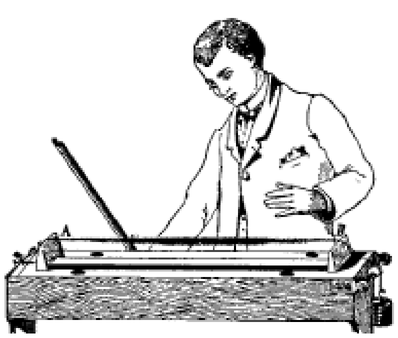
KUNGL TEKNISKA HÖGSKOLAN

Dept of Speech, Music and Hearing

ACOUSTICS FOR VIOLIN AND GUITAR MAKERS

Erik Jansson

Chapter V: Vibration Properties of the Wood and Tuning of Violin Plates



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ACOUSTICS FOR VIOLIN AND GUITAR MAKERS

Chapter 5 – Applied Acoustics
VIBRATION PROPERTIES OF THE WOOD AND TUNING OF VIOLIN PLATES

Chapter 5.
VIBRATION PROPERTIES OF THE WOOD AND TUNING OF VIOLIN PLATES
First part: VIBRATION PROPERTIES OF THE WOOD

INTRODUCTION

In this first part of chapter 5 fundamental vibration properties of wood will be introduced. First fundamental theory is presented. It is followed by presenting measurement methods and ends with giving vibration (mechanical, acoustical) properties of wood.

5.1 FUNDAMENTAL THEORY

We have previously seen how properties like stiffness, mass and internal friction determines the vibration properties of a plate. We shall try to sort out how one should design a violin top to give it wanted acoustical (vibration) properties. The properties we shall design a top plate to have are 1) specific nodal line patterns and 2) specific resonant frequencies. In order to give a better understanding for the problems related to top and back plates and possible solutions we shall again summarise some vibration basics concerning the properties of resonances of bars and plates. Thereafter follows measurement methods of the resonance properties (resonant frequency, level, bandwidth and nodal line pattern), their use for deduction of mechanical vibration properties of wood (moduli of elasticity and internal friction) and some data of different wood species.

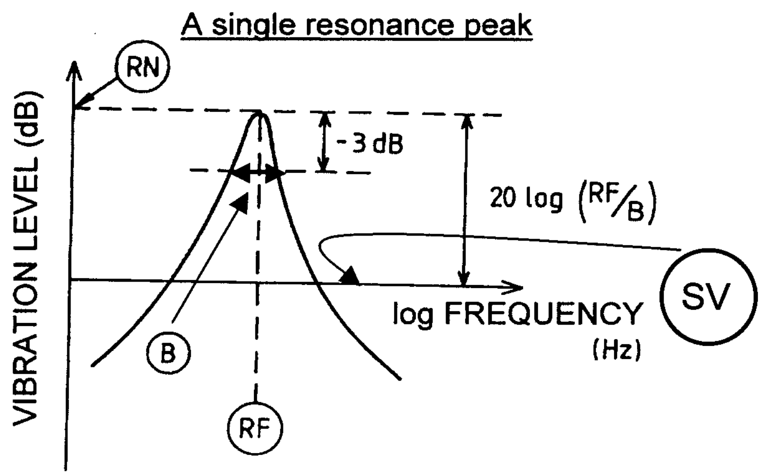


Figure 5.1 Definition of acoustical (vibration) measures at a resonance peak.

PROPERTIES OF A SINGLE RESONANCE (resonant frequency, level, bandwidth, and specific vibration sensitivity (specific mobility))

The vibration sensitivity at the driving point is a measure of how easily a guitar, a violin or a violin plate is set into vibration. The driving-point vibration sensitivity varies with frequency. At low and high frequencies the driving-point vibration sensitivity is low for the simple system with only one resonance (as the rubber band yo-yo). At an intermediate frequency the driving-point vibration sensitivity is maximum and the vibration sensitivity shows a resonance peak, see fig. 5.1.

In a diagram of the driving-point vibration sensitivity as function of frequency three acoustical (vibration) properties can be read: the frequency of the resonance peak (RF Hz), the level at resonant frequency (RL dB) and the bandwidth of the resonance (B Hz, i.e. the width 3 dB below the peak value).With the resonance removed the specific vibration sensitivity (SV, i.e. peak value minus 20log[RF/B]) is obtained. Inversely if we know that we have a simple system with one resonance only, the three properties; frequency at, bandwidth of, and level of the resonance peak are sufficient to predict (plot) the behaviour at all frequencies. Thus the curve for a simple resonance can be described by the three measures without any loss of information, c.f. fig. 5.1.

The decay of resonance vibrations (after turning off the driving) is determined by the bandwidth of the resonance. The vibration sensitivity of the mechanical system is the combination of specific vibration sensitivity and resonance properties.

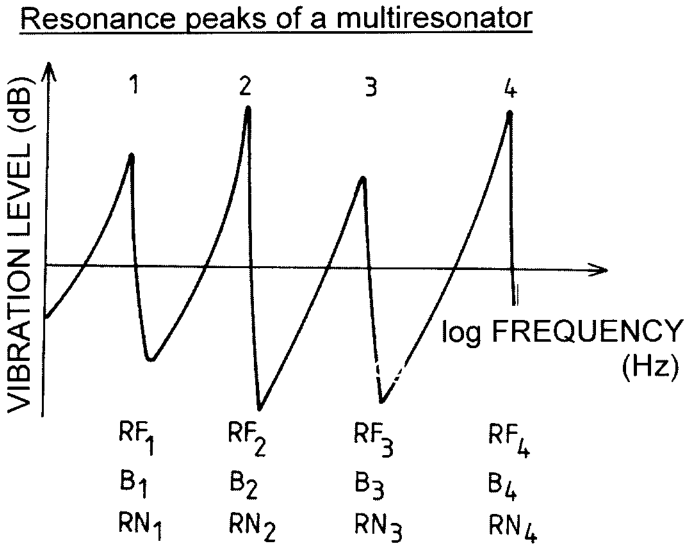


Figure 5.2 Predicted VIBRATION SENSITIVITY curve for a wooden plate (in principle).

MECHANICAL PROPERTIES (mass, stiffness, and friction)
The simple resonance (as the rubber band yo-yo) has three mechanical parts: 1) a spring (the rubber band), 2) a mass (the weight), and 3) friction (the air friction when the weight is moving). Between the mechanical and the vibration properties there are mathematical relations as presented in section 5.11 appendix.

VIBRATION (ACOUSTICAL) PROPERTIES OF A MULTIRESONANCE SYSTEM (vibration modes at resonance, nodes and antinodes)
If we replace the simple resonator (the rubber band yo-yo) with a thin plate and measure the driving-point vibration sensitivity we shall obtain a large number of resonance peaks. Each resonance is described by the frequency, the level and the bandwidth of each peak, see fig. 5.2. The complete driving-point vibration sensitivity curve can be predicted (plotted) from the three measures of all resonances. In fact, a violin plate is a multiresonance system with a large number of peaks.

What the driving point sensitivity curve does not reveal is that the plate vibrates in a different way for each resonance. At a given resonant frequency, different points of the plate vibrate with different magnitudes varying between a maximum and no vibrations. This vibration pattern (vibration mode) must be added to the three vibration sensitivity measures for a complete description of the vibration (acoustical) properties of the plate. The positions of maximum vibrations are called antinodes and the lines of no motion are called nodal lines.

BAR AND PLATE PROPERTIES

Nodal lines for a bar or a plate can be measured with a loudspeaker and particles sprinkled over the bar or plate. Small pieces of foam plastic are placed under "suspected" nodal lines, see fig 5.3. The position of the supports are adjusted to the real nodal lines after the measurement has been started.

Nodal lines of a thin rectangular spruce plate are shown in fig 5.3b. Nodal lines were first visualised by Ernst Chladni, and another name of the nodal line patterns are Chladni patterns. A rectangular plate can in some of its lower modes be regarded as made of broad bar along the grains or a broad bar across the grains, see fig. 5.4. In the plate there is a certain degree of coupling between vibrations spread along the two directions.

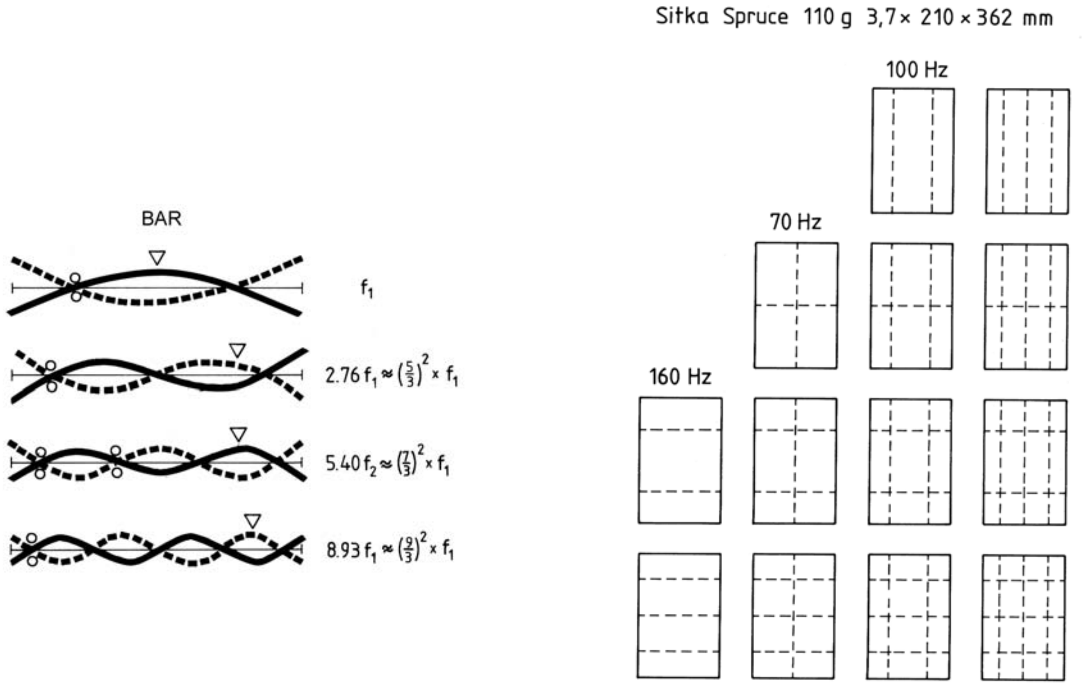


Figure 5.3. Vibration distribution for the resonances of a) a bar with free ends (an antinode marked with triangle and a node with circles) and b) a rectangular plate with free edges (dashed lines are nodal lines, Sitka Spruce 362 x 210 x 3.7 mm and 110 g).

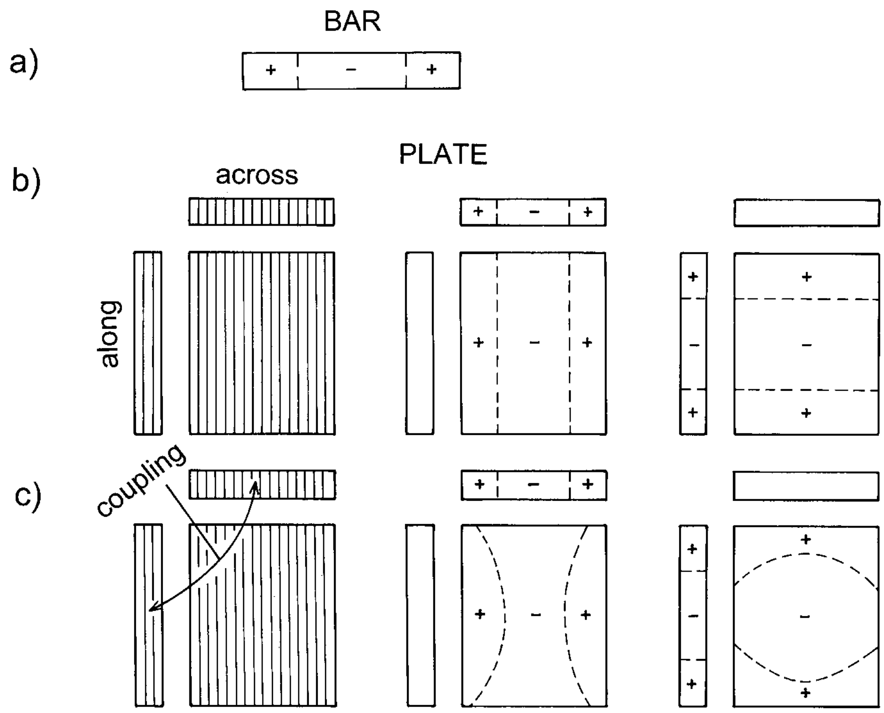


Figure 5.4. Fundamental vibration modes of a) a free bar, b) a free plate across and along with no coupling, and c) a free plate across and along with coupling.

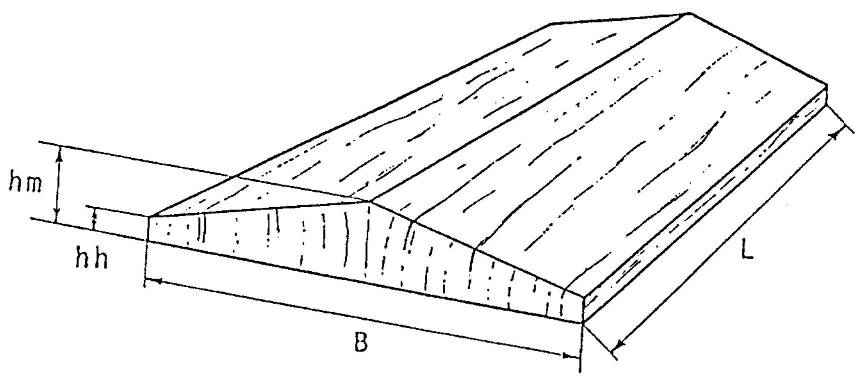


Figure 5.5. Dimension of top plate blank for test of material properties; for violin: 385 x 215 x (20 in the middle, 7.5 mm along edges) and for viola: 450 x 260 x (25 in the middle , 78 mm along edges) mm - proposal worked out by Gunnar Mattsson, Stockholm's violin makers club.

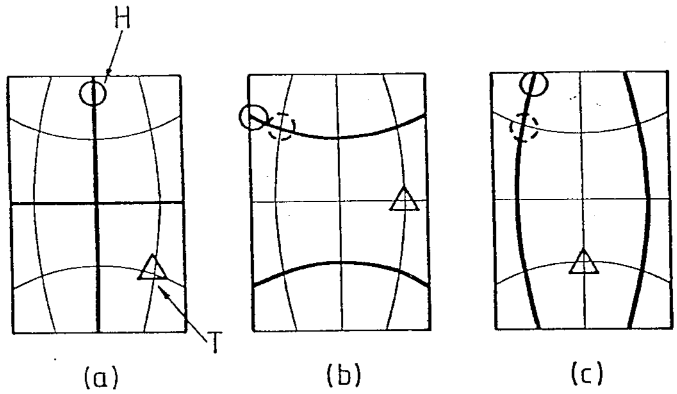


Figure 5.6. Positions of holding (at circle H, full lines for the best but somewhat more difficult position to find, dashed lines for the position simple to find) and tap positions for tapping (triangles T) for a blank (from Molin et al, 1988).

5.2 MEASUREMENT METHODS (resonant frequencies, antinodes and nodal lines)
In the process of experimenting, standard measures have been proposed for blanks, see fig. 5.5. If these measures of blanks are used mechanical material properties can be measured by tapping. The tap tone related to the closest tone of a piano, for instance.

METHOD OF TAPPING AND LISTENING (resonant frequencies).
The resonances of a bar or a plate can detected by taping and listening using the two main rules, c.f. fig. 5.6.and 5.7.

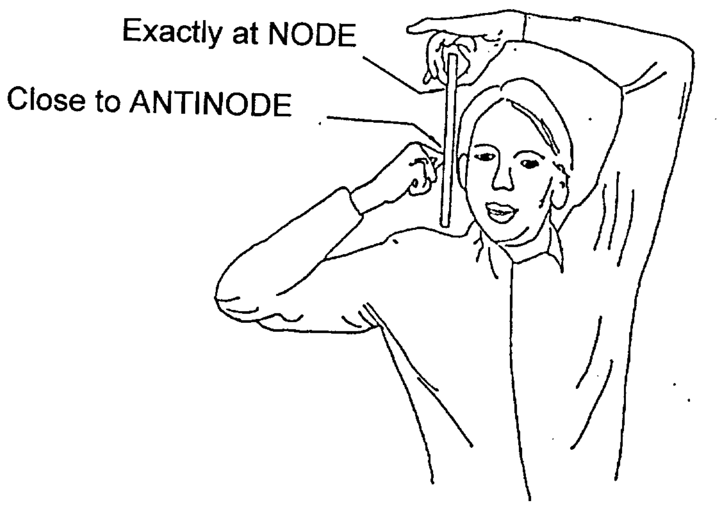


Figure 5.7. Suitable way to hold a bar or a violin plate for tapping of a resonance. Hold lightly at a node and tap closely to an antinode. Only the thumb, the index finger and the knuckle (at the moment of tapping) are allowed to touch the bar or plate.

1. **Hold lightly at a nodal line** (one must hold at a nodal line).
2. **Tap close to an antinode**.
The method can be refined to obtain safer and more information by applying additional rules 3 and 4:

3. To suppress an interfering resonance - tap at a nodal line and hold close to an antinode of the resonance to be suppressed. Note that one must hold at a nodal line of the resonance being investigated.
4. With some practice nodal lines and antinodes can be localised in two different ways:
I) Start holding at a nodal line and tap at an antinode. Vary the holding point but not the tapping point. Mark the holding points where the tap tone of the resonance can be heard the best. Connect the holding points with lines. If correctly done, the lines mark nodal lines. Many "holding" points are needed.
II) Hold at a nodal line and tap at many different points. Mark the points where the tap tone of the resonance cannot be heard. Connect these points and the nodal lines have been marked. Many "dead" points are needed. Method I should be more reliable but method II faster.

The author has found it convenient to hold the plate between the thumb and the index finger of the left hand, c.f. fig. 5.7. The arm is held over the head as shown in the fig. 5.7 close to the right ear. The plate is tapped with a finger tip (low frequency tap tones), a knuckle or a nail (high frequency tap tones) level with the ear. The left arm is lowered or raised to position the tapping point close to an antinode at the right ear. By determining the frequencies of the resonances in fig. 5.6 the violin maker can determine the twisting, the longitudinal and the cross stiffness of the wood of a blank. Ultrasound methods can also be used but the method presented has the advantage that no extra apparatus is needed.

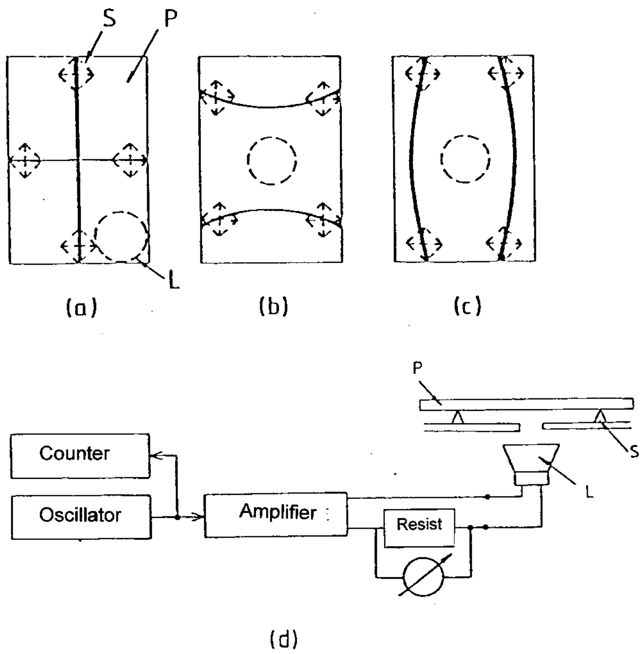


Figure 5.8. Set-up for measurement of Chladni patterns of the three lowest resonances (a, b, and c) of the plate P. The supports are marked with squares S, and the loudspeaker with circles L. Schematic diagram for measurement system (d, from Molin et al 1988)

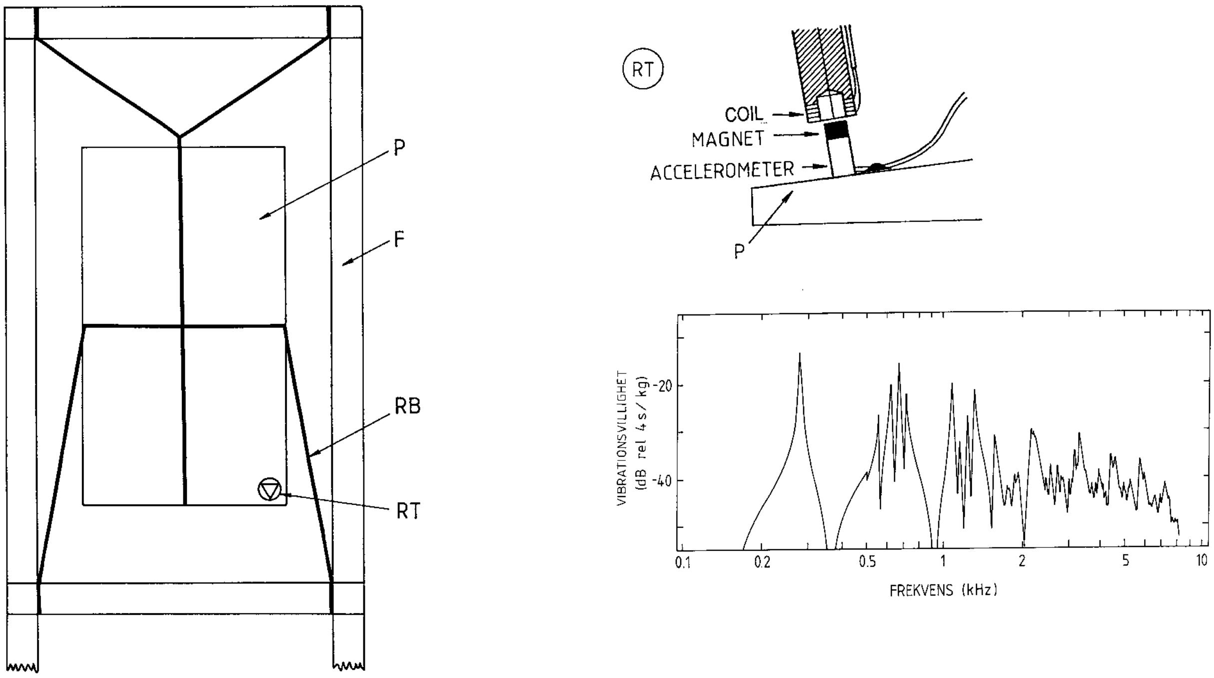


Figure 5.9. Measurement of vibration sensitivity: a) the plate P is hung in a frame F with rubber bands RB and the measurement sond RT is fastened with wax in a corner. The measurement sond consists of a contact microphone and a magnet. By means of an electric coil a vibration force is obtained. b) Vibration sensitivity for a blank measured as shown in a (from Molin et al, 1988).

METHOD OF CHLADNI PATTERNS (resonant frequencies, nodes and antinodes).
Chladni methods to investigate vibrations of violin plates were probably first used by Felix Savart. For this purpose he simplified the geometry of the violin to a flat triangular body. Lately the method has been reintroduced and further developed by Beldie and Hutchins. They have investigated properties of arched violin plates. The method is the following. The plate to be tested is placed over a loudspeaker in a table, c.f. fig. 5.8. The plate is lifted up a cm or two above the table with four pieces of plastic foam. Small particles, saw dust, tea leaves or similar, are sprinkled over the plate. By means of an audio oscillator and a powerful amplifier (about 15 W) the loudspeaker gives a loud tone. The frequency of the tone a adjusted until the particles jump the most. We have then found a resonance and the frequency of the loudspeaker tone is the frequency of the plate resonance. The positions of maximum jumps of the particles mark the antinodes. The particles will soon move and collect at the nodal lines. The supporting plastic foam pieces should be positioned at nodal lines and the loudspeaker at an antinode for the best results. Some experimenting may be necessary to find such best positions. Thus the method gives resonance frequencies and nodal lines, but with a little extra observation also antinodes.

LABORATORY MEASUREMENT METHODS FOR VIBRATION SENSITIVITY AND VIBRATION MODES.
The vibration sensitivity of a vibrating plate can be measured in the acoustical laboratory by a method developed by Jansson and Alonso, c.f. fig. 5.9 The object is hung in rubber bands and the driving and measuring sond is attached. The vibration sensitivity is obtained by slowly varying the driving

frequency (c.f. glissando) and by simultaneously measuring the resulting vibration amplitude. A diagram of the vibration sensitivity as function of frequency can be plotted within a couple of minutes (c.f. fig. 5.2). The resonance peaks give accurately the frequencies, the levels and the bandwidth at the resonances.

Optical methods have been developed by Biedermann, Ek and Molin to measure vibrations. The advantage with the optical methods is that the measurements are made contact free, i.e. no weights attached and disturbing the plate vibrations. The last apparatus in this development line is the Vibravision. With a case containing a special optical interferometer, a laser and a TV-camera the vibrations are made visible on a TV-monitor. The method gives quickly and accurately the vibration amplitudes of the whole surface. Furthermore resonant frequencies are easily obtained and with some work bandwidths and vibration levels. The method is much more sensitive than the Chladni method.

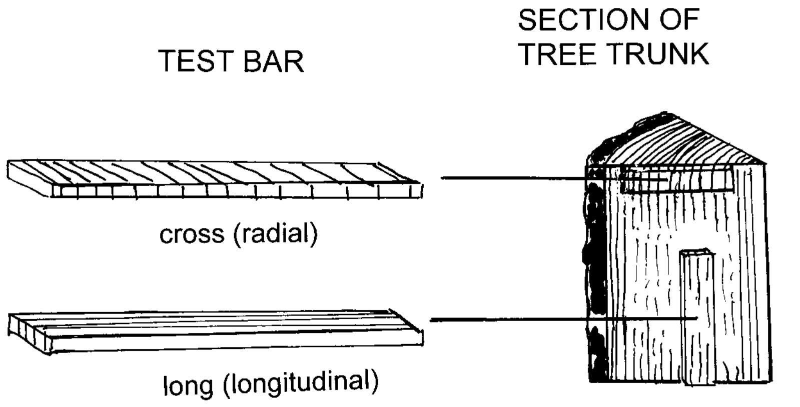


Figure 5.10. Bars for test of material properties .

5.3 ACOUSTICAL AND MECHANICAL PROPERTIES OF WOOD (mass, stiffness, internal friction)

Table 5.1. Density (kg/m^3, mean from Haines, 2000).

Spruce	460 kg/m^3
Maple (Czech)	620
Cedar (red)	390
Mahogany (Khaya)	550
Rosewood (Indian)	730
(Brazilian)	830
Ebony	1200*

Table 5.2. Stiffness (elasticity modulus GPa, 1 GPa is 100 "kg/mm^2" from Haines, 2000).

	shear	longitudinal	radial
Spruce	0.84 GPa	15 GPa	0.76 GPa
Maple (Czech)	1.7*	10	2.0
Cedar (red)	0.65	9.1	0.72
Mahogany (Khaya)	0.63	12	0.90
Rosewood (Indian)	2.2	13	2.4
(Brazilian)	3.0	16	2.8

* for German subset no data for Czech one, GPa stand for billions of Pa (Pascal).

Table 5.3. Internal friction in the form of bandwidths at low frequencies (200 - 1000 Hz) and at high frequencies (10 000 - 15 000 Hz) for longitudinal and radial bars (bandwidth B Hz at frequency F kHz, B = F x log decrement x 3.14, calculated from Haines' data).

	B longitudinal		B radial	
Spruce	5.2	239	6.6	232
Maple (Czech)	5.5	226	4.6	493
Cedar (red)	5.6	173	4.0	146
Mahogany (Khaya)	3.8	321	4.2	402
Rosewood (Indian)	2.0	351	3.9	203
(Brazilian)	1.9	116	3.0	141

TEST BARS AND WOOD PROPERTIES

A wooden plate contains the three mechanical properties - it "tries" to unfold when folded, i.e. it contains a spring, it has a specific mass (weight) and friction. It is interesting to know (how the three mechanical properties mass, stiffness and internal friction) determine the vibration (acoustical) properties of the plate. One way to test these properties is by means of test bars, see fig. 5.10. Often the dimensions of the bars are selected to 100 mm length, 10 mm width, and 3 mm thickness. The bars are cut along the grain (longitudinal bars) and across (radial bars, c.f. fig. 5.9).

The first resonant frequency of the bar is a measure of its elastic properties. The elasticity modulus can be calculated from the resonant frequency, the geometry and the mass of the bar. In principle the frequency can be identified by the tap tone method, except from the fact that the tap tone is very short and weak. The Chladni method is however more suitable. The bar to be tested is laid on top of two plastic supports shaped as wedges. The wedges are positioned 22.4% of the bar length from its ends for the first (lowest frequency) vibration mode. The loudspeaker sets the bar in vibration and the tone frequency is adjusted to maximize the motion of the particles, i.e. to the lowest resonance frequency. With laboratory methods the internal friction and the twisting stiffness of the wood can also be measured. Examples of elasticity modulus for vibrations along, across, and twisting along are given in Tables 5.1-5.3.

PLATES AND WOOD PROPERTIES

A rectangular plate can sometimes be thought of as a bar of great width, both across and along the grain, c.f. fig. 5.4. The plate will thus get the same nodal patterns as the corresponding bars across and along the grain. In a real plate there is coupling between the vibrations along and across the grain and the nodal lines will generally be bent, c.f. fig. 5.4c. Resonance frequencies of the plate can be obtained by the tap tone method. The resonance frequencies, the nodal lines and the antinodes are easily obtained with the Chladni method.

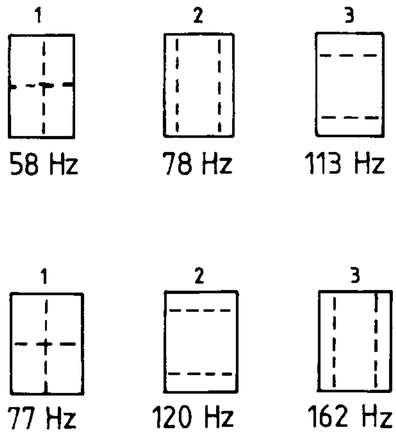


Figure 5.11. Typical nodal line patterns for spruce and maple - for the maple plate the frequency order is reversed compared to the spruce platefor the higher two modes shown (from Beldie, 1965).

Such measurements may give the result shown in fig. 5.11. The lowest resonance has two nodal lines forming a cross. In the second, the plate vibrates as a "wide bar" across the grains and in the third resonance as a "wide bar" along the grains. If the plate material is changed to maple the second and third resonance shift positions of nodal lines. This means that the first vibration mode of the plate is a twisting motion. In the following two modes the plate vibrates mainly in two bending motions across and along the grain for the spruce plate and vice versa for the maple plate. With resonance frequencies, length, width and thickness known together with the density the three elastic moduli can be calculated. This can be done with the tap tone method in principle. It may though be difficult to find suitable sizes for plates to obtain suitable tap tone frequencies without destroying the material for building.

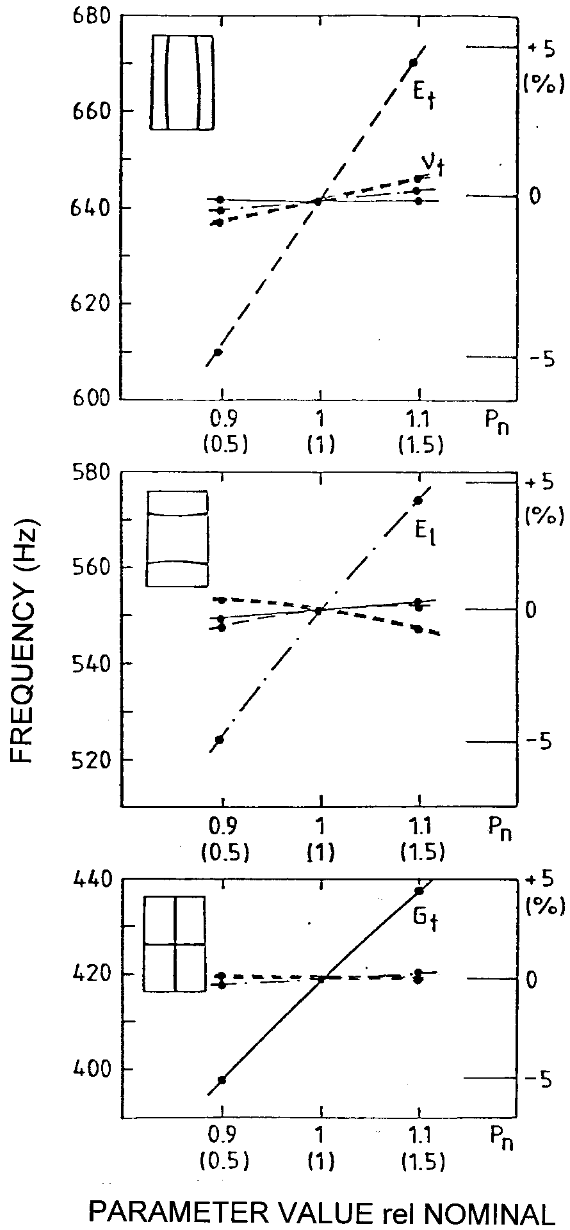


Figure 5.12. Numerical experiments showing that the resonance frequency no 1 is determined by the shear modulus G_l (lowest frame), resonance frequency no 2 by the longitudinal elastic modulus E_l (middle frame) and resonance frequency no 3 by the transversal elastic modulus E_t (topmost frame, from Molin et al, 1988).

We have experimented with blanks for top and back plates. By means of the Chladni method, the resonance frequencies, the nodal lines and the antinodes can be recorded and if the vibration sensitivity is recorded the internal friction can be measured in addition. We have started with a standard size for blanks, see fig. 5.5.

For the blanks we will in principle obtain the same order of nodal lines as sketched in fig. 5.11b (for the evenly thick maple plate). By means of computer calculations (finite element calculations) we have proved that the three resonances are mainly determined by a single and separate material property. The first resonance is mainly determined by torsion stiffness (the shear modulus), the second by the longitudinal stiffness (the longitudinal elastic modulus), and the third by the radial stiffness (the radial elastic modulus), c.f. fig. 5.12.

The computer calculations have also given simple formulas to calculate the material properties if the test blank is close in size to our defined standard, i.e. the length and width measures should be within 1 mm, the thickness within 0.5 mm. If so the density of the wood becomes the blank weight divided by the blank volume (the volume is length x half width x (edge thickness + center thickness)). The elastic moduli can be calculated as follows:

modulus for shear	17 x 1000 x weight x frekv^2 Pa
longitudinal	89 " " " "
radial	4.4 " " " "

For the shear modulus the frequency of the first resonance should be used, for the longitudinal the frequency of the second resonance, and for the radial modulus the frequency of the third resonance.

5.4. SUMMARY: VIBRATION PROPERTIES OF THE WOOD

After a repetition of properties of resonances, methods to measure these properties have been presented: the tapping method, c.f. fig. 5.7, the Chladni method and by measuring vibration sensitivity. Material properties for tone wood have been measured and how these influence the resonance properties. Finally methods for determining material properties have been described, which can be used in the maker's workshop.

5.5 KEY WORDS:

Resonant frequency, vibration sensitivity, specific vibration sensitivity, bandwidth, nodal lines, antinodes, mass (weight), stiffness, friction, and elasticity (Young's) modulus.

Chapter 5.
Second part: TUNING OF THE TOP AND BACK PLATES OF THE VIOLIN

INTRODUCTION

In this second part some results are presented that can be useful for the maker. First the fundamental principles for tuning followed by typical data of free violin top and back plates, and finally advices on practical tuning of violin plates.

5.6. FUNDAMENTAL PRINCIPLES FOR TUNING (frequencies, bandwidths and nodal lines)

There is no simple answer either from the violin maker or the researcher on how a violin top plate should be tuned. Therefore the reader should not expect to find such answers in this work. We shall, however, look at some published works and compare the results with reasonable predictions, and with the results of our own research. Dr. Carleen Hutchins has for many years worked with such methods and is the most prominent maker-researcher of today. The results presented can be used by the maker (both the violin and the guitar maker) to give clues in his own research to improve his or her instruments.

TUNING OF A BAR (frequencies, bandwidths, and nodal lines)

The mechanical properties of the bar are stiffness, mass and internal friction. When wood is removed from the bar both the mass and the stiffness is reduced. As the stiffness is more sensitive to the thickness (proportional to the thickness to the third power) than the mass (proportional to the thickness), then the resonant frequency (proportional to the thickness) decreases when the bar is thinned by a constant amount over the whole length.

J. Alonso made series of experiments to investigate the principles of bar tuning. A number of bars were made and their properties were measured. Thereafter wood was removed at well defined positions with a milling machine. Nodal line shifts and resonant frequency shifts were measured, see fig. 5.13.

The experimental results gave the following rules:

1) The resonance frequency is lowered in all cases except from thinning close to a free end.
2) The nodal lines are shifted the most but not much for thinning close to a nodal line. The closest nodal line is shifted towards the near end, and the other nodal line is shifted less but in the same direction.
3) The bandwidths were little influenced

For the bar this implies the main tuning rules:

a) the resonance frequency is lowered by thinning between the nodal lines, b) nodal lines can only be shifted a little by thinning at nodal lines.

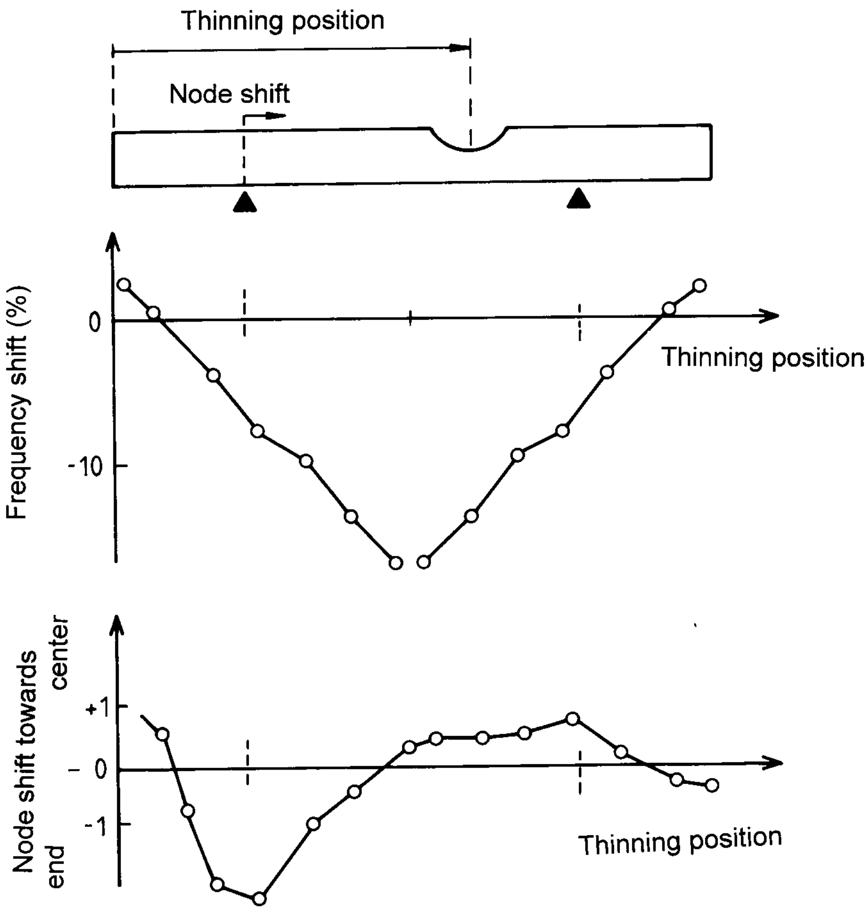


Figure 5.13 Frequency and nodal line shifts for thinning of a bar (from J. Alonso).

OUTLINE OF THE PLATES (Frequencies) :

Beldie (1969) made some experiments on the resonant frequencies and nodal lines of violin plates. A flat rectangular spruce plate had the resonance frequencies and nodal line patterns shown in fig. 5.14 upper two lines. When the outline of a top plate is made, the Chladni patterns are changed and the resonant frequencies are shifted. The frequency of the first mode is increased (mass is mainly removed at antinodes, i.e. at the corners). The second resonant frequency has increased which should be expected as the width of the plate is decreased. The frequency of the third resonance is decreased, which also should be expected as the C-bouts give a plate of less width at the position of maximum bending for the corresponding bar. For the last two cases detailed information on the nodal lines are needed for more definite conclusions. Thus our main point here is: the outline of a violin plate has influence on its resonant frequencies.

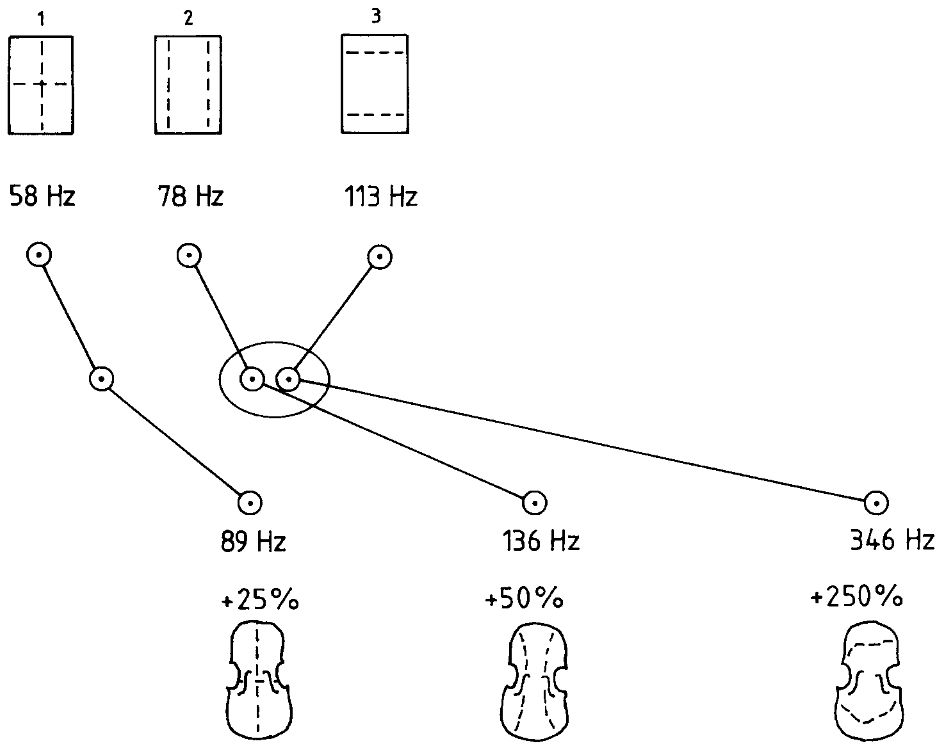


Figure 5.14.Nodal lines and resonant frequencies for a rectangular spruce plate (360 x 212 x 3 mm with the elasticity modulii 8.9 Gpa and 0.52 GPa and the density 410 kg/m^3), flat top plate with contour as a violin, and arched top plate with bass bar (from Beldie, 1965).

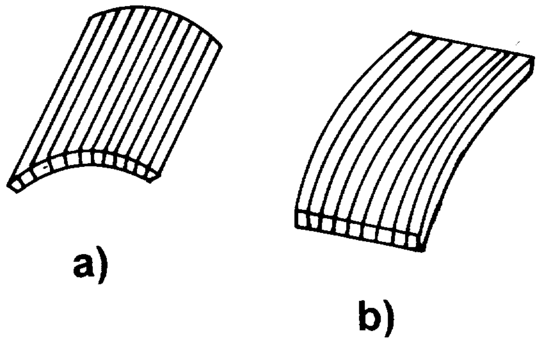


Figure 5.15 Arch a) across and b) along the grains.

THE ARCH OF THE PLATES (Frequencies and nodal lines)

The arch height of a top or a back plate is fairly small. It is less than 1/5 of the smallest width (1/5 of 10 cm is 2 cm). The plates should therefore be regarded as somewhat arched plates (in technical terms so called "shallow shells").

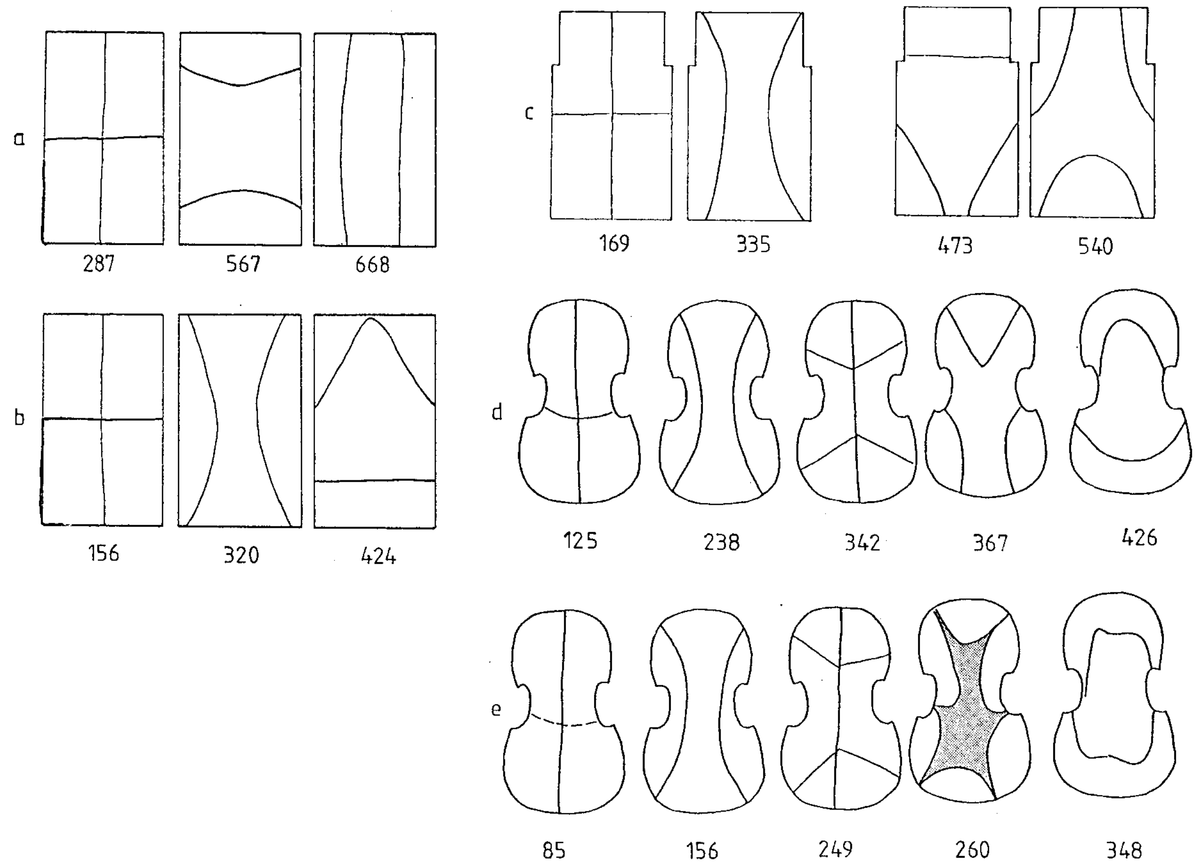


Figure 5.16. From a blank to a finished top plate - nodal lines and frequencies for a) the blank, b) 8 mm thick rectangle with internal and external violin arching , c) as b but somewhat shorter and narrower upper part, d) 4 mm in the upper and lower parts, and 5.1 mm in the middle, and e) the finished top plate 2.8 mm thick (from Jansson, Alonso Moral and J. Niewczyk, 1988).

The radius of curvature across the violin plate is of the magnitude 0.2 m and that along the plate 1.5 m. The difference in radii implies that the arching will increase the cross stiffness more than the length stiffness of the violin plate. Experiments were made with two arched rectangular plates, c.f. fig. 5.15 by Jakub Niewczyk, with cross and length radii, respectively, as given above. Thereby it was found that

1) the first resonance had the nodal lines in a cross as for the rectangular plate

2) the plate become much stiffer than the corresponding flat plate for bending across the arch but about the same for bending along the arch.

3) the influence of length/width together with grain orientations was large, i.e. the so called edge effects are large.

For the plates with violin shaped outline it is not so simple to make detailed comparisons. Assuming that the nodal lines are the same for the flat and the arched plates in fig. 5.14, this can however be done. One finds that the first and second resonances increase considerably with the arching (approximately 50 %). From the third resonance of the flat plate and to the fifth of the arched top plate the resonant frequency is much increased (approximately 200 %). The effect of arching can be "translated" in thickness. This means that the 50 % increase in resonant frequency from the length arching corresponds to 50 % increase in thickness, i.e. an increase in thickness from 3 to 4.5. In the same way the cross arching corresponds to a 200 % increase, i.e. thickness increase from 3 to 9 mm. Beldie's experiments imply a large influence by the arching on the top and back plate stiffness.

BLANKS, TOPS AND BACKS (Frequencies, arching and thickness)

The development of the nodal lines of the finished violin top plate from those of the blank have been investigated by Jakub Niewczyk and the author, see fig. 5.16. Starting with the blank we find two nodal lines forming a cross for the first resonance. This nodal cross remains through all following steps of adjustments. The second resonance has two horizontal nodal lines initially but changes to those typical for the top plate in violin arched and 8 mm thick but still rectangular (step b). This nodal pattern remains thereafter. Note that although the nodal lines changed from step a to b the antinodes (at the edges between the nodal lines) remained and throughout the whole experiment. The third resonance has in the step b one straight and one curved nodal line. The pattern but upside down was found in step c.

In step d (the plate thickness varied from 4 to 5 mm) the fifth violin plate resonance, the ring mode was found. The ring mode became more rectangular with further thinning. This experiment implies that when the plate is worked to a certain thickness related to the arching, then the ring mode is obtained. In step d the third resonance of the violin plate was found (which is the same as the fourth of the blank). In the experiments the main features of the nodal patterns were little shifted with the thinning in the different areas. The fifth mode was the most sensitive to thinning.

5.7 TYPICAL PROPERTIES OF FREE VIOLIN TOP AND BACK PLATES

DATA FOR BLANKS

Experiments have been made with blanks of the standard dimensions (see fig. 5.5) to determine the relations between material properties and vibration properties. Ten top blanks and ten back blanks (not necessarily typical material properties) gave the first three resonance frequencies which fell in the ranges (tone names within the following brackets). By means of the formulas given in the appendix below the vibration properties were estimated. For the top-plate blanks the frequencies were 270-333 Hz (C4-E4), 471-577 Hz (A#4-D5), and 596-727 Hz (D5-F#5). The masses (weights) were 445-545 g. For the back-plate blanks the frequencies were 326-352 Hz (E-F), 474-540 Hz (A#4-C#5), and 682-770 Hz (E5-G5). The masses were 630-710 g. The nodal lines varied moderately. Only in one case of a top-plate blank a large deviation was found.

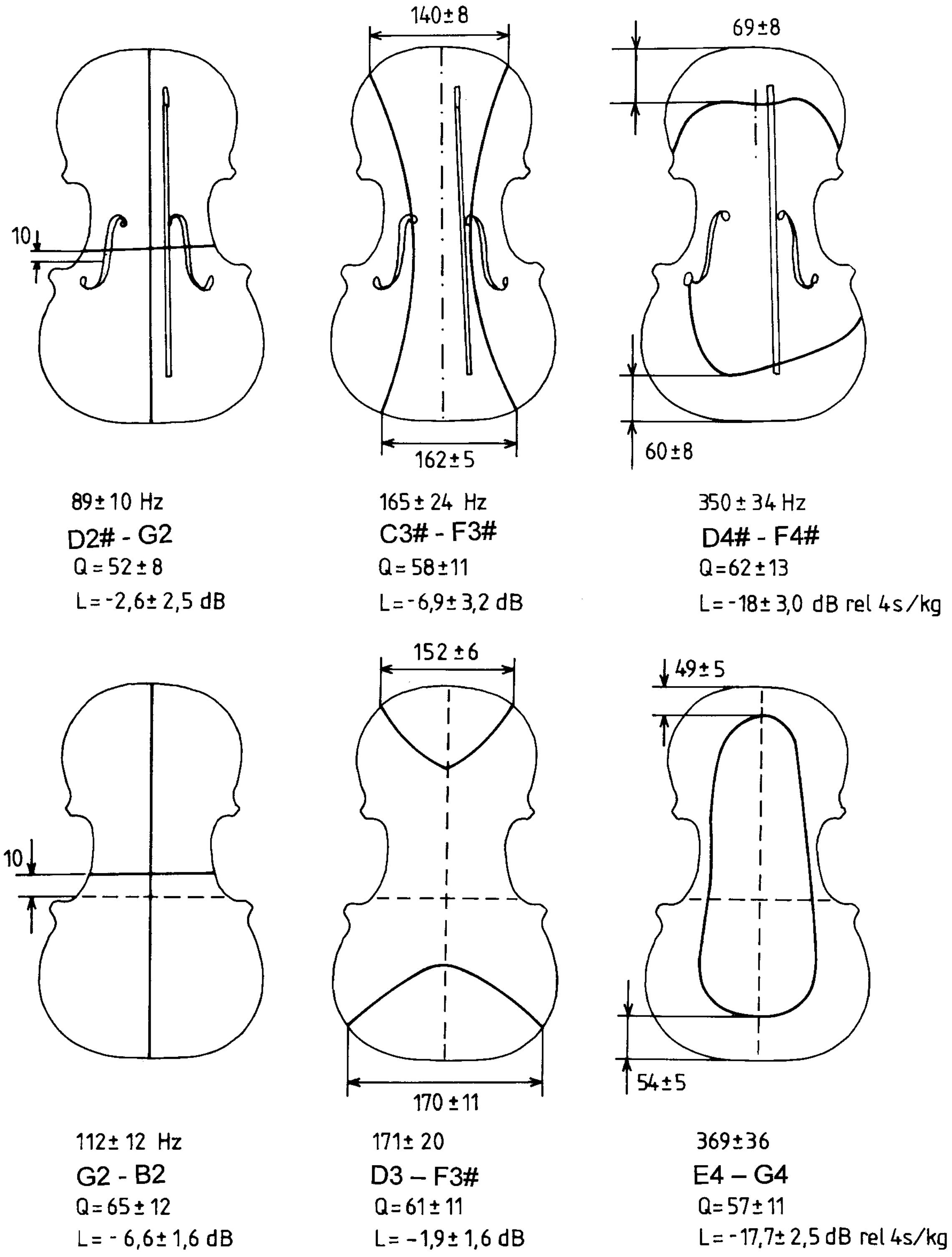


Figure 5.17 Typical resonant frequencies, quality factors and nodal line patterns for top and back plates (L stands for vibration level measured in the very experimental arrangement)

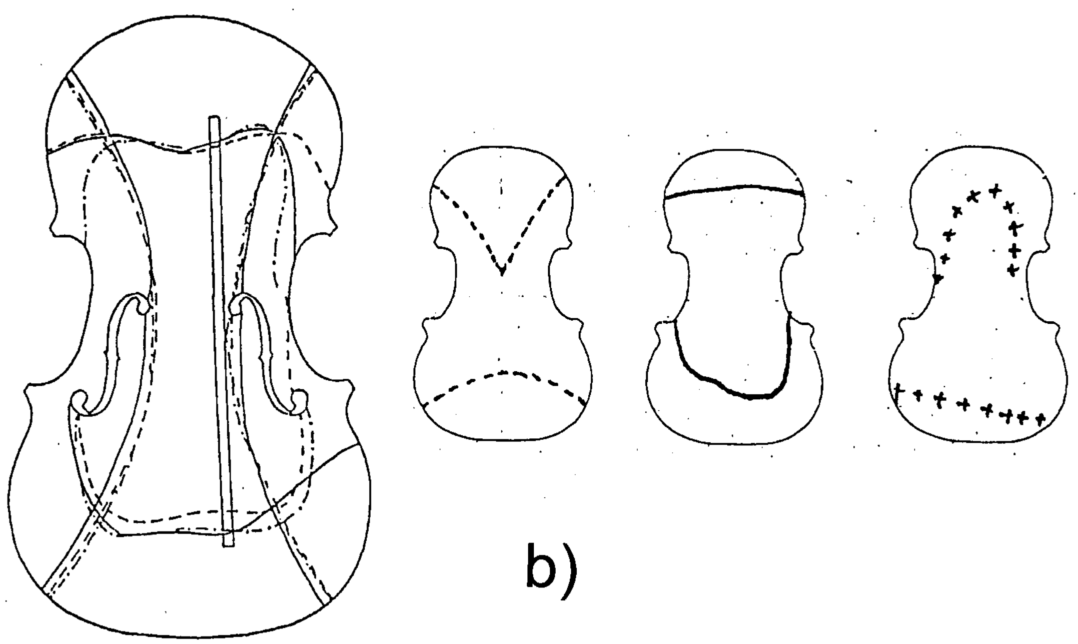
CLADNI PATTERNS (resonance frequencies, bandwidths, and nodal lines)
The resonance vibrations have been recorded of free top and back plates by the Chladni method, see fig.5.17. The three resonances can easily be recorded and can be used as guidance in making. In the first resonance, c.f. fig. 5.17, both the top and the back plate have two nodal lines forming a cross. The positions of maximal vibrations, antinodes, are at the edges between the nodal lines. Diagonally positioned antinodes vibrate in phase. The antinode below or beside vibrate in antiphase (i.e. a twisting mode).

The second resonance has maximum vibrations also along the edges and between the nodal lines, but now in centre of the upper and lower edges, and at the C-bouts. The nodal lines of the typical top plate are shaped as two vertical brackets)(and the nodal lines of the back plates of two horizontal but bent nodal lines. Note that the vibration maxima are in the same positions both for the top and the back plates but the nodal lines look rather different.

The third resonance, which in reality is the fifth resonance has a vibration maximum in the centre and others along the edges. The nodal line tends to close and is therefore called the ring mode. For the back plate the node is closed but for the top plate it opens at the C-bouts.

The typical nodal line patterns shown in fig. 5.17, were obtained from measurements of 14 top and back plates, which had not been tuned. These nodal patterns can be compared with those of the blanks. Thereby one finds that the first resonance has the same nodes for the blanks, the top and the back plates. The second resonances of the blanks and of the back plates look similar. If one compares positions of maximal motions one finds that these positions are similar for the second resonances of the blanks, of the top, and of the back plates. There are also similarities for the third blank resonances and for the ring modes of the top and back plates; maximal vibrations in centre and at edges (at corners). The first, second and fifth resonances of the free plates could be used to copy vibration properties of free plates. Carleen Hutchins has successfully used this method and it will be presented in the next section. The implied similarities between blank properties and plate properties must not be taken as evidence that the blank modes and the plate modes are the same. The relations are far more complicated. The ranges of resonant frequencies and bandwidths (Q-factors) are given in fig. 5.17.

From theory and measured nodal lines some general predictions can be made. In mode no 1 the plate is twisting around the crossing points of the nodal lines. Thus reducing the thickness around the nodal cross should give a large influence. In mode no 2 there is bending both longitudinally and transversally with the main bending in the middle and thinning here should give large influence. In mode no 5 the plate is bending both longitudinally and transversally, and is twisting. Thinning off the edges and off the middle should give the largest influence on this mode.



a)

Figure 5.18. Nodal lines for resonances 2 and 5 (average of five top plates) a) without f-holes (point-dashed lines), with f-holes (dashed lines) and with bassbar (full lines) and b) with ribs (vibration mode 2 with dashed lines and two resonances approximately as no 5 with full lines and cross lines, respectively, in cooperation with Hansen).

Table 5.4: Frequency shifts and average frequencies for five violin top plates (Hansen)

frequency change	mode no 1	no 2	no 5
with f-holes	- 7 %	- 11 %	- 10 %
plus bassbar	8 %	+ 4 %	+ 13 %
plus ribs	-14 %	+ 11 %	-25 resp -18 %
resonant frequencies			
with f-holes and bassbar	89 Hz	150 Hz	342 Hz

F-HOLES AND BASSBAR

Two large additional changes are made to the top plate. The first one is the cutting of the f-holes and the second is the instalment of the bassbar. Experiments were made together with Birgit and Carlo Hansen, who made five top and five back plates of the same geometry with f-holes and bassbar. The shifts of nodal lines and resonance frequencies were measured and the average measures are given in fig. 5.18 and Table 5.4. The experiments show that the f-holes lowered all three frequencies and the second and fifth the most (this should be expected from the experience of the author). The bassbar influence the cross stiffness little but the stiffness of resonance no 1 and 5 considerably.

When tuning plates it is mainly the vibration properties such as resonant frequencies and modes of vibration (nodal lines and antinodes) that are adjusted. It seems also to be advantageous to be able to adjust the bandwidths. The possibilities for the maker are that he can choose properties of his wood material, the arch height of the plates and their thickness distributions. In addition the violin maker has some freedom with the design of the bassbar and the f-holes, and the guitar maker with stiffening ribs and the bridge design. The tuning of violin plates is most common and will only be discussed in the following.

For five top plates the nodal lines were investigated in detail, see fig. 5.18 and table 5.4. Thereby it was found that the nodal lines of the resonances no 2 and no 5 cut each other in closely the same positions. The positions were not noticeably changed by f-holes or bassbar and were also the same in five back plates.

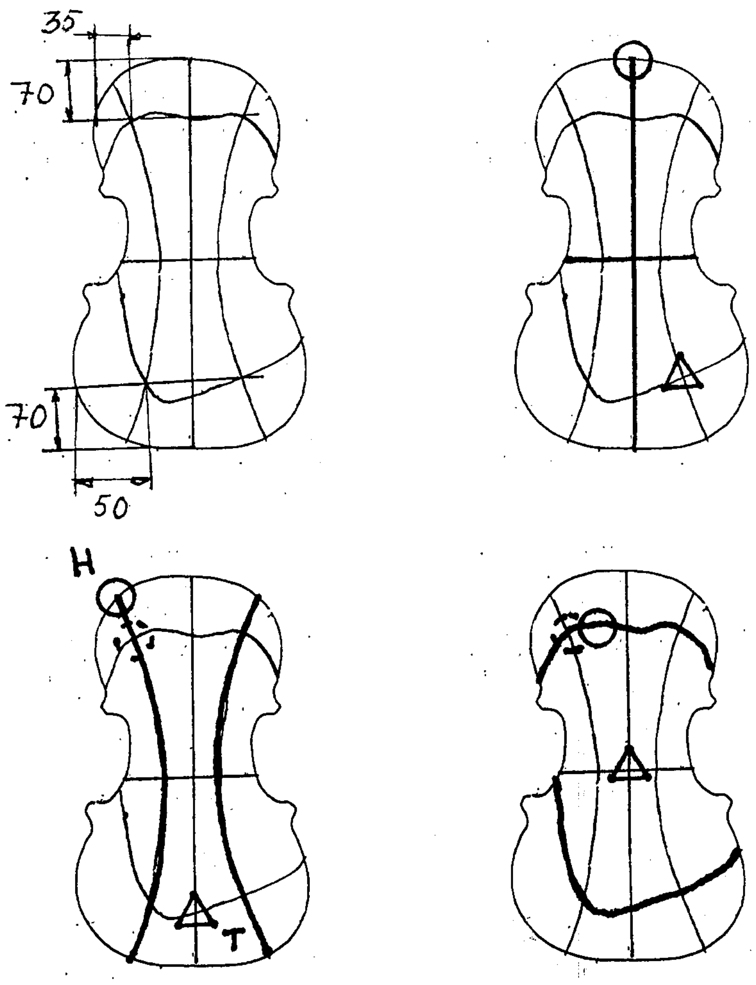


Figure 5.19 Suitable holding and tapping positions for tests of free top and back plates. Hold at circle (full line for the best but somewhat more difficult place to find , dashed circle for the position simple to find but not the best) and tapping positions (triangles) for a free top plate and back plate (the correct holding point should be within 10 mm of the given measures).

5.8 ON PRACTICAL TUNING OF VIOLIN PLATES

GENERAL

The effects of changing material properties and sizes of the plates have been demonstrated. Note that the order of nodal line patterns may change for very large changes of properties, i.e. the sizes of the test blanks must not deviate much from standard. This shift of order implies that it is the resonant frequencies and not the nodal pattern that are the most important. Therefore the frequencies of the blanks obtained bý tapping, c.f. Figs 5.6 and 5.19 are very important The results are supported by experiments with blanks employing the Chladni methods, vibration sensitivity and optical measurements.

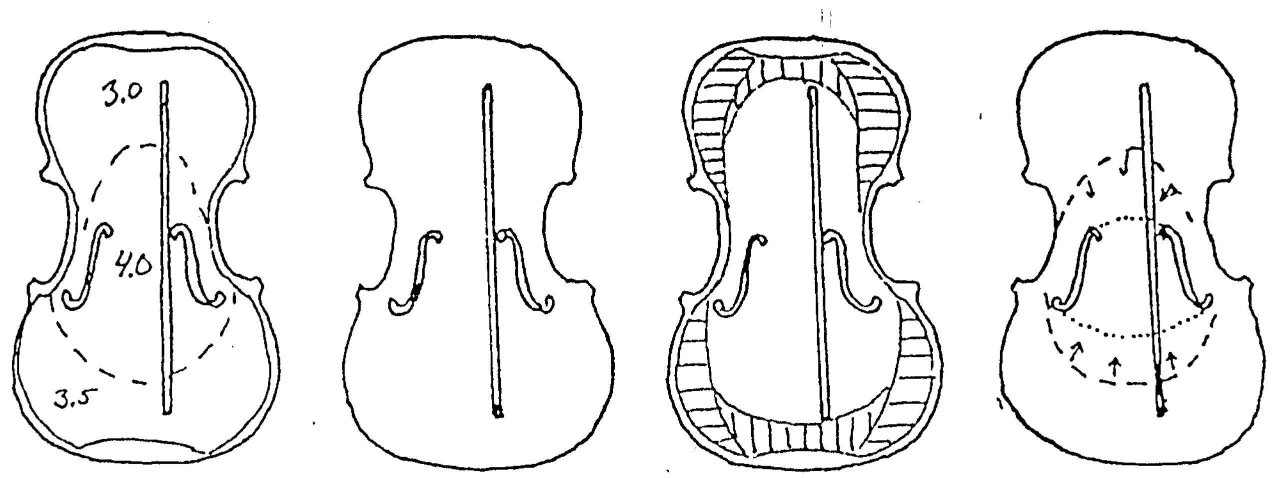


Figure 5.20 General rules for tuning of the second and fifth resonance of the top plate (from Hutchins, 1983).

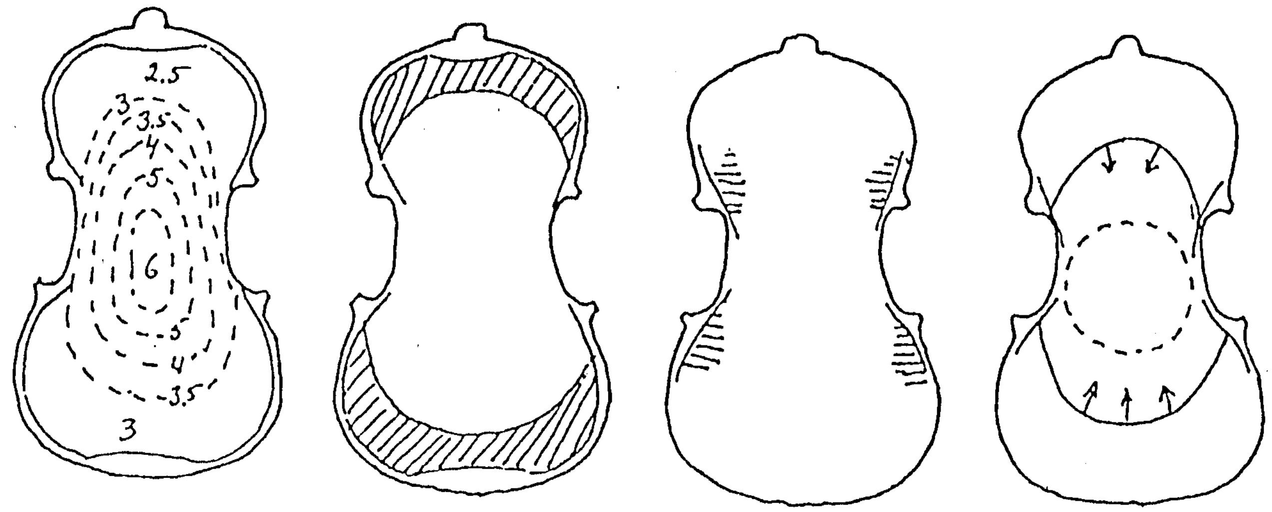


Figure 5.21 General rules for tuning of the second and fifth resonance of the back plate (from Hutchins, 1983).

By means of the tap tone method the violin maker can obtain the resonant frequencies of the three resonances of a blank, c.f. fig. 5.6. He or she holds the blank at a nodal line of the wanted resonance and taps close to an antinode, c.f. fig. 5.6. By keeping a standard size close to ours, the mass, and the three resonance frequencies give a record of the wood properties. By using blanks of our sizes the technically defined elastic parameters can be calculated. We hope that violin makers will start to use this method and thereby be able to define blank properties suitable for their making and also to give clues to choice of arching and thickness of plates.

CARLEEN HUTCHINS' RULES - MORE DETAILED TUNING

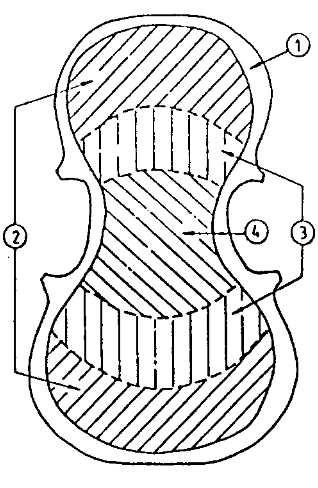
Carleen Hutchins has much experience with tuning helped by Chladni patterns and has given some directions for use of the second and the fifth resonances. One should begin with a top plate without f-holes and bassbar that is a little too thick, c.f. the leftmost sketch in fig. 5.20. Thinning at the edge and a few centimetres inside lowers the frequencies of the two resonances by approximately the same amount. If the plate is thinned in the regions just above or below the f-holes the frequency of resonance no 2 is lowered more than that of resonance no 5. Thin from broken line towards the line of dots. It should be possible to tune resonance no 5 with the bassbar.

For the back plate it is suggested to start from a thickness distribution as the leftmost sketch of fig. 5.21 Thinning along the edges as shown in the following sketch result in the frequency of resonance no 5 being lowered more than that of resonance no 2. Thinning inside the corners lowers the frequencies of resonances no 2 and 5 by the same amount. If the back is thinned towards the centre then the frequency of resonance no 2 is lowered more than that of resonance no 5. Start by thinning from the edges and towards the centre 3 to 2.5, 3.5 to 3 etc. and make the thickness distribution more circular in the centre.

NIEWCZYK AND JANSSON'S TUNING RULES

Table 5.5 Frequency shifts for thinning in different areas (-3/-9 means that a thinning on the outside (5.1 to 4.0 mm) gave a frequency shift of -3 % and a thinning on the inside (4.0 to 2.8 mm) gave a frequency shift of -9 % (areas defined in table figure).

Frequency shift rel. previous step for resonance	no 1	no 2	no 5
Thinning in area 1	-3/0	-1/-1	-1/-1
2	-2/-2	-2/-6	-3/-9
3	-8/-8	-9/-11	-4/-1
4	-6/-11	-11/-9	-1/-4



In the later steps of the J. Niewczyk experiments (fig. 5.16) the thining were made in such a way that comparisons could be made with the presented experience by Hutchins. Thereby it was found that when the whole plate was thinned, then the frequencies of resonance no 1 and 2 were lowered 70 % of the thickness decrease, while that of the resonance no 5 was only lowered 50 %. For a flat plate the resonance frequencies are lowered 100 % of the thickness reduction. Thus it can be concluded that the arching has a large influence and mainly on resonance no 5.

The effects on frequencies of thinning in the different steps showed that the two outmost areas influenced mainly resonance no 5 and the two central ones mainly resonances no 1 and 2, i.e. in agreement with Hutchins' findings, c.f. Table 5.5. The results are also in agreement with theoretical predictions and finite-element calculations.

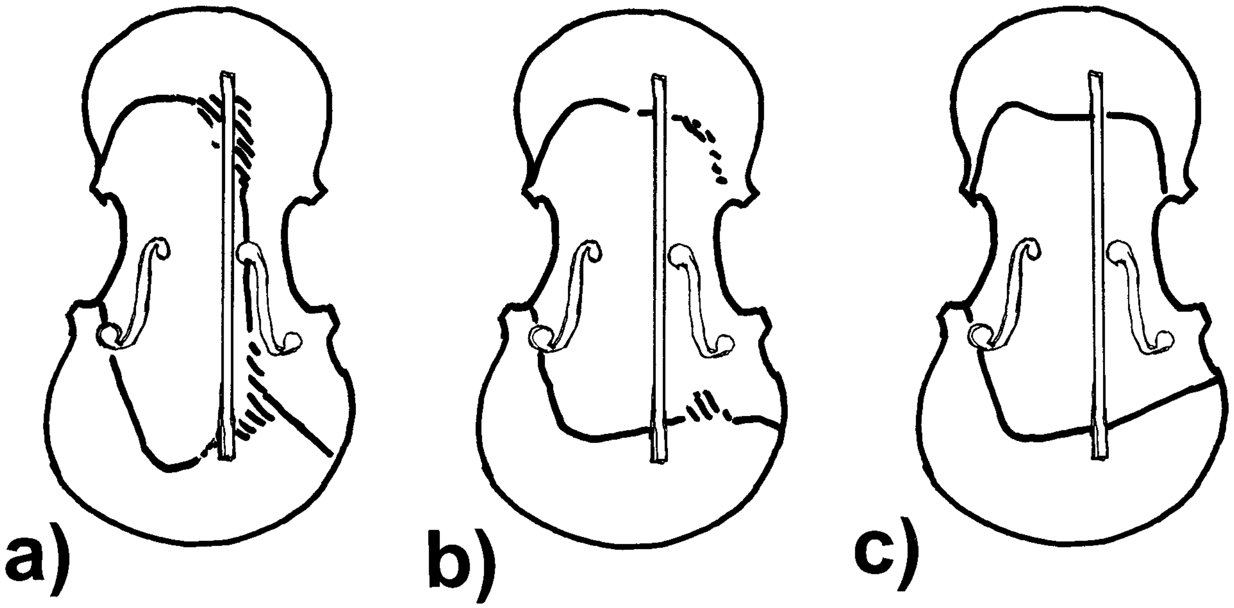


Figure 5.22 Nodal lines and tuning of the bass bar. Shadings mark diffuse nodal regions. Start in a) with a too high bassbar (17.2 mm and 313 Hz), in b) bassbar lowered to 14.4 mm (308 Hz) and ending in c) bassbar height 12.8 mm and 307 Hz (from Bissinger and Hutchins, 1976).

THEORETICAL PREDICTIONS

Calculations with finite element methods predicted that the resonances no 1 and 2 should be the most sensitive to the thickness and that resonance no 5 is the one most sensitive to the arching. Furthermore the calculations indicated that the resonances 1 and 2 are the ones most sensitive for thinning in areas 3 and 4 but the resonance no 5 is most sensitive for thinning outside the middle (areas 2 and 3). The presented information agrees on that the central thickness influences mode no 2 more than mode no 5 and that the bassbar influences mode no 5 more than mode no 2 (table 5.4).

BASSBAR TUNING

The Chladni method can be used to help with adjusting the bassbar, see fig. 5.22, which shows the Chladni patterns for three stages of adjustment. With the very strong bassbar the nodal lines of resonance no 5 do not pass the bassbar towards the nearby edge. The top plate is so stiff that it does not want to vibrate in across the bassbar. By thinning and cutting down the bassbar the resonant frequency is lowered approximately 6 Hz and at least a tendency for a ring mode is obtained. By further successive thinning and lowering the ring mode starts appearing. The changes are large for the nodal lines on the right side (as shown in the figure) but small on the left side. The last adjustment on the upper and middle parts of the bassbar seems mainly to "fold" the lower nodal line up to the wanted cutting point along the edge close to the bassbar.

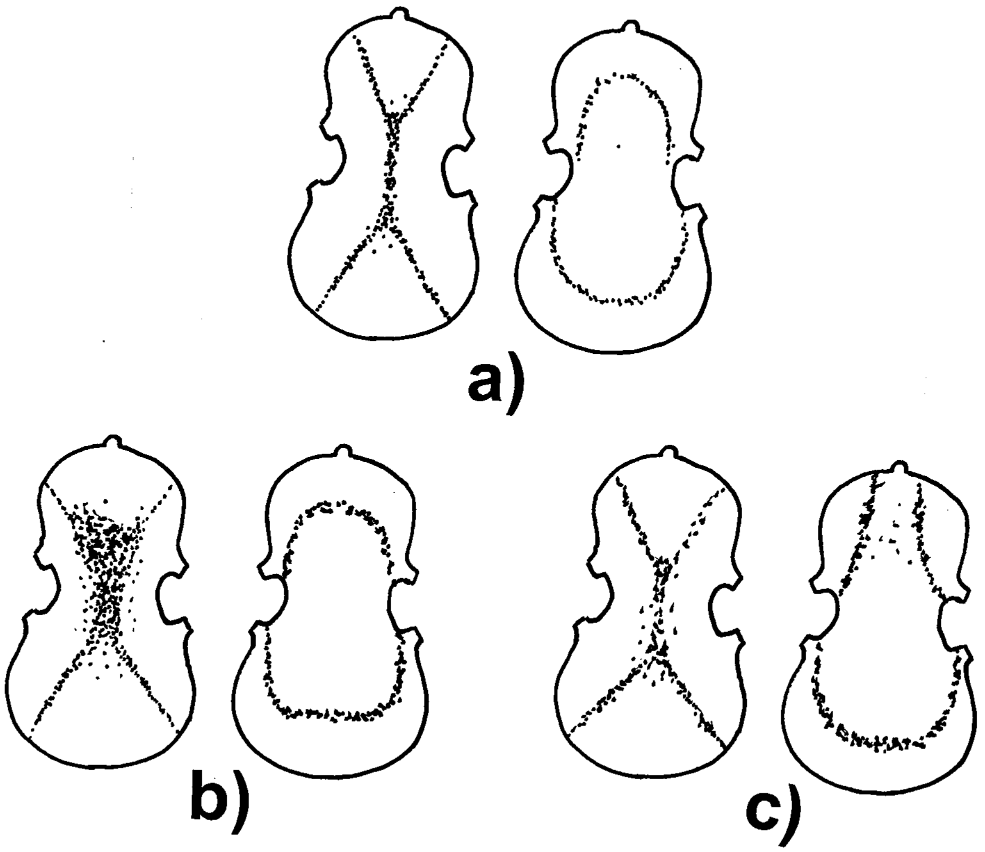


Figure 5.23 Resonance no 2 and no 5 in the back plate a) with well balanced thickness distribution, the back b) with the upper nodal line spread in the upper part (upper part too thick compared to the lower part) and back plate c) with the upper nodal line of resonance 5 cutting the edges (plate too stiff between c bouts, from Hutchins 1989).

WHAT THE NODAL LINES CAN TELL US

If the nodal lines differ from the expected one, this means that the distribution of stiffeness and mass in the plate deviate from the “right” one. If we learned the “language” spoken by the nodal lines, they tell us what is “wrong” or “erroneous”.

Two examples of erroneously tuned back plates have been given by Carleen Hutchins, see fig. 5.23. Only second and fifth modes are discussed. The Chladni patterns of the second resonance look as if there is a central nodal line. This is, however, only an area of little motion and no nodal line. Thus the second resonance has two nodal lines, the upper one shaped as a v and the lower one shaped as an upside down v. The fifth resonance has an almost closed ring node. The plate in b) has an upper part too thick compared to the lower one, which the distorted second resonance shows towards the second resonance of the blank, i.e. a much too thick plate, but the fifth resonance indicates somewhere between step d and e in fig. 5.16, i.e. a thin plate). With the central part too thick, the plate in c), the upper nodal lines of the ring "spill over" the edges (comparison with the Niewczyk experiments suggest that the back qualitatively is somewhere between steps b and d, i.e. a much too thick plate). Thus there is at least a partial agreement between our experiments and the examples by Hutchins. The deviations may stem from the fact that we are comparing a spruce top plate with a maple back plate.

Increasing the cross stiffness much, with the ribs for instance, gives the top plate two modes corresponding to the third mode of step b the way it is shown and the upside down version. c.f. fig. 5.18b. The ring mode divides into two resonances.

5.9 SUMMARY: TUNING OF THE TOP AND THE BACK PLATE

This chapter has been more of a research character than earlier, as we are at present in the area of research. It is difficult to give accurate rules for the best properties of a free top and back plate. Therefore typical properties have been presented together with principles for tuning, i.e. principles for how the resonances can be affected.

5.10 KEY WORDS

Resonance, frequency, nodal lines, resonance no 1, 2 and 5, the ring mode

5.11 APPENDIX FORMULAS AND CALCULATIONS

As a preparation for the physics experiments that the inclined violin maker might wish to carry out, the formulas and calculations for the determination of material properties are given below. For these calculations we introduce the bar length l, thickness t, and width b. Furthermore we introduce the elasticity modulus E, the mass M and the density ρ and the π = 3.14.

FORMULAS:

a) Density of the wood the bar is made of: $\rho = \frac{M}{blh}$

b) First resonant frequency of a bar with free ends: $F = h \cdot \frac{1}{l^2} \cdot \sqrt{\frac{E}{\rho}}$ (exact formula F = 1.028·)

c) If the first resonant frequency, weight and dimensions of the bar were measured, one could

calculate the elasticity modulus $E = \rho \frac{l^4}{h^2} \cdot F^2 = M \frac{1}{b} \frac{l^3}{h^3} F^2$

d) Specific vibration sensitivity $SV = \frac{1}{\sqrt{SM}} = \frac{blh}{M} \frac{1}{2\pi F}$

e) Peak level $RN = 20 \cdot \log(\frac{F}{B} \cdot SV)$

f) Reverberation $e^{-\pi Bt}$. If the bandwidth B was measured, one could calculate the decay time T_{60} of the free vibration $T_{60} = \frac{\ln 1000}{\pi} * \frac{1}{B}$

Note, the value of T_{60} is valid only for the bar or plate whose resoance delivered the B value.

NUMERICAL EXAMPLES

To give a feeling for material properties, usefulness of methods and formulas, some numerical examples are presented in the following.

Example 5.1. The density of wood can be calculated by dividing the mass by the volume. A spruce bar weighs 1.4 g and a maple bar 2.0 g. Both are 3 mm thick, 10 mm wide, and 100 mm long. What is the density of the spruce and the maple, respectively?

Solution: with equation a
Mass of the spruce bar 1.4 g = 1.4/1000 kg
the volume is 100 mm x 10 mm x 3 mm =
= 100/1000 m x 10/1000 m x 3/1000 m = 3/1000 000 m^3
density (mass in kg / volume in m^3) =
= (1.4/1000 kg)/(3/1000 000 m^3) = 466 kg/ m^3

Calculated in the same way gives the density of the maple is 666 kg/m^3.

Example 5.2. The elasticity modulus of wood can be calculated from weight, resonance frequency, length, thickness, and width of a bar. Two bars of spruce cut along and across the grain (see fig. 5.9) have the resonance frequencies 1710 and 390 Hz, respectively. Corresponding values for similar maple bars are 1200 and 540 Hz, respectively. The bars have the same weights as in example 1. What are the elasticity modulus in the four cases?

Solution:
A little calculation from the frequency formula above (the c equation) gives the elasticity modulus as

spruce bar along (longitudinal)	15.2 GPa
spruce bar across (radial)	0.79 "
maple bar along (longitudinal)	10.1 "
maple bar across (radial)	2.2 "

(15.2 GPa = 15.2 x 1000 000 000 Pa = 15 200 000 000 000 Pa)

Example 5.3. The internal friction is measured in form of bandwidths. Examples of values for the four bars (Example 5.2) are given below in the first column.

Solution:
The formula for the decay gives a decay time (-60 dB) of the values listed below in the second column

spruce bar along (longitudinal)	11.4 Hz	0.19 s
spruce bar across (radial)	8.5 "	0.26 "
maple bar along (longitudinal)	14.5 "	0.15 "
maple bar across (radial)	9.6 "	0.23 "

The decay times 0.15-0.23 sec are very short compared to that of a room, approx. 1 sec.

5.12. REFERENCES:

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