PHYSICAL PROPERTIES OF VIOLIN STRINGS

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String players, like other human beings, develop attachments for and prejudices against various elements of the equipment used in the pursuit of their musical objectives. These opinions are usually formed and altered by inputs from teachers, dealers and by remarks attributed to famous players or instrument makers. This process is of great commercial importance; it leads to decisions which result in success or failure of individuals or companies which supply instruments or accessories to the musical world.

In no area of choice is there more disagreement than in the matter of strings. Players tend either to use one brand loyally and exclusively, or to try every new thing that comes along. As in most other aspects of string playing, there is a tendency to invest the matter of strings with an element of mystery. Inasmuch as very little technical information is provided by string manufacturers, it is no wonder that musicians have no better basis for selection. The work reported here was undertaken to supply at least some objective measurements on some popular violin strings to help in the selection process.

The most significant variable among strings at a given nominal pitch is the tension. Measurements of tension as a function of time and humidity clearly show what musicians already know: that gut strings take a long time to stretch to a stable tension and that they lengthen with increased humidity; that strings with synthetic cores stabilize more quickly and are little affected by humidity; that steel-core strings do not stretch at all nor are they affected by humidity.

Flexibility of the string at normal tension is important to preserve harmonic relationship of overtones. It cannot be estimated by flexing an unmounted gut or synthetic string; windings are applied with the core stretched, so a string will seem much stiffer when relaxed. Paradoxically, steel-core strings seem much more flexible than wound gut ones, although the opposite may prevail at working tension. In this study, string flexibility was deduced by measurement of the harmonicity of overtones.

The importance of torsional stiffness is difficult to estimate; for strings of large diameter, it is certainly not desirable to have them roll under the bow nor to generate substantial torsional oscillations at unrelated high frequencies. Torsional damping is an indication of string construction to control unwanted modes, and is probably a good indication of damping in the desired transverse modes.

MEASUREMENT TECHNIQUE

The test bed consists of a rigid aluminum bar, 2.0" by 0.75" in section, with two massive bridges 329 mm. apart. The strings are supported on the bridges by miniature precision ball bearings which obviate sticking on the bridges as tension is varied. One end is terminated in an accurate force gauge. The other is wound on a geared capstan which permits fine adjustment of tension. At one-tenth the string length, polepieces produce a magnetic field of 5240 gauss across the string. The magnetic circuit is of grain-oriented silicon steel with polefaces 11.23 mm. wide and 13.44 mm. high, with an air gap of 2.64 mm. Imbedded in the polepieces are a light source and photodetector. A sharp shadow of one edge of the string is used to make amplitude measurements. An audio-frequency current is passed through the string from end to end, which provides the driving force by reaction with the fixed magnetic field. The power level is below 100 milliwatts, which avoids possible heating of the string and ensures linearity at the detector. Great pains are taken to eliminate random noise. The entire apparatus is bolted to a bench weighing several hundred pounds; proof that the strings are terminated in a very high mechanical impedance is the fact that at all frequencies the direct sound is almost inaudible.

For torsional measurements, a small pendulum is clamped to the exact center of the stretched string. It weighs 4.12 grams and has a pendulous frequency of 5.4016 Hz. and an effective torsional stiffness of 30.355 gm-cm per radian. An accurate depth stop is machined at the bottom of a screw-adjustable slot so that it can be attached to cylindrical wires of from 0.25 to 1.0 mm. diameter with good repeatability. When clamped to the string, the increase in frequency permits accurate measurement of the string contribution to restoring force, and the number of swings for a specified drop in amplitude is a measure of the logarithmic decrement, or damping coefficient.

Because of the very high Q of a string vibrating under these low-loss conditions, it is possible to set the driving frequency within close limits by observing amplitude. A one-cent change is easily seen. It is therefore possible to drive the string at approximate multiples of the fundamental frequency and measure departure from harmonicity with excellent repeatability. A Seiko tuning indicator was calibrated and used for these observations.

Measurements of string length and diameter were made in the relaxed condition, as string gauge is usually determined. It would be a welcome change for manufacturers to label their strings with metric diameters rather than by the arcane system now more or less in use. Better still would be a listing of unit mass or wave impedance. At the very least it would be useful to know the actual string tension at nominal pitch for a standard length, say 329 mm. for violin strings, 380 mm. for viola strings and 690 mm. for cello strings. The table gives such information for a few of the more popular violin strings:

EXPLANATION OF COLUMNS IN TABLE

All strings were new and purchased from well-known distributors. Only medium-gauge types were used except for the Super Sensitive E strings, where medium and thin were selected. Whenever possible, six of each were measured; for each type the spread in results was extreme-

PHYSICAL CONSTANTS OF VIOLIN STRINGS

	NOMINAL PITCH	MAX. DIA.	MIN. DIA.	LENGTH	TENSION	WAVE IMPED.	REL. MASS	STIFF. TORSION	DAMP. COEFF.			TUNING OF OVERTONES				
										2	3	4	5	6	7	8
UNITS>		MM.	MM.	MM.	NEWTONS	N-S/M	MG/CM	G-CM/RAD				CENTS DEVIATION				
SCALING FACTOR>		10	10	1	1	100	1	1	100			FROM INTEGER RATIOS				
DOMINANT	E(1)	3.15	3.07	565	72.56	16.66	3.83	15.57	.69	0	-1	0	2	1	1	6
SUPERSENS.	E(2)	2.64	2.64	552	84.01	19.29	4.43	24.67	.38	2	1	2	2	4	6	6
SUPERSENS.	E(2)	2.49	2.49	551	73.76	16.94	3.89	17.36	.21	0	-1	0	2	1	4	4
JARGAR	E(1)	2.59	2.54	553	77.77	17.86	4.11	22.81	.25	1	0	0	1	2	3	4
CORELLI	E(2)	2.59	2.59	545	72.25	16.59	3.81	18.48	.32	0	1	2	2	3	4	5
KAPLAN	A	6.81	6.68	550	49.96	17.19	5.92	9.79	2.23	1	1	2	2	3	5	6
KAPLAN	A	6.91	6.81	557	50.59	17.41	5.99	18.40	2.74	2	3	3	2	3	3	5
KAPLAN	A(5)	6.83	6.66	570	54.15	18.64	6.41	12.35	10.36	0	-3	-4	1	-2	1	-
GOLD LABEL	A	6.86	6.78	570	54.15	18.64	6.41	11.64	2.09	0	0	0	2	2	5	5
GOLD LABEL	A	6.91	6.81	566	51.48	17.72	6.10	13.46	2.27	1	-1	-1	-4	3	2	1
EUDOXA	A	6.71	6.63	570	48.89	16.83	5.79	11.93	2.19	0	-1	0	1	1	4	4
DOMINANT	A(3)	6.86	6.76	590	56.25	19.36	6.66	24.85	10.33	1	3	5	6	5	10	10
JARGAR	A(1)	5.08	4.91	580	56.07	19.31	6.64	25.69	10.67	9	6	7	9	10	12	13
SUPERSENS.	A(1)	4.65	4.52	600	63.51	21.86	7.52	22.97	1.54	-4	-1	-2	0	1	2	3
CORELLI	A	7.01	6.88	570	51.03	17.56	6.04	12.58	2.4	1	1	2	2	3	4	3
KAPLAN	D	9.14	8.81	543	39.22	20.22	10.43	17.74	3.51	-1	-1	0	1	2	1	
KAPLAN	D(4)	6.91	6.81	557	58.38	30.11	15.52	8.68	1.13	0	0	-1	-1	-3	2	3
KAPLAN	D(5)	6.86	6.71	575	39.00	20.11	10.37	22.67	20.23	1	3	6	10	15	23	
GOLD LABEL	D	8.59	8.51	551	40.11	20.68	10.66	20.18	3.63	2	4	6	7	6	7	11
GOLD LABEL	D	8.69	8.61	551	38.24	19.72	10.17	17.09	2.28	-1	-2	-4	-5	-3	-5	-3
EUDOXA	D	8.86	8.74	545	41.01	21.14	10.91	24.13	4.86	2	3	4	6	7	11	14
DOMINANT	D(3)	8.01	7.95	565	43.72	22.54	11.62	42.58	6.75	-2	1	-2	3	0	2	3
JARGAR	D(1)	7.39	7.34	564	61.73	31.83	16.41	100.77	82.66	5	8	8	11	11	15	24
SUPERSENS.	D(1)	7.52	7.39	523	57.14	29.46	15.19	60.86	23.62	1	3	3	6	10	11	17
CORELLI	D	8.43	8.33	558	34.76	17.92	9.24	9.54	1.37	2	4	5	7	7	10	13
KAPLAN	G	8.20	8.15	546	43.68	33.75	26.07	25.83	5.12	1	-1	1	4	2	7	9
KAPLAN	G	8.11	8.01	554	40.91	31.61	24.42	15.35	4.79	1	2	5	6	7	10	13
KAPLAN	G(5)	8.10	7.90	572	46.44	35.88	27.72	10.24	7.20	-2	-1	-4	-3	-5	-2	-1
GOLD LABEL	G	8.13	8.08	523	40.78	31.51	24.34	18.79	3.67	0	1	1	2	1	3	5
GOLD LABEL	G	8.26	8.15	535	38.33	29.68	22.88	19.07	3.43	1	-1	2	1	3	5	5
EUDOXA	G	8.03	8.01	511	39.18	30.27	23.38	20.02	3.03	1	4	3	4	6	11	14
DOMINANT	G(3)	8.08	8.03	567	44.57	34.43	26.61	28.36	18.37	1	0	1	3	1	4	4
JARGAR	G(1)	8.21	8.01	535	46.13	35.64	27.53	177.29	55.11	4	6	8	12	20	30	40
SUPERSENS.	G(1)	8.33	8.21	525	49.92	38.56	29.79	64.96	15.75	1	7	5	5	6	9	13
CORELLI	G	8.18	8.1	577	35.43	27.37	21.15	15.07	1.85	-1	-1	-2	3	3	6	7

NOTES: (1) Wound steel
(2) Solid steel
(3) Perlon core
(4) Silver wound
(5) Synthetic core
All the rest are wound on gut.

FACTORS: Diameters are given in tenths of millimeters.
Divide tension in Newtons by 4.457 to obtain pounds.
Multiply wave impedance by ten for cgs units. Figures listed are in Newton-seconds per meter times 100.
Relative mass is actual weight per cm. in milligrams.

ly small, attesting to good quality control by the manufacturers. Where a given brand appears more than once in the table, it signifies a different type or source of that brand. In the case of Pirastro Gold Label, one batch was made in Germany and the other, presumably, in this country. Kaplan is represented by different label names.

Nominal pitch is shown with indication of the basic material types. Perlon is a trade name for an aramid or Nylon derivative, depending on what chemist one consults, but whatever it is, it has some fine properties for string use. "Synthetic" means that the manufacturer isn't talking, and the material may or may not be similar to Perlon.

Relaxed string diameters are given in tenths of millimeters, and variation along the string shown by presenting both maxima and minima.

The length is the full dimension overall. There is less uniformity in this dimension than one would expect.

Tension is recorded at exact frequencies of 196.0, 293.7, 440.0, and 659.3 respectively. No final measurements were made until strings had "settled down" to a very low drift rate. In the case of gut strings this required as long as 48 hours of frequent retuning.

Wave impedance is analogous to the characteristic impedance of a coaxial transmission line. It is the ratio between the driving force and the transverse velocity at one end of a string of "infinite" length. It is equal to the square root of the tension times the mass per unit length of the string. Its significance is the numerical expression of the relative energy required to drive one string compared to another.

The mass of the string per unit length can be derived from the tension, the length and the frequency, all of which are accurately known. All of these parameters vary together; a massive string requires more tension to reach a given frequency, has a higher wave impedance, requires more energy to drive, and imparts more energy to the bridge of an instrument for a specific amplitude -- in other words, is "louder". It also takes longer to reach a given amplitude, a musical effect of considerable importance.

Torsional stiffness is measured by the increase in frequency of the pendulum swings described above. Damping is derived from the logarithmic decrement of the swings. The importance of these parameters is not well established, and there is a wide variation in them even in the products of a single manufacturer.

The harmonicity of overtones is an indication of the transverse stiffness of the string at working tension. As is well described in every text on the subject, a string in which all the restoring force after displacement is provided by the tension has higher modes which are simple whole number multiples of the fundamental. A bar in which stiffness alone provides the restoring force will have partials at 2.720, 5.404, 8.933, 13.345, etc. times the fundamental frequency. A real string may lie somewhere between, if the transverse stiffness is not negligible. Significant overtone inharmonicity will affect tone color and ease of bowing.

COMMENTS ON RESULTS

From the violinist's standpoint, predictability of response in crossing strings is possibly his greatest concern and most obvious string-related problem. An orderly progression of string impedances from E to G helps in this regard, although perturbations in response and intonation still exist at the principal resonances of the instrument body, as I have shown in earlier work. The advice of Leopold Mozart to strive for equal tension in all strings is not to be taken seriously today, and I wonder whether he ever achieved it. It would result in a weak high register and/or serious problems in bowing the G string, depending on the actual tension selected. Most modern string sets establish E string tension at close to the breaking point and scale the A, D and G at about 70%, 50% and 50% of that value. This progression elevates the G string levels somewhat and causes a distinct difference in "feel" in changing from the D to the G. In some instruments it gives the D a "flabby" impression. For this reason, some companies are making silver-wound D strings, which actually go rather far in the opposite direction. There seems to be agreement that G strings should not be made too heavy, since among all types and brands measured the spread was small. D strings, however, varied over a wide range - probably reflecting the efforts of string makers to help violinists solve the problem of balance between D and G. One danger in using a heavier D string is the exacerbation of any potential wolfnotes in the region of C or C#.

As a practical matter, satisfactory string balance is more likely to be achieved if one begins with a not-too-heavy E string. The "medium" grade wound strings or solid steel strings not over 0.25 mm. diameter are a good place to start. Such strings are responsive to rapid bow changes, have less tendency to "whistle" and have a clear, ringing sound as shown by the good distribution of overtones.

The choice of A string depends largely on the instrument itself, and the importance of tuning stability. Strings with thin gut cores have advantages in response to rapid bowing and production of a clear sound. Disadvantages include tuning difficulties, cost and short life. Synthetic materials are now available which can be used to make strings of the highest performance, and they are being used by more and more of the leading players. The advantages of finely-stranded synthetic cores show up most strongly in the construction of D and G strings where larger-diameter gut is less flexible.

The musical significance of overtone inharmonicity is not easily expressed in quantitative terms. As already mentioned, strings with large deviations in the harmonic series are more difficult to bow and sound less brilliant, because severely mistuned overtones are not easily excited by the sawtooth wave at the fundamental frequency. (Ref. 2.) Good string players do seem to prefer strings with low harmonic deviation.

There are hundreds of strings on the market, and it is impossible to test them all. It would be interesting if musicians would demand factual information from manufacturers - - perhaps it would set off a "specification war" such as occurred in the audio equipment field, for example. At least the consumer would know how one product relates to another when making a choice. Strings are no longer a minor budget item, and the leading manufacturers have much to be proud of in their technical achievements. Let us hope that they begin to boast a little about them in real numbers.

RELEVANT LITERATURE

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2. Lothar Cremer, *The Physics of the Violin*, MIT Press, 1983, Section I.

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