The Influence of Different Machining Processes on the Acoustic Properties of Wooden Resonant Board

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The influence of the machining of wooden resonant boards for guitars on the theoretical acoustic properties of this instrument has been studied. Square-shaped spruce boards (*Picea abies* Karst.) were selected to represent a typical portion of the guitar resonant board. Three different machining processes were used to prepare the test specimens: planing, sanding and milling. Vibration of the specimens was initiated by impacting them with a small wooden ball. The resulting oscillations, measured by an accelerometer mounted on the board, were processed by a frequency analyser. The measured response of the differently machined boards was analysed statistically in terms of amplitude, damping and power spectrum, in order to distinguish between the different acoustic properties of the boards. For the chosen material, board shape, and board clamping, it was found that the type of machining selected had a strong effect on the vibrational, and thus acoustic, properties of the tested boards.

1. INTRODUCTION

According to Arakelian (1978), many old violins of Italian origin were made from average-quality wood with non-uniform tissue. This finding encouraged us to search for the reason for the high quality of these instruments. Cumpiano and Natelson (1987) emphasized that the best luthiers make very few instruments in a year, and that they work mostly by hand. Hutchins (1983), and Rodgers (1991) described methods for additional improvements of violins by changing the thickness of their tops and backs: wood removal is performed by hand. In this paper, we investigated to what extent different machining processes affect the condition of the surface layers of resonant boards and thus result in different acoustic properties of the boards. As is well known, wood is an anisotropic and non-homogeneous material, which means that considerable variability in the mechanical (acoustic) properties of wooden resonant boards can be expected. The effect of different machining processes will thus be evident only if it is significantly greater than the effect resulting from non-homogeneity of the tested boards.

2. METHODS

2.1. MACHINING OF SPECIMENS

Two types of spruce wood (*Picea abies* Karst.) were used in the experiment: wood A was seasoned for 5 years and wood B was seasoned for 30 years. In addition, the two types originated from two different trunks. For each type of wood, two adjoining raw boards were cut radially out of the same log. Therefore, the variability of mechanical properties due to anisotropy and non-homogeneity of these two samples is considered normal. Table 1 shows the characteristics of the applied cutting processes. In planing of wood A, the depth of cut was 4 times 1 mm for some specimens, and 4 mm in one pass for others. The final products made of raw boards (1600 mm × 180 mm × 11 mm) were square specimens (150 mm × 150 mm × 3 mm) with equal grain and ring orientation. The planes of cutting and feeding speed were always parallel to the grain orientation (see Figure 1). The technological parameters of each cutting process were chosen to attain good surface quality of specimens.

TABLE 1
The characteristics of planing, face milling and belt sanding

Wood A: planing	**Wood B: planing**
-diameter of cutting tool: 130 mm	-diameter of cutting tool: 117 mm
-number/material of cutting edges: 4/HSS	-number/material of cutting edges: 3/HSS
-cutting speed: 41 m/s	-cutting speed: 37 m/s
-sharpness/rake angle: 45°/30°	-sharpness/rake angle: 45°/30°
-feeding speeds (m/min): 7, 14, 21	-feeding speeds (m/min): 7, 14
-depth of cut: 1 mm on each side (4 passes) 4 mm on each side (1 pass)	-depth of cut: 2 mm on each side (2 passes)
Wood B: face milling	**Wood B: belt sanding**
-milling tool: face clearance angle=0°, axial clearance angle=10°, axial rake angle=15°, diameter of tool=80	-coating of the contact wheel: rubber, 40 Shore -number of transversal oscillations of belt: 60/min

mm, radius of roundness (main - side cutting edge)=30 mm, inclination angle of tool=0°	
-number/material of cutting edges: 2/HSS	-abrasive material: garnet, grain size 60
-cutting speed: 50 m/s	-speed of belt: 21 m/s
-feeding speed: 8 m/min	-feeding speed: 7 m/min
-depth of cut: 2 mm on each side (2 passes)	-depth of sanding: 1 mm on each side (4 passes)

All terms are adopted from the wood-cutting terminology (Kollmann and Côté (1968)), therefore they are not interpreted.

2.2. TESTING OF SPECIMENS

The device for testing of specimens and the measurement set-up are shown schematically in Figure 1. Both frames of the testing device imitate the body of a musical instrument with a resonant board. After fixing the specimen between the wooden frames, the accelerometer was mounted with bees wax, and the vibrations were produced by pinging the board with a wooden ball (2 cm in diameter, ash). The two accelerometer positions, the location of the ball's impact and the orientation of the specimens are also shown in Figure 1.

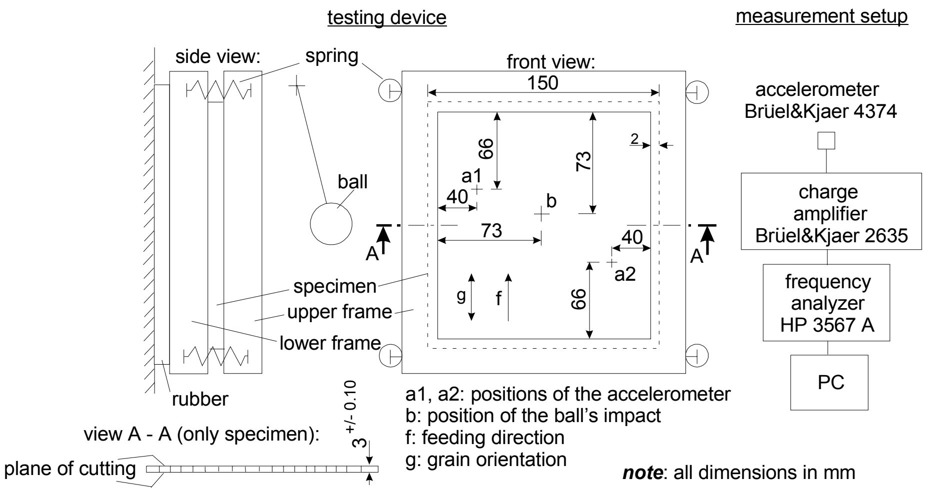

Figure 1: Testing device, specimen orientation and measurement set-up.

At each position of the accelerometer, 10 measurements of the acceleration from the time of the ball's impact into the specimen were made (*i.e.,* 0 second to 1.0 second). Each of the 10 resulting signals was transformed into an amplitude spectrum with the Fast Fourier Transform technique, and after that an averaging was performed (Hewlett-Packard (1989)):

$$A_z = \frac{\sum_{i=1}^{10} D_i}{10}, \tag{1}$$

where D_i indicates the i-th amplitude spectrum. With an inverse Fourier transformation of A_Z, the plot of the acceleration (*i.e.,* average signal) in time domain was obtained (Hewlett-Packard (1989)). The position of the accelerometer did not affect significantly the average signal. Figure 2 shows schematically a section of a typical transient plot of the average signal. Its actual discrete form is approximated by the analytical envelope $c_k(t)$:

$$c_k(t) = a_k \cdot e^{b_k \cdot t}, \tag{2}$$

where a_k and b_k indicate the coefficients determined by least-squares fitting, t indicates time after the ball's impact and subscript k indicates the conditions of the experiment (see Table 2).

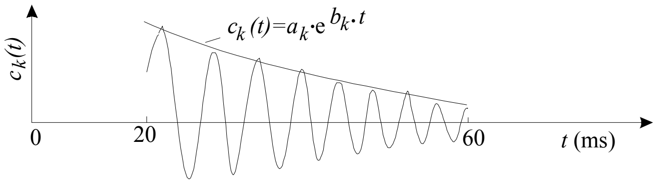

Figure 2: Acceleration of the specimen - average signal (schematically).

Function (2) was fitted to the average signal from 20 ms to 60 ms after the ball's impact. The coefficient of determination, which expresses how accurately the analytical function $c_k(t)$ describes empirical data, was for all fits between 0.76 and 0.98. After obtaining the analytical function $c_k(t)$, the logarithmic decrement of damping for each average signal was calculated:

$$\Delta_k = ln \frac{c_k(t_i)}{c_k(t_{i+1})}, \tag{3}$$

where t_i is the time of the i-th amplitude peak of the average signal. The second quantity calculated from the empirical results was the intensity of the average signal at time 20 ms:

$$C_k = c_k(t=20\ \text{ms}). \tag{4}$$

For each A_Z (see equation (1)), the k-th one-sided discrete power spectrum plot (*i.e.,* power spectrum) was calculated (Hewlett-Packard (1989)). The frequency line spacing was 1 Hz and the range was from 0 Hz to 3200 Hz. Next, for each power spectrum the following eight spectral characteristics were determined:

- position (Hz) of basic frequency component: $F0_k$
- power (m^2/s^4) of basic frequency component: $P0_k$
- position of frequency component with the largest magnitude: $F1_k$
- power of frequency component with the largest magnitude: $P1_k$
- position of frequency component, with the second largest magnitude: $F2_k$
- power of frequency component with the second largest magnitude: $P2_k$
- position of frequency component with the third largest magnitude: $F3_k$
- power of frequency component with the third largest magnitude: $P3_k$,

Comment:

3. RESULTS

3.1. TIME DOMAIN

Group j has the average logarithmic decrement of damping $\overline{\Delta}_j$ and the average intensity $\overline{C}_j$:

$$\overline{\Delta}_j = \frac{1}{n} \sum \Delta_k \ , \tag{5}$$

$$\overline{C}_j = \frac{1}{n} \sum C_k \ , \tag{6}$$

where subscript j indicates a group of n average signals that were acquired by measuring the specimens with the same final machining. Table 2 defines group j; subscript k and the quantities $\overline{\Delta}_j$ and $\overline{C}_j$ with corresponding standard deviations. Because the acceleration was measured at two positions of each specimen, the actual number of the average signals n is twice as large as the number of specimens.

A hypothesis was made that the quantities $\overline{\Delta}_j$ and $\overline{C}_j$ of any two groups of differently machined specimens are significantly different at the statistical significance level of 0.05 (Kanji (1993)). The T and F tests were used for statistical calculations. The comparisons are shown in Table 3. In these calculations, it was assumed that Δ_k and C_k are distributed according to the Gaussian distribution.

TABLE 2

The quantities $\overline{\Delta}_j$ and $\overline{C}_j$ for groups of differently machined specimens

group j	*applied cutting process*	*type of wood*	*feeding speed (m/min)*	*depth of cut (mm)/Nr. of passes on each side*	*n*	*k*	$\overline{\Delta}_j$ / *std. dev.*	$\overline{C}_j$ / *std. dev. (m/s^2)*
1	planing	A	14	4 / 1	40	1 to 40	0.286/0.127	156/54
2	planing	A	14	1 / 4	40	41 to 80	0.214/0.085	133/25
3	planing	A	21	1 / 4	40	81 to 120	0.248/0.085	100/38
4	planing	B	7	2 / 2	40	121 to 160	0.163/0.035	133/11
5	planing	B	14	2 / 2	40	161 to 200	0.140/0.024	144/22
6	sanding	B	7	1 / 4	40	201 to 240	0.211/0.045	149/34
7	milling	B	8	2 / 2	40	241 to 280	0.229/0.128	171/100

TABLE 3

Comparisons of differently machined specimens (time domain)

compared groups j	*equality of* $\overline{\Delta}_j$	*equality of* $\overline{C}_j$
1 and 2	YES	YES
1 and 3	YES	**NO**
3 and 2	YES	YES
4 and 5	YES	YES
4 and 6	**NO**	YES
6 and 7	YES	YES
5 and 6	**NO**	YES
4 and 7	YES	YES
5 and 7	**NO**	YES

3.2. FREQUENCY DOMAIN

The same procedure as in section 3.1. was performed with data obtained from the frequency analysis. The average quantities $\overline{F0}_j$, $\overline{P0}_j$ ... $\overline{P3}_j$ were calculated by analogy to $\overline{\Delta}_j$ from expression (5), where Δ_k was replaced by $F0_k$, $P0_k$ ... $P3_k$, respectively. The results of calculations with corresponding standard deviations are shown in Table 4. The comparisons of the eight spectral characteristics for groups of differently machined specimens are shown in Table 5.

TABLE 4

The quantities $\overline{F0}_j$, $\overline{P0}_j$ ... $\overline{P3}_j$ for groups of differently machined specimens

group j	$\overline{F0}_j$ / *std. dev. (Hz)*	$\overline{P0}_j$ / *std. dev. (m^2/s^4)*	$\overline{F1}_j$ / *std. dev. (Hz)*	$\overline{P1}_j$ / *std. dev. (m^2/s^4)*	$\overline{F2}_j$ / *std. dev. (Hz)*	$\overline{P2}_j$ / *std. dev. (m^2/s^4)*	$\overline{F3}_j$ / *std. dev. (Hz)*	$\overline{P3}_j$ / *std. dev. (m^2/s^4)*
1	381/6	50/8	381/6	50/8	1047/370	36/7	863/325	22/10
2	384/6	47/13	552/381	50/12	781/431	34/5	1087/406	26/8
3	387/4	31/5	571/243	33/4	661/407	27/6	1196/400	19/5
4	368/7	51/9	455/281	54/8	979/325	39/8	903/389	28/6
5	361/2	62/10	360/2	62/10	1138/134	40/8	758/229	29/9
6	373/7	49/11	453/255	51/10	710/246	27/9	971/325	21/9
7	375/5	52/8	375/5	52/8	1042/369	28/6	904/325	21/5

TABLE 5

Comparisons of differently machined specimens (frequency domain)

compared groups j	*equality of* $\overline{F0}_j$	*equality of* $\overline{P0}_j$	*equality of* $\overline{F1}_j$	*equality of* $\overline{P1}_j$	*equality of* $\overline{F2}_j$	*equality of* $\overline{P2}_j$	*equality of* $\overline{F3}_j$	*equality of* $\overline{P3}_j$
1 and 2	YES	YES	YES	YES	YES	YES	YES	YES

1 and 3	**NO**	**NO**	**NO**	**NO**	YES	**NO**	YES	YES
3 and 2	YES	**NO**	YES	**NO**	YES	**NO**	YES	**NO**
4 and 5	**NO**	**NO**	YES	YES	YES	YES	YES	YES
4 and 6	NO	YES	YES	YES	YES	NO	YES	YES
6 and 7	YES	YES	YES	YES	**NO**	YES	YES	YES
5 and 6	**NO**	**NO**	YES	**NO**	**NO**	**NO**	YES	YES
4 and 7	NO	YES	YES	YES	YES	**NO**	YES	**NO**
5 and 7	**NO**	**NO**	**NO**	**NO**	YES	**NO**	YES	**NO**

4. DISCUSSION

The logarithmic decrement of damping, the intensity at 20 ms after the ball's impact, and some spectral characteristics of the acceleration of the specimens were analyzed. Because two different types of wood were used in the experiment, the comparison of the results obtained with specimens of wood A and B is not useful. The experiments prove that the cutting process influences the acoustic properties of the specimens in general:

1. For wood A:

- Variations of feeding speed and depth of cut did not significantly affect $\overline{\Delta}_j$ of differently planed specimens.
- A difference in $\overline{C}_j$ for differently planed specimens occurred only when feeding speed and depth of cut were different. Greater $\overline{C}_j$ was a consequence of a lower feeding speed and a smaller depth of cut.
- The difference in depth of cut was not sufficient to cause a difference in the spectral characteristics of the signals acquired for specimens machined by planing. But the difference in feeding speed only, or feeding speed as well as depth of cut, caused a difference in the power spectrum of acceleration.

2. For wood B:

- The milled and sanded specimens had significantly greater $\overline{\Delta}_j$ than planed specimens regardless of the feeding speed of planing.
- No differences in $\overline{C}_j$ occurred for differently machined specimens.
- The spectral characteristics of the acceleration for each of the four differently machined groups of specimens are shown in Figure 3. For specimens milled or planed with feeding speed 14 m/min, $\overline{F0}_j$ coincides with $\overline{F1}_j$, which is not the case for specimens sanded or planed with feeding speed 7 m/min. As for wood A, the difference in feeding speed of planing was sufficient to cause the differences in the power spectra of acceleration.

Wooden resonant boards, which determine the tone quality of various musical instruments, should translate most of the input energy into sound radiation. According to Kollmann & Côté (1968), losses due to internal friction are not desired. Thus, it is presumed that the logarithmic decrement of damping $\overline{\Delta}_j$ should be low and intensity $\overline{C}_j$ high. If so, planing of wood B with lowest feeding speed and smallest depth of cut gives the best $\overline{\Delta}_j$ relative to other tested cutting processes and their variations, while $\overline{C}_j$ was not significantly affected by any process. For wood A, the planing with lowest feeding speed and smallest depth of cut gives the best $\overline{C}_j$, while $\overline{\Delta}_j$ was not significantly affected by the alterations in feeding speed and depth of cut.

The explanation of the different behavior of the specimens in the frequency domain is more complicated than that in the time domain, although in principle, information about a certain signal in both domains is equivalent. In any case, an explanation in the frequency domain is also less valuable, because the various frequency responses of the stimulated specimens are not so demonstrative as if the real resonant boards built into guitar were tested. We can conclude that the frequency response of the specimens depends on their final machining.

The most probable reason for the different behavior of the differently machined specimens is to be sought in the differences in their surface layers. Considering that the thickness of tested specimens was only 3 ±0.10 mm, it was clear that the shape of the thin surface layer was important. It is well known that the surfaces of sanded and planed boards are different. Sanded boards have torn fibers whereas planed boards have chopped fibers. In face milling, some fibers are torn, and some are chopped. Tearing of fibers damages the integrity of the surface much more than chopping. The different shape of surface layers results in either or both of the following consequences:

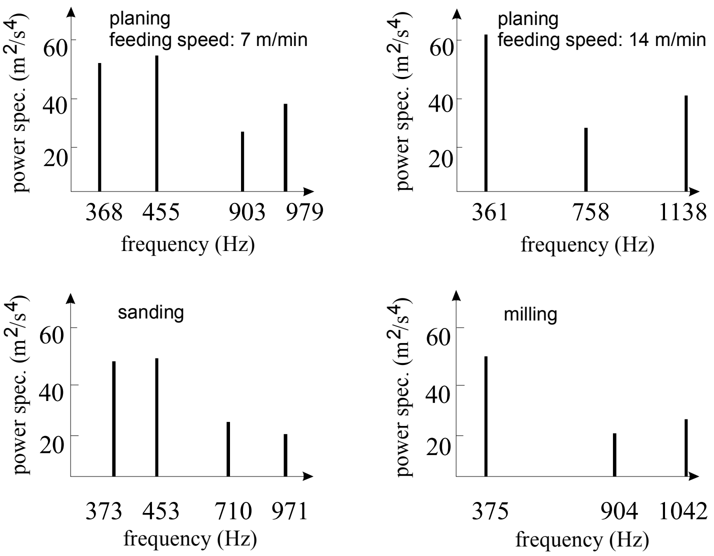

Figure 3: Spectral characteristics of the acceleration (wood B).

- ***Different modulus of elasticity (E) of specimens.*** This can be explained by Hooke's law as it applies to wood (Bodig & Jayne (1982)):

  $$\sigma = E \cdot \varepsilon\,, \tag{7}$$

  where σ is stress, and ε is deformation of a specimen. It is likely that the specimen with less damaged surface will have a higher E in the static bending test than the specimen with damaged surface. The undamaged surface results in higher strength of specimen, which means smaller deformation and higher E at a certain stress level (see equation (7)). Our experiment was actually a dynamic test and probably the dynamic strength is even more affected by the surface than the static one (Hayashi et al. (1976)). In addition, Tsoumis (1991) suggests that either the usual static bending test, or the dynamic test is sufficient for determining E. Due to anisotropy and non-homogeneity, on the one hand, and different strength properties of the two surface layers and the middle layer of the wooden specimen, on the other hand, E is, in fact, some sort of an average modulus. Rheological characteristics of wood (Bodig & Jayne (1982)) are not considered in this analysis, because the periods of the specimen vibrations were short (milliseconds).
- ***Different density (ρ) of specimens.*** For all three tested cutting processes, the different cutting forces on the specimens are typical. Due to wood plasticity and tissue compression, the cutting process is likely to result in the differences in the density of the specimens. As in the case of E, an average density of the specimen is considered in this analysis (see equations (8) and (9)).

Figure 4 (a) shows the surfaces of planed and sanded specimens and the possible consequences of the surface differences. Kollmann & Côté (1968) established that E and ρ are the only parameters in the expressions that define sound wave resistance ω and damping of sound radiation ϑ. (These two equations determine the sound propagation and internal frictional losses of solid materials).

$$\omega = \sqrt{\rho \cdot E} \tag{8}$$

$$\vartheta = \frac{\sqrt{E/\rho}}{\rho} \tag{9}$$

Variations in E and ρ will also result in changes to the dynamic Young's modulus. This modulus is defined by Yano et al. (1997) as a ratio of stiffness to specific gravity of the specimens. The stiffness and specific gravity can be compared to E and ρ, respectively. Figure 4 (b) shows the dependence of the damping of sound radiation on the sound wave resistance for different wood species and other materials. The presented relations confirm that in sound boards of musical instruments, low damping due to internal friction and high damping due to sound radiation are desirable. In other words, high rather than low dynamic Young's modulus of sound boards is preferred.

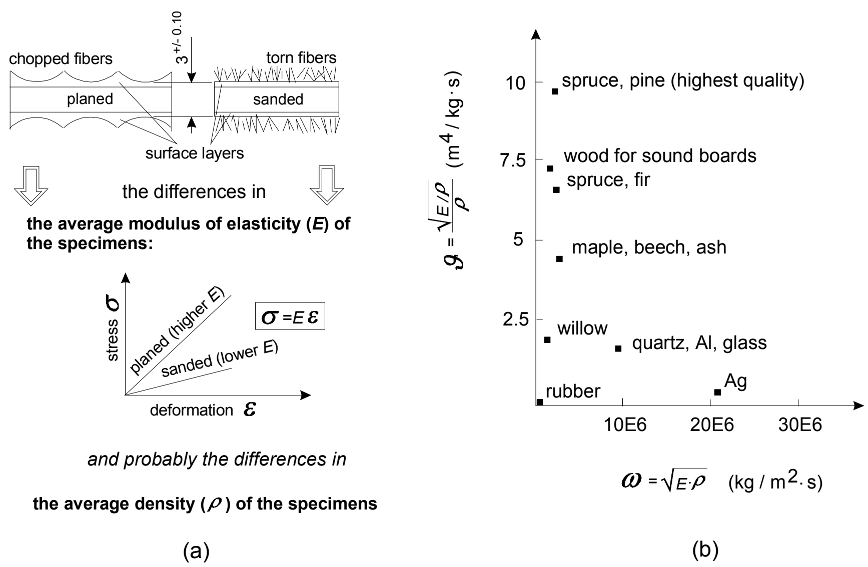

Figure 4: Relation between acoustic and mechanical properties: (a) the mechanical consequence of the different surfaces of planed and sanded specimens; (b) dependence of the damping of sound radiation on the sound wave resistance for different wood species and other materials. ω and ϑ were obtained from Kollmann & Côté (1968).

From equations (8) and (9) we can see that the ratio E/ρ is most advantageous (high) for planed specimens and bad (low) for sanded and milled specimens. This is reasonable because the planed specimens have a surface with smooth chopped fibers that have a higher strength (higher E) in comparison to milled and sanded specimens. It is, however, more difficult to discuss the effect of density on the acoustic properties because we do not know the differences in the density of surface layers of the specimen. For a thorough analysis of the role of surface layers density we would need to know the exact cutting forces on the specimen, which is impossible for sanding.

5. CONCLUSION

1. This paper has demonstrated that the machining processes used for finishing the soundboard play a significant role in the production of wooden musical instruments.
2. All three tested cutting processes and their technological parameters were suitable for generating a good surface quality of the specimens made from two types of wood. In one type of tested wood (spruce, seasoned for 5 years) the roles of feeding speed and depth of cut in planing were estimated. The comparison of planing, sanding and milling was performed with specimens made from another spruce, which was seasoned for 30 years. In some cases statistically significant differences in the acoustic response of differently machined specimens have been demonstrated.
3. The cutting process affects the average modulus of elasticity and probably also the average density of wooden boards.
4. The significant correlation between the cutting process and the theoretical acoustic properties of a wooden resonant board is established and explained by the modulus of elasticity and density.

5. Experiments with both types of wood showed superiority of planing with low feeding speed and small depth of cut.

No implications for guitarmaking could as yet be made. Perhaps the observed correlation is not even important for making resonant boards of real guitars. Only future experiments can help us understand the interplay between the cutting process and the acoustic properties of the resultant resonant board. However, the current results and experimental set-up provide a good starting point to address this larger question.

6. REFERENCES

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