Quality of Violin, Viola, 'Cello, and Bass-Viol Tones. I

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The elements that are important in the identification of the violin, viola, 'cello, and bass-viol tones were analyzed. These elements were found to be the harmonic structure of the middle portion of the tone; the harmonic structure of the ending portion of the tone (certain partials decayed rapidly leaving an afterring); the attack and decay of the tones; the vibrato (when present) of the tones; and the noises inherent in the mechanics of producing the tones. With the exception of vibrato, the important elements were determined and successful synthesis was accomplished. By the use of a jury of observers, identification tests were made. A successful description was arrived at when and only when synthetic tones could not be identified from real tones. It was found that there is a vibrato both in frequency and relative intensity.

INTRODUCTION

THIS paper reports that part of our general research study on the quality of musical tones which is concerned with the violin, viola, 'cello, and bass viol. The general procedure used in this study is the same as that described in our two previous papers.[1,2]

The tones are recorded on magnetic tape. They then are reproduced from the tape and elements that are important in identification of them are analyzed. These analyses enable one to construct synthetic tones. Such synthetic tones are then compared to the real tones by an identification test, using a jury of observers. When such synthetic tones cannot be identified from the real tones, then, and then only, can one be sure that the analysis is correct and that all the elements such as frequency, intensity, partial-tone structure, attack and decay, underlying noise, and the variation of these with time for the duration of the tone, have been given proper attention. It is well known that when such musical tones are recorded on the usual magnetic-tape machines the phases are changed, and consequently the waveform is changed. It is also known that these changes do not change the quality of tones as heard by the ear, except in extreme cases.

The tones from the violin, viola, 'cello, and bass viol are somewhat like those from the human voice in that there is a wide variation in quality depending upon the whim of the person producing the tone. The frequency, the intensity, the vibrato, and the attack and decay are produced with the guidance of the player's ear rather than by any mechanical means. For this reason, it is difficult for a player to produce two or more tones that are alike. It will be seen that, even when the player thinks that the tones are alike, an analysis shows very definite differences.

The tones for this study were produced by students of music who were considered good musicians. They were asked to produce four successive tones that were alike, then to switch to another note and produce four other tones until they had covered the range of the instrument. Some tones were produced with and some without vibrato. The duration of the tones was between 1 and 3 sec. For discussion, the duration time has been divided into three parts; the beginning or attack, the central period, and the ending or decay. During all these phases, the amplitude and the frequency of each harmonic varied with time. It was found that during the central portion the harmonic structure changes were small, however, and could be imitated by a synthetic tone having constant harmonic structure.

The attack is so fast that the harmonic structure during this beginning period was made the same as for the central period. For some tones from stringed instruments, the harmonic structure for the ending period is very different from that during the central portion. The tone continues after the bow is removed, and this part of the tone is referred to as the afterring.

During the central period, there may be a vibrato

[1] H. Fletcher, E. D. Blackham, and R. Stratton, "Quality of Piano Tones," J. Acoust. Soc. Am. 34, 749–761 (1962).
[2] H. Fletcher, E. D. Blackham, and D. A. Christensen, "Quality of Organ Tones," J. Acoust. Soc. Am. 35, 314–325 (1963).

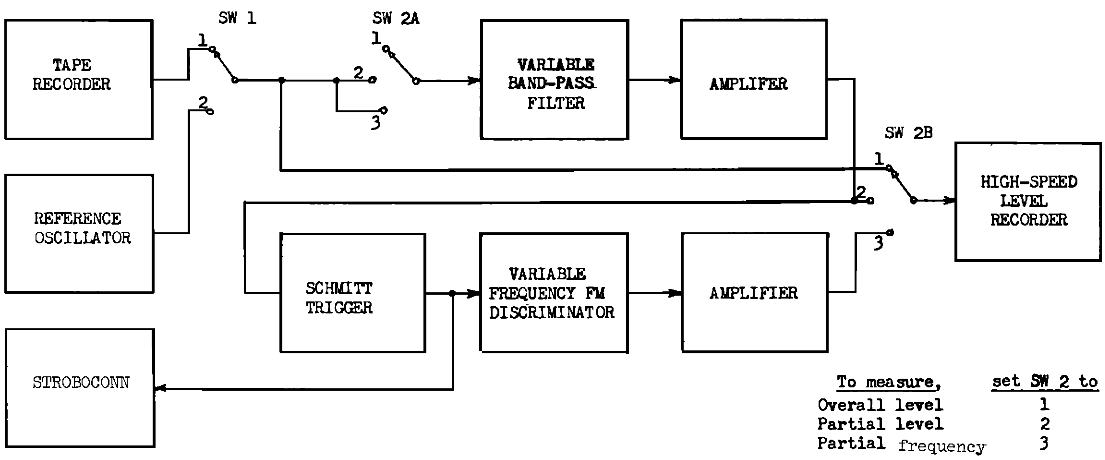

FIG. 1. Block diagram of the system used to measure the relative intensity and frequency fluctuations.

that is a periodic variation of both the frequency and intensity level of the tone. The vibrato is an important aspect of the quality of the tone. The frequencies of the partials of these central-period tones were measured and found to be harmonic within the accuracy of our measurements. The tone with all its harmonics is called the total tone.

Frequency level as used in this paper refers to the reading of the Stroboconn, which gives the interval in cents sharp or flat from one of the notes of the chromatic

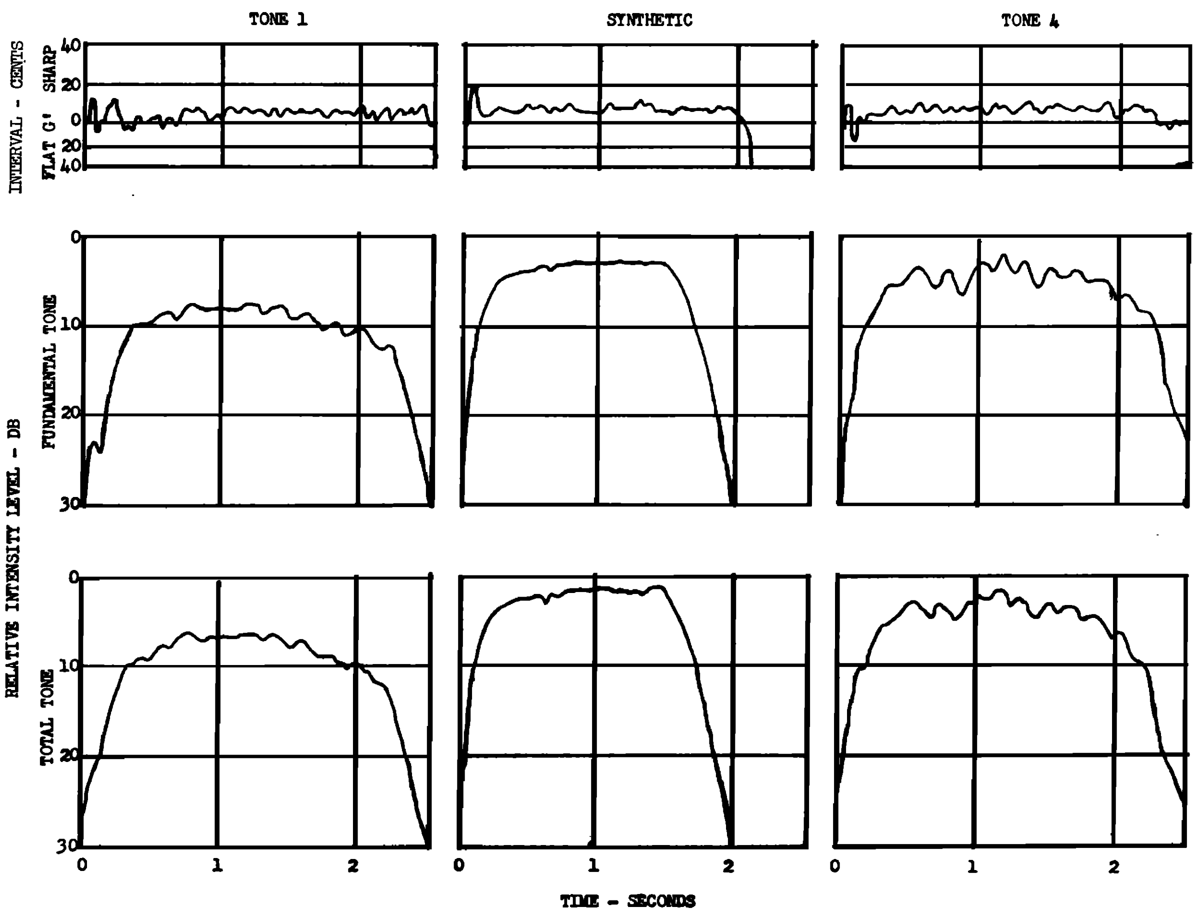

FIG. 2. Frequency and intensity level vs time for violin G′.

scale. It reads from C''', corresponding to a frequency of 32.7 cps, to B_3+50 cents, corresponding to a frequency of 4066.8 cps.

I. ANALYSIS OF VIOLIN TONES

The tones selected for these tests were G'-196, G-392, G_1-784, and G_2-1568. These tones were considered to be typical of those usually produced in a good orchestra. The player was asked to produce four tones on each note that were as nearly alike as possible. Each of these tones was analyzed to find (1) the interval in cents versus the time in seconds; (2) the intensity level in decibels versus the time in seconds for the harmonic (usually the fundamental) used for determining the pitch; (3) the intensity level in decibels versus the time in seconds for the total tone.

II. MEASUREMENT OF FREQUENCY AND INTENSITY LEVEL

A block diagram of the system used to measure the relative intensity level fluctuations is shown in Fig. 1. In order to plot the over-all level of the particular tone, the signal from the tape recorder was passed directly to the high-speed (1000-dB/sec) level recorder (B&K type 2305). Since this level recorder measures the true root-mean-square value of the input signal, the plot is independent of the waveshape of the tone.

To record the level versus time of a particular partial of a tone, the signal was first filtered by a variable-frequency, variable-width, bandpass filter (HP model 302A). The filter is centered on the average frequency of the tone and the bandwidth is adjusted so as to include all of the significant sidebands of the FM spectrum according to the expected deviation ratio.

To record the frequency versus time of any partial, the filtered signal was passed into a Schmitt trigger to produce a square wave of the same frequency as the filtered partial. Since the square wave is rich in odd harmonics that change in frequency in synchronism with the fundamental component, the variable-frequency FM discriminator could be set to detect the frequency of one of the higher harmonics of the square wave. By doing this, a small time constant in the discriminator is achieved and unwanted transients in the output are avoided. With the discriminator thus set, its output was amplified and fed to the input of the high-speed level recorder, which then plotted the instantaneous relative frequency of the partial being analyzed. A static calibration of this system was made

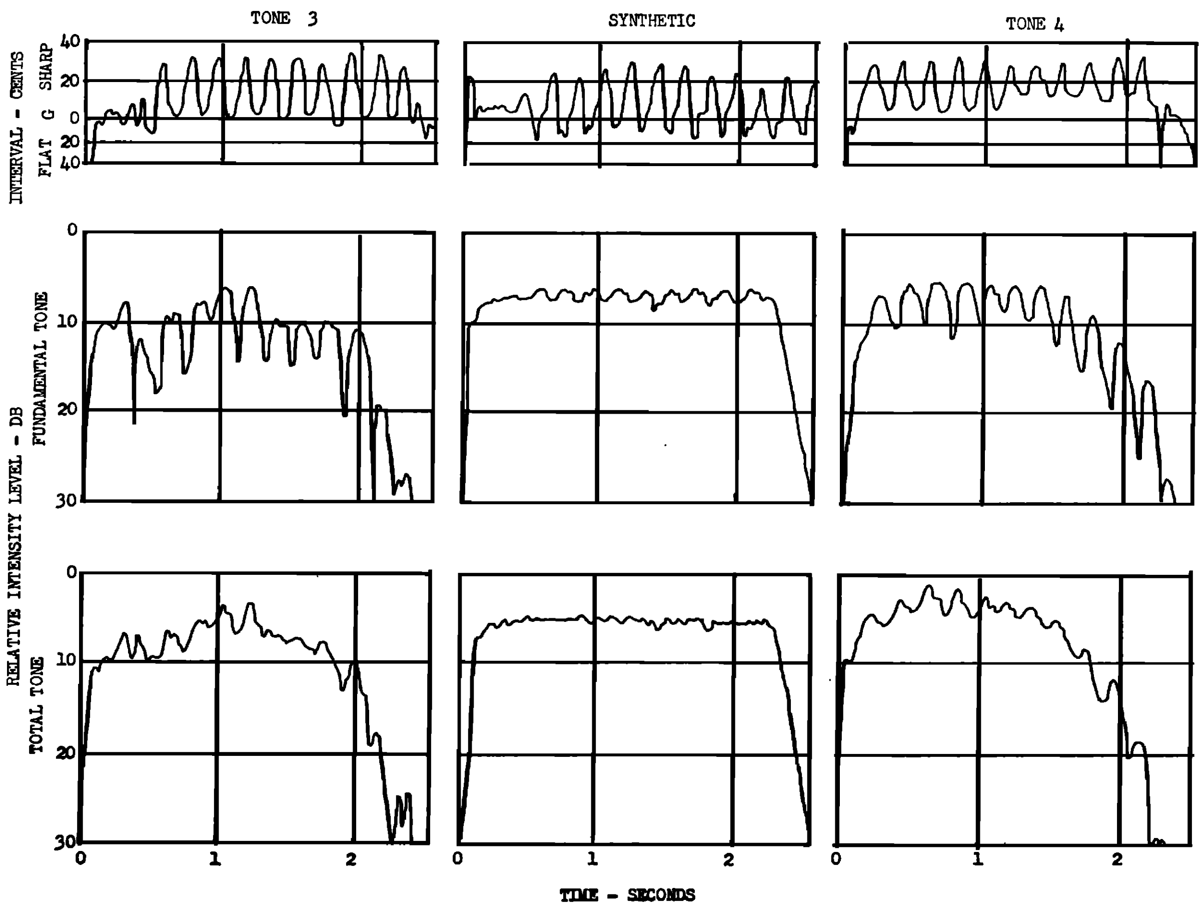

FIG. 3. Frequency and intensity level vs time for violin G.

by use of a reference oscillator and a Stroboconn, which measures frequency level to an accuracy of 1 cent.

With the exception of the Schmitt trigger, the system just described was composed of apparatus already at hand. Consequently, it was not possible to design the system for optimum performance and the amount of usable data obtained was limited. Some difficulty was caused by the slight hysteresis effect in the Schmitt trigger circuit. A new system is now being developed that will allow a more extensive investigation to be made.

Samples of these measurements are shown in Figs. 2–5, corresponding to G′, G, G_1, and G_2. In Fig. 2, the three top curves are for the frequency variations of the tone G′. The one at the left is for tone 1, the one at the right is for tone 4, and the one in the middle is for the synthetic tone representing G′. The second row gives the relative intensity level (decreasing downward) for the second harmonic of these three tones, and the bottom three curves show similar variations for the total tone. It is seen that there are no definite periodic fluctuations either in frequency or intensity. This tone was produced on an open string so no vibrato would be expected.

In Fig. 3, the results for G are given. It is seen here that there is a strong vibrato both in frequency and intensity level. The strong intensity vibrato may be due to the body resonance of the violin. As the frequency of the tone moves toward and away from resonance frequency, there are large changes in the amplitude of the fundamental. It will be noticed that such large changes did not occur in the synthetic tone. No device was available to produce a synthetic tone having a separate control of vibrato amplitude and frequency. This is discussed later. For G_1 and G_2, the vibrato of the synthetic tone was approximately the same as for the real tone. It is convenient to define the extent of the frequency vibrato as the average interval in cents between the maximum and minimum frequency. Also, the extent of intensity-level vibrato is the average difference in decibels between the maximum and minimum level. For example, in Fig. 3 the extent of the frequency vibrato for tone 3 is 33 cents, and the extent of the intensity-level vibrato is 8.2 dB. The vibrato rate is the average number of maximums per second. This is the same when either the intensity-level curve or the frequency-interval curve is used. For example, in Fig. 3, tone 3, the vibrato rate is 5.1/sec. Measurements of

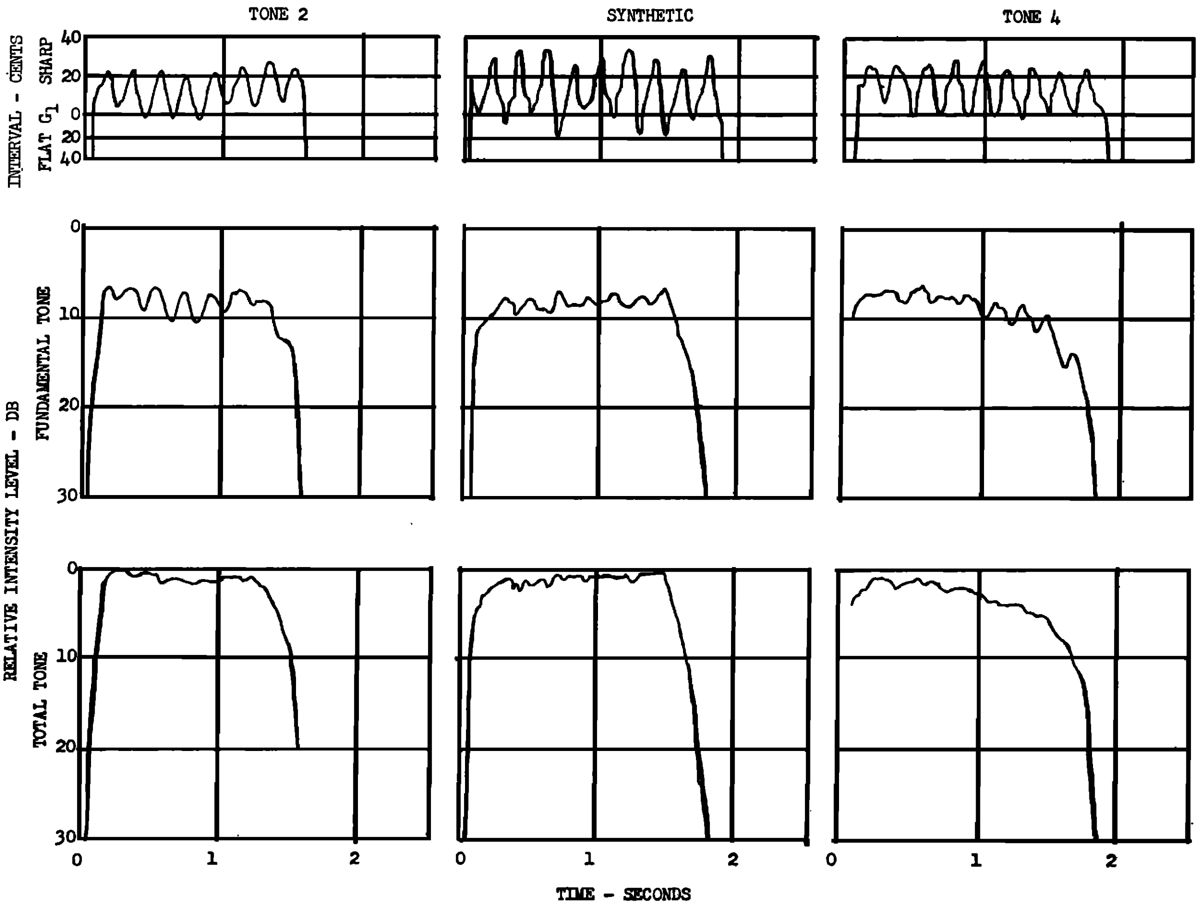

FIG. 4. Frequency and intensity level vs time for violin G_1.

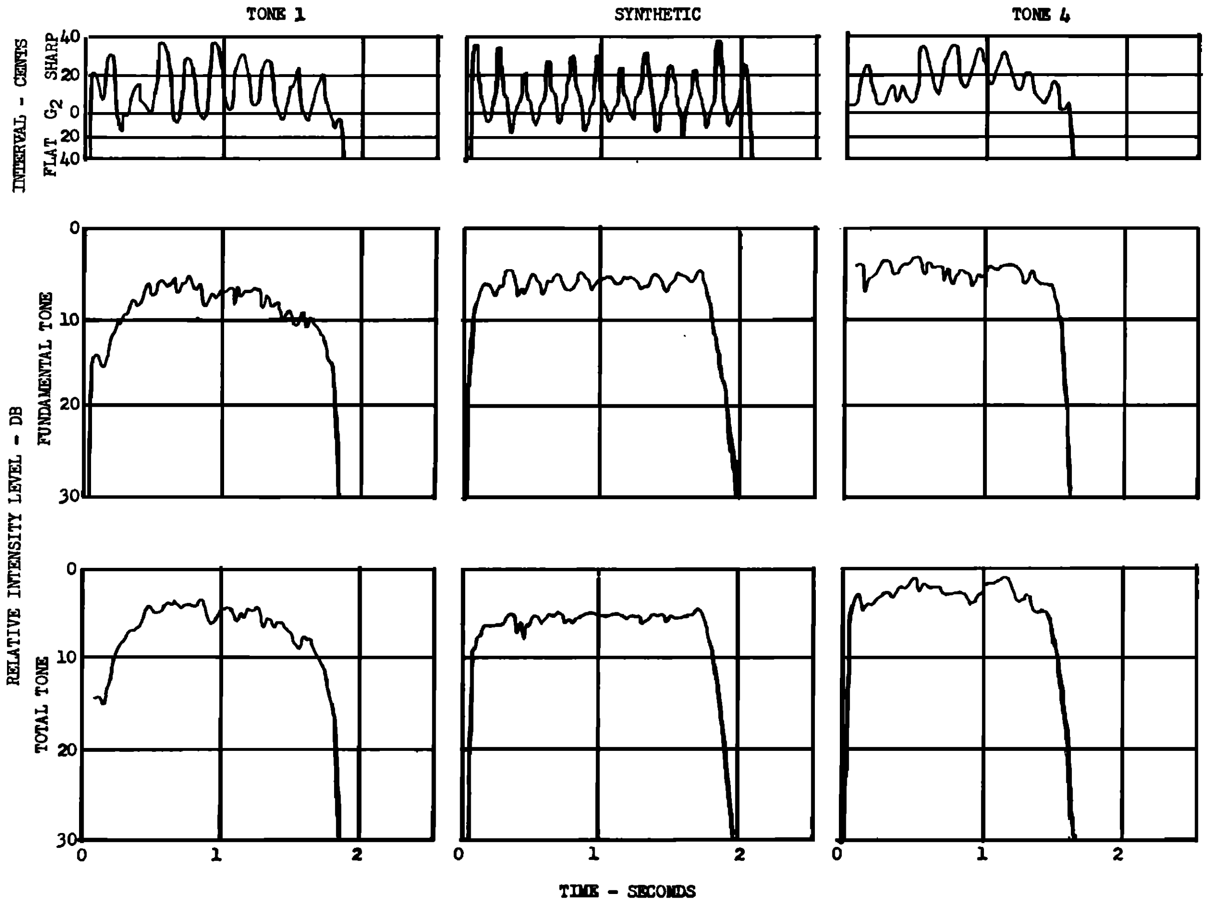

FIG. 5. Frequency and intensity level vs time for violin G_2.

these three vibrato characteristics were made on all 16 violin tones. The average values are shown in Table I.

It will be seen that the vibrato rate is approximately the same for the three different notes. This rate depends upon the player. These three notes when played by a different violinist gave values of 6.0, 6.4, and 6.5 max/sec.

III. ATTACK AND DECAY TIMES

The attack time (t_A) is defined as the number of seconds required for the relative intensity level to rise 20 dB. Likewise, the decay is defined as the number of seconds (t_D) required for a drop of 20 dB. Either of these two times cannot be measured precisely. For real tones, it is difficult to find either the first maximum or when the intensity level begins to make the final drop. So, the values shown in Table II can be considered only as approximate values. One must examine the attack curve to get a more accurate picture. For the synthetic tone, the attack curve can be drawn from one number and the decay curve from another one. If S is the setting on the dials of the attack and decay amplifier, then $t_A = 3.14S$ and $t_D = 1.24S$. These relations come from the characteristics of the attack and decay amplifiers.

IV. NOISE

There is always a noise produced by drawing the bow across the string. It is hardly noticeable for tones below G, but is definitely noticeable for tone G_1 and higher tones.

The intensity of the noise with respect to the tone was measured as follows: with the 4-cps-band analyzer,

TABLE I. Vibrato rates and extents for violin tones.

	Rate max/sec	Extent cents	Extent dB
G′	⋯	⋯	⋯
G	5.12	44±8	7.0±0.6
G_1	5.15	32±7	2.9±1.0
G_2	5.17	29±5	<1

TABLE II. Attack and decay times for violin tones.

Note	t_A (sec)	t_D (sec)
G′	0.2–0.3	0.5–1.5
G	0.07–0.2	0.5–0.7
G_1	0.08–0.2	0.4–0.5
G_2	0.08–0.10	0.2–0.25

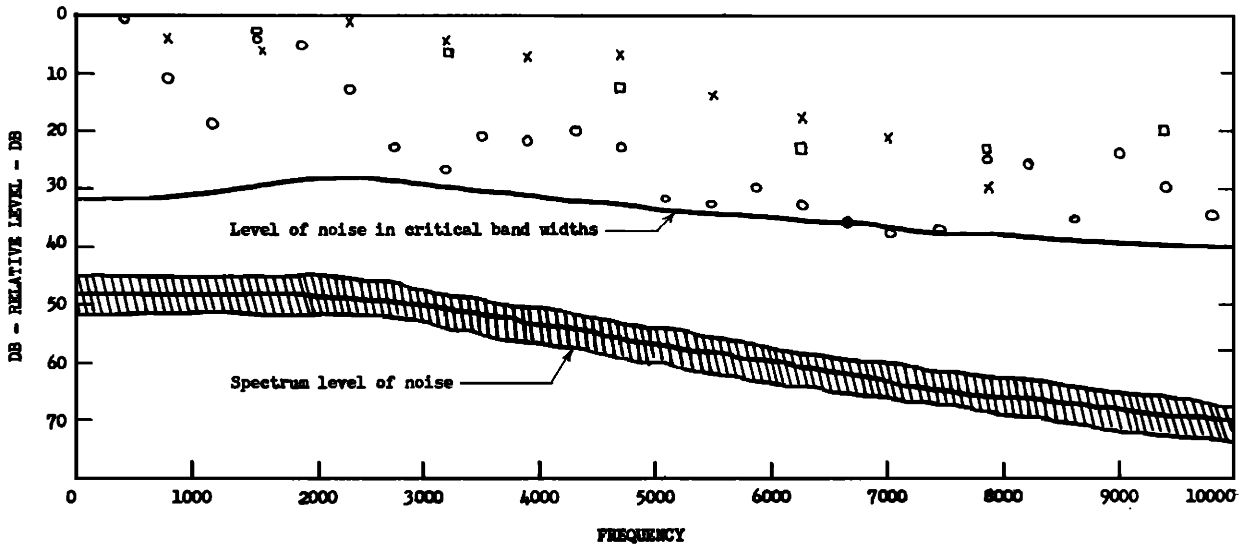

FIG. 6. Noise levels vs frequency for violin playing. Circles for partials of G, crosses for G_1, squares for G_2.

the levels of the noise compared to the level of each harmonic tone were measured. For a steady tone, the level through this filter will drop 60 dB if the frequency is changed 50 cps from the resonance frequency of the filter. Therefore only experimental values of level were considered due to noise when the frequency of the filter was set at least 100 cps different from that of any of the harmonics of the tone. The result of such measurements are shown in Fig. 6. The spectrum level was obtained by subtracting 10 log4=6 dB from the measured 4-cps

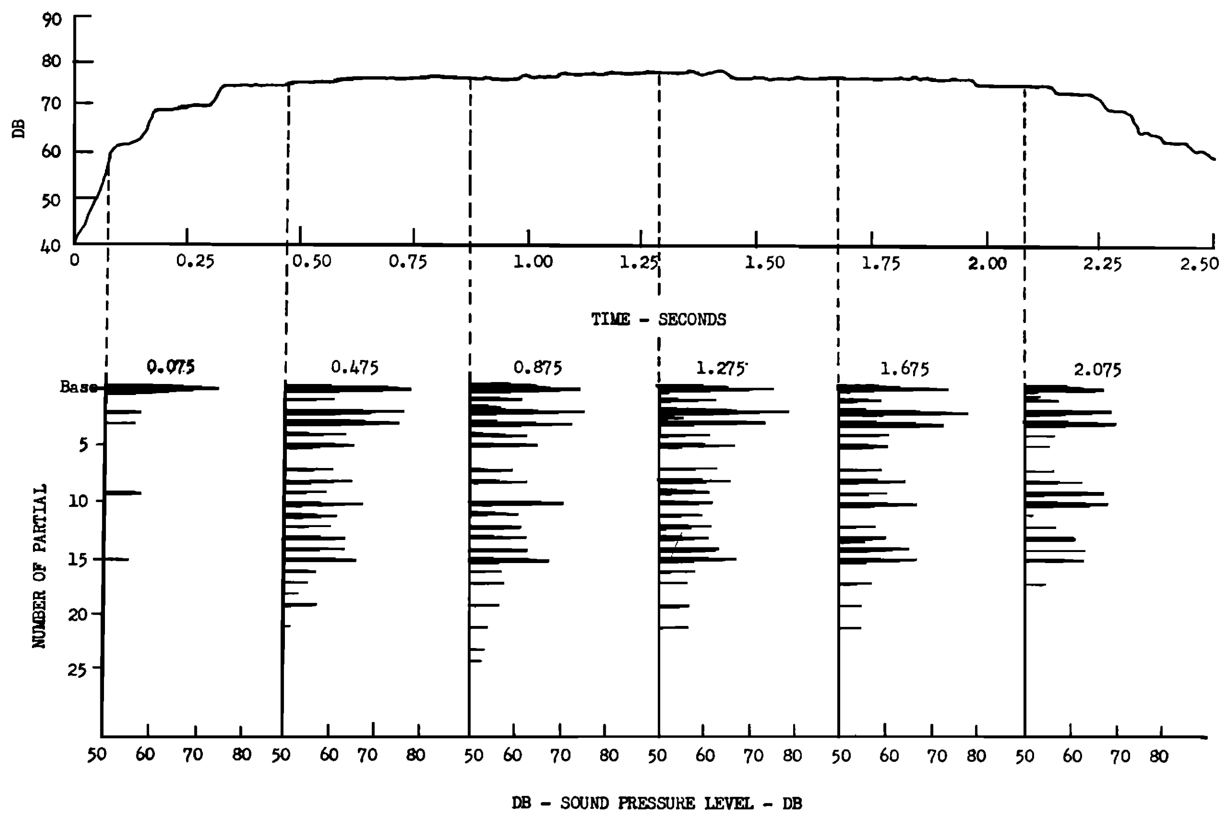

FIG. 7. Sonogram for G′, tone 4. The over-all sound-pressure level is plotted at the top.

level, and the critical-band level was calculated by adding 10 log$W/4$ to the measured level where W is the critical bandwidth[3] in cps.

The circles represent the levels of the partials of G whose fundamental frequency is 392 cps. Similarly, the crosses and the squares represent the levels of the partials for G_1 and G_2. Valid measurements on G′ could not be made, as the harmonics were too close together. It was presumed that the bowing-noise level is approximately the same for G′ as for the other notes.

An examination of Fig. 6 shows why for the tones G′ and G the noise is inaudible. The fundamental and the harmonics mask the noise. For both G′ and G, the noise that is lower in frequency than that for the fundamental is masked by the fundamental. However, this is not true for G_1 and G_2. For example, for G_2 the fundamental frequency is 1568 cps. When the sound-pressure level of this fundamental at the ear is about 80 dB, then it will not mask pure tones that have frequencies below 1000 cps and levels higher than 50 dB.

The noise in a critical band acts like a pure tone. So it is seen why the noise for G_2 is audible. The same is true for G_1. The tone G is on the border line so the noise is neither definitely audible or definitely inaudible.

A noise similar in character can be produced by drawing the bow across the bridge of the violin. This can be done without setting the strings into vibration. It was this noise that was used in the production of the synthetic tones.

V. PARTIAL-TONE STRUCTURE OF VIOLIN TONES

The frequencies of the partials in the steady tone were found to be harmonic—that is, integral multiples of the fundamental frequency. It has been seen that the fundamental and consequently all of the partial frequencies do not remain constant but are continually varying with time. For example, if the fundamental frequency varies 4 or 5 cps, the 10th harmonic varies 40 or 50 cps. For this reason, the partial tones would not remain long enough in the band of our analyzer to obtain accurate measurements. Therefore, the Sonograph was used for the analysis.

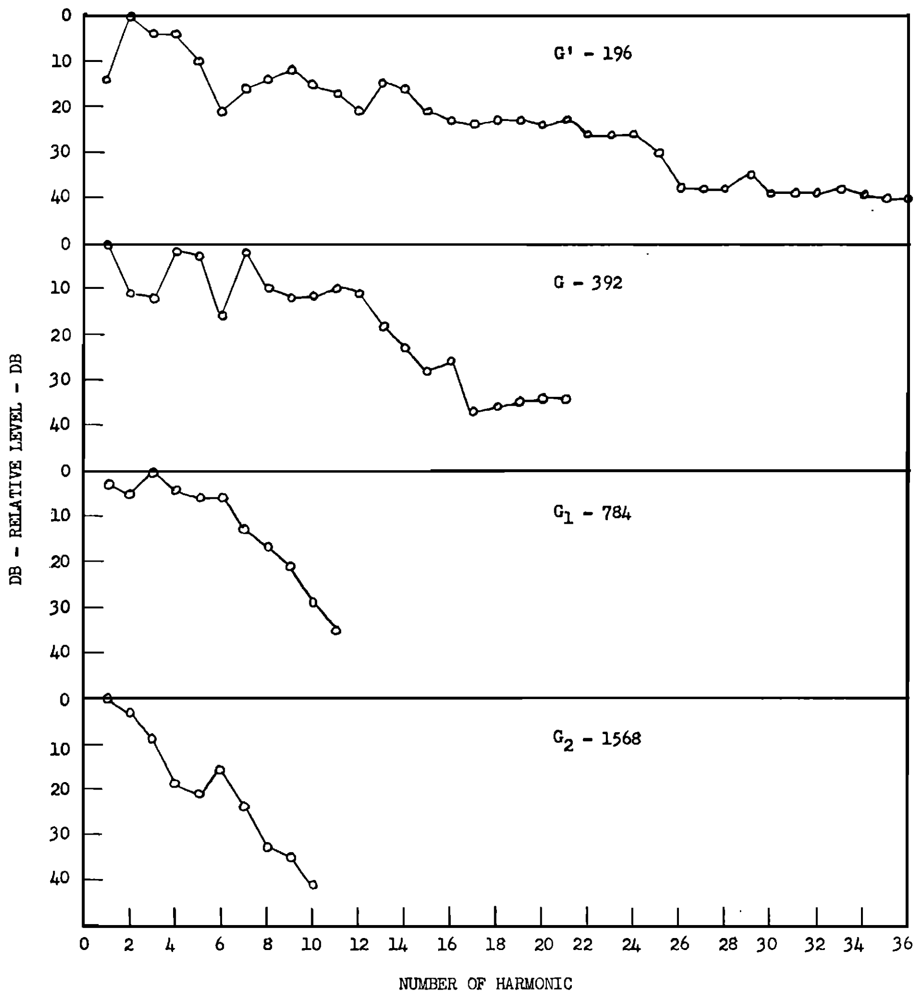

FIG. 8. Harmonic structure for violin tones.

[3] H. Fletcher, *Speech and Hearing in Communication* (D. Van Nostrand Co., Inc., New York, 1953), p. 101.

TABLE III. Relative level in dB of partials of violin tone G_1.

	Tone 1 Time (sec)						Tone 2 Time (sec)					Tone 3 Time (sec)					Tone 4 Time (sec)				
Partial	0.04	0.44	0.84	1.24	1.64	1.88	0.02	0.34	0.66	0.98	1.20	0.05	0.45	0.85	1.25	1.65	0.02	0.42	0.82	1.22	1.62
1	32	37	43	44	37	30	19	42	40	42	34	33	38	42	43	40	28	44	42	40	33
2	27	38	40	39	35	31	21	28	37	38	32	32	37	38	41	37	26	41	41	38	32
3	29	40	41	43	35	31	27	45	42	43	36	31	37	39	41	36	30	45	43	40	34
4	24	33	30	33	19	23	19	38	36	35	39	30	39	34	37	32	26	43	42	40	35
5	28	32	29	32	27	22	15	34	33	31	21	25	33	32	27	25	24	38	37	36	29
6	20	31	30	32	25	23	14	31	31	31	22	20	29	29	31	38	17	31	34	30	23
7	8	18	20	27	23	14	7	25	24	26	17	11	24	27	24	21	13	25	27	23	13
8	···	19	19	26	17	7	···	19	14	17	···	7	11	23	22	16	9	8	18	17	13
9	···	16	18	17	16	4	···	23	28	16	···	6	9	17	21	16	4	22	20	15	10
10	9	17	15	20	15	···	···	23	10	10	7	11	13	12	19	16	9	16	16	12	16

The recorded tones were sent to the Sonograph, which makes an analysis and a record similar to that shown in Fig. 7. The record shown is for G′, tone 4. The lengths of these spikes in millimeters give the relative levels of the partials in decibels. The sound-pressure levels plotted as abscissas were obtained from the relative levels and the total sound-pressure level 5 or 6 ft from the violin. The time from the beginning of the tone to when the section was taken is shown at the top for each section in Fig. 7. The time position of each section is given by the top curve.

In this way, the harmonic tone structure of the violin tones was obtained. The results are given in Fig. 8. These curves give an oversimplification of the data. For example, in Table III data taken from the Sonogram are given. These are the data for the four tones of G_1 on the violin. The time in seconds from the beginning of the tone is given at the top of each Table. The num-

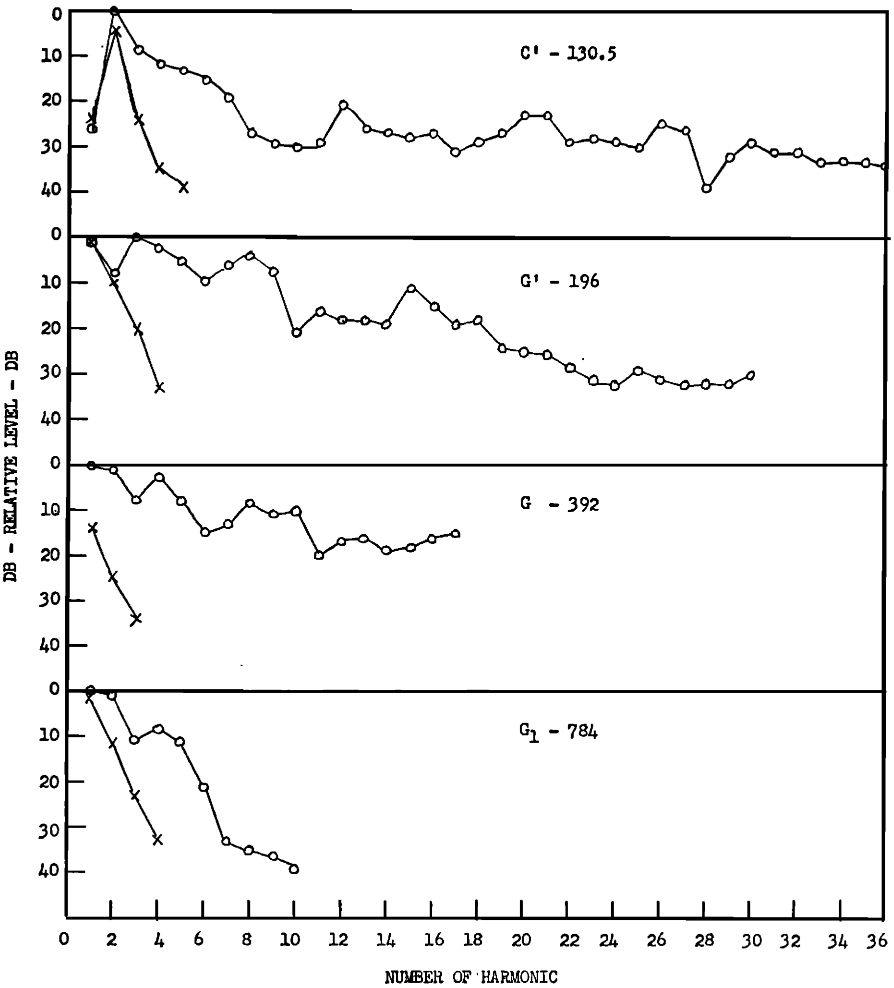

FIG. 9. Harmonic structure for viola tones.

TABLE IV. Attack and decay times in seconds from sonograms for violin, viola, 'cello, and bass viol.

	Tones	Attack 1	2	3	4	Synthetic	Decay 1	2	3	4	Synthetic
Violin	G′	0.4	0.15	0.3	0.3	0.3	0.24	0.5	0.6	1.5	0.9
	G	0.08	0.07	0.10	0.15	2.5	0.5	0.5	0.7	0.7	0.7
	G_1	0.08	0.10	0.08	0.10	0.15	0.5	0.4	0.4	0.4	0.4
	G_2	0.05	0.10	0.08	0.07	0.10	0.2	2.5	0.2	0.2	0.3
Viola	C′	0.25	0.5	0.27	0.3	0.29	0.5	0.7	0.96	0.8	0.6
	G′	0.4	0.4	0.35	0.5	0.45	1.1	0.9	0.8	0.9	0.9
	G	0.5	0.5	0.5	0.3	0.4	0.8	0.5	0.7	0.7	0.5
	G_1	0.25	0.3	0.23	0.25	0.25	0.42	0.54	0.26	0.36	0.4
'Cello	G″	0.6	0.8	0.6	0.6	0.7	1.6	1.6	1.7	1.8	1.7
	G′	0.6	0.7	0.5	0.6	0.7	1.4	1.5	1.5	1.4	2.2
	G	0.4	0.2	0.3	0.6	0.5	0.54	0.5	0.6	0.5	0.7
	G_1	0.1	0.13	0.2	0.18	0.2	0.16	0.8	0.2	0.22	0.2
Bass Viol	G‴	0.5	0.2	0.25	...	0.3	0.5	1.5	1.5	...	1.0
	G″	0.4	0.25	0.18	0.17	0.4	0.9	1.2	0.9	0.9	0.85
	G′	0.3	0.25	0.25	0.6	0.5	1.1	1.1	0.7	1.2	0.7
	C										

bers under each time give the relative level of the partials at this time. It is seen that in the central portion of the time the level of each harmonic remains approximately constant. This is shown by the fact that the number along a horizontal line remain essentially constant, except for the first and last column. Therefore,

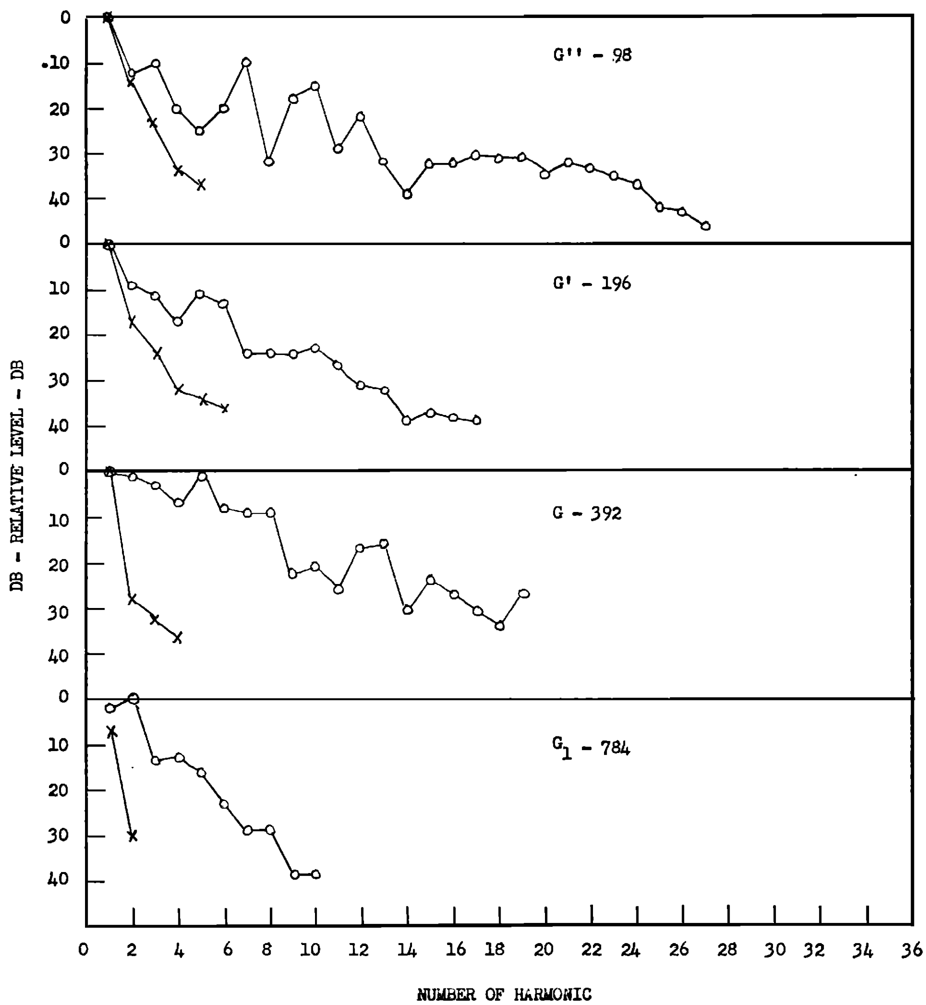

FIG. 10. Harmonic structure for 'cello tones.

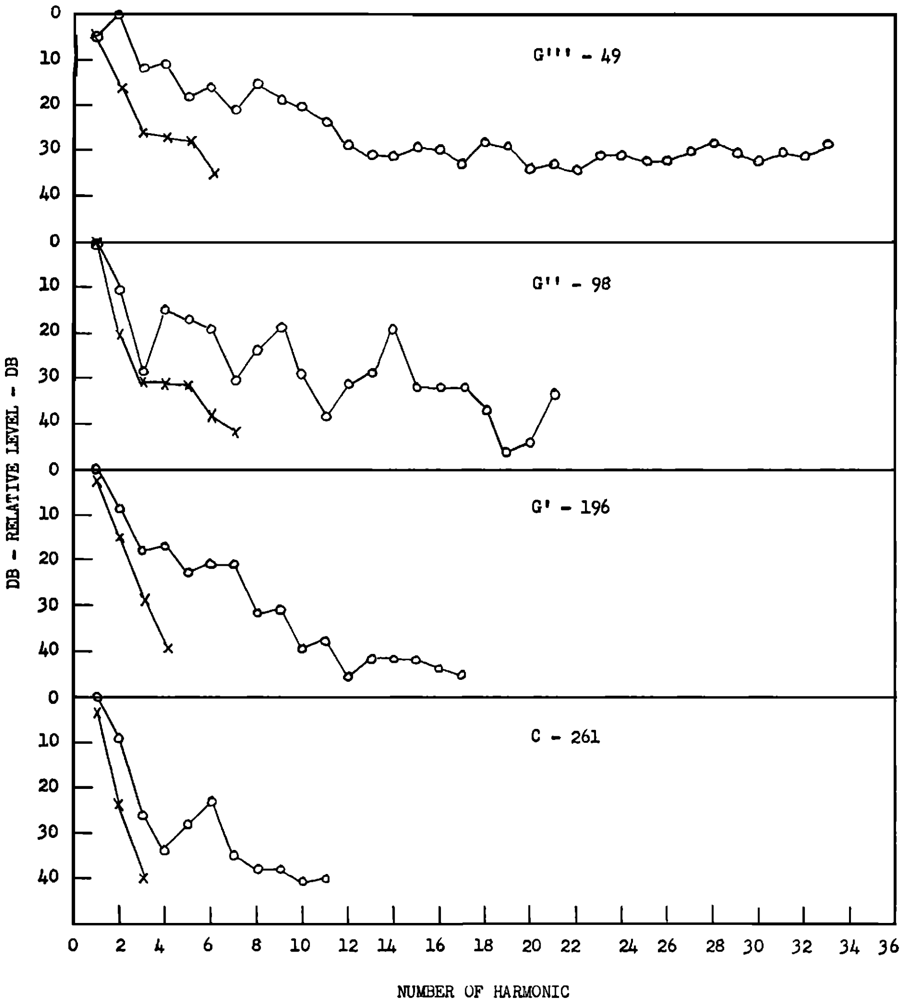

FIG. 11. Harmonic structure for bass-viol tones.

averages of these levels for each partial were taken on each of the four tones. The data were then normalized so that the highest level was made zero. The values thus obtained were plotted and are represented by the curve for G_1 in Fig. 8. So, the circles in these curves represent an average of about 16 observed values. Similar data were taken on four tones for G′, G, and G_2. From these data, the other three curves in Fig. 8 were obtained.

An examination of the ending of these tones indicated that when the bow is removed the partials of higher frequency decay much faster than the fundamental. Consequently, at the end of the tone there is a ring that has a different quality than the main part of the tone as shown by these curves. The structure of this ring consists of the fundamental and 3 or 4 partials only. For this reason, the ring at the end was added to the G′ synthetic tone. For the other synthetic tones, the partial-tone structure was held constant from the beginning to the end of the tone. The harmonic structures used for these synthetic tones were those shown by the four curves in Fig. 8. For these tones, the logarithmic attack and decay-time characteristics shown in Table IV and vibrato characteristics that best matched the real tones were used.

VI. ANALYSIS OF VIOLA, 'CELLO, AND BASS-VIOL TONES

The procedure of analyzing these tones was the same as that described for violin tones. Since considerable difficulty was encountered both in the analysis of these and synthesis of vibrato tones from these instruments, only those tones without vibrato were used in the investigation that is reported in this paper. New work on vibrato tones will be reported in a separate paper.

For the viola, the notes C′, G′, G, and C_1 were used. For the 'cello, the notes G″, G′, G, and G_1 were used, and for the bass viol the notes G‴, G″, and G′ and C were used. The harmonic structures of the tones for these three instruments are given by the curves in Figs. 9–11. The circles connected by the solid line represent the values for the central part, and the crosses are for the ending or ring part.

The wide-band sound-pressure level versus time for these tones is shown by the curves in Figs. 12–14.

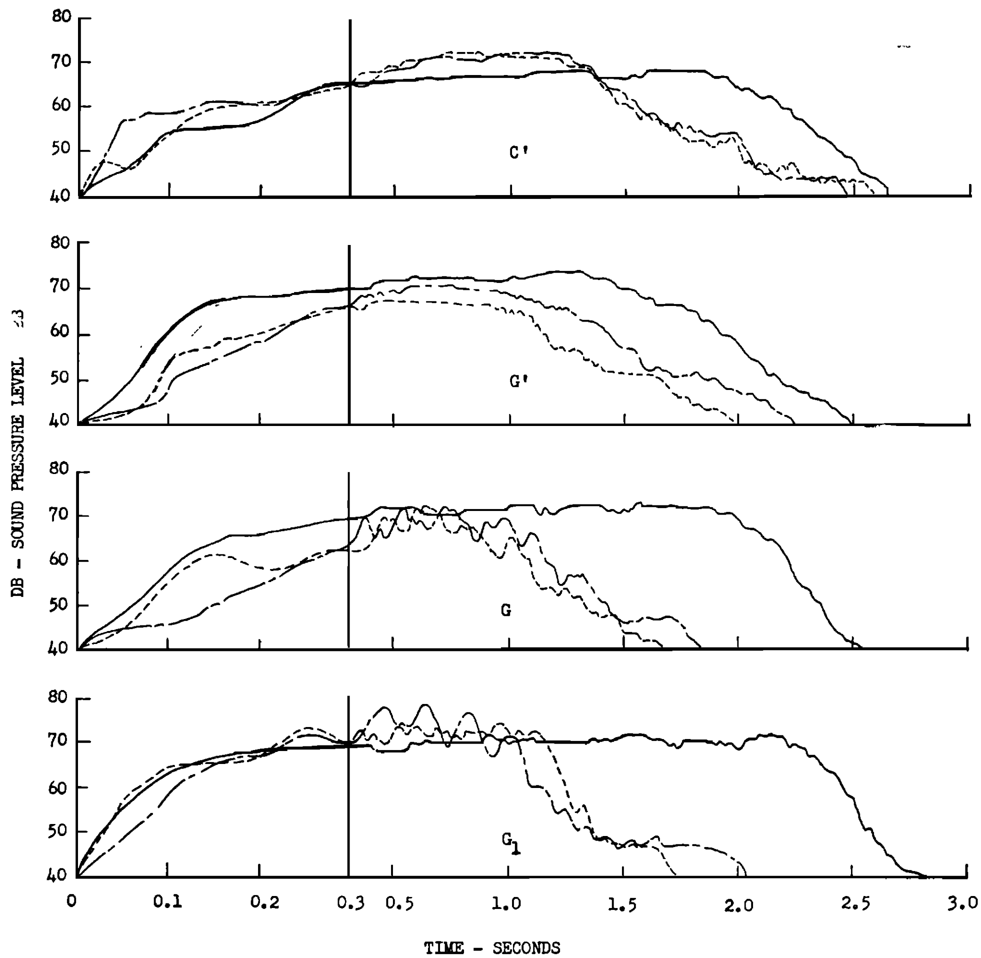

FIG. 12. Sound-pressure level vs time for viola tones. ---- Real tone. — — — — Real tone. ——— Synthetic tone.

The solid curves represent the synthetic tones. The dotted and the dashed curves represent two typical real tones. It is seen that the duration of the real viola tones was somewhat shorter than the synthetic tone. However, this is not important in the identification of the tones.

In general, it was found that the background noise for these tones was not noticeable. However, in playing a musical selection, particularly when plucking the strings is employed, there is a very definite background noise. The slapping of the strings against the body of the bass viol makes rather loud chatter. However, for the synthetic tones used here, it was not necessary to introduce background noise.

VII. CONSTRUCTION OF THE SYNTHETIC TONES

The harmonic structures for the ending were first set up on our synthesizer.[1] The attack was set to be slower than that shown by the sound-pressure-level versus time curves, but the decay was set so that it matched these curves for the ending. Also, the length of the tone was made about the same as that shown by the curves. The tone thus created by the synthesizer was recorded on our tape machine. This machine was arranged so that the eraser could be removed and a second recording made.

So, the harmonic structure shown under the caption "synthetic tone—middle part" was set up on the synthesizer. The attack for this tone was made to match approximately that shown by the level-versus-time curves and the decay made to be much quicker than that shown by these curves. The duration time was made about the same as for the real tone. The tone thus tailored was recorded directly over the recording of the ending tone described above. In this way, the combination of the two tones was made to sound very similar to the real tone. It will be seen from the tests described below that synthetic tones produced in this manner could not be readily distinguished from the real tones.

The vibrato for the synthetic tones of the violin was produced as follows. After the tone was tailored and recorded as described above, it was then rerecorded. During this rerecording, a transverse vibration was given to the tape at a position 5 or 6 in. ahead of the recording head. This gave enough change in speed to

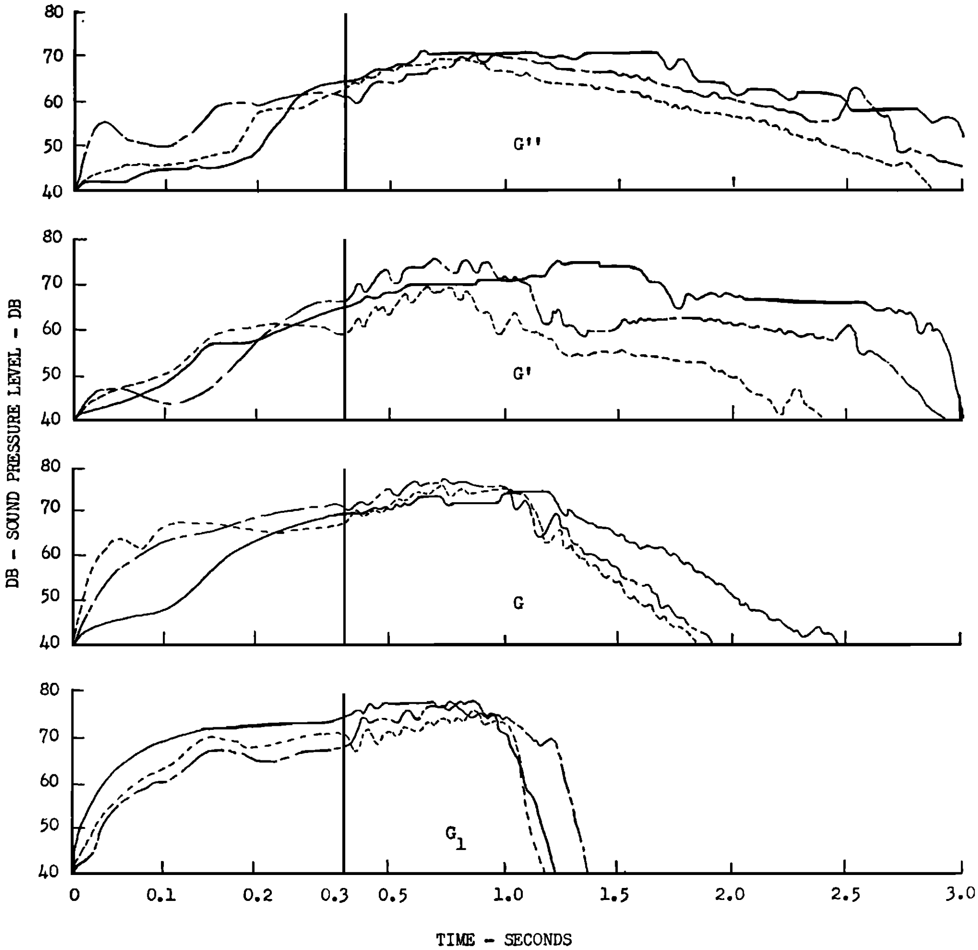

FIG. 13. Sound-pressure level vs time for 'cello tones. ---- Real tone. — — — — Real tone. ——— Synthetic tone.

produce the desired vibrato. As stated above, this turned out too unsatisfactory, because it left out the intensity vibrato. However, the violin tones were included in these identification tests.

III. IDENTIFICATION TESTS

A record of identification tests in the form of a tape recording was made so that the string tones described in this paper occurred in a haphazard manner: namely, 16 violin tones, 16 viola tones, 16 'cello tones, and 16 bass-viol tones. These were interspersed with a similar number of synthetic tones, making a total of 128.

A jury of 7 musicians and 7 nonmusicians made the test in an anechoic room. The tones were numbered from 1 to 128 and presented to the jurors through our high-fidelity loudspeaker system.[1] The results of these tests are given in Table V.

The numbers in this Table give the percent of tones (either real or synthetic) that were presented that were called real by the jurors. Since there were 14 jurors and each note was presented 4 times, there were 56 presentations of real tones and 56 presentations of synthetic tones. Thus, each number in this Table is the percent of 56 that the tone was judged to be real. For example, for G′ the jurors judged 33 real tones to be real. They also judged 23 real tones to be synthetic. Likewise, 50 synthetic tones were judged to be real and 6 synthetic tones were judged to be synthetic. This

TABLE V. Percent of times presented that either real or the synthetic tones were called real tones in identification tests.

	Tones															
	Violin				Viola				'Cello				Bass Viol			
Note	G′	G	G_1	G_2	C′	G′	G	G_1	G″	G′	G	G_1	G‴	G″	G′	G
Real	59	58	51	57	75	79	77	58	75	71	79	64	81	58	58	64
Synthetic	89	27	36	16	59	54	44	41	69	52	52	58	58	65	59	56

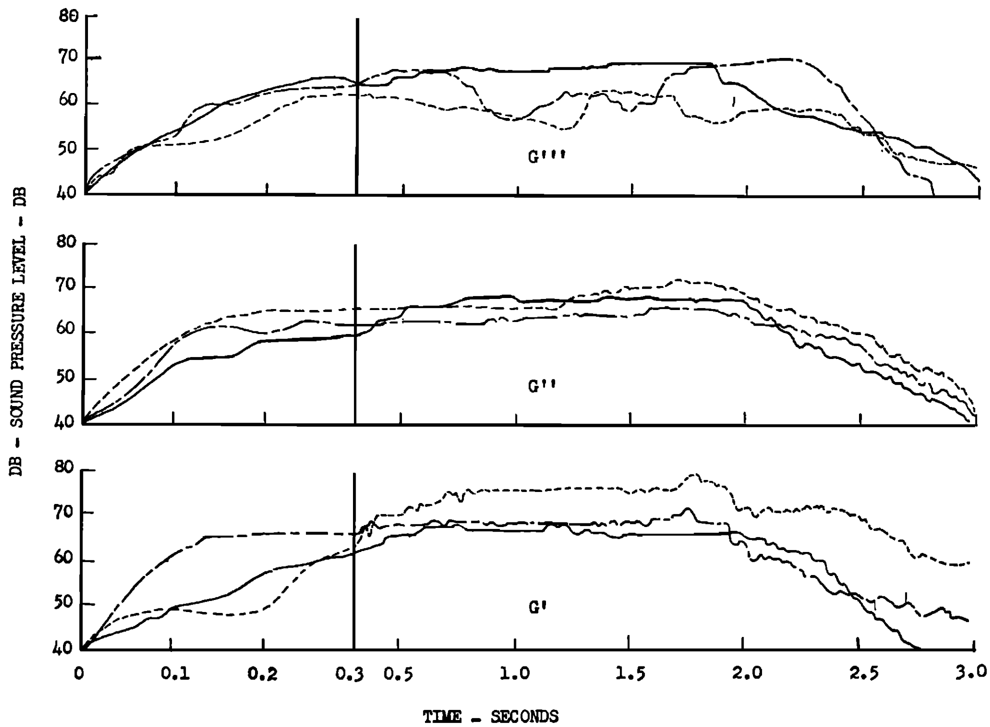

FIG. 14. Sound-pressure level vs time for bass-viol tones. ---- Real tone. — — — - Real tone. ——— Synthetic tone.

shows that the synthetic G′ violin tone was considered a true violin tone. This tone was played on the open string and had no vibrato; this was not true for the other three violin tones, G, G_1, and G_2, that had a vibrato. With the exception of the viola G and G_1, the synthetic tones for viola, 'cello, and bass viol were called real somewhat more than one-half the times presented; a score of near 50% indicates that the element of guessing was considerable.

From the study herein discussed, it is concluded that:

• As far as this study went, the frequency of the partials were found to be harmonic.

• Inharmonicity of the steel string was not observed to be a factor in the synthesis of a tone; probably this aspect of the quality needs further study.

• The characteristics, essential to describing a tone, are the harmonic structure of the middle portion of the tone, the harmonic structure of the ending of the tone, the vibrato (when present) of the tone, and the noises inherent in the mechanics of producing the tone.

• Tones without vibrato can be synthesized very satisfactorily; we feel that, with further study, tones having vibrato can be synthesized.

ACKNOWLEDGMENT

We wish to acknowledge the assistance of Kenneth Rogers in the development of the apparatus for measuring the frequency and intensity level vibrato of violin tones.