tion, which would make possible reflection at angles perpendicular to the layer provided the region of discontinuity were small compared with the wave-length.

One more effect ought to be mentioned. Since the earth's field exhibits daily, yearly and secular variations the propagation of wireless waves around the earth ought to exhibit corresponding variations. Daily and yearly variations, of course, are a well established fact. These variations, as well as reflection and absorption, are at present attributed to the presence of free ions or electrons with densities estimated at about 10^5 for the case of the electrons and 10^9 for the ions, whereas the effect of the much more numerous and almost equally effective water dipoles is neglected. How much of such effects are due to free charges and how much to the dipoles remains to be determined. However, the existence of these effects, however small they may turn out to be, ought to be recognized. Thus, we believe we have shown that the electric field of the earth acting on the polar molecules in the earth's atmosphere, is capable of appreciable modification of the medium with respect to the propagation of wireless waves.

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THE VIOLIN.[1]

BY

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INTRODUCTION.

The acoustical problems involved in the violin or other stringed instruments of similar construction have, for the last two centuries, interested many scientists, but it must be admitted that very little success, if any, has been gained in obtaining an explanation or a principle for the violin's acoustic action, or a method by which such instruments could be made to achieve the tonal beauty which made the violins of Stradivarius, Amati and other old Italian violin-makers so justly famous.

In the following pages I shall try to explain a point of view of the action of the resonatory body of the violin and show how a new theory or acoustical principle can be deduced. To confirm this principle, it will be followed by several analyses of sounds from instruments made accordingly. At the same time, these results will be compared with similar results on sound analyses of tones from a few famous Italian violins obtained by Professor Backhaus in Germany.[2]

THE CONSTRUCTION OF THE VIOLIN.

The present shape of the violin is the result of an empirical development which can be traced back to the earliest known periods of culture in the Orient, but it was not until the fifteenth century that the form was completed and made somewhat similar to our present viola. The quality of tones

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[1] "Strygeinstrumentets Resonanslegeme Betragtet Som et System af Elektrisk Koblede Svingningskredse" (*Ingenioren*, XXXIX, No. 23, p. 278, June 7, 1930), and "Violinen-Undersogelser af Resonanslegemet-Udfort paa Bell Telephone Laboratories Inc., New York" (*Ingenioren*, XLI, No. 12, p. 157, March 19, 1932).

[2] H. Backhaus, *Z. f. techn. Phys.*, 8, p. 509, 1927. *Naturwissensch.*, 17, p. 811, 1929. *Z. f. Phys.*, Bd. 62, p. 143, 1930.

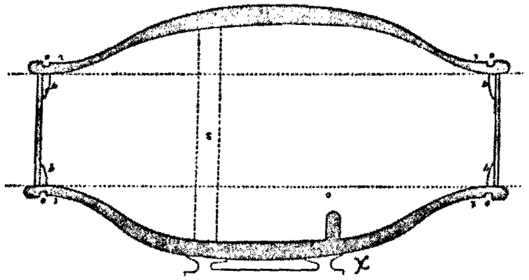
in the older stringed instruments was probably very harsh and noisy; but at that time the resonatory body was made of a smaller and larger size to cover the tone register of the soprano, alto and bass voices of the singers, thereby opening the way to the great improvement of volume and mellowness achieved during the seventeenth and eighteenth centuries by the famous Italian violin makers.

The resonatory body of the violin is quite remarkable. Its usual form, shown in Fig. 1, consists mainly of the bottom plate or back, the sides and the top plate, in which the two holes are cut like an *S*. At the upper end of the body the neck is fastened, ending with the snail, which has four screws with which the strings are tuned. In the middle, between the two sound holes in the top, is placed the bridge, over which the four strings are stretched. The other ends of the strings are fastened to the stringholder, which again is fixed to the lower end of the violin.

FIG. 1.

Side view of violin.

FIG. 2.

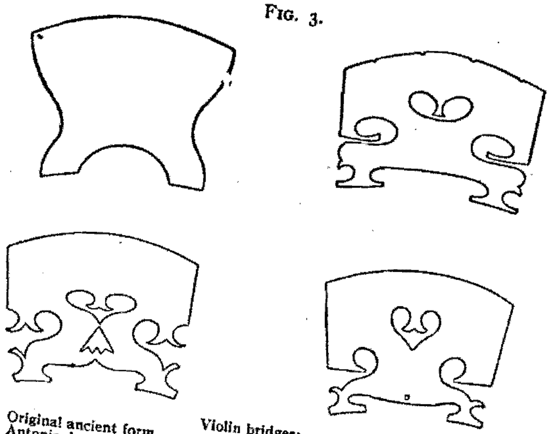


Cross section of violin.

The cross section, Fig. 2, shows the bass-bar, which runs inside the top plate about two-thirds of the full length and under the one support (*x*) of the bridge. This arrangement allows the distribution of the load and the vibrations from the bridge. Near the other support of the bridge is placed the sound-post, which also carries the load from the bridge and transfers the sound vibrations to the back.

Although this construction is quite interesting, the names of the inventors of the sound-post and the bass-bar and the origin of the use of heavy wood (maple) for the back, or of light wood (spruce) for the top, etc., are not known. The construction, in these respects, was really finished before the famous Italian violin-makers endowed their violins with the beautiful tone quality not later exceeded.

FIG. 3.



Original ancient form. Antonio Amatis.

Violin bridges:

Stradivarius. Nicolaus Amatis.

The Italian violin-makers brought about, in acoustical respects, a marvelous epoch in the history of the development of musical instruments, as they changed and improved the tone quality without altering the original construction. Only the bridge underwent a slight change in design in the hands of the two Amatis and Stradivarius, as is indicated in Fig. 3.

It has been an enigma ever since if such results were reached by a well-defined method, using certain acoustical principles, or merely by empirical treatment of the vibrating plates, combined with intuition and mastering an ideal aural impression of tones. As a matter of fact, the classic period of

Italian violin-making two centuries ago left us only a number of violins made by Nicolaus Amati, Guarnerius, and Stradivarius, and several others which are still highly appreciated for their pure tone quality and enormous carrying capacity of the tones.

The art of building such violins died out soon after the death of Stradivarius (1737), and the following years of violin-making have mainly consisted of copying the dimensions of the masters' violins, a method which has hardly given satisfaction. This method, however, is still used and its poor results, compared with the former creations, give a measure of the helpless position in which the technique of violin-making nowadays is placed, even with our much greater knowledge of acoustics. If a violin-maker now and then happens to make a well-sounding violin, it is mainly a piece of good luck, and it has not been possible to prove why one violin was turning out better than others.

Since those days, however, not only the violin-makers but many of the best scientists as well have worked on these problems but without much success until recently, since the methods used for detecting objectively in which way the tone quality from the famous masters' violins diverged from the tone quality of the ordinary violin were not exact enough. The electrical amplification of sound waves, however, has made this possible. Professor H. Backhaus has been very successful in obtaining photographic pictures of the sound from quite a few famous violins, among them one made by Stradivarius, so that by the help of harmonic analysis, the features of the tone quality could be seen.

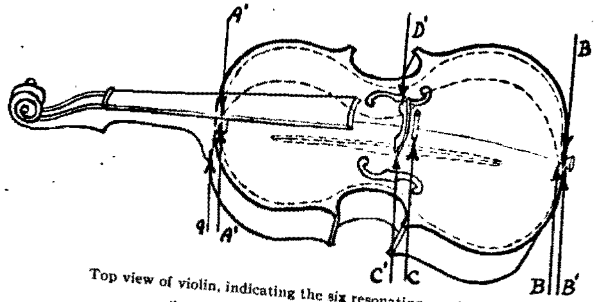
The following is a translation of Professor Backhaus's conclusion of some of his results:

> "Some features which were noted from the sound analysis follow: Hewlett found that more sound energy was given to the lower partials on the good violins than on the poor ones. This fact was confirmed by the present investigation. Obviously, it is desired to have the timbre controlled by the fundamental if a pleasant aural impression is to be produced. If any other partial is stronger than the fundamental, the sound is sharp and less pleasant. It appeared that it was difficult, if not impossible, to produce timbres controlled by the fundamental with most of the tones from cheap violins; however, some tones from the best and most valuable violins also indicated such defects. This, of course, is often due to the material of the string."

Accordingly, it would be expected that a method of improving the tone quality should demonstrate the above statement as fully as possible. We, therefore, shall often refer to this statement during the following discussion.

After the new acoustical principle for the action of the resonatory body of my violins was developed, assisted mainly by my aural impressions and helped by the familiar acoustic laws according to Helmholtz and others, and after such violins were given practical tests at several concerts,[3] I had the privilege of making a similar tone photographic investigation of my instruments in the Bell Telephone Laboratories, New York City. It may be said here that the harmonic analysis of these oscillograms seems to confirm the statement of Professor Backhaus.

FIG. 4.



Top view of violin, indicating the six resonating portions.

The point of view which I had found for the acoustic action of the resonatory body before applying the above-mentioned tests follows from the construction shown on Fig. 4. By the location of the bridge on the top and of the sound-post be-

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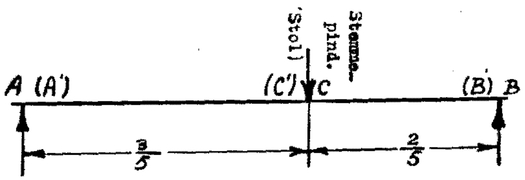
[3] K. F. W. Askoe, *Ingenioren*, XXXIX, No. 48, p. 581, November 29, 1930, and "A New Theory of Violin Building," *Musical Courier*, New York, p. 14, May 16, 1931.

tween the top and back, these plates are altogether divided into six different vibrating and mechanically coupled parts, the dimensions of which determine the quality of the sound which is transmitted from the body when the strings are excited by the violin bow.

Two of these parts belong to the bottom, as the sound-post divides it into a longer part A–C and a shorter part C–B. The other four parts are in the top. As this is glued together in the middle of two symmetrical parts, each of them is divided by the bridge at the left side into the parts A'–C' and C'–B' and at the right side into the parts A'–D' and D'–B'.

As the structure of the wood is longitudinal, the above-mentioned plates have the character of strings, and the frequencies of the respective parts must approximately follow the usual expression for the number of vibrations of a string:

FIG. 5.



Pressure of the sound-post upon the back of violin; and the bridge upon the left side of top pla

$$f_n = \frac{1}{2l}\sqrt{\frac{g\cdot P}{Q\cdot S}}, \qquad (1)$$

where l is the length of the plate parts, g the acceleration of gravity, P the tension, Q the area of the section, and S the specified weight of the wood.

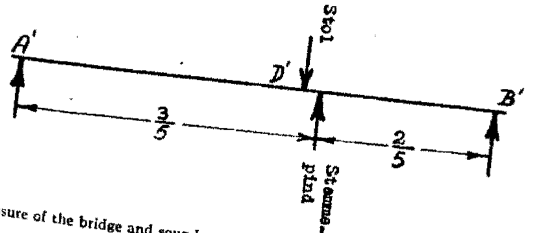
From equation (1) it is seen that the frequency of the fundamental tone is decreased, if the length l, the area Q and the weight S are increased and vice versa if the tension P in the plate parts is increased.

In Fig. 5 is shown the static condition caused by the pressure of the sound-post on the bottom. In the same way, the left side of the top with the bass-bar is actuated by the one support of the bridge. On Fig. 5 is further shown the right side of the top, as this is actuated by the one support of the bridge as well as the sound-post.

From the use of two different kinds of wood for the top and bottom, thereby giving the six plate parts of the resonatory body different fundamental frequencies, it is immediately seen how this way of explaining the acoustic action of the body allows practically all the tones played on the strings to find a corresponding plate part of the resonatory body through which the sound will be transmitted to the air. This, however, brings in one important question: what is the most advantageous frequency to which each plate part has to be tuned or corresponded?

The solution of this question can be explained by referring to Fig. 5. Let us assume the back as a suspended string made,

FIG. 6.



Pressure of the bridge and sound-post upon the top plate (right side) of violin.

it is, of wood with the total length l and cross section S, and that the sound-post is actuating at a point C at 3/5 of the length from A. The frequency of A–C will be of the reciprocal ratio to the length and, therefore, in proportion to the frequency of the part B–C, equal to $\frac{3}{2}$ because $\frac{3}{5} : \frac{2}{5} = \frac{3}{2}$. From this, it follows that the frequency of B–C is a fifth or five tones higher than the frequency of A–C. Let us combine this with the fact that the whole length A–B will vibrate with a given frequency, and assume that the point C is moved 1/20 of the whole length against A; then it is evident that if the whole length A–B has a certain frequency (for example, the fundamental tone G equals 98 vibrations per second), then the part A–C will have the frequency equal to approximately 196 vibrations per second, or the octave to *G*; and further, the part *B–C* will have the frequency *d′* equal to 294 vibrations per second or the twelfth to *G*.

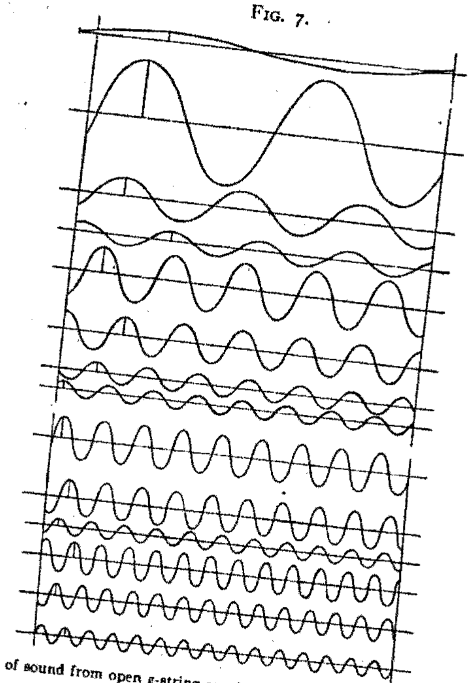
This way of explaining the best frequency distribution is quite possible and is also consistent with the mathematical investigation of the possible vibrations of a string made by Daniel Bernoulli. He found that the string vibrates, besides its fundamental tone, with a number of partials or overtones (Helmholtz), which number of vibrations equals the number of vibrations of the fundamental tone times the numbers 1, 2, 3. . . .

In dividing the resonatory body as indicated, not only the fundamental tone of the vibrating string but, at the same time also, its 2nd partial or the octave to the fundamental will be transmitted by one part and the 3rd partial or twelfth by another part of the bottom. Or at the time at which the two plate parts are transmitting the 2nd and 3rd partial, the fundamental may be created as a beat frequency between these two parts. In both cases, the actual result is the same and in contradiction to what would happen at any other division of the resonatory body (ratio between the length of the plate parts).

The vibrating parts *A–C* and *B–C* may also be considered individually as strings, and their respective 2nd partials will correspond to the 4th and 6th partial of the fundamental of the string vibration. On the other hand, the 5th partial of the string vibration, which is a third in the natural chord from the string, will not be able to find resonance in any of these plate parts, and if this should happen, the only possibility is as a partial to the vibration of the whole length of the back. Now, if this should be the case, the 5th partial of that "string" *A–B* would require a node for every 1/5 of its length. Therefore, one node will be located near the point *C*, where the sound-post is placed. This, however, is not likely to happen, because the vibrations from the string are transferred to the back at this spot, and it is, therefore, important that this transmission of energy be not hindered by the tendency of holding the "string" *A–B* at rest at this point (the creation of a node here) such as would be required if the 5th partial should be transmitted (amplified).

As the frequency of the back, as mentioned above, is low, around 98 vibrations per second, only the lower tones will find resonance here. It is therefore the mission of the top to give resonance to the other and higher tones which can be played on the violin.

Fig. 7.



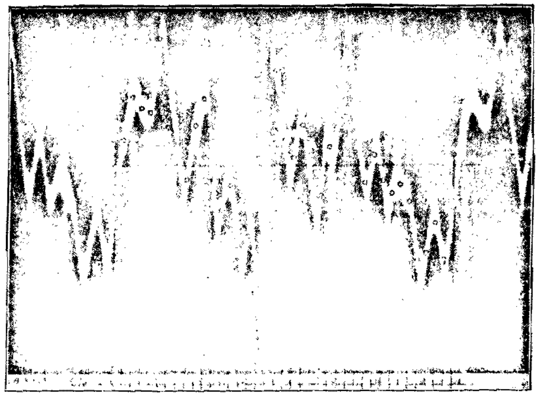
Harmonic analysis of sound from open g-string on violin, 196 vib. per second. Elementary sine-waves of 1′–11′ and 13′–15′ partials.

In applying the above acoustical principle to the parts of the top and going up a fifth, the plates in the one-half with the bass-bar will then have the frequencies *a′* = 440 and *e″* = 660 vibrations per second, and the corresponding other parts of half the top will have the frequencies *h″* = 980 and *f‴*-sharp = 1470 vibrations per second. (This notation with primes indicates to which octave the specified note belongs. For example, the note is *a′*, then it belongs in the octave from

$c' = 260$ vibrations per second to $c'' = 520$ vibrations per second. If the note belongs to the octave below this, it is given without primes; for example, $a = 220$ vibrations per second. The next lower octave has the primes at the base of the letter; for example, $a_1 = 110$ vibrations per second, etc.)

Now, by tuning the respective pair of combined plate parts in tones following each other with intervals of five tones or a fifth, the build-up of the 5th partial in the sound of the played tones is hindered, unless in the sound from the lower tones. For example, if $G = 98$ vibrations, the 5th partial is $h' = 490$ vibrations, and this will consequently find some resonance in the part $(B'-C')$ of the top, as the frequency for resonance here is $a' = 440$ vibrations per second.

FIG. 8.

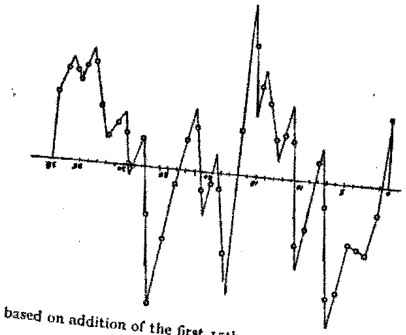


Enlarged oscillogram (19) of open g-string on violin No. 1 with axis and ordinates.

From this it follows that tones played on the violin, of which the 5th partials are higher than the frequency of the highest tuned plate part (in this case f'''-sharp = 1470 vibrations per second), will not have the 5th partial amplified. As a whole, it is to be seen that the above-mentioned principle for tuning the resonance body will permit the 5th partial to be suppressed in the sound of the tones from the two highest strings a' and e''. The resonance from the top on the other side makes it impossible to avoid the 5th partial in tones played on the lower strings.

The above are the fundamental facts concerning the constitution of the sound from the violin. This theory is satisfactorily confirmed by the harmonic analysis of actual oscillograms. Such oscillograms were taken at the Bell Telephone Laboratories and analyzed with the aid of Pollak's tables. The results are graphically shown in Fig. 7, where the elementary sine-waves or the fundamental with its partials are given, with their phase relations. In Fig. 8 is shown the enlarged oscillogram on which the analysis is based, and on which the 38 ordinates necessary for the computation are traced, together with the axis. For checking this method, a curve is drawn in Fig. 9, based on the addition of the first fifteen computed forms without the twelfth, whose amplitude is negligible. It is easily seen that this agrees very well with the original curve of the oscillogram.

FIG. 9.



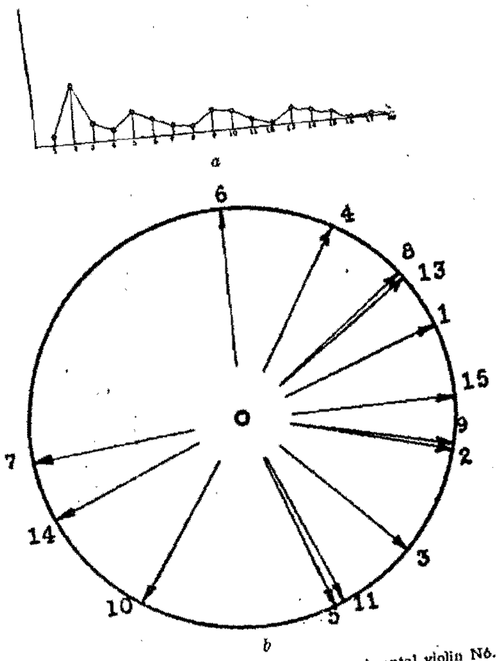
Curve based on addition of the first 15th computed forms from Fig. 7.

In Fig. 10 is drawn an amplitude diagram where all the amplitudes of the first eighteen partials are shown. The following section will explain what can be found in the action of the resonatory body.

EXPERIMENTS WITH STRINGED INSTRUMENTS.

The purpose of the experiments and of using harmonic analysis to explain the oscillograms was to indicate the influence of the action of the resonance body on the structure of the transmitted sound, as this would change the difference in the amplitudes of the partials and indicate whether or not the plates are tuned according to the theory developed here.

FIG. 10.



a) Relative amplitudes of vibrations of open *g*-string on experimental violin No. 1. *b*) Faredia-gram. The Face-angles between the partials.

If, at the same time, it is possible to prove that a similar structure is found in the sound from the famous master violins, which, of course, does not mean that the latter do not contain other valuable features, then this will emphasize the æsthetic importance of the facts here mentioned.

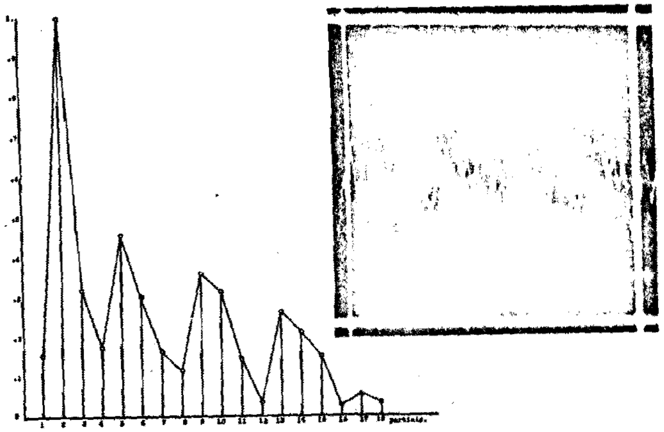
The results given here will concern only a few of the most important experiments of the quite extensive tests conducted.

Further, only the harmonic analysis of tones from the four open strings of the violin, which are tuned in the fifth *g*–*d′*–*a′*–*e″*, will be given, as these give enough data to determine the distribution of the resonance among the different parts of the resonatory body. In Fig. 10 is shown the amplitude diagram of the open *g*-string on violin No. 1, which, in respect to tone quality, was the best I have made.

This diagnosis indicates that the amplitude of the fundamental is very small compared with the amplitude of the 2nd partial, the octave. Further, the 3rd and 4th partials are smaller and the 5th and 6th partials are somewhat greater, and so forth. If, at the same time, it is remembered that the number of vibrations of a harmonic is so many times greater than the number of vibrations of the fundamental, as is indicated by the number of the partial, then this is a convenient way of expressing the results of an analysis from a given sound.

The amplitude diagrams of the four open strings are shown in Fig. 11. Regarding the *g*- and the *e″*-string (the last one was, in all the experiments, of steel) only a single analysis is shown, where several analyses are given of the *d′*- and *a′*-string.

FIG. 11.



Relative amplitudes of vibrations of experimental violin No. 1. Open *g*-string, 196 vib. (19). Open *d′*-string, 294 vib. (20) full line, (20*a*) and (20*b*). Open *a′*-string, 440 vib. (21) (upper curve). Open *e″*-string, 660 vib. (22).

Fig. 11 continued on pages 232 and 233.

FIG. 11.—*Continued.*

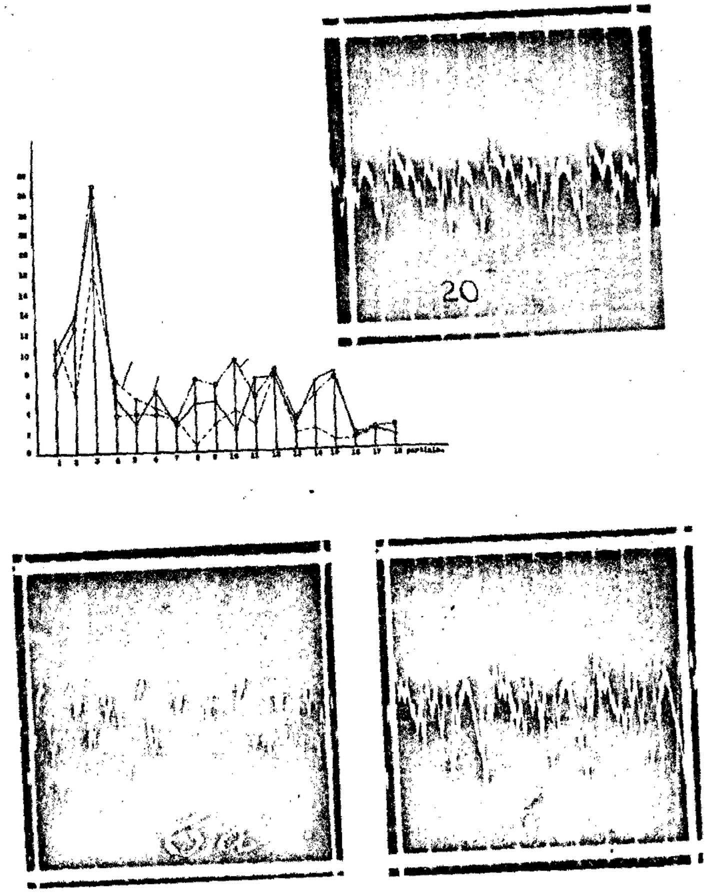


FIG. 11.—*Continued.*

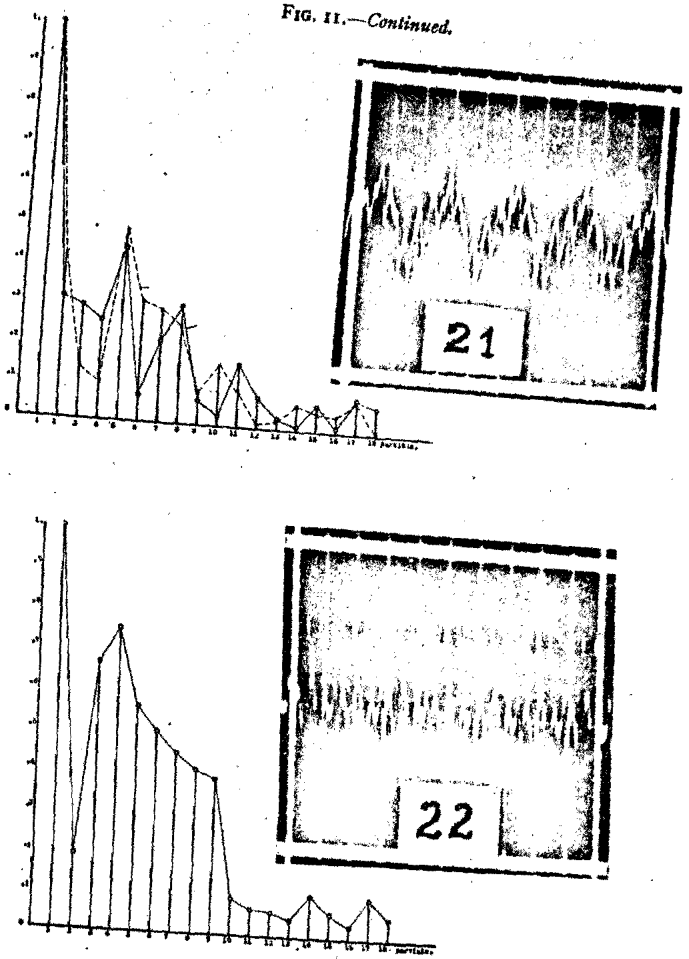
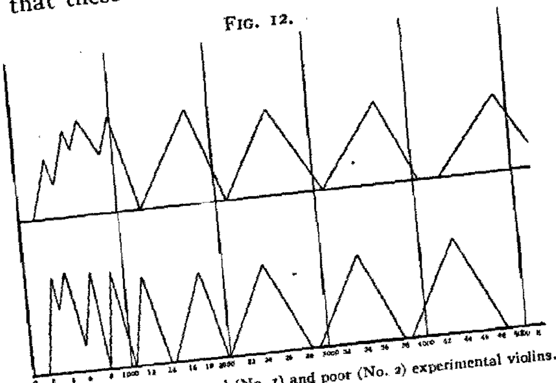


FIG. 12.



Location of resonance in good (No. 1) and poor (No. 2) experimental violins.

The form of the oscillogram from these two strings was quite interesting and remarkable and indicated a variation of the tone energy; that is, a variation of the fundamental and the partials as well. The resonatory body, however, has not been changed; so this variation must be due only to the action between the string and the violin bow. How the tone quality is changed can easily be followed in Diagrams 20 and 21, but it is not possible to ascertain by inspection the law of these changes. The analysis, for example, of the *d'*-string (No. 20) indicates that a gain in the fundamental may cause an increase as well as a decrease of the 2nd partial. It is, therefore, obvious that these changes must either be due to the action between the string and the violin bow or to the reaction from the resonatory body or presumably to both actions at the same time. As this question seems quite involved, attention will merely be called here to this relation. After this, we proceed with pointing out that the diagrams also indicate certain minima and maxima which we can use to determine the resonance of the plates of the violin. By inspection of these four diagrams, it is possible to find, as shown in Fig. 12, the location of the resonance of the six-plate parts of the violin inside the limit of about 2000 vibrations per second. The location of resonance found in the corresponding amplitude diagram from another experimental violin (No. 2), not so good, is also given in Fig. 12. Comparison shows that a resonance located around 392 vibrations per second is not found in violin No. 2, and further, that the number of vibrations of its plates is higher than that found in the plates of the good violin.

An investigation of these oscillograms from the two violins proves the basic assumption that the resonatory body consists of six different tuned plate parts.

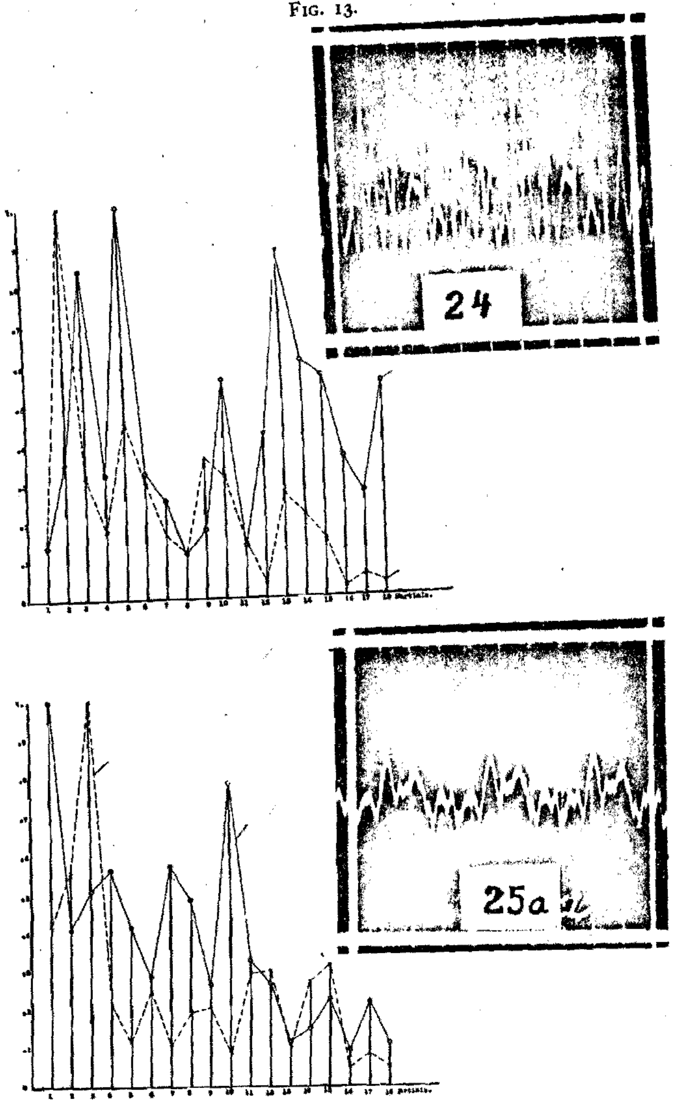
Now, let us compare, in Fig. 13, the structure or quality of the same tone in the amplitude diagrams of the open strings of the two violins, and we shall see that while the fundamental from the open *g*-string has about the same amplitude, this is far from being the case with the higher partials.

In the good violin, the 2nd partial on the *g*-string is the most dominating, which is what Backhaus also found in the old master violins. My experiment, on the other hand, indicated that in the poor violin the 5th partial was the strongest, although a strong part is also found around the 12th to 18th or at still higher partials. Compared to this, the amplitude diagram of the open *d'*-string is much better, even if the higher partials here are somewhat pronounced, compared to the corresponding partials in the good violin. Comparison of the *a'*- and *e''*-strings shows, on the other hand, no noteworthy difference between the good and the poor violin. The highest strings in both violins gave also a good aural impression of tone quality.

The difference in the two experimental violins is related to the dimensions of the resonatory body, as it is to be found in the back of the poor violin. This is too thin or has too little mass; the top in both violins is tuned about the same. From this, it follows that, provided the back of the poor violin was replaced by a heavier one and tuned according to Fig. 5, a violin of a much better tone quality could be obtained.

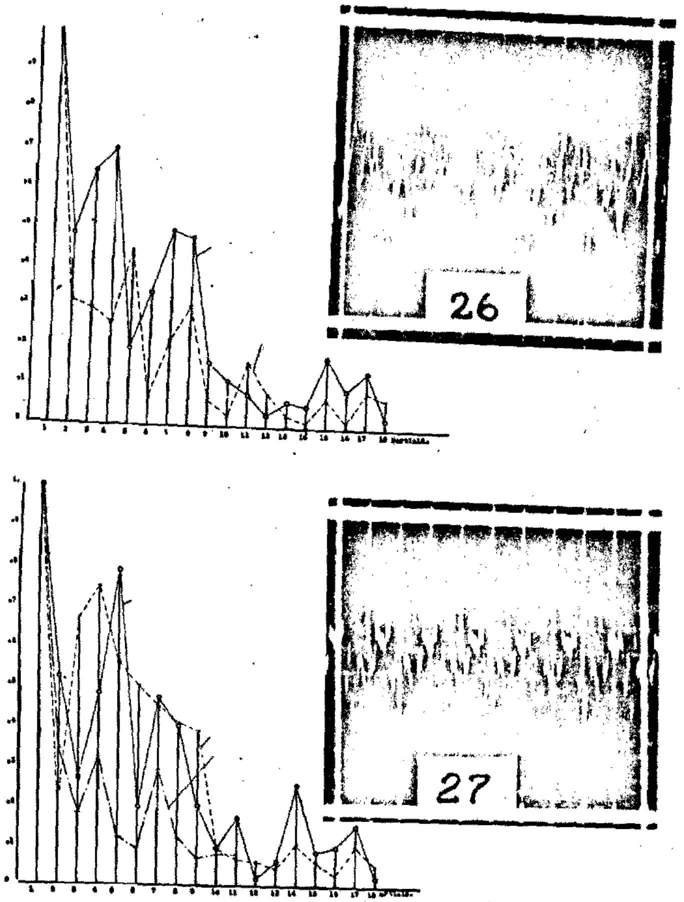
The amplitude diagrams indicate, also, the same structure as was found by Backhaus; namely, that the sound is built up of a far higher number of partials than were earlier found. My experiments explain further the fact found by Backhaus, that it is because of the tuning of the resonatory body that one does not succeed in getting a greater fundamental on the open *g*-string, as is often the case.

FIG. 13.



Relative amplitudes of vibrations. The full drawn curves refer to experimental violin No. 2; the dotted curves to experimental violin No. 1. Open *g*-string, 196 vib. (19, 24). Open *d*′-string, 294 vib. (20, 25a). Open *a*′-string, 440 vib. (21, 26). Open *e*″-string, 660 vib. (22, 27). Storioni-violin, dash and dot (Backhaus).

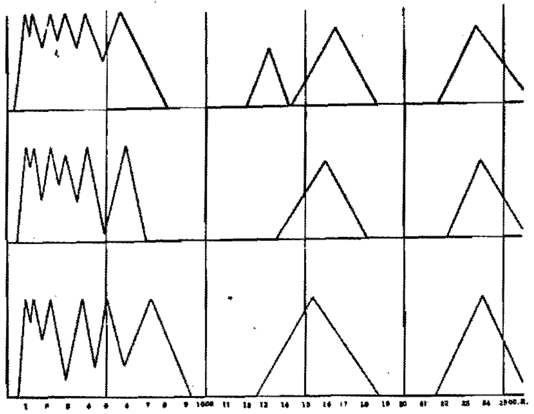
FIG. 13.—*Continued.*



What is said here about the resonatory body of the violin concerns also the viola, the violoncello, and the double bass. As the resonatory body on those instruments must give resonance for lower tones, it should have greater dimensions, and it is an old rule that the length of the string determines the approximate length of the resonatory body. Otherwise, the construction is similar to that of the violin in Fig. 4.

The experimental results given here will be limited to those obtained with a violoncello. This instrument, like the violin, has four open strings, but they are tuned in the fifth *C–G–d–a*.

FIG. 14.



Effect of position of the bridge upon the body resonance of the experimental 'cello.

Three experiments were made with the violoncello to show the change in the tuning of the resonatory body which was caused by moving the supports of the bridge near the pin about 3 mm. against the latter. This is more fully explained by examination of Fig. 6.

The location of resonance in the body is based on the three sets of analyses from the four open strings, and the results are combined, as shown in Fig. 14. The trace on the base line indicates the location before the bridge was moved; that in the middle the condition after the move, and the upper trace the location of resonance after the bridge was moved back to its proper place, according to the aural impression of the most mellow and pleasing sound.

A glance at Fig. 6 will show that the tension of the concerned plate parts of the top is decreased; consequently, according to equation (1), the number of vibrations should be smaller after the move. This is confirmed by the distribution of resonance in Fig. 14, which indicates that moving the bridge decreases the respective vibrations of the three highest tuned plate parts. This is especially to be found at the two highest tuned plate parts *A′–D′* and *D′–B′*; see Fig. 6, which number of vibrations is about 100 vibrations per second lower than before the move.

Before the third oscillograph record was taken, all the plate parts of the resonatory body were adjusted by moving the bridge and sound-post until the tone quality most pleasant to the ear was obtained. This adjustment is the last made before an instrument leaves the violin-maker.

The results of this are shown in the upper trace in Fig. 14. They indicate an even better distribution of resonance than before. Further, the amplitude diagrams of the four open strings, according to this last condition, are given in Fig. 15. It is shown in the open *G*-string (= 65 vibrations per second) that there is a location of resonance of the top which amplifies the 5th and the 6th partials. On the other hand, the last amplitude diagram of the open *a*-string indicates the suppression of the 5th partial. When we add to this picture the slight decrease in amplitudes in the open *G*-string and the open *D*-string, then the suppression of the 5th partial of the sound from the higher tones is a proof of the perfect tuning of the resonatory body. At the same time, this permits the tone quality to be primarily dominated by its greatest fundamental; also the matching of lower partials which give the tonal beauty and a well-balanced acoustical impression as a whole.

That this result is more obvious from the analysis of the tones from the violoncello than from the best experimental violin is due to its better distribution of resonance.

For checking the oscillographic record, the tone from the open *G*-string was also analyzed with the electrical analyzer[4]

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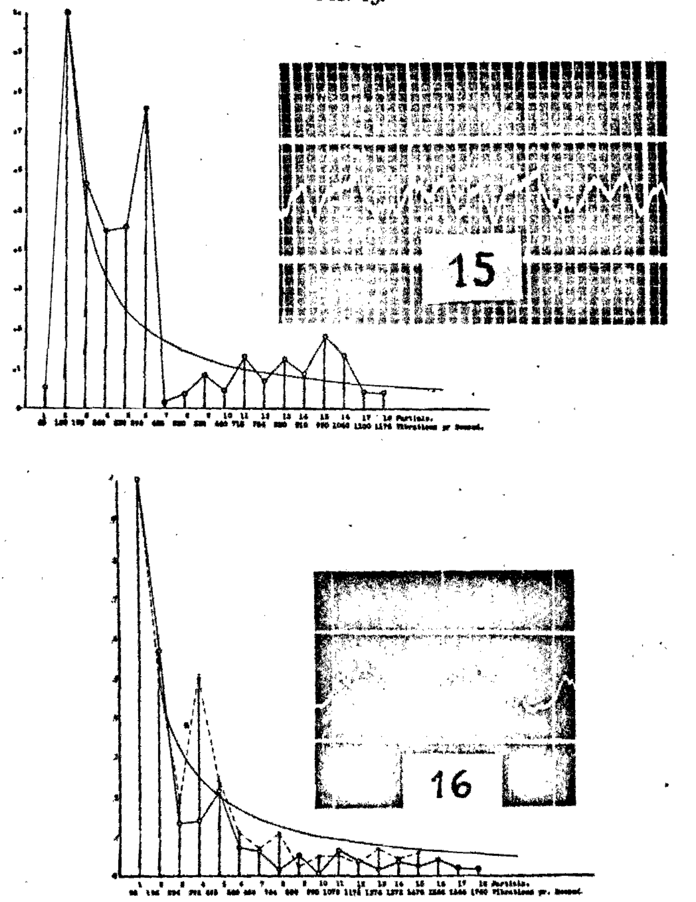
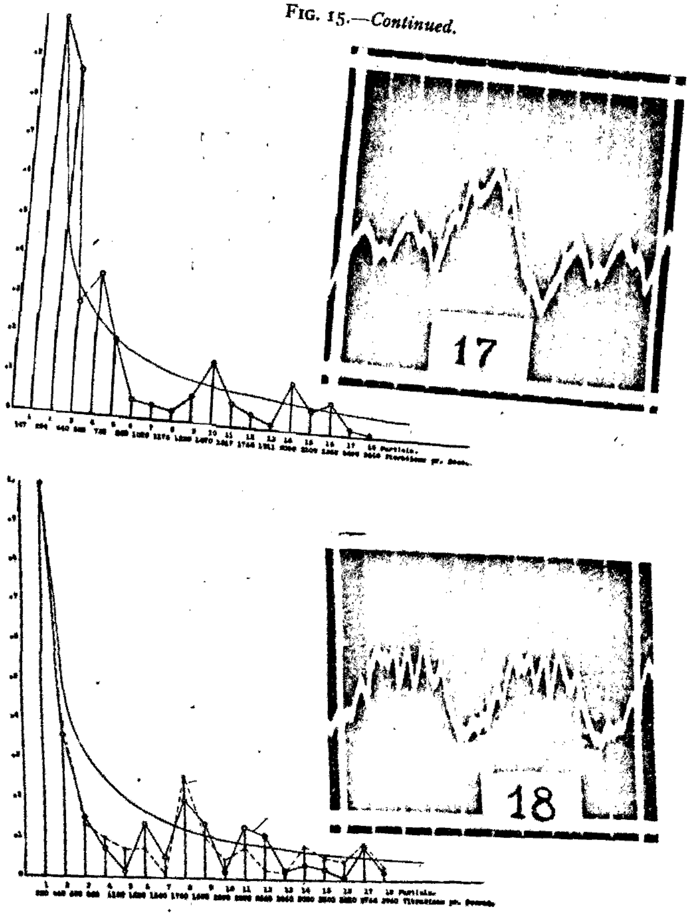
[4] R. L. Wegel and C. R. Moore, *Bell Syst. Techn. Journal*, 3, 1924, p. 299.

FIG. 15.



Violoncello. Open c_1-string, 65 vib. (15). Open G_1-string, 98 vib. (16). Open *d*-string, 147 vib. (17). Open *a*-string, 220 vib. (18).

FIG. 15.—*Continued.*



by Wegel and Moore. The dotted curve in the amplitude diagram indicates that this test was satisfactory.

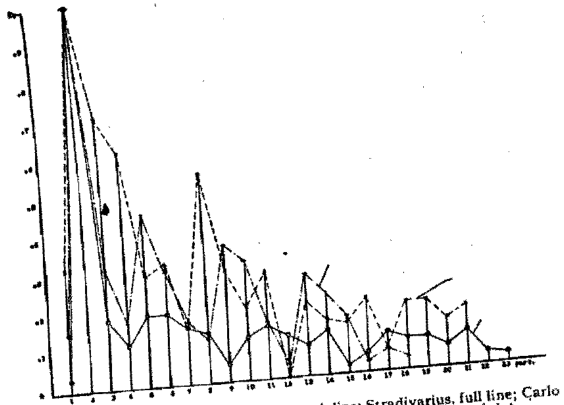
In each of the last diagrams there is drawn a hyperbolic curve by which the form of the respective amplitude curves may be compared. The use of this curve is based on the following assumption:

Let us consider the expression for the intensity of a sound vibration

$$J = \tfrac{1}{2}SC(\omega a')^2, \tag{2}$$

where a' is the amplitude of the vibrating particle, S is the average value of the density of the air, C the sound velocity, and ω the number of vibrations per second, or the frequency.

FIG. 16.



Relative amplitudes of vibrations of open g-string of violins: Stradivarius, full line; Carlo Bergonzi, dotted line: (Backhaus); experimental violin No. 1—dash and dot.

Assuming that this sound is solved into its partials and that we have a constant and equal distribution of the intensity between the fundamental and each of the partials, then the amplitude a' of a given partial must be just so many times less as its number of vibrations is increased. A tone with this feature we shall call an ideal sound.

The intensity of an ideal sound of a given tone can, therefore, be expressed solely by the number of vibrations of the fundamental and its amplitude a', as follows:

$$J_i = \tfrac{1}{2}SC\left[(\omega_1 a_1')^2 + \left(2\omega_1\frac{a_1'}{2}\right)^2 + \left(3\omega_1\frac{a_1'}{3}\right)^2 + \cdots + \left(n\omega_1\frac{a_1'}{n}\right)^2 + \cdots\right]. \tag{3}$$

If this ideal sound is used as a kind of unit for comparing an equal tone from another instrument, then this can be expressed by some coefficient of partials. Thus, the new tone with an arbitrary sound feature can be written:

$$J_a = \tfrac{1}{2}SC[(\omega_1 a_1')^2 + (2\omega_1 a_2')^2 + (3\omega_1 a_3')^2 + \cdots + (n\omega_1 a_n')^2 + \cdots] \tag{4}$$

and as $a_n' = k_n\frac{a_1'}{n}$ we have

$$\begin{aligned} J_a &= \tfrac{1}{2}SC\left[(\omega_1 a_1')^2 + \left(2\omega_1 k_2\frac{a_1'}{2}\right)^2 + \left(3\omega_1 k_3\frac{a_3'}{3}\right)^2 + \cdots + \left(n\omega_1 k_n\frac{a_1'}{n}\right)^2 + \cdots\right] \\ &= \tfrac{1}{2}SC(\omega_1 a_1')^2[1 + k_2^2 + k_3^2 + \cdots + k_n^2 + \cdots]. \end{aligned} \tag{5}$$

According to the way this expression (5) is deduced, it must not be considered as an expression to which numerical value can be given. As any tone, however, can be decomposed into its fundamental and partials, this coefficient k_n will give just the ratio of the component of the sound tested to the corresponding component of the ideal sound; it will therefore be easy to discriminate the tone quality and thereby to obtain a picture of the value of the violin.

Professor Vladimir Karapetoff of Cornell University, who himself has experimented with stringed instruments and developed a five-stringed cello,[5] has authorized the following statement:

> "I am a proud owner of one of Mr. Jarnak's cellos, and have also used another cello and a double bass of his in public recitals. His instruments possess a rich and mellow

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[5] Vladimir Karapetoff, *The Journal of the Franklin Institute*, 207, p. 645, May 1929.

tone unusual in 'green' violins and cello; their carrying tone quality, with a slight pressure of the bow, is indicative of a ready response of the resonating body. His contribution to the science and art of stringed instruments is of great importance; the same acoustical principle can probably be extended to other groups of musical instruments."

CONCLUSION.

As a result of a series of theoretical developments and experiments, I have succeeded in building some superior stringed instruments. These instruments give tones exceedingly rich, mellow, and pleasing to the ear; and a comparison of oscillograms of these tones with those obtained by Backhaus on old Italian instruments indicates that the tone quality, as far as it can be measured in the oscillograms, is very near to that of the old masters' violins.

This investigation may be pursued even further, but it is my hope that the application given here may revive the art of violin building.

Further, a method for the objective appreciation of new types or new forms for the resonatory body is given which may open the way for subsequent scientific work on other forms or materials designed to produce even greater volume and more mellow tone quality.

No attempt will be made here to discuss these problems. It may only be suggested that the development here given may result in the five-stringed violoncello,[6] used at an earlier epoch, again coming into use. Johann Sebastian Bach (1685–1750) has composed for it, and several violin-makers have since tried to introduce it, as the added fifth string to a considerable extent facilitates the playing. Recently, Professor Vladimir Karapetoff has taken the problem under consideration and has investigated what material and dimensions can best be used for the string. The final solution seems now only to require a satisfactory, strongly constructed and well-tuned resonatory body.

Finally, it may be said that it is much easier to produce tones with the bow in my improved violins and that the sound has a greater carrying capacity and will even fill great concert halls. This is evidently caused by the better efficiency in the energy transformation between the vibrating string and the resonance body and by the resulting possibility of improved emission of sound, as is explained above.

For the courtesy of the Bell Laboratories and for the assistance of John C. Steinberg, Daniel W. Farnsworth and Arthur Meyer in recording the tones with the new rapid oscillograph, I wish to express my thanks. I also wish to thank E. H. Mynster and W. Marstrand for their help and suggestions.

The financial assistance for the harmonic analysis of this investigation has been granted by the trustee of the H. C. Oersted Foundation.

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The Mechanical Action of Instruments of the Violin Family

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INTRODUCTION

NEARLY ten years ago a group in the Harvard laboratories began to study the mechanical behavior of violins, in the hope of finding out how the best ones differ in their vibration from those which are recognized as inferior. It was hoped that the results might lead to improvements in new violins. Since this work has spread over several years, and notes on it have appeared in various places, we should begin with a brief summary of it.

The first publication[1] included an account of an analyzer developed for this work; the embarrassing variety of harmonic patterns disclosed in violin tones; the response (or frequency) curves obtained by means of the analyzer from many new and old violins; the curves of total intensity against frequency; the mechanical efficiency of violins; the effects of variations of bowing, and of moisture, string tension, etc.; the friction between bow and strings; etc. This article raised many unanswered questions.

It was followed by a paper[2] in which the response curves of several famous violins were compared among themselves and with those of new violins; the filtering action of the bridge was discussed; a suggestion was made in regard to the meaning of the term "carrying power" so often used by violinists; and an account was given of the results of a test of the ability of an audience to pick out the tone of a Stradivarius, when it and two new violins were played in succession behind a screen.

The next publication[3] was a short one in which the excellent old instruments of the Curtis String Quartet were shown to have response curves very like those produced by copies recently made of them by a skilled craftsman in Philadelphia. An account was included of tests conducted by the Quartet on the judgment of eight audiences in trying to discover which set of instruments was being played on, behind a screen. A brief discussion of the psychological effects involved was added in the attempt to explain why these judgments depended mainly on the order in which the two sets of instruments were played.

A note in the *Year Book of the American*

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[1] J. Acous. Soc. Am. 9, 81 (1937); referred to as *A* below.

[2] J. Frank. Inst. (Jan., 1940); hereafter referred to as *B*.

[3] In Overtones (April 1940), the journal published by the Curtis Institute of Music in Philadelphia.

Philosophical Society (1940) mentioned some experiments in which Jascha Heifetz took part, which were designed to measure and compare, from high speed records of actual playing, the periods of growth and of decay, when an excellent and a bad violin were used in succession; hence to secure an indication of the value of the damping in the wood of these violins. The results of these experiments are given later on in this article.

The last publication was by Watson, Cunningham, and Saunders[4] and gave an account of a new and superior method of obtaining response curves directly, without tone analyses, by exciting the violin electromagnetically with a force oscillating with a single frequency, which could be varied over the whole range of the instrument. All response curves recently obtained have been done by this method, but this part of the experimental work came to an end in 1941. The new method included direct measurements of the decay of pure tones, from which the damping at a few selected frequencies could be obtained. One of these frequencies was chosen to coincide with that of the main vibration of the air inside the body; the others coincided usually with natural vibrations of the body, which were unaffected by the inside air.

A preliminary report of the latest work was made at the meeting of the Acoustical Society in May, 1943. The present article covers this work to date.

RESULTS FROM RESPONSE CURVES OF STRADS BY THE NEW METHOD

The response curves obtained by the old and new methods differ in certain respects. The old curves are based on observations taken a semitone apart, while the new curves are continuous, and include all frequencies. Thus a narrow peak of response which might be missed by the first method is caught by the second. This is important in the high frequency region, where the overtones of the violin body are so crowded that two or three may occur inside the interval of a semitone.

In the old method, the intensities obtained for two or three of the lowest tones were made somewhat uncertain by experimental difficulties, which tended to raise the values. This error could have been removed by increasing the duration of each record, but this might have introduced other errors due to uneven bowing. In the new method the violin body is excited at all frequencies through the foot of the bridge which is under the *G* string, through forces acting on a wire which takes the place of the *G* string. If the response in this method is integrated by semitones, a curve is obtained which agrees well with the curve of the first method in the middle ranges but is lower at both extremes of frequency. These differences are not very important, since the object of the experiments was to compare good violins with bad, and this can be done well enough if both are measured by the same method. It is still possible to compare the response curve of a violin measured by the second method with one measured by the first, by making allowances for the differences discovered by measuring several violins by both methods.

All the response curves have been integrated by planimeter to find the average intensity of response in decibels (db) above an arbitrary level in different regions of frequency. If one chooses small ranges of frequency the results vary so much as not to be useful; if one uses a large range one may miss some important peculiarity of the violin. A fair compromise would be to choose octave intervals. This procedure has been adopted except at the two extremes of frequency. In the region from 200 to 350 c.p.s. the emission of sound in all good violins is largely due to the vibrations of the included air. It seemed wise to treat this interval of somewhat less than an octave separately. The interval next above was made a little more than an octave, to make the first two equal to two octaves. Above 4000 c.p.s. the emission usually drops sharply. In order to trace this drop more in detail it seemed wise to split the upper octave into two shorter ranges. The ranges used in the violin tables to follow are denoted by I, II, etc.; I covers from 196 to 349 c.p.s.; II from 349 to 784; III from 784 to 1568; IV from 1568 to 3136; V from 3136 to 4186; VI from 4186 to 6272. The intensity above 6300 is relatively negligible in good violins.

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[4] R. B. Watson, W. J. Cunningham, and F. A. Saunders, J. Acous. Soc. Am. 12, 399 (1941); referred to as *D*.

TABLE I. Stradivarius violins. Average intensities (in db) in different frequency ranges measured by the new method.

	Ranges					
Violin	I	II	III	IV	V	VI
Strad B "Halir" (1694)	15.2	25.0	24.6	26.5	20.8	7.1
Strad D "Darnley" (1712)	16.0	23.9	23.8	24.2	26.3	9.0
Strad E (Joachim, Kneisel, 1715)	15.2	25.1	24.6	26.2	21.7	6.5
Strad G "Tom Taylor" (1732)	11.6	23.0	26.9	25.9	23.7	10.6
Strad J "Marquis de Riviere" (1718)	11.9	22.3	24.7	25.3	24.5	16.4
Strad S "Spanish" (1723)	14.3	23.3	30.1	28.6	25.5	14.0
Strad W "Titian" (1715)	14.5	23.2	25.0	24.6	22.7	12.7
Averages	14.1	23.7	25.7	25.9	23.6	10.9

Different ranges are used below in considering violas and cellos.

Many violins, including two or three of the seven Strads for which we have curves by the new method, show a weakness in the range 1300 to 1800 or 2000 c.p.s., amounting to a drop of 4 to 8 db. This appears not to have been noticed by violin experts, and to have no important effect on the reputation of the violins concerned. Our range ending at 1568 almost bisects this "hole," and this accident hides it from view in our tables. In such a violin there is a weakness in the fundamental of the tone in the first few semitones of the second octave on the *E* string; but the upper overtones may be so strong as to make up the deficiency to the ear. On this account it has not been thought worth while to choose any different ranges in this region.

Table I shows the average intensity emitted in the chosen frequency ranges by seven well-known Stradivarius violins. The values were obtained with somewhat different amplifications. The distance of the violin from the microphone was about 40 cm but it could not be kept quite constant. For these, or perhaps other reasons, it is not possible to compare the total intensity emitted by one violin with that from another. Instead, all records were reduced to the same total area, first by integrating the audiograph curves with a planimeter, then reducing the frequency scale to a uniform logarithmic one, and then adjusting the base level from which the areas were measured until the total area for each violin was the same. This is approximately the same as reducing each violin to the same loudness. Most of the sounds measured were loud enough so that the loudness was approximately proportional to the intensity in db. The purpose of the measurements was to compare the *distribution* of loudness in one violin with that in another. The errors of our methods are not likely to affect this comparison seriously.

Table I discloses considerable variations in strength in different ranges, especially at the extremes. Some of these variations may be due to differences in the spatial emission pattern for different wave-lengths. The values are given to tenths of one decibel, but the error (due to all causes) may amount to as much as 2 db; the relative accuracy of the values for one violin is probably higher. The table shows that all Strads do not sound alike, as experts already know, Probably this was true even when they were new. but some differences may have arisen from the changes since made in these violins. Some players prefer a "full" or "round" tone, with more strength in low frequencies than in high; others prefer a more biting tone, with the strengths reversed. Table I cannot settle which Strad is best, or which should have the highest price. These data apply to *steady tones only*, and the quality of a tone (meaning by this the distribution of strength among its partials) is not the only item of importance about a violin. In fact it is so variable from one tone to another that it may be rather unimportant compared with other effects, such as those occurring near the beginning and end of each tone. All these Strads must be considered as excellent since they command high prices, and since a large number (if not all) of the experts have agreed upon them. We have assumed that the average distribution of strength in our chosen ranges furnished by these seven Strads represents the closest approach to a standard of excellence that we can attain.

It should be noted that the complete history of these (and of most other) Strads is not known. Some are in Hill's great book on Stradivarius, but even these histories usually begin a century or so after the date of birth of the violin. Data about alterations made in famous violins are not usually made public. None of these instruments can be in their original condition. The standard of pitch has risen, requiring increased tension in the strings of old violins; hence longer bass-bars have been put into them to increase their strength. These changes serve to satisfy the demand for louder violins to fit our concert halls. If the changes have been well made they may not lower the value of the violins. The longer bass-bars may be valuable; and the changes in the wood itself that have come with age or long playing have probably improved the quality. It is not surprising that Strads are found to differ among themselves, even if they were made on the model of the "golden age."

THE HEIFETZ TEST

In April, 1940 an interesting test was conducted by Jascha Heifetz, with the help of Sascha Jacobson. American violin makers had been invited to send in samples of their work for comparison, and nearly 100 violins had been received. The first tests eliminated a large number of these. The final tests on the four best violins should be described. Two violins to be compared, A and B, were played by each of the artists, H and J. With his back turned, J listened at one end of a large room, while H at the other end played a certain passage from a concerto on one string of violin A and then changed to violin B, repeating the same passage on the same string of B. The one acting as judge did not know which of the two violins was being played, but decided which one sounded better on this string. The same process was repeated on the other strings of violins A and B in turn. Then J became player and H judge with the same violins. In case the judgments did not agree (which was unusual) more tests were made until agreement was reached. The differences between two violins on the same string were sometimes very small, but usually quite definite; even the author, who was permitted to be present, was soon able to detect them. But so delicate were these differences that a change in the music played, or any conversation between the tests of A and B, tended to destroy the accuracy of judgment. When the relative merits of violins A and B were settled on all four strings, violins A and C were treated in the same way, then A and D, B and C, etc., taking all possible combinations. Thus the relative positions of the four violins were settled. If A represents the winner, B the one in second place, and so on, it is interesting to note that when A and D were compared it was agreed that D had the best *E* string of the four, and nearly as good a *G* string as A. This shows how close were the qualities of these four instruments.

TABLE II. Modern violins in the Heifetz test. Average intensities in different frequency ranges.

Violins	I	II	III	IV	V	VI
	Ranges					
Yurkevitch	12.7	24.4	27.1	25.3	22.0	8.6
Phillips	13.1	23.5	25.2	26.8	22.9	10.0
Sangster No. 35	12.4	23.5	23.8	25.6	28.9	11.0
Average	12.9	23.8	25.4	25.9	24.6	9.9
Strad average	14.1	23.7	25.7	25.9	23.6	10.9

This test can be criticized on the ground that the violins were played as they had been adjusted by their makers. Their order might have been different if they had all been adjusted by the same person, or if they had been supplied with different strings, or bridges, or bass-bars. It was not practicable to do any of these things. In spite of this possible defect, the test had a particular value in connection with our research. Mr. Heifetz had the idea from the beginning that the winners should be tested in the Harvard Laboratories, and later on this was done with three of the four at the top. But we profited in other ways than by securing the opportunity of measuring some interesting violins. After a few judgments had been made during the test, it seemed obvious, if one was at all accustomed to making tone analyses by ear, that the artists wanted two qualities in a violin; first, great power; second, an even distribution of strength among all ranges of frequency, the lowest octave being of special importance. It was said after the test that the winner gave the impression that the limit of its power was never reached. One should add that even a poor violin can be made to emit a great deal of sound, such as it is. The power referred to here is limited by the condition that the tone must remain good; with most violins a very loud tone becomes unpleasant.

Since the power output could not readily be measured, and probably depends somewhat on the player, we put the winning violins through the same tests as already outlined for the seven

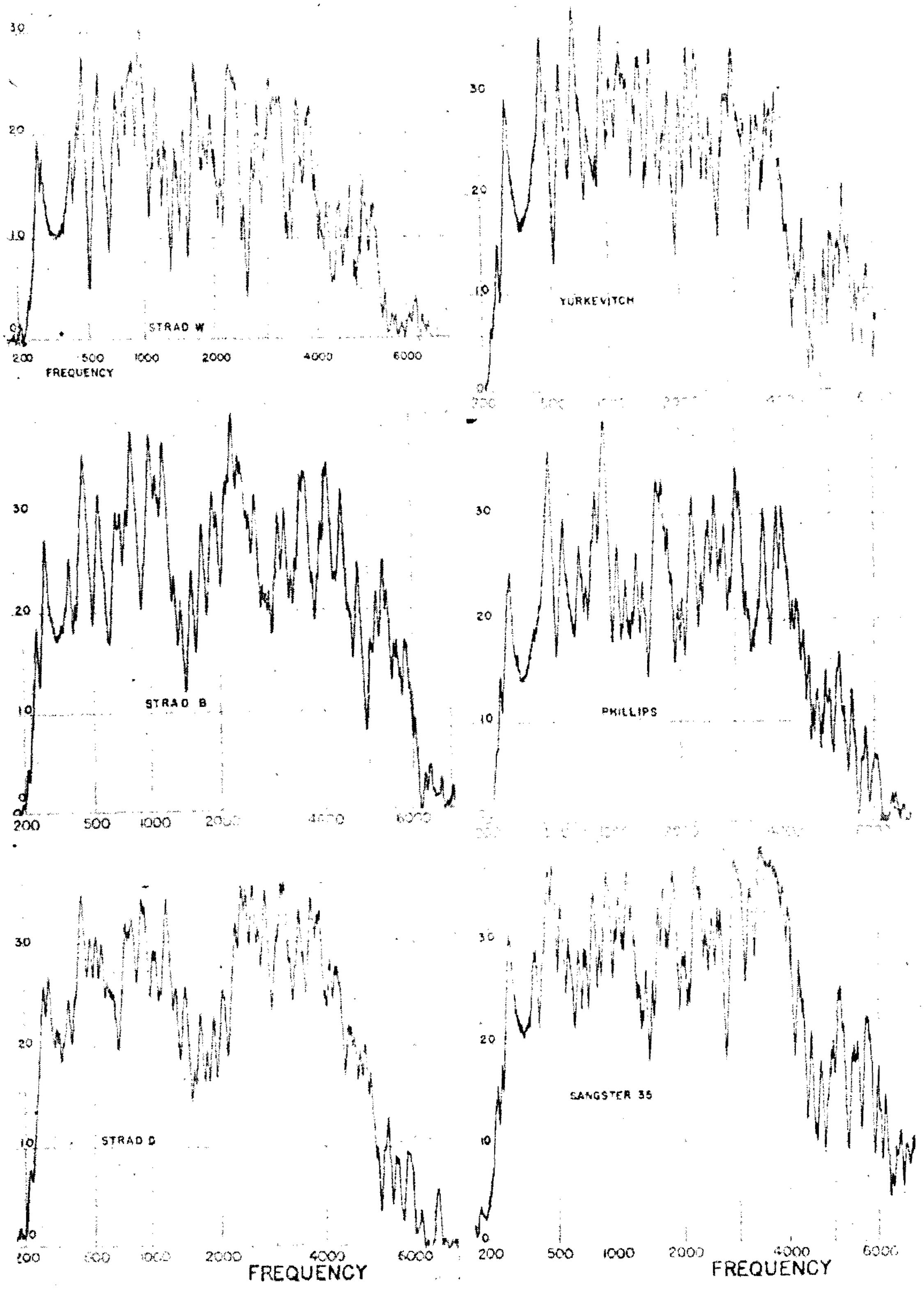

FIG. 1. Response curves by new method of three Strads, and three new violins which led in the Heifetz test.

Strads. The violins tested were (A) by M. V. Yurkevitch (1938) of New York City; (B) by B. F. Phillips of Pittsburgh, Pennsylvania; (D) by E. H. Sangster, now of Worcester, Massachusetts. Table II shows the results. The distribution of strength in different ranges is unusually uniform (the ranges were the same as in Table I), and its average is the same as the Strad average, within the allowable experimental error.

The response curves of these three violins (particularly the Yurkevitch) show an evenness of response which is unusual. They still dance up and down in a way that no proper loudspeaker curve does, but the general level is steady, more so than is usual even among famous old violins. Figure 1 shows a series of response curves, all taken by our new method. Three Strads are shown, and the three violins of the Heifetz test. There is a "hole" in the middle of the curve for Strad D (and others), amounting to a drop of 8 or 10 db in the region from 1300 to 2000 c.p.s. The only effect of this hole seems to be to produce differences in tone quality of which the player is not aware, or which he may even enjoy for their variety.

We can find no evidence in such response curves for the existence of any special "formant," or region of strong response, which is supposed to give the characteristic quality to the sound of a violin. In fact, it seems likely that we recognize a violin tone as different from that of an oboe, for instance, by the way the tone starts and stops. There is no marked difference in the tone analyses of the two instruments. It would not be difficult to test this by experiment, permitting the listener to hear the tones only after they had started, and not allowing him to hear their natural endings.

Table III. Average values of intensity in the same frequency ranges, by old and new methods.

	Ranges					
	I	II	III	IV	V	VI
9 violins, averages, old method	37.0	42.4	38.0	38.6	37.5	27.3
Same by new method	13.7	23.3	25.3	26.3	23.8	11.6
Difference due to method	23.3	19.1	12.7	12.3	13.7	15.7
7 Strads, new method only	14.1	23.7	25.7	25.9	23.6	10.9
5 Strads, old method only, but corrected to new	14.6	24.4	24.0	25.4	23.1	11.7
10 Strads, both methods	14.2	23.8	24.7	25.7	23.9	10.7

RESPONSE CURVES BY BOTH METHODS

The intensity distribution for a number of other new violins, measured by the new method, is given in Table IV, along with the results obtained by the old method, which we must next consider.

In our article (D) on the new method it was stated that the results differed from those by the old method at both ends of the frequency range. In the old method ordinary human bowing is used, and ordinary strings. In the new method only one "string" (a phosphor-bronze wire) is used, and only from the *G*-string position. Its tension is equal to that of the ordinary *G* string, but its linear density is less. It could not be expected to shake the whole violin exactly as the *G* string does; the loudness is appreciably less, though this may be mainly due to the absence of overtones. The observed reduction in the highest frequencies by the new method may be due to the fact that the excitation is from the *G*-string position. Some writers state that if the *E* and *G* strings are interchanged, the high notes are weakened. These differences raise a difficulty in comparing the results of the two methods.

A method of reducing the values obtained by one method to those by the other was found by studying the violins which were measured by both. These were five Strads and four new violins. The average value in each of the six frequency ranges was obtained for each of these nine violins by both methods. The averages for the nine were then obtained (Table III). If the new-method values are subtracted from the corresponding old-method ones, these differences may be used to convert any old-method results to new, or *vice versa*. This assumes that the violins were in the same condition in both tests, and that no other variations occurred, such, for instance, as might come from diffraction effects. With nine violins to work with it seems reasonable to hope that the averages are not seriously affected by any such variations.

In all, 73 violins were studied. Response curves were taken for 60 of these, 48 by the old method, 22 by the new, 10 by both. We have the response curves of 38 violins by the old method only. This mass of observational material is of value by itself, but it is better to be able to compare the

TABLE IV. Intensities in different frequency ranges.

Violins	Method	Ranges I	II	III	IV	V	VI
Strads, by both methods							
Strad K (1684)	old	15.9	22.9	22.3	24.5	24.7	11.4
Strad A (1691)	old	15.5	23.7	24.1	21.9	25.7	15.7
Strad B (1694)	old	17.3	19.9	28.1	25.9	25.7	7.3
	new	15.2	25.0	24.6	26.5	20.8	7.1
Strad M (1698)	old	11.7	24.5	25.3	26.7	24.1	10.5
Strad J (1709?)	old	15.1	24.9	25.1	26.1	22.9	6.9
	new	11.9	22.3	24.7	25.3	24.5	16.4
Strad D (1712)	new	16.0	23.9	23.8	24.2	26.3	9.0
Strad E (1715)	old	15.3	24.1	25.7	24.3	24.7	9.1
	new	15.2	25.1	24.6	26.2	21.7	6.5
Strad W (1715)	old	12.5	23.3	23.9	27.3	24.5	12.9
	new	14.5	23.2	25.0	24.6	22.7	12.5
Strad S (1723)	old	13.1	23.9	24.6	26.3	25.3	12.3
	new	14.3	23.3	30.1	28.6	25.5	14.0
Strad H (1731)	old	14.9	25.1	23.7	26.5	19.7	10.0
Strad G (1732)	new	11.6	23.0	26.9	25.9	23.7	10.6
Strad N (1737)	old	10.1	25.7	24.7	27.3	21.5	11.3
Strad average		14.1	23.8	25.1	25.8	23.8	10.8
Guarnerius d. Gesu violins; old method							
Guarnerius R (1743)	old	10.3	25.7	24.5	26.3	25.9	10.3
Guarnerius H (1742)	old	13.6	24.9	27.6	25.5	21.9	5.9
Guarnerius B (1728)	old	12.9	23.7	25.1	27.9	24.1	10.1
Guarnerius F (1738)	old	11.9	22.3	27.9	25.3	22.1	13.5
Guarnerius average		12.2	24.1	26.3	26.2	23.5	10.0
Old Italian violins; makers probably as indicated							
Maggini	old	15.7	23.7	26.3	23.3	22.5	12.3
P. Guarnerius (Cremona)	old	14.6	19.4	22.8	28.7	27.6	15.7
Stainer	old	14.5	21.3	24.1	27.5	24.5	14.5
A. Guarnerius	old	13.5	24.5	25.7	25.1	20.5	11.9
Stradivarius	old	12.7	22.7	24.9	25.7	23.5	15.1
Guarnerius, J	old	18.1	23.3	24.7	24.1	22.9	11.3
Gagliano	old	18.1	27.1	28.3	22.5	14.7	5.7
Guadagnini	old	15.1	23.5	24.1	25.1	21.1	14.1
Pressenda	old	12.5	22.3	24.3	27.1	22.1	16.7
These old violins, average		15.0	23.1	25.0	25.5	22.2	13.0
New violins							
J. A. Gould (1882)	old	13.5	22.9	27.3	25.7	25.5	9.7
W. S. Goss (1912)	old	10.1	24.1	27.7	24.3	21.5	15.1
Sangster's No. 30	old	10.3	26.1	23.5	27.7	23.7	11.3
	new	13.4	22.1	24.6	26.2	24.6	13.3
Sangster's No. 33	old	12.9	26.1	26.1	25.3	21.3	9.0
Sangster's No. 34	new	13.0	23.2	21.0	27.4	27.1	13.9
Sangster's No. 35	new	12.4	23.5	23.8	25.6	28.9	11.0
Sangster's No. 37	new	11.7	24.9	23.3	25.8	26.2	11.9
Sangster's No. 38	new	12.6	22.5	24.4	26.6	23.2	13.8
Moennig, copy of Strad B	old	12.1	24.0	24.3	24.7	28.3	15.3
	new	11.3	21.3	27.8	26.2	23.2	13.4
Moennig, copy of Strad J	old	11.1	24.5	26.3	23.1	21.9	16.9
Moennig, copy of a Strad	old	14.5	21.3	22.6	23.6	28.8	17.8
Moennig, copy of a Guadagnini	old	15.2	20.8	26.4	22.7	22.3	17.9
Yurkevitch	new	12.7	24.4	27.1	25.3	22.0	8.6
B. F. Phillips	new	13.1	23.5	25.2	26.8	22.9	10.0
Koch	old	15.3	21.9	25.9	26.7	18.9	14.1
	new	14.0	23.8	23.2	26.2	24.9	11.5
Stanley	old	12.5	20.9	26.5	28.1	20.7	15.5
	new	13.5	23.6	23.1	26.9	25.9	10.7
Moglie (1930)	new	11.5	23.3	29.3	26.2	22.6	6.9
Averages of good new violins		12.7	23.3	25.1	25.8	24.0	12.7
Two bad violins							
Violin X ($5.00)	new	13.9	18.5	29.5	23.4	22.6	17.6
Violin Y	new	2.6	20.5	20.9	42.2	17.0	16.4

results of the two methods, as we can by the above procedure. Table III includes the average values for 7 Strads by the new method, for 10 Strads by both old and new methods (reduced to new), and for 5 Strads which were measured by the old method only. These results show only small differences, indicating that the process of comparison is successful.

We next consider the results of measurements on the most interesting of the violins measured by the new method, and also those by the old method translated to the new-method scale. The 12 Strads included in Table IV are all pedigreed thoroughbreds of unquestioned standing, though one naturally does not know just how their present condition differs from that of their infancy. Two of these (A and B) are of the "long" model, and one (K) is of the high model (1684). The results do not agree with a common belief that the differences in shape affect the distribution of strength throughout the range. The two long-model violins do not agree with each other. There is a rather uncertain trend in the direction of diminishing low frequency emission with increase in age of the master craftsman, but these differences are usually less than the possible error of the measurements.

In Table IV there are four famous violins made by J. Guarnerius (del Gesu) whose average is fairly close to that of the Strads. There seems to be slightly less emission in the lowest frequency range, though this difference is too small to be sure of; there are also some individual variations. The second in the list is the "David," played by

TABLE V. Intensity distribution in violins chosen by one artist.

Violins	Ranges I	II	III	IV	V	VI
Strad H	14.9	25.1	23.7	26.5	19.7	10.0
Guarnerius H	13.6	24.9	27.6	25.5	21.9	5.9
Yurkevitch	12.7	24.4	27.1	25.3	22.0	8.6

Heifetz; the third the "Verviers," played by Z. Balokovic; the fourth the "Fontaine," played by Miss Thelma Given.

A group of Italian violins follows, arranged approximately in the order of their ages, which run from 370 to 100 years. While these instruments are all valuable and undoubtedly old Italian, some of them lack the highest certificates, so that one can say only that the makers are probably as indicated. This group again shows marked individual variations, with an average not far from that of the Strads, though the emission at both ends of the scale is a little higher. Note how the Gagliano emphasizes the lower tones, while the highly arched P. Guarnerius puts more strength into the higher ones.

The group of new violins in Table IV shows the same variations as the other groups. If one were certain that any particular Strad was ideal in its distribution, and should be copied by all makers, then one could find in this table at least one modern violin which approximately duplicates it. This matching can be done for high model violins, or for low. One cannot say that one model is good and another bad. Artists who are much in the public eye use different models, and are presumably pleased with what they have. It happens that we are in a position to gauge the preferences of Mr. Heifetz. We have measured a Strad and a Guarnerius, both chosen for his own use, and we have the winner of the new-violin test, which also represents what he prefers. Table V presents the distribution in these three violins; the consistency of judgment shown in their selection is indicated by the values presented here. The Heifetz type is evidently one in which the two upper ranges (which together cover the octave from 3136 to 6300 c.p.s.) are relatively weak compared with the middle ones, and the lowest range is fairly strong. Since no artist can flourish if his listeners are not pleased, and since Mr. Heifetz has a great many listeners, we might assume that his type is generally preferred; but it is to be remembered that a great violinist can play a rather ordinary violin in such a way that the average listener is quite content, and thinks that he is hearing a famous instrument.

The data in Table IV on Sangster's violins enable us to test the variability of the product of one modern maker, using the same model throughout. Actually, as the results show, his violins vary less than the Strads do, though the differences are uncertain on account of experimental error. This table also includes an interesting violin made by Moennig in Philadelphia, a handsome copy of Strad B. Comparing the values for this copy with those of the original, we see that the Strad is stronger in the low frequencies and weaker in the high than its copy, though the differences are not greater than those that occur among Strads. Smaller differences are found between Strad J and its copy by Moennig. The Koch violin is of some interest since two lecture audiences thought it was more surely Italian (and old) than a Strad with which it was being compared (behind a screen). Its distribution of strength with frequency follows the Strad pattern rather closely. The Stanley (Boston) is not very different from the Koch.

There are some unpleasant irregularities in Table IV. For instance, the values taken by old and new methods for Strad B differ unreasonably. In this case the violin had been treated to a new bass-bar in the interval between tests, and the change was probably real. The very large difference in the upper range for Strad J may again be due to a change in the instrument. Similarly, in the Koch and Stanley violins (range V) there are differences which are larger than the experimental error. In all these cases there was a gap of a year or two between the two tests, and in this time all the instruments had been played a good deal, and their bridges and strings had been changed. Unfortunately, we took no tests by both methods on the same instrument at the same time, so that we cannot say positively, when differences are found, whether these are due to the peculiarities of the methods or to changes in the violins. Unpublished tests which we have made on bridges and on strings have shown that a violin is sensitive to changes in these items; even the change from a thin string to a thicker one affects the distribution of strength over the frequency ranges. Hence we believe that the above irregularities are probably real.

At the bottom of Table IV two violins are entered. Violin X is one of the cheapest type, made in Czechoslovakia; it could be bought with case, bow, and a set of directions for playing it, for less than $15.00. It had, however, been somewhat "doctored" by a new bridge arranged to filter out some of the excessive high frequencies, and by new strings to give more strength in the low ranges. It sounded well when Mr. Heifetz played it, but not otherwise. The figures given for it make it appear better than it was since it had strong emission above 6300 c.p.s., which our tables do not include. Violin Y was a flat-topped model made out of common lumber by an unskilled workman for his own pleasure. It possessed to his ear a beautiful tone, though its low frequency emission was almost absent, and its high frequency strength extended far beyond the proper range.

RESPONSE CURVES OF VIOLAS AND CELLOS

Nine violas were measured, six old and three new. No. 1 was the "McDonald" Stradivarius (1701) in the Warburg collection; No. 2 the Amati (1677) used by M. Aronoff of the Curtis Quartet; No. 3 a Gaspar da Salo (about 1570) owned by Miss Eunice Wheeler, an especially large and responsive instrument; No. 4 a Storioni belonging to Marcel Dick; No. 5 a probable Gaspar da Salo; No. 6 possibly a Klotz (made about 1770); No. 7 a new viola made by Haenel of Toronto; No. 8 a copy of No. 2 made by Moennig; No. 9 by Dieudonné (1939). The ranges of frequency used with violas were seven, four octaves and three shorter intervals; I from 131 to 262 c.p.s.; II from 262 to 523; III from 523 to 1046; IV from 1046 to 2093; V from 2093 to 3136; VI from 3136 to 4186; VII from 4186 to 6272.

Table VI was obtained by a procedure similar to that used for violins. Viola 6 was the only one of the nine which was measured by both old and new methods. Violas 4, 5, and 9 were measured by the new method only; violas 1, 2, 3, 7, and 8 by the old method only. The differences in values by the two methods were found from data on viola 6, and were used (lacking a more accurate way) to convert from one method to the other. The values given are in terms of the old method, because more of the violas were measured this way. The total areas of the response curves were equalized, as with violins, to make the results comparable. The first (lowest) frequency range is taken as an octave and includes the region affected by the air resonance. The second range (another octave) is relatively strong in most violas and includes the first body resonance, which is the source of the "wolf" tone. This body resonance is stronger in the larger instruments, and has the effect of strengthening the tones in its region. It must on this account be regarded as actually beneficial, and it is of course unavoidable. The actual wolf is found only at the exact point of maximum resonance but the beneficial effects of this resonance spread over a considerable range on either side. The wolf can be reduced by any device which tends to check the production of the particular pattern of subdivision of the top plate of the instrument which is responsible for the excessive resonance. The other (higher) body-resonances are well scattered and numerous. The values for the three short frequency ranges at the top of the scale vary somewhat erratically in instruments of equal merit. If a strong resonance happens to fall in the middle of one of these ranges its effect is fully evident in the measurement for this range; if, however, it falls at a boundary, its effect is spread between two ranges, and is then partly hidden in our numerical values.

Figure 2 shows the response curves (old method) for four of the most interesting violas in this group.

TABLE VI. Intensities in different frequency ranges for violas.

	Ranges						
Violas	I	II	III	IV	V	VI	VII
Viola 1	26.3	37.7	35.3	29.9	29.1	24.3	18.1
Viola 2	29.0	38.0	33.2	32.8	29.0	19.6	15.2
Viola 3	27.3	35.9	33.1	31.7	32.1	23.7	17.5
Viola 4	28.2	38.2	28.8	35.0	35.3	23.8	18.8
Viola 5	27.3	38.9	31.1	34.6	36.9	22.0	16.0
Viola 6	28.2	39.6	30.6	35.6	30.8	22.0	18.6
Viola 7	24.0	35.8	29.2	33.8	37.0	26.2	19.4
Viola 8	27.8	36.8	33.2	28.2	30.4	28.0	19.0
Viola 9	27.8	37.1	30.2	33.6	33.7	26.0	23.1

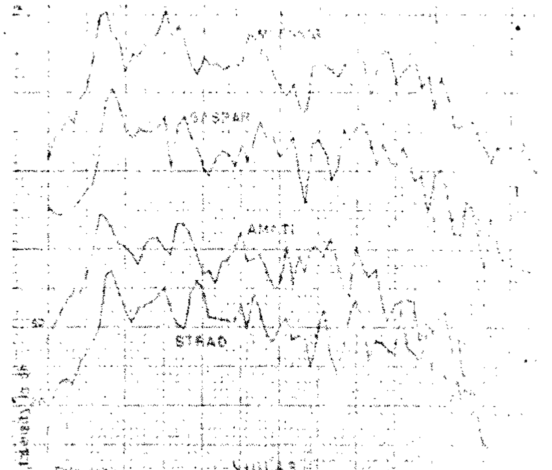

FIG. 2. Response curves of four violas (Nos. 1, 2, 3, and 8) taken by the old method. The scale below is like a piano keyboard, 12 divisions to the octave; frequencies of C's given. The vertical scale shows the logarithm of the intensity, in decibels. The numbered scale refers to the Strad; the other curves are shifted each 20 db upward in succession, to save confusion. Thus, the line marked 40 is the zero for the Gaspar.

Four cellos were studied by the old method. The results are shown in Table VII.

Cello 1 is a Pressenda, played by Maurice Stad; No. 2 is a Montagnana played by Orlando Cole of the Curtis Quartet; No. 3 is a Strad, the "Vaslin," played by Gerald Warburg; No. 4 is a copy by Moennig of No. 2. Table VII shows that these four differ remarkably little among themselves in their intensity distribution. They all show a large emission in the main body-resonant region (II), and again in range VI. The one new instrument in the group has high emission in the lowest range, and relatively low in the high ranges; in other words, it shows the emission characteristics which we have come to associate with the best old instruments. As before, in treating the measured results on cellos, the areas of the curves were equalized. Thus the relative strength in different ranges is given, but not the actual intensities.

It is unfortunate that no cellos could be measured by the new method. Our apparatus was not large enough, and it was not thought likely that results of any new type would be obtained from a larger one. Figure 3 shows the response curves (old method) of Cellos 2, 3, and 4. They resemble one another in the lower frequencies. The data at high frequencies suffer from the fact that the observations were taken only at semitone intervals, thereby missing much interesting detail. The two oldest cellos show sharp peaks at the two lower resonances, while the new one shows wider peaks. Sharpness in resonance may be a sign of very free vibration, and may well increase with age; but a wide peak spreads its helpful influence over several semitones, which is distinctly better.

CONCLUSIONS FROM RESPONSE CURVES OF VIOLINS, VIOLAS, AND CELLOS

Two positive conclusions can be drawn from this part of the work. These are that there is no correlation between the price of an instrument and its distribution of strength with frequency; and that, whatever is the best distribution, it is not exclusively the property of old instruments. There is about the same variation in distribution among the old as among good new ones, and whatever type the player prefers, he may find it either in old or new instruments. This being so, we must examine other properties of these instruments to seek the reason for the very high regard in which old Italian instruments are held.

While it is true that the response curves of violas and cellos strongly resemble those of violins, there is an interesting difference in the position of the main air resonance point, as well as in the strength of the main body resonance. Counting by semitones from the lowest tone of the instrument, the air resonance usually occurs in violins near No. 6, in violas near No. 9, and in cellos near 7 or 8. The main body resonance comes somewhere near 17 in all these instruments, with variations of two semitones either way. There is a region of weakness near the bottom of the scale and another between the two main resonances. The position of the air reso-

TABLE VII. Cellos. Intensities in different frequency ranges, each an octave lower than for violas.

Cellos	Ranges I	II	III	IV	V	VI	VII
Cello 1	35.2	46.5	35.9	32.1	29.9	36.3	27.3
Cello 2	35.0	44.4	36.8	32.8	27.4	37.4	29.2
Cello 3	36.8	45.2	35.4	31.2	28.8	35.6	30.2
Cello 4	39.1	45.9	36.5	31.3	27.7	31.9	26.9

nance can be lowered permanently only by making the volume of the body greater, or by making the total area of the openings of the *f*-holes smaller; but it may be lowered experimentally by filling the body with carbon dioxide gas through a small rubber tube, or by covering a considerable part of the *f*-hole openings with "Scotch" tape (which peels off again without injury to the varnish). The great masters of the craft placed it about midway between the bottom and the first body resonance, where it would do the most good in strengthening the otherwise weak lower tones. Why does it not occur at the same position in all instruments of the violin family?

The answer to this question is not certain, but two suggestions can be made. One which applies particularly to violas is that, as Professor Curt Sachs has pointed out, violas were made longer and deeper before 1700 than they are now. This might well have brought the air resonance down to where it is in violins, but such instruments were so deep as to be clumsy to play, and they have been superseded by smaller ones. Many old ones were then altered to be less deep, thus raising their air resonant points. This has made the tones on the lowest string in many small violas rather weak, and sometimes mean in quality; but there are many long violas of recent make which seem satisfactory, even with rather high air resonances. This anomaly can be explained by a suggestion made in the next section.

CURVES OF INTENSITY (OR LOUDNESS)

We must now consider other types of tests which throw light on the peculiarities just mentioned. The simplest of these are curves giving the total intensity (or approximately the loudness) of tones over the whole range of the instrument. These may be obtained by means of a sound-meter. The player keeps a constant distance from the sound-meter in a deadened room, and first plays as softly as he can on one tone while the loudness is read on the meter. This is repeated for each tone (by semitones) over the range of the instrument. Then the whole experiment is repeated, but this time to measure the maximum loudness that can be produced. Each set of observations yields a curve in which the main resonant frequencies show as peaks, and the two curves run approximately parallel. The difference between the loud and soft values at each tone is nearly constant, though there are small erratic errors due probably to the player. These differences give the range of loudness of the instrument, which for a violin varies little from 30 db. This number is of no special interest because it is nearly the same for old and new, and for good and bad violins. If, however, we average the two values at each tone, we get a set of numbers yielding an average loudness curve, which is significant. It differs from the response curves already considered. The latter show the response of the violin for one frequency at a time, dealing with only one partial tone (e.g., the fundamental). Loudness curves show the response produced by the bow for one tone at a time, but each tone contains all its partials. The loudness curve does not discriminate between a tone which has a strong fundamental and weak partials, and one having a weak fundamental and strong partials. Every peak on the response curve appears on the loudness curve, but the latter may show additional peaks not present in the former. The most important case is that in which the fundamental is not strong, but the second partial is so loud that it more than makes up for the weakness of the fundamental. This happens one octave below each of the most important body resonances. Thus a violin may have its air resonance at the open *D* (294 c.p.s.) and a body peak near *B* flat on the *A* string (466 c.p.s.). The result is that the loudness curve shows a peak at

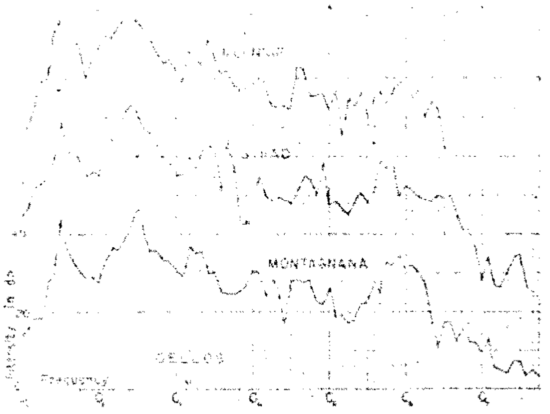

FIG. 3. Response curves of three cellos (Nos. 2, 3, and 4). The scales are as in Fig. 2. The note C_2 has a frequency of 131 c.p.s.

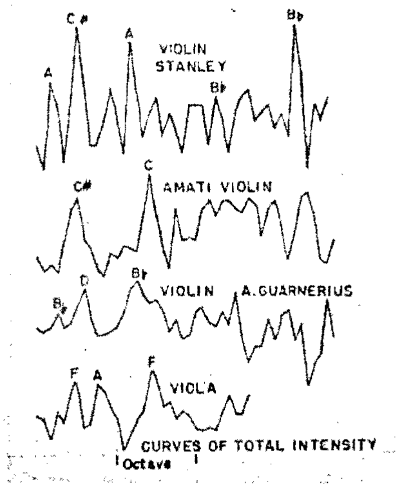

FIG. 4. Curves of average intensities for a viola (No. 6), two old violins and a new one. The horizontal scale is the same as that in Fig. 2 for the viola, but for the violins the lowest tone is *G*. The vertical scales are as before.

233, as well as those at 294 and 466. Since the resonances are not very narrow, such an arrangement yields a fairly satisfactory loudness over the lower range of the violin. If, however, the air resonance is at *C* sharp (277) and the body resonance is about an octave higher, the loudness near 277 is needlessly enhanced by the strength of the second partial, and there is nothing to strengthen the weak tones below 277, or in the interval between 277 and 554. The lower tones of such a violin are weak, as well as those centering around 410, midway between the two peaks. We know of one famous violin in which strong resonances occur near all the *C*'s in four octaves, to the detriment of the strength of many other tones in its range.

Figure 4 shows three average loudness curves for violins, and one for a viola. The top curve shows a body resonance at *A* (440) which increases the loudness at 220. This makes a much better arrangement, especially for the *G* string, than that shown in the curve below for an old Italian violin, probably Amati, where there are weak hollows because the two main resonances are about an octave apart. The next violin shows the body resonance at *B* flat (466) helping to fill out the tone in the region of 233. Viola 6 at the bottom has a strong body peak between *F* and *F* sharp (about 360) which exerts an excellent effect an octave below. Of the twelve Strads listed in Table IV, five have a good arrangement strengthening the lowest tones, three definitely lack this advantage, and four are intermediate for one reason or another. New bass-bars which have been put into all these violins have probably shifted the body resonances, so that we cannot say that this record dims the halo over the head of Stradivarius.

In violas, if the ones tested are representative, there is some variability. Many have weak *C* strings, but more have their lower tones strengthened by the help of body resonances an octave higher. Since the air resonance lies higher than it does in violins (relatively), the chance that the air and body resonances will be an octave apart is smaller. Moreover, the body resonances are usually strong. Here may be the reason for placing the air resonance near the ninth semitone, rather than at the sixth, as in violins. This applies to cellos also. If there is no wolf tone there is no strong body resonance, and hence the *C* string is likely to be weak; in such cases a relatively low air resonance would be of some advantage.

In all the four cellos tested the main body resonance is about an octave above the air resonance. The curves in Fig. 3 show this. It is likely that the *G* strings of these cellos would be appreciably improved if the air resonance were moved upward, say by enlarging the *f*-holes (scandalous as such a suggestion may be). The main body resonance is strong enough to give ample loudness an octave below, and there would be a more even response over the low tones.

EASE AND QUICKNESS OF RESPONSE

We must now consider other qualities of violins to which players frequently refer. These are vaguely included in their idea of the tone quality of the instrument. These attributes are referred to as the ease of playing, or the quickness of response, or "facile articulation," or by many other phrases. Some of these have to do with the growth of the sound at the beginning of a tone, or its decay at the end. Players assume that if the tone is easily produced it must start quickly and continue on for a long time after the bow ceases to act on the string, but physicists know that if a vibration is slow to decay it must also be slow in starting. This is true if the conditions of vibration are the same in both cases, which is not quite

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the case with bowed violins, since the bow is in contact with the string during the growth, but not during the decay. These effects deserve some study. Violins also differ in efficiency, that is in the amount of power which must be exerted by the player to make them sing. This may be connected with the quickness of growth of the tones, but it is not the same thing. Two lines of investigation are suggested by these thoughts: (1) to measure the power needed to make various violins sing; (2) to measure the rate of growth of their tones, or the rate of decay. The decay is perhaps more characteristic of the violin than the growth, and less of the player; the decay is also much easier to measure.

RAMAN CURVES

The measurement of power is done by means of a type of apparatus devised by Raman (see article *A*). We call the resulting curve the Raman curve of the violin. This yields the same distribution of resonances that is given by the loudness curve, and it is more difficult to measure accurately; but it also yields numerical values for the power needed to make the instrument speak, which are not obtainable otherwise. We have restricted these measurements to the tones in the first octave on each of the two lowest strings, and will save space here by presenting only the average values for the thirteen tones measured on each string. These average numbers are found to depend greatly on the type of string used, that is, on its tension and linear density. Since an artist cannot be asked to change the strings on his violin, we have had to content ourselves with what we found there, trusting that his selection was the best possible. The numbers given in Table VIII are in grams of force with which our rotating wheel bow pressed on the string while its circumference was going by at a speed of 38 cm per sec., a speed kept approximately constant. The distance of the bow from the bridge was held at 4 cm; the results would be altered if either of these numbers were changed.

According to these numbers the easiest violin to play in this list is the Balistrieri (1776, owned by W. Wolfinsohn). The next "best" is one of the Moennigs, which was perhaps two years old when measured. The Sangsters average a trifle easier than the Strads, and the latter are easier than those by J. Guarnerius. The $5.00 fiddle comes out very near one Guarnerius! This shows rather conclusively that the ease of playing has little to do with the merits of a violin. Evidently these forces, varying from eight to twenty grams or so, are so small that no violinist notices them, or cares about them. These data refer to the production of soft sounds (piano on the musical gradation); in fortissimo passages one can easily exert a force of 150 grams with the part of the bow nearest to the hand, but even this (one-third of a pound) is too small to fatigue the player, and it is small compared with the force which he must exert to raise his own arm. The differences in ease of playing may not be detectable by the player when they are small, but it seems likely that the difference could be felt when it amounts to 20 grams or more, even though it does not bother him. Certainly if the player wants a violin that is easy to play he can find one without trouble among either old or new instruments. It is also possible that the violin that is hardest to play may be the loudest, and may on this account be preferred by the player.

DAMPING

We now turn to the study of the rate of damping of the vibration of a violin. Many experts consider that the sound of the best violins rings on for a relatively long time after the excitation has ceased to act. One can give the back of a violin a sharp rap with a knuckle and hear a brief sound thereafter, and the duration of this sound may be an indication of the quality of the instrument. To make this test properly one must prevent the strings and the tail-piece from

TABLE VIII. Average force in grams needed to press bow against string to make violin speak.

Old violins	*G* string	*D* string	New violins	*G* string	*D* string
Strad B	13	11	Yurkevitch	14	14
Strad J	12	13	Phillips	13	11
Strad S	12	13	Sangster's No. 30	12	10
Strad W	14	11	Sangster's No. 33	12	10
Strad G	13	11	Sangster's No. 34	13	9
Strad D	14	15	Sangster's No. 35	11	9
Strad average	12.9	12.4	Sangster's No. 37	11	9
Guarnerius R	17	12	Sangster's No. 38	13	9
Guarnerius H	15	10	Stanley	11	9
Balistrieri	9	8	Koch	12	10
Stainer	20	14	Moennig, copy of		
P. Guarnerius	16	17	Strad J, first	11	8
			Strad J, second	13	11
			Strad B	13	11
			Violin X ($5.00)	16	12

vibrating, in order to be sure that what one hears comes only from the body, or the included air. A gifted violinist may have only to hold the violin resting on his extended hand and feel its vibration while he talks to it. Such effects depend on the lightness of the violin, and on the rate of growth or decay of vibrations in it.

The growth of sound when a bow touches a string is a complex affair, and takes place at a different rate from the decay of the sound after the bow leaves the string. Our first experiments on growth and decay were carried out with the help of Mr. Heifetz, who played his Guarnerius, and then the $5.00 fiddle, in front of a microphone. With a specially quick-acting circuit and a high speed moving-film camera we were able to record the motions of the spot of a cathode-ray oscilloscope, thus getting the wave-forms of the vibrations in great detail. The film moved at a rate from 200 to 500 cm/sec. A repeating pattern of eight tones was played spiccato with extraordinary speed and cleanness, at the rate of about 14 tones per second. An interval of silence was found between each pair of tones except in the case of one of them (*A* 880) which resonated with a harmonic of an idle string. The tone of the Guarnerius was louder than that of the cheap fiddle, and took *longer* to grow or to decay by some 25 percent. But the form of the complex waves which were produced altered so much during a change in loudness that measurements of rates of growth or of decay were very uncertain (see Fig. 5). This alteration was due to the fact that the rate of growth or decay changes with frequency.

Some details of a single typical record are worth giving. The tone had a frequency of 569 c.p.s.; the film speed was 370 cm/sec., and the record of this tone covered 26 cm of film. In spiccato bowing the bow bounces clear of the string between one tone and the next. The initial contact of the bow with the string shows clearly and can be measured to about 0.0001 sec. For about 0.005 sec. the contact was being made, more and more of the bow-hairs coming to grips with the string. During this interval an irregular motion occurred with one or more strong high frequency components (5000 to 7000 c.p.s.), but this sound was both short and relatively weak, so that it probably did not contribute much to the total effect. After the bow made full contact, the tone grew in volume for about 0.012 sec., then lasted at full volume for 0.014 sec. Then the bow left the string, taking about 0.004 sec. to do so, and an irregular motion occurred in this time while the string was taking on its free type of vibration. The decay then followed, lasting about 0.018 sec. Finally there was an interval of 0.02 sec. of almost complete silence. The period of growth of the tone was less than that of decay, and the form of the vibration was different, as one might expect since in the first case the bow was driving the string, while in the second the string was free. These figures were obtained from a record of the cheap fiddle, which was the one which reacted more quickly. With a good instrument the times of growth and of decay are both longer, as was shown from the records of the Guarnerius. In fact the decay was so slow that there was no longer complete silence between successive tones, though this difference was not noticed by the listener.

Figure 5 gives a reproduction of part of the record of Heifetz playing the rapid finger exercise already mentioned on his Guarnerius. The end of the decay of a tone of frequency 880 c.p.s. is shown and the beginning of a tone of frequency 740 c.p.s. The open *A* string resonated with its second partial tone in the interval between, though this is mixed with other tones from the violin, whose vibrations were dying out slowly. The film speed was 240 cm/sec. Here the maximum amplitude goes off the film. The figures given in the previous paragraph apply to this record also, approximately, as they are characteristic of the player rather than the instrument. The beginning of bow contact for the second tone is very definitely shown in the figure, and the high-frequency component in the irregular motion at that stage has now a frequency near 10,000 c.p.s.

Since the experiments just described could not yield accurate measurements of the rate of decay of a vibrating violin, we turned to the method of pure-tone excitation (article *D*). By this method of shaking a violin at one frequency at a time, it was easy to choose particular frequencies at which to take high speed records of decay. This was done for a considerable number of violins, both old and new. Records were also taken of

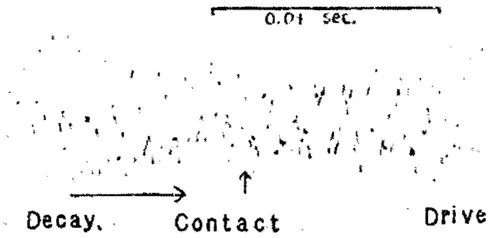

FIG. 5. A high speed record of the vibrations produced by Heifetz on his Guarnerius near the interval between two short tones.

knuckle knockings, in which case the vibrations disclosed were made up of the main air resonance, which persisted longer than any others, together with two or three body-resonant vibrations. The duration of the main air vibration could be measured almost equally well by both methods of excitation.

The logarithmic decrement (δ) of the amplitude on the records is found from the equation

$$\delta = (2.303/n) \log_{10} (A_0/A),$$

where n is the number of vibrations between the two whose amplitudes were measured, A_0 is the initial amplitude, and A the final amplitude selected for measurement. If the decay is exponential, δ should be the same at all frequencies produced by the same type of vibration. The damping of the air resonance may possibly be different from that of the body resonances, since it may be caused largely by radiation of sound through the *f*-holes, and less by viscosity in the wood. Of course, the body resonant vibrations also lose energy by radiation, but the process is likely to be less efficient than in the case of the air resonance.

There are many indications that the energy put into a violin is largely dissipated as heat in the wood itself, so that only a small part of it escapes as sound. The latest work on this was by Rohloff[5] who measured the motion of the wood in different places over the violin when it was made to vibrate over a considerable range of frequencies both in ordinary air and in a partial vacuum of about 1.7 cm of mercury pressure. In the best violins the energy at the air-resonant frequency was almost entirely absent at the low pressure, though with the body resonances it was often as high as usual. Assuming a low efficiency for the violin, the damping must be due mainly to viscosity in the wood, with one possible exception, namely at the main air-resonance frequency.

The frequencies which we chose as points at which to take readings were almost all resonant peaks, and they are recorded in Table IX as air or body resonances, with their approximate frequencies. The values of δ are given in this table for various violins and for a few violas. The damping coefficients here given may be in error by as much as ten percent. The knocking times measure the duration of the air resonance, since this is the most persistent sound after the knock. The amount of energy given to the violin by the knock varies somewhat from one trial to another, but that given by the electromagnetic excitation is much more uniform. The variation in time of decay from the knocking is not large, as the initial decay is very rapid. Unfortunately, this table is not complete in all items, as the necessary observations could not always be made.

When the electromagnetic excitation is cut off, there is a redistribution of energy among the natural modes of vibration of the violin, and this gives rise to beats. The beats have frequencies which are the differences of frequency of the strongest adjacent natural modes. Such beats were first observed by Knudsen in a small room in which pure tones of low frequency and considerable energy were being started and then stopped. In our case this redistribution accounts for the fact that the first part of the decay is not exponential. Observations taken of the decay of the first few vibrations led to higher values of the damping; the listed values were derived from measurements of some 15 to 20 vibrations, after most of the initial disturbance had subsided.

The conclusions that can be drawn from a study of these damping coefficients are again as confusing as before. The average knocking time of the old instruments is slightly longer than for the new, but the damping coefficients average about the same. Individual new instruments (e.g., the Yurkevitch and one by Moennig) have as low damping as the lowest of the Strads (B and J). The values for Strad S (a famous and beautiful violin) would, of themselves, place it among the least promising of the new instruments. On the

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[5] E. Rohloff, Ann. d. Physik **38**, 177 (1940); Zeits. f. Physik **177**, 64 (1940).

contrary, the values for the violins of the Heifetz test place these in their proper order; first, Yurkevitch; second, Phillips; third, Sangster (35). One must not lean too heavily on these numerical values, but they certainly suggest that damping is an important quality. It is unfortunate that the Strads differ so much among themselves; one regrets that no blindfold tests could be made among them to indicate which are the best Strads. If it turned out that those with the smallest damping were the most highly regarded, we could make more definite conclusions.

The violas that have been tested in this way are too few in number to draw conclusions from, but the results indicate a longer time of "ring" in the larger instruments, and a range of values for the damping coefficients which is as wide as it is for violins. Unfortunately no cellos were tested.

TABLE IX. The logarithmic decrement (δ) at various frequencies in violins and violas.

	δ	Type of vibration	Frequency	Knocking time
		Old violins		
Strad S	0.140	air	277	0.11 sec.
	0.144	body	451	
Strad W	0.13	air	270	0.12
	0.10	body	476	
Strad E	0.11	air	279	0.14
	0.12	1st body	457	
	0.085	4th body	1017	
Strad J	0.096	air	277	
Strad B	0.082	body	465	
	0.067	body	536	
Strad G	0.10	air	275	0.11
	0.068	body	454	
	0.136	body	831	
Strad D	0.13	air	276	0.12
	0.077	body	427	
Balistrieri	0.12	air	306	0.14
	0.094	body	452	
		New violins		
Yurkevitch	0.092	air	286	0.12
	0.079	body	460	
	0.077	body	685	
	0.077	body	965	
Phillips	0.105	air	280	0.12
	0.070	body	473	
	0.058	body	944	
Sangster No. 30	0.10	air	274	0.10
	0.12	body	429	
	0.11	body	500	
Sangster No. 34	0.14	air	262	0.09
	0.12	body	456	
Sangster No. 35	0.12	air	266	0.12
	0.090	body	480	
	0.070	body	1060	
Sangster No. 37	0.11	air	278	0.09
	0.087	body	465	
	0.084	body	675	
Sangster No. 38	0.13	air	278	0.10
	0.09	body	470	
	0.09	body	880	
Moennig copy of Strad B	0.090	air	278	
	0.085	body	540	
Koch	0.12	air	266	0.10
	0.062	body	452	
	0.075	body	942	
Stanley	0.13	air	269	0.10
	0.14	body	498	
	0.12	body	1141	
	0.16	off peak	1131	
Violin X	0.17	air	278	0.09
	0.10	body	527	
		Violas		
Viola Gaspar (?)	0.11	air	255	
(not Viola 3)	0.066	body	348	
Viola Storioni	0.15	air	228	0.19
	0.070	body	392	
Viola Dieudonné	0.14	air	240	
	0.11	body	381	
	0.10	body	470	

DISCUSSION OF RESULTS

The net result of this research so far is that we have found no physical quality in the best violins of the old makers that cannot be found also in new ones. The "characteristic tone" of old Italian instruments does *not* depend (a) on the quality of their steady tones, nor (b) on the mechanical ease with which steady tones are produced, nor (c) on the distribution of strength with frequency, nor (d) on the length of the duration of the tone after the excitation is cut off. Whether other trials by more accurate methods would disclose very small but positive differences between old and new instruments we cannot say. We hesitate to yield to the temptation to say that there is no real difference in the tones of old and new instruments, for the reason that a very few especially gifted and experienced listeners can distinguish an old violin of high quality, even over the radio. We suspect that there are minute differences which are either too small for us to measure, or which have been masked by the large variations which we have found. Some of the old instruments which we have taken as standards of excellence may not have been quite worthy of this honor. The results show that we could, if we omit certain violins, make them come out in favor of the old, or of the new, as we pleased. Certainly we may justly conclude that all people except the most gifted fail to make the distinction. The audience tests noted in our articles *B* and *C* show this very clearly, and there are lurid details to emphasize this point which we do not feel free to publish. Many other tests of this sort have led to the same result. We know of one conducted by Mr. Stokowski on the members of an orchestra, and another by the famous violinist Isaye on a group of professional musicians; there are several others recorded.

We have not made accurate measurements on the maximum volume of tone that an artist can produce on violins of different sorts, nor on the efficiency of these instruments as producers of sound energy; these may be important to the artist, but we are sure that they are not to the listener, who neither knows nor cares how hard the player is working, and whose impression of loudness depends as much on the acoustics of the concert hall as on anything else. The crucial quality which we seek does not lie in this field.

The extraneous noises produced by the scraping of the bow, especially at moments of contact with the string, or release of the string, are so small as not to enter into the listener's judgment. They are not noticed at any considerable distance, and they are so weak in the case of steady tones that our analyses do not show them; that is, they are at least 30 db down from the maximum of the component partials. The "scratchy" tone of the cheapest violins is almost certainly due to the presence in their steady tones of an excess amount of very high frequency energy.

There is one experiment on violins which is very difficult to carry to completion; this is to find the effect of centuries of time on them. It seems to be a general belief that a good violin improves with age; whether a bad one also improves no one seems to know. There are two effects that might be included in the process of ageing; (1) chemical and physical changes in the wood, or in the varnish, due to the passage of time, with its inevitable accompanying fluctuations of temperature, atmospheric moisture, impurities in the air, etc.; and (2) effects due to the playing process. The latter consist mainly of effects due to continued vibration, but the influence of the heat and moisture contributed by the player may greatly accelerate the chemical and physical changes mentioned above. The air near a player's body in warm weather is almost saturated with water vapor, and a considerable amount of this will be absorbed by the violin during a long playing session. This will make the wood expand across the grain, and thereby change the forces in the violin body somewhat. Daily playing for years might thus do something to a violin which would not happen to one which is resting in its case.

Our measurements indicate that old violins weigh less on the average than new ones. Seven Strads varied from 373 to 394 grams (with chinrests removed); average 383 grams. Six other old violins varied from 354 (Stainer) to 389 grams; average 374. Thirteen new violins varied from 381 to 435 grams; average 410 grams. The three violins in the Heifetz test weighed from 391 to 413 grams; average 410 grams. The new violins are 7 percent heavier than the Strads. Naturally, the lighter a violin is, the easier it is to shake. It ought to be as light as is safe, considering the strong forces which the tension of the strings imposes on the instrument. Modern makers have said that one cannot safely make a violin top as thin as those of Stradivarius without danger of collapse. This can hardly be due to any change in 200 years in the nature of the wood available from the tree whose wood is almost universally preferred, the Norway spruce, *Picea excelsa.* It is true that the tension of violin strings is now greater than it was 200 years ago, because of the rise of musical pitch; but the Strads, fitted with stronger bass-bars, are capable of withstanding this. So we conclude that the wood has gained strength with age, or that it was treated by the early makers in such a way as to increase the strength at the time, or at least to make an increase in strength more likely through age. It has been stated that the few Strads that have survived without having been played very much are not as good as those which have been in active use. It is also true that Strads have grown greatly in reputation, and probably in merit, since they were new. These facts point to an aging process accelerated by playing, which is responsible for the present strength of the wood in Strads.

We have already mentioned (article *A*) that with age and long playing a certain amount of cracking of the glue is found in the purfling, and perhaps elsewhere, so that the top of the violin has become less tightly bound, and is better able to vibrate. This may be an important part of the ageing process, though it does not satisfy the requirement of an increase in the strength of the wood.

More research is needed on the effects of age, and of continued vibration, on wood, and this is most conveniently done on small strips of wood, rather than on whole violins, where the properties of the wood (Young's coefficient of elasticity, density, velocity of sound in the wood, damping coefficient, etc.), can conveniently be measured. At the same time the effects of various varnish treatments (or of the first "filler") can be studied, and a search begun for a substance with which to impregnate the wood so as to add to its strength, protect it from moisture, decrease its damping, etc. One might also search for better woods, now that wood from all over the world can be obtained. Some of these studies have been started, conducted by various interested people, and methods of treatment involving heat or changes in pressure are being tried. As far as we know none of these methods have as yet led to any very striking results. Future work must include a long program on treated strips including further studies of their damping.

Our sincere thanks are due to many artists and collectors for permission to test their precious instruments, and in some cases for active assistance in the tests. The list includes Jascha Heifetz, Wolfe Wolfinsohn, Jacques Gordon, Leo Reisman, Z. Balokovic, the members of the Curtis Quartet (Messrs. Brodsky, Jaffe, Aronoff, and Cole), Marcel Dick, Gerald Warburg, Bernard Robbins, William Lincer, Miss Thelma Given, Maurice Stad, Mrs. W. E. Ellery, Mrs. Olga Petzoff, Mrs. E. Ginn, Miss Lillian Shattuck, Miss Sally Dodge, Henry Guerlac, Kerr Atkinson, H. S. Shaw, A. P. Saunders, Malcolm Holmes, F. C. Keyes, and many others, both amateur musicians and violin makers. We are especially indebted to Professor Curt Sachs for advice, and to E. H. Sangster, Wm. Moennig and Son, and J. A. Gould and Sons for loans of instruments, adjustments, etc. Finally, the credit for the operation and adjustment of the apparatus, and for the construction of much of it, goes to Dr. Robert B. Watson without whose skillful help this research could not have been done.

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Regular Contributions

Recent Work on Violins

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(a) Loudness-frequency curves of violins disclose peaks caused by natural vibrations of the body and of the inner air. "Overtone peaks" occur when a natural vibration coincides with one of the partials of the tone. Shifting the frequencies of the natural vibrations is possible and can produce a more even distribution of strength.

(b) The volume of tone is very sensitive to the thickness of the top plate along the line where it is attached to the rest of the body. Thinning a groove part way around the top has produced marked improvements in several instruments.

(c) The air inside the box produces one noticeable peak only in the loudness curve. Tuning forks placed in front of the *f*-holes produce responses but they are the result of body vibrations.

(d) Experiments on *f*-holes show that long ones are somewhat better than short, and also that the main function of the bass-bar is to carry vibrations from the active foot of the bridge to the wider areas.

(e) Resonating strings reduce loudness rather than increasing it. Interesting phase differences occur between strings, or the inner air, or parts of the body.

(f) A string gives more tone when the others are relaxed.

THE research on violins which was reported on earlier[1] seemed fairly complete at the time, with one or two small exceptions. Since then, however, a small crop of items of some interest has been gathered from records of experiments done in the Harvard Physical Laboratories, together with two new subjects which seem to have considerable practical importance. These results have been obtained chiefly by a further study of loudness curves, which we once considered relatively unimportant. Through the kindness of the Physics Department of Mount Holyoke College, a General Radio sound-level meter has been made available, and a long series of sound-level *vs* frequency curves has been obtained, always under constant conditions, in the same room, at the same distance from the source, and with the same player. The loudest tone which is of good quality is produced from each of 14 tones on each string, and the meter readings are plotted against the musical scale. The sound levels used were from 70 to 100 db. With a little experience, it is possible to get consistent readings. We call these *loudness* curves for short, for the sort of comparisons we wish to make.

The loudness of a violin began to appear important in 1940, when J. Heifetz and S. Jacobson tested a large number of new violins and made it quite evident that loudness was one quality they demanded in their profession, so long as it did not involve a deterioration of quality. In addition, it seemed that no other quality of violins could account for the superior reputation of the old Italian ones. It is true that if musicians submit to tests of the "blindfold" type, in which they do not know what violin they are listening to, all but a very few are incapable of picking out an old Italian instrument from a group of other good ones. Our earlier work showed that there was no difference in tone quality (i.e., "color"), in ease of playing, or in the decay of tones, which old Italian violins have which was not also possessed by some modern instruments. Nevertheless, there remained one obstinate little fact, namely that a *very* few people with extraordinary gifts and experience could recognize an old Italian violin on hearing it, even over the radio. These rare people could not describe how they did it, but one of them thought that the tone seemed to come out more easily from the old violins. This made us suspect that there was a little difference in loudness.

QUALITY OF VIOLIN

LOUDNESS CURVES AND OVERTONE PEAKS

A typical loudness curve (called a 'total-intensity curve previously[2]) has a strong peak caused by the vibration of the air inside the box. This is usually the lowest strong peak, and its tone has a very strong fundamental component. Its beneficial effect is widespread on account of high damping and it thus enriches the tone in a region several semitones wide. We shall call this the *air peak*, and denote it by A, for short.

The frequency of the air peak can be shifted in several ways, of which the only practical ones are changing the volume of the air and the total area of the *f* hole openings. The change of frequency is shown by theory to be proportional to the fourth root of the area of the holes and inversely proportional to the square root of the volume. Making the area of the *f* holes 25 percent larger produces only a semitone rise in frequency of the air tone, and such an increase is supposed to ruin the appearance of a good violin. If we are making a

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[1] F. A. Saunders, J. Acoust. Soc. Am. 17, 169 (1946).

[2] F. A. Saunders, J. Acoust. Soc. Am. 9, 81 (1937).

violin, it is easy to plan to have an internal volume such as to bring the air tone where we want it, and this is done by changing the depth of the box (the height of the sides). The frequency will vary (roughly) inversely as the square root of this depth.

The other peaks which are found in the loudness curves are caused by vibrations of the body in its natural modes; actually the top plate seems to be the only important part involved. The principal peak, which we shall call *P*, is associated with a wolf-tone if one exists; this helps to settle which peak is *P* in many cases. Its position on the musical scale can be lowered by loading the bridge with a mute, or, permanently, by thinning the top of the violin. With experience in making violins, its position can be predetermined with sufficient accuracy, when a desirable place for it has been decided upon.

TUNING

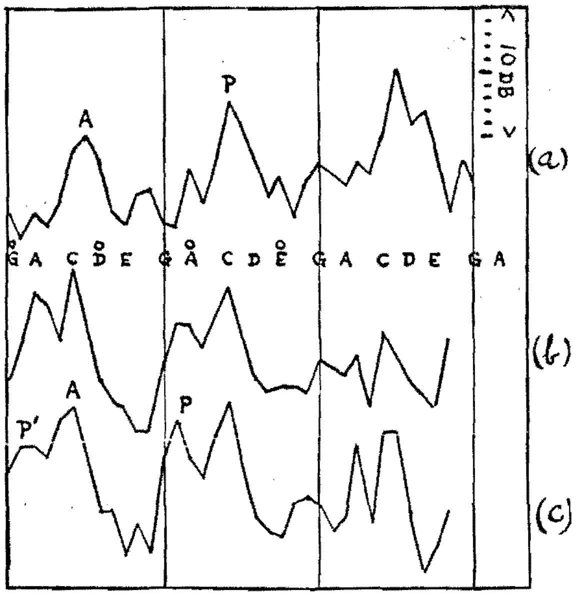

FIG. 1. Violin "loudness" curves. The ordinates are the sound level here used as a measure of loudness; the scale of decibels is indicated at the right. The abscissas are the notes of the piano scale, indicated across the middle. The open strings are marked by an "O". (a) An old high priced Italian violin of the era of Stradivarius. Its three important peaks lie at C or C sharp, thus tending to make other tones weak, and a very uneven scale. (b) A respectable modern German violin. (c) The same after thinning the edges of its top; note rise in loudness of middle and upper peaks.

There are other peaks in the loudness curves which are of minor size but sometimes important. Years ago H. Fletcher proved that a complex tone appeared to have the pitch of the fundamental component of the harmonic series, even if that component is entirely absent. The only effect of that absence was a slight change in tone quality. It is equally true that if the tone of one of the upper partials is strengthened, the addition of strength appears to be at the fundamental pitch. Thus, if a string tone (with its attendant harmonics) has a fundamental frequency of 220 cps, and if its second partial (440 cps) coincides with a strong natural mode of vibration of the body, it will be strengthened, and the ear will hear it as an increase in loudness at 220 cps. The peak which thus occurs at the lower note we call an *overtone peak* (and designate it by *P'* to indicate its dependence on *P*). Such peaks, which are often found about where this example indicates, serve to increase the strength of the low tones in a region where the radiation of energy becomes difficult on account of the small size of the violin. Figures 1 and 2 show these peaks in a few cases.

PEAKS

Other overtone peaks may be caused by the coincidence of a second, or even a third, partial with a natural mode of the plate. Also there is an overtone peak caused by the *air* vibration, which lies near 140 cps, below the range of a violin. This peak may, however, be of great use in small violas as we shall see presently.

To illustrate overtone peaks, the loudness curve for a viola is shown in Fig. 2(d). It shows the main body and air peaks, *P* and *A*, with the overtone peaks, *P'* and *A'*, derived from them. It is apparent that the low C string tones would be much less good if the overtone peaks did not occur. The curve shows loudness variations up to 10 db or more. This range of loudness is quite usual, even in the most expensive instruments. The frequent statements of earlier writers to the effect that the tone is absolutely even (in loudness) are thus seen to indicate the extent to which the musical ear may ignore variations in loudness.

SPACING OF PEAKS

Figures 1(c) and 2(b), 2(c), 2(d) show also that when *A* and *P* are about a fifth (7 semitones) apart the positions of the four marked peaks are distributed so as to avoid the occurrence of wide valleys of weakness between the peaks. An unfortunate situation arises quite often when *P* is about an octave above *A*. *P'* and A then coincide, strengthening an already strong peak and losing for us the assistance of *P'* in filling up an otherwise bad valley (see Fig. 1(a)). This situation appears to be common in highly arched violins. It occurs in five Strads that we have tested, of which four are highly arched. Of course we cannot say whether this condition existed in these violins when they were new, or has arisen on account of changes in their long history. The specimens we have tested of the work of Andreas Guarnerius (two), of Maggini (one), of Joseph Guarnerius (*dG*) (three out of four), and of Guadagnini (one) do not suffer from this defect. Five Strads are also well arranged. The Guarnerius and the Strad owned by Heifetz have *P* and *A* in the best positions; and, as further evidence of his sensitive ear, the two modern violins which were placed highest in the test referred to above, are similarly good. We offer this spacing as a criterion of excellence in violins, along with others.

Judging from the well-known vibrations of a rectangular plate, we should expect that the natural modes should be closer together (on the musical scale) in the high frequencies than in the low. This seems to be true of violins. Wide valleys of weakness are commoner in the low frequencies. A violin with the main peaks well placed is likely to be good all over. There is no hope of getting a uniform loudness curve. In fact some wise people think that the resulting uniformity in tone-color would be monotonous.

In 1949, the writer was fortunate in meeting a skilled wood-worker (and former teacher of physics), Mrs. Morton Hutchins of Montclair, New Jersey, who offered to make experimental instruments in connection with this research. She had at that time completed two very good violas, and has by now eleven to her credit. The discoveries which we have made on account of her work have led to very interesting results, and Mrs. Hutchins deserves credit not only for the instruments but for many good ideas which she has contributed. The musical aspects of this work are being reported elsewhere in a joint article, but may be briefly summarized here.

In 1830, or thereabouts, Savart suggested that the air peak should be similarly located in both violins and violas. In the violin it is usually from 6 to 8 semitones from the lowest note; in violas from 8 to 12. We eventually got a viola into this condition by using a large body and very small holes, but the holes limited the volume of sound at the air tone too much. Also the soft booming tone on the C-string was quite different from the usual tones there, and musicians disliked it. To reach Savert's condition properly the viola would have to be so large that it could not be played in the usual manner. Hence this idea was abandoned.

Later we made a greatly improved small viola, whose air overtone peak (A' in Fig. 2d, for instance) was moved up the scale, so that it became fully effective. The low tones are then astonishingly powerful and of good quality. Later still a viola small enough for a child was made with the same success. From this work it is now possible for people with small hands to play a viola without difficulty, and still produce proper deep tones.

THINNED EDGES

A second group of results was obtained by means of a viola which had a flat top. With this it was possible to make a long series of experiments in which changes were made in the *f* holes, but without finding anything new; and also the stiffness of the top was altered by gluing strips of wood on it. These acted, of course, as though they had been attached inside, but they could be taken off or otherwise altered without trouble. We sought a way of removing some strong wolf-tones which marred the action of this viola. We could sprinkle cornmeal on the flat top and observe the dominant pattern when a peak tone was played, but it was not possible to get these pure and simple, as they would be for a single driving frequency. Changes in the patterns guided us in placing the added stiffnesses, and we found out how to destroy the wolf-tones, but we at the same time ruined the loudness of the instrument. Since the wolf-tone acts like an unstable vibration, it seemed likely that a less binding connection between the top and the rest of the viola might remove the instability. This proved to be correct and very helpful. A small ditch was cut in the top, about 1 mm wide and deep, which effectively reduced the thickness of the top at a point just inside the line where it was glued to the body. This reduction of thickness was not carried all the way around the top; the central line under the finger-board

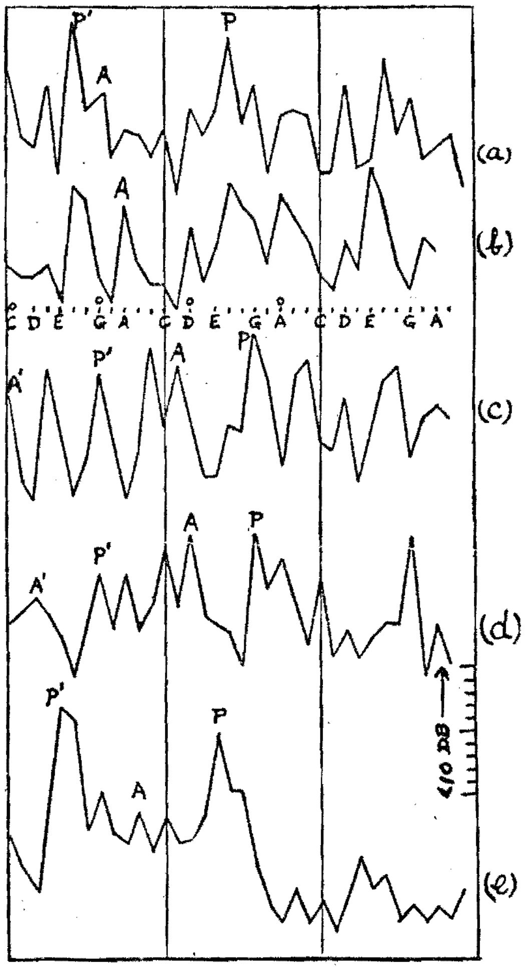

FIG. 2. Viola and cello curves. (a) A new viola (C. M. Hutchins, No. 4) of good quality, but the air peak A was too close to P'. (b) The same after enlarging the *f* holes so as to move A up a little and give a better distribution of strength. (c) A new viola (C. M. Hutchins, No. 11) of 16 inch length, but ribs very low, so as to reduce the internal volume. Half of the A' overtone peak is above C_0, the open C-string tone. (d) A new small viola, 15 inches long (C. M. Hutchins, No. 9), with volume small enough to bring the whole of A' into use, giving remarkable strength to the low C-string tones. (e) An unfortunate cello of undistinguished lineage; a type in which the air vibration is feeble, probably because the wood is too thick. Its P and P' are its only strong tones.

and the tail-piece was left untouched, so that the top could still safely withstand the tension of the strings. This thinned edge cured all the ills of this viola. It became almost entirely free of wolf-tones; its peaks were higher and its gain in average loudness was about 2 db. This seems a small gain, but it is very noticeable and satisfactory to the player. Since then, many violins, violas, and one cello have had their edges thinned (on the inside, of course) and they have all been improved, most of them greatly so. This peculiar sensitiveness of the top to the thickness of its edge we believe to be new, and very important.

From data within our reach we understand that old Italian violins are usually thin enough (about 2 mm) at the sensitive edge already, while good violins from other sources are often thicker there. Since the old Italian instruments have a better reputation, we suggest that this is at least partly caused by the thin edges. Some modern makers have been using thin edges for some time; if others follow suit, the improvement in new violins should be marked. Existing violins with thick edges can by this simple alteration be greatly advanced in quality with little addition to their cost. Our $5.00 "standard of badness" has so risen in this way in rank that it was recently credited by a distinguished violinist (blindfolded) with Italian tone; and a musical audience who were not allowed to see it voted it as good as an old Italian violin. Whoever hears one of these treated instruments is surprised by its relative loudness and the apparent ease with which the tone comes out of it; and these qualities are precisely what has been supposed to be characteristic of old Italian violins.

Fixin' Bad Violins

It should be remembered that until recent times it has been impossible for anyone to make a simple experiment such as ours mentioned above, directly measuring by the sound meter the effect of thinning the edge with *no other* alteration. It is only by such measurements that the "thinned-edge effect" could have been discovered.

VIBRATIONS OF THE INNER AIR

Writers on violins differ as to the function of the inner air. Some go so far as to state that most of the sound of a violin comes out of the *f* holes, while others think that the air does nothing useful except to strengthen the fundamental tone in the region of the main air resonance. We have tried to settle this question and to search for overtones emitted by the air.

The use of a sound meter helps to find the contribution of the air to the total loudness. Maximum-loudness curves are taken covering the whole range of the violin under two conditions: with the *f* holes first plugged with soft cotton, second, open holes. The plugs must be really soft, so that they do not affect the free vibrations of the violin top, and yet so tight that they effectively stop vibrations in the holes. When correctly plugged, the air peak is eliminated from the loudness curve, but no other noticeable effect is produced on it. Since the air peak raises the loudness of the tones in an interval of about seven semitones in the region of the maximum, the plugs lessen the vibrations from about B flat on the G-string to E. This reduces the loudness on the G-string and slightly affects the D-string, but the other two strings are unaffected by the plugs. A typical set of measurements gave averages for the first ten semitones on each string as follows: G-string, 90.0 decibels when holes are open and 86.8 when plugged; D-string, 90.0 open and 88.8 plugged; A-string, 89.1 open and 89.0 plugged; E-string, 89.5 open and 90.1 plugged. These data show a reduction by plugging of 3.2 db on the G-string, 1.2 db on the D, and within experimental error no change in the others. We conclude that no measurable vibration comes out of the [redacted] except those near the main air vibration, though a more delicate method might disclose traces. We shall see below that this is true.

The body vibrations should affect the air inside as well as that outside. The body when it vibrates forms at many frequencies a pattern of areas in opposite phases, as in the Chladni plate. Thus the combined effect of adjacent areas is very small compared with what we might get if the whole plate could vibrate in one phase. Backhaus has found that it does this at the main air tone, but the plate motion is feeble compared with that of the air inside since there is no natural mode of the plate at that frequency. The combined action of all the vibrating areas of the plate gets into the inner air, the different phases fight it out with one another and what comes out at the *f* holes has a phase which is probably different from that of the wood nearby, and is certainly opposed to the contribution of some areas on the outside of the violin top. Thus we cannot assume that the air vibration coming out of the *f* holes is useful, except when it is very large, as at its natural frequency.

Resonance can be detected at the *f* holes by placing sources of pure tones (tuning forks, etc.) close to one opening and listening at the other. The effects are faint, but many frequencies have been published as air resonances. The fact that different violins with approximately the same volume give different frequencies indicates that these are resonances of the *body*, not the air, excited through the inner air at the frequencies of the normal body modes. The body frequencies are known to be different in different violins.

In addition to the indication already mentioned that the overtones of the inner air vibration coming out of the *f* holes, do not affect the form of the loudness curve, we have tried to study these overtones by five other methods.

Method 1

Savart blew a stream of air from a nozzle against the edge of an *f* hole and thus set the inner air in vibration as a flute-player does with his air column. A very satisfactory tone was obtained when we tried this, using a blast of air and nozzles of different sizes. Analyses of these sounds by methods[2] described earlier, showed that there were overtones present, but without exception these proved to be overtones of the nozzle. No trace of an overtone of the air-body vibration was found; its sound level must be at least 30 db below that of the main air resonance. This result was derived from tests on two violins and a viola.

Method 2

A single silk fiber was fastened by one end to the edge of an *f* hole, or to an independent support, the other standing free in the middle of the hole. This free end was viewed through a microscope at such an angle that in-and-out vibrations could be measured on a scale in the eyepiece. Each division on this scale was equivalent to 0.023 mm of motion, and one-tenth of this was easily read. The bowing was done by an automatic bow running at constant speed, bow pressure, and bow distance from the bridge. The frequency of the tone was set by a finger, as in normal violin playing. At the main air vibration an amplitude of 0.15 mm was observed (total motion 0.3 mm). At the main *body* resonance for this violin ($f=480$ cps) an amplitude about one-tenth as great was found. No other body resonance affected it visibly. No motion was detected in the wood around the hole. The method was very awkward, but it might have been more successful with a stronger microscope. The results are interesting in showing that the main body resonance can produce a little sound coming out of the *f* hole, but, as stated above, it is a question whether the phase of this sound is such as to add to the loudness of the violin or as to diminish it.

Method 3

This and the later methods consist in comparing response curves (described in the earlier papers) for a violin in its normal condition with those for an abnormal one. The curves were all taken with an audiograph, and the violins were excited electrically.[3] The third method consisted in studying the change in the response curve when a mute was fastened in the usual way to the bridge. The mute lowers the frequency of each of the natural modes of the body by an amount which (near 500 cps) makes a change of 14 cps per gram of load; but the mute leaves the air vibration unaffected. Many tests of this sort were carried out by our older method from which no accurate results could be obtained. By the new and better method only a few curves were taken. The small effect to be expected from an air overtone may happen to be superimposed on a peak, or a hollow, or on the side of a hill. The mute itself may change the height of the peaks a little. These and the other inevitable errors combined to make the results too uncertain to be worth presenting.

Method 4

The fourth method consists of comparing a normal response curve with one taken when the body of the violin, held horizontally, is filled with a stream of carbon dioxide. The main air vibration falls about a minor third (frequency ratio 6:5), and the air overtones should fall similarly. This method is better than the preceding one because the changes in the response curve are few, and thus easier to observe.

The search was carried out with one curve mounted on a drawing board, and the other parallel and just above it. With a T-square as a guide, the vertical distances between the curves could be measured everywhere. If the normal curve were above the gas-shifted one, the difference curve would run constant except at an air peak, when a hollow is found at the lower frequency to which the air resonance is shifted by the gas and a peak at its true position. These features could be made out in a few cases in spite of disturbances of an electrical nature which made the curves not absolutely repeatable.

The results obtained are that the main air resonance for one violin (Koch, 1930) is about 275 cps, and there appear to be upper air resonances near 1300, 2600, and 3660 cps. There were similar indications near 1100, 2250, and 4100 cps, but these lie so close to body vibrations that they are probably caused by the top. These frequencies were read from the chart marked by the audiograph, and this device needed frequent calibration. It was never intended for more than frequency indications. The values above might be out by as much as 50 cps.

Experiments made by the old method gave evidence for the 1300-cps air overtone in another violin, a good modern American instrument. Since small differences in inner volume and area of *f* holes occur between different violins, the air overtone frequencies may not be quite the same in different violins.

Method 5

The best method is to compare a normal response curve with one obtained when the *f* holes are plugged with soft cotton. This eliminates air vibrations without materially affecting the vibrations of the body. If the latter produce vibrations in the inner air, which normally come out of the *f* holes, these will be blocked by the cotton, along with the true air overtones. If the air-hole vibrations are nearly in phase with the average outside body vibrations, the blocking of the holes will diminish the total sound slightly. We have already shown that there is no change in the loudness of the sound of a violin from this cause, except in the case of the main air resonance. We assume that the phase differences between the outside body vibrations and

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[3] Watson, Cunningham, and Saunders, J. Acoust. Soc. Am. 12, 399 (1941).

those in the *f* holes are small; if so, the air overtones must be very weak, as method 2 had suggested, and the body vibrations transmitted to the inner air and out through the holes are weak also.

INNER AIR

The two response curves obtained by method 5 are very much alike. A normal curve was placed on a drawing board with a plugged-holes curve directly above it, and the distance was measured between the two curves at all points. The difference curve thus obtained is a nearly straight line except where some air vibration occurs (a natural air overtone or a vibration imposed by a natural vibration of the body) and at such a point a hollow may be found in the curve. Since this is a small hollow and may occur at the top of a body peak, on the side of one or in a valley, its appearance will be distorted and it will not be noticed until the difference curve is drawn. If the hollow occurs at the tip of a peak, it appears as a slight reduction in height and it is probably caused by the peak where it occurs; but if no peak is near, a hollow indicates a true air vibration.

The curves were good, though not entirely free from small disturbances, and a few definite observations were made. The strongest air overtone was found in the region of 1300 cps (from 1260 to 1320) and was found in five violins whose fundamental air tones varied very little (from 275 to 284 cps). There was no body peak nearby in these cases. There seem also to be two other air overtones near 1730 and 2650 cps, but found in two violins only; and one near 3700 which appeared on a particularly good record, although only in one violin. Of these five violins four had a Stradivarius pattern, and the other a J. Guarnerius. Since the shape of the instruments did not affect the value of the main air resonance, it would probably not alter the frequencies of the air overtones greatly.

F-HOLES

In conclusion it should be pointed out that we do not measure the motion in the *f* holes, except in method 2. The results observed by the last three methods might depend on the relative phases of the air vibration and the average outside body vibration. If these two were opposite in phase, the *f* hole plugs in method 5 would *increase* the loudness, instead of lessening it, as we have assumed. If the phase difference were intermediate, it might be that there was no observable effect from the plugs. It would not seem possible for strong air vibrations to exist and hide from observation in this way on account of the fact that only one body vibration was found in method 2, and the effect of that was small. We conclude therefore that the output of the *f* holes is unimportant except near the frequency of the main air resonance.

We have not found any theory that deals with the overtones of an air cavity resembling that of a violin. Rayleigh[4] states that the overtones are very high in the case of a simpler cavity than ours. Our data show that the first overtone has a frequency about five times that of the fundamental tone.

ON *f* AND *C* HOLES

The flat-topped viola mentioned above was generously supplied with two tops, to be altered by experiments *seriatim*. On the first some experiments were made to find out if the length of the *f* holes affected the tone materially. The holes used were nearly straight and not of the usual shape. They were at first narrow and about two inches long. These were tested, then lengthened by slow stages to over four inches, taking a loudness curve at each stage. The average loudness increased a little with increase in length, especially in the high pitches. From this we may infer that the portion of the top which lies between the holes and supports the bridge is the most active emitter of the highest tones. This is what one would expect, since the active foot of the bridge from which the whole top gets its vibrations lies in the middle of this area.

Many observations with this viola and other instruments have shown that very narrow holes are not effective in producing a strong air vibration. From physical considerations one would suppose that circular holes would be best for this purpose; but these could not be crowded into the available space without cutting too many of the fibers of the top and thus weakening the general vibrations it emits. This was found to be the case when the holes were almost entirely two one-inch circles. The widths usually used seem to be a good compromise. A slight gain is made by lengthening the holes to four inches, though this is not very important.

The second flat-top was supplied by Mrs. Hutchins with *C* holes, copied from an old viol in the Metropolitan Museum of Art. These were placed as usual, with the curled-over ends facing outward. The usual *f* holes face each other so that they narrow the uncut width of the top of the violin, and (one would suppose) inhibit the passage of sound waves in the wood from the active foot of the bridge to the smaller half of the body, which lies beyond. The experiments done with the *C* holes consisted in taking loudness curves with them and then making a saw-cut toward the middle of the instrument, starting from the point which is nearest to the other *C* hole and proceeding to the bass bar on one side, and an equal cut from the other side. Thus the solid top was cut to the same extent as it would have been if the holes had been of the *f* type. *No change* in loudness occurred. The explanation is that the bass bar has the purpose of carrying the vibrations from the active foot of the bridge to both halves of the violin and that it does its job adequately. This function of the bass bar is in addition to its help in resisting the forces acting on the top from the tension of the strings. The conventional dimensions of the bass bar appear to be adequate for carrying on both functions.

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[4] Lord Rayleigh, *Theory of Sound* (MacMillan and Company Ltd., London, 1896), second edition, Vol. 2, p. 189.

THE USE OF RESONATING STRINGS

One cannot be sure what the first users of such an instrument as the *viola d'amore* expected to get from the resonating strings with which it was furnished. At the present time some violin players use one of its strings as a resonator to be excited by a tone produced on another string. The general impression seems to be that greater loudness is thereby obtained or perhaps an interesting new tone-color.

In regard to loudness the matter is easily tested with a sound level meter. Many experiments have thus been made in which lifting a finger allows an idle string to resonate. A *loss* of loudness is observed. At 70 db sound level the change is usually of the order of 2 db, so that it is not necessarily very important. The tuning has to be quite exact or there will be no reduction, because there is no resonance. From energy considerations it is obvious that if the energy is fed to the active string at a constant rate, the energy taken from this string to drive the idle one must reduce the amount in the first string. If there is no loss in transmitting this energy, one might expect that the reduction in sound from the active string would be made up by the contribution of the idle one. But there are losses in transmission of vibrations through wood on account of its viscosity. For this reason the total sound should be slightly reduced when the idle string is set free to vibrate in resonance. We shall see below that the relative phases of the string vibrations also affect this result.

As to the tone-color, which is determined by the presence and strength of the harmonics, the idle string will be as likely to pick up the upper harmonic vibrations as the fundamental, assuming that the tuning is exact and that the strings are alike. The phase relations may not be the same in the harmonics, and this should be considered also. In general one would not expect any noticeable difference in tone-color in the tone emitted by the resonating string, and this statement is based partly on the fact that the human ear is not very acute in detecting small differences. There is one case, however, in which a change might be noticed. Heifetz once said that he sometimes plays his open G-string with the G above (on the D-string) resonating to it in a sort of indirect vibrato. This gives a certain liveness to the otherwise dull tone of the open G-string. When the upper G is responding, its first partial resonates with the second partial of the G-string. The third partial of the G-string would be at D and could not occur as a partial of the upper G tone. Thus *all* partials of the G-string cannot produce resonance in the tone of the upper G, and this will alter the tone-color of the combination. One might say that in all cases where the two tones are not in unison, there will be a small change in tone color for this reason; but, again, it is doubtful if many people could hear it.

The relative phases of the active and the idle strings in resonance must be considered. Since both strings act through the bridge to shake the violin top, their effects must be added, but this process will not be simple addition if their phases are different.

The theory of resonance shows that if the coupling is loose and the damping small, the phase difference between the two strings will not be far from 90°, which is the most effective phase angle for transmission of power from one to the other. This assumes perfect tuning, which is rarely achieved. If there is a difference in frequency, the phase lag is greater than 90° when the frequency of the driving string is the greater, and less when the frequency difference is in the other direction. In no case is an agreement in phase to be expected; this means that the resultant of the displacements will be less than their sum. Thus the loudness will be reduced by the phase difference. This reduction is combined in our experiments with the other loss, caused by viscosity; but both are probably small.

Another aspect of the phase difference should be mentioned. We have assumed that the power supplied by the player is (or can be made to be) constant. If the phase lag can change and does change to a value more favorable for the transmission of energy between the strings, what would be expected to happen? Does the player automatically (and unconsciously) increase the power, and thereby make the tone louder? Or can the experiment be done so that this does not happen? If the bow is drawn slowly and uniformly across the string, and the idle string is freed by the lifting of a finger for a second or two, the pointer of the sound meter dips down as soon as resonance begins, and a time of two seconds is all that is needed for the experiment. The meter returns to the same reading when the lifted finger goes down again, which would not happen if the power supply were not constant. It does not seem possible that the power supply could change fast enough to make any observable difference in the result.

An interesting experiment demonstrating the differences of phase that occur in resonance should be mentioned. Two parallel steel wires were stretched over the same sonometer bridge, about one centimeter apart. One was driven by a 60-cycle alternating current electromagnet, which very obligingly furnishes a full set of harmonics on account of the distortion of the sine form by hysteresis. The frequency of the magnetic field was 120 cps, and the active wire was tuned for maximum response to the field. The idle wire was at nearly the same frequency. Both wires were viewed through a three-power magnifier, and the system was lighted by short pulses coming through a perforated disk run by a synchronous motor. The wires appeared quite stationary whether resonance occurred or not, but differences of phase (when both vibrated) were shown by the positions the wires took. The changes in phase produced by altering the frequency of the idle wire were estimated, and the agreement with theory was very satisfactory. The lag varied from somewhat less than 90° to over 140° as the frequency of the idle wire was slowly lowered through the resonant value. If the frequency of the light flashes were doubled there were two glimpses of the wires in each oscillation, and the distance apart gave a better idea of the phase changes than the 120 cps flashes furnished. It would not be difficult to make this experiment into a quantitative one.

THE RIGHT NUMBER OF STRINGS ON A VIOLIN

One takes it for granted that four strings are correct for a violin, and this number has persisted unchanged for a very long time. Further back in history the number on a lute rose to nineteen, and later five or more were common on viols. In recent years a five-string cello has been made (by Professor Karapetoff) and admired, but this number has not been generally adopted.

It seems worth while to consider the loudness of a violin supplied with different numbers of strings. If a tone is produced on one string and it begins to make the bridge move, the vibrations which it creates are opposed by the strong forces also acting on the bridge, contributed by the other strings. One thinks of a person sitting on a long bench and wishing to move it. The difficulty of doing so will depend greatly on the number of people who are also sitting on the bench. The exceedingly faint tone of the lute is thus readily explained, and we see also why in the course of history the number of strings used has steadily diminished to its present value. To see what might happen in the future if we lessened this number, a violin G-string was played with its maximum (good) tone, which can be done with fairly constant results. Then the upper strings were relaxed, one by one. In one test, playing on the G-string, a value of 80.0 decibels was read on the meter when all strings were tuned normally. When the two upper strings were relaxed, the value rose to 81.7 db, and when the third one was also loose, it rose to 82.3. The maximum change was thus 2.3 db, which seems small but is by no means negligible if the tone of the violin is to stand out over accompanying sounds. It is comparable with the gain which comes from thinned edges, and either change may determine the audibility of a violin over an orchestral accompaniment in a large hall. Future soloists who wish to perform the "Aria on the G-string" would do well to relax the other strings.

We are not suggesting the use of three strings on a violin. This would reduce the range of the instrument by an amount which would be intolerable unless their tuning was different. If the present interval between strings, a fifth, was to be changed to a sixth or more, we should not have fingers enough to be able to play scales quickly and easily on it. So long as man has only four fingers for this purpose, four strings are recommended.

Here there seems to be another fact indicating the importance of loudness in violins, which we stressed in the beginning of this paper. In the course of the evolution of stringed instruments we have moved continually toward an increase of loudness. While we may have lost thereby some of the intimacy of music in one room, inaudible elsewhere, we have gained the possibility of hearing our greatest artists in the largest halls.

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Regarding the Sound Quality of Violins and a Scientific Basis for Violin Construction*

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Response curves, important both for steady sound and transients, give a far-reaching insight into the objective characteristics of violins: good ones exhibit large amplitudes at low frequencies and small ones at high frequencies, a broad minimum near about 1500 cps, and larger amplitudes between about 2000 and 3000 cps. The musical subjective significance of these physical properties is mentioned briefly. In general, the sound pressure radiated from a violin follows the inverse-distance law, being independent of frequency. The influence of wood thickness is very important, that of the varnish is comparably small. Pine has a greater damping at high frequencies than at low frequencies. This seems to be a good acoustical reason for making important parts of stringed instruments of pine. Sapwood is better than heartwood. Similarly, some kinds of varnish produce more damping at high frequencies than at low frequencies. If a resonance curve is to be imitated in detail, it is necessary to change carefully the wood thickness of certain parts of the violin body. The applicability of present-day scientific knowledge to the construction of violins is here outlined.

INTRODUCTION

The physical behavior of violins is reviewed as background for a discussion of technical details that influence the quality of the violin sound. More specifically, we first consider response curves of violins, the law of radiation, and the transient response. Then we look at the influence of kind of wood, varnish, and wood thickness. Finally, we summarize present status of violin making on a scientific basis.

A. REGARDING THE SOUND QUALITY OF VIOLINS

A comparison of old Italian violins with present-day ones is an obvious way to start research on tone quality. For example, response curves have been measured for such comparison. F. A. Saunders and his cooperators in the United States deserve praise in this connection as does also G. Pasqualini in Italy. Similarly, H. Backhaus and collaborators in Germany are to be named.

Response Curves

Whereas some have used electrical excitation in recording response curves, we generally prefer to bow the violin in an automatic way. To do so is indeed more troublesome, because it requires sound analyses in small frequency intervals. It does, however, supply curves under rather natural conditions, and that is what the present-day investigation sometimes needs very urgently. Furthermore, these curves are easily reproducible.

If the comparatively small sound pressures at high frequencies vary in their production or measurement by even 10%, the appearance of the resonance curve is changed very slightly, but the difference is readily audible. This surprisingly strong subjective effect arises from the fact that these variations usually concern at least several (with low-frequency sounds, *many*) partials in the high-frequency region, where the ear is very sensitive.

Examples of response curves we obtained[1] for each string are represented in Fig. 1, where the frequency is plotted on a logarithmic scale horizontally and the sound pressure measured at a distance of about one meter is plotted vertically on a linear scale. These curves have been obtained from the best Stradivari which I ever had the opportunity to test. This was the concert instrument of Joseph Joachim and Karl Klingler, a violin of fascinating, fine tone quality. Such a group of curves exhibits all the sound spectra generally possible under the conditions of bowing used. In regard to the superb violin timbre the following peculiarities are significant.[2]

TIMBRE

(1) Large amplitudes at low frequencies in the response curve mean large amplitudes for the low harmonics of the sounds. Subjectively, this means that the sounds are agreeably sonorous and that they "carry" well.

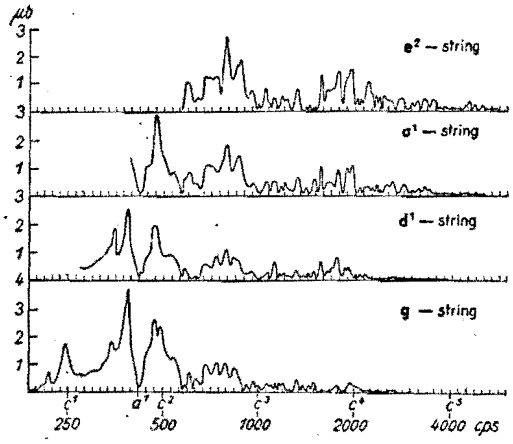

Fig. 1. Response curves of Joachim-Klingler Strad (1715), a violin of fascinating, fine tone quality.

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* Presented at the Second International Congress on Acoustics, held in conjunction with the Fifty-First Meeting of the Acoustical Society of America, Cambridge, Massachusetts, June 17–23, 1956.

[1] H. Meinel, Akust. Z. 2, 22–33 (1937); 2, 62–71 (1937); 5, 283–300 (1940).

[2] H. Meinel, Akust. Z. 4, 89–112 (1939).

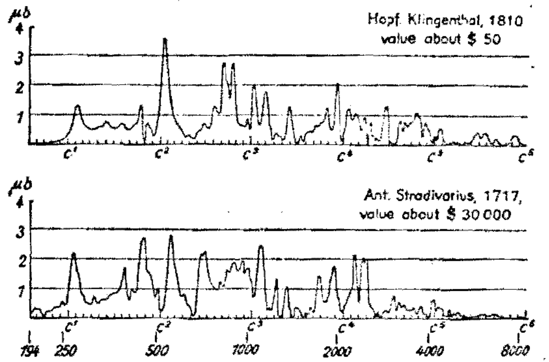

FIG. 2. Response curves of a Strad (a violin of very good tone quality) and a Hopf, Klingenthal (a violin of mediocre tone quality).

(2) Small amplitudes at high frequencies (above about 3000 cps) give the sound a harmonious softness and a fine, pure response; see also the results of F. A. Saunders[3] and G. Pasqualini.[4]

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(3) Small amplitudes near 1500 cps prevent a very nasal character.[2] Such a condition is likewise very favorable to the tone quality of other instruments.[5,6]

(4) If the region from 2000 up to 3000 cps is stressed the sound acquires a very agreeable, pithy, and dull brightness. Less good violins do not exhibit these signs of quality to the same degree as shown in Fig. 1.

For the present we are working mostly with simpler curves obtained in a manner which is detailed in the literature,[7] such as those shown in Fig. 2 for Stradivari and Hopf. Again we found that the Stradivari exhibits smaller amplitudes at high frequencies and larger amplitudes at low frequencies. There is an impressive minimum near 1500 cps and then a rise in the region from 2000 cps to about 3000 cps. Therefore, these curves also demonstrate the most essential characteristics of a violin of good tone quality.

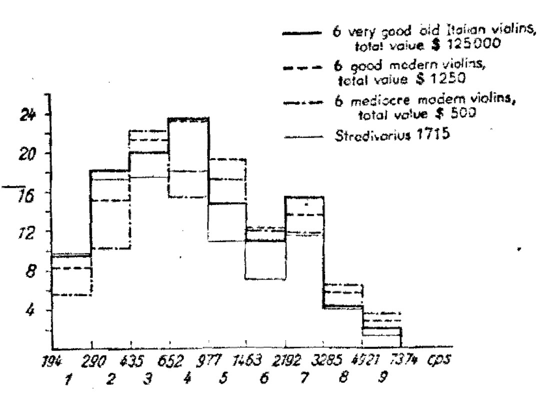

FIG. 3. Average response curves of groups of violins of different tone quality.

We have still further simplified by forming avera values over intervals of a fifth, for groups of violins equal worth: that is to say, a group of distinguished ol Italian violins, a group of good modern violins, an finally a group of mediocre present-day ones. As Fig. shows, again the best violins have the smallest amplitudes at high frequencies, the largest amplitudes at lo frequencies, small amplitudes in the vicinity of abo 1500 cps, and a stress of the frequency range fro about 2000 up to about 3000 cps. Thus the group also exhibit the differences which have been stated f single violins. That is why we consider them as typica For comparison, the curve of the Joachim-Klingle Stradivari has also been drawn in.

Curves for some bad violins[8] are shown in Fig. 4 i comparison with the average curve of the best ol Italian master-violins. Here we see that bad violin exhibit large deviations from the mean curve of ol Italian violins. Therefore, we consider the mean curv to be the ideal one for violins; we concede, of course that the individually different, artistic taste allows deviations. From the physical point of view, however these deviations are relatively small, especially at hig frequencies; see also Fig. 3.

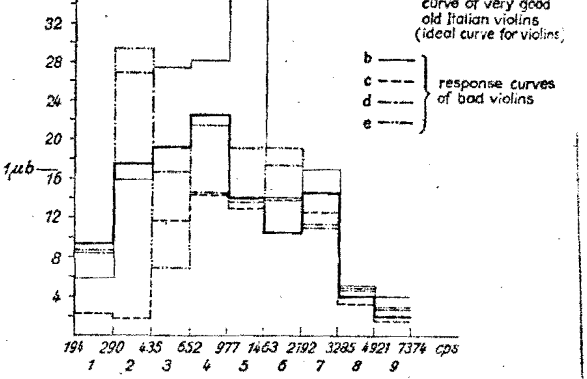

FIG. 4. Response curves of bad violins in comparison with th average response curve of very good old Italian violins.

The differences mentioned above refer to beauty o sound, response, carrying power, and quantity o sound which are important properties. If we want t obtain a still more comprehensive picture of a violin's tonal qualities, it is necessary—in addition to the response curves shown in Fig. 1—to record for eac string, to make measurements of the dynamic range (the difference between largest and smallest amplitudes and of the efficiency.[9] In performing all these tasks several standard violins, some of which have been in my personal possession for more than 20 years, have been faithful helpers. All of them represent instruments physically tested and artistically judged.

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[3] F. A. Saunders, J. Franklin Inst. 229, 1–20 (1940).

[4] G. Pasqualini, Ist. naz. elettroacust. O. M. Corbino (I.N.E.A.C.) 20, 1–48 (1939); 44, 1–19 (1943).

[5] E. Thienhaus, Akust. Z. 6, 34–45 (1941).

[6] W. Lottermoser, Physik. Bl. 4, 103–109 (1948).

[7] H. Meinel, Akust. Z. 2, 22–33 (1937).

[8] See particulars in Akust. Z. 5, 124–129 (1940).

[9] F. A. Saunders, J. Acoust. Soc. Am. 9, 96 (1937).

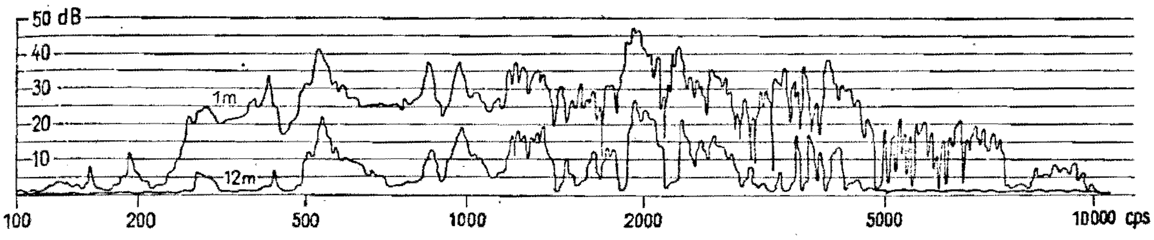

FIG. 5. Violin response curves at distances of 1 and 12 meters. Note that the difference is very near to 21.5 db as required by the inverse-distance law.

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Law of Radiation

The response curves shown in Figs. 1–4 were recorded at a distance of about one meter. We now consider the question whether at a larger distance there are any other changes aside from the effect of sound divergence. In winter, when there was deep snow, the surface of which was very loose, we excited violins electrically to radiate from an open window into the outside without any reflection. The recording microphone was taken as far as 12 meters distance into the open air, without damaging the surface of the snow. At different distances we recorded response curves. These demonstrate that in the absence of reflection the sound pressure varies inversely as the distance and that this relationship is practically independent of frequency. See for instance Fig. 5 which shows the curves obtained at distances of 1 and 12 meters, for which the theoretical difference is 21.5 db. On the whole the evidence indicates that the sound is finally spreading spherically, in spite of the selective radiation at high frequencies.[7] There results no evidence for a preferred radiation at special nodal lines.

If one performs such tests in an unsuitable room or commits any other mistake (such as measurement very near to the violin, 50 cm or less) the $1/r$-law is apparently not satisfied (see Fig. 6). In such a case there is a larger frequency dependence for the decrease of amplitudes and a considerable influence of the various nodal lines of the violin body on the spreading of sound. Also we see that within a distance as small as 12 meters (Fig. 5) the high-frequency sound of a violin is no longer significant. Should the curves not be recorded in the open air, but in a crowded concert hall, the high frequency amplitudes would be even more suppressed due to their stronger absorption.[10]

According to experience, the piercing sound of a violin being played in a concert hall dies away within a short distance. This observation agrees with our measurements, according to which a good violin—a violin with good carrying power—has the high point in its sound spectrum at low and medium frequencies. By contrast, the sound of a violin that has large amplitudes at high frequencies is markedly reduced by the absorption in the concert hall. The effect is even more noticeable subjectively, because the ear is particularly sensitive to sound in frequency region concerned. Such violins do not possess good carrying power.

CARRYING POWER

Many a violinist, playing in an orchestra, wants to hear distinctly the sound of his own violin and eventually to take the lead with his instrument, too. He is therefore fond of a somewhat more penetrating sound. That may be warranted, however, without having anything to do with the longing for fine tone quality. On such concertmaster violins really small amplitudes at high frequencies are not to be found. For this reason I always entrust—if possible—a group of experts with the selection of high-quality violins before testing the instruments. Thus I obtain reasonably clear results.

Transient Response

In order to clarify questions relative to response I but recently showed a prominent concertmaster a very good present-day violin with small amplitudes in high frequencies, in accordance with observations noted above. He felt obliged to say that this violin sounds beautifully and responds more easily than his own, somewhat piercingly sounding Italian violin. Perhaps one may explain this result on the basis of Raman's[11] well-proved theory that the force, required for obtaining the partial vibration of a string, is inversely proportional to the ordinal number. Applied to the transient response, it means that in setting the bow upon the string just at the beginning of the bow pressure, it is the high partial vibrations of the string and thus the high harmonics of the resulting airborne sound that are being produced first, and the lower ones later. If

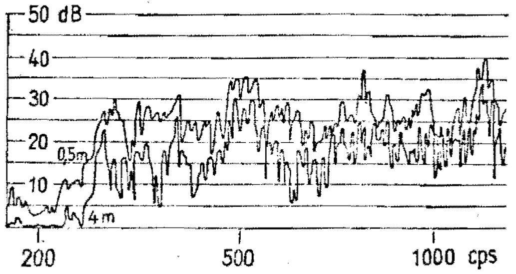

FIG. 6. Violin response curves at distances of 0.5 meter (too near the violin) and 4 meters. The curves differ by much less than the 18 db that would be required by the inverse-distance law.

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[10] H. O. Kneser, Akust. Z. 5, 256–257 (1940).

[11] C. V. Raman, Indian Assoc. Sci. Bull. 15, 62 (1918).

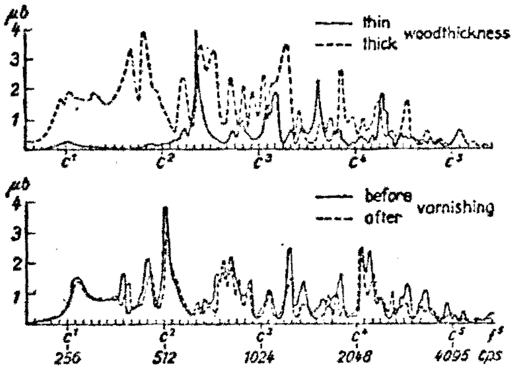

FIG. 7. The influence of wood-thickness is relatively great; the influence of varnish is comparatively small.

ATTACK

the high harmonics have small amplitudes, they are scarcely audible in the transient. The sound that appears without this preliminary high-frequency noise articulates better. This difference of response between violins possessing strong and weak high-frequency amplitudes is audible, especially distinctly by the player himself.

On this occasion we may further refer to the work of J.-G. Helmbold,[12] who in another direction reveals distinctly the relations between the response curve and the nature of transients. Inasmuch as the damping of a violin with its influence on the duration of the transients expresses itself in the resonance curves, one may say that the kind of transients is also contained in the response curve recorded from the stationary sound. Thus if one duplicates the response curve of distinguished violins he likewise duplicates the transient response.

B. THE RESPONSE CURVE AS A TECHNICAL TOOL

We now consider how the response curve can help practical violin making. The influence of wood-thickness changes[7] is relatively great (see Fig. 7). Though not to be disregarded, the influence of varnish is comparatively small. Further influences of the construction have likewise been tested.[7,13,14] Now all these features which change the response curves need to be investigated exactly, in order to make it possible to construct violins exhibiting the desired characteristics.

Kind of Wood

For the most comprehensive researches in respect to the important influence of wood on the damping of violins we are indebted to E. Rohloff.[15] According to his findings, the logarithmic decrement for bending vibration—such as in stringed instruments—from 10 up to 10 000 cps is independent of the frequency. However, that did not seem right to us. Pasqua who also carried out comprehensive investigations, no especial interest in violin wood and therefor not study its behavior at high frequencies. E. P found a rise in damping of pine with increa frequency, but according to E. Skudrzyk,[17] he tinguished between tone-pine on the one hand timber-pine on the other, and the age of the w Thus we had to start from the beginning.

Wood such as used in making musical instrumen being tested in this research which is still in progr pine (spruce), maple, pear, cherry, oak, elm, mahoga rosewood, ebony, and other kinds.

Between 100 cps and 5000 cps we study rods, ab 400 mm long, 20 mm wide, and several millimeters th Sticks of half the width yield nearly the same resu so any influence of radiation damping, even in h frequencies, could not be stated from our investigation The test method which—as far as we know—has n yet been employed previously, is to fix the rod at end and to excite electrically the free end at vari frequencies. Hanging up the rods at two vibration n did not prove to be satisfactory, particularly at hi frequencies. The damping is determined by means the resonance curves, recorded capacitively. Figure shows some results.

The damping of the various kinds of wood used f making musical instruments is different: maple, o elm, rosewood, mahogany, and other sorts show smaller increase of the damping with the frequen than does the typical violin-resonance wood, pi We find that from 100 cps up to 5000 cps the dampi of pine is doubled, a change almost twice as great as f the other kinds of wood. The significance of the results must be judged according to the acousti demands on the various instruments. As to violins, t requirements are: small sound amplitudes at hi frequencies, large amplitudes at low frequencies. Owi to its greater damping at high frequency, pine distinct complies with the requirements better than do oth kinds of wood. It seems this peculiar damping proper is an acoustical reason for making the important bel of stringed instruments of pine.

By means of this method one can also demonstra differences of damping in pine samples which on differ as to their position inside of a piece of tone-woo Sapwood is better than the heartwood, because it h a distinctly stronger damping at high frequencies. Th is a significant result; and there the far-reachin empirical experience of the violin maker is obvious. T bellies of the stringed and fretted instruments ar joined in such a way that the sapwood is placed at th center and heartwood at the edge.

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[12] J.-G. Helmbold, Akust. Z. 2, 256-261 (1937).

[13] G. Pasqualini, Ist. naz. elettroacust. O. M. Corbino 22, 622-639 (1940).

[14] F. A. Saunders, J. Acoust. Soc. Am. 25, 491-498 (1953).

[15] E. Rohloff, Z. Physik 117, 64-66 (1940); see also, F. Krüger and E. Rohloff, Z. Physik 110, 58-68 (1938); and E. Rohloff and W. Lawrynowicz, Z. tech. Phys. 5, 110-111 (1941).

[16] J. Barducci and G. Pasqualini, Ist. naz. elettroacust. O. Corbino 87, 1-32 (1948).

[17] E. Şkudrzyk, Acustica 4, 249-253 (1954).

† It seems, however, that the latest still running investigatio made by vacuum show an influence of radiation damping wit the highest frequencies here investigated.

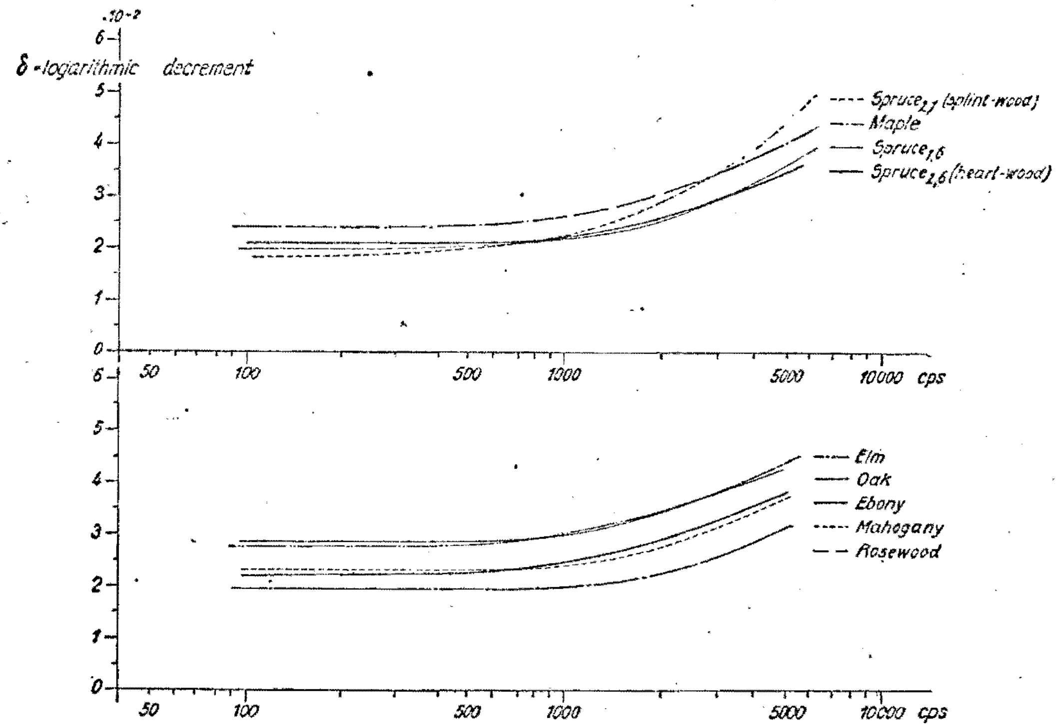

Fig. 8. Loga-nic decrement of ent kinds of . According to ent measure-ts, the damping pine (spruce) its a greater in-e with the fre-y than does the ping of other s of wood.

The experiments show, incidentally, that rosewood small damping at both low and high frequencies, that it is particularly suitable for fretted instru-nts that do not produce very much sound. This ult of measurement is likewise in accord with many ades of empirical experience.

Influence of Varnish

The same method of measuring damping, by means vibrating wooden rods, is also used for our (still running) varnish inquiries. From Fig. 9 in comparison with Fig. 8 we see that the varnishing increases the damping. Furthermore, we see that a hard varnish increases the damping at high frequencies less than does a soft varnish.[18]

These measurements of the influence on damping of wood and varnish confirm acoustical results[7,2] formerly obtained by recording in quite another way the response curves of violins. Thus a procedure lies before us for investigating kind of wood and of varnish

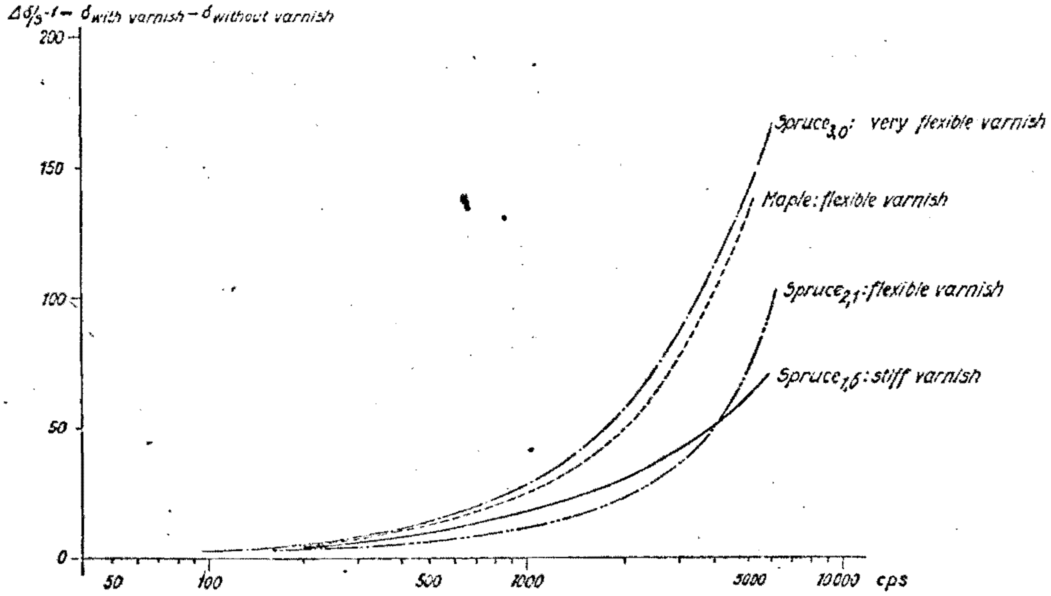

Fig. 9. Change the logarithmic ment by var-. A hard varnish ases the damp-t high frequen- less than does a varnish.

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[18] This varnish was produced by Dr. Ing. Karl Letters, Köln-Lindenthal, Sielsdorfer Str. 9. During the investigations the soft nishes were not quite dry.

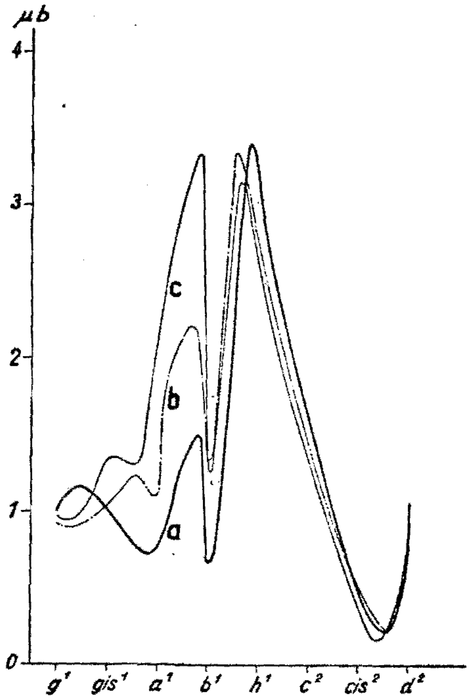

FIG. 10. Influence on the response curve of certain changes in the wood thickness at the left middle bow of the back. Condition *c* for most wood removed.

with reference to its acoustical adaptability to violin making.

Influence of Wood Thickness

In connection with wood thickness, I want to point out particularly a result of F. A. Saunders.[14] He discovered that the loudness can be distinctly increased by diminishing the scoop at the corners. This disclosure appears to me to be of great importance. By means of just such discrete changes in wood thickness, restricted to certain parts of the violin body, we are able to copy small significant properties. Having already formerly started experiments[19] of this kind, we are now continuing them again. Thus, for instance, a resonance range near 500 cps (just above a^2), being originally too weak, is reinforced by gradually removing wood from the left middle bow of the back. (See Fig. 10; the wood was thickest for condition *a*, thinnest for condition *c*.) The same effect can also be obtained by diminishing the wood thickness at certain other parts of the violin body. Probably the effect is influenced by the position of the nodal lines. The effect does not always occur; obviously it depends on the physical state of the violin at hand. Unduly thinning the wood spoils the result. An aftereffect seems to exist: there may be c change in an acoustical effect for several days a change of wood thickness. This may be cau adjustments in the internal stress set up by rem the wood, which take place after a few days. Som the desired effect is really obtained, but unwish effects appear at the same time in other freq ranges. Everyone who surveys the importance of few statements will, I think, understand that now facing the real problem of making a violin has the desired acoustical effects. We likewise rec the extent and difficulty of the work still before

C. STATUS OF SCIENTIFIC VIOLIN MAKING

Even before we succeed in mastering the resp curves completely, partial results may be obta that enable us to recognize whether or not the taken will be the right one. Figure 11 shows the c

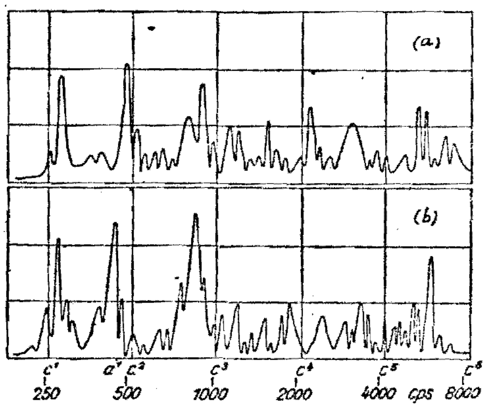

FIG. 11. Response curves of a Strad (above, a) and a mo violin (H. Meinel, below, b) measured by Dr. Karl Ste Tübingen, 1950. The approach of the modern violin to Italian model is good, but the result is not yet entirely satisfy

of a Stradivari and that of a violin made about 1 according to the scientific-technical experience of t time. These curves were recorded by K. Steiner at University of Tübingen, Württemberg. The violin question is not a consciously intended imitation the Stradivari, but the striking similarity of the thr most important maxima and of the mean amplitudes high frequencies show that one can arrive at a usef approach to Italian models by use of general princip now available. Although we are standing at th beginning, in view of what is still to be done, there is n doubt that research on violins will solve the mos important problems in a measurable time.

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[19] H. Meinel, Elek. Nachr. Tech. 14, 119–134 (1937).

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Subharmonics and Plate Tap Tones in Violin Acoustics

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From the study of subharmonic series found in the violin and related instruments, it is evident that the quality and loudness of the instruments depend on the pitch and variety of the subharmonic series, and on the characteristics of the wood and the fashioning of the top and back plates. Details are given on the nature of subharmonic series and their presence as observed in several methods of testing. The single air tone, heretofore reported, is shown by more detailed tests to consist frequently of two or more closely related peaks. Observations made in a series of experiments carried on during the construction of 35 violins, violas, and cellos indicate a method of controlling tone quality and volume of the completed instrument by means of the tap tones and the acoustic properties of the free plates. Experimental equipment which makes these findings possible is described in detail. With this concept of subharmonic series and the techniques described, a large field for experimental evaluation of string instruments may well be opened up.

INTRODUCTION

MODERN equipment and methods have made possible scientific investigations into the acoustics of the violin and related instruments whose tonal qualities formerly depended largely on the skill of the violin maker and the ear of the musician. However, knowledge is still not adequate to the problem of creating violins, violas, and cellos consistently equal to the best of the instruments made 300 years ago by such masters as Stradivarius and Guarnerius. The work here reported offers several ways of bringing scientific techniques to bear on the art of violin making.

Recent experimental methods for testing violin tone are described briefly, giving the special usefulness of each. Subharmonic series are found in violin tones, by use of several of these methods. More refined measurements indicate the existence of complex air tones instead of the single peak previously observed. Details in construction of new testing equipment are given, with a method for making permanent records of the vibrations of an instrument or of its plates separately. These records are used in an investigation of the principal vibrations of the unattached top and back plates of violins, violas, and cellos. The findings have been obtained during the construction and evaluation of 35 instruments which have been judged by professional musicians to be of exceptionally good quality.

This paper is divided into four sections: I. Experimental Methods, II. Subharmonic Series and Air Tones, III. Description of New Testing Equipment, IV. Plate Tap Tones and their Application to the Tone Quality of a Finished Instrument.

I. EXPERIMENTAL METHODS

Methods of attack on the problem of violin acoustics are reported previously in this Journal.[1–4] The first method used a harmonic analyser developed by H. H. Hall[5] which produced complete harmonic analyses of each note in the range of the violin (for brevity the term violin will be used in this article to represent a violin, viola, or cello) played with a bow in the usual manner and at semitone intervals over the whole range of the instrument. Over sixty instruments were thus treated. This work produced a great mass of numerical data from which response-frequency curves were derived. These earlier data have proved to be a satisfactory field in which to search for subharmonic series, described in Sec. II.

The second method[1] yields what were first called curves of total intensity, but are now usually referred to as "loudness curves." The violin is bowed normally at semitone intervals to produce the loudest tone at each note in its range. The sound level is measured in decibels with the *C*-weighting on a General Radio Sound Meter. The name "loudness curve" is used since sound level is unfamiliar to many readers, the range of level is not wide, the measurements all relative, and exact values not needed. "Loudness curves" show at each measured frequency the combined strengths of all the harmonics. The fundamental tone (the first of the harmonic series) is not always the loudest. At some frequencies there may be a peak of "loudness" even though the fundamental is weak. Such peaks are absent from response curves, which deal only with the strengths of the fundamentals. They were called "overtone peaks" at first, but are now listed as members of subharmonic series.

In the third method,[3] the violin was driven electromagnetically from a source producing simple tones which were variable in frequency. The receiving micro-

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[1] F. A. Saunders, J. Acoust. Soc. Am. 9, 81–98 (1937).

[2] R. B. Watson, W. J. Cunningham, and F. A. Saunders, J. Acoust. Soc. Am. 12, 399–402 (1941).

[3] F. A. Saunders, J. Acoust. Soc. Am. 17, 169–186 (1946).

[4] F. A. Saunders, J. Acoust. Soc. Am. 25, 491–498 (1953).

[5] H. H. Hall, J. Acoust. Soc. Am. 7, 102–110 (1935).

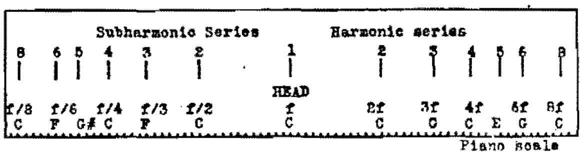

FIG. 1. Relation of the harmonic and subharmonic series.

phone controlled a device which made a pen-and-ink record showing relative strengths on a scale of logarithmic pressure versus frequency. This record was continuous from 60 to 10 000 cps, and no details could be missed since there were no semitone gaps as in the first two methods.

The present work uses a better form of electromagnetic "driver," described in Sec. III, and an oscilloscope. The microphone which picks up the sound from the violin is connected to the "vertical" terminal of the oscilloscope, and the amplitude of travel of the oscilloscope spot (with no sweep) can be measured; or the waveform (with sweep) observed. The frequency is read from the dial of the audiogenerator. This is a simple and versatile method of measuring the sound spectrum of a violin. We call it the "oscilloscope method." If the vertical amplitude of the spot is continually photographed on a moving film as the frequency rises, we call it the "Hopping method." Such photostrips are permanent records and make possible a great many new experiments.

Performance tests of each instrument are compared with the results of the more objective test methods. An instrument is played by high-ranking professional and amateur musicians under various conditions, such as the large symphony orchestra, the solo performance, and the intimate chamber music group. These musician comments have agreed remarkably well with the results of the other test methods.

Of these methods, the harmonic analysis one is the most complicated, but the best for studies of tone quality. The "loudness curve" method is good for locating the main resonances and for evaluating the comparative "loudness" of an instrument. But it shares with the first the defect of not giving a continuous curve, thus failing to indicate what happens between the frequencies that define each semitone. The oscilloscope method is the simplest and quickest in producing a complete sound spectrum and in measuring the changes in frequency and amplitude which are produced by alterations in external conditions. The Hopping method has the very great advantage of yielding a permanent record of the important frequencies of the violin body and of the included air, as well as the tap tones of the detached plates.

II. SUBHARMONIC SERIES AND AIR TONES

Harmonic series are familiar; the difference between them and subharmonic series, and the usefulness of the latter, are best illustrated by an example.

A pianist may sound a note of frequency f, for example middle C at 262 cps (Fig. 1). He thus creates a complex tone which consists of an ordinary *harmonic* series with frequencies given by nf, n being an integer. In the figure, the "head" of this series is the central C, and the horizontal scale is that of the piano. The head is the fundamental or the first member of the harmonic series. The *subharmonic* series is defined as one whose frequencies are given by f/n, running the "wrong" way, down from the head into the deep bass. It not only has the same head as the harmonic series but also the same intervals or frequency ratios. An octave below the head is C 131 whose second harmonic is C 262; the third member has the frequency 262/3, and its third harmonic is C 262; and so forth. The existence of a very nearly harmonic series in piano tones can easily be shown by giving the key of frequency f a strong but brief blow while the strings corresponding to the frequencies nf are kept open. The open strings respond at once by the action of resonance and several of the series tones are heard if the tuning is correct. If this is repeated, except that the keys corresponding to f/n are kept open, we hear nothing but C 262. All the subharmonic series members have that frequency as a harmonic, and no lower tones can be produced. A *subharmonic* series cannot be sounded as a whole without playing each one of the f/n keys.

It is well known that if one harmonic of a complex tone can be strengthened, the ear will hear this as an increase in loudness of the whole tone, with a slight change in quality, but no change in pitch.[6] This benefits the lower tones of the violin, which are often weak; and they owe this gain to the existence of many subharmonic series in each instrument. The wooden body of the violin, like many other pieces of wood, has its favorite tones which are heard when the body is tapped. These tones are called "natural vibrations," or body tones. They show prominently on "loudness curves." Among the other peaks on these curves there is one which is caused by the main vibrations of the inner air, and we call this the air tone. Between peaks the violin has to be forced to vibrate and so produces a weaker sound.

TABLE I. Analyses of tones from a Gaspar da Salo viola.

Note	Sub-harmonic series	cps	Strengths of harmonics of each series member measured in decibels. Harmonic numbers 1	2	3	4	5	6	7	8	9	10	11
F ♯	1($f/1$)	1480	*60*	48	44	34	28	20	3				
F ♯	2($f/2$)	740	58	*50*	55	42	50	39	25	33	15	21	21
B	3($f/3$)	493	47	49	*52*	46	42	40	40	30	37	26	17
F ♯	4($f/4$)	370	55	45	40	*51*	38	43	32	27	28	17	20
D	5($f/5$)	296	52	40	40	51	*47*	38	48	46	38	30	29
B	6($f/6$)	246	56	43	39	49	32	*48*	36	30	29	34	36
A −	7($f/7$)	211	48	55	46	45	41	34	*35*	26	31	42	37
F ♯	8($f/8$)	185	36	52	33	37	45	39	34	*41*	30	31	38
E	9($f/9$)	164	30	50	42	39	34	44	39	36	*40*	36	40
D	10($f/10$)	148	29	50	51	36	43	50	38	40	28	*39*	32
G+	11($f/11$)	135	26	48	44	35	38	39	45	40	30	29	*40*

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[6] H. Fletcher and W. Munson, J. Acoust. Soc. Am. 5, 82–108 (1933).

Each natural vibration is the head of a subharmonic series.

An example of harmonic analyses and the subharmonics found in them was given in the paper "Two Famous Violins" published[7] in 1957. The violins were those used by J. Heifetz, a Guarnerius, and a Stradivarius. Similar data are presented here taken from the analyses of an excellent viola made by Gaspar da Salo before 1600, and now owned by Miss Eunice Wheeler of Worcester, Massachusetts. Each note was played by bowing in the usual manner.

These data are shown in Table I. The first columns show the notes' names and numbers of eleven series members, headed by *F#* 1480 cps, which form the subharmonic series. Their frequencies in the third column are derived by dividing 1480 by the number of each member, a process which yields approximate values, close to those in the scale of equal temperament, except for number 7 which is always "off scale." On the right opposite to each series member, its harmonic analysis is spread out, with the relative strength of each harmonic indicated in decibels. The numbers of the harmonics are given, and below each number the strength of this harmonic for each of the tones. The numbers along a diagonal line are italicized; these are the harmonics of each subharmonic member having the frequency of the head, *F#* 1480 cps. Certain subharmonics in this table show unexpected strength in a few of their harmonics without apparent regularity. Each of these stronger harmonics is itself linked to another subharmonic series. For instance, the second harmonic of *D* 148 is linked with the first of *D* 296 which is the head of the series *D* 296, *D* 148, *G* 99, *D* 79, etc. This can be followed even farther down scale by the oscilloscope method. Numbers 3, 5, 6, and 8 are all members of other subharmonic series with strong heads, and they all contribute importantly to the loudness and quality of *D* 148.

Since each series head contributes to the quality and loudness of a number of tones below it in the scale, it is evident that several heads favorably placed can strengthen many notes in the lower part of the scale. One can understand, then, how the violin tone and individual character depends on the frequency location and variety of the "loudness" peaks, and on the characteristics of the wood and the fashioning of the top and back plates. This conception has guided the investigation of the tap tones and acoustic properties of the plates in relation to those of the assembled instrument, reported in Sec. IV of this paper.

There is no lack of peaks to serve as heads of subharmonic series. Thirty-four were counted in the sound spectrum of this Gaspar da Salo viola, and forty in the Heifetz Guarnerius. A now famous viola made by Moennig in Philadelphia was found to have forty-two heads of series. This quality is not related to the age of an instrument. It may be caused not only by the way the wood of the violin is shaped and balanced, but by low internal friction in the wood itself. The less the friction, the more readily will sound waves travel through the wood, and the greater will be the effect of resonance between the head and a harmonic of a lower tone, on which the occurrence of subharmonic series depends.

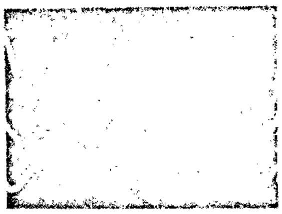

FIG. 2. Waveforms in subharmonic series.

The most direct method for the study of subharmonic series is by "loudness curves" where they were first recognized. However, it is much easier to follow them into the low frequencies by the oscilloscope method. If the receiving microphone is placed in front of an *f*-hole, the air tone subharmonic series is emphasized and can be followed to very low frequencies. The members of subharmonic series have characteristic waveforms, and one can identify $f/2$ or $f/3$, for instance, at sight. Figure 2 shows a combination of three waveforms photographed in succession and then placed one over another. The top record is that of the head, which is a nearly pure sine curve. The one below is $f/2$, and shows two waves of the head to one of the octave below. The bottom waveform is that of $f/3$. The wave of the head persists in all because it is a strong harmonic of each of the lower members of the series. The patterns for $f/4$ and those beyond are more complicated, but they have been recognized to $f/6$.

It sometimes happens that the subharmonic series crowd one another at the lowest frequencies, but they can be sorted out by the waveforms, combined with the frequencies which are known in advance if the head is measured. If the audiogenerator is of the resistance-capacity type, the errors of frequency readings are often below 1%, and there are good ways of checking them. The useful range of frequency is from 40 to 1000 cps for most work on these series.

Doubts as to whether a vibration is produced by the body of the violin or the air inside can be resolved in various ways. The bridge of the violin can be loaded with a heavy mute; then the body peaks move to lower frequencies while the air tone remains fixed. The mass of air inside the violin can be replaced by carbon dioxide in which sound travels more slowly; the air tone then moves down the scale by two or three semitones, while the body vibrations are unaffected. A much simpler procedure is open to the operator with a good ear; he can hear the air tone as a more nearly pure tone, i.e., one having fewer harmonics. There is also a method in which a single barb of white fluffy feather (called a "wisp" for short) is anchored to the end of a stiff wire

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[7] F. A. Saunders, The Strad (London) 68, 54–58, 102–108 (June, July 1957).

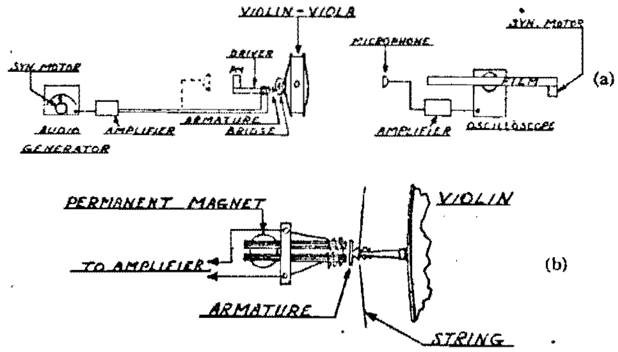

FIG. 3. Diagram (a) showing placement of equipment for testing a violin in playing condition. Microphone is placed at dotted position to pick up the response from string side of the instrument. Diagram (b) gives details of the driver from above.

by a bit of wax. The wire is supported by a stand which also holds a microscope of about 40 power. The wisp, set in the focus of the microscope and strongly illuminated, is then placed in the middle of an *f*-hole, the violin being vertical. The top of the wisp moves in and out when the inner air vibrates. It moves very little for any body vibration, but becomes quite active at an air tone. With this device we have recently found that the air tone is often double or more complex. The components are not far separated, and we shall continue to refer to the group as the air tone. Multiple air tones are desirable since thay spread their beneficial action over a wide range and thus prevent too strong a concentration of "loudness" at one frequency.

Air f-holes

To explain this odd effect, the air in a violin may be regarded as being in two unequal chambers with a connecting passage in which the *f*-holes lie. The two *f*-holes can be expected to act as one, so long as their separation is small compared with the wavelength of the air tone (four feet). The oscillations of this odd-shaped mass of air are analogous to those of two direct inductively-coupled circuits, and this is a problem that has been solved mathematically. The answer indicates that two resonance frequencies[8] should be found, probably of unequal output. Evidently, if the analogy is good, the action of the air in a violin is not so simple as it is in a bottle. Earlier observations rarely detected paired or multiple air tones, and those were not fully understood at first. Although they are now found to occur often, further observations are needed before they can be called usual.

Air Resonances

III. DESCRIPTION OF NEW TESTING EQUIPMENT

The prime requisite for activating electrically a wooden plate or instrument such as the violin and determining its response at each frequency in the audible spectrum is a vibrator or "driver" which has no measurable inherent resonances in the working range. Many commercial devices of this nature were tested and found to have objectionable inherent resonances due largely to the necessity for leverages, return springs, and suspensions in their design which distorted the test results of the violin or parts thereof so badly that their responses could not be determined accurately. Negative feedback was used for a time to smooth out some of these inherent resonances, but this brought added complications in equipment and power requirements, reducing the over-all reliability.

The driver described here is designed to eliminate these difficulties. It consists of a two-pole permanent magnet attached by magnetic attraction to a pair of laminated rods made of transformer steel. Each of these laminates has a winding so that the permanent magnetic field can be modified at any desired frequency by an alternating current, such as that from an audiogenerator. An armature, consisting of a small piece of transformer steel is glued to the wood plate or clipped to the bridge of the violin. An air gap between the magnet and armature, kept as constant as possible, is necessary to insulate the wood under test from extra resonances caused by any physical coupling with the vibrator. The violin must also be insulated from vibrations carried by the supporting equipment.

Photostrips were made to compare this permanent magnet type of driver with a moving coil type. They showed no considerable defects in the magnetic type, which is preferable because of the ease with which it can be used. Figure 3 shows the setup for testing a violin in playing condition. Oscillations from an audiogenerator whose dial is driven slowly by a synchronous motor are amplified and carried to the driver. To this point the oscillations are electrical. The air gap between magnet and armature is kept as nearly as possible at 0.5 mm. A mechanical oscillation is produced in the violin through the interaction between the magnet and armature. At a distance of 45 cm, a microphone picks up the sound emission of the violin or the wood panel at each frequency throughout the testing range. This is then amplified and transmitted to an oscilloscope where its vertical amplitude is recorded on a moving film strip, the speed of which is synchronized by a second motor with the scanning rate of the audiogenerator. The record of the oscilloscope pattern, thus made, is called a photostrip in this article. Temperature and humidity are recorded during each test period. Since the violin is made of several different kinds of wood that absorb moisture in varying amounts, it is more sensitive even than electronic equipment to changes in these two factors.

From the 60-cps line voltage the frequencies of 60, 120, 180, 240, 300, 360, 480 cps are determined by Lissajous figures and marked on the audiogenerator scale before each test. These calibrated frequencies are recorded on the photostrip during each test by a transient mechanically-produced sound of sufficient magnitude to cause the beam from the oscilloscope to traverse the full width of the film. The mechanical sound was chosen in preference to an electrical signal because the

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[8] The generous help of Professor F. V. Hunt of Harvard University is gratefully acknowledged in this matter.

latter produced unwanted distortions of the oscilloscope pattern. From the possible frequency range of 20 to 20 000 cps these frequencies have been selected and marked on the photostrip where the response peaks most useful in this work occur.

These photostrips give a permanent record of the response of the wood under test from which the frequency of a given peak below 600 cps can be determined quite accurately. Several of these photostrips are shown in Sec. IV.

IV. PLATE TAP TONES AND THEIR APPLICATION TO THE TONE QUALITY OF A FINISHED INSTRUMENT

For several hundred years the question that has been asked many times and answered in a variety of different ways is: What sounds should the top and back of an instrument give before they are joined? The violin maker usually holds the free plate, top or back, at thumb and forefinger distance from one end near the midline, and taps the wood with his knuckle at various points, listening carefully for the tone or tones of the wood plate. The clearest tones can usually be heard when the plate is tapped near its center.

Savart,[9] writing in 1840, reported,"a top of spruce and a back of maple tuned alike produced an instrument with a bad weak tone." He tested the plates of a number of violins made by famous Italian makers and found that the sound varied "between $C\#3$ and $D3$ for the top, and $D3$ and $D\#3$ for the back, always one tone or one semitone difference, the back being higher than the top." Heron-Allen[10] in 1885 said, "Nearly every author who has written on the subject has declared that the back should be a tone lower than the belly. It is useless to persuade them that exactly the reverse is the case, as many of them probably never made a fiddle." Recently, one of the world's best living violin makers reported that Stradivarius tuned his plates to the same frequency, thus disagreeing with the previous statements. In view of these conflicting ideas, the need for further experiments of increased accuracy is obvious.

TABLE II. Ways of holding plate for vibration tests.

A. Plate vertical, clamped at H_1 or H_2.
  - H_1—on the midline 1/5 of total length of plate from upper end
  - H_2—at the same distance from the lower or saddle end

B. Plate horizontal, resting on two small pieces of sponge rubber without being clamped.
  - H_1 and H_2
  - H_1 and H_3 (at the lower or saddle end on the midline)

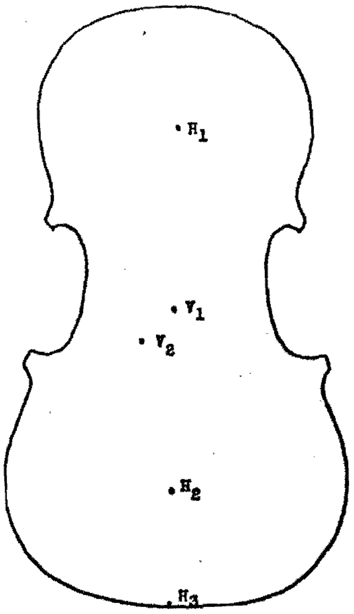

FIG. 4. Violin plate showing holding and tapping points.

Before one taps a violin plate, it is necessary to settle where the plate is to be held and where tapped. Savart[9] described the thumb and forefinger holding of the violin makers as the "point where two nodal lines cross, one transverse, the other longitudinal, corresponding to the two directions of elasticity of spruce or maple." The holding point of several violin makers was checked by direct observation and found to be about $\frac{1}{5}$ of the length from the end and usually along the midline. The clearest tones can be heard when the plate is tapped near the center. However, tones of different frequencies can be heard more or less clearly when, for example, the edge is tapped at different points. This is particularly true of the top plate when complete with *f*-holes and bass bar.

In order to set up constant holding and tapping points for the electrical testing of the plates which would be comparable to the violin maker's rule of thumb, a series of tests was made by use of a flat plate of selected spruce properly graduated as a viola top with *C*-holes and a bass bar. This plate had been used as the top of a completed viola to demonstrate to an audience the wave patterns throughout the range of the instrument.

The spruce plate was held in four different ways, as shown in Table II, and photostrips made of its response to vibration as described in Sec. III. Two vibrating points were used for each position, V_1 at the exact center of the plate, and V_2 where the active foot of the bridge would normally rest on the bass bar.

For violin and viola plates test H_2V_1 was chosen for subsequent tests, because the amplitudes observed for the peaks were greatest throughout the range of frequencies tested. The plate was clamped in a vertical position about $\frac{1}{5}$ of its length from the lower end, and tapped at the center. This approximates closely the holding and tapping points of the violin maker. For cello plates, because of their size, best results were ob-

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[9] F. Savart, "Analyses de Cours Scientifiques. Cours de Physique Experimentale, professe au College de France pendant l'annee scolaire 1838–1839, par M. F. Savart, professeur" (L'Institut, Paris, France, 1840), Vol. 8, p. 69–71.

[10] Heron-Allen, *Violin Making: as it Was and Is.* Being a historical, theoretical, and practical treatise on the science and art of violin-making, for the use of violin makers and players, amateur and professional (Ward Lock and Company, London and Melbourne, 1885), p. 132, footnote reference.

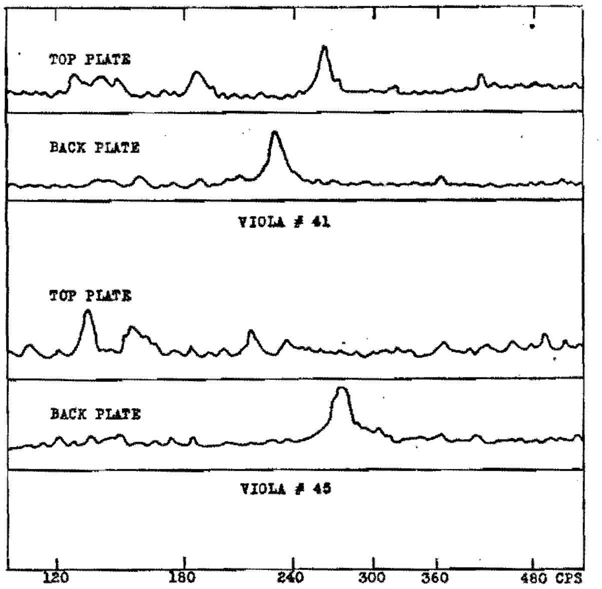

FIG. 5. Tracings of photostrips of the free top and back plates of Viola No. 41 which is preferred for orchestra and solo performance; and Viola No. 45 selected for its "rich low tones and ease of playing."

tained by resting the plate horizontally at H_1 and H_2 and vibrating at point V_1 (Fig. 4).

Relation of Plate Tap Tones to the Tone Quality of a Finished Instrument

Plate tap tones have been obtained for thirty-five instruments, violins, violas, and cellos, during the process of their construction. The thinner a piece of wood, the more flexible it becomes and the lower the frequency it produces when tapped. Thus, by thinning a top or back plate its main frequencies can be moved down scale as desired. Photostrips made of each piece of wood show that the movement to a lower frequency of the peaks in the range 120 to 600 cps can be correlated directly with the removal of wood as each plate is thinned.

In each instrument, in order to trace a connection between the vibrations of the free plates, top and back, and the vibrations of the assembled instrument, one plate was graduated to the desired thickness, while the other, usually the top, was left too thick. Photostrips were made of the response of each plate and the instrument completely assembled. Three evaluation methods, the "loudness curve," the Hopping method, and the performance test were then applied to the instrument in playing condition. In each instrument at this stage the results were unsatisfactory. The instrument was then opened, the thick plate thinned, and another photostrip made of its responses; the instrument reassembled and again subjected to the three evaluation methods. This thinning and testing process was repeated, sometimes three or four times for each instrument. The main vibrations of the free top and back which finally produced the best condition in each of 35 finished instruments have been carefully studied. The photostrips of the free plates were compared with the results of the evaluation of the assembled instruments at each stage.

Early tests on these instruments show that in general the back plate has one predominant peak in the range 120 to 600 cps and perhaps several smaller ones, while the top plate with *f*-holes and bass bar most often shows two main peaks with several smaller ones. However, on the basis of over 400 photostrips of free plates, it is evident that there may be one or more main peaks in the back plate and two or more main peaks in this range in the top plate of a good instrument. This may serve to explain the conflicting statements of the violin makers.

When in the range below 600 cps the frequencies of the main peaks of the *top* plate *alternate* at an interval of a tone or a semitone with those of the *back* plate, the resultant violin, viola, or cello has been judged *good* by our three evaluation methods. The comments of musicians on these instruments have been: "powerful, even quality on the four strings, open-toned, good carrying power, speaks easily pianissimo or fortissimo, pleasing tone quality, etc." The three evaluation methods also show that when the peaks of the top plate come at the *same* frequencies as those of the back plate, or are more than a whole tone apart, the instrument is *poor*. The test instruments assembled with the plates in this condition have been described by the musicians as "harsh, gritty, nasal, uneven, booming in spots, difficult to play, weak, unresponsive, closed-in tone, poor carrying power." (These are not acoustical terms as such, but are given because they reflect expert opinion.)

Tests indicate that the tone quality of a finished instrument may be varied by two ways of alternating the relative position of the peaks between the top and the back plate. The arrangement for a specific instrument depends, not only on the relative thickness and arching of the two plates, but on the acoustical properties of the two pieces of wood selected.

If the main peaks of the top on a photostrip are labelled T^1, T^2, T^3, T^4, etc., and those of the back plate B^1, B^2, B^3, etc., with the progression from high to low frequency being 1 to 4 etc., then the two principal arrangements for the alternation of peaks may be illustrated as follows:

When T^1 is higher in frequency than B^1 and the alternation progresses diagramatically, thus,

$$\begin{array}{ccccccccc} T^4 & & T^3 & & T^2 & & T^1 & & \text{Top plate} \\ & B^3 & & B^2 & & B^1 & & & \text{Back plate.} \end{array}$$

When T^1 is lower in frequency than B^1 and the alternation progresses, thus,

$$\begin{array}{ccccccccc} T^4 & & T^3 & & T^2 & & T^1 & & \text{Top plate} \\ & & & B^3 & & B^2 & & B^1 & \text{Back plate.} \end{array}$$

Figure 5 shows two sets of photostrips which illustrate this point. Viola No. 41, based on the first arrangement of plate peaks, is presently in a large symphony orchestra. Viola No. 45, based on the second arrangement of plate peaks, is played in a first-class amateur chamber music group.

Instruments which have the arrangement of Viola No. 41 show in general an even distribution of "loudness" when evaluated by the "loudness curve" and the Hopping method. Twenty instruments made this way have been selected by professional musicians who prefer the loudness and even distribution of tone that this arrangement of plate peaks produces for us quite consistently.

Instruments which have the arrangement of Viola No. 45 show a shift of tone to lower frequencies when compared to those of the previous type. Some chamber music players prefer these instruments for their "rich low tones and ease of playing." In order to get an instrument in this condition it is necessary sometimes to make a top quite thin; in one or two cases, too thin for durability under years of hard playing. Several instruments which had enough wood in their top plates to allow for thinning have been shifted from the first arrangement of plate peaks to the second. At each stage the three evaluation methods for a finished instrument have reflected the change in tone described in the foregoing.

When the free plates are attached to the rest of the instrument the frequency of the prominant vibrations increases, due to stiffening when the edges of the plates are glued to the ribs. To determine the amount of this increase, the frequencies of one or two main peaks in the free top and back plates, described above as T^1, T^2 and B^1, B^2 were averaged. In a given instrument this average tap-tone frequency was compared with the frequency of the main body tone or peak of that particular instrument when completely assembled, and tested by the "loudness curve." In each of twenty instruments the main body peak was found to be seven semitones above the average of the free plate peaks.

In spite of the many variations encountered in the free plate vibrations, the one outstanding result is that when the frequencies of the peaks of the back plate alternate with those of the top plate, at intervals of not more than a whole tone, the resulting instrument has been judged good by the evaluation methods. When the frequencies of the main plate peaks match or are more than a whole tone apart in top and back plates, the resulting instruments have been judged poor by the same methods. Instruments based on the two types of peak arrangements described have proved excellent under varied playing conditions. Several instruments made as part of these experiments have been purchased by professional musicians in large symphony orchestras and well-known quartets. Further experiments on the acoustical effect of other variables in violin construction, and the application of these principles to instruments of all sizes from a small violin to the double bass, are in progress..

SUMMARY

Subharmonic series are described and shown to be important in the evaluation of violin tone. The effect of many subharmonic series is to strengthen the lower tones of the violin which are weak because the area of the body is too small to emit natural responses in this range. In some excellent instruments as many as 30 or 40 subharmonic series have been found. Testing equipment of increased accuracy gives evidence of double or multiple air tones. An electrical analog shows that these are to be expected from the shape of the violin.

The Hopping method of vibrating an instrument or its plates and recording the response at each frequency in the audible range gives permanent evaluation records that are very useful, especially in long-term investigations.

Tone quality can be controlled to a large degree, before the instrument is assembled, by the arrangement of the plate peaks between the free top and back. When the frequency of the peaks of the top plate alternate with those of the back plate, and are not more than a tone apart, the instrument has been judged good by three evaluation methods. When the plate peaks match or are more than a tone apart, the resulting instrument has been judged poor.

ACKNOWLEDGMENT

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