THE UNIVERSITY OF NEWCASTLE
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SEMINAR

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TOPIC: **"The Art, History and Science of Violin Making"**

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PLACE: Room ES209, D.W. George Building, Engineering

ABSTRACT

The violin (representing bowed stringed instruments) embodies all the known acoustical phenomena. It evolved during the Renaissance while Leonardo da Vinci was alive and before Galileo established the Science of Mechanics. It has not undergone a fundamental change since about 1520.

The violin has a close link to the human voice in its basic operation and use; its development occurred in Lombardy and Piedmont and specifically at Cremona on the river Po. It has been the subject of scientific study since Felix Savart in the early 19th century but more intensively since the 1930's. Today very sophisticated techniques are used including Modal Analysis, Finite Element Methods, Scanning Electron Microscopy, Acoustic Spectroscopy, Holography and Physical Methods of Chemical Analysis.

Mr McLennan has had an interest in the violin for many years and his address will cover some of the aspects of this unique instrument.

ALL INTERESTED PERSONS ARE INVITED AND WELCOME TO ATTEND

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THE ART, HISTORY AND SCIENCE OF THE VIOLIN.

What is it about the sound of the violin that excites our interest. The body of the violin generates sound from the agitation imparted to it by the bridge which is placed between the strings and the top plate. Because of the nature of resonance in a structure the amplifying effect is not constant at all frequencies so that some frequencies will be amplified more than others and some not at all. We can therefore refer to the behaviour of the violin as "spiky". There are so many overtones coming from the string and so many "spikes" in a good violin that the "spikyness" is not noticed in the sound. Because of this characteristic of the violin, vibrato adds another dimension of change as the overtones move back and forth across the "spikes". As a result no two notes have the same quality and no single note is the same from moment to moment. This is the basis for the complexity and richness of bowed string sounds.

The violin (as does the viola, cello and double bass) has four strings stretched across a box with a ~~handle~~ neck that gives easy access to them by one hand, usually the left, while the other hand wields a bow, the hair of which is coated with rosin, to bring the strings into vibration. fingers ~~The~~ left hand stop~~s~~ the notes on the strings and executes the vibrato, a form of frequency modulation. There are no frets on the fingerboard.

The violin is made entirely of wood, the back, sides and neck traditionally of European maple; the top of European spruce. Other fittings, pegs, fingerboard and tailpiece are ebony or boxwood which is lighter. The bridge is sycamore. Blocks and linings are pine or willow. All these parts are glued together with hot water glue so they can be easily dismantled for repair. The four strings have a combined tension of about 23 Kg and put a downbearing at each bridge foot of about 5 Kg on the top plate. The body weighs about 280 g (all up the violin weighs about 420 g) and is a very stable structure. The top and back have convex arching to increase their stiffness. Nothing on the violin is redundant and it represents a Baroque artifact of restrained and elegant design.

Let us look briefly at the history of the violin. Plucked and bowed instruments have been in existence for thousands of years. Great advances occurred in the middle ages reaching a high point in the Renaissance prior to 1550. We have to go back to early accounts and paintings for our information. These developments took place largely in Northern Italy, namely Lombardy and Piedmont. The Spanish were in power in the region at the time except for the independence of Venice. By the time the Austrian Hapsburgs gained control of the area early in the 18th century, the development of the violin was complete. During the 17th century the Dukes of Mantua, the Gonzaga~~s~~ were supportive of the arts as were the Medici in Florence, and the Visconti and Sforza in Milan.

Some prominent people living at this time and who would have been aware of the violin were Leonardo da Vinci at the beginning of the 16th century, Galileo in the 17th and Izaac Newton at the end of the 17th century. They were not involved with violin development as far as we know except that Galileo recommended in a letter that Cremona violins were the best.

So where did it come from? Prior to 1500 there were fretted instruments that were plucked, lutes and guitars, amd there were bowed fretted instruments, the viols. There were also a large variety of bowed unfretted instruments classed as "fiddles". They were very variable in shape as seen in contemporary paintings. To quote Carl Forseth:

> "The viol, lyra and violin entered the stage of history not so far apart. The first crude viol may have been assembled as early as 1450, but the fully developed instrument did not appear till 1550, at which date the violin form was fully developed. The lyra appeared in Venice towards the end of the 15th century. In 1499 in Venice was pictured the first two cornered lyra, and six years later, 1505, we see a four cornered lyra representing the true violin body. The maker was probably Francesco Linarolli. Putting a viol head on this lyra body, reducing the strings to four may have occurred around 1515".

Venice seems to have been the melting pot for these activities. Carl Forseth again:

> "The history of musical instruments is the survival of the loudest. Early in the 1500's someone contrived a small but noisy instrument that could outshout a passel of viols. It had the arched top of the rebec, viol and lyra, also their soundpost and the bassbar of the latter two. In particular it had the arched back of the lyra and the head of the viol. It was a small instrument, containing no more wood than necessary and that judiciously distributed; and the stresses were so well balanced that it awoke from a touch of the bow"

Cremona became the centre for violin making for 200 years from 1550. Andrea Amati (1525 - 1611) established a family of makers who perfected the design as we know it. Antonio Stradivari (1644 - 1737) perfected the sound quality. He was apprenticed to Andrea's grandson, Nicolo. Another maker, today ranked with Stradivari, was Guiseppe Guarneri del Gesu (1698 -1744) whose grandfather was apprenticed to Nicolo Amati along with Stradivari. These instruments were well thought of at the time. For example, Andrea Amati made 24 instruments for Charles IX of France, while Stradivari made a quartet for the Spanish court.

This "perfection of sound quality" concerned the shaping of the box i.e. the nature of the arching and plate thicknesses. This occurred over 150 years at a time when the viols, preferred by the nobility, were being displaced in popularity by the violin. The bow in use was short and sturdily built. The playing style for Baroque music at the time was detached notes played off the string and was popular for dancing by composers like Correlli, Vivaldi and Bach. The bow underwent a change in the 1780's when Francois Tourte, in Paris, lengthened the stick, introduced the reverse cambre, standardised the frog and widened the hair ribbon. This facilitated legato playing on the string much used by classical and romantic violinists and composers.

Claudio Monteverdi (1567 - 1643) whose patron was the Duke of Mantua, was the first composer to have used massed violins in the production of his opera "Orfeo" in Venice in 1608.

Since 1800 some changes in the violin setup have taken place. Ludwig Spohr introduced the chinrest in 1820 prior to which the violin was played at the shoulder using the padding supplied by the clothes worn and with the chin to the right of the tailpiece if indeed placed on the instrument. With the Baroque setup the neck of the violin was not deliberately angled, was thicker and with the wedged fingerboard enabled the violin to be held largely by the left hand and played in the lower positions. With the increase in the skill and number of virtuosi, the string length was increased by lengthening the neck to give more separation of notes in the higher positions. The neck was angled, the thick wedge removed and it was morticed into the top block whereas previously it had been butted onto the ribs and nailed through the block from inside the instrument. Angling the neck allowed a higher bridge and the bassbar and soundpost were strengthened. The outcome of all this was an increase in sound output which was desireable for the larger concert halls.

It must be realised that the violin has to fit the human anatomy. This has been a problem with the viola, the size of which has never been settled. A larger size has a more tenor like sound but is a greater strain to play. Originally there were two sizes, a smaller alto and a larger tenor. The larger violas have mostly been cut down since two sizes are no longer used.

It is of interest to note that the four instruments: violin, alto viola, tenor viola and bass (our violoncello) were used to double voice parts, particularly by the church. It turns out that the waveform generated by the action of the bow on the string is the same as that produced by air passing over the vocal cords. The significance of this coincidence is that each waveform contains an unlimited number of harmonics. Vowel sounds get their quality from the mouth and nasal cavities which impose a "formant" on the harmonics coming from the larynx. Some tenors can learn to excite that part of the larynx above the vocal chords to give a brilliance to their voice that is equivalent to the "bridge hill" effect in the violin (see below). In a parallel way, the violin body imposes a "formant" on the string waveform that imitates the desireable qualities of the human voice. These qualities include sonority brought about by strong fundamentals at frequencies up to 1 kHz; brilliance and carrying power by strong resonances in the 2 - 3 kHz region; a low nasal character by weak resonances in the 1.3 - 1.8 kHz region and a rapid fall off above 4 kHz to lower the metallic, harsh quality.

This combination of sound qualities has become known as "Italian Tone" and was achieved early in the 16th century and perfected over the next 200 years. This set the norm for all subsequent makers. Classical Italian instruments from this period sell for $1/2M - $1M; the top figure paid for a Stradivari was $4M. They mostly reside in bank vaults instead of being heard. Today's makers rely on closely adhering to the form and dimensions of classical instruments with minor modifications based on the findings of research. There is a lot of scepticism about the value of the results of research and few craftsmen adopt them.

This brings us to the heart of our present interest; namely how does it work? We start by briefly considering the action of the bow on the string as the source of the signal that is shaped by the violin to give the sounds we hear. Figure 1 illustrates what is happening. When a string is bowed it is pulled to one side until the resisting force in the string disengages it. The kink produced always moves first towards the bridge and then back to the bow as the string slips under the hair. When the kink reaches the bow, the string is picked up by the hair and carried with it, but the kink travels past the bow to the string nut and back to its starting point ready to slip again. If A440 is being played, the kink travels round this circuit 440 times per second. Changing the direction of bowing reverses the motion of the kink. Changing the note with a finger on the string raises the frequency and hence the speed of the kink around its path. The path is made up of sections of two parabolas. The change in string length with deflection from the rest position is appproximately linear so that the string tension will change at a linear rate as the kink moves round the circuit. The kink first moves towards the bridge since the string length is thereby shortened and the string tension lowered. Should the kink go the other way the principle of least action would be violated.

Pushing the string to one side puts a sideways force on the bridge, which is suddenly reversed when the "kink" arrives at the bridge and departs for the bow. On the kink leaving the bridge, this force gradually builds up until the kink arrives back at the bridge when it again reverses. A similar event occurs at the string nut but is oppositely directed. This "saw tooth" behaviour of the force at the bridge is transmitted as a rocking motion to the top plate, the treble foot remaining stationary to a first approximation. This "saw tooth" contains all the overtones that reach the top plate of the violin via the bridge. This is the simple Helmholtz explanation. The real behaviour has additional features. With the bow near the fingerboard, the kink is more rounded resulting in greater sonority (not so many higher harmonics), when close to the bridge the kink is sharper and the sound has more edge to it (there are more higher harmonics).

To see how a violin turns this force into sound we start with a very crude model, a string stretched along a beam with a fingerboard and bridge attached as shown in figure 2. There would be very little sound as the string disturbs so little air. By putting a soundboard, say the size of a violin top, under the bridge we could gain some improvement. The loudest sound would be at about 1 kHz. The loudness of sounds above and below this would be less. Below 1 kHz the length of the soundboard is smaller than the wavelength for the very low notes and air flows readily around it cancelling the pressure changes while above 1 kHz there is a decrease with frequency of 6 dB per octave common to amplifiers. This assumes no resonances in this soundboard. The design of the violin compensates for these deficiencies. Below 1 kHz where most of the fundamentals lie, by adding a back and sides and putting in sound holes, we can arrange to have a number of air and body resonances to amplify the sound and lift the response.

The lowest major resonance, Ao, is an air resonance determined by the volume of the box and the size of the ff-holes. This is just below the Helmholtz air resonance which interacts with a higher body resonance to produce the air resonance Ao. The air volume which is largely determined by the rib height, is designed for this air peak to occur at about 280 Hz. This is on the lowest string, the lowest note of which is G196 and where the body length is only 1/4 wavelength. Higher air resonances do not appear as peaks when excitation comes via the bridge. Instead energy is absorbed and a trough occurs. The next higher air resonance, A1, occurs at about 480 Hz and is determined by the length of the box as the air vibrates back and forth inside. There are about 25 body resonances below 1 kHz not all of which amplify sound. One of major importance is the main top plate resonance, T1, at about 550 Hz. These three resonances play a major part in lifting the response below 1 kHz. At higher frequencies the bridge introduces a resonance at about 3 kHz. This produces a "Bridge Hill" raising the response at an important location.

Following this brief survey we should look at some aspects in more detail. Violins are traditionally made of wood. Other materials have been tried, the most recent has been carbon fibre/ epoxy resin composite. The object was to offer consistent high quality sound at factory production costs. The reason for this was the need of talented students for good sounding instruments. The top only was made and while the properties were matched the costs were too high; and it was black. To vernier for appearance would add to the cost. The traditional woods are European Spruce and Maple although in this country Australian timbers are being used. The problem with woods other than the traditional is the resale value of an instrument in a very conservative profession.

As mass, stiffness and damping are involved in determining resonant behaviour, the density, elastic moduli and damping of the wood used are important properties. Typical values for spruce and maple are:

		Spruce	Maple
Density	Kg/m^3	400 (370 - 570)	580 (560 - 730)
E_L	N/m^2	10.1 x 10^9	11.7 x 10^9
E_R	"	1.4 "	2.0 "
E_L/E_R		7.3	5.8
G_{LR}	"	0.55 "	1.50 "
G_{LT}	"	0.60 "	1.0 "
C_L/C_R		2.7	2.4
C_L/D Radn. Resistance)		12.4	7.8
Q(E_L)		121.75	83.7
Q(E_R)		14.47	30.0
Q(G_{LR})		56.6	59.7
Q(G_{LT})		44.0	51.9

Tone wood is cut(split) on the quarter to maximise the stiffness. Young's modulus can be easily calculated from a measurement of the velocity of sound in the wood. The damping is not so easily measured. If Young's modulus is measured using a vibrating beam method one can move the excitation off resonance to measure the band width at half power and determine Q. The shear moduli can be determined using a torsion pendulum which allows the Q to be found as well. The results are shown above. Features to notice are the ratio of Young's modulus in the L and R directions and the corresponding ratios of sound velocity. The grain is made to run lengthwise in the top and back giving maximum stiffness which is enhanced by the cross arching, along the plates. The ratio of the two velocities together with the dimensions in the L and R directions indicate that a sound wave will reach the edge of the plate at the same time. This has been demonstrated by experiment. The other number is the ratio of sound velocity and density which is a measure of the acoustical power. This is the radiation resistance, a high value correlating with a higher sound output. The product of sound velocity and density is the sound wave resistance and should be low as this represents energy lost internally as heat. Spruce has long been used as soundboard material. Softwoods have higher values of radiation resistance than hardwoods and the ratio of 2:1 turns out to be right for violins. The top is the most active member particularly between the sound holes.

The free plates are tuned as they are thinned from the inside after having completely finished the outside arching. The old makers and many today used a "Tap tone" technique. Research has shown that irradiation with a variable frequency sound from a speaker enables the mode frequencies and Chladni patterns of the plate vibrations to be determined. Good sounding instruments are obtained when the low frequency modes of the two plates are matched approximately. The effect of arching is to allow separation of the three lower modes by an octave. The higher of the three modes is tuned to 370 Hz to make a concert violin which is demanding to play, down to 320 Hz for a chamber music instrument which is softer toned and easier to play. The maker has to reduce the mass of the top as much as possible yet keep the frequencies up, so he chooses light wood with a high modulus and gives the plate an appropriate arching. Cutting the sound holes in the top drastically lowers the higher mode frequency and the plate tuning is lost through loss of longitudinal stiffness. The bassbar allows this stiffness and tuning to be restored.

When the plates are assembled by gluing to the ribs to make the box, the vibration behaviour is quite different. Modal analysis and holography have been used to delineate the mode shapes. No close correlation has been found between the two states except that higher plate modes tend to coincide with a higher frequency for the main top plate resonance, T1.

A recent finding has shown that the frequency interval between the first higher air resonance, A1, and the main top plate resonance, T1, may be important in determining the quality of the violin. An interval of 50 to 70 Hz coincides with a concert violin quality. At a greater interval, e.g. 100 Hz, the instrument is unbearably harsh. Below an interval of 30 Hz, the violin is easier to play and not as loud.

The soundpost is an important component. At the low end of the range where the violin is smaller than the wavelength, it has to act as a "Simple source" to radiate effectively. This means that the body modes below 1 kHz require a high monopole content. The asymmetry created by the soundpost ensures this "breathing" action. The soundpost together with the sides allows the balance in output between the strings to be even. At higher frequencies the plates subdivide into smaller regions that radiate directly.

At low frequencies the bridge acts as a lever and behaves as an integral part of the top plate. The motion at the left foot is 1.5 times less than at the bridge top. The real amplitude at the left foot of the bridge is about equal to the thickness of the varnish. At high frequencies it has a life of its own. Between 2 and 3 kHz the bridge has a resonance where the top half rocks in the plane of the bridge. This produces the "Bridge hill" that was mentioned earlier and enhances the response of the violin in this region. The cuts in the sides of the bridge filter out all flexural motion and allow only transverse rocking motion to reach the violin top.

Response curves enable the location and strength of peaks to be determined. It is in fact the instrument "Formant". One can link broad differences in sound quality with the overall shape of the curve. Individual peaks can be studied by mass loading at an antinode to determine the frequency shift and evaluate the effective mass, effective stiffness and from the bandwidth, the Q thus enabling the radiation resistance to be calculated. Since the left foot of the bridge is antinodal to most of the sound producing peaks, placing the small weights near it allows most peaks of importance to be studied.

The features of the violin response outlined, and the variation between instruments leads to the question of how we judge sound quality. By closely adhering to established dimensions a maker will build in the main resonances. How well he does this makes the difference. The range of the instrument is divided into bands that approximately reflect the sound quality of the voice formant. The ranges with an approximate descriptive label are as follows: 190 - 650 Hz sonority, 650 - 1300 Hz nasal and boxy, 1300 - 4200 Hz brilliance and good radiation also evenness of overtones, 4200 - 6400 Hz harsh and lack of clarity. A good sound is produced by a violin with a strong lower air resonance, strong body resonances, a suppressed nasal region and a "Bridge Hill".

We have not been very successful at achieving these requirements. Figure 3 summarises the study of 5 groups of makers. About 20% of our output compares with the old masters. The relative success of the "Hobby" makers can be attributed to their greater interest in research findings compared with traditionally trained makers. It should be kept in mind that the sample of old Italians is most likely biassed in favour of good instruments since they are the ones most likely to have been preserved.

The bow, by comparison with the violin, is a lesser known quantity but is no less important. In the context of this talk, it will have resonances and other properties e.g. weight, balance and resilience, that will influence the player in attaining that optimum string action necessary for a good sound. An early textbook on the Physics of Music by Alexander Wood published by Methuen in 1944 points out that "the force - due to the bow - has no natural frequency of its own, so that the system whose vibration is forced - the string - vibrates with its own natural frequency." This would seem to be a desireable situation but resonances have been found in the bow stick so the understanding of the bow is still poor.

Varnish has received a lot of coverage in the literature. There is no magic associated with it. It is there to protect the violin from dirt and moisture and enhance its beauty. Acoustically, it adds about 10 g to the weight, increases the damping slightly which is good and lowers the peak frequencies a little. There are two types of varnish; a spirit based solution of natural resins which can dissolve a lot of colour and an oil based solution of natural resins with a poor ability to dissolve colour. The latter is much slower drying but usually produces a more flexible film. Application of oil varnish has employed a "glaze" technique to achieve the depth of colour with fewer coats. Some makers today are using polyurethane varnish. An old violin from which most of the varnish has been worn off will not be revarnished except after repair. The ability of these instruments to remain clean has led people to speculate that a special wood preparation had been used. Two adages can be cited to sum up the present attitude to varnish:

(1) that it must be a little and look a lot, and

(2) not too hard, not too soft and not too much.

In summary, we have a most remarkable product of human craftsmanship. A little wooden box of exquisite shape weighing about 400 g, the parts glued together with gelatin hot water glue and able to withstand a combined string force of 23 Kg. The four strings, tuned in fifths, give a range of 3 1/2 ctaves and it is capable of an output of more than 90 dB. Moreover, there are a few violins 400 years old still being played.

Sources and further reading.

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J.E. McLennan

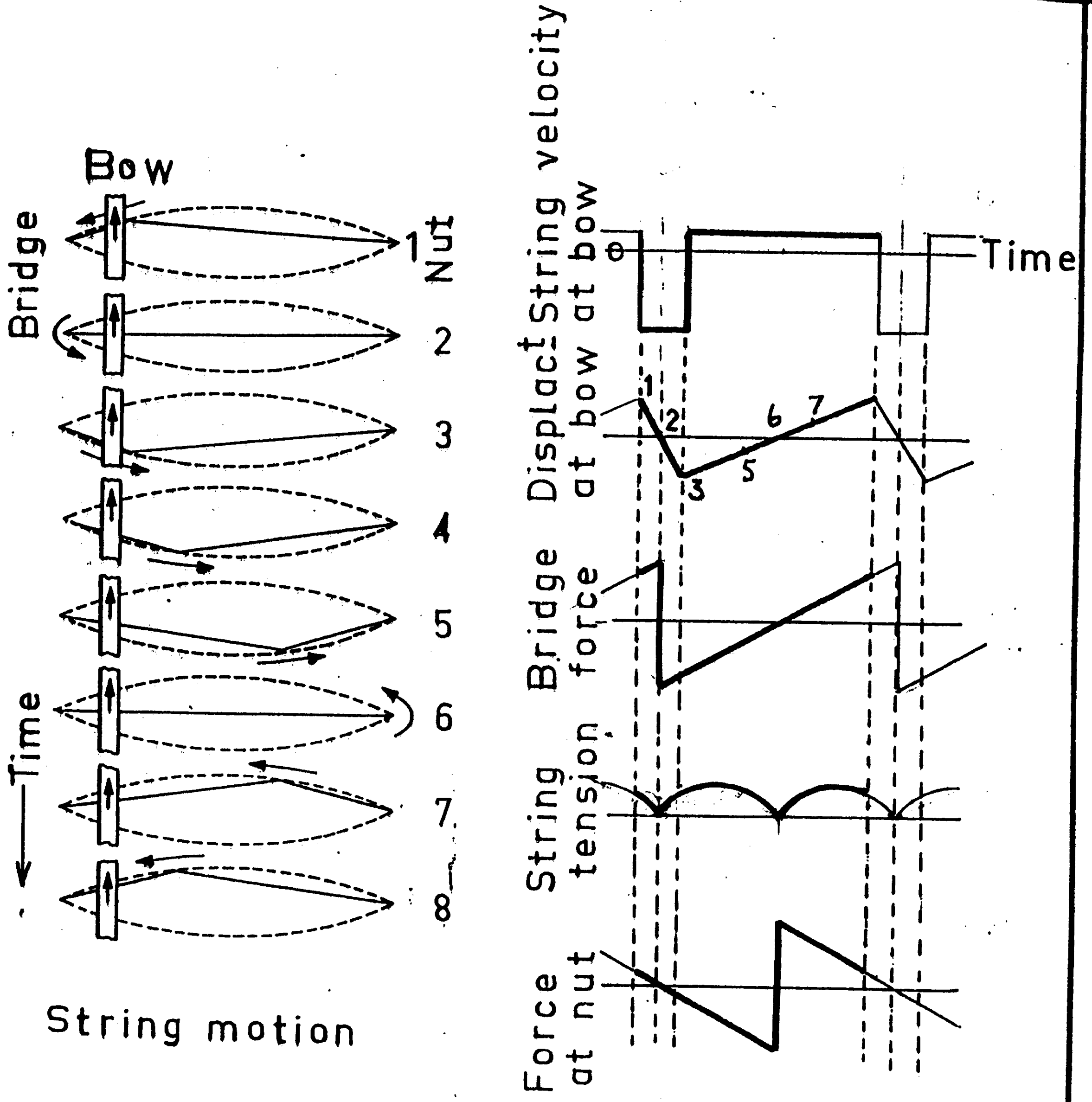
String motion

Fig. 1 Bowed string motion and associated effects

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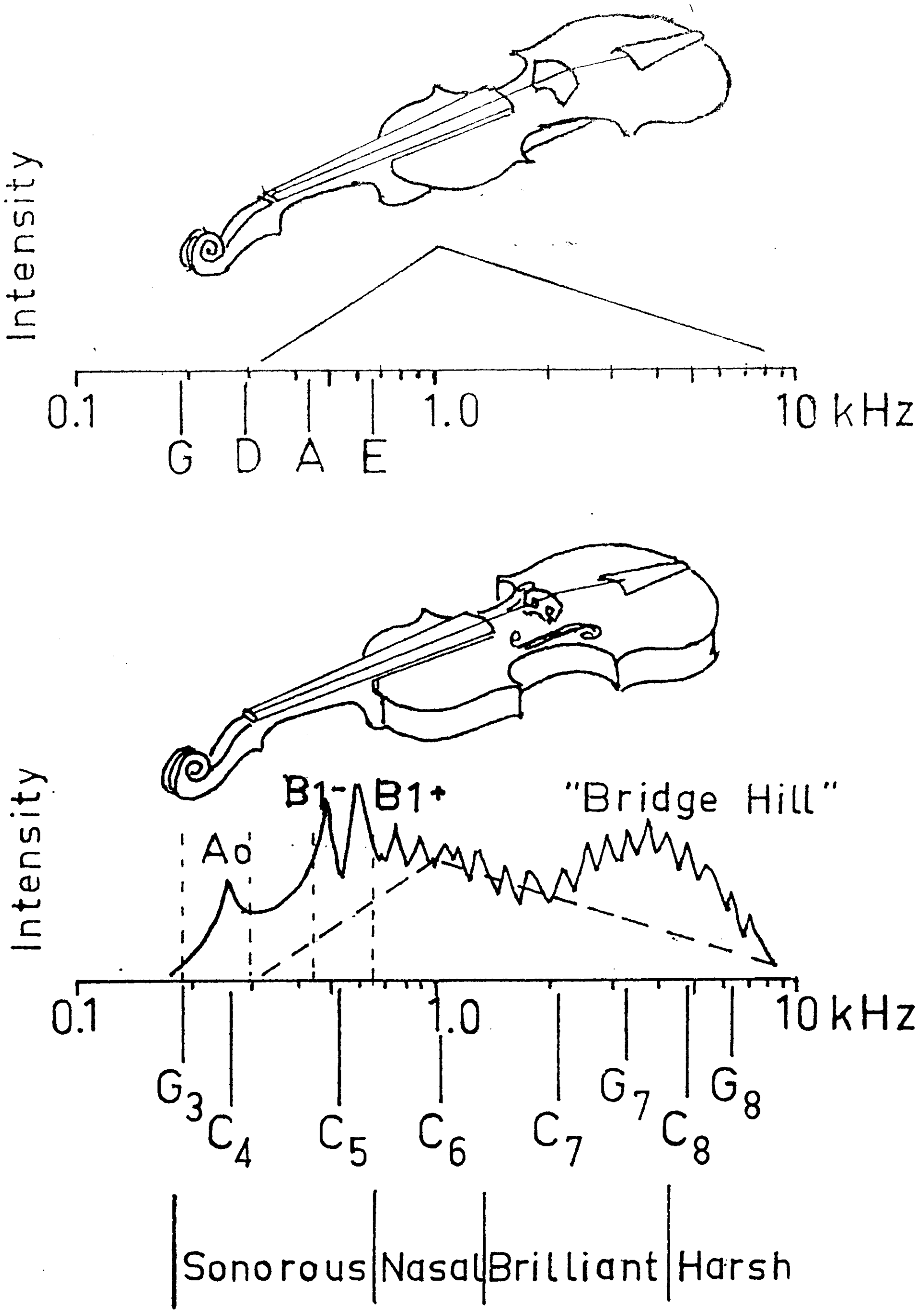

Fig. 2 Effect of Violin Body on String Sound Intensity

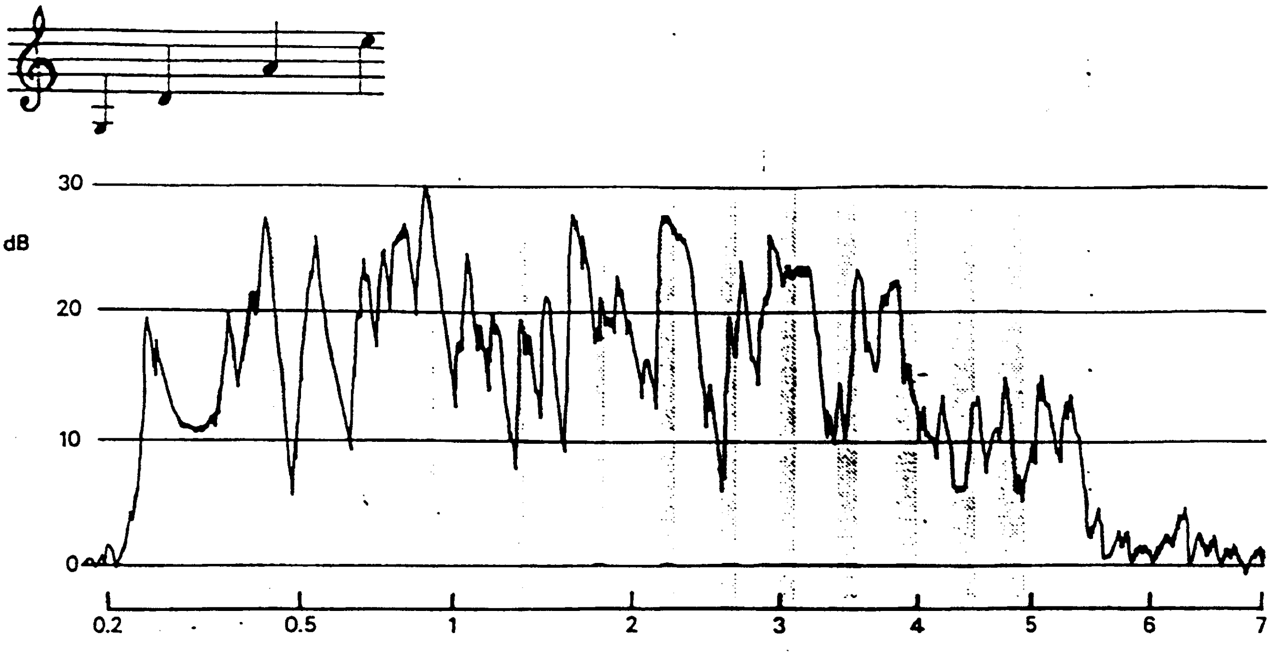

Fig. 3 Response curve of a Stradivarius violin (the 'Titian' of 1715, after Saunders[31]). Sound intensity at one microphone position is plotted against frequency. The musical notes shown are those to which the open strings are tuned. The shaded bars indicate the range of variation of harmonics of the note 440 A during a vibrato cycle.

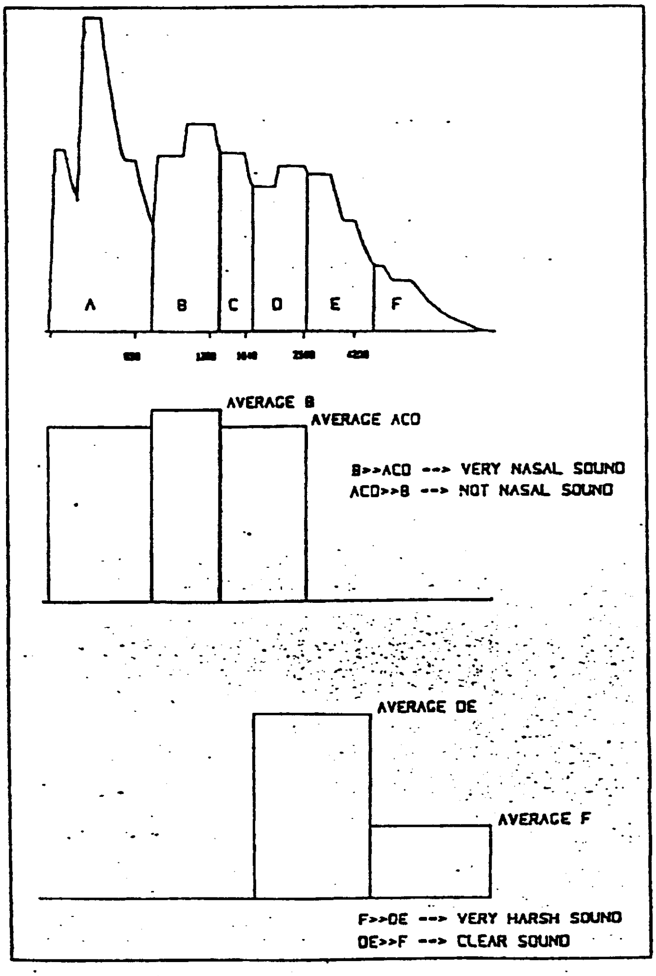

Fig. 4 Calculation of relative loudness in different frequency bands.

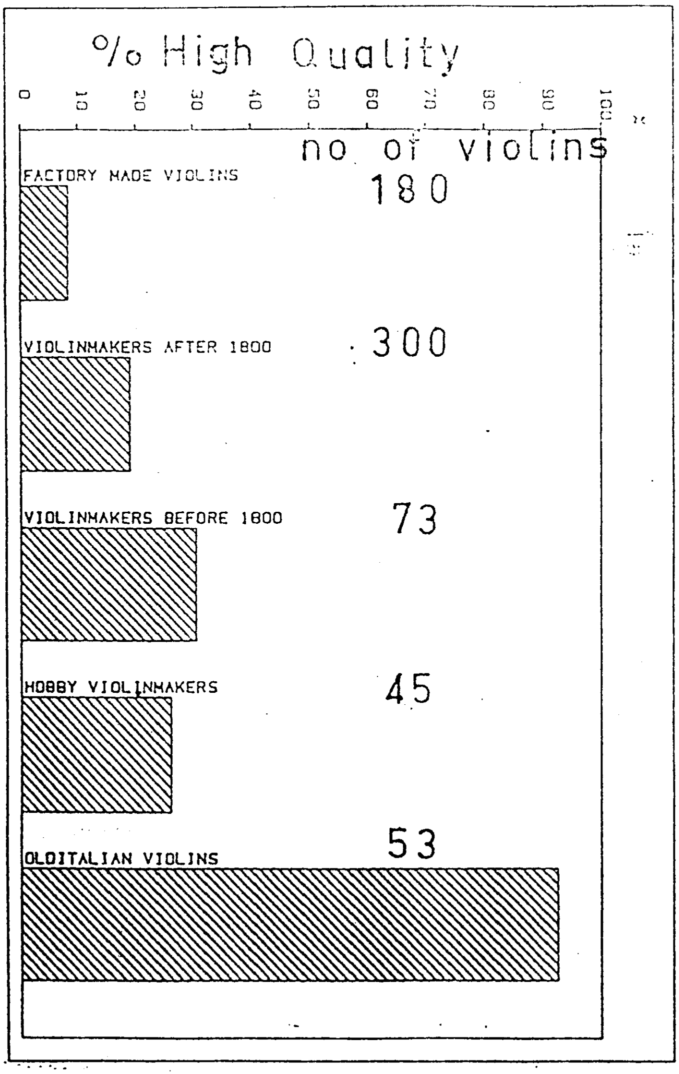

Fig.3 Success rates for different groups of makers.