ON MAKING "TONAL COPIES" OF A VIOLIN

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The author describes some physical principles that determine the changes of violin modal patterns. He illustrates these principles with empirical results showing how variations in the distribution of mass and stiffness of violin plates change certain mode shapes (and thus the sound radiation) of the instrument. Using results of the analysis and experiments, the author has constructed a "tonal copy" of an old Italian violin (Domenicus Montagnana 1740). Every natural mode of vibration (eigenmode) in the frequency range investigated was reproduced, with only slight differences in mode shape, and in the same spectral sequence. The author compares his copy of the Montagnana with a copy of a Stradivari model and finds that some eigenmodes of the Montagnana do not appear at all in the Strad copy.

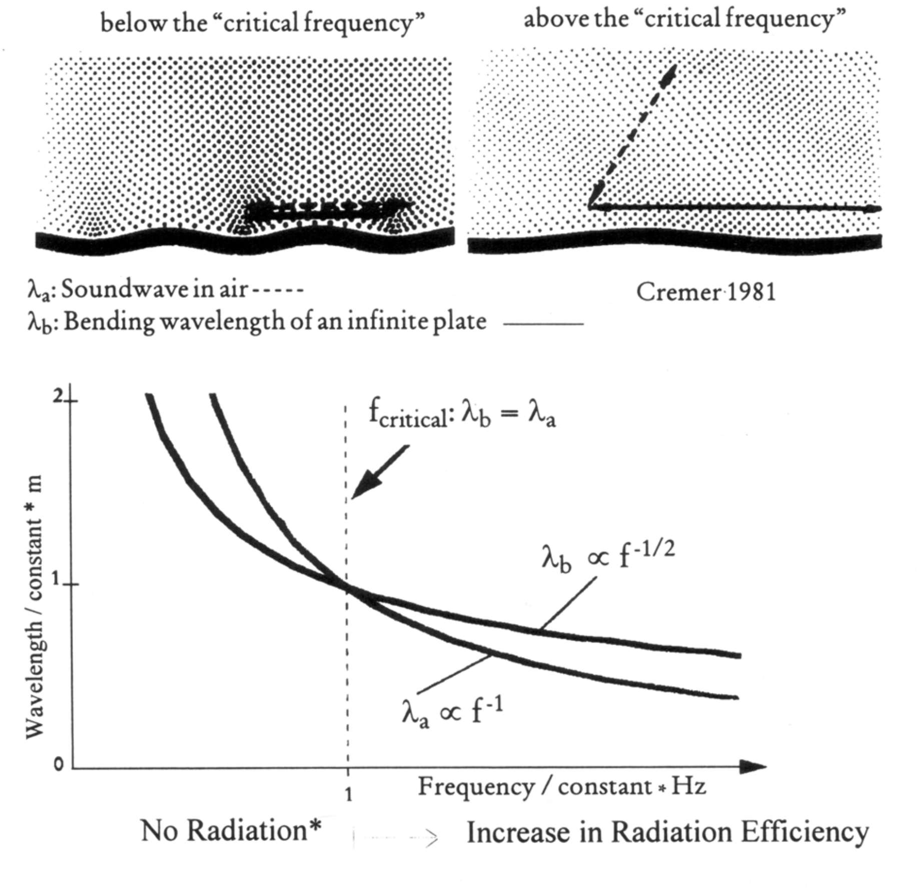
If a system is excited in one of its natural resonances or eigenfrequencies, it oscillates in a certain vibration pattern which is characterized by antinodes and nodal lines. At any one resonance, the locations of antinodes and nodal lines do not vary. There is a stable mode of vibration with its definite "standing pattern." As two modes (and therefore two different vibration patterns) can have the same eigenfrequency, there can be more than one vibration pattern for each eigenfrequency in the spectrum. The vibration pattern belonging to each eigenfrequency is named its "mode shape."

This paper continues the examination begun in Schleske (1996) of changes in the eigenmodes of a violin as it is being created. The previous paper examined eigenfrequencies. This paper deals with the mode shapes.

Mode Shapes and Radiated Sound

The mode shapes are responsible for the sound radiation from a mechanical system. One way to increase radiation efficiency would be to increase the ratio of bending wave length (of the plate) to the sound wave length (in air). For the violin this ratio is critical. The sound

Figure 1 - Sound radiation



* soft dividing line for finite structures

wave length of the lowest fundamental frequency (g-string, 196 Hz) is 1.7 m. This is far greater than the maximum theoretical bending wave length of 35 cm (the body length of the violin). The frequency of a sound wave of this length is about 950 Hz. This is more than two octaves above the lowest playing range of the violin.

At the so called "critical frequency" (Cremer 1981), the bending wave length equals the sound wave length. Above the critical frequency (as sound waves become shorter than bending waves) there is a sharp rise in radiation. This can be seen in Figure 1, showing the particle movement in the vicinity of an infinite plate that is excited to vibrate in bending waves. When the bending wave is shorter than the sound wave (left hand side), there is a "hydrodynamic short circuit" and therefore no radiation. When the bending wave is longer than the sound wave (right hand side), there is radiation into the far field. (For finite structures the critical frequency is difficult to calculate.)

The length of a sound wave in air decreases inversely as the frequency, whereas the bending wave length decreases inversely as the square root of the frequency (see Figure 1). Because the sound wave length decreases relatively faster as frequency increases, it is fortunately possible to achieve a critical frequency in the playing range of the violin.

This means that finding a way to bring down the critical frequency (increasing the plate bending wave length) can be an important way to influence the higher eigenmodes in a tonally relevant frequency range of the instrument.

The bending wave lengths depend on the elastic properties of the violin plates (resulting from the material properties and construction). The challenge for the violin maker is to achieve long bending wave lengths by "creating" high bending stiffnesses and low oscillating masses. The effort to meet the challenge affects his choice and treatment of wood and his choice of contours, especially of the arching. It is not sensible to widen the outline of the violin in the cross grain direction with its low Young's modulus (as has been so often attempted in history). This would only promote the division into vibrating areas of opposite phase.

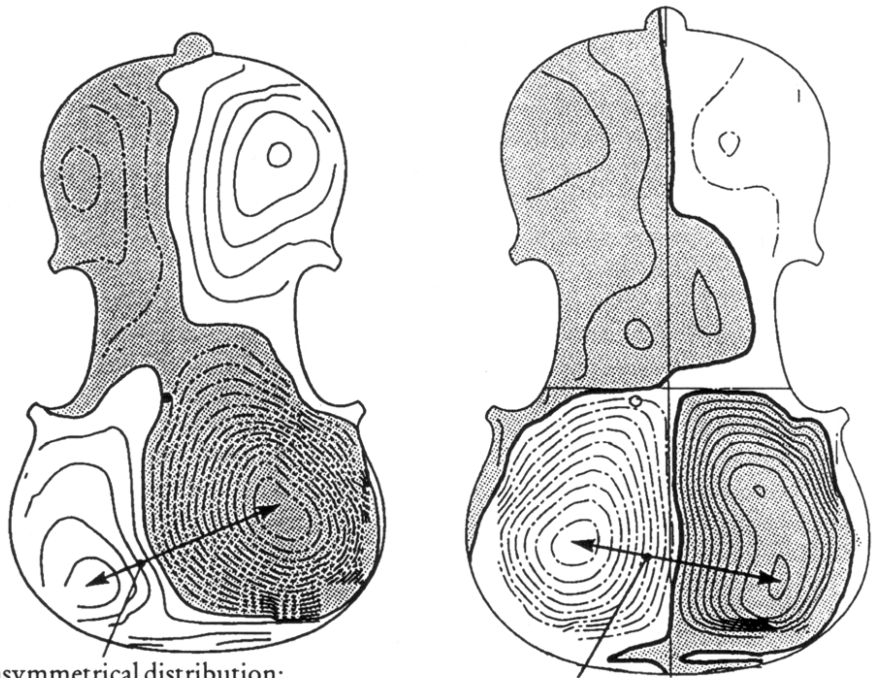
For those eigenmodes of vibration below the critical frequency (where the sound wave is longer than the bending wave) there is a second possibility for increasing radiation efficiency. The intensity of the sound radiated from an antinode is proportional to the square of the volume below the surface defining the deflection pattern of the mode of vibration. On closer consideration of mode shapes one realizes that formation of nodal lines divides the radiating plate into vibrating areas having opposite phases. Consequently, the volumes can subtract from one another and cause a decrease of sound radiation.

By deliberately modifying the affected mode shapes, nodal lines can be shifted in such a way that an asymmetrical distribution of antinodes in opposite phases is achieved.

The aim is that antinodes in opposite phases (at maximum displacement) take up a different amount of volume, since the sound intensity radiated by an antinode is proportional to the square of the volume under the deflection surface. These volumes depend on the sizes and amplitudes of antinodes. This is how even with a critical ratio of bending wave length to sound wave length a net volume flow can be achieved. So radiation efficiency can be increased for those lower eigenmodes that are important to the sonority and the "seed" of tone.

In this respect there can be a strong difference between instruments of different tonal quality. Figure 2 shows the same type of mode shape of two violins, A being a powerful violin by Domenicus Montagnana, anno 1740, and B, a carefully made but weak sounding violin. The mode shapes (measured by Modal Analysis with a FFT analyzer and plotted with an interpolation program) are quadrupole-like eigenmodes of the corpus back plates with their typical nodal cross. In both cases the sound

Figure 2 - Increase of radiation efficiency by asymmetrical distribution of cophasal amplitudes



asymmetrical distribution: radiation into the farfield

Violin A
(662 Hz $\eta = 2.9 * 10^{-2}$)

symmetrical distribution: "acoustical short circuit"

Violin B
(731 Hz $\eta = 1.2 * 10^{-2}$)

wave in air is about twice as long as the bending wave of the plate.

The mode shape on the right hand side (B) shows a symmetrical pattern as to amplitudes and sizes of antinodes in opposite phase. This promotes the above mentioned hydrodynamic short circuit. The player with his head in the near field might have the impression of a highly vibrating and radiating instrument, but as those symmetrical modes do not radiate efficiently into the far field the audience will not have the impression of a "carrying" instrument.

It is worth mentioning that the acoustical short circuit decreases measured radiation damping and thus even increases the mobility of vibration. As an aside, the dominant peak that consequently appears in a measured mobility (or admittance) curve does not tell anything about the acoustical output.

The mode shape on the left hand side (A) radiates efficiently. This is because of an asymmetrical distribution of amplitudes and sizes of antinodes in opposite phase. The one sided dominance of the right lower bout weakens an acoustical short circuit, causing a net volume flow. A more monopole-like radiation characteristic is achieved. The higher radiation of this mode of violin A can also be seen by comparing the loss factors between the two modes. Because of the higher energy radiation of the mode of violin A, the loss factor determined by measuring the 3 dB bandwidth of the peak of the admittance curve plot is more than twice as high as that of violin B, (see Figure 2).

To summarize, the radiation of the violin depends on the ratio of bending wave length to sound wave length and on the volume ratio of antinodes in opposite phase. This emphasizes the need to study the detailed mode shapes of the assembled violin.

The Assembled Violin

Figure 3 shows the mode shapes of the violin described in Schleske (1996) (up to 1 Hz) after the final working step (14f). The top plate is on the left hand side and the back on the right, both viewed from the outside. We define deflections of the top and back of the corpus as cophasal if they expand or compress the plates simultaneously. We illustrate cophasal oscillations using the same pattern (white or grey).

Some characteristics of the mode shapes of the assembled violin will be pointed out to show the differences between corpus modes and free plate modes. In contrast to common belief, corpus modes are not like cophasal membrane vibrations. Such vibrations would be characterized by a nodal pattern running rather parallel to stiff edges. For the first corpus modes (up to mode #8) the reality is different. Their nodal lines leave the plates at an angle close to 90 and enter into the other plate through the ribs. So the first modes are characterized by one nodal line that runs around the corpus (symbolized by the arrows in Figure 3). The corpus bends and twists as a whole. If a modification of mass and stiffness makes a nodal point at the edges move, the other plate will be modified in mode shape because the nodal points at the edges are forced to correspond with each other and to meet through the ribs.

From mode #9 on, the mode shapes begin to have the typical characteristics of the so called plate modes (Müller). The plates begin to separate into various "islands." More and more the nodal lines run parallel to the edges and thus top and back plates begin to decouple from each other. At mode #9 the ring shaped nodal line on the upper part of the back plate is still closed by making its way through the top plate. At mode #10 for the first time there occurs a separate "island" (in the lower part of the back plate).

The Free Violin Top Plate

Figure 4 shows the first seven mode shapes of the free violin top plate after the final working step ST 14. Hutchins (1991) attaches importance to a tuning of mode #1,#2, and #5. This seems well justified by the fact that each of these modes mainly depends on one of the elastic parameters (Molin, Lindgren, Jansson 1988). Observations on old master instruments make it likely that tap tones of at least mode #5 were used as a guide for thickness graduation (Möckel 1926). But the appropriateness of this guide seems questionable as there is no correlation between free plate tuning and the frequency response of the instrument (see Schleske 1996).

The Free Violin Back Plate

Figure 5 shows the mode shapes of the free back plate after its final working step ST 13. The torsion mode, Mode #1, is comparable with the first mode of the top plate. Mode #2 pattern is less longitudinal than that of the top. Mode #5 has a closed nodal ring, in contrast to the open nodal ring of the top plate.

The mode shapes of the assembled violin (Figure 3) are different from those of its free plates (Figures 4 and 5). Because of the different distributions of amplitude and curvature in the vibration deflection patterns of the assembled instrument, changes in thickness graduations will affect eigenfrequencies and mode shapes of the instrument in very different ways from those of the free plates.

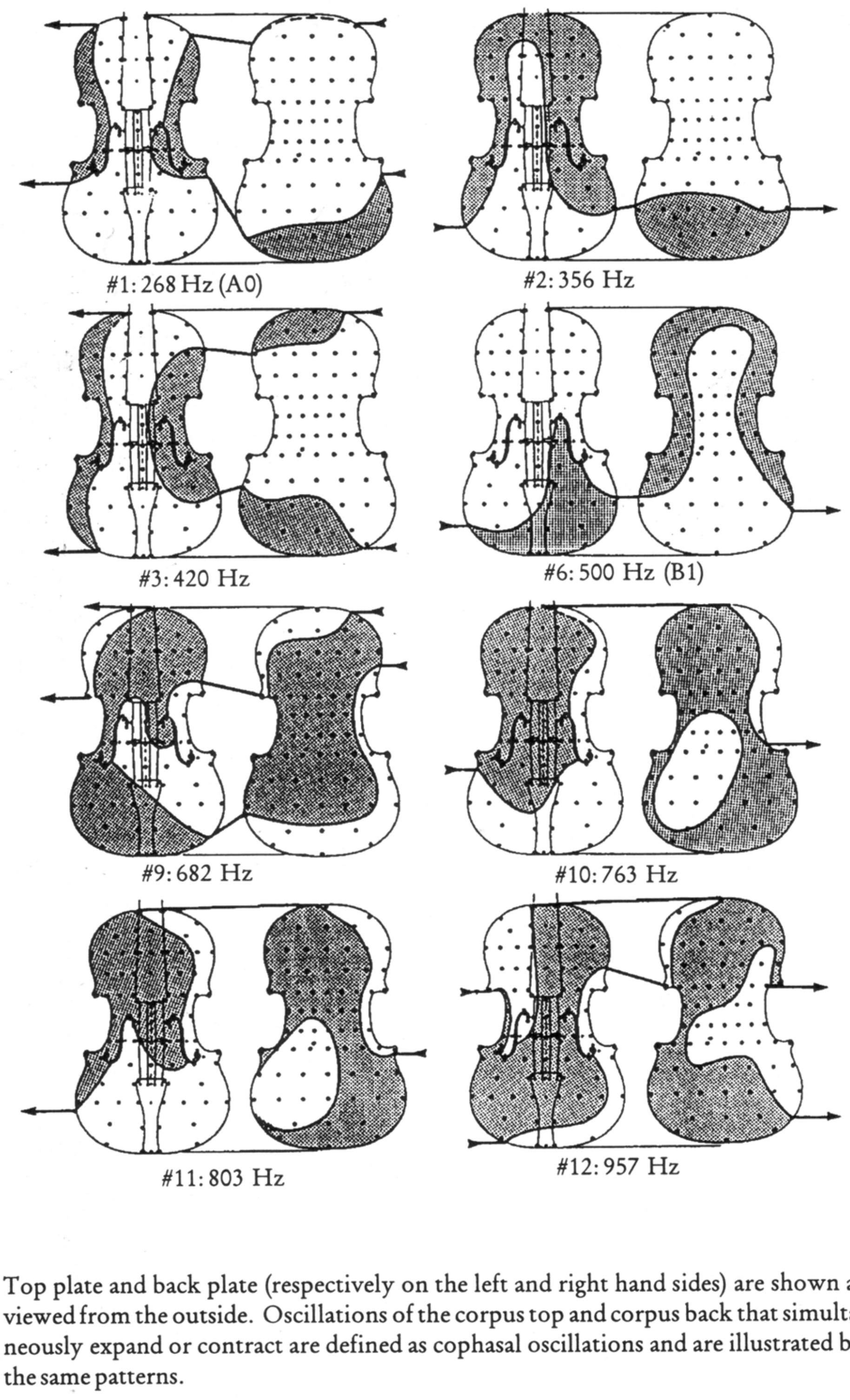
Mode Shape Modifications

It is important to focus one's attention on the mode shapes as one graduates the top and back plates, for empirical observation shows that *the influence of thickness graduation on the mode shapes is clearly larger for the assembled violin than for the free plates.* Consequently, the thickness graduation technique provides freedom to modify the sound radiation. At the same time it clearly affects the peak amplitude in the "acoustical spectrum" but—as was explained in the previous paper—only slightly affects the position of the peaks in the spectrum.

Experiments with a Vibrating Bar

It is helpful to deal with a simple structure in order to acquire some experience and some concepts about dealing with the distribution of mass and stiffness as one makes a violin. We chose a simple beam vibrating under different boundary conditions. The mode shapes were measured. The beams were 200 x 32 x

Figure 3 - Mode shapes of the assembled violin after working step 14f (see Schleske 1996)



Top plate and back plate (respectively on the left and right hand sides) are shown as viewed from the outside. Oscillations of the corpus top and corpus back that simultaneously expand or contract are defined as cophasal oscillations and are illustrated by the same patterns.

3.2 mm with about 10g weight. They were excited by a tiny loudspeaker located very near the surface at 10% of the length and fed with a sinusoidal signal input. Response amplitudes and phases were measured at 11 points using the measuring method described in Schleske (1996).

The graphs of the peak displacements as a function of length shown in Figure 6 illustrate the mode shapes. The upper graph shows the first eigenmode with free boundary conditions; the lower graph the eigenmode with the ends hinged (unable to deflect but able to rotate). Case A is the unmodified beam. Case B has a small mass glued on. In Case C the thickness in one section was doubled. This doubles the mass in that section while greatly increasing the stiffness (stiffness increases approximately as the cube of the thickness).

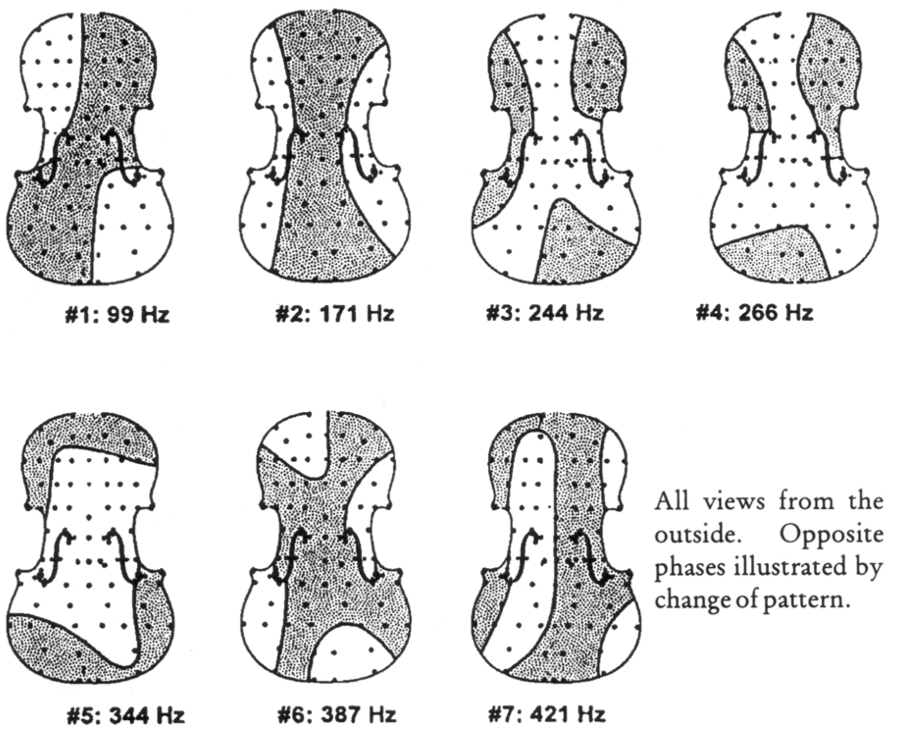
The results are very obvious. Both modifications cause the nodal lines to move toward the region but for different reasons. The added mass decreases the amplitudes of vibration. The added stiffness reduces the curvature of the deflection curve at the modified location (and, therefore, the deflections as well). In the hinged beam the decrease of curvature is very obvious at the right antinode, being located in the higher thickness region. The local curvature is nearly zero in the thick section. (In principle these mass and stiffness modifications act in the same way both with other boundary conditions and at higher modes.)

The effect can be understood by considering the maximum potential and maximum kinetic energy of the beam when vibrating. The maximum potential energy V_{max} is one half of the local bending stiffness $EI_y(x)$ multiplied by the square of the local curvature $w''(x)$ summed up over the length x of the beam.

$$V_{max} = \frac{1}{2} \int EI_y(x) \bullet w''^2(x)dx$$

The maximum kinetic energy T_{max} is one half of the local mass $m(x)$ multiplied by the square of the local displace-

Figure - 4 Mode shapes of the free top plate after workingstep 14 (Completed)



All views from the outside. Opposite phases illustrated by change of pattern.

ment *w(x)* of vibration squared summed up over the length *x* of the beam multiplied by the angular frequency w^2.

$$Tmax = \frac{1}{2} w^2 \int m(x) \bullet w^2(x)dx$$

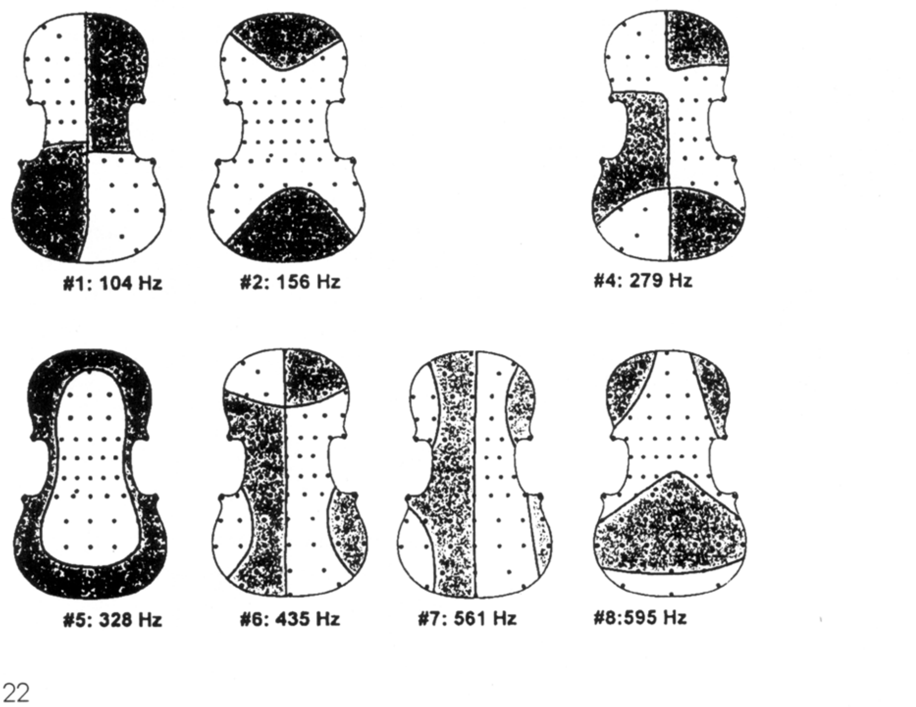
Both energies can be calculated if the eigenfunction (mode shape) over the length of the beam is known.

Due to the law of minimum energy, a locally high bending stiffness will create a small curvature. Otherwise there would be a locally high contribution to the potential energy. Conversely, if the beam is reduced in stiffness by modification of the plate the curvature and thus the amplitude of vibration will increase. The effect is that surrounding nodal lines are pushed off and both the area of antinode region and amplitudes of the antinodes in that less stiff region increase.

Or in other words: the structure is not "willing" to be bent in sections of high stiffness but will "try" to shift the bending to less stiff sections. The decrease of the factor of stiffness is compensated by an increase of the factor of curvature, so that the sum of the potential energy of the antinodes in opposite phase is equal.

It is the same principle with the mass and the kinetic energy. A locally inserted mass will decrease the amplitude at this location in order to avoid too high a contribution to the kinetic energy. A locally reduced mass will increase the amplitudes of antinodes in this area and will push off the surrounding nodal lines. Both the size of the area and the amplitudes of the antinodes in that reduced mass section increase. Again the sum of kinetic energy of the antinodes in opposite phase is equal.

Figure - 5 Mode shapes of the free back plate after workingstep 13 (Completed)



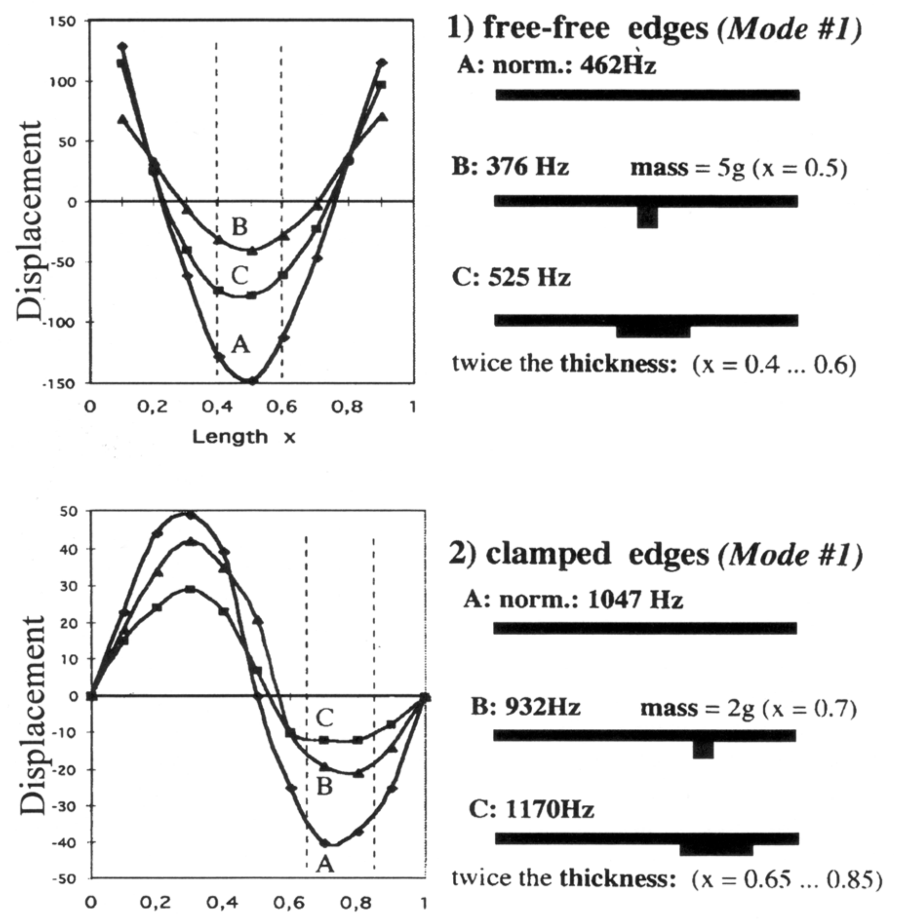
Independent Distribution of Mass and Stiffness

With regard to the violin as a complex structure, it is worth mentioning that the properties of wood give the violin maker the opportunity to adjust mass distribution and stiffness distribution independently in the creation of the violin plates.

The mass depends on the thickness and the material properties (density) of the plate. The bending stiffness of the plate depends on the material properties (e. g. Young's moduli) and on the thickness as well but also on the local orientation of the fiber elements relative to the direction of the local mid-surfaces of the arched plates.

A thin section of a plate in which the fibers are not cut can have the same stiffness as a thicker section where the fibers lie at an angle to plate surfaces and are cut. Both sections may have the same

Figure 6 - Modifications of a thin spruce strip: measurements of eigenmodes of vibration



Strip dimensions: 200 x 32 x 3.2 mm^3
Normal strip mass: 10 g
Sinusoidal excitation (x = 0.1) by loudspeaker (∅ = 20 mm)
Response measured by microphone at 11 points

stiffness but a different mass.

On the other hand two sections with the same thickness graduation can have the same mass but may have different stiffnesses if the orientation of the fibers is different (see Figure 7). This makes it obvious that thickness graduation, shape of arching, properties of wood and orientation of fibers must be taken into account together. They act as a unit in giving a certain mass and stiffness distribution which is responsible for the tonal fingerprint of the instrument.

Empirical Results

As an example of a mode shape modification done on a white instrument, the left hand side of Figure 8 shows the influence of the soundpost on the Helmholtz resonance (A0) and the right hand side shows the main corpus resonance (B1). In Figures 8 and 10 and 11, the broken lines indicate the nodal patterns before the respective treatment as indicated by the legends, the unbroken line those after treatment. The corpus with its thin walls "recognizes" the soundpost as a locally attached stiff spring. At the Helmholtz resonance the nodal line of the top plate no longer finds its way through the right *f*-hole but is attracted by this point of high stiffness created by the soundpost.

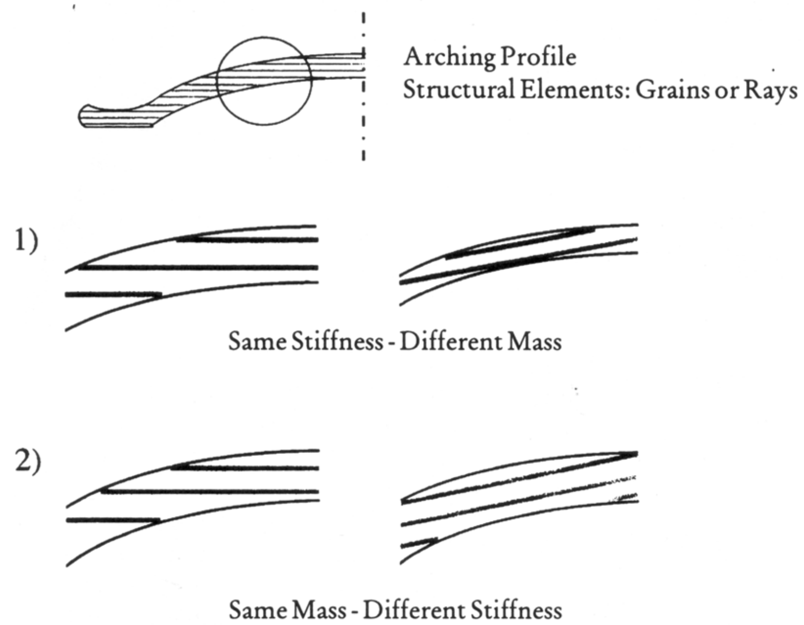
This is even more evident with the main corpus resonance. The nodal line is forced to make a detour to the upper part, through the high stiffness before finding about the same exit point to continue through the ribs to the back plate. The mode shape pattern changed in such a way that now a minimum curvature occurs at the high stiffness point of the sound post location. (The nodal line of vibration curvature is a good approximation to the location of the nodal line of amplitude.) Because of this, a minimum potential energy is saved by this eigenmode. The potential energy would rise dramatically if the high contribution of soundpost stiffness were connected with the initially high curvature of vibration.

A similar reaction is the reason for the asymmetrical quadrupole-like mode shape described above. As Figure 9 shows, the asymmetrical thickness graduation (left hand side) creates an asymmetrical distribution of bending stiffness. The effect is to distort the usually symmetrical quadrupole pattern. The consequence is the increase of radiation efficiency previously described. The longitudinal nodal line is pushed off by the decreased bending stiffness, so that, in the respective integral of the potential energy, the higher contributions of stiffness are connected with small contributions of curvature. The low bending stiffness of the right bout is connected with a high curvature. Therefore, as the equi-amplitude plot in the right side of Figure 9 shows, the bout cannot have high amplitudes.

The same reason causes a modification of mode shape #2 as shown in Figure 10. The upper and lower parts of the back plate were reduced in thickness while the center remained stiff. The nodal line is attracted by the relatively increased bending stiffness of the center, so that again the high contributions of stiffness are connected to small contributions of curvature.

The effect on mode #2 of cutting the *f*-holes is of interest, as it shows a fundamental difference between corpus mode modifications and free plate mode modifications. The plates joined to form a corpus are no longer free to act sepa-

Figure - 7 Distributing stiffness and mass



rately, for the condition of the one plate affects the other.

As Figure 10 shows on the left hand side, the upper nodal line on the back plate just disappears (and thus a whole antinode in the opposite phase). The reason is that the two nodal lines on the top plate (initially connected through the back plate) now meet in the top plate.

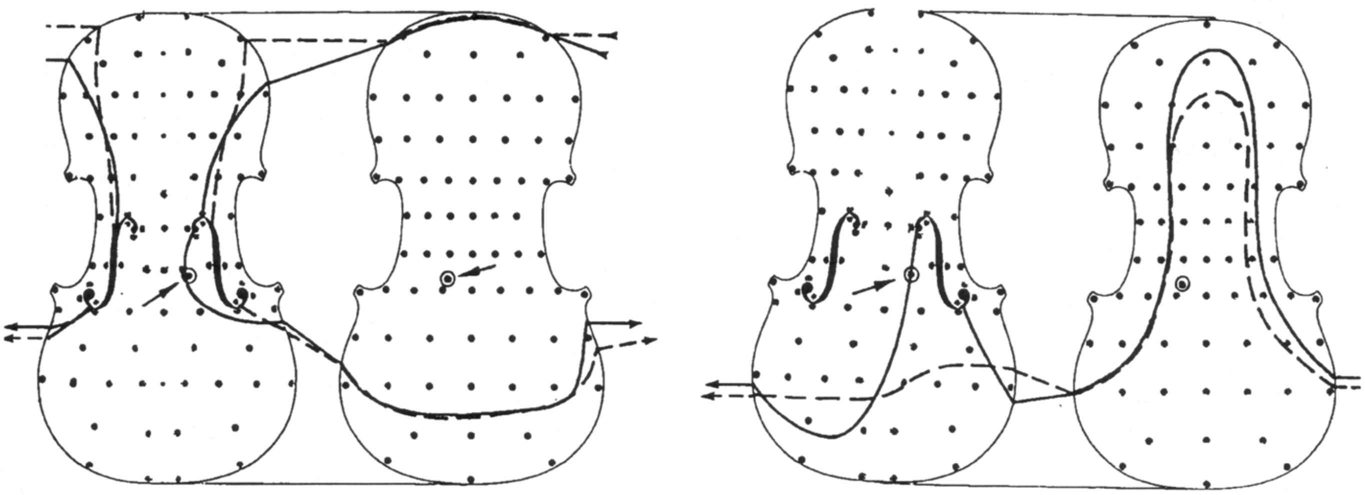
A further, fairly common, example of the finding that the condition of the one plate can affect the other is given in Figure 11. It illustrates the modifications of corpus mode #9. The initial nodal lines show that both plates had been characterized by a ring mode pattern. By thinning the edges of the back plate the nodal rings are "cracked" and connected with each other. At the upper bout of the back plate the nodal line is pushed off (obviously by the thin area) and closes through the top plate. The same happens on the whole left side of the back plate.

Consequences for Violin Making

In a recent issue of this Journal, Rodgers (1994) discusses results in the field of violin acoustics since the 1970's and states that there has been "increased activity on visualizing and understanding of the workings of the violin.... The result was a bewildering number of mechanical modes and no clues about which modes were important in producing sound and how they might be adjusted." It would be very helpful for the violin maker if psychoacoustical research gave some clues on how differences in the "acoustical spectra" of violins have to be interpreted to do justice to human sense of hearing.

The current paper gives some clues about how modes might be adjusted, but not which modes should be ad-

Figure 8 - Modification of two mode shapes

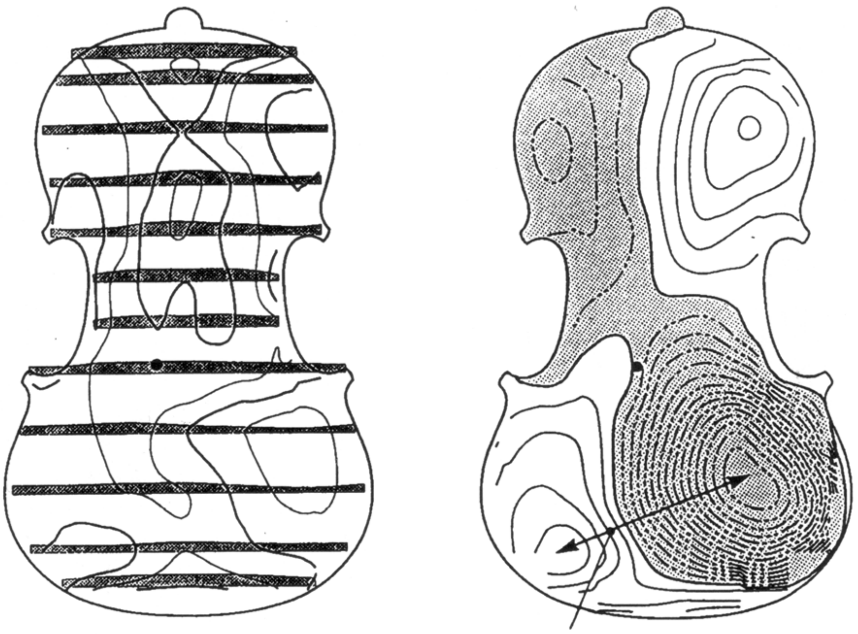


Helmholtz resonance (A0)
----- 258 Hz ——— 282 Hz

Corpus resonance (B1)
----- 536 Hz ——— 541 Hz

——— Nodal lines *with* soundpost inserted
------ Nodal lines without soundpost

Figure 9 - Asymmetrical distribution of amplitudes by asymmetrical thickness



Thickness Graduation of Back Plate

Mode Shape of Corpus Mode #11 (662 Hz)

Principle: Thickness attracts nodal line

justed, or which differences or changes are particularly recognized by our sense of hearing. In this respect scientific research could be a great help for the violin maker as it would promote the practice of deliberately designing to achieve selected tonal results.

Tonal Precision Work

As an attempt to put the techniques described above into practice, the author has made another violin. Instead of a tonal aim expressed in words, its acoustical properties were intended to agree as well as possible with those of a given instrument, a concrete physical goal. As a reference, the modes of a violin by a Venetian master, Domenicus Montagnana, anno 1740, were analyzed. In the production process of the new violin both the frequencies and nodal patterns of the modes were adjusted to match those of the Montagnana violin. In Figure 12 the modes of the original instrument are compared with the modes of the tonal copy.

The broken lines are the nodal lines of the original violin with a fine pattern illustrating its cophasal antinodes. The solid lines are those nodal lines for the tonal copy with a coarse-grained pattern illustrating its cophasal antinodes. The agreements of mode shapes of both instruments are shown by the overlapping of the different patterns. The eigenfrequencies of the original violin are in brackets, those of the tonal copy without brackets. The differences of eigenfrequencies in semitones are given in italic letters below each mode.

The mode with 268 Hz is the Helmholtz resonance. The next mode (337 Hz) with a twisting motion does not radiate efficiently. Next occur two very similar modes with different frequencies (367 and 418 Hz). The mode with 475 Hz is the main corpus resonance (B1). Slightly below there is a mode with a strong cophasal pumping of the lower part of the back plate. Finally the B1 mode is followed by two plate resonances at 625 and 662 Hz.

Comparing the original violin with the tonal copy, the following points are to be emphasized:

- Every mode in the observed frequency range occurs on both instruments.
- The modes have the same spectral sequence.
- The agreements of eigenfrequencies amount to a narrow band of between -0.59 and +0.51 semitones for the corpus modes (up to 468 and 475 Hz) and of -0.68 and +1.24 semitones for the two following plate modes of the instruments.
- The divergences of nodal patterns are relatively small, especially at the lower frequencies. Even at the high frequencies the type of mode remains the same. Often even in details the mode shapes are similar. For example, the nodal patterns of the main corpus mode (B1,475/468 Hz) on the back plate are closed through the top plate. (This is a question of the bending stiffness in the upper part of the back plate.) In contrast to this, there exist many instruments—such as the Strad model depicted in figure 3—where the B1 nodal lines on the back plate meet in its upper part.

Modal Differences due to Different Contours

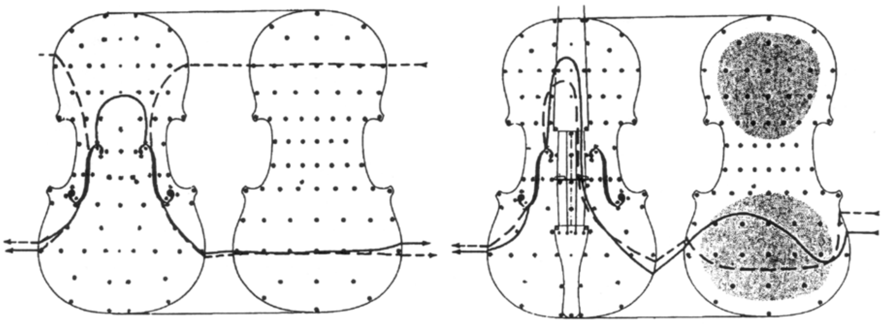
The small amount and nature of modal differences between the genuine Montagnana and the tonal copy becomes obvious if one compares these differences to the differences between two newly made violins having different contours, the Montagnana of 1740 (Figure 12) and the Stradivari of 1715 (Figure 3).

- The mode shapes of the plate modes above the main corpus resonance B1 do not match. As for the higher eigenmodes it is a question of different modes.
- The eigenmodes that match in mode shapes show clearly different eigenfrequencies:

  Mode #3 for the Stradivari at 420 Hz corresponds with mode #3 for the Montagnana at 378 Hz— 1.8 semitones difference

Figure 10 - Modification of mode shape #2

______ Nodal lines *after* workingstep
-------- Nodal lines *before* workingstep



ff-holes cut — -------409 Hz ______ 372 Hz

Thickness reduced in shaded area — -------369 Hz ______ 364 Hz

Mode #4 for the Stradivari at 433 Hz corresponds with mode #2 for the Montagnana at 345 Hz — 3.9 semitones difference.

- The eigenmodes that match in mode shapes appear in a different spectral sequences—the Stradivari mode #4 corresponds with mode #2 in the Montagnana.
- The "Montagnana-Instruments" have corpus modes that do not occur at all during the whole working process on the Stradivari model, although drastic modifications of thickness graduations were done in this process (see Figure 1 in Schleske 1996). Note in particular mode #6 with the cophasal "pumping" lower bout of the back plate. Furthermore the occurrence of a corpus mode at 367 having a "twin" close above at 418 Hz as regards mode shapes seems to be characteristic of the "Montagnana Instruments."

The modal differences (up to 1000 Hz) between different violins are very significant as there are different modes and sometimes a different spectral sequence.

Considering these significant modal differences, the divergences between the 250 year old genuine Montagnana and the newly made tonal copy appear to be small. Because of that it would seem to suggest that apart from thickness graduation, other construction parameters like shape of arching, contour and wood properties are of great importance. The author carefully considered these parameters during the working process on the tonal copy.

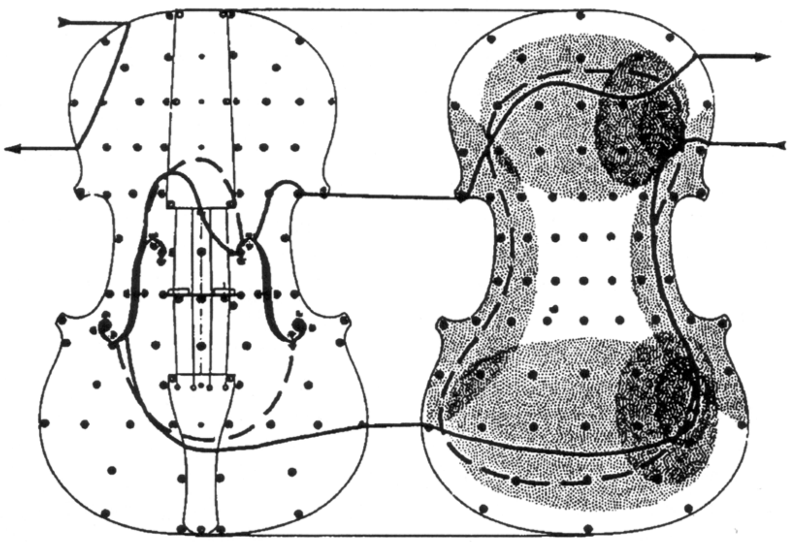
Demands on the Violin Maker

In the opinion of the author, creating a tonal precision copy presents the violin maker with the following challenges:

- Choice of wood: As identical wood is not available, the wood chosen should at least have the same speed of sound in the fiber direction (ratio of Young's modulus to density). With a lower speed of sound the target eigenfrequencies can only be achieved with thicker plates and thus with a larger oscillating mass. This results in an increase of impedance.
- Construction: A different but comparable wood demands calculated divergences from the construction of the target instrument. A simple mechanical copying will come up with a different tonal result. In making the Montagnana tonal copy, the author found that the tonal copy needed differing plate thicknesses in various areas. Furthermore, unconventional ways had to be used—in certain areas various small strips had to be glued in.
- Philosophy of work: It is not sufficient to tune only the free plates but rather one must adjust the modes on the assembled instrument from the outside (this may require provisionally assembling the instru-

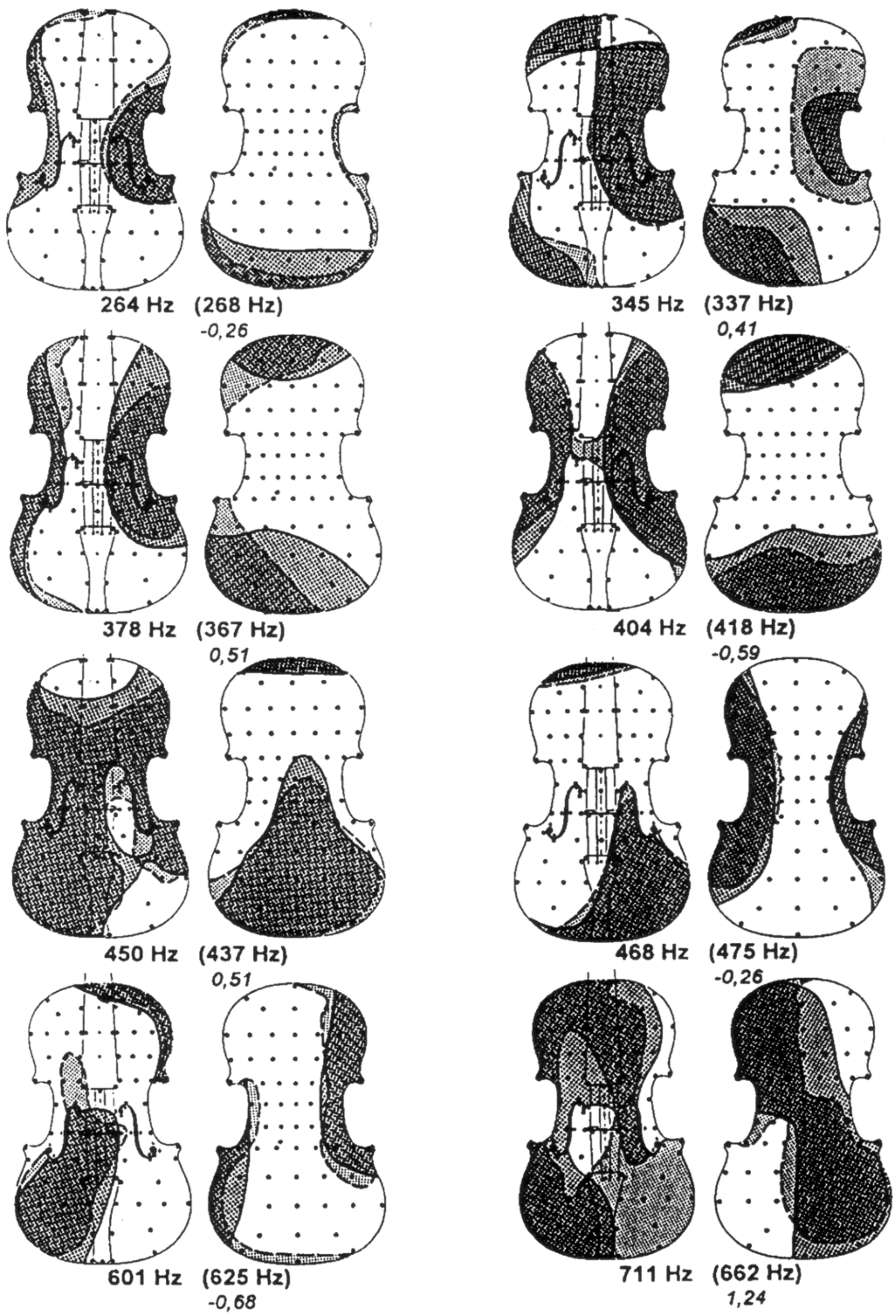
Figure 11 - Modification of a mode shape

______ Nodal lines *after* workingstep
-------- Nodal lines *before* workingstep



Thickness on back plate reduced in shaded areas
______ 699 Hz --------731 Hz

Figure 12 - Comparison of two violins



Original Instrument (Montagnana 1740): Broken lines indicate nodal lines; fine pattern indicates cophasal antinodes; eigenfrequencies are in parentheses.
Tonal copy (Schleske 1994): Solid lines indicate nodal lines; coarse pattern indicates cophasal antinodes; eigenfrequencies are not in parentheses.
The agreements of mode shapes of both instruments are shown by the overlapping of patterns. The differences of eigenfrequencies are given in semitones below the modes.

ment). The author changed the order of his working steps by at first finishing the plates from the inside, assembling the instrument, and then finishing the archings and thicknesses by "tuning" the assembled instrument from the outside (even with strings on and thus having the opportunity of listening to the sound before the instrument is finished). It should be noted that some observations on the edge treatment of classical master instruments make it seem likely that such a path was also followed by the Cremonese tradition in the 18th century (Hargrave 1990).

- Varnish: To be qualified to treat the instrument according to acoustical criteria, a maker must have a detailed knowledge of the acoustical effects of primers and varnishes. Here the main influence concerns the loss factors of the eigenmodes (Schleske 1989). In order to match the damping properties of the tonal copy with those of the target instrument (having measured the 3 dB bandwidths of each mode in between the coats of varnish during the varnishing procedure) some coats were deliberately replaced by another varnish.

Conclusion

The violin is not only a complex physical structure, but also an expression of a certain aesthetic idea. This paper has shown how physics can be a helpful tool in making a violin. But the aesthetic quality of a violin finally achieved (its external expression and its tonal content) cannot be realized by physical methods. Aesthetics is not a subsidiary branch of physics. Natural science does not offer the appropriate method of recognition for every topic and idea. Certainly the musical instrument can be analyzed as a physical body in the same way that music can be investigated concerning its acoustical material. However the effect of music in its spiritual idea and the effect of the instrument's sound and timbre in its aesthetic idea can only be realized by one who is willing to sharpen his musical awareness by learning to listen. Only one who gets involved with music as someone who is deeply moved and who has temporarily forgotten his desire for understanding will understand it in its idea.

Now I know in part; then I shall understand fully, even as I have been fully understood.
I Corinthians 13, verse 12b

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REFERENCES

Cremer, L. 1981. *The Physics of the Violin*, (MIT Press, Cambridge, 1984, English translation by J. Allen of *Physik der Geige*, Stuttgart, Hirzel Verlag).

Hargrave, R. 1990. "Classical Edge Work," *Journal of the Violin Society of America*, vol. 10, no. 2: 49-65.

Hutchins, C. M. 1991. "A rationale for Bi- Tri-Octave Plate Tuning," *CAS Journal*, vol. 1, no. 8 (series II): 36-7.

Möckel, O. 1926. "Beiträge zur Geigenkunde (16th part)," *Die Giege*, vol. 2, no. 5 : 97-107.

Molin, N. E., Lindgren, L-E., Jansson, E. V. 1988. "Parameters of violin plates and their influence on the plate modes," *J. Acoustical Society of America*, vol. 83, no. 1: 281-291.

Müller, H. A. *Skriptum zum Physikunterricht an der Geigenbauschule Mittenwald*, (unpublished).

Rodgers, O. E. 1994. "The Next Task in Violin Tuning," *CAS Journal*, vol. 2, no. 5 (series II): 11-14.

Schleske, M. 1989. "The Influence of Typical Violin-Varnishes on the Acoustical Properties of Thin Spruce Strips," ISMA '89, Mittenwald. Abstract in *CAS Journal* vol. 1, no. 4 (Series II): 38.

Schleske, M. 1996. "Eigenmodes of Vibration in the Working Process of a Violin," *CAS Journal* (May): 2-8.