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Quality of Violin Vibrato Tones

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Typical violin tones with vibrato were recorded on magnetic tape. From a special analysis, synthetic tones were constructed that were very difficult to distinguish from real tones. The analysis showed that not only the frequency was varying up and down about six times per second, but there were three other important characteristics varying at this same rate. All of the harmonics had the same variation of the frequency level, in cents, from the note being played. There was also an intensity-level variation of the harmonics at the same vibrato rate, but the intensity-level variation was greatly different for different harmonics. Also, the intensity of some of the harmonics would be rising while that of others would be falling during the vibrato period. Thus, a curve showing the relative intensity level of the harmonics at any instant changed back and forth during the vibrato cycle. The intensities of the sympathetic tone coming from the open strings also varied either at the vibrato rate or twice the vibrato rate, while the frequencies of these tones remain constant and correspond to the natural frequencies of the fundamental and harmonics of the open strings. The after-ring is due principally to these transient tones. This effect is negligible when the frequencies of the fundamental and its harmonics are not close to those of the open string.

INTRODUCTION

IN an earlier paper,[1] the quality of nonvibrato violin tones was discussed. From the physical measurements that were made, synthetic tones were produced that could not readily be distinguished from real tones. However, with the data and apparatus available, the synthetic tones having vibrato that were produced could readily be distinguished from real tones. Therefore, it was assumed correctly that some of the important characteristics of these tones had not been detected or measured.

Since then, new apparatus and techniques have been developed that make it possible to measure more accurately the important quantities that vary periodically at the vibrato rate, usually five or six times per second.

In our investigation, there were four quantities varying at the vibrato rate that were considered important in the determination of the quality of the tone. The first is the variation of the frequency level which is recognized by the ear as a pitch change. It is the same for all of the harmonics of the bowed string. The second is the variation of the intensity level, and this is widely different for the different harmonics. The third is a variation of the harmonic structure, that is, the relative amplitudes of the harmonics change periodically at the vibrato rate. The fourth is a complex tone coming from the open strings induced by a sympathetic vibration with the bowed string. Then there are three other quantities not related to the vibrato that affect the quality of the tone, namely, the beginning and the ending of the tone, and the noise produced by the bowing of the string. The first six quantities are represented by curves, and the last by an acoustic spectrum.

I. FREQUENCY-LEVEL-VS-TIME CURVES (FLV)

The frequency level is measured in cents, the reference or zero level being the frequency level corresponding to the frequency of the note being played. It is represented by a curve showing the frequency level in cents vs the time in seconds. On a curve representing a tone having a vibrato rate of 6/sec, there will be six maxima and six minima for every second of time. The frequency level difference between the maximum and minimum is called the extent,[2] in cents of the vibrato. A typical vibrato extent is about 30 cents, but it varies between 10 and 60 cents. It was found that the FLV curves for all the harmonics were similar in shape and extent, so that one curve can represent the variation in frequency level for all the harmonics.

[1] H. Fletcher, E. D. Blackman, and O. N. Geertsen, "Quality of Violin, Viola, Cello, and Bass Viol Tones," J. Acoust. Soc. Am. 37, 851–863 (1965).

[2] C. E. Seashore, *In Search of Beauty in Music* (Ronald Press Co., New York, 1947), Chaps. 5 and 13.

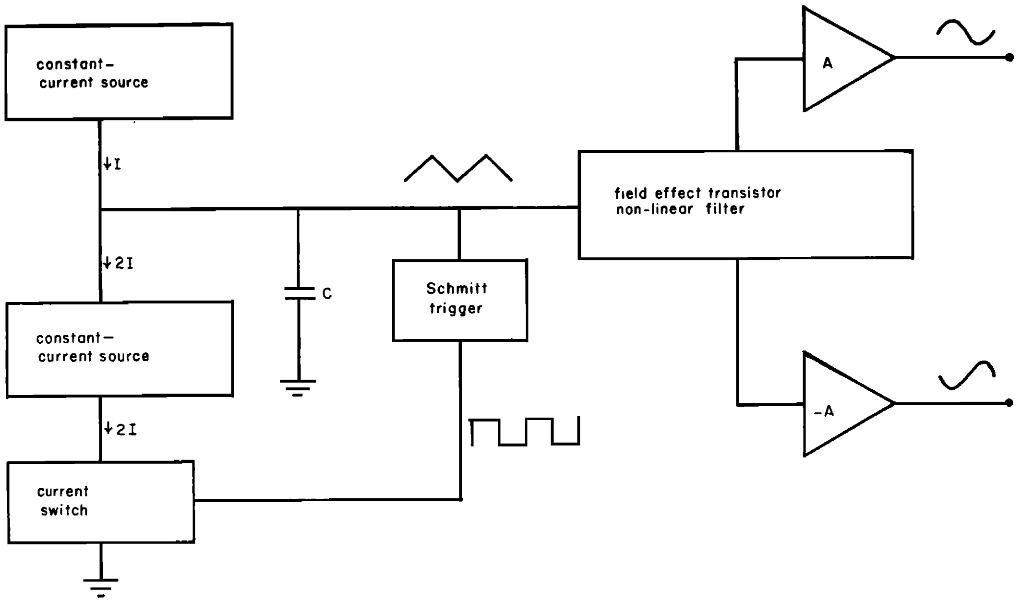

FIG. 1. Vibrato control oscillator circuit.

II. INTENSITY-LEVEL-VS TIME CURVES (ILV)

The intensity level of each harmonic is varying at the vibrato rate. It was found that both the shape and the extent of this variation was different for each harmonic. So, a series of curves of intensity level vs time are necessary to represent this aspect of the vibrato. The extent of the intensity level vibrato may be 0 dB for one harmonic and as much as 20 dB for another one in the same tone. Also, for some of the harmonics, the intensity level is increasing while at the same time it is decreasing for others. In other words, there is a phase difference in the variation of the amplitudes of the various harmonics. As a consequence of this, the harmonic structure (the relative intensity levels) at one instant of time is different from that at a short time before or after this instant of time.

III. HARMONIC-STRUCTURE VS TIME CURVES (HSV)

The harmonic-structure curves can be constructed from the ILV curves just described above. At any given time corresponding to a common point on the time abcissa, the value of the intensity level for each harmonic is the value of the ordinate corresponding to this common abcissa point. If curves are taken at times corresponding to every maximum and minimum intensity level, then to represent a tone 4 sec long with a vibrato rate of 6/sec would require 48 such curves. However, it was found that those corresponding to the maximum were very similar and that those corresponding to the minimum were also very similar. These two sets of curves are not only at different levels but have different shapes.

IV. SYMPATHETIC TRANSIENT TONE (STT)

When any string is bowed, it creates vibrations in the other three open strings. Usually, these are so low in amplitude that they affect the total tone quality by only a very small amount. However, when the frequencies of the bowed string coincide with those of the open string, tones from these strings may become comparable in level to those emitted by the bowed string. When the bowed string is constant in frequency, this (STT) becomes part of the harmonic structure. But when vibrato is present, transient tones are produced with all of their harmonics, which rise in amplitude twice for every vibrato cycle—once when the frequency of bowed string is rising and passes through the resonance frequency of the open string and again when it is lowering and goes through the resonance frequency. The open string acts as though it had been plucked twice for every vibrato cycle. Between each pair of maxima, it decreases to a lower level, depending upon the damping of the open string. This transient tone will produce a characteristic after-ring unless the player dampens it.

Superimposed upon the tone proper is the noise due to bowing the string, which has a characteristic spectrum and pattern. For the notes of lower frequency, this noise is usually inaudible, but it is very noticeable for the notes of higher frequency. In addition, there are a characteristic beginning and ending of the tone, which contribute to its quality.

V. APPARATUS AND METHODS OF MEASUREMENT

Objective measurements of these quantities influencing the tone quality were obtained upon typical vibrato violin tones. These measurements were obtained with

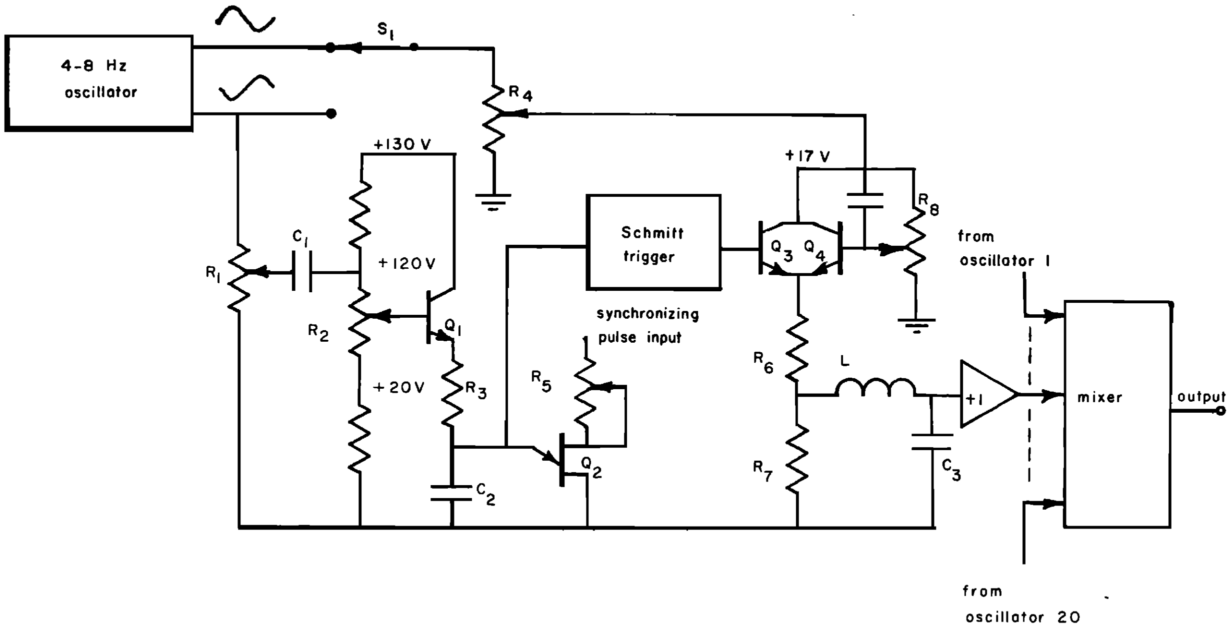

FIG. 2. Schematic circuit for the vibrato synthesizer.

the apparatus described in a previous paper[3] plus some additions and improvements, which are now described.

A. Vibrato Synthesizer

In the vibrato synthesizer, the vibrato control signal is generated by the 4–8-cps oscillator diagramed in Fig. 1. The oscillator consists of a constant-current source charging a capacitor C. The capacitor is periodically discharged by another constant-current source. A Schmitt trigger with a large, adjustable hysteresis senses the voltage on the capacitor and controls the discharging current. The triangular wave generated across the capacitor is shaped by a nonlinear filter that uses[4] a field-effect transistor as the active device. The sine-wave output is available from each of two amplifiers with one output in phase opposition to the other.

The output of the 4–8-cps oscillator is used to frequency-modulate the relaxation oscillator formed by R_3, C_2, and Q_2 in Fig. 2. A synchronizing pulse derived from the first oscillator is fed to the top of R_5, along with a supply voltage. The negative synchronizing pulse serves to reset periodically the relaxation oscillator to the beginning of each cycle. R_5 serves as a fine frequency control for each oscillator, while R_2 is a coarse control varying the frequency of all the oscillators. The output of Q_2 is shaped with a Schmitt trigger to provide a symmetrical square wave in which even harmonics have small amplitudes. This simplifies the filtering that is done later. Q_3 and Q_4 act as a clipper which, by varying the clipping level, modulates the amplitude of the signal as illustrated in Fig. 3. L and C_3 filter the signal, delivering a sine wave of the fundamental frequency to a unity gain amplifier which feeds a mixer. The output signal from this synthesizer consists of 20 components that are frequency modulated by a 4–8-cps sine wave. The first 10 components are periodically phase locked with the first, but the remaining 10 follow the frequency variations of the first but are not phase locked by the synchronizing circuit. The amplitude modulation of the components is individually adjustable and the phase of the modulating signal is individually selectable to be either in phase or out of phase with the frequency-modulation signal. The selectable phase feature is in the

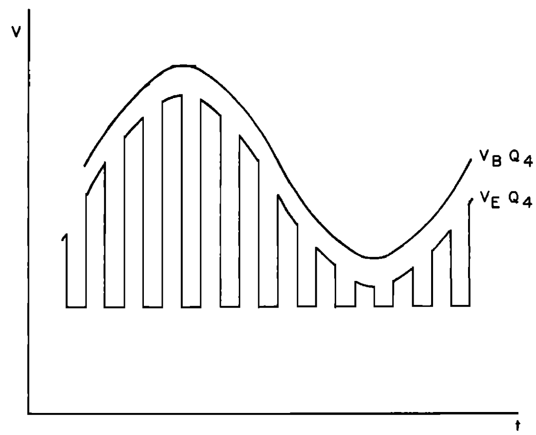

FIG. 3. Output waveforms of modulator.

[3] H. Fletcher, E. D. Blackman, and R. Stratton, J. Acoust. Soc. Am. 34, 749–761 (1962).
[4] R. D. Middlebrook and I. Richer, "Nonreactive Filter Converts Triangular Waves to Sines," Electronics 38, 96–101 (8 Mar. 1965).

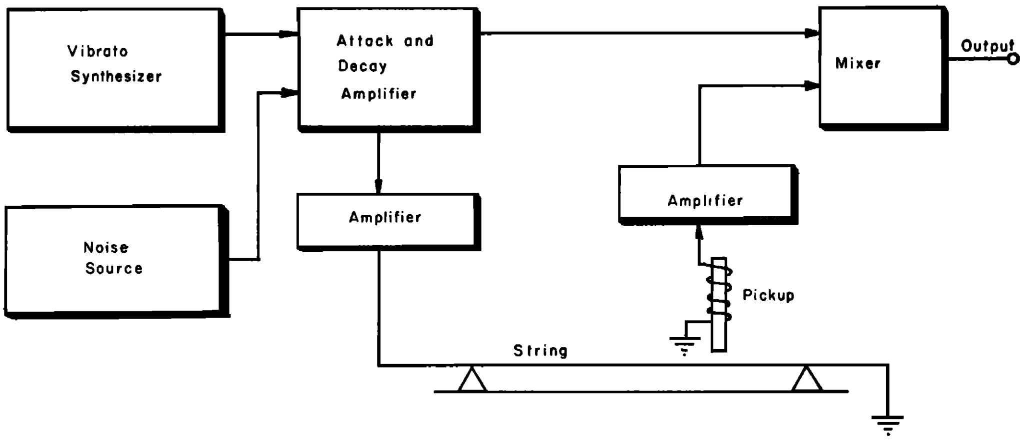

FIG. 4. General circuit arrangement.

first six oscillators only. The amplitude of each component is individually adjustable.

It must be pointed out that the synthesizer described here does not represent the best possible instrument for this type of work. The process of periodically phase-locking the relaxation oscillators generates small spurious signals that can be troublesome if the frequency of each oscillator is not carefully adjusted. A system using a series of oscillators incorporated in a phase-locking loop would probably be more satisfactory.

The general arrangement of the system used to measure the violin tones remains as described previously,[1] with the exception that the Schmitt trigger and the variable bandpass filter have been replaced by improved models. The variable bandpass filter currently in use is a General Radio type 1900A, which has a band pass of 3, 10, or 50 cps. The Schmitt trigger circuit, that described by Robinson,[5] has a hysteresis of only 10 mV. The previous Schmitt trigger had a hysteresis of about 200 mV. The general arrangement of the system for producing synthetic tone is shown in Fig. 4.

B. Production of the Violin Tones

The violin tones were produced by the concertmaster of the Brigham Young University orchestra in our anechoic chamber where no audible noise or noticeable reverberation was present. The tones were recorded on an Ampex model 350 tape recorder. These recorded tones then were used for analysis and for the real tones in the identification tests.

To illustrate the type of record obtained, the violinist was asked to play $1\frac{1}{2}$ oct of the chromatic scale starting with C on the G string. In Fig. 5 is shown a record of the (FLV) and (ILV) for the total tone. It is seen that most of these notes were played flat. However, owing to the frequency vibrato, the tones went through a level corresponding to the exact frequency represented by the zero line. The time scale is shown on the bottom of the figure. It is seen that the duration of the tones was about $2\frac{1}{2}$ sec and the vibrato rate about 6/sec.

These curves are reproductions of the actual curves drawn by the level recorder. On the original curves, 1 mm corresponded to 1 dB. The FLV scale shows the departure in cents from the level corresponding to true frequency. It is not linear with the millimeter scale. The calibration curve for the discriminator[1] is shown in Fig. 6. If this is taken into account, it is found that the extent of the FLV is between 35 and 50 cents and is about the same for all of the notes. In contrast to this, the extent of the intensity level varies from 9 dB for

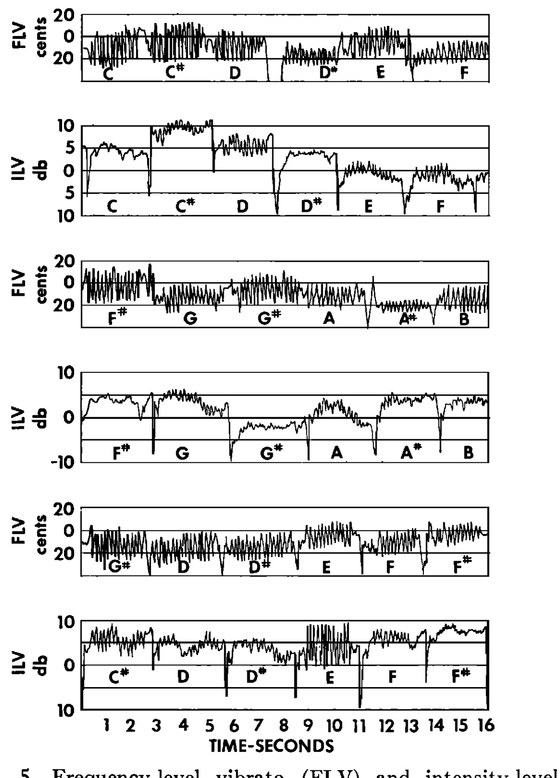

FIG. 5. Frequency-level vibrato (FLV) and intensity-level vibrato (ILV) curves for the total tones of the chromatic scale played on the violin.

[5] D. D. Robinson, "Diode-Coupled Schmitt Trigger," Electronics 37, 50 (14 Dec. 1964).

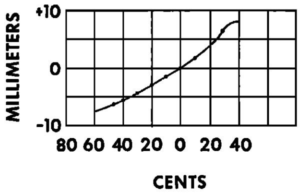

FIG. 6. Calibration curve for the discriminator showing cents deviation vs deflection in millimeters.

high E to less than 1 dB for D# or F#. The high E was played on the A string. The sympathetic resonance of the open E string probably causes this large ILV.

It can be noticed that the average intensity level of these vibrato tones ranged 13 dB. The same notes were played without vibrato, and the range of levels was about the same. These levels are plotted in Fig. 7. The close correspondence of the levels for vibrato and nonvibrato tones indicates that the same cause was operating in both cases to give the range of levels indicated, either body resonance, string resonances, or the habit of the player.

These preliminary tests indicated that probably the large intensity vibrators were due to resonances of the open strings with the bowed string and guided us in the selection of violin tones for this study. The tones selected were: D and A on the G string; D#, G#, A, and E on the D string; A#, C#, E, and G on the A string; and D on the E string.

The quantities described above were measured by the methods and apparatus described. From these measurements, synthetic tones were produced by our new vibrato synthesizer. The data for G# and A on the D string and A# and E on the A string are typical of both real and synthetic tones, and are shown in Figs. 8–11. These curves are photographs of the curves drawn by the level recorder.

In Fig. 8, for example, the curves at the top represent frequency level variation, the ordinates being the number of cents deviation from the level corresponding to G#. The one on the left is for the real tone, the one on the right for the synthetic tone. The other curves in this figure are for ILV. The ordinates give the number of decibels down from an arbitrary zero, which is the same for all the curves. The first two heavy horizontal lines, which correspond to the total tone and first harmonic, are marked with a large 10, which means that when the curves cross these lines the intensity level is 10 dB down. The smaller letter 20 opposite the thinner line is for 20 dB down. For the other nine harmonics, the heavy lines are 20 dB down (and 30 dB in later figures). It is seen that the total tone and first two harmonics show a vibrato extent of about 2 dB, while the third harmonic has an extent of 14 dB. The solid vertical line is a fiducial time line. The points where it crosses the curves gives the levels at this same instant of time. It is seen that when the FLV is at a maximum, the ILV is a maximum for Harmonics 1, 5, and 7 and is a minimum for Harmonics 2, 3, 4, and 6. In Figs. 9 and 11, the tones A on D and E on A show much larger vibrato extent than those in Fig. 8 and 10. The bowed string for these tones causes greater resonances on the open A and E strings and for A# and G#. It is seen that the curves representing the ILV become more complicated as the intensity level of the harmonics becomes lower. No good reason was obtained as to why the third harmonic of G# should have such a large extent.

From these level-vs-time curves, the harmonic structure at any given time of each violin tone can be constructed. It was first thought that one such curve could represent the harmonic structure and that it would oscillate up and down in intensity level at the vibrato rate. However, the shape of the harmonic structure curve is constantly changing with time.

An approximate representation of this function was obtained by giving only two curves at each vibrato period, one at the time when the frequency level was at maximum, and the other at the time when it was at a minimum. Since there were about 20 vibrato cycles for each of our tones, 40 such curves were required. These curves were determined and drawn. Upon examination, it was found that all the harmonic-structure curves corresponding to the 20 maxima of frequency level were similar and those corresponding to the 20 minima were similar, but the two sets were very different. Such detailed data for A on the D string are shown in Fig. 12. The times for successive maxima of frequency level were designated by the odd numbers 1, 3, 5, ··· 39, and the times for minima by the even numbers 2, 4, 6, ··· 40. The values of intensity level for the times 10–30 are given by the small dots in Fig. 12. It is seen that the two curves are fairly well defined but are very different in shape. The harmonic structure is changing from one shape to the other at the vibrato rate. As the time goes from that corresponding to maximum frequency level to that corresponding to minimum, the components 1, 2, 3, and 6 go up in intensity level while 4, 5, 7, 8, and 9 go down in level, thus changing the shape of the first curve into that of the second one. This, of course, changes the quality of the tone that the ear perceives.

In Figs. 13 and 14, similar curves are shown for A and D on the G string, for D#, G#, A, and E on the D

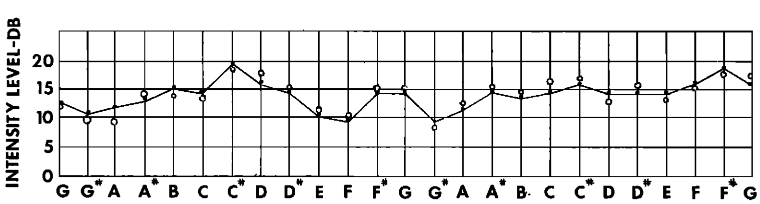

FIG. 7. Relative average intensity levels of vibrato and nonvibrato tones of the chromatic scale.

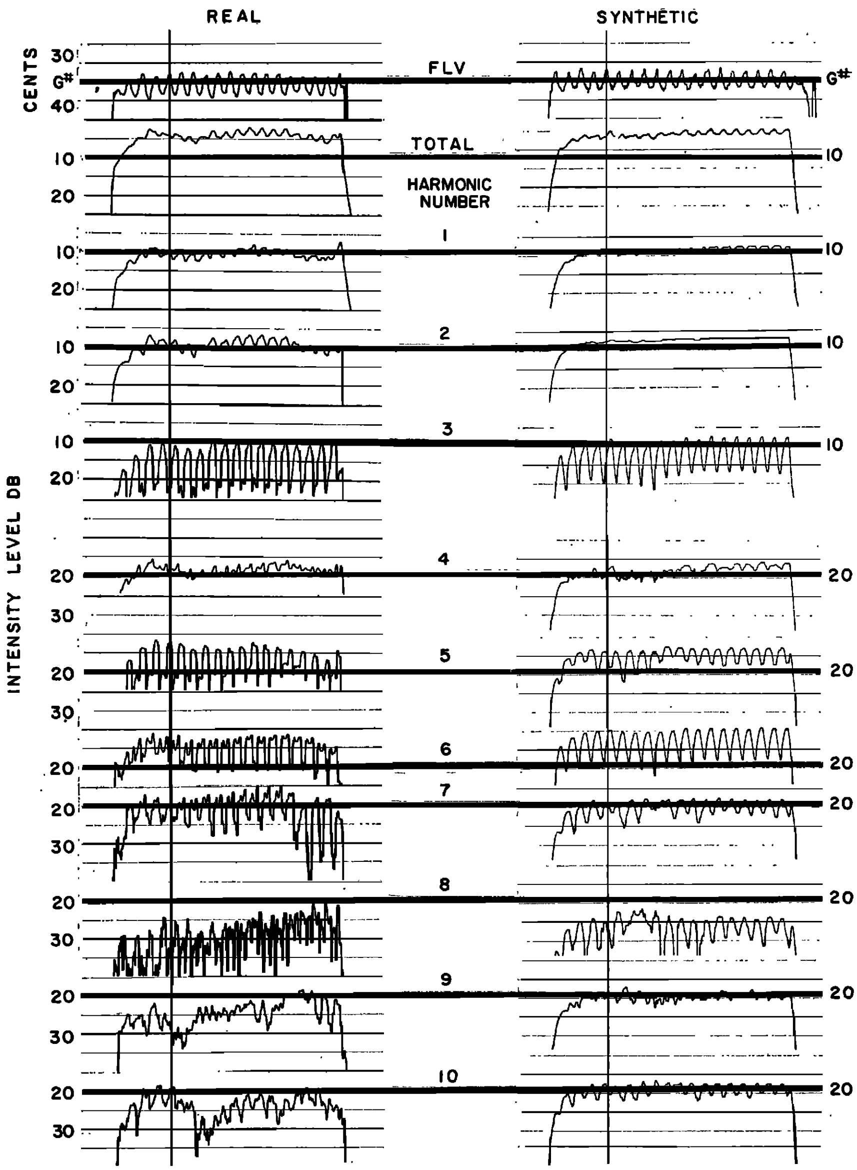

FIG. 8. Frequency level vibrato (top line) and intensity level curves for the total tone and first 10 harmonics when G# is played on D string of the violin.

string; for A#, C#, E, and G on the A string, and for D on the E string. In general, the two sets of curves for the sharp notes are more similar than those for the unsharpened notes. One would expect this difference for D on the G string, A on the D string, and E on the A string; and it is seen that this is true.

With our apparatus, we found no easy method of measuring directly the sympathetic transient tone. However, from the ending of the tone, one can obtain an approximate value of this transient component. The tone from the bowed string decays rather quickly owing to the damping by the finger of the player. As illustrations, the transient endings for the three tones D on the G string, E on the D string, and A# on the G string are shown in Fig. 15. These curves give the relative intensity level vs the time in seconds as the tones decay. It is seen that the tones D on the G string and E on the D string have a definite after-ring that is composed principally of the fundamental. For example, the first tone at the time $\frac{1}{4}$ sec after the fiducial time represented by the vertical line is only 3 dB below its maximum value. But at this time, the second harmonic is 16 dB down; the third harmonic is 30 dB, the fourth harmonic 20 dB, and the fifth harmonic 32 dB down from this maximum level. At $\frac{1}{2}$ sec, the fundamental is only 17 dB down, while the other components are all more than 60 dB down or below audibility. This indicates that this after-ring is coming principally from the open D string. So, from these curves, one can estimate the levels of these harmonics during the steady part of the tone and how these decrease with time during the ending of the tone. Similar things could be said about the ending of the tone E on the D string. The after-ring is due to the transient tone coming from the open E

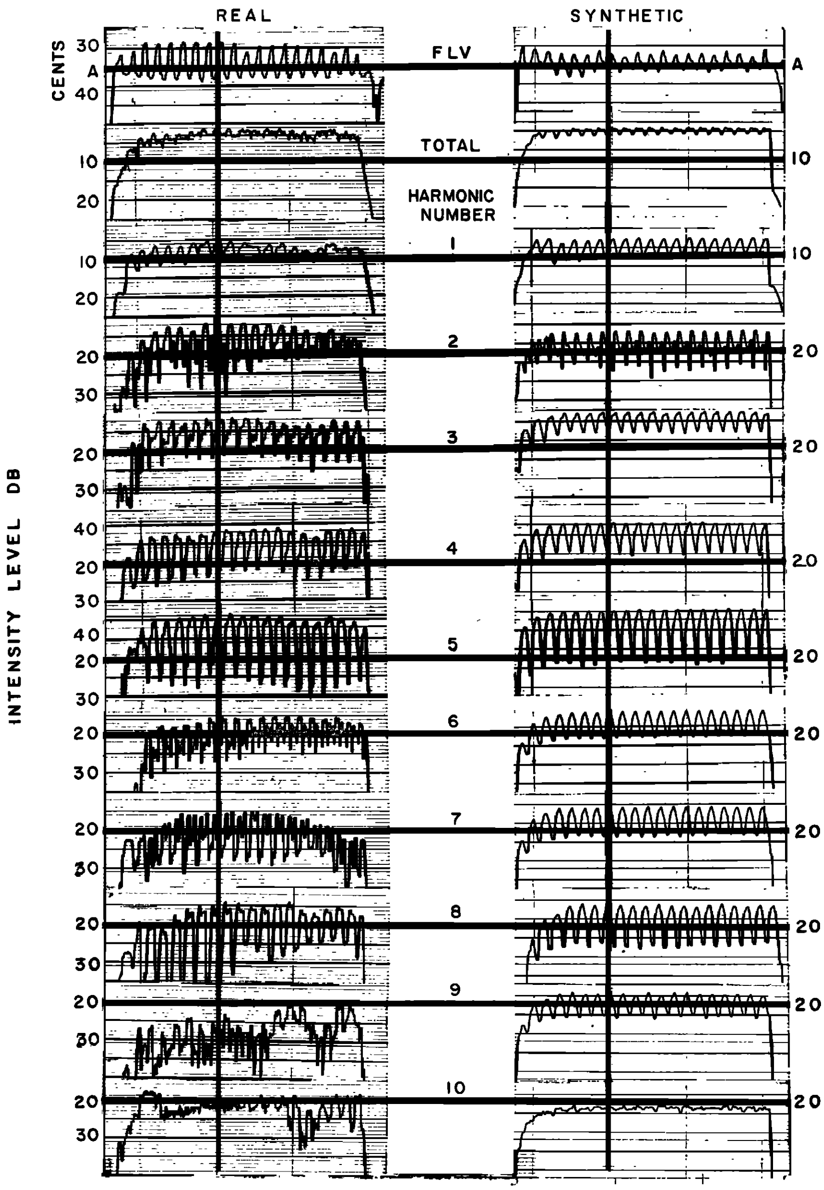

FIG. 9. Same as Fig. 8 when A is played on D string.

string. However, for the A# on the G string, there is little after-ring and the curves give the rate the tone decays from the bowed string.

C. Bow Noise

The last quantity of those mentioned above is the noise due to bowing. The method of measuring the spectrum level with respect to the level of the fundamental harmonic was explained in our earlier paper[1] on quality of violin tones. The spectrum level of this noise is approximately the same for all the notes, but it only becomes audible for the notes of higher frequency.

VI. PRODUCTION OF SYNTHETIC TONES

With the new vibrato synthesizer, the first 20 harmonics can be approximately matched to those found for the real tones. The intensity level of each harmonic was adjusted in level so that for the synthetic tone it was approximately equal to that for the real tone. Then the vibrato was introduced so that the extent was equal to the average of that for the real tone. Owing to the great variation of this quantity in the real tone, this could be done only approximately. The apparatus was adjusted so that, for the first six harmonics, the phase of the ILV could be the same as that for the FLV or opposite to it. If in phase, when the frequency of the harmonic is at its highest value, the intensity level will also be at its highest value. If it is opposite in phase, then the intensity level of the harmonic will be at this time at its lowest value. The success we had in matching the synthetic tone with the real tones can be judged from the curves shown in Figs. 8, 9, 10 and 11. If these

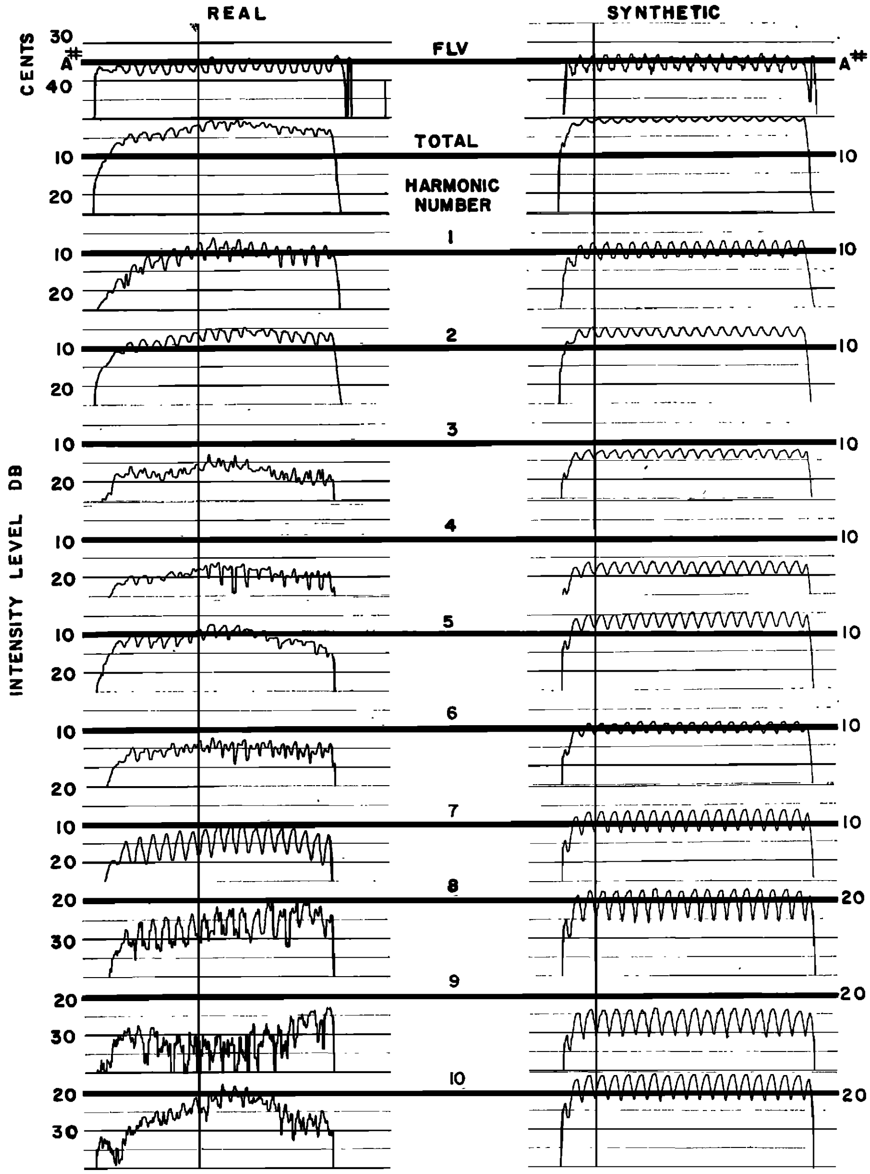

FIG. 10. Same as Fig. 8 when A# is played on A string.

curves were a perfect match, then the harmonic-structure curves such as those in Figs. 12, 13, and 14 would also be matched.

The frequency level was set to be equal to the average of the real tone. Next, an extent was set equal to that for the real tone, thus making the variation of frequency level up and down equal to the average variation for the real tone. Next, the phase variations of the vibrato for the first six components were adjusted to be the same for the real and synthetic tone. It was found that although this match was far from perfect, the synthetic tone did have the approximate characteristic harmonic structure change.

Next, the harmonic transient tone was introduced. For this purpose, a stretched steel wire was used (see Fig. 4). The tension could be controlled by the usual screw; the length controlled by a movable bridge. The damping could be controlled by a movable rubber wedge. The wire was placed in a strong magnetic field. The electrical current coming from the vibrato synthesizer was sent through the wire, thus causing it to vibrate. A small electromagnetic pickup placed near the wire generated a current having the frequencies corresponding to the resonance frequencies of the wire. This current was then sent through an amplifier and then finally mixed with the original synthesizer tone. By adjusting this amplifier and the damper, a transition could be produced that would match the endings of the tones shown in Fig. 14. This was the only device used for creating the proper ending. This addition of the sympathetic transient tone greatly improved the quality of the tone during the entire duration of the

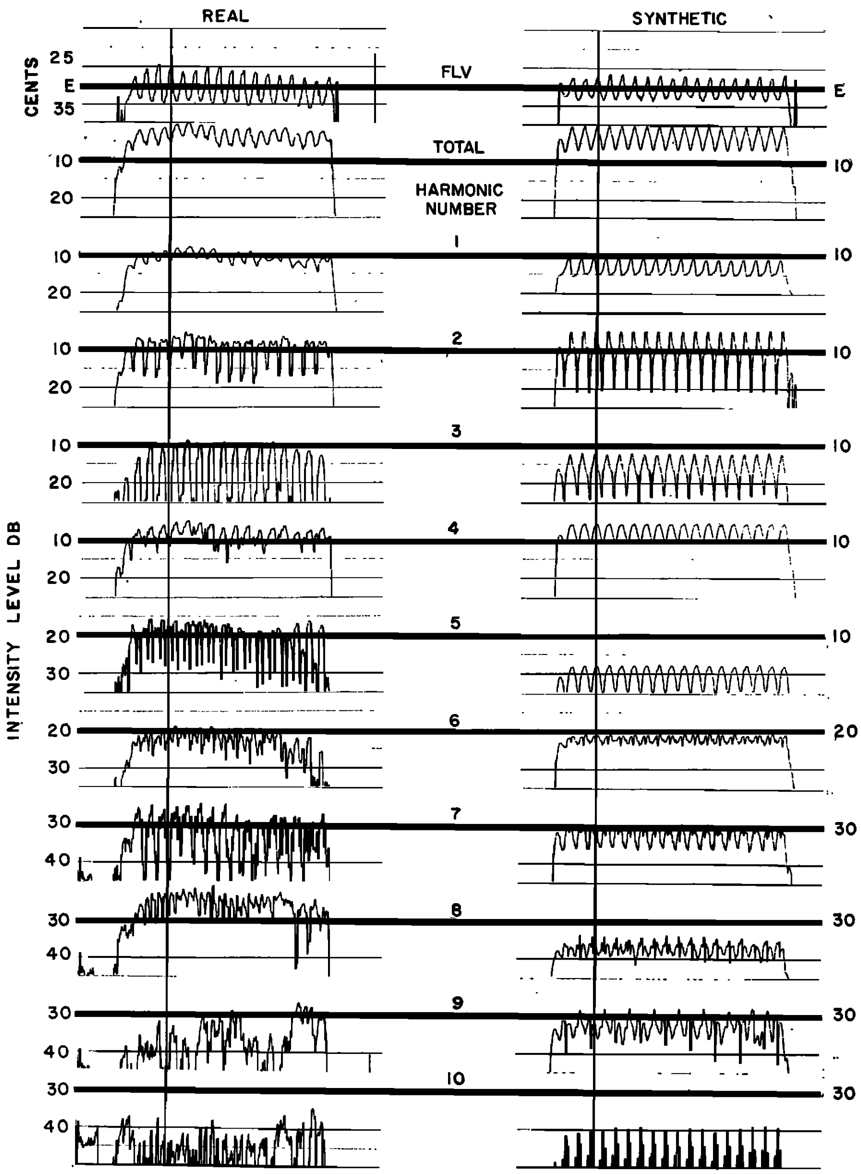

FIG. 11. Same as Fig. 8 when E is played on A string.

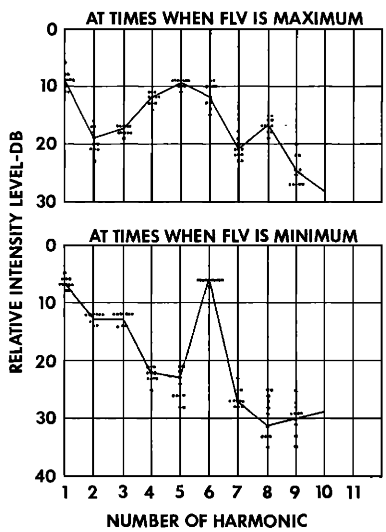

FIG. 12. Harmonic structure curves for E on the A string at times when frequency level is maximum and minimum.

tone. There was always some richness lacking before it was added. When there is no vibrato, this richness disappears.

Finally, the bowing noise was added at the proper level, as described in the previous paper.[1]

VII. IDENTIFICATION TESTS

Identification tests were made with two different juries, one of "novices" and one of "experts." The novices were students picked at random. The experts were graduate students or advanced students in music, physics, mathematics, or engineering. The jurors were seated in an anechoic chamber in front of a special loudspeaker system. The loudspeakers were concealed by curtains. Only six jurors were used at one time. After listening to each tone, the jurors checked on sheets to indicate whether the tone was real or synthetic.

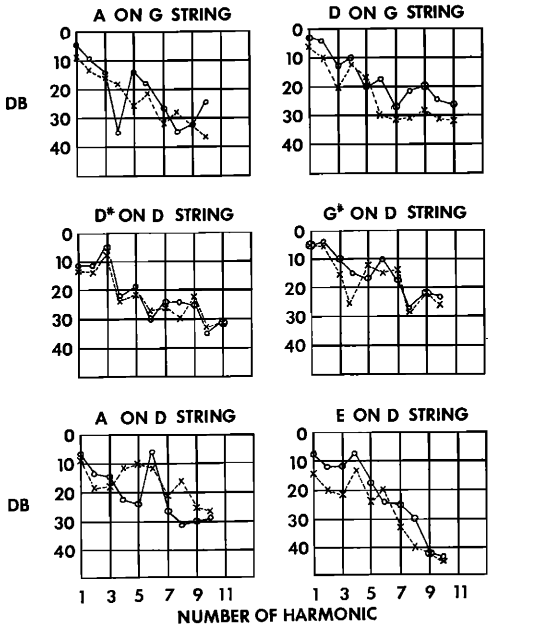

FIG. 13. Harmonic structure curves for A and D on the G string; D#, G, A, and E on the D string. Open circles for maximum frequency level, crosses for minimum.

In the first column of Table I are shown the notes used for the identification tests. The next two columns give the results for the novices, and the last two columns the results for the experts. The numbers give the percent of trials for which the tone was checked as real. A number greater than 50 in the synthetic column means that the synthetic tone was called real more often than synthetic.

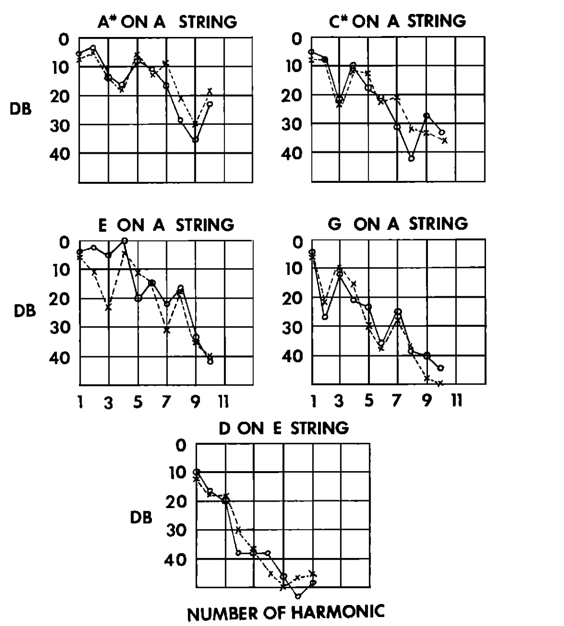

FIG. 14. Harmonic structure curves for A#, C#, E, and G on the A string and for D on the E string.

TABLE I. Identification tests. Percent of 30 trials that the note was judged to be real.

Note	Novices Real	Novices Synthetic	Experts Real	Experts Synthetic
A on G string	80	42	83	17
D on G string	72	47	90	34
D# on D string	77	50	95	5
G# on D string	61	51	72	20
A on D string	86	35	82	24
E on D string	58	56	70	17
A# on A string	60	48	82	35
C# on A string	36	50	72	14
D on A string	69	31	62	7
E on A string	58	31	80	10
G on A string	46	31	84	28
D on E string	47	63	88	29

If we had used only novices, we might conclude from the results that the synthetic tones were satisfactory duplications of the real tones. For five of the tones listed, the novices called the synthetic tones real 50% or more of the time. However, the results by the experts show that the rough approximations made in this study were not good enough and could be detected by very careful listening. Nevertheless, the results gave us confidence that the measurements here reported of the various quantities that affect the quality of vibrato

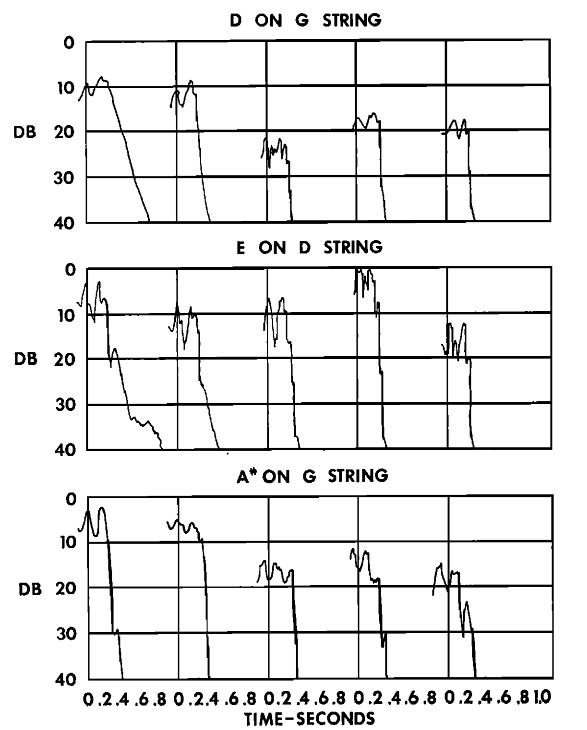

FIG. 15. Typical transient ending curves for tones D on G string, E on D string, and A# on G string.

violin tones are valid except perhaps for the very high harmonics of low intensity.

IX. CONCLUSION

In conclusion, let us summarize the quantities or characteristics that affect the quality of vibrato violin tones. The vibrato rate is about 6 cps and varies with the player. The frequency level (pitch) varies at this rate for all the harmonics with an extent of 20–60 cents, depending upon the note and the humor of the player. The intensity level varies at this rate but is greatly different for each harmonic of the same note. The amplitude of harmonics not only vary in amplitude but differ in phase.

As a consequence of this difference in phase, the harmonic structure (the relative level of the harmonics) changes with time at the vibrato rate. There is a group of tones that do not come from the bowed string but from the open strings. The frequencies of these tones are the natural frequencies of the fundamental and harmonics of the open strings. The intensity level of these tones rises and falls at the vibrato rate. They have an important effect upon the quality of the tone from the violin only when any of their natural frequencies are near those of the tones from the bowed string. These tones are an important part of the afterring. Finally, the bowing noise affects the quality of the tones, particularly those produced by the A and E strings.