Speed of sound and damping of spruce in relation to the direction of grains and rays

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ANISOTROPIC QUALITIES OF THE STRUCTURE

The fascinating architecture of spruce results in considerable anisotropic structural qualities [1,2]. Spruce consists of tracheid cells, whose longitudinal axis is parallel to the axis of the tree and are aligned with the grain. These cells are more or less regularly interrupted by the rays. The rays stiffen the structure in radial direction to the axis of the tree. The grains and the rays are cross-link united and together form the stabilization system of the wood. The anisotropic structure of the wood substance results in a considerable directional dependence of stiffness and damping. Figure 1 shows the orientation of the wood with respect to the longitudinal (L), radial (R) and tangential axes (T).

In longitudinal direction of the grains, the speed of sound is about four times as high as in the cross direction. This means that the axial stiffness is sixteen times as high as the radial stiffness. The damping in the direction of the grains amounts to only 1/3 of the damping in cross direction of the grains. This fundamental difference is well-known [3,4].

Speed of sound and damping in longitudinal direction depend on the direction of the grains; in cross direction they depend on the direction of the rays.

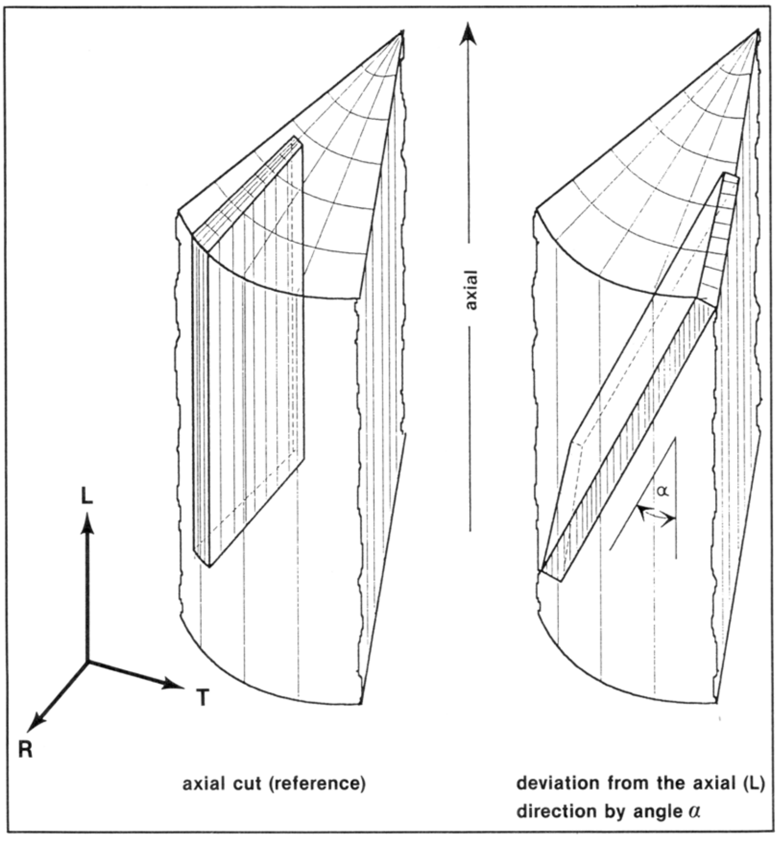

Figure 1. Strips cut at several angles with respect to the direction of the grains.

DEPENDENCE ON GRAIN DIRECTION

In order to determine the degree of this dependence, 10 wood strips of the same thickness were carved out of split spruce. As is shown in Figure 1, the strips deviate from the axial direction (longitudinal axis of the tree). Next, the first free bending mode of the strips, which had been supported at their two nodal lines, were measured in frequency and half-bandwidth. The experimental method was similar to that employed and reported by Hutchins [5]. From the results, the speed of sound (as measured for the stiffness) and the loss factor (as measured for the damping qualities) for the respective strips were calculated. The achieved quantities describe the wood properties independent of the size of the specimen tested.

Figure 2 shows the result of tests on ten specimens. The longitudinal strip, which is exactly in the split direction (in German *Spalt*) and has $\alpha = 0°$, has the highest speed of sound, i.e. more than 5300 m/s. The speed of sound decreases conspicuously with the increasing deviation angle of the grains. With $\alpha = 20°$ it amounts to only 3300 m/s.

Figure 3 shows the percent changes of the speed of sound and of the loss factor for the 10 specimens with $\alpha = 0°$ as reference. The loss factor, η, represents the amount of vibrational damping of the wood. It is related to the logarithmic decrement, δ, as reported by Schelleng [3], Haines [4], and Hutchins [5] by $\eta = \delta/\pi$.

Even minimal deviations from $\alpha = 0$ result in a **de**crease of the speed of sound and in an **in**crease of the loss factor: At the strip, for which $\alpha = 5°$, the speed of sound decreases by 7% while the loss factor increases by 19%. At 10°, the speed of sound decreases by 17% while the loss factor rises by 51%. At a deviation of 20°, the speed of sound decreases by 38%, while the loss factor increases by 145% compared with the longitudinal strip which runs exactly in the split direction.

If we express this as a change of the Youngs modulus, which results from speed of sound squared multiplied by the density (not taking into account the Poisson interaction) the Youngs modulus has decreased by 62%.

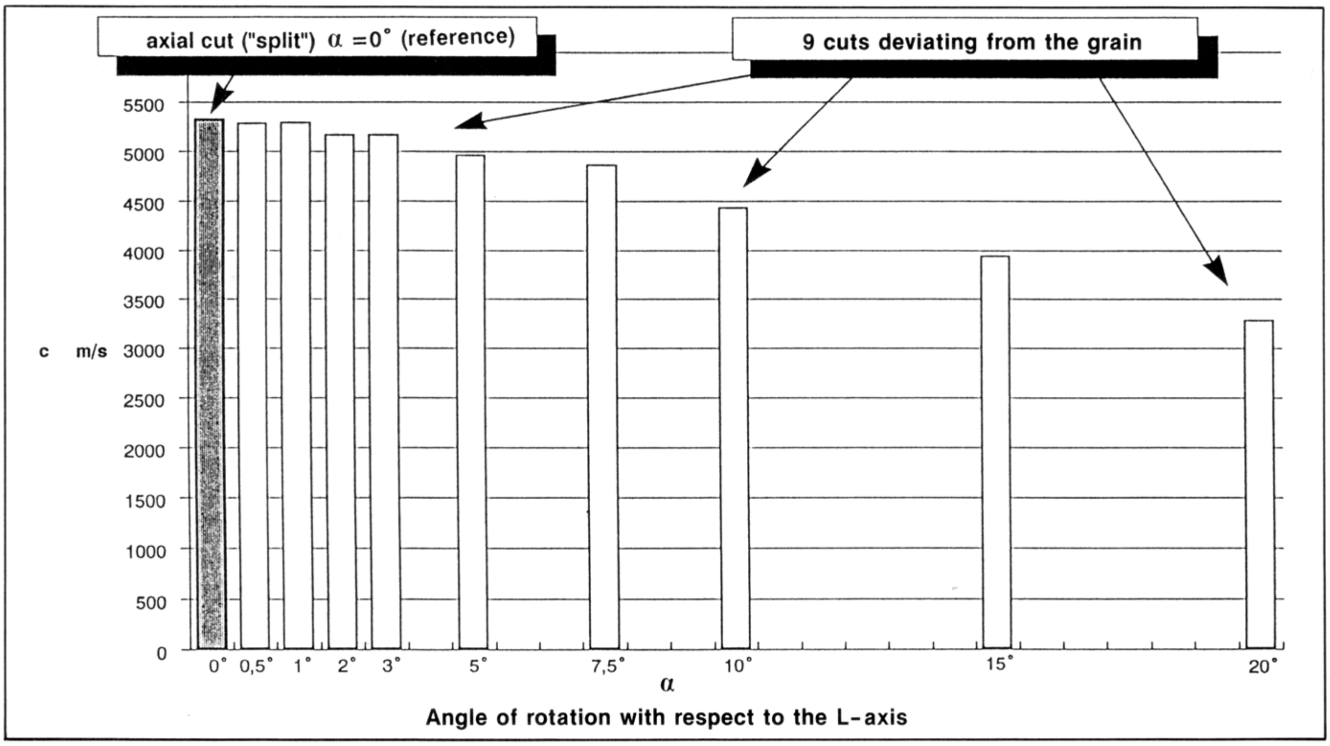

Figure 2. Speed of sound of spruce depending on the direction of grain.

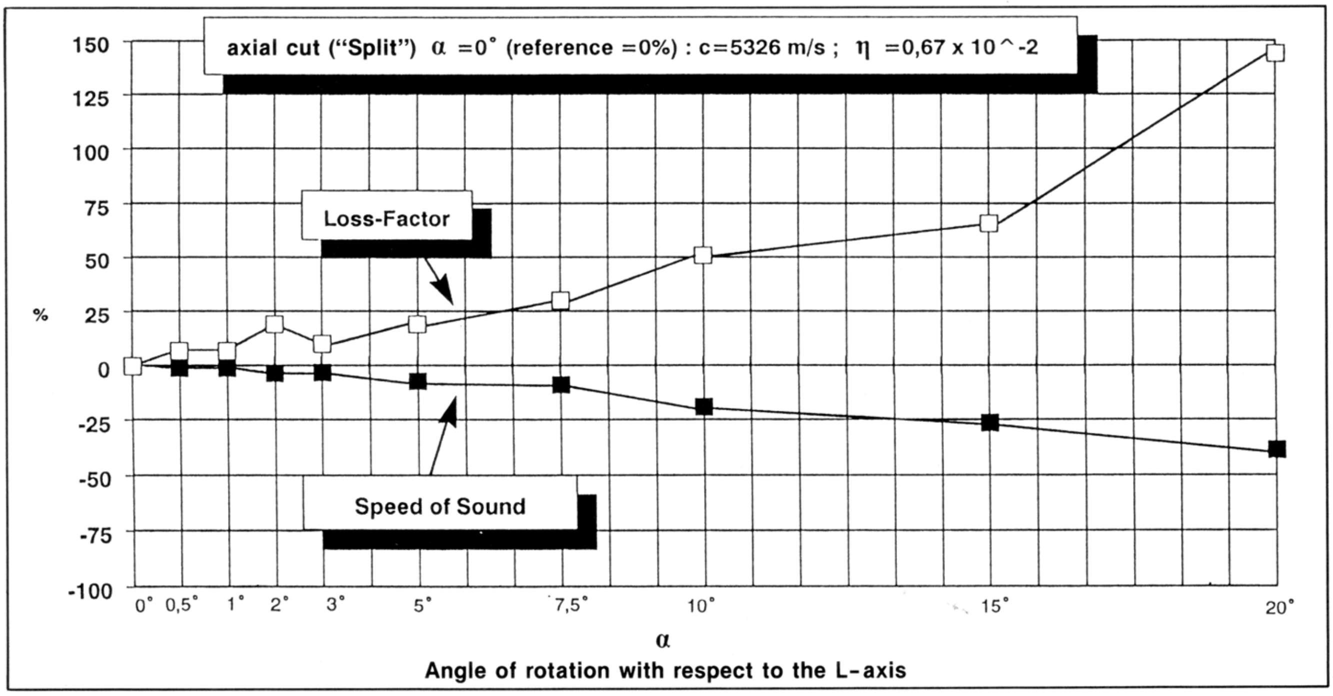

Figure 3. Speed of sound and loss-factor of spruce depending on the direction of grain (L-direction).

DEPENDENCE ON RAY DIRECTION

In order to determine how much the speed of sound and the loss factor depend on the direction of the rays, the same test was carried out with spruce strips in cross direction.

As can be seen in Figure 4 from the slice of a spruce trunk, strips of the same thickness were cut which deviated progressively from the radial direction. With radial cuttings, the rays are not intersected; if we inspect their end-grain, we receognize the vertically "standing" rings. In the case of chordal cuttings, the rays are intersected and the strips have diagonally "lying" rings.

Figure 5 shows the result of tests on thirteen cross-direction strips. Speed of sound for eleven chordal sections which increasingly deviate from the radial section by the angle β and the tangential section have been plotted. The vertical axis again shows the speed of sound in m/s.

The radial section has the highest speed of sound, i.e. 1600 m/s. It decreases as β increases. For $\beta = 18°$, it is only 900 m/s, and for $\beta = 55°$, it reaches its lowest point at 580 m/s. For the pure tangential section, which gets a certain stiffness by the tangentially arranged grains, the speed of sound is greater then 1100 m/s.

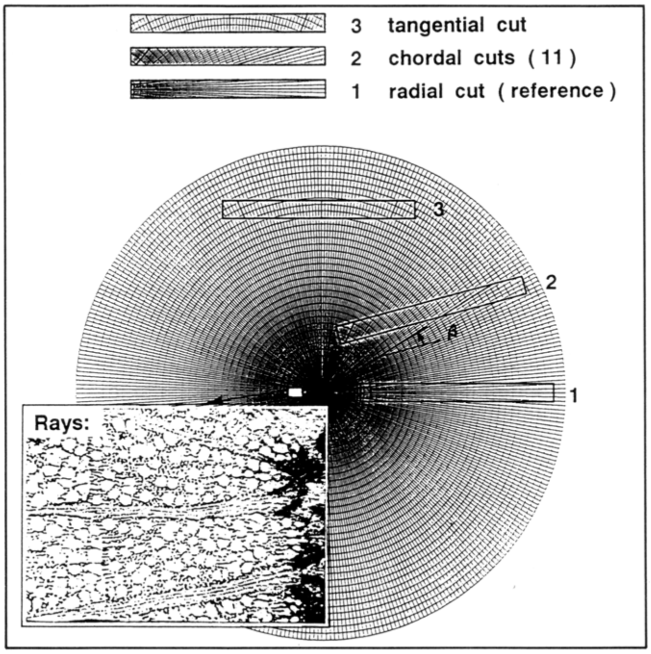

Figure 4. Orientations of cross direction strips with respect to the direction of the rays.

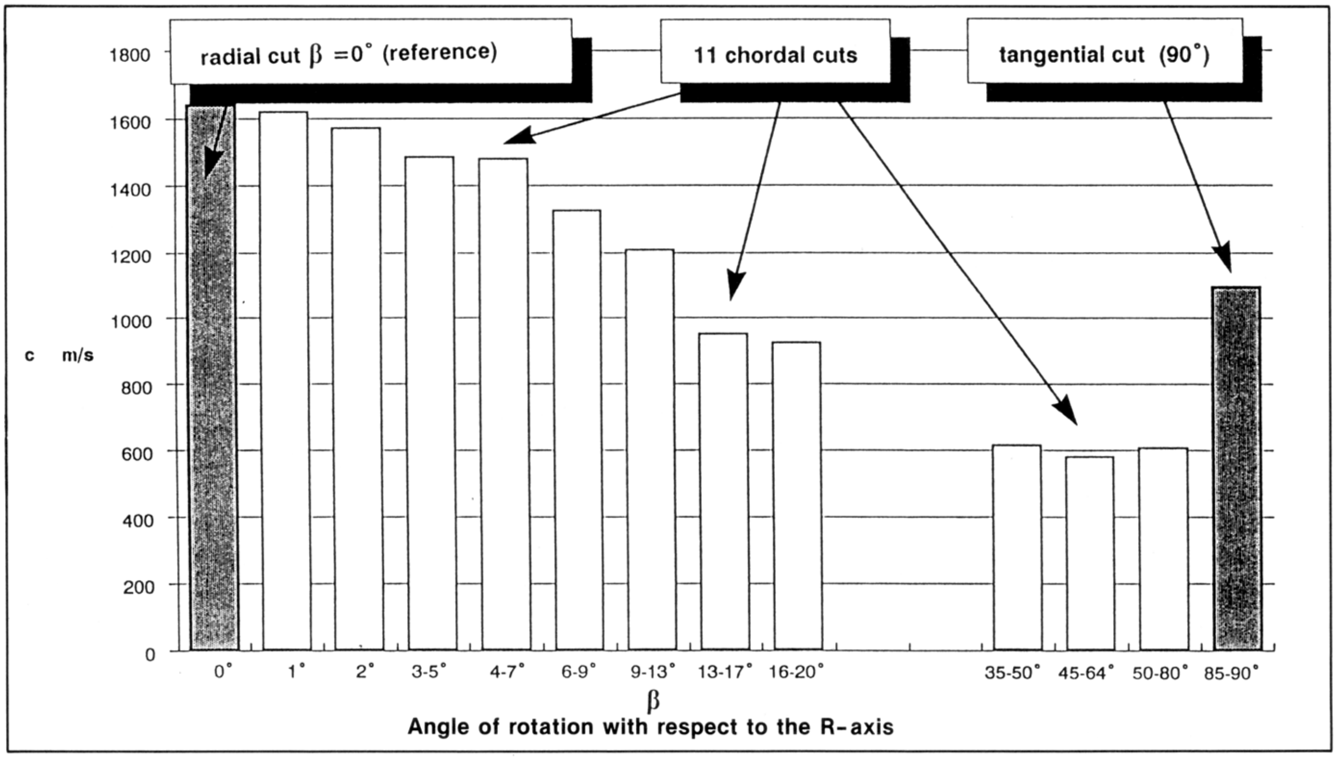

Figure 5. Speed of sound of spruce depending on the direction of the rays.

Figure 6 shows the speed of sound for the radial section as reference quantity and the percentage change of the speed of sound and the loss factor for the chordal sections, and the tangential section.

For $\beta = 5°$, the speed of sound decreases by 10% and the loss factor increases by 6%. For $\beta = 11°$, the speed of sound decreases by 26% and the loss factor increases by 19%. For $\beta = 55°$, the speed of sound decreases by 65%, and the loss factor increases by 70% compared to the radial section.

For cuts approaching the tangential section the values reverse their trends. The speed of sound of the tangential section is 33% lower and its loss factor is 50% higher than that of the radial section.

From experimental results not presented here, it should

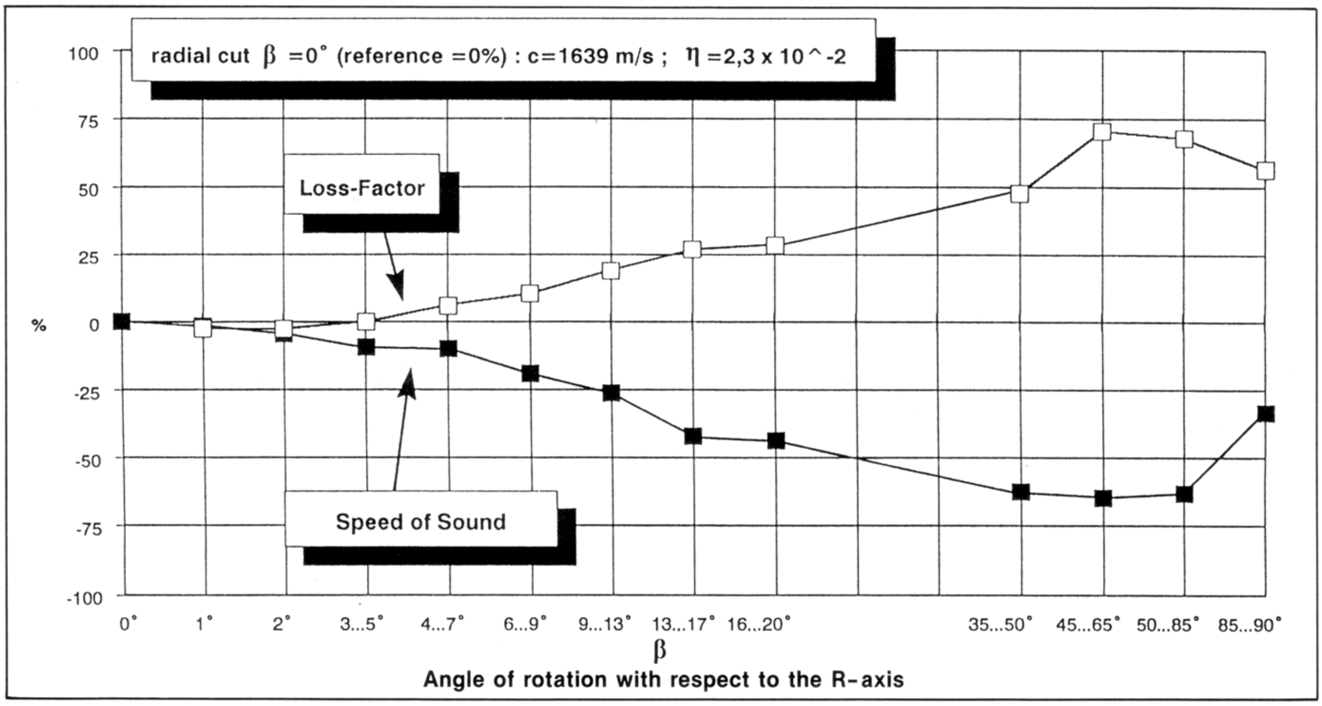

Figure 6. Speed of sound and loss-factor of spruce depending on the direction of the rays.

be pointed out that with the longitudinal wood strips as well as with the cross strips, the percentage change of speed of sound and of the loss factor **does not depend on the thickness** within the different thickness-gradiation of the violin plates of the samples.

INFLUENCE OF THE ARCHING ON THE DYNAMIC BEHAVIOR

If the violin maker takes the direction of the wood structure into account in the arch design, he can deliberately influence the dynamic qualities of the instrument.

In order to show this possibility, two different kinds of arching strips were produced. As Figure 7 shows, some of the strips were carved out of solid wood while others were originally flat wood strips which had been permanently bent with the heated rib bending tool. The eigenfrequencies of the stiffly clamped arching profiles were measured and compared. As the strips had the same form and thus the same form stiffness, the measured differences between the carved and the bent strips are due to the stiffness of the wood structure.

Figure 8 shows the resonance frequencies of the stiffly clamped arching profiles. On the right, you can see the shape of the mode: it has a node in the middle. Under the flat strip, you see the cross profiles which are increasingly bent. The black bars visible in the diagram show the frequencies of the bent strips while the grey bars show the frequencies of the carved strips. This means that the black bars left represent the frequency difference between the bent and the carved arching strips of the same form.

First of all it is noteworthy that in both cases with an increasing curvature the frequencies fall. It is, however, evident

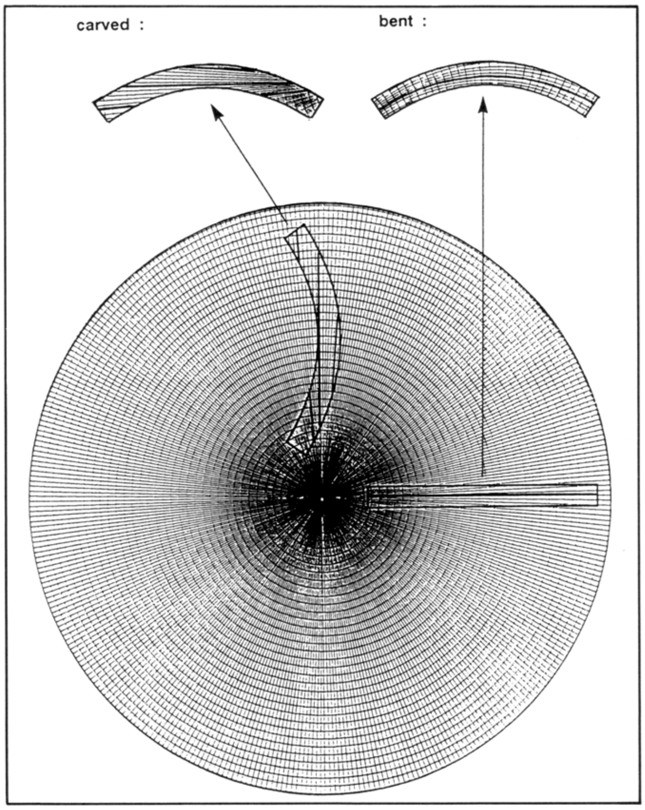

Figure 7. Carved and bent cross - arching - profiles.

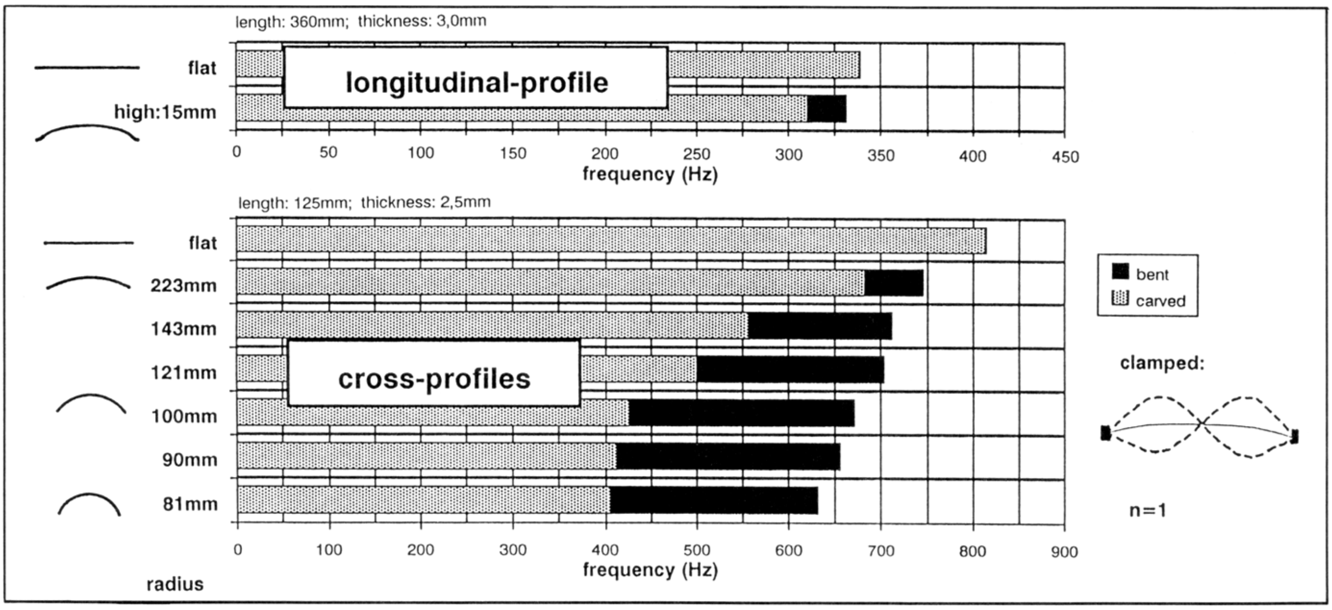

Figure 8. Arching: resonance-frequencies of bent and carved spruce strips (1st mode#).

that the bent strips, whose rays have not been cut, have higher frequencies, that means a higher stiffness than the carved ones, whose rays have been cut the more steeply the higher the arching is.

For a strip with a radius of 100 mm, which corresponds to the arching profile of the top plate in the C-bout, the frequency of the carved strip is 35% lower than that of the respective bent strip.

With the longitudinal strip, which corresponds to the surface profile in longitudinal direction, the differences are less striking. Here, the frequency of the carved strip lies 7% under the frequency of the bent one.

SURFACE ARCHING

If we take into account the direction of the grains and rays within the top arching, the assumption that their direction affects the dynamic and static qualities of the violin top plate is justified. As is well known, the top plate of the violin consists of two radially cut small wedge boards. On the higher longitudinal side, these are shaped in such a way that a roof-shaped board develops from which the arching is made. This method allows an optimal use of the anisotropic anatomy of the wood structure:

The pipe-shaped grains run in the top arching in the longitudinal direction and parallel to the surface level. Thus they allow an optimal use of the longitudinal stiffness in the long middle range of the arching.

In the exactly radially cut wedge boards, the rays run in cross direction within the cut and curved top plate arching and thus create an optimal cross stiffness.

Grains and rays are drastically shortened where cut by the arch contour. Through the resulting decrease of the stiffness, we can achieve an effective decoupling of the whole violin top plate at the edge. If we use the results of the two dimensional strip measurements, the Youngs modulus in the edge range of the C-bout amounts to only 30% of its value at the middle of the surface. This is with a cross arching of 20 to 25 °, even if the thickness of the surface is constant. This effect can even be intensified by a decreasing thickness.

SUMMARY

It has been shown that the elastic and the damping qualities considerably depend on the direction of the grain as well as on the direction of the rays. Therefore the static and dynamic qualities of the arching, which determine the individual resonance qualities of the instrument-plates, can be deliberately influenced by the violin maker. This is the case if he strives to feel the direction of the grains and the rays each time he carves and surfaces the arching and if he then uses this direction for the distribution of the stiffness and decoupling.

Moreover, it should be noted that with the strips as with the profiles, the orientation of the rays has a far greater influence on the cross properties than the orientation of the grains has on the longitudinal properties.

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