we have shown results of frequency measurements, i.e. a parameter which is probably not too important by itself but probably a good general indication of other important properties. Therefore in the next step we will show detailed frequency responses i.e. information both on vibration level and frequency. Recorded inadmittances are plotted in Fig. 11 1) for normal assembly, 2) for no soundpost and 3) for rigid and heavy back plate.

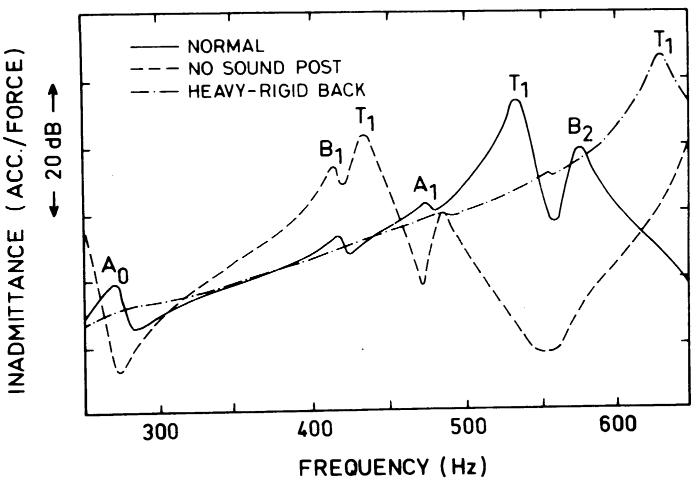


Fig. 11. Inadmittance curves for three different assemblies; air resonances (A_o and A_1), back or body resonances (B_1 and B_2) and first top plate resonance (T_1).

The normal assembly plot shows clearly five peaks corresponding to the five previously discussed resonances, A_o, T_1 and B_2 being the most prominent ones. By removing the soundpost the T_1 resonance is lowered considerably in frequency as has been previously shown (Fig.10). Fig. 11 furthermore shows that the A_1 peak becomes more prominent while the B_2 peak vanishes. With heavy and rigd back plate the T_1 peak is prominent at a high frequency while the A_o, B_1, A_1 and B_2 peaks have vanished. These results demonstrate that the resonance frequency shifts are accompanied by considerable variations of inadmittance level. Thus the results support the statement that the resonance frequencies may be important as indirect measures of other properties (e.g. on the question how different parts work together) than they are by themselves.

Let us now look a little closer at the vibrations of different parts. Vibrations at the driving point of the top plate vibrations of the back plate in opposite position and vibrations in the air volume (soundpressure in the upper bouts) are shown in Fig. 12. From the diagram two major conclusions can be drawn.

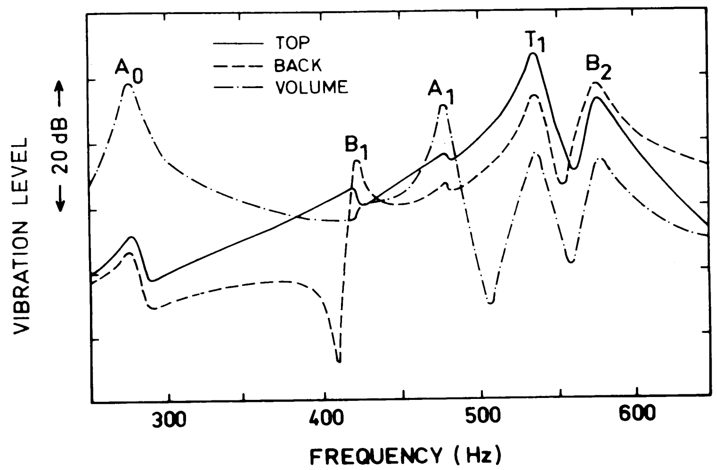


Fig. 12. Vibration level recorded in three different parts; air resonances (A_0 and A_1), back or body modes (B_1 and B_2) and first top plate resonance (T_1).

1) All resonance peaks can be traced in the top plate, the back plate and the air volume, although the T_1 resonance appears most clearly in the top plate vibrations (inadmittance), the air resonances in the air volume vibrations and the B_1 and B_2 resonances in the back plate. This means that the vibrations are mainly in some single parts/areas of the instrument but that all parts may be important for the function.

2) The back plate vibrations are by no means neglectable in the main wood frequency region, i.e. the sound radiation of the back plate cannot be neglected in this frequency region.

Detuning of the first top plate resonance

As a last step let us see what happens if we detune resonance T_1. A top plate was selected with a fairly high T_1 resonance frequency. This frequency was lowered in the normal assembly in small steps by adding small masses. Data from approximately every third out of 12 steps of massloadings are plotted in Fig. 13 (p.244). The figure shows that the A_1 mode can affect the inadmittance considerably. The lowering of T_1 increases the B_1 peak while the B_2 peak is flattened out, i.e. the influence of the T_1 resonance influences properties beyond its own resonance frequency range.

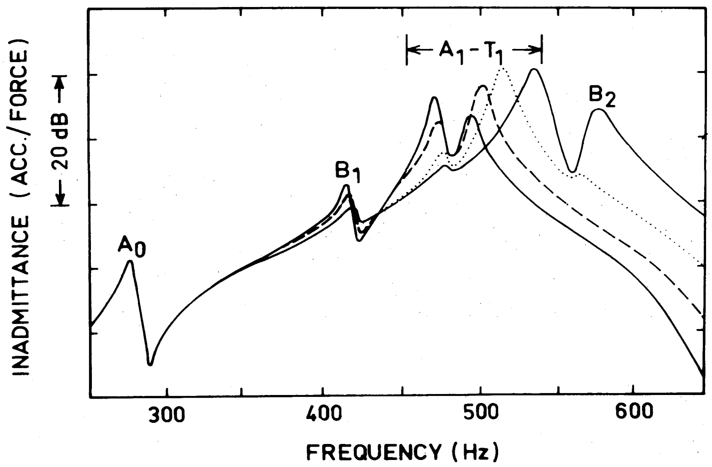


Fig. 13. Inadmittance curves for four cases of increased massloading of the first top plate resonance (T_1); air modes (A_o and A_1) and back or body modes (B_1 and B_2).

In conclusion, we have thus found the following by our detailed investigations of the main wood frequency range. This frequency range is complex and influence of four resonances can be found in top plate, in back plate and in air volume vibrations. Cooperation between the fairly frequency-fixed second airmode and the other modes implies that the absolute frequency of the first top plate mode is, at least indirectly, important.

Not published pilot investigations suggest that amplitude balance of vibrations in the upper and the lower part of the top plate are likely to be important for this cooperation.

Conclusion

In this report we have shown that inadmittance measurement is a powerful analysis tool. The inadmittance curve predicts properties of sound radiation and is well suited for resonance measurements. Measurements on free violin top plates indicate that the thickness is the main parameter. Measurements on a body assembly indicates that four resonances are important to the function of the violin in the frequency region of the main wood resonance.

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SOUND EXAMPLES

Side A

Chowning: Computer synthesis of the singing voice.

Track I

Ex. 1 a) a recording of a soprano tone
b) synthesis of the same tone with an attempt to approximate the spectrum, portamento, and vibrato of the recorded tone (11").

2 Six voices in polyphonic texture 1 (15")

3 Six voices in polyphonic texture 2 (21").

4 Voices in close harmonic voicing (4").

Track II

5 Four pitches for vowel "a" as in "father" with

a) second formant computed from table as function of pitch
b) second formant at constant harmonic, i.e. transposed spectrum.

Four pitches for vowel "e" as in "he" with

c) as in (a)
d) as in (b) (21")

6 Linear and non-linear amplitude scaling for *Amp* values of 1.0, 0.5, 0.125, and 0.062 in

a) with linear scaling (from eq. 3, *Amp* with exponents)
b) with non-linear scaling (from eq. 3, *Amp* with exponents) (11").

Track III

7 Synthesis in steps. First fundamental, secondly fundamental plus harmonics, and finally fundamental plus harmonics and vibrato at a) 400 Hz, b) 500 Hz, c) at 600 Hz and d) a,b, and c together, with independent vibrato parameters (1' 17").

8 Two examples of basso profondissimo in polyphonic tectures (48").

Benade: Wind instruments and music acoustics.

Track IV

Ex. 1 Sounding tones and their dynamic ranges of

a) normal clarinet
b) single-response-peak clarinet (35").

2 Pitch grouping during diminuendos on a specially modified clarinet (12").

Track V

3 Multiphonics on a normal clarinet controlled via changes in the reed´s own natural frequency (20").

Track VI

4 a) Register changes with a normal register key of a clarinet.
b) Pianissimo playing gives the second register, if the first air column is of reduced height.
c) Strong attacks start in the low register but the pitch changes up to the second register, if the first air column peak is of reduced height.
d) Fortissimo playing gives the second register but the pitch changes up to a detuned first register during a diminuendo, if the first air column peak is displaced in frequency but left tall (1' 4").

Side B

Benade: Wind instruments and music acoustics.

Track I

5 a) Normal clarinet sounds near C_4 (262 Hz).
b) Fairly normal sound near C_4 on the isospectrum clarinet.
c) Dark sounding low notes of the isospectrum clarinet.
d) Bright sounding upper notes of the isospectrum clarinet.
e) Chromatic scale on an isospectrum clarinet gives a change in tone colour from dark to bright (42").

Track II

Ex. 6

a) Normal clarinet. Notice pitch, tone colour and the register change which is a musical twelfth.
b) Clarinet with its reed and mouthpiece replaced by a flute-type head joint. Notice the new pitch, tone colour and the fact that the register changes are now approximately an octave.
c) A simple flute tune on the clarinet with the flute-type head joint (40").

Track III

Hutchins: The new violin family.

Hosanna-Benedictus-Hosanna from Mass: "L'Homme armé" by G.P. Palestrina (1525-1594) arranged by Frank Lewin played on the new family of violins.

Treble violin:	Gunnar Eklund
Soprano "	Ulf Edlund
Mezzo "	Semmy Lazaroff
Alto "	Per Blendulf
Tenor "	Peter Molander
Baritone "	Miroslav Jovic (3' 56")