TAP ROUTINE

The importance of tap-tones has largely been ignored in mainstream violin literature. Maker JOSEPH CURTIN argues their case and shares his latest research

Hold a violin top between two fingers and tap it, and one or more distinct pitches, or 'tap-tones', can be heard. No one knows whether the old Italian makers tuned their plates in any systematic way, yet the tap-tones of their instruments have interested makers and researchers since at least the early 1800s. In the 1960s Carleen Hutchins measured a Stradivari top, found an octave relationship between the tap-tones known as mode 2 and mode 5, and later developed an influential method for plate tuning. Since then, there has been much debate over the meaning and relevance of tap-tones – at least among researchers. In mainstream violin-making literature, they are politely ignored.

Also ignored is weight. Odd though it seems in a profession that records everything about the old Italians, from their purfling points to their graduation patterns, there is no public record as to how much a top or back typically weighs. I never thought of weighing a plate until Hutchins suggested it in 1986. Five years later, Gregg Alf and I had the top off a 1716 Stradivari violin, and what struck me

▸ Glitter highlights the nodal lines created when a violin top is vibrated at mode 2 frequency (left) and mode 5 frequency (right). When the top is set into vibration, the glitter moves toward the areas of least vibration. The + and – signs represent anti-nodes: when one of these areas bends upwards, the other bends down. See box on page 51 for further details

ALL PHOTOS JOSEPH CURTIN

first was how light it was – 54g without bass-bar, or some 20 per cent lighter than any top I had made.

We all have a sense of what weight is, but what exactly are tap-tones? Every object has innumerable resonances, known to science as 'normal modes of vibration'. Engineers analyse the modes of car bodies in order to identify sources of noise and geophysicists map out the normal modes of the earth, which are set into vibration by earthquakes. The frequency of a mode is determined by an interplay between stiffness and mass in the structure. This in turn, is determined by the geometry of the structure and the properties of its constituent materials. Tap-tones are an informal sampling of a violin plate's lowest modes, chosen for their pertinence to graduation. Modes 2 and 5 are of special interest, being most directly related to the stiffness of the plate across and along the grain.

Violin makers typically assess stiffness by flexing a plate in various directions. Because such judgements are difficult to quantify and record, some makers have built devices using weights to load a plate and micrometers to measure the resulting deflection. I believe that tap-tones in combination with weight yield much the same information. Because tap-tone frequency is determined by the ratio of stiffness to mass in the underlying mode, provided we know both frequency and mass we can work backwards to identify the stiffness. More on this later.

Table 1 (see page 51) gives tap-tones and weights for nine old Italian violin tops. All are concert instruments; several are in the hands of major soloists, including Elmar Oliveira, Vladimir Spivakov and Maxim Vengerov. Of particular interest to me are the values for the tops without bass-bar. A sample of nine violins is a small number from which to draw reliable statistical conclusions – still, the average weight of 59.9g strikes me as low. I don't know what a typical new top weighs, but I would guess it is at least 10 to 20 per cent heavier than the Italian average. Nor do I have tap-tone data for new tops other than my own. Looking at a random sample of 30 of these, however, I found that mode 5 is almost identical to the Italian average of 309Hz – but this is no surprise because I have tended to tune mode 5 with the Italian norms in mind, while letting the frequency of mode 2 float. It is interesting, then, that my mode 2 average is 155Hz – significantly higher than the Italian average of 131Hz or 134Hz. This can to some extent be explained by my typically lower archings and thicker central regions – both of which favour high values for mode 2 relative to mode 5. But even with a dimensionally accurate copy of the 'Booth' top, I found it difficult to get ▹

MODES AND NODAL LINES

When a plate mode is set into vibration, the plate divides itself along 'nodal lines' – lines connecting points of zero motion. As the distance from a nodal line increases, so does the amplitude of vibration, reaching a maximum at the centre of the 'anti-node'. In the two photos of a violin top on pages 48 and 49, modes 2 and 5 are made visible by a method popularised by Carleen Hutchins: the top is sprinkled with glitter, then suspended above a loudspeaker fed by a sine-wave generator. When the sine-wave frequency matches that of a particular mode, the top vibrates vigorously – causing the glitter to migrate toward the relatively still regions near the nodal lines.

Adjacent anti-nodes move in opposite phase to one another (indicated by the blue + and – signs): when one area bends upwards, the other bends down. The bending tends to be perpendicular to the nodal lines. If the nodal lines for mode 2 happened to be straight and parallel, the top would be bending across the grain only. Similarly, if the nodal lines for mode 5 were straight and parallel, then the top would be bending along the grain only. The extent to which the nodal lines curve indicates the extent to which there is bending in two directions simultaneously. For mode 2, then, the plate is bending mainly across the grain. For mode 5, it is bending in both directions, though mainly along the grain. The mode shapes pictured are typical for normally built tops. For any given top, the exact shape will depend on such factors as arching, graduation, and local variations in wood stiffness and density.

TABLE 1: TAP-TONES AND WEIGHTS

INSTRUMENT	WITHOUT BASS-BAR			WITH BASS-BAR			
	M2	M5	Weight	M2	M5	Weight	Bar
'Booth' Stradivari, 1716	127	305	54	150	345	58	4
'Kreutzer' Stradivari, 1727	117	276	55.5	139	324	60	4.5
'Petri' Stradivari, 1700	126	332	65.5				
'Alard' Stradivari, 1728	*127*	*304*	*61.7*	146	351	66	*4.3*
'Stretton' 'del Gesù', 1726	143	308	64.1	155	362	68.4	4.3
Carlo Landolfi, 1762	*150*	*321*	*59.2*	172	371	63.5	*4.3*
Carlo Tononi, c.1730	*127*	*332*	*62.9*	146	384	67.2	*4.3*
Carlo Testore	143	322	60.5	164	366	65	4.5
Francesco Rugeri, 1685	*150*	*324*	*61.2*	171	375	65.5	
Average (no estimates)	131	309	59.9	155	360	64.2	4.3
Average (with estimates)	*134*	*314*	*60.4*	155	360	64.2	

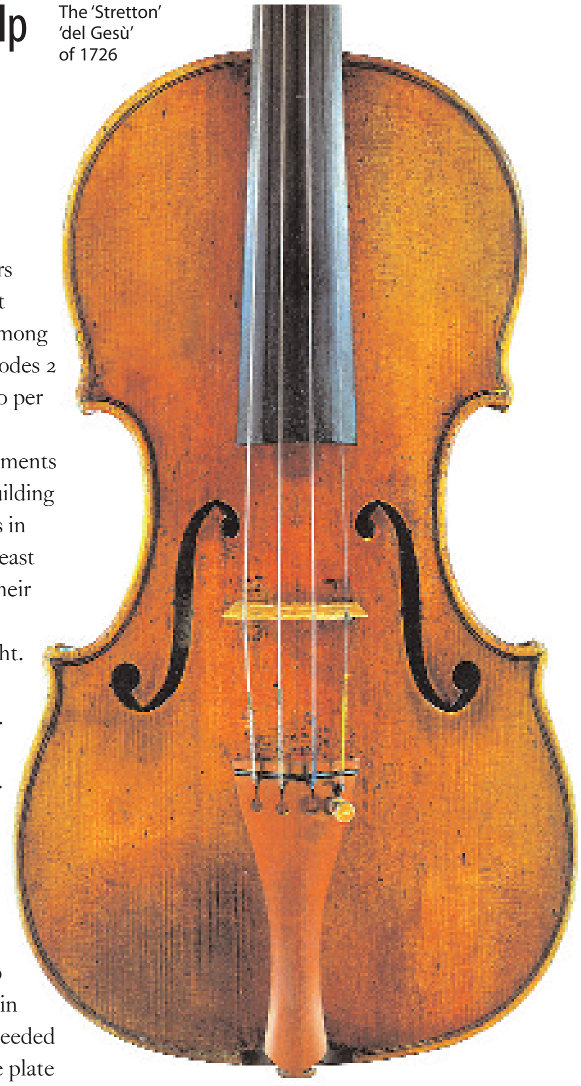
Modes 2 and 5 (in Hertz) and weight (in grams) for nine old Italian violin tops. Not all tops were available both with and without the bar, so estimated values (indicated by italics) were arrived at by firstly subtracting the average bass-bar weight from the total weight; and then by reducing the frequency of each mode by the average per cent frequency shift produced by the bar in the measured tops

mode 2 below 138Hz (compared with 127Hz for the original) without sacrificing the mode 5 match. As mode 2 reflects the cross-grain stiffness of the wood far more than does mode 5, this suggests that the spruce found in old Italian tops may be stiffer along the grain, and/or weaker across it, than new wood. Since cross-grain stiffness is highly dependent on the cut of the wood (and even a few degrees deviation from the quarter will reduce it significantly), it is possible that the Italians' tops were not perfectly quarter-cut, and this showed up in the tap-tones. I don't believe this is the explanation, but unfortunately did not keep track of grain orientation and so cannot rule it out. At any rate, more data on both new and old instruments would help to clarify the situation.

It is interesting to consider what the data in Table 1 implies about the relative stiffness of the tops. For mechanical resonances in general, stiffness is proportional to mass. Imagine, for example, two wooden bars of the same dimensions and tap-tone frequencies. If one bar is twice as heavy as the other, then it must also be twice as stiff. With this in mind, consider the tops (without bass-bar) of the 'Booth' and the 'Stretton'. Their mode 5 frequencies are nearly identical but the 'Stretton' is roughly 20 per cent heavier than the 'Booth'. To the extent that they share the same overall dimensions and mode shapes, the stiffness governing mode 5 is about 20 per cent greater for the 'Stretton' (see Table 2 on page 53).

Now consider the 'Booth' and the 'Kreutzer' – again without bar. While their weights are roughly the same, there is about a ten per cent difference in mode 5 frequency. Looking at mechanical resonances in general, stiffness is proportional to the square of the frequency. This means that a relatively small difference in frequency indicates a relatively large difference in stiffness. Consider two wooden bars of identical dimensions ▹

> One reason for studying old instruments is to help to establish guidelines for building new ones



The 'Stretton' 'del Gesù' of 1726

and weight. If the tap-tones of one were twice as high as those of the others, then it would be four times as stiff. Since mode 5 for the 'Booth' is about ten per cent higher than for the 'Kreutzer', the stiffness governing mode 5 is about 21 per cent higher (110% x 110% = 121%).

Of course, old Italian tops are not dimensionally identical wooden bars. They all differ somewhat in terms of outline, arching and graduation pattern – and therefore in the distribution of stiffness and mass. For this reason, the above assessments of relative stiffness are only estimates. Still, it would be useful to be able to make such estimates for plates that differ in terms of both tap-tones and stiffness. Violin maker Nigel Harris proposes a formula for doing just that in his article 'On Graduating the Thickness of Violin Plates'. I use his approach in a modified, more narrowly defined way (see box below), to get a 'stiffness number' for mode 2 and mode 5. Because these numbers are easy to calculate, they are useful in assessing changes in stiffness during graduation, and for comparing plates. Table 2 gives stiffness numbers for the five Italian tops. They suggest a surprising range of top stiffnesses among successful concert violins: for both modes 2 and 5, the highest values are about 70 per cent greater than the lowest.

One reason for studying old instruments is to help to establish guidelines for building new ones. Looking at the Italian tops in Table 1, there is little evidence – at least from their current condition – that their makers shared any particular target values for tap-tones, stiffness or weight. This does not mean that tap-tones, stiffness and weight are unimportant. On the contrary – they are primary determinants of acoustical behaviour. The question, then, becomes: if you are interested in copying a particular old Italian plate, what kind of wood is needed to reproduce both its tap-tones and weight? Put another way, if during restoration you need to replace a significant amount of wood in a plate, what kind of repair wood is needed so that the stiffness and weight of the plate can remain unchanged? Is it a question ▸

MODE STIFFNESS NUMBERS

As I define it, the 'stiffness number' for a mode is equal to the weight of the plate times the mode frequency squared, divided by 100,000. The number refers in a general way to the stiffness of the anti-nodes of the particular mode – that is, the areas of the plate that bend during vibration (see 'Modes and Nodal Lines' box, page 51). Comparisons between plates are meaningful to the extent that the plates share the same overall dimensions and mode shapes. Keep in mind that the stiffness governing a mode is only indirectly related to the stiffness felt when flexing a plate. The best way to get a sense of this relationship is to calculate stiffness numbers for a few plates and then see how the numbers tie in with the feel of the plate when it is flexed.

TABLE 2: STIFFNESS NUMBERS

INSTRUMENT	M 2	M 5
'Booth' Stradivari	8.7	50.2
'Kreutzer' Stradivari	7.6	42.3
'Petri' Stradivari	10.4	72.2
'Stretton' 'del Gesù'	13.1	60.1
Testore	12.4	62.7
Average	10.4	57.5

Stiffness numbers for modes 2 and 5 of the five Italian violin tops for which there were direct, rather than estimated measurements

The 'Booth' Stradivari of 1716

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of wood density, or stiffness, or some other factor?

It turns out to be a particular relationship between density and stiffness that is important – a relationship that the Bell Labs researcher John Schelleng captured in the term 'radiation ratio'. Radiation ratio is an expression of something like the 'stiffness-per-unit-mass' of a material. The higher the radiation ratio, the stiffer the material is for its weight. Radiation ratio is most conveniently measured in the workshop by dividing the speed of sound through the wood (as measured by a Lucchi Elasticity Tester) by the density of the wood. It can be measured in any direction, but readings across and along the grain are sufficient for dealing with modes 2 and 5. Values along the grain for new European spruce range from 12 and below to as high as 16 and beyond – though this is rare. There is a statistical correlation between low density and high radiation ratio, so if no Lucchi Meter is available, choosing the least dense woods tends to yield those with the highest values. Note that run-out (when the wood is cut so that the long-grain is not parallel with the surface) lowers radiation ratio along the grain, and off-quarter grain orientation dramatically reduces it across the grain. In any given direction, radiation ratio varies somewhat throughout a piece of wood, so a perfect match between any two pieces is unlikely. But in principle, if the radiation ratio of the new wood matches that of the old plate both across and along the grain, then a new plate can be made that matches the old in terms of both tap-tones and weight. If the densities of the woods also match, then so can the plate thicknesses.

Although radiation ratio is straightforward to measure in a wedge of wood, it is not with a finished top. Density is hard to get at without knowing the volume of the top, and the speed of sound, as measured over the arching, tends to be lower than when measured directly through the wood. From practical experience in trying to copy some of the Italian tops listed, and by using some seat-of-the-pants calculations (which there is not space here to explain), I have estimated the radiation ratio along the grain for the Italian tops listed in Table 2. Though these estimates, shown above in Table 3, should not be taken too seriously, they correlate well enough with my own workshop -experience that I think they give at least a first approximation of the range of material properties found in old Italian tops. Finding wood to match the lowest value of 13.9 is not difficult. Finding wood to match the 'Booth' or the Testore, however, is a very different matter.

TABLE 3: RADIATION RATIOS

INSTRUMENT	RADIATION RATIO
'Booth' Stradivari	16.7
'Kreutzer' Stradivari	13.9
'Petri' Stradivari	16.1
'Stretton' 'del Gesù'	14.1
Testore	16.5
Average	15.3

Estimated radiation ratio (along the grain) for five old Italian violin tops

In concluding, let me stress that a copy that is faithful in terms of geometry, tap-tones and weight is not necessarily an acoustically perfect match. There remains the question of damping – of how quickly vibrations tend to die away due to internal losses in the wood. Damping strongly affects quality, response and power, but unlike tap-tones and weight it is difficult to measure in accurate, meaningful ways, especially at higher frequencies. Research will hopefully yield useful guidelines in the not-too-distant future. In the meantime I believe there is much to be learnt by recording and sharing data on the tap-tones and weights of a wide variety of instruments – both old and new. ■