Effects of seasoning on the vibrational properties of wood for the soundboards of string instruments

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Abstract

The vibrational properties of green spruce wood samples were measured intermittently during drying and subsequent conditioning in ambient condition to clarify the effects of seasoning. After drying, the equilibration of mass, the sound velocity of wood continued to increase and its internal friction significantly decreased during 6 months of seasoning. However, those seasoning effects disappeared once the wood was moistened at 100% RH. Physical aging and stress relaxation of wood polymers was assumed to be responsible for. This coincides with the empirical knowledge of violin makers: seasoning for a few years is more important than long-term aging over centuries.
I. INTRODUCTION

Wood is widely used for the soundboards of various string instruments such as violins, guitars and harps. Its lightness, elasticity, appropriate damping, and excellent durability are suitable for that purpose, and synthetic materials cannot currently replace its workability, availability, and sustainability.

Wood aging has been of interest to musicians and artisans dealing with musical instruments, because the acoustic quality of wood is believed to improve by long-term aging over centuries. Although there are few direct evidences for such an “aging effect”, recent studies on hygrothermal acceleration of aging predicted a slight increase in the specific dynamic Young’s modulus ($E_i/\rho$), and a decrease in the internal friction ($Q_L^{-1}$) of spruce wood by aging at room temperature ($20^\circ$C) and moderate relative humidity (60–80% RH) for several hundred years (Zeniya et al., 2019a; 2019b). This fact suggests that there is a slight improvement in acoustic conversion efficiency due to long-term aging; and this coincides with the empirical knowledge of musicians and artisans.

On the other hand, the effect of short-term aging for less than 5 years, defined as the “seasoning effect”, is still debatable. Most violin makers consider the seasoning, rather than long-term aging for the acoustic quality of instruments (Carlier et al., 2015). However, wood scientists have not paid attention to the seasoning effect because wood is chemically stable, and no significant change is expected over such a short period of time (Kohara, 1958).

It should be remembered that wood is a natural polymer composite in which hydrophobic crystalline fibers are embedded in hydrophilic amorphous matrix substances. In general, the mechanical and viscoelastic
properties of polymers can change over time through their conformational change, even when their chemical structure remains unchanged (Struik, 1978). Such a phenomenon is called physical aging and may be a major mechanism behind the seasoning effect; however, only a few studies so far have dealt with the physical aging of wood (Hunt and Gril, 1996).

In this study, we first observed the vibrational properties of wood during drying from their green state and subsequent seasoning in ordinary conditions to determine the effects of seasoning. The reversibility of the seasoning effect was also discussed by comparing the vibrational properties of seasoned and aged wood specimens before and after moisture treatment. The results explain the mysterious effects of seasoning, and may help musicians appropriately use their instruments.

II. MATERIALS AND METHODS

A. Short-term seasoning of green wood

Green spruce wood were dried and seasoned over 6 months, while its vibrational properties were intermittently measured. The term “green” means recently cut fresh wood that has never been dried. Twenty green Sitka spruce (Picea sitchensis) lumber were cut into 20 samples with dimensions of 4 – 5 mm (tangential, T) × 18 – 20 mm (radial, R) × 180 mm (longitudinal, L), and these samples were dried in a conditioning room at 20±0.1 °C and 60±1% RH. After the drying for 1 day, those samples were precisely re-shaped using a hand planer into 3 mm (T) × 17 mm (R) × 180 mm (L), and continuously conditioned for 212 days while their mass, density (ρ), $E_L$, $Q_{L^{-1}}$, and sound velocity ($V_L$) along the grain were measured.
intermittently. The detailed method of vibration measurement will be described later on. Next, the wood samples were moistened at 20 °C and 100% RH for 1 month, conditioned at 20 °C and 60% RH for 2 days, and then their properties were measured again. Finally, the wood specimens were oven-dried at 105 °C for 24 h to determine their absolute dry mass.

B. Vibration measurement of seasoned wood

In order to characterize the acoustic behavior of wooden musical instruments, we need to know the viscoelastic constants of wood in three different directions (L, R and T), because wood is an anisotropic material (Haines, 2000; Bucur, 2016). In the present study, however, the dimensions of seasoned and aged wood samples were not enough to precisely measure their properties in R and T directions. Therefore, we decided to focus on the wood properties in L direction as the first step. Seasoned or aged spruce lumber were acquired from artisans and companies making violins, harps, pianos or guitars. These lumber were cut into strips with dimensions of 0.9–5.0 mm (T) × 8–21 mm (R) × 83–181 mm (L), depending on the size of the original lumber. The origin of the samples and their estimated seasoning time are listed in Table 1. Most samples were identified to be from the spruce family. Two lumber (S9 and S14) could not be clearly identified but may possibly be spruce or cedar wood. As the precise time of cutting was unknown in most of the seasoned wood samples (S5 – S15), the acquisition year was regarded as the year of cutting.

The vibrational properties of wood strongly depend on its moisture sorption history, as well as its moisture content (MC). To compare the vibrational properties of wood samples under the same conditions, all samples were once dried completely at 20 °C with P₂O₅, and then conditioned at 20±0.1 °C and 60±2% RH
for 1 month prior to the vibration measurement.

To investigate the reversibility of seasoning effect, the vibration measurements were repeated after the moistening treatment: wood samples were moistened at 20 °C and 100% RH for more than 1 month. After the moistening, the wood samples were dried completely at 20 °C on P₂O₅, conditioned at 20 °C and 60% for 1 month, and then their vibrational properties were determined again. These moistening–drying–conditioning processes were repeated twice as shown in FIG. 1.

### TABLE I. Origin of tested wood samples.

<table>
<thead>
<tr>
<th>Category</th>
<th>Abbreviation</th>
<th>Use</th>
<th>Species</th>
<th>Year of cutting or acquisition</th>
<th>Year of testing</th>
<th>Seasoning time (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>N</td>
<td>Common</td>
<td><em>Picea sitchensis</em></td>
<td>2017</td>
<td>2017</td>
<td>0</td>
</tr>
<tr>
<td>S1</td>
<td>Violin</td>
<td><em>Picea sitchensis</em></td>
<td>2014</td>
<td>2017</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>Guitar</td>
<td><em>Picea sitchensis</em></td>
<td>2013</td>
<td>2018</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>Harp</td>
<td><em>Picea sitchensis</em></td>
<td>2011</td>
<td>2018</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>Common</td>
<td><em>Picea abies</em></td>
<td>1995</td>
<td>2018</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>Unknown</td>
<td><em>Picea abies</em></td>
<td>1990</td>
<td>2018</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>S6</td>
<td>Violin</td>
<td><em>Picea abies</em></td>
<td>1980</td>
<td>2018</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>S7</td>
<td>Lute</td>
<td><em>Picea abies</em></td>
<td>1975</td>
<td>2018</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>Seasoned</td>
<td>S8 House</td>
<td>Unidentified</td>
<td>1914</td>
<td>2017</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td>S9</td>
<td>Guitar</td>
<td><em>Picea sitchensis</em></td>
<td>1905</td>
<td>2018</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>S10</td>
<td>Unknown</td>
<td><em>Picea abies</em></td>
<td>1898</td>
<td>2018</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>S11</td>
<td>Unknown</td>
<td><em>Picea abies</em></td>
<td>1840</td>
<td>2018</td>
<td>178</td>
<td></td>
</tr>
<tr>
<td>S12</td>
<td>Unknown</td>
<td><em>Picea abies</em></td>
<td>1780</td>
<td>2018</td>
<td>238</td>
<td></td>
</tr>
<tr>
<td>S13</td>
<td>Violin</td>
<td>Unidentified</td>
<td>1715</td>
<td>2017</td>
<td>302</td>
<td></td>
</tr>
<tr>
<td>S14</td>
<td>Unknown</td>
<td><em>Picea abies</em></td>
<td>1700</td>
<td>2018</td>
<td>318</td>
<td></td>
</tr>
</tbody>
</table>

a) For commercially supplied wood, the year of cutting may be 1–2 years earlier than that of purchase.

b) Estimated time elapsed after cutting or acquisition.
The $E_L$, $V_L$ and $Q_L^{-1}$ values of wood were determined using free flexural vibration method, which is widely used to measure the vibrational properties of wood (Obataya et al., 2000; Brémaud, 2012; Brémaud et al., 2012). The strip-shaped sample was horizontally hung by silk threads, and its resonant vibration was excited by a magnetic driver or an audio speaker, while the amplitude of vibration was measured using an eddy-current sensor (Keyence, EX-202), a laser displacement sensor (Keyence, LK-G30), or a precision microphone (Ono Sokki, MI-1431). An appropriate combination of driver and sensor was selected for precision, depending on the mass and resonant frequency of wood samples. The combinations of equipment are illustrated in FIG. 2. Method I is popular and employed frequently in the vibration measurement of wood: small iron pieces are glued at the ends of a specimen with one end excited by a magnetic driver,
while the deflection at the other end is detected by an eddy-current sensor. This method achieves sufficient precision when the mass of the iron piece (< 0.05 g) is negligibly smaller than the wood sample (> 2 g). The first-mode resonance frequency was in the range from 300 Hz to 800 Hz. When the frequency was higher than 900 Hz, the deflection was observed using a microphone, while the vibration was excited by a magnetic driver placed at the center of the sample (method II). Vibrations were excited using a speaker beneath the sample for particularly thin and/or light (0.5–0.9 g) samples, and the deflection was detected by an eddy-current sensor (method III) or a laser displacement sensor (method IV).

![Combination of exciter and detector used in vibration test.](image)

(a) Wood specimen; (b) supporting thread; (c) iron piece; (d) magnetic driver; (e) eddy current sensor; (f) microphone; (g) aluminum foil; (h) audio speaker; (i) laser displacement sensor.

The $E_L'$ and $V_L$ values were calculated from the dimension and resonance frequency ($f_r$) according to the following equation (Hearmon, 1958):

$$V_L = \sqrt{\frac{E_L'}{\rho}} = \frac{4\sqrt{3\pi l^2 f_r}}{m_n^2 h},$$  

(1)

where the $h$ and $l$ are height and length of the sample, respectively. The $m_n$ is a constant depending on the
mode of vibration, and \( m_1 = 4.73 \) for the first-mode flexural vibration. The \( Q_{L}^{-1} \) value was determined by approximating the resonance curve with the theoretical equation for viscoelastic solid. An example of the approximation of a resonance curve is exhibited in FIG. 3.

\[
\begin{align*}
fr &= 382.0 \text{ Hz} \\
Q^{-1} &= 0.0055 \\
r &= 0.995
\end{align*}
\]

FIG. 3. Example of the resonance curve: amplitude of deflection of a wood sample plotted against frequency. Plots, experimental values; curve, approximated values.

III. CHANGES IN WOOD PROPERTIES DURING SEASONING

MC is an important factor affecting the vibrational properties of wood (Obataya et al., 1998). The MC value is defined as

\[
MC \, (\%) = 100 \times \frac{\text{Mass of moisture in wood}}{\text{Absolute dry mass of wood}}
\]

(2)
FIG. 4. Changes in MC, $V_L$, and $Q_L^{-1}$ values of spruce wood during the 6-month conditioning. Open circle, green wood was dried and conditioned; filled circle, conditioned sample moistened once and then conditioned; bars indicate standard deviations.
FIG. 4 shows the changes in MC, $V_L$, and $Q_L^{-1}$ values of wood plotted against the conditioning time over six months. The MC value of green wood (80–100%) was reduced to 25% within 1 day, and then almost equilibrated at 11.7% within 2 days. In this case, the initial two days are the drying period, and the following conditioning is regarded as the seasoning period. Some artisans suggest that the seasoning improves the dimensional stability of wood, but in the present case, MC value or hygroscopicity of wood remained unchanged during the seasoning. This fact indicates that no dimensional stabilization is expected by the seasoning. Probably the term “stabilization” for artisans means "stabilization of shape of lumber" due to the viscoelastic relaxation of internal stress (growth stress and drying stress), rather than the reduction in the hygroscopicity of wood.

If the seasoning is just a drying process as artisans sometimes say, the vibrational properties of wood should remain unchanged after the equilibration of MC. However, the $V_L$ value continued to increase, and $Q_L^{-1}$ value decreased with the elapse of time even after the equilibration of MC. This fact indicates that the seasoning is not just a drying process, but also a kind of treatment that affects the vibrational properties of wood. In general, the soundboards of strings made from particular wood species, such as spruce, western red cedar, and paulownia present relatively low $\rho$ and high $V_L$ values (Brémaud, 2012) or a low anti-vibration parameter, $\rho V_L$ (Yoshikawa, 2007). In fact the overall quality of spruce lumber evaluated by violin makers show a significant and positive correlation with the radiation ratio, $V_L/\rho$ (Carlier et al., 2018). In addition, higher $V_L$ and lower $Q_L^{-1}$ give greater acoustic conversion efficiency, $VQ/\rho$ (Yankovskii, 1967) or greater transmission parameter, $VQ$ (Yoshikawa, 2007). According to Ono (1996), greater $E_L/\rho (=V_L^2)$
and smaller $Q_L^{-1}$ of wood result in greater amplitude of sound radiation. Therefore, the seasoning effects, increase in $V_L$ and decrease in $Q_L^{-1}$, are ideal for efficient sound radiation from wooden soundboards. Despite the advantageous effect of seasoning, its process is still debatable. Because wood is chemically stable in dry conditions, several months of seasoning is not enough to induce significant chemical changes in the wood polymers. Therefore, the most probable mechanism behind the seasoning is the physical aging of wood polymers. Physical aging is the time-dependent approach of a polymer towards thermodynamic equilibrium, and that of artificial polymers has been extensively studied by Struik (1978). The physical aging of wood was first reported by Hunt and Gril (1996). Once the wood was destabilized via moistening or drying they found that the $E_L'$ and $Q_L^{-1}$ of wood can change with little changes in the MC. This delayed equilibration of viscoelastic properties is qualitatively similar to our present results. The viscoelastic stress relaxation of wood polymers explain their destabilization and stabilization during drying, and the subsequent seasoning. FIG. 5 illustrates the structure of wood and its cell wall. The wood cell wall forms fiber-reinforced structures where rigid crystalline cellulose (microfibrils) are embedded in amorphous matrix substances consisting of lignin and hemicelluloses. FIG. 6 illustrates the structural changes in the wood cell wall during drying and the subsequent seasoning. Note that this model simply explains the initiation and relaxation of internal stress in the cell wall, and cannot be used to calculate the $V_L$ and $Q_L^{-1}$ values of wood. In green wood, the matrix polymers are completely swollen with the adsorbed water, whereas the crystalline microfibrils contain no moisture (FIG. 6a). During drying, the matrix polymers shrink with the removal of adsorbed water; however, their shrinkage is mechanically restricted by
the adjacent microfibrils. Consequently, the stressed matrix polymers are unnaturally distorted, likely resulting in lower rigidity and greater mobility in the matrix polymers (FIG. 6b). In the subsequent seasoning, the remaining stress gradually relaxes because the matrix polymers are viscoelastic (FIG.6c). In this relaxation process, $V_L$ increases and $Q_L^{-1}$ decreases with the rearrangement of matrix polymers and the reformation of intermolecular hydrogen bonds. This model has been originally proposed to explain the temporary changes in wood properties due to heat treatment (Obataya and Tomita, 2002; Obataya, 2010; Endo et al., 2016), and reasonably explains the effects of seasoning.

**FIG.5.** Appearance of wood at the macroscopic level (a), cellular structure at the microscopic level (b), laminated structure of the wood cell wall (c) and fiber-matrix composite structure at the macromolecular level (d).

**FIG.6.** Schematic illustration for the initiation and relaxation of drying stress in the cell wall.
If the hypothesis above is valid, the seasoning effects are predicted to disappear once the wood is exposed to humid conditions (FIG. 6a) where the matrix polymers can recover their original conformation, and then dried (FIG. 6b). In FIG. 4, the filled circles indicate the MC, $V_L$, and $Q_{L-1}$ values of wood after moistening. The $V_L$ and $Q_{L-1}$ of the seasoned wood recovered their initial values almost completely as predicted. This fact proves that the seasoning is not an irreversible chemical reaction but a temporary phenomenon, which can be recovered via moistening.

IV. DIFFERENT EFFECTS OF SEASONING AND LONG-TERM AGING

In contrast to the recoverable effect of seasoning, long-term aging (> 100 years) induces irreversible chemical changes of wood polymers, such as oxidation of lignin, hydrolysis of amorphous polysaccharides, and crystallization of cellulose (Kohara, 1958). Here we define the term “seasoning” as the reversible change in wood properties that can be recovered by moistening, whereas "aging" is the irreversible change due to the chemical reaction in wood polymers.

The effect of aging has been discussed by comparing the physical properties of aged wood with those of “new” recently cut wood (Kohara, 1958; Yokoyama et al., 2009, Kraditz et al., 2016). However, in many cases conclusions are unclear because of the numerous original variations in wood properties. As wood is a natural material, its density and density-dependent mechanical properties vary widely even in a single tree. Even at the same density, vibrational properties of wood also vary widely depending on the average angle of microfibrils in the cell wall (Obataya et al., 2000). Thus, it is difficult to discuss the effect of aging as
long as we compare new and aged wood samples, which originate from different sources.

On the other hand, Zeniya et al. have recently proposed time-temperature-humidity superposition, allowing artificial acceleration of aging and precise reproduction of aged wood (Zeniya et al., 2019a; 2019b).

Currently, their results are the most reliable because 1) the temporary effects of seasoning were excluded by moistening treatment prior to the vibration measurement, and 2) the same sample was tested before and after the artificial aging to eliminate the natural variation in wood. The result of the artificial aging predicted that the $V_L$ value of spruce wood would increase by 2% and its $Q_L^{-1}$ value would decrease by 2% during 2000 years of aging at $20 \, ^{\circ}C$ and 63–81% RH. That is, the acoustic conversion efficiency of wood can be slightly improved by natural aging over centuries, when the wood is kept at moderate RH levels.

Those changes are qualitatively similar to the effects of seasoning, but less than those due to seasoning, which reduces $Q_L^{-1}$ by 20% as shown in FIG. 4. Therefore, it is reasonable that violin makers prefer seasoning for years or a few decades rather than long-term aging over centuries (Carlier et al., 2015).

V. EVALUATION OF SEASONING EFFECT

Because the seasoning effect disappears once they undergo moistening, the vibrational properties of seasoned or aged wood are expected to irreversibly change once exposed to humid conditions. Therefore, the degree of seasoning can be evaluated by comparing the vibrational properties of wood before and after the moistening. Table 2 shows the vibrational properties of new and aged wood specimens. No correlation was recognized between the vibrational properties and seasoning time (correlation coefficient $\leq 0.07$).
because the effects of seasoning and aging were masked by numerous original variations in wood properties.

TABLE II. Average values ± standard deviation of moisture content (MC), dynamic Young’s modulus ($E_L$), sound velocity ($V_L$), internal friction ($Q_L^{-1}$), and acoustic conversion efficiency (ACE$_L$) of wood samples at 20 °C and 60% RH before moistening treatment ($V_0$).

<table>
<thead>
<tr>
<th>Seasoning time (year)</th>
<th>$n$</th>
<th>Method</th>
<th>MC (%)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$E_L$ (GPa)</th>
<th>$V_L$ (m/s)</th>
<th>$Q_L^{-1}\times 10^3$</th>
<th>ACE$_L$ (m$^4$/s kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0</td>
<td>I</td>
<td>11.7±0.3</td>
<td>474±8</td>
<td>14.7±0.4</td>
<td>5572±58</td>
<td>5.9±0.2</td>
<td>1984±84</td>
</tr>
<tr>
<td>S1</td>
<td>3</td>
<td>II</td>
<td>11.3±0.1</td>
<td>370±8</td>
<td>9.1±0.3</td>
<td>4973±77</td>
<td>7.7±0.3</td>
<td>1746±77</td>
</tr>
<tr>
<td>S2</td>
<td>5</td>
<td>II</td>
<td>10.9±0.4</td>
<td>422±14</td>
<td>12.4±0.9</td>
<td>5415±111</td>
<td>5.9±0.3</td>
<td>2170±117</td>
</tr>
<tr>
<td>S3</td>
<td>7</td>
<td>II</td>
<td>10.8±0.3</td>
<td>489±21</td>
<td>12.2±1.5</td>
<td>5001±247</td>
<td>6.5±0.5</td>
<td>1583±182</td>
</tr>
<tr>
<td>S4</td>
<td>23</td>
<td>II</td>
<td>10.9±0.2</td>
<td>486±13</td>
<td>11.5±0.7</td>
<td>4868±105</td>
<td>6.2±0.3</td>
<td>1620±95</td>
</tr>
<tr>
<td>S5</td>
<td>28</td>
<td>II</td>
<td>11.7±0.2</td>
<td>418±5</td>
<td>8.8±0.4</td>
<td>4583±127</td>
<td>6.3±0.0</td>
<td>1752±73</td>
</tr>
<tr>
<td>S6</td>
<td>38</td>
<td>II</td>
<td>11.3±0.4</td>
<td>459±21</td>
<td>12.3±1.3</td>
<td>5170±174</td>
<td>6.4±0.2</td>
<td>1770±47</td>
</tr>
<tr>
<td>S7</td>
<td>43</td>
<td>II</td>
<td>10.8±0.3</td>
<td>553±34</td>
<td>15.4±1.7</td>
<td>5267±211</td>
<td>5.9±0.5</td>
<td>1618±170</td>
</tr>
<tr>
<td>S8</td>
<td>48</td>
<td>II</td>
<td>12.0±0.1</td>
<td>393±3</td>
<td>10.2±0.3</td>
<td>5097±77</td>
<td>6.0±0.4</td>
<td>2176±166</td>
</tr>
<tr>
<td>S9</td>
<td>103</td>
<td>II</td>
<td>10.9±0.1</td>
<td>426±26</td>
<td>11.4±1.5</td>
<td>5172±270</td>
<td>6.1±0.5</td>
<td>1994±228</td>
</tr>
<tr>
<td>S10</td>
<td>113</td>
<td>II</td>
<td>11.1±0.3</td>
<td>515±33</td>
<td>11.8±1.2</td>
<td>4785±127</td>
<td>7.3±0.5</td>
<td>1284±109</td>
</tr>
<tr>
<td>S11</td>
<td>120</td>
<td>II</td>
<td>11.5±0.1</td>
<td>528±29</td>
<td>14.8±1.7</td>
<td>5298±181</td>
<td>7.0±1.2</td>
<td>1471±252</td>
</tr>
<tr>
<td>S12</td>
<td>178</td>
<td>II</td>
<td>11.8±0.3</td>
<td>415±17</td>
<td>9.3±1.5</td>
<td>4737±316</td>
<td>6.9±0.6</td>
<td>1675±217</td>
</tr>
<tr>
<td>S13</td>
<td>238</td>
<td>II</td>
<td>11.5±0.3</td>
<td>418±8</td>
<td>10.9±0.4</td>
<td>5119±117</td>
<td>6.3±0.5</td>
<td>1962±245</td>
</tr>
<tr>
<td>S14</td>
<td>302</td>
<td>II</td>
<td>10.7±0.2</td>
<td>477±15</td>
<td>15.0±0.7</td>
<td>5613±143</td>
<td>6.0±0.6</td>
<td>1966±192</td>
</tr>
<tr>
<td>S15</td>
<td>318</td>
<td>II</td>
<td>11.3±0.6</td>
<td>458±16</td>
<td>11.3±1.4</td>
<td>4963±302</td>
<td>6.6±0.7</td>
<td>1660±228</td>
</tr>
</tbody>
</table>

a) Number of samples tested; b) combination of exciter and detector shown in FIG. 1; c) ACE$_L$ is defined as $V_LQ_L/\rho$.

TABLE 3 and FIG. 7 show the changes in wood properties from repeated moistening treatment. The new wood showed little change in MC, $V_L$, and $Q_L^{-1}$ after the moistening. This fact suggests that the seasoning effect was small in the recently cut wood. In contrast, seasoned and aged wood specimens showed a significant decrease in $V_L$ and increase in $Q_L^{-1}$ after the first moistening treatment, and no remarkable
change in their properties occurred after the second moistening treatment. This indicates that the temporary
effect of seasoning (increase in $V_L$ and decrease in $Q_L^{-1}$) disappeared when the wood was exposed to humid
condition, in which the wood polymers recovered their original conformation.

**TABLE III.** Average values ± standard deviation of changes in wood properties by repeated moistening
treatment.

<table>
<thead>
<tr>
<th>Seasoning time (year)</th>
<th>$n^a$</th>
<th>Changes in MC (%)$^b$</th>
<th>Changes in $E_i$ (%)$^c$</th>
<th>Changes in $V_L$ (%)$^d$</th>
<th>Changes in $Q_L^{-1}$ (%)$^e$</th>
<th>Changes in ACE% (%)$^f$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$V_0$ to $V_1$</td>
<td>$V_0$ to $V_2$</td>
<td>$V_0$ to $V_1$</td>
<td>$V_0$ to $V_2$</td>
<td>$V_0$ to $V_1$</td>
</tr>
<tr>
<td>N 0</td>
<td>20</td>
<td>0.1±0.1</td>
<td>0.2±0.0</td>
<td>0.0±0.2</td>
<td>-0.2±0.2</td>
<td>0.0±0.1</td>
</tr>
<tr>
<td>S1 3</td>
<td>8</td>
<td>-0.2±0.1</td>
<td>0.1±0.1</td>
<td>-0.8±0.2</td>
<td>-1.2±0.1</td>
<td>-0.3±0.1</td>
</tr>
<tr>
<td>S2 5</td>
<td>8</td>
<td>0.5±0.1</td>
<td>0.8±0.0</td>
<td>-1.7±0.3</td>
<td>-2.6±0.3</td>
<td>-1.1±0.2</td>
</tr>
<tr>
<td>S3 7</td>
<td>20</td>
<td>0.6±0.2</td>
<td>0.8±0.1</td>
<td>-1.0±0.5</td>
<td>-0.8±0.6</td>
<td>-0.8±0.3</td>
</tr>
<tr>
<td>S4 23</td>
<td>20</td>
<td>0.4±0.1</td>
<td>0.6±0.1</td>
<td>-0.8±1.3</td>
<td>-1.1±1.5</td>
<td>-0.6±0.6</td>
</tr>
<tr>
<td>S5 28</td>
<td>2</td>
<td>0.3±0.0</td>
<td>0.4±0.0</td>
<td>-1.0±0.1</td>
<td>-1.3±0.4</td>
<td>-0.6±0.0</td>
</tr>
<tr>
<td>S6 38</td>
<td>5</td>
<td>0.2±0.0</td>
<td>0.3±0.1</td>
<td>-0.8±0.3</td>
<td>-1.5±0.2</td>
<td>-0.5±0.2</td>
</tr>
<tr>
<td>S7 43</td>
<td>8</td>
<td>0.0±0.0</td>
<td>0.1±0.0</td>
<td>-1.0±0.2</td>
<td>-0.6±0.4</td>
<td>-0.5±0.1</td>
</tr>
<tr>
<td>S8 48</td>
<td>8</td>
<td>-0.1±0.1</td>
<td>0.0±0.2</td>
<td>-1.3±0.5</td>
<td>-1.7±0.3</td>
<td>-0.6±0.3</td>
</tr>
<tr>
<td>S9 103</td>
<td>19</td>
<td>-0.2±0.1</td>
<td>0.1±0.1</td>
<td>-1.4±0.5</td>
<td>-1.4±0.9</td>
<td>-0.7±0.2</td>
</tr>
<tr>
<td>S10 113</td>
<td>17</td>
<td>-0.1±0.0</td>
<td>0.1±0.1</td>
<td>-2.1±0.5</td>
<td>-2.3±0.3</td>
<td>-1.0±0.3</td>
</tr>
<tr>
<td>S11 120</td>
<td>7</td>
<td>0.0±0.1</td>
<td>0.2±0.1</td>
<td>-1.0±1.2</td>
<td>-1.8±0.7</td>
<td>-0.5±0.6</td>
</tr>
<tr>
<td>S12 178</td>
<td>14</td>
<td>-0.2±0.1</td>
<td>0.1±0.1</td>
<td>-1.5±0.6</td>
<td>-1.0±0.6</td>
<td>-0.6±0.3</td>
</tr>
<tr>
<td>S13 238</td>
<td>5</td>
<td>0.1±0.1</td>
<td>0.1±0.1</td>
<td>-1.5±0.8</td>
<td>-0.2±0.9</td>
<td>-0.8±0.4</td>
</tr>
<tr>
<td>S14 302</td>
<td>16</td>
<td>-0.1±0.1</td>
<td>0.3±0.2</td>
<td>-1.4±0.2</td>
<td>-1.8±0.4</td>
<td>-0.6±0.1</td>
</tr>
<tr>
<td>S15 318</td>
<td>9</td>
<td>0.2±0.0</td>
<td>0.3±0.0</td>
<td>-0.7±0.4</td>
<td>-1.0±0.5</td>
<td>-0.5±0.2</td>
</tr>
</tbody>
</table>

a) Number of samples tested; b) amount of change in percent; c) percentage rate of change.
Judging from the degree of seasoning (changes in $V_L$ and $Q_L^{-1}$), the seasoning was thought to be completed within several years, and no further effect is expected by prolonged seasoning over centuries. Therefore, it is logical that violin makers think much of the initial seasoning for a few years rather than long-term aging over centuries (Carlier et al., 2015). Some samples (e.g. S7, 10–12) showed relatively smaller changes in $V_L$ and $Q_L^{-1}$ after the moistening. Although their moisture sorption histories are unknown, these lumber may have experienced humid conditions (humid place or long humid season), and therefore, the seasoning effects were partly lost. In any
case, the acoustic quality of seasoned and aged wood is irreversibly degraded when exposed to humid
conditions. To maintain the quality of seasoned and aged instruments, it is advisable to keep them dry.

Finally we need to mention the limitation of the present result. In this paper, we focused on the vibrational
properties in L direction as the first step. However, that is not enough to describe the acoustic behavior of
wooden musical instruments, because the wood is an anisotropic material. For clearer understanding of the
seasoning effects, the other wood properties in R and T directions should be clarified in the future.

VI. CONCLUSIONS

When green wood was dried and conditioned at 20 °C and 60% RH, its sound velocity ($V_L$) gradually
increased and its internal friction ($Q_L^{-1}$) decreased significantly over 6 months, whereas its moisture content
equilibrated within 2 days. That “seasoning effect” was explained using the physical aging and stress
relaxation of wood polymers. The seasoning effect was lost after the seasoned wood was moistened and
reconditioned. It is advisable not to expose the seasoned instrument to humid conditions to keep its
improved acoustic quality. The effects of seasoning were greater than those of long-term aging, while
involving irreversible chemical changes. This fact coincides with the empirical knowledge of violin makers
that seasoning is more important than long-term aging over centuries.

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REFERENCE


