Directional tone color

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(Received 23 August 1996; revised 11 December 1996; accepted 16 December 1996)

Above about 1 kHz, the angular radiation pattern of a violin begins to vary rapidly not only with direction but also with frequency, typically changing drastically from one semitone to the next. In an enclosed space, this characteristic, which we have named ''directional tone color,'' can sometimes produce the illusion that each note played by a solo violin comes from a different direction, endowing fast passages with a special flashing brilliance. It also has important consequences for the perception of vibrato, for the difference in sound between a solo violin and an orchestral section playing in unison, for the problem of reproducing violin sounds through a loudspeaker, and possibly for the mysterious quality called ''projection.'' This paper introduces the theoretical basis of directional tone color, presents data to support its existence, and discusses the various ways in which it can be musically important. © *1997 Acoustical Society of America.* [S0001-4966(97)05804-9]

PACS numbers: 43.75.De, 43.20.Rz [WJS]

I. THEORY

Except at the lowest frequencies, a violin radiates sound primarily through the vibration of its wooden shell. (It has been suggested[1] that air modes may possibly again become important at very high frequencies, where their density becomes larger than that of wood modes; but that would, in any case, not greatly affect the argument of this paper.) Accordingly, we begin by discussing the nature of the modes of such a shell.

A. Density of wood modes in frequency

If the elastic properties of the shell were isotropic, the frequency density of wood modes would be easy to compute.[2] First, we note that the density of such modes in the **k** plane is approximately constant and equal to $A/(2\pi)^2$, where A is the area of the shell. Second, we relate the absolute value of **k** to the frequency of a bending wave, which is proportional to k^2; hence, the area of the circle in the **k** plane containing modes up to a certain frequency is proportional to that frequency. Third, by multiplying this area by the density of modes, we obtain the total number of modes with frequencies up to any specified value; it, too, is proportional to the maximum frequency. Finally, the amount by which the maximum frequency changes when the number of modes is incremented by 1 is the average spacing Δf between them. The foregoing argument shows that it is constant; a simple calculation gives its value as

$$\Delta f = a c_W / A\sqrt{3}, \tag{1}$$

where c_W is the speed of compressional waves in the wood, and a is the thickness of the shell.

Unfortunately, the problem is made very much more complicated by the anisotropy of the wood. Not only are the speeds of compressional waves drastically different along and across the grain, but the effective Young's modulus for compressions in a direction making an angle α with the grain of the wood has the form

$$Y(\alpha) = L \cos^4 \alpha + 2M \cos^2 \alpha \sin^2 \alpha + N \sin^4 \alpha, \tag{2}$$

where $L,\ M,\ N$ are three independent elastic constants. We see from this that the wave speeds in two mutually perpendicular directions still do not provide a sufficient specification of everything that we need to know. Further serious complications are introduced by the arching of the plates.

On the other hand, the fact that the average spacing of modes approaches constancy at high frequencies remains true even in these more complicated cases. We follow Cremer[2] in estimating it by replacing c_W in Eq. (1) with the mean proportional of the wave speeds in the two principal directions, resulting in values of Δf of 73 Hz for the top plate and 108 Hz for the back plate; the two then combine to give an overall average spacing for the instrument of about 44 Hz.

B. Distribution of radiation from a shell mode

In general, the angular distribution of radiation from a radiating system, or ''antenna,'' is governed above all by the relation of the size of the antenna to the radiated wavelength λ, or rather to $ƛ \equiv \lambda/2\pi$. If the antenna is much smaller than $ƛ$, the details of its structure become unimportant. The radiated sound is then isotropic, and its amplitude is determined by the net amplitude of pulsating volume, with parts of the surface that move outward being compensated by others which, at the same moment, move inward. (An exception occurs if the net pulsating volume is zero. This happens for a violin at very low frequencies,[3] an effect that we shall mention again in Sec. II G).

If, on the contrary, the antenna is large, individual regions of approximate size $ƛ$ will radiate more or less independently, producing ''beams'' which do, however, spread out with distance and hence interfere with each other (somewhat the way the two slits in a double-slit diffraction experiment do). The result is an angular distribution of radiation which becomes progressively more complex with increasing number of independently radiating regions.

To estimate the frequency at which a violin might be expected to pass from the ''small antenna'' to the ''large antenna'' regime, we note that for a spherical radiator this transition occurs when its radius is equal to λ. Taking the ''radius'' of a violin to be 7 cm, we then obtain a transition frequency of approximately 800 Hz. (We use a rather small value of radius, corresponding to a path that connects top and back via the C-bouts, since that is where the ''short-circuiting'' of the air flow, which defines the long-wavelength regime, will first occur.) Accordingly, we expect the radiation of a violin to be roughly isotropic below 800 Hz, becoming progressively more anisotropic above.

The next question is: To what degree, and beginning at what frequency, does the detailed pattern of a shell mode affect the directional distribution of radiation? In other words, are the sizes of the regions that move independently sufficiently large compared to an air wavelength to be individually effective? If we think of each of those regions as a rigid piston whose size is half a wavelength of the bending wave, we obtain as the corresponding transition frequency f_c/π^2, where f_c is the so-called *coincidence frequency*, the frequency at which the wavelength of a bending wave is equal to the wavelength of an air wave. For the violin top, for example, Cremer[4] estimates f_c as 4.87 kHz for waves along the grain and 18.42 kHz for waves perpendicular to it, which would give us transition frequencies of about 500 Hz and 2 kHz, respectively. Without attempting too detailed an interpretation, it is clear that the individual modes are apt to influence the radiation pattern at all frequencies that are of interest to us.

C. Excitation of individual modes

A driving force of a certain frequency, such as is provided by a steadily bowed string, will, in principle, put each mode of the violin into vibration; quantitatively, however, this excitation will be appreciable only for modes whose normal frequency is within a resonance width of a strong Fourier component of the driving signal. It is not always easy to determine, by simple inspection of radiativity curves, whether the individual peaks and valleys of the response are produced by single modes or by statistical combinations of many; knowing, however, that the modes have an average spacing of around 45 Hz (Sec. I A), it becomes clear that the observed peaks correspond either to single modes or, at most, to combinations of a small number of them (see Sec. II H). Accordingly, we would expect the angular pattern of violin radiation, once it begins to change at all, to change fairly drastically every 50 Hz or so.

We remind the reader that, by our definition, it is this very rapid variation of directivity with frequency that constitutes ''directional tone color.''

II. EXPERIMENT

All of our measurements are based on the principle of reciprocity, which relates the *outgoing* acoustic field radiated per unit transverse force on the bridge (the radiativity) to the motion of the bridge that results from a corresponding *incoming* unit acoustic field applied to the violin. In the original application of the principle to violin physics,[3] it was desired to obtain the radiativity as an expansion in multipole moments, which required the angular dependence of the corresponding incoming fields to have a controlled multipole nature as well. In the present work, the situation is conceptually much simpler: In order to measure the radiativity for outgoing waves in a particular direction, we need to expose the violin to an incoming plane wave *from* the same direction, and normalize the signal by the pressure amplitude as measured by a microphone in the same location as the violin is going to be.

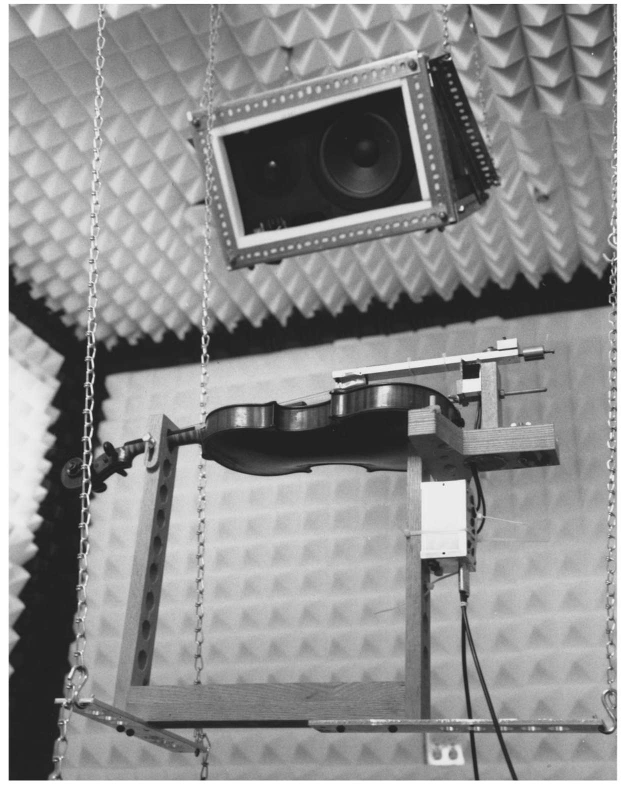

FIG. 1. Violin on its frame suspended in the Sonex-lined chamber. The ''tone arm'' holding the phonograph pickup is seen extending over the violin. ''Speaker 1'' is overhead; ''speaker 2,'' pointed to by the neck of the violin, is not visible.

Since our aim is to search for strong directional dependence, we have arbitrarily chosen two directions in which to compare the radiativity, namely, (1) more or less normal to the top plate of the violin, and (2) outward in the direction of the neck.

A. Transducers and electronics

The two necessary stimulus waves are generated by a pair of identical JBL model 4408 loudspeakers placed in our quasi-anechoic chamber, which is an approximately rectangular space 10×12×10 ft high fully lined with 4-in. Sonex.

The velocity of the violin bridge is sensed by a standard magnetic phonograph pickup whose stylus rests on the bridge halfway between the D and A notches. The violin is loosely held in a horizontal position by a padded wooden frame which is in turn suspended from the ceiling of the chamber by three metal chains (Fig. 1). The phonograph pickup is mounted on a ''tone arm'' which rests on a knife edge attached to the frame so as to allow it to pivot freely around a horizontal axis, maintaining the stylus at the correct vertical force. This force is adjusted by a counterweight attached to the arm.

The normalizing signal is measured by an inexpensive electret microphone at the end of a thin boom which is introduced when the violin is removed; it, too, then occupies what would otherwise be the midpoint between D and A notches of the bridge. (The choice of microphone position is discussed in Sec. II C.)

The speakers are driven by a signal comprised of a repetitive series of 8192 digital values generated at a 50-kHz sampling rate by the 12-bit D/A converter of a Data Translation DT2821 board controlled by a Pentium 100-MHz desk computer. It has the form of a Schroeder chirp[5] that covers the range from 122 Hz to 24.4 kHz in steps of 6.2 Hz. In synchronism with it, the 12-bit A/D converter of the same board receives the response signal, accumulating the sum of 16 passes after first allowing four passes (about two-thirds of a second) for the violin to reach steady state.

The driving voltage is filtered by an eight-pole Butterworth anti-alias filter with an 18-kHz cutoff before being applied to the voice coil of the appropriate speaker by a Crown D-150 power amplifier. The return signal—whether from the phonograph pickup or the microphone—is amplified by a low-noise preamplifier before leaving the chamber, and enters the A/D input of the DT2821 after being filtered by a second identical anti-alias filter.

B. Frequency limitations

Even though the computer-generated driving signals can easily cover a range of 18 kHz or more, the properties of our system are such as to make the data at very high frequencies undependable. The chief limitations come from (a) the phonograph pickup and the properties of the tone arm, whose own resonances appear clearly in the high-frequency data, especially when stylus motion is examined in the vertical direction; and (b) direct electromagnetic coupling between the speaker cable and the cable that connects the magnetic pickup to the preamplifier, since the signal level decreases at higher frequencies while capacitative coupling increases.

Although it is possible to address these factors, we decided that, for an investigation whose basic aim is the demonstration of directional tone color, it is sufficient to limit ourselves to the region up to 5 kHz, where (to the best of our knowledge) the data can be taken at face value.

C. Choice of microphone position

In order to obtain a valid measurement of radiativity, the complex velocity of the bridge must, at each frequency, be divided by the complex pressure amplitude of the incoming wave. Now it is, of course, a property of a pure traveling plane wave that its amplitude has the same value regardless of where it is measured, only the phase changing as a function of position. Therefore, a displacement of the microphone that provides the normalizing signal would merely change the phase of the measured radiativity; in other words, the choice of microphone position corresponds simply to a choice of origin with respect to which the radiativity will finally be specified. As explained in Sec. II A, we chose this origin to be, for simplicity, at the same place where the bridge velocity will be measured, but in fact it could just as well be anywhere else (although it is, naturally, important to keep it consistent between measurements).

Of course the situation changes if, as must be true in real life, the incoming-signal is *not* a pure traveling plane wave. Accordingly, we cannot interpret our results before carefully examining our stimulus waves.

D. Characterization of the stimulus waves

In order to test the degree to which sound waves generated by the speakers in our chamber conform to the above requirements, we compared the two complex amplitudes received from a given speaker when the microphone is displaced a few inches in a direction away from the speaker. As indicated in the previous section, (a) the magnitude of this ratio should be unity independent of frequency, and (b) its phase should be linear in frequency, changing by 2π when the frequency increases by $c/\Delta L$, where ΔL is the displacement and c the speed of sound.

Figure 2 shows the experimental value of this ratio plotted for each of the two speakers. It is clear that, although the overall behavior resembles what is expected, deviations do exist, indicating the presence of residual reflections; under such circumstances, our experimentally deduced radiativity in a particular direction will contain a coherent admixture of the radiativity in the reflected direction. We discuss the implications of this separately for the regions below and above 1 kHz.

Above 1 kHz, the directivity data are, as discussed in Sec. I C, expected to vary rapidly with frequency by considerably larger amounts, and on a finer frequency scale, than the driving signals of Fig. 2, an expectation which will be born out by our results (Sec. II F). So long as our purpose is to establish the existence of strong directional tone color, rather than investigate its precise fine details, a small amount of directional mixing is not important.

Below 1 kHz, the deviation from wave purity shown in Fig. 2 becomes worse, which is not surprising in view of the decreasing absorptivity of Sonex in this range. On the other hand, our expectation is, as discussed in Sec. I B, to see a more or less isotropic radiativity here; this expectation, too, will be born out by our data. But if the radiativity is truly the same in all directions, then the admixture of two directions should, in principle, make no difference, regardless of how large it is.

This reasoning assumes that the violin is sensitive only to the pressure (that being what the microphone measures), and not, for example, to its gradient. Since we know that in the long-wavelength region the monopole radiativity of the violin is much larger than $1/\lambda\!\!\!^-$ times its dipole radiativity,[3] the assumption of pure monopole sensitivity is valid as long as we do not place the violin too near a node of the field, which we have taken care not to do. (Another possible exception, also discussed in Ref. 3, will be taken up in Sec. II G below.)

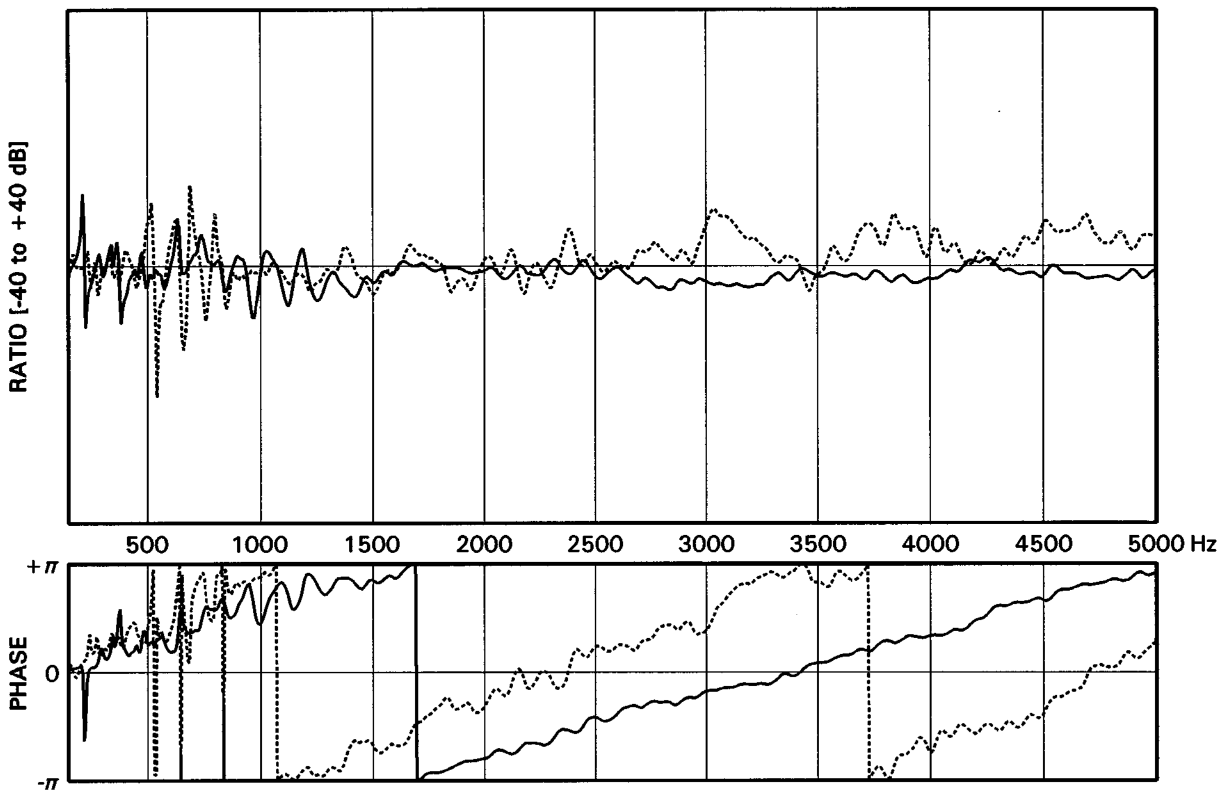

FIG. 2. Complex ratio by which the microphone's signal is multiplied when it is moved away from the speaker by a few inches. Solid curve: ''speaker 1;'' dotted curve: ''speaker 2.'' Top: amplitude of ratio; bottom: phase of ratio. (The amount by which the microphone was moved is not the same in the two cases.)

We conclude that, in either frequency region, the stimulus signals produced by our two speakers are sufficiently close to pure traveling waves for the purposes of this investigation.

E. Results for the radiativity

As already indicated, our aim in the present work is to compare the radiativities of a violin in two arbitrarily chosen directions, by first obtaining the response of the bridge stylus to a signal from each of the loudspeakers, then dividing by the microphone signal from the same speaker. Of course the data consist, after Fourier transformation, of a complex amplitude for each of 4096 frequencies, so that ''dividing one signal by another'' means performing one complex division at each frequency.

Figure 3 shows a comparison of the two radiativities so obtained for two frequency ranges: 150–1000 Hz (top) and 1500–3500 Hz (bottom). It will be seen from the top graph that, except for an unusual feature at about 230 Hz to be discussed in Sec. II G, the radiativities are pretty much the same up to about 800 Hz, in agreement with our expectations of isotropy (Sec. I B).

The situation is, however, radically different at higher frequencies, as shown in the bottom graph of Fig. 3. We note that the *frequency placement* of peaks and valleys which characterize the radiativities in the two directions are very similar—which is, of course, exactly what one would expect, since the same normal modes are represented in both cases. The magnitudes and phases of the two curves are, however, quite different from each other, and that in a completely irregular manner—again in agreement with our theoretical discussion.

F. Results for the directivity

Our four violins were picked to sample a large range, the purpose being to demonstrate a property which, we claim, is a necessary consequence of the instrument's structure. We identify them as follows:
LAB: A very ordinary student instrument;
MEL: A high-quality student instrument;
DAN: A modern professional instrument;
COM: A violin made of laminated synthetic material.
In each case, we obtain a measure of the directivity by dividing the radiativity along the neck (''direction 2'') by that perpendicular to the top plate (''direction 1''). Figure 4 shows the results of performing this division for the four violins, plotted on a log–log scale, and omitting the phase to simplify the graphs. Here the ratio is specified in decibels where, of course, 0 dB denotes isotropy (at least with regard to the two chosen directions), and positive values mean that the radiativity in ''direction 2'' exceeds the one in ''direction 1.'' The four graphs are offset vertically for clarity.

The frequency axis in Fig. 4 is also logarithmic, so that equal horizontal displacements mean equal musical intervals. In fact, this axis is labeled, in addition to the logarithmic frequency scale at the bottom, with steps of one-third octave, or four semitones, at the top, using the conventional musical notation in which A_4 corresponds to a frequency of 440 Hz.

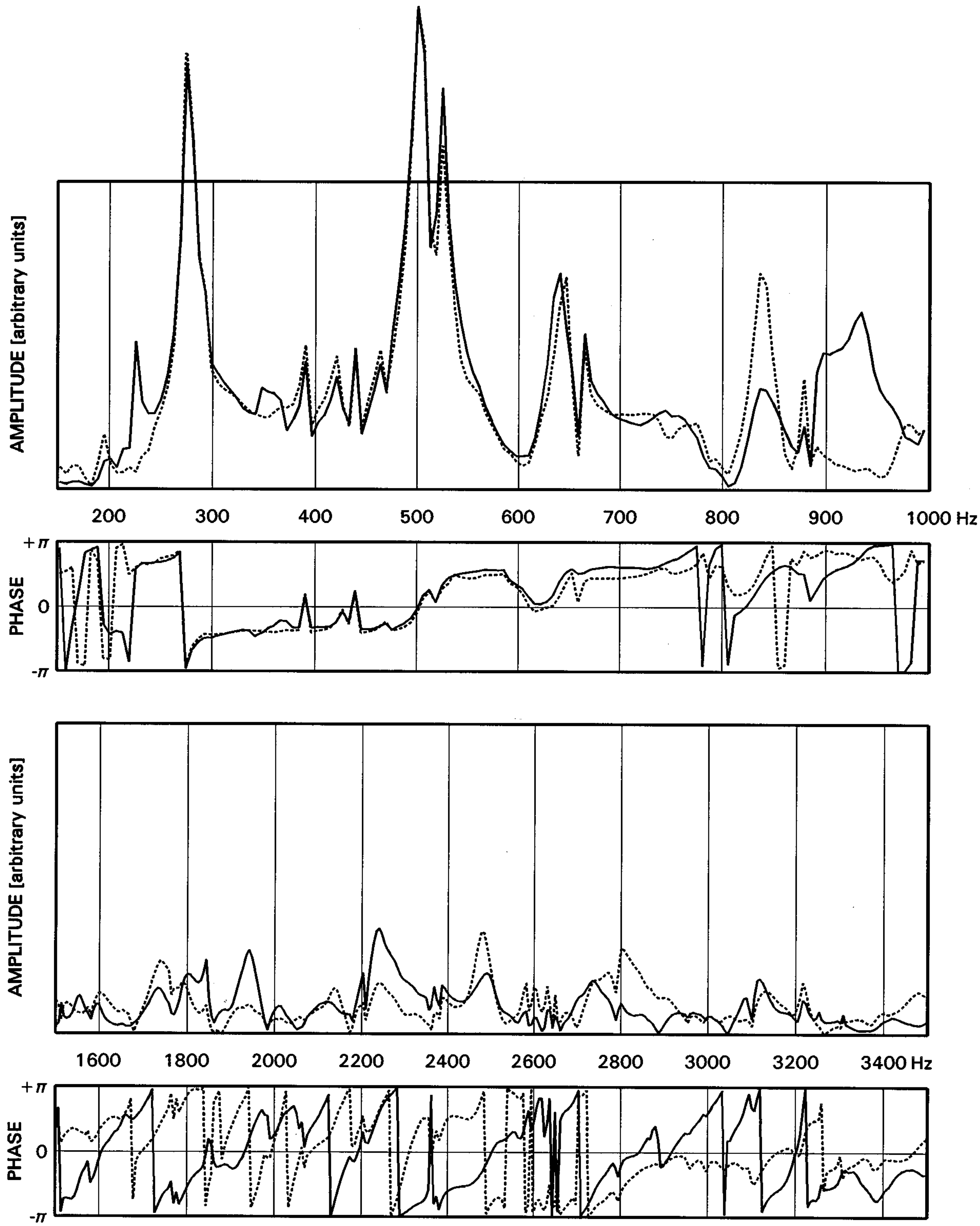

FIG. 3. Two frequency ranges of the radiativity amplitude and phase of violin ''DAN'' (linear scale) measured in two directions. Solid curves: ''direction 1;'' dotted curves: ''direction 2.'' The vertical scales are the same for both ranges.

We observe the following features in all four graphs:

(a) Except for the peculiar phenomenon around A3, all four violins exhibit a fair degree of isotropy up to about A_5, as expected.

(b) Above that frequency, the patterns become wildly irregular, jumping up and down by amounts that sometimes exceed 40 dB peak-to-peak; this is, of course, precisely the quality of ''directional tone color'' that we defined at the beginning of the paper. We also note that, as expected from the discussion of Sec. I C, the spacing of these peaks and valleys is in

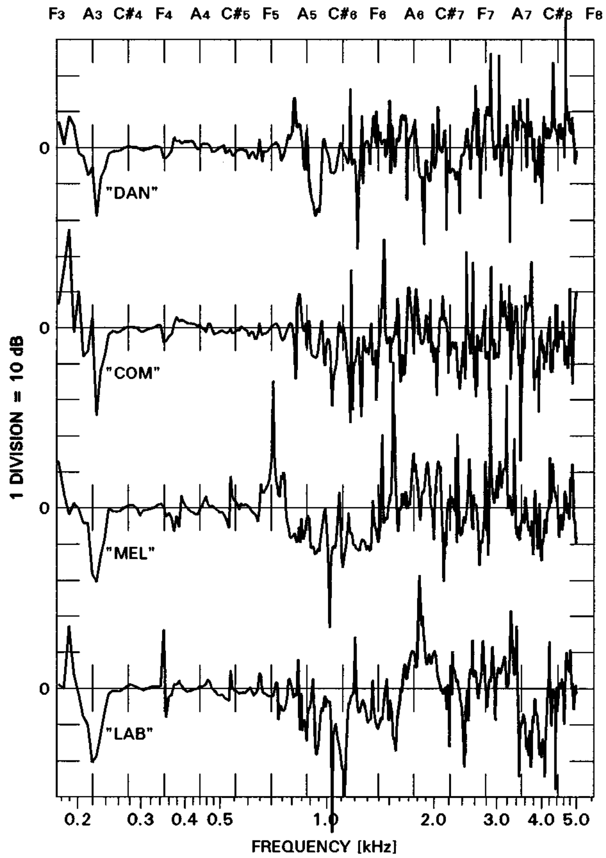

FIG. 4. Ratio of radiativity in ''direction 2'' to that in ''direction 1'' for four violins. The phases are not shown.

the vicinity of one semitone where they first begin, with some tendency to become progressively finer as the frequency rises.

Our results appear to be generally consistent with those of Meyer[6] and of Saldner *et al.*,[7] neither one of whom, however, used the close frequency spacing required to detect the directional tone color phenomenon.

G. The feature around low A

As indicated in Sec. II D, the stimulus signals tend to deviate appreciably from pure traveling waves below about 1 kHz. Although this makes it difficult to interpret anisotropy data in detail in that band, it is nonetheless true, as we mentioned, that if the radiativity were truly isotropic such a deviation ought not to make any difference. Accordingly, even if a quantitative characterization is risky, one may state with some assurance that *below about 250 Hz the radiativity of our violins again begins to deviate from isotropy*. Indeed, the patterns in which they do so are rather similar (although by no means identical) for the four instruments.

In fact, this behavior appears precisely in the frequency region where the dipole moment of the violin begins to dominate.[3] That is, in our opinion, the most probable reason for the low-frequency anisotropy, which seems otherwise difficult to explain.

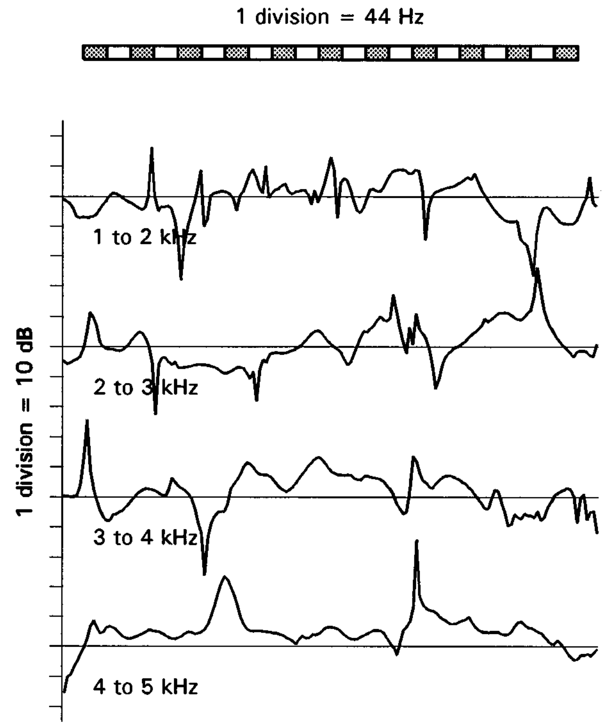

FIG. 5. Ratio of radiativity in ''direction 2'' to that in ''direction 1'' for violin ''DAN'' plotted against linear frequency. The scale above shows the expected density of wood modes.

H. To what degree do the modes overlap?

Figure 5 repeats, for one of the violins (''DAN''), the same directional characteristic already shown in Fig. 4; this time, however, the frequency axis is linear instead of logarithmic, and the region from 1 to 5 kHz is stretched out into four sections so as to make its details more visible. For reference, we also show, at the top of the diagram, a scale whose divisions are 44 Hz, equal to the estimated average spacing of wood modes (Sec. I A). It appears that the first range of the graph, from 1 to 2 kHz, has a structure whose frequency scale is reasonably well described by this estimate; but the directivity becomes successively more ''washed out'' as we go toward higher frequencies (although not on a logarithmic scale!).

The most likely explanation of this behavior is, of course, that in the range of a few kHz the damping of modes increases so that they begin to overlap each other. It should be noted, however, that there may well be an additional factor contributing to this effect, namely the gradual appearance of air modes, whose density will be approaching that of the wood modes in the same approximate region.[1]

III. DISCUSSION

The phrase ''directional tone color'' in the sense of this paper was first introduced[8] in 1993. In this section we outline some of its consequences from the point of view of musical performance.

A. ''Flashing brilliance''

This phrase, also first introduced in Ref. 8, describes the fact that, in an enclosed space large enough for the ear to perceive the timing of separate reflections, the way that the radiation pattern of a violin changes drastically from one semitone to the next can confuse the common psychoacoustic directional cues, thus endowing the sound of the instrument with a characteristically striking spatial sense. Although, as always with subjective perceptions, it is difficult to find a verbal description that satisfies all listeners, we have heard comments that range from ''every note appears to be coming from a different direction'' to the much less specific ''the sound of a violin seems to be disembodied in mysterious and fascinating ways.''

The perception of this property of ''flashing brilliance'' is, of course, made especially complex (and, we suspect, especially brilliant) by the fact that the directional cues can be quite different for different harmonics of the same note. It should be noted here that, according to the discussion of Secs. I B and II F, the effect we are talking about will be strong for all partials of notes above the bottom of the E-string; but even for the lowest notes of the G-string it will be present starting with about the fourth partial.

B. Vibrato

As discussed in detail by Meyer,[9] vibrato on a violin—executed by a motion of the left wrist that causes the fingertip to roll forward and back on the fingerboard, thus causing an oscillatory variation of the string length—is reflected not only in frequency modulation but also in amplitude modulation of the played note, because of the way that the normal frequency of the string moves with respect to the peaks and valleys that characterize the instrument's radiativity. Since the peak-to-peak frequency range covered by a typical vibrato can exceed three-quarters of a semitone, we now see that the result will be a strong modulation of the directional radiation pattern as well.

The effect can be visualized in terms of a number of highly directional sound beacons, all of which the vibrato causes to undulate back and forth in a coherent and highly organized fashion. It is obvious that such a phenomenon will help immensely in fusing sounds of the ''differently directed'' partials into a single auditory stream; one may even speculate that it is a reason why vibrato is used so universally by violinists—as compared to wind players, from the sound of whose instruments directional tone color is generally absent. The reason is not, of course, that wind instruments lack directivity, but that they are unlikely to show a variation in their directivity which is anywhere near as large in amplitude or as dense in frequency.

C. *Solo* versus *tutti*

Although various explanations have been given[10] of the striking way in which a solo violin can be clearly heard above an orchestra even when the latter contains two dozen violins playing at more or less the same dynamic level, directional tone color may well, in fact, be the major factor contributing to this phenomenon. The point is, of course, that even though the *presence* of large and closely spaced variations in the instrument's directivity, which is what ''directional tone color'' means, appears to be characteristic of every violin, the *exact placement* of these maxima and minima has no detailed correlation among different instruments. As a result, the process of summing a number of them will strongly diminish the variability of the total.

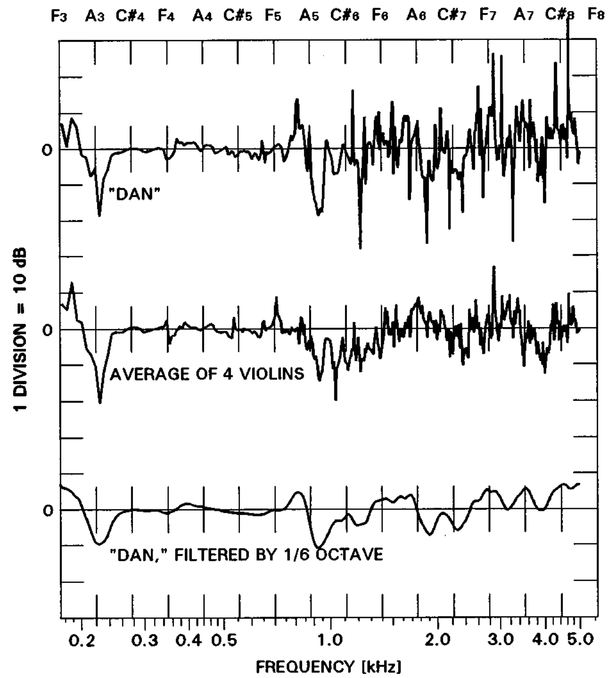

FIG. 6. Top: directivity amplitude of violin ''DAN,'' repeated from Fig. 4. Center: average of directivity amplitudes of the four violins of Fig. 4. Bottom: Directivity amplitude of ''DAN,'' as shown in the top graph, but filtered through a one-sixth octave filter.

This effect is demonstrated in Fig. 6, which shows three different directivity curves. On top, we repeat the characteristic for one of the violins (''DAN'') that was already shown in Fig. 4; in the middle, the average of all four of our violins is plotted; and finally, the bottom curve shows the one for ''DAN'' digitally filtered through a one-sixth octave filter, which might be considered a reasonable estimate for what happens when 10 or 12 violins are playing together (on the assumption that the frequency scale on which any one violin changes its directivity is in the vicinity of a semitone). It is clear that averaging as few as four violins diminishes the directional tone color considerably, while the one-sixth octave filter essentially eliminates it entirely. Under such circumstances it is not surprising that a single solo violin, with a good vibrato to consolidate its auditory stream, can musically soar with ease above its orchestral environment.

In this connection it is interesting to note a curious situation that occurs in the fourth movement of the Sixth Symphony of Tchaikovski, the score of the first few measures of which (string parts only) is shown in Fig. 7. In this case the theme has its notes alternating between the first and second violins, so that the first note is played by the second violins, the next note by the first violins, and so on (a similar alter-

FIG. 7. Opening of the fourth movement of Tchaikovski's Sixth Symphony (string parts only). The well-known descending scale theme is heard as an alternation of notes between first and second violins.

nation appears in the two lower parts as well). Remembering that the normal way for an orchestra to be seated was, at that time, to have the first violins at the left of the stage and the second violins at the right, such an orchestration results in alternate notes of the same theme coming from radically different directions. It is hard to avoid the speculation that Tchaikovski, perhaps unconsciously, chose this unusual voice leading in order to give the violin sections a kind of artificial directional tone color, thus endowing a *tutti* passage with some of the tonal quality of solo instruments.

D. ''Projection''

Violinists place an attribute which they call ''projection'' of an instrument high on their list of desirable qualities; it seems to refer to an ability for its sound to fill a hall, although its adherents will emphasize that this does not just mean generating a lot of power but something rather different. If one tries to paraphrase such a quasi-definition by saying that ''projection'' refers not so much to the ability to permeate an auditorium with decibels as to *command attention* from listeners in various parts of it, then the physical quality of directional tone color immediately comes to mind. It might be, for example, that for a given individual instrument there are bands in which the variation of directivity is relatively weak or relatively slow, in which case that instrument might be observed to ''lack projection'' for frequencies that have important harmonic content in those bands. We emphasize that this hypothesis is, at the present moment, entirely speculative.

E. Electronic reproduction

Pierre Boulez has observed[11] that loudspeakers have the property of ''anonymizing'' the sound of musical instruments, that is, of making them all sound the same. Given the superb objective specifications of good modern loudspeakers, it is hard to put physical meaning to such a statement in terms of qualities such as frequency response or distortion. Yet there is one attribute of a loudspeaker which it does, indeed, impose upon all sounds that it generates, and that is its own directivity. Specifically, when music is played through a loudspeaker the quality of directional tone color is instantly and totally obliterated.

The damage is, perhaps, not excessively serious for wind instruments, and especially for the brasses, whose live sound is projected through a circular bell of a size not too radically different from that of a typical loudspeaker. As a result, the directional properties of this sound, essentially those of a circular piston of comparable diameter, remain—by coincidence, to be sure—relatively faithful. But when violin music undergoes the same process, the result is similar to what one would hear if the violinist were on the other side of a solid wall in which a circular hole the size of the speaker had been cut: none of the effects that we have enumerated in Secs. III A–D can any longer occur.

Indeed, a number of music lovers with whom the author has spoken are of the opinion that separating the sound of a solo violin from an accompanying orchestra is much easier to do in a concert hall than when listening to a recording, although others strongly disagree. Unfortunately, the question is complicated on the one hand by the presence of visual cues in a live performance, and on the other by the ability of recording engineers to enhance whatever part they wish to emphasize.

ACKNOWLEDGMENTS

This project benefitted enormously from the talent and expertise of Colin Holmes, who designed and built most of the electronics; from the help of Maureen Mellody, who together with him did most of the data collecting; and from the support of Joseph Curtin, who (among other things) lent us some of the violins that were used. The manuscript was critically read by Xavier Boutillon, Judith Brown, René Caussé, Joseph Curtin, Carleen Hutchins, Juergen Meyer, Thomas Rossing, Robert Schumacher, Olivier Warusfel, and James Woodhouse, every one of whom provided interesting and helpful comments (it goes without saying that all remaining blunders are the author's). Last but by no means least, the support of the National Science Foundation under Grant No. PHY-9319567 is gratefully acknowledged.

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