String tone quality related to core material

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INTRODUCTION

Players of bowed instruments often have preferences for certain types of strings, usually identified by core material — gut, synthetic polymers or steel, for example. Among these, recognizable differences in tone quality and bowing properties do exist, and this paper explores such differences for the three core types at two tensions or "gauges", heavy and light, at two different combinations of bow velocity and pressure. FFT frequency analyses are tabulated for each.

NOTE: The musicians' term "bow pressure" will be used throughout to denote the normal component of bow force against the string [1, p.10).

EXPERIMENTAL PROCEDURE

Together with most people working in musical acoustics, it was my good fortune to know Art Benade and discuss the results of some observations on practical strings. Referring to his "Fundamentals of Musical Acoustics" and Chapter 23 in particular, he pointed out that his actual string experiments had been made with only one or two samples, whereas I was testing strings by the hundreds. Inasmuch as results with strings of different construction would be of great interest to musicians, with his encouragement I have repeated his experiments with many different types.

Because of the large amount of data required to complete these tests and the number of tables needed to display results, this study is restricted to six violin A strings bowed by a computer-controlled machine at two different combinations of bow pressure and velocity. The machine is a refined version of one which has been under development for more than ten years, and has the capability of driving a normal violin bow at precisely controlled speeds, pressures and distances from the bridge. It can be used either on actual instruments or, as in this case, on a "sonometer", a rigid bar with two stationary bridges 328 mm. apart, equipped with an optical device for converting string amplitude to an electrical signal by projecting the shadow of one edge of the string onto the sensitive element of a phototransistor. It reads displacement in the plane of bowing.

One set of runs was made at a bow velocity of 10 centimeters per second (a 6-second stroke) with the hair 1 centimeter from the bridge, to simulate conditions used by an accomplished player in producing the maximum product of tone duration and power; another set was run at 15 centimeters per second, 2 centimeters from the bridge, a condition which maintains about the same string amplitude but for only four seconds per bow stroke.

To define "distance from bridge" more clearly, it must be explained that the bow used has a ribbon of hair a uniform 7 millimeters wide (compared to the varying 12 to 8 mm. of a conventionally-haired bow) and distance is measured to the nearer edge of the hair. At 1 centimeter from the bridge, therefore, hair is in contact with the string from 1.0 to 1.7 centimeters. The optical sensor is located at 8 millimeters from the opposite end of the string, at 1/41 of the active length. Inasmuch as only the first 20 partials are being considered, this gives more than adequate high frequency response, and small amplitudes at that point make linearity comparatively easy to achieve.

Runs were made under stated conditions for each string starting at 10 grams bow pressure, increasing by 10 gram increments until steady-state tone was no longer possible. Because string response is slow at light pressures [2], for values below 80 grams the bow was started with 50 grams added downward force, maintained for 100 milliseconds. 400 milliseconds after release of the added pressure, waveform recording began. Each data block consists of 4096 12-bit readings of the voltage from the optical sensor. Amplitude is therefore measured directly and not derived, in the usual way, from velocity signals. The A/D conversion rate is 40 Khz, so the sample wave is 102.4 milliseconds long (approximately 45 cycles at 440 Hz). At the completion of sampling an FFT analysis is made, and the list of partial amplitudes printed by the computer and stored on disc. It is these data, as well as waveform samples under various conditions, which form the basis for this paper.

STRINGS TESTED

CORE MATERIAL	WINDING	DIAMETER IN.	DIAMETER MM.	TENSION LBS.	TENSION N.
Steel	Nickel	.0192	.488	17.5	77.8
Steel	Aluminum	.0191	.485	13.1	58.3
Perlon	Aluminum	.0269	.683	12.7	56.5
Perlon	Aluminum	.0242	.615	9.1	40.5
Gut	Aluminum	.0285	.724	13.9	61.8
Gut	Aluminum	.0250	.635	9.7	43.1

Strings intermediate in tension in each category were also tested, but for space considerations results are not reported here; they are, as expected, midway between those for the high- and low-tension strings. Steel strings are usually supplied in higher tensions than other types; in these tests the low-tension steel string used was at about the high value for the other two types.

DISPLAYING RESULTS

Table I gives the data, as recorded by the method described above, for the steel-core strings bowed at 15 centimeters per second, 2 centimeters from the bridge. Each row of numbers represents the relative levels of partials for a single bow stroke at the specified bow pressure. Averaging several

PRELUDE STEEL/NICKEL VIOLIN A STRING - 17.5 #
SPECTRUM VS. BOW PRESSURE AT 15 CM/SEC 2 CM FROM BRIDGE

RELATIVE LEVELS IN DB.

PARTIAL GRAMS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
10.0	43.4	37.6	33.5	30.5	27.9	25.5	23.3	20.5	18.9	17.3	15.2	12.9	2.7							
20.0	43.7	37.8	33.9	31.0	28.5	26.3	24.2	21.6	20.2	18.6	16.4	15.1	9.1	4.9	2.8	1.2	1.9			
30.0	43.9	38.0	34.1	31.3	28.8	26.6	24.5	22.1	20.8	19.2	16.9	16.8	14.6	12.1	8.5	7.2	6.9	4.9	3.5	
40.0	43.9	38.0	34.2	31.4	28.8	26.6	24.6	22.4	20.9	19.2	18.2	18.3	16.1	14.7	10.6	9.4	8.0	6.5	5.6	2.9
50.0	43.8	37.9	34.2	31.7	29.4	27.5	25.8	24.0	23.2	22.3	20.7	19.5	15.8	14.0	9.2	7.2	4.5	3.7	3.0	1.0
60.0	43.8	38.0	34.4	31.9	29.7	28.0	26.5	24.9	24.5	24.0	22.8	21.7	18.0	17.1	12.2	10.0	7.3	6.2	5.2	3.0
70.0	44.1	38.3	34.6	32.1	30.0	28.3	26.8	25.3	24.9	24.4	23.2	22.0	18.7	17.8	13.0	10.7	8.0	7.0	6.2	4.3
80.0	43.9	38.0	34.3	31.7	29.4	27.4	25.8	24.0	23.6	22.9	21.4	19.9	15.6	14.8	9.6	7.9	5.9	5.3	5.2	4.0
90.0	43.6	37.5	33.5	30.5	27.6	24.9	23.4	23.1	24.0	24.7	24.4	23.5	18.7	18.1	13.3	10.3	6.2	4.5	3.1	2.0
100.0	43.7	37.8	33.8	30.8	28.1	25.7	23.4	22.8	23.9	24.7	24.5	23.6	19.1	18.9	14.0	10.4	6.6	5.5	5.2	2.9
110.0	43.1	36.1	30.5	29.8	29.2	28.2	26.7	24.3	23.2	24.3	25.5	24.5	18.1	17.1	11.9	6.7	5.3	4.4	5.6	3.8
120.0	42.7	34.8	32.0	31.2	29.6	27.2	23.5	24.3	26.3	27.2	26.0	22.2	16.8	17.0	13.5	8.5	4.6	3.9	6.8	5.8
130.0	42.3	33.9	33.2	31.5	28.4	25.2	26.6	25.8	25.2	25.0	27.5	26.2	15.7	12.8	12.1	9.1	3.9	2.8	6.5	5.4
140.0	41.8	34.9	33.4	30.5	26.3	27.9	27.0	23.3	26.2	28.3	27.3	25.4	16.9	14.8	10.3	9.4	7.6	2.7	8.2	8.7
150.0	41.4	35.6	33.7	29.8	27.9	28.2	25.8	24.3	27.6	27.6	27.7	28.0	16.4	13.7	13.8	8.7	5.6	6.1	7.6	3.2
160.0	40.8	36.1	33.3	27.4	29.2	27.1	25.4	26.1	25.5	28.3	29.8	24.3	16.8	15.4	12.2	9.9	3.1			
170.0	40.1	36.1	32.3	28.9	29.1	24.8	26.8	25.0	26.2	29.3	26.9	27.6	15.7	14.6	14.3	5.8				
180.0	40.0	36.4	32.4	29.2	29.2	24.4	27.0	24.0	27.2	29.0	28.7	28.2	14.2	16.2	14.4	1.1				
190.0	40.1	36.7	32.7	29.7	29.5	24.6	27.3	24.8	27.6	29.7	29.6	30.3	14.9	16.5	13.7	4.0				

PRELUDE STEEL/ALUMINUM VIOLIN A STRING - 13.1 #
SPECTRUM VS. BOW PRESSURE AT 15 CM/SEC 2 CM FROM BRIDGE

PARTIAL GRAMS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
10.0	44.0	38.0	33.8	30.7	27.9	24.8	22.7	20.1	17.7	15.1	14.7	8.7	8.1	2.4						
20.0	44.1	38.1	34.2	31.3	28.7	26.1	24.5	22.5	21.0	19.2	18.0	13.9	13.0	7.3	5.4	2.9	1.6	4.8	1.2	1.2
30.0	44.1	38.2	34.3	31.5	29.0	26.5	25.1	23.3	22.0	20.6	19.6	15.1	15.1	8.4	5.7	2.3				
40.0	44.0	38.0	34.0	31.0	28.2	25.1	23.4	21.2	21.1	20.8	20.9	17.5	20.3	15.9	13.9	10.0	7.3	6.4	7.7	7.8
50.0	44.1	38.2	34.5	31.8	29.5	27.1	26.2	24.9	24.1	23.3	22.7	17.1	20.1	15.0	13.1	8.8	4.8	2.7	8.4	9.8
60.0	43.9	38.1	34.4	31.9	29.7	27.6	26.8	25.8	25.5	25.1	24.9	19.3	23.1	18.2	17.0	12.6	7.8			
70.0	44.2	38.1	33.9	30.9	27.8	24.8	24.6	24.8	25.6	26.1	26.9	19.4	23.6	18.3	17.0	12.6	7.3			
80.0	43.5	36.9	31.8	28.5	28.2	27.5	27.2	26.4	26.0	25.0	23.9	15.8	21.6	17.6	17.2	13.2	8.2			
90.0	43.4	36.4	30.6	30.0	29.2	27.9	26.9	25.0	23.4	24.6	26.8	17.8	21.8	16.4	14.4	8.9	6.9			
100.0	43.0	34.3	33.6	32.1	29.0	25.0	27.2	27.3	26.6	25.2	29.3	18.6	21.7	14.7	16.8	14.2	9.6	4.4	9.0	15.5
110.0	41.4	36.7	33.9	28.7	29.6	28.1	24.9	27.5	27.6	27.7	32.5	17.2	21.2	18.7	15.8	14.9	11.6	6.3		
120.0	39.9	37.0	31.5	31.2	28.6	27.3	27.4	25.7	28.3	27.5	33.5	14.4	20.7	15.6	8.4	3.9				
130.0	39.1	36.8	29.7	30.8	25.6	27.5	24.5	27.0	25.3	29.2	31.1	16.2	15.6	11.0	7.4	3.9				
140.0	40.4	34.1	28.5	28.3	25.2	25.3	24.7	23.6	24.8	27.6	32.5	12.6	14.1	8.3	7.6	3.2	1.0			

TABLE I

PRELUDE STEEL/NICKEL VIOLIN A STRING - 17.5 #
SPECTRUM VS. BOW PRESSURE AT 10 CM/SEC 1 CM FROM BRIDGE

RELATIVE LEVELS IN DB.

PARTIAL GRAMS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
10.0	33.9	22.5	32.3	22.3	4.1	5.2	5.1	3.2	1.5	1.0	1.5	1.1	1.5	1.6	1.0	1.0	1.2	1.0	1.0	0.0
20.0	34.6	23.2	26.8	28.0	12.7	15.4	15.0	6.7	3.6	2.2	4.0	3.5	3.9	4.0	2.9	2.5	2.7	2.5	2.5	0.5
30.0	33.6	37.5	29.4	28.5	25.6	20.9	20.0	9.6	16.7	9.6	11.2	6.6	8.4	8.8	4.3	3.9	4.5	3.9	4.0	0.7
40.0	41.1	36.8	34.0	27.3	28.6	25.0	21.4	19.7	17.9	17.1	14.8	13.1	12.7	11.9	9.2	8.2	10.5	8.2	4.8	1.1
50.0	42.5	37.2	34.2	29.9	28.7	24.7	21.9	21.0	18.4	20.1	16.0	18.0	16.2	13.1	16.0	9.8	14.4	13.9	6.2	5.7
60.0	44.5	38.8	34.5	31.1	28.1	25.1	23.8	23.4	22.4	21.9	20.6	19.6	18.7	17.1	15.9	14.9	14.0	14.6	8.9	5.6
80.0	44.3	38.6	34.4	31.1	28.1	25.3	23.5	23.1	22.2	21.8	20.6	19.8	19.0	17.6	16.5	15.6	15.2	15.5	10.9	6.1
100.0	44.3	38.6	34.7	32.0	29.5	27.4	25.5	23.8	21.6	20.0	17.8	17.1	16.9	16.3	16.0	16.0	16.9	19.4	15.5	10.9
120.0	44.1	38.5	34.8	32.2	30.0	28.2	26.6	25.4	23.7	22.6	21.1	20.1	19.2	18.2	17.3	16.5	17.4	19.6	15.8	8.9
140.0	44.0	38.4	34.7	32.1	29.9	28.1	26.5	25.3	23.6	22.5	21.0	20.2	19.2	18.3	17.3	16.5	17.7	20.4	16.4	8.3
160.0	43.5	38.0	34.5	31.7	29.7	27.7	26.2	25.1	23.4	22.4	20.7	20.2	19.5	18.5	17.6	16.5	17.9	19.5	16.2	6.9
180.0	42.0	37.3	33.9	31.0	29.4	26.8	25.9	24.8	22.9	22.5	20.1	20.4	19.9	19.0	18.5	16.7	17.8	17.0	15.0	4.9
200.0	39.6	36.0	32.8	28.2	28.6	24.5	24.8	24.2	20.9	22.7	19.0	20.7	20.9	20.2	23.4	16.9	17.7	14.0	12.9	1.0
220.0	39.8	26.7	24.5	22.6	16.7	16.5	14.1	13.4	9.9	11.4	10.9	14.2	14.7	12.3	9.5	9.9	11.4	11.1	4.2	

PRELUDE STEEL/ALUMINUM VIOLIN A STRING - 13.1 #
SPECTRUM VS. BOW PRESSURE AT 10 CM/SEC 1 CM FROM BRIDGE

PARTIAL GRAMS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
10.0	28.4	32.8	19.6	15.0	9.6	13.3	2.1	2.0	3.5	3.6	4.0	3.1	2.5	1.9	1.3	1.1	1.0	2.0	1.0	0.5
20.0	37.1	36.3	31.2	22.7	20.6	19.7	6.3	12.4	9.1	8.5	8.1	7.5	6.5	4.5	4.1	3.6	2.9	3.9	2.9	1.0
30.0	44.1	37.2	31.0	30.3	28.9	26.8	24.3	21.1	17.4	16.4	15.2	14.4	12.0	10.5	8.3	6.5	4.6	8.0	4.2	1.8
40.0	44.2	37.2	32.1	31.3	29.7	27.3	24.5	20.6	20.4	19.7	18.5	17.3	14.3	12.0	12.0	12.1	10.4	11.5	6.4	4.1
50.0	44.1	36.7	32.5	31.9	30.2	27.8	24.7	21.1	22.0	21.6	20.2	18.8	14.9	14.7	15.1	15.3	13.0	12.1	9.9	8.9
60.0	43.8	36.7	31.6	31.0	29.6	27.5	25.0	21.5	20.7	20.8	20.0	19.4	16.5	14.1	15.0	16.2	14.8	14.0	10.0	8.2
70.0	43.8	37.0	31.8	30.2	29.1	27.5	25.5	22.8	21.3	20.8	19.8	19.8	17.3	16.1	16.0	16.6	14.4	13.8	11.1	9.2
80.0	43.9	37.3	32.0	29.5	28.6	27.4	26.0	24.1	21.9	20.8	19.6	20.2	18.1	18.2	17.2	17.0	14.0	13.6	12.3	10.3
90.0	43.4	37.1	32.6	29.8	28.6	27.2	25.7	23.9	21.7	20.8	19.3	20.7	18.9	19.7	19.7	21.1	18.2	13.6	12.5	11.1
100.0	42.9	36.9	33.2	30.2	28.6	27.0	25.3	23.8	21.4	20.8	18.9	21.2	19.7	21.3	22.1	25.0	22.7	13.5	12.8	11.9
120.0	43.4	37.5	33.9	31.1	28.7	26.8	24.9	23.4	21.9	20.4	19.3	20.7	17.8	19.5	20.7	24.2	21.6	11.8	11.3	10.7
140.0	43.2	37.2	33.3	30.1	27.0	25.1	24.5	23.7	22.9	21.6	21.1	22.9	20.2	22.7	22.7	26.0	21.8	11.2	11.3	10.9
160.0	43.1	37.0	32.9	29.6	26.1	24.5	24.3	24.1	23.6	23.0	22.5	24.8	22.3	23.4	23.7	27.3	22.6	11.6	11.5	11.2
180.0	43.0	37.0	32.8	29.4	25.9	25.0	24.9	24.5	23.9	23.2	22.6	24.7	22.2	23.2	23.5	28.0	24.0	12.1	11.9	11.5
200.0	43.0	37.0	32.8	29.2	25.5	25.5	25.1	24.9	24.3	23.4	22.7	24.5	22.1	23.1	23.0	29.5	25.7	13.6	12.9	11.9
210.0	39.9	33.3	30.9	27.5	22.5	22.4	21.6	21.1	21.1	19.9	18.9	19.5	18.7	18.8	18.7	21.2	20.3	11.9	11.5	10.1
220.0	35.9	27.8	28.7	17.0	13.0	15.1	10.2	11.7	11.2	10.5	15.0	13.3	13.9	14.0	13.8	15.7	10.2	2.0	2.6	2.1

Numbers in the tables are decibels above an arbitrary reference.

TABLE II

such strokes would have smoothed the data somewhat, since the process of bowing a string has an element of randomness under some conditions [3, Sec.23.4]. This would not have altered the principal findings of this work in any way.

PERFORMANCE OF STEEL STRINGS

An estimate of tone quality can be made by considering a line of data at a given bow pressure. In Table I for the high-tension string, observe that the lower seven partials maintain their relative levels over the range of bow pressure from 10 to 80 grams, and that partials 8 through 12 rise smoothly by from 3 to 6 decibels over that same range. Higher partials are very weak at low pressures because of "rounded corners" [1, Sec.5.2], but rise rapidly once they are excited. The two most significant things shown in these curves are the wide range of bow pressure tolerated by this string, and the fact that a rise in high-frequency output with increased pressure occurs mainly in partials 11 and 12, while higher ones actually drop off. The effect on perceived tone quality is characteristic of steel-core strings, and the reason for it will be discussed later.

The second part of Table I shows the same information for the low-tension steel-core string. The range of useful bow pressures is greatly reduced; higher partials are weak at low and high bow pressures, with the exception of the 11th, which rises steadily by nearly 20 dB with respect to the fundamental. Note that, with this exception, string amplitude does not increase with increased bow pressure, contrary to the belief of many string players. An increase in only this one discordant partial *may* give an impression of increased loudness, but it would be at the expense of tone quality [3, p.519].

Table II lists the data for the same two strings under a different set of conditions; bow velocity is 10 centimeters per second and the bow is set at 1 centimeter from the bridge. The range of useable bow pressures extends over a much wider 60 to 200 grams; the partial which rises most at high pressures is the fifteenth. The string spectrum is quite uniform over a wide range, but light bow pressures are impossible. Control of such a string is difficult, and delicate nuances are beyond its capabilities. It must be pointed out, however, that this is an extraordinarily high-tension violin A string, which would be used only where maximum power is wanted and other considerations are secondary.

The second part of Table II illustrates results for the light steel A string. The range of useable pressures begins at 30 grams and extends to about 200. Partials up to the tenth remain quite uniform in amplitude over the entire range; those from 11 to 15 rise slightly, but the 16th and 17th show a drastic increase, beginning at about 80 grams. The origin of these selective partial enhancements will now be considered.

Viewing a plot of a waveform gives a good idea of the probable spectrum; a perfect sawtooth wave has an unlimited number of partials whose amplitudes drop as a linear function of order. In an actual wave produced by a bowed string, there are many deviations from perfection: Flyback after bow release occupies some time, depending on the bowing point [3, p.516], and partials with nodes at that point are suppressed at the bowing point. Rounded corners indicate the loss of high frequencies, and identifiable ripples at multiples of the fundamental reveal prominent partials. It is the latter which are the principal concern in this paper.

If there were space to illustrate the waveforms associated with the data in Table II for the heavy-gauge string, it would be seen that there is a synchronous ripple on the rising portion of the sawtooth (when the string is moving with the bow) whose amplitude increases dramatically with bow pressure. This is the phenomenon described in the translation of Helmholtz's work as "crumples" [3, p.517]. Its frequency is 12 times the fundamental, and it rises with bow pressure. As clearly explained by Benade [3, p.518] its frequency is determined by the bowing point and its amplitude at each bow pressure is a function of damping. In this case, the effective bowing point is at about 2.7 cm., along the edge of the bowhair furthest from the bridge.

A similar waveform for the light-gauge steel string shows that the ripple occurs at 11 times the fundamental, which implies a bowing point of 3 cm., slightly beyond the actual position of the bow.

Similar waveform plots (not shown) for the strings bowed at 1 centimeter show that the ripple frequency has increased to 16 and 17 times the fundamental for the respective strings, again slightly lower than expected. (1.7 cm. from the bridge is 1/19 of the length.) It is interesting to note the "quantum" nature of the frequency jumps. There must always be an integral number of ripples on the ascending wave, so the string "selects" the nearest one at each set of bowing conditions. Because of the width of the ribbon of hair, a range of "effective" bowing points is available. It is likely that at times, the ripple frequency jumps between adjacent values, giving rise to accentuation of more than one partial.

STRINGS WITH PERLON CORES

Table III gives the values of partials for two Perlon-core violin A strings. Bow pressure was varied in 10-gram steps, and the velocity was 15 centimeters per second at 2 centimeters from the bridge. The test procedure was identical with that used for steel-core strings. String tensions are considerably lower, and the more limited range of bow pressures is attributable to that fact. For the heavy-gauge string, the useable range is from 10 to 120 grams. The eleventh partial is the one associated with the bowing point (actually at L/12), but its rise is not as great as with steel strings because of somewhat greater damping. Partials above the fifteenth are at a very low level; the best operating range is from about 30 to 90 grams bow pressure.

The light-gauge string has a more restricted useable bow-pressure range of from 10 to 90 grams. Very high partials are strongest in the 40 to 60 gram range. There is some increase in the level of the tenth and eleventh partials. Table IV lists partial amplitudes for the same two Perlon-core strings bowed at 10 centimeters per second, 1 centimeter from the bridge. The heavy-gauge string shows a fundamental range of from 20 to 150 grams, with a peculiar drop above 110 grams, but higher partials are not well developed until about 50 grams pressure. This characteristic might give a skillful player an opportunity to control tone quality with pressure alone when playing close to the bridge. Partials from 12 to 15 are elevated above 100 grams, and the ones from 16 to 20 are highest in the midrange of bow pressures, an unexpected finding.

			PROARTE PERLON/ALUMINUM VIOLIN A STRING - 12.7 #																	
			SPECTRUM VS. BOW PRESSURE AT 15 CM/SEC 2 CM FROM BRIDGE																	
PARTIAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GRAMS				RELATIVE LEVELS IN DB.																
10.0	42.6	34.1	32.4	30.7	27.9	24.0	22.8	22.6	20.9	17.8	17.3	17.0	11.3	4.2						
20.0	42.6	34.4	32.0	30.9	28.8	25.7	21.2	22.4	22.1	20.2	19.5	17.3	13.2	7.9	5.2	2.1				
30.0	42.1	34.6	30.5	29.8	28.4	26.3	23.3	21.1	21.9	21.5	22.7	20.1	12.5	9.3	7.8	5.6	2.4			
40.0	42.8	36.0	31.1	27.8	27.6	26.8	25.8	24.9	22.7	20.4	20.6	20.8	15.8	11.3	8.5	5.1	2.0			
50.0	42.5	36.4	32.5	29.2	26.5	23.8	22.8	23.1	22.7	22.6	24.8	23.0	16.7	11.6	7.6	3.9	1.7	1.4	2.0	2.8
60.0	42.8	36.9	33.5	30.9	29.1	27.5	26.4	26.0	24.7	24.2	26.3	23.8	17.2	12.5	8.3	4.5	2.7	3.8	5.2	6.0
70.0	42.3	36.1	32.1	28.6	25.7	24.3	24.4	25.0	24.4	24.5	26.9	24.0	16.7	11.6	6.0	1.3				
80.0	41.2	33.9	29.5	29.1	28.4	26.8	24.7	22.6	22.8	24.2	27.1	22.7	14.2	9.5	6.5	2.5				
90.0	41.3	33.8	29.7	29.2	28.3	26.8	24.5	21.9	23.3	24.6	27.5	23.6	14.2	10.5	7.4	2.8	1.1	1.6	2.8	5.5
100.0	40.6	33.3	32.5	29.9	25.6	26.2	26.2	24.7	23.0	25.3	27.2	20.3	15.0	12.0	6.2					
110.0	39.2	34.4	31.8	26.0	27.7	25.1	23.7	25.1	21.9	24.0	26.5	19.0	13.5	9.4	3.3					
120.0	37.5	34.7	29.4	28.2	25.9	24.0	22.5	21.3	20.6	21.1	21.7	17.7	10.1	6.7	1.6					
130.0	35.6	30.6	22.4	22.4	20.5	17.2	14.9	13.1	11.8	16.6	14.9	8.6	2.8							
			PROARTE PERLON/ALUMINUM VIOLIN A STRING - 9.1 #																	
			SPECTRUM VS. BOW PRESSURE AT 15 CM/SEC 2 CM FROM BRIDGE																	
PARTIAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GRAMS																				
10.0	41.1	35.0	32.3	26.4	25.9	24.4	18.6	18.4	17.0	13.0	13.5	11.4								
20.0	41.5	35.6	33.1	28.4	27.2	26.3	22.2	22.0	22.1	19.0	20.3	18.7	9.1							
30.0	42.5	33.4	32.5	30.9	28.0	23.3	24.6	24.3	22.9	20.2	21.5	20.7	14.7	9.8	7.5	6.0	5.0	2.9		
40.0	43.1	35.9	30.4	29.0	28.3	27.2	26.0	24.5	22.4	21.4	22.6	21.4	15.9	13.0	7.7	4.1	3.4	6.9	9.4	8.5
50.0	42.9	36.7	33.0	30.4	28.0	26.1	24.6	23.6	22.7	22.5	21.4	19.6	14.1	11.8	7.8	5.6	4.1	7.4	10.0	9.4
60.0	42.4	35.8	31.5	28.1	25.0	24.8	24.9	25.5	25.5	26.3	25.8	21.6	14.6	11.0	6.2	2.4	1.7	6.4	9.7	7.8
70.0	41.3	32.3	31.5	30.5	27.7	23.7	24.9	26.4	25.9	24.9	26.5	22.9	17.0	12.1	7.7	1.6				
80.0	40.5	34.3	32.7	29.0	26.8	27.0	24.8	25.1	26.9	27.0	26.6	22.3	15.5	12.3	9.7					
90.0	39.1	35.2	31.4	28.4	28.0	23.3	26.2	25.7	26.2	29.1	26.0	22.0	15.2	13.6	9.7					
100.0	38.9	31.8	27.1	28.2	25.9	23.6	21.8	23.7	22.9	24.0	11.4	7.8	4.4	3.5						

TABLE III

				HEAVY PERLON/ALUMINUM VIOLIN A STRING - 12.7 #																
				PARTIAL AMPLITUDE VS. BOW PRESSURE AT 10 CM/SEC 1 CM FROM BRIDGE																
PARTIAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GRAMS		RELATIVE LEVELS IN DB.																		
10.0	32.9	33.2	25.4	17.1	18.4	9.1	7.5	4.7	2.1	3.0	3.0	2.5	2.3	2.1	1.0	1.5	1.1	1.0		
20.0	43.1	33.5	25.2	24.5	23.0	16.6	13.1	12.5	10.2	8.1	7.5	6.5	6.3	4.5	2.2	3.5	2.3	2.2		
30.0	44.1	34.5	32.9	30.6	27.3	22.1	20.8	19.9	17.9	14.8	12.4	10.6	11.1	9.6	5.2	7.6	5.3	3.8		
40.0	44.1	36.3	35.1	32.1	27.5	26.6	25.9	23.0	19.6	20.0	17.7	14.6	14.8	13.5	9.2	11.5	5.5	4.5		
50.0	44.3	37.7	36.2	32.6	28.0	28.7	27.1	22.6	22.9	21.9	17.8	18.2	18.4	15.0	8.4	12.5	7.5	6.0		
60.0	44.2	36.9	35.7	32.7	27.7	27.8	27.2	24.0	22.0	22.2	20.1	16.7	18.7	17.4	14.5	14.1	8.6	7.5		
70.0	44.2	36.5	34.9	32.7	28.9	26.9	26.2	24.7	22.9	21.4	19.1	18.3	19.2	17.1	14.6	17.6	17.5	13.9		
80.0	44.3	35.8	34.3	32.8	30.2	26.0	25.1	25.4	23.8	20.7	18.2	20.0	19.8	16.8	14.7	21.6	20.9	16.2		
90.0	44.2	36.3	32.9	31.9	30.1	26.8	25.1	23.6	22.5	20.7	19.0	19.5	18.5	15.3	15.5	21.6	19.9	14.6		
100.0	44.1	36.7	31.9	31.1	29.9	27.6	25.2	22.0	21.1	20.8	19.8	19.1	17.2	13.7	16.2	21.7	18.9	13.1		
110.0	42.1	36.3	31.8	29.6	28.9	25.6	24.5	22.8	20.7	21.2	19.0	21.0	20.2	17.2	17.0	19.6	15.0	10.5		
120.0	39.4	35.0	31.7	28.1	28.0	23.6	23.8	23.7	20.4	21.6	18.2	22.9	23.2	21.0	17.7	18.1	11.1	7.7		
130.0	39.2	34.8	31.5	27.5	27.5	23.8	23.2	23.9	20.4	21.4	16.7	21.1	21.3	19.2	16.3	15.5	10.1	6.5		
140.0	39.0	34.5	31.0	26.8	27.1	24.1	22.5	24.2	20.3	21.1	13.9	18.5	17.6	15.6	12.7	12.7	7.7	4.3		
150.0	38.7	34.1	30.5	26.1	26.6	24.3	22.0	24.4	20.3	20.8	11.4	15.9	10.6	7.6	5.4	10.1	1.6	3.3		
				LIGHT PERLON/ALUMINUM VIOLIN A STRING - 9.1 #																
				PARTIAL AMPLITUDE VS. BOW PRESSURE AT 10 CM/SEC 1 CM FROM BRIDGE																
PARTIAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GRAMS			RELATIVE LEVELS IN DB.																	
10.0	31.1	24.1	22.7	17.5	10.9	9.5	5.5	4.5	3.2	1.5	1.0	1.2	1.0	1.1	1.0	1.0	1.0	0.5	0.2	0.1
20.0	41.8	30.8	23.9	18.0	14.3	10.4	10.0	9.5	6.1	3.7	2.0	2.6	2.1	2.2	2.1	2.2	2.1	0.9	0.5	0.2
30.0	42.5	32.0	24.7	20.9	15.6	13.1	15.4	13.6	10.4	7.0	3.7	4.5	3.5	3.1	4.2	5.0	4.3	1.5	1.0	0.5
40.0	43.5	35.7	29.6	25.7	24.4	23.6	22.5	20.2	16.8	12.7	7.2	4.7	6.2	7.5	11.0	10.9	8.8	2.9	1.6	0.9
50.0	44.7	38.8	34.9	32.1	29.7	27.6	25.7	23.9	22.2	20.9	19.3	17.9	16.7	17.9	18.9	18.9	19.7	13.0	2.4	1.6
60.0	45.0	39.1	35.3	32.5	30.2	28.1	26.4	24.7	23.1	21.9	20.5	19.3	18.5	20.3	21.1	21.0	20.9	14.1	6.1	4.7
70.0	44.5	38.5	34.5	31.5	28.8	25.5	24.9	23.6	22.6	21.7	20.5	19.5	18.9	21.0	21.7	21.8	20.0	12.7	5.6	4.6
80.0	44.1	37.8	33.6	30.2	27.0	23.7	23.1	22.5	22.1	21.6	20.6	19.7	19.3	21.8	22.6	22.6	19.2	9.5	4.9	4.5
90.0	43.1	35.5	32.8	30.6	27.5	23.4	23.6	23.1	22.1	19.9	20.2	19.8	19.3	21.0	24.0	25.0	19.3	9.4	5.3	5.3
100.0	42.1	33.1	32.4	30.8	27.7	22.9	24.0	23.7	22.0	18.4	19.7	19.9	19.4	20.3	25.3	27.5	19.4	9.3	6.4	6.8
110.0	41.2	31.3	30.1	27.5	25.1	20.1	20.2	21.1	18.7	13.2	15.4	15.5	18.6	17.7	22.2	22.7	17.4	7.6		
120.0	38.0	29.2	23.6	19.8	17.5	16.2	12.0	15.0	10.8	9.8	8.3	8.0	11.2	10.8	10.7	7.9	4.2	1.6		

Numbers in the tables are decibels above an arbitrary reference.

TABLE IV

For the light-gauge Perlon-core string, bowing pressure range is curtailed, and partials 15 and 16 show considerable increase from 50 to 100 grams. Although the fundamental is well developed by 20 grams pressure, higher partials rise more slowly, full brilliance requiring at least 50 grams, again due to rounded corners.

			GUT/ALUMINUM VIOLIN A STRING - 13.9 #																	
			SPECTRUM VS. BOW PRESSURE AT 15 CM/SEC 2 CM FROM BRIDGE																	
PARTIAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GRAMS				RELATIVE LEVELS IN DB.																
10.0	42.3	35.2	29.4	28.9	27.8	26.4	24.2	21.9	17.5	18.7	17.6	16.8	14.2	10.1	3.5	2.4	1.3			
20.0	42.8	36.7	32.5	29.3	25.9	23.4	23.0	23.2	21.9	22.3	20.2	20.1	17.2	14.5	8.4	3.8				
30.0	41.7	34.4	29.5	29.1	27.9	26.4	23.8	21.2	20.0	21.7	19.9	19.5	15.4	12.1	8.4	5.5	1.8			
40.0	42.8	36.5	32.0	28.3	25.9	26.0	25.5	26.0	24.2	24.7	21.1	21.1	16.9	13.1	10.6	4.6	2.4			
50.0	42.8	37.1	33.5	31.4	29.1	28.1	26.5	26.7	24.7	25.8	22.6	23.3	20.4	16.0	12.0	3.5	2.7	1.7	2.3	1.0
60.0	42.0	35.9	31.5	28.4	25.1	25.7	25.1	26.2	24.7	26.3	22.8	22.7	19.0	12.6	6.7					
70.0	41.6	34.9	29.4	28.9	27.9	27.9	26.2	26.0	22.6	23.9	22.7	23.6	20.9	14.8	8.4					
80.0	41.4	33.6	31.5	31.1	28.6	26.3	23.9	26.6	25.1	25.9	20.4	21.6	19.8	13.2	6.8					
90.0	40.0	34.9	32.4	28.4	27.7	27.9	23.0	26.6	25.2	23.3	24.2	22.5	17.7	12.5	6.9					
100.0	38.4	35.8	30.8	29.8	27.7	25.9	26.0	23.3	25.2	24.5	23.9	21.1	18.2	10.7	3.1					
110.0	38.7	35.0	31.3	27.2	27.6	26.0	24.2	25.7	22.7	24.4	17.7	17.3	9.8	2.8						
120.0	39.1	32.6	31.0	29.8	25.0	26.5	25.6	25.0	22.6	18.4	16.7	8.3	5.2							
130.0	37.3	33.7	28.5	24.8	23.8	24.2	19.9	22.1	20.3	22.8	19.1	16.9	12.4	1.1						
			GUT/ALUMINUM VIOLIN A STRING - 9.7 #																	
			SPECTRUM VS. BOW PRESSURE AT 15 CM/SEC 2 CM FROM BRIDGE																	
PARTIAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GRAMS																				
10.0	43.4	35.0	32.7	31.2	29.0	25.8	22.3	23.2	22.3	22.0	17.6	17.0	14.6	10.6	6.3	2.7	2.2	1.8		
20.0	43.4	36.6	31.7	27.7	27.3	26.7	25.7	24.6	22.5	22.3	19.1	18.3	16.5	12.9	8.9	7.0	5.3	2.9	1.2	3.3
30.0	43.7	37.5	33.7	30.4	27.8	25.4	23.1	22.1	21.5	23.5	22.4	21.2	18.4	13.8	8.8	6.4	5.8	4.4	4.2	4.8
40.0	43.5	37.5	34.0	31.1	29.2	27.4	26.1	24.9	23.3	24.8	7.0	20.4	16.5	11.3	5.7	3.1	1.9			
50.0	42.3	33.9	32.0	30.6	28.9	25.6	23.6	24.5	23.8	24.8	20.4	19.7	16.7	10.9	4.3					
60.0	42.0	36.0	32.7	29.8	28.5	26.4	25.9	24.9	23.3	25.9	23.5	19.5	15.3	9.9	4.7					
70.0	42.1	34.9	29.9	28.1	28.5	26.7	26.1	24.5	21.6	24.1	23.4	18.3	15.0	9.2	3.5					
80.0	39.2	34.5	32.0	26.1	28.6	25.0	24.6	25.4	21.0	25.3	23.5	15.4	13.0	7.8	3.1					
90.0	37.6	35.0	29.5	29.1	26.9	26.1	24.7	25.3	24.0	25.0	25.7	15.2	5.7	5.8						
100.0	38.6	31.5	30.1	26.5	23.0	20.3	20.0	19.9	16.4	20.3	21.6	7.8	7.5							
110.0	38.7	30.5	27.7	23.4	23.3	20.2	17.9	19.0	15.0	14.8	14.1	3.4	2.7							

TABLE V

				HEAVY GUT/ALUMINUM VIOLIN A - 13.7 #																
				PARTIAL AMPLITUDE VS. BOW PRESSURE at 10 CM/SEC 1 CM FROM BRIDGE																
PARTIAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GRAMS																				
10.0	44.7	36.6	30.3	25.5	23.2	17.6	6.8	7.0	4.1	4.2	4.3	4.1	3.9	3.5	2.7	2.2	2.0	1.8	1.1	0.9
20.0	44.9	37.2	32.4	28.4	25.3	21.2	19.1	15.8	8.3	9.5	10.0	9.1	8.9	8.1	6.2	4.7	4.1	3.8	3.2	1.0
30.0	45.4	38.3	32.6	31.2	30.5	29.2	27.5	24.9	21.9	19.9	20.4	18.8	17.6	15.6	11.5	8.6	8.0	7.1	5.1	1.9
40.0	45.3	38.5	33.1	30.5	30.0	29.1	27.9	26.1	23.9	20.5	19.9	19.2	19.0	18.0	15.2	13.4	9.8	8.6	7.8	6.4
50.0	45.4	38.9	34.4	30.6	28.7	28.4	27.7	26.9	25.7	23.6	22.1	18.7	16.7	17.2	15.8	16.0	14.1	12.7	10.3	6.7
60.0	45.4	39.0	34.7	30.9	28.9	28.3	27.1	26.5	25.7	24.2	23.3	20.7	19.2	17.0	13.9	14.9	13.8	13.4	11.7	9.3
80.0	44.3	38.0	34.7	31.8	29.7	28.1	27.0	26.1	24.8	21.6	21.0	20.2	19.5	18.5	13.3	13.7	11.7	10.8	9.3	6.5
100.0	43.4	36.0	31.5	28.7	28.6	28.2	27.2	25.8	24.4	20.7	21.2	20.3	21.2	21.5	18.3	18.2	14.1	12.7	12.3	9.8
120.0	43.6	35.8	30.7	30.0	29.5	28.3	26.7	24.3	22.1	22.0	23.5	20.9	20.7	19.2	15.3	17.7	15.7	14.5	11.5	6.9
140.0	42.5	35.6	30.6	29.5	28.4	27.3	25.5	22.8	21.6	20.7	21.7	18.5	19.2	18.4	14.9	16.7	14.1	13.2	10.6	4.8
150.0	39.1	35.3	30.6	28.1	25.6	23.1	22.4	19.8	21.2	17.7	20.4	15.0	18.2	17.7	13.5	15.6	9.9	8.5	4.7	3.0
160.0	37.5	34.5	30.1	28.7	26.4	21.5	20.9	18.5	20.8	16.1	17.5	13.5	14.7	15.4	10.0	12.3	7.7	6.9	4.5	1.8
				LIGHT GUT /ALUMINUM VIOLIN A STRING - 9.7 #																
				PARTIAL AMPLITUDE VS. BOW PRESSURE AT 10 CM/SEC 1 CM FROM BRIDGE																
PARTIAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GRAMS																				
10.0	43.4	34.0	25.1	19.4	14.3	9.6	7.9	6.3	2.2	1.0	4.1	3.7	4.0	3.8	3.1	2.0	0.9	0.9	0.5	0.5
20.0	43.3	34.3	26.6	21.0	19.0	13.4	11.6	9.1	8.0	2.8	8.3	7.9	8.1	8.2	6.1	4.1	1.6	1.6	0.7	0.7
30.0	44.4	36.9	35.6	32.6	27.9	27.4	26.6	23.7	20.5	21.0	19.7	15.4	15.0	15.6	12.3	7.0	2.1	2.9	0.9	0.9
40.0	43.8	36.5	35.3	32.2	27.1	27.5	26.7	23.5	21.6	21.9	20.3	15.5	17.0	17.5	13.8	6.9	2.8	4.2	1.1	1.1
50.0	44.2	36.6	35.5	32.7	28.1	27.6	27.1	24.7	21.2	22.2	21.4	17.7	17.1	18.6	16.1	11.2	3.9	8.3	1.3	1.3
60.0	44.0	36.2	34.4	32.6	29.6	28.0	26.7	25.6	23.5	21.5	21.6	20.1	18.3	16.4	15.6	15.9	17.5	11.7	1.4	1.4
80.0	44.2	36.9	34.4	32.2	29.7	28.5	26.4	24.2	23.5	21.1	21.8	20.7	19.2	19.1	15.1	15.4	19.6	16.4	8.5	9.6
100.0	44.1	37.9	34.7	31.8	29.4	27.8	26.0	25.0	23.4	21.6	21.3	19.4	18.2	19.8	17.4	15.0	18.4	14.7	5.5	7.8
120.0	43.2	36.5	31.9	28.0	27.5	27.2	26.1	25.7	23.8	21.3	20.3	19.2	19.4	24.2	22.8	18.8	21.0	16.0	5.5	8.6
140.0	40.5	34.4	30.2	26.5	26.1	25.9	23.8	23.5	21.6	18.5	17.4	15.9	15.4	22.5	20.1	16.6	19.0	14.2	4.3	6.7

Numbers in the tables are decibels above an arbitrary reference.

TABLE VI

PERFORMANCE OF GUT-CORE STRINGS

Table V lists the data for two different gut/aluminum violin A strings. As expected, the string with higher tension has a wider range of allowable bow pressures. Note that this string responds well at pressures as low as 10 grams and that partials above the tenth drop off above 100 grams. There is very little selective rise of any one or two partials at high bow pressures. Partials above 15 exist at measurable amplitudes only at low pressures. These are factors in the preference for "gut" sound on the part of many players, inasmuch as the presence of strong high partials, particularly at discordant ratios with the fundamental, are associated with rough, unmusical sound quality.

The light gauge string shows similar response with the expected shorter range of bow pressures. In this case there is a significant rise in the 11th partial at the higher bow pressures, although not as great as in the Perlon and steel strings.

Table VI contains the data for the same two strings bowed at 10 centimeters per second at a distance of 1 centimeter. Useful range is from 30 to 150 grams pressure, and the spectrum is quite uniform over the entire range. High-frequency rise with increased pressure is slight, although much more energy exists in the very high partials when bowed this close to the bridge. Much of the violin literature and technique makes use of "tone control" associated with bowing distance; it appears that this string is helpful in that respect.

For the lighter string bow pressure range is from 30 to approximately 130 grams. There is a definite rise in partials 14 and 15 above 100 grams. Higher partials are at considerably higher amplitudes than they were at two centimeters from the bridge. Spectral uniformity over the range is quite good.

A look at the waveforms associated with each string at various bow pressures gives an explanation of the behavior of the two gauges of aluminum-wound gut strings. Compared with strings of other types these have a lower ripple amplitude; in fact, it is not until just before the string loses contact with the bowhair and snaps back that the ripples reach a significant amplitude — anticipating the fact that the string is on the verge of leaving the bow, and hastening the process by the increase in acceleration. It is interesting to observe how little difference there is between waveforms at 90 and 110 grams. It is apparent that at the higher pressure some instability is developing, since the peaks vary somewhat in height.

Careful study of the waveforms for the lighter string reveal that the ripples are generally of higher amplitude, beginning with the lowest bow pressure, and continuing throughout the series. This agrees with the FFT analyses and indicates that this particular string has lower damping than the other gut-core string, although more than either Perlon or steel types.

An effect which is clearly evident from period measurements of the waveforms is the flattening of pitch with increased bow pressure [1, Sec.5.7]. This is a subject to be treated separately. It must be emphasized that this study is confined to the behavior of full-length strings terminated in immovable bridges, and ignores the effects of the instrument, fingering, tilting of the bow and other complications which exist in actual playing. A good violinist can exert an amazing degree of control over tone quality, but it is hoped that knowledge of inherent string properties will assist in the long and difficult tasks of teaching and learning these skills.

I wish to express my thanks to J. D'Addario and Co., Inc. for supplying the experimental strings, and my deep regret at not being able to discuss the observations with Art Benade, who so often headed me in the direction of understanding.

Lack of space prevented publication of the graphs and waveforms referred to in this paper. For those sufficiently interested, the author will be happy to supply them for the cost of reproduction and mailing.

CONCLUSION

When driven by a machine-controlled bow, violin A strings made with three different core materials show distinctive differences in spectral response, particularly at high bow pressures. Solid steel cores have the highest high-frequency output and the greatest change with bow pressure. Gut cores show the least variation, and synthetic polymer cores are somewhere between. The effects illustrated are attributed to high-frequency oscllations and the degree of damping associated with them.

REFERENCES

1. Cremer, Lothar, *The Physics of the Violin*, (Translated by John S. Allen. MIT Press, Cambridge, Massachusetts, 1983).
2. Pickering, N.C., "Transient Response of Certain Violin Strings," J. Catgut Acoust. Soc., 45, pp.24-26, (1986).
3. Benade, A.H., *Fundamentals of Musical Acoustics*, (Oxford University Press, New York, 1976).