Compression Wood Quality Assessment with Different Ultrasound Wave Parameters in Radial Direction of Spruce Disks

Mohammadali SAADATNIA*1 Kambiz POURTAHMASI
Mohammadhadi MORADIAN1 Ladan POURSARTIP 1

1Wood and Paper Department, Khatam Alanbia University of Technology; Behbahan, Iran; Phone/fax: +98 (61) 52721662; e-mail: msaadatnia92@gmail.com, moradian_h@yahoo.com, lpoursartip@yahoo.com
2Wood and Paper Department, University of Tehran; Karaj, Iran; e-mail: pourtahmasi@ut.ac.ir

Abstract

In this investigation, the experimental determinations of different wave parameters and anatomical properties variations were carried out in the radial direction of normal and compression wood of spruce (Picea abies) disks. To prepare samples, 3 disks with thickness of 10 cm were taken at breast height of the stem. The experiments were conducted on cubic specimen with dimensions of 2×2×10 cm3 taken in distance of 4, 8 and 12 cm toward the bark. The results showed that compression wood had lower acoustical constants comparing with normal wood. Furthermore, phase velocity greatly increased in longitudinal direction of compression wood but the variations of group velocity and acoustic radiation were not pronounced especially in transversal directions. Finally for both normal and compression wood the acoustic radiation and the phase velocity were correlated more strongly with density. It could be estimated that the outer samples are better for construction materials need more strength.

Keywords: Quality assessment, compression wood, ultrasound, spruce

1. Introduction

Ultrasonic technique, a nondestructive test, is being widely used to evaluate building construction materials like wood and wood products. Considering the heterogeneous and orthotropic structure of wood, successful quality assessment is difficult when compared to isotropic materials. This problem is more pronounced when a tree ages and gets thicker in diameter because by adding annually growth rings, the wood inhomogeneity increases. In response to unsuitable conditions, reaction wood (known as compression wood in softwoods) is formed in standing trees. Compression wood is completely different from normal wood in physical and mechanical behaviors. For example it can dramatically wrap and twist as well as becomes dangerous under applied stress, so it is better to avoid using parts containing compression wood. A usual way of detecting compression wood is visual inspection suggested for species with colorful reaction woods[1]. Since the anatomical microscopic observation is time consuming, researchers have strived to apply nondestructive methods to acoustically qualify and characterize compression wood. But an accurate estimation of mechanical behavior of compression wood by ultrasound technique needs simultaneous views on its structure and different wave parameters. Previous scientific reports show that the most investigators were interested in using sound velocity to differentiate reaction wood from normal wood and some of them haven’t successfully attained desired results. For example Nyström and Kline (2000) reported that X-ray information was not reliable to automatically classify compression wood [2]. The early wood and late wood deposition in annual rings which create acoustic impedance and stop bands for propagated wave, can affect
sound velocity in Spruce and pine disks. By applying this method, the line between juvenile and mature wood was successfully demarcated [3]. In addition, a remarkable continuous increasing of wave velocity observed from the pith to the bark in soft woods was reported by some researchers [4,5]. Hassegawa et al., (2011) introduced three main factors (fiber orientation, wall thickness as well as microfibril angle) which affect acoustical behavior of wood. But the velocity of wave is not enough for studying acoustical behavior of wood. The sensitivity of more wave parameters should be examined for precise evaluation of physical, mechanical as well as acoustical properties of wood [6]. Saadat Nia et al, (2011) used various wave parameters to differentiate the acoustical properties of reaction and normal woods. They observed the anatomical features are the most important factor affect wave propagation through reaction wood samples [7]. In another research, the effect of tension wood was studied on different wave parameters in transversal direction of aspen disks. The results showed that wave velocity and acoustic radiation were significantly varied in distance between pith and bark. These variations were less important in radial and tangential of orthotropic directions of cubic samples [8]. Thus, the aim of the present research is to study the effect of growth rings and the distribution of compression wood and normal wood of spruce disks on different parameters of wave propagated in different orthotropic directions. Also the interaction between different wave parameters (phase velocity, group velocity, attenuation coefficients, and acoustic radiation) and compression wood structures, resulting from its specific gravity and anatomical elements during the life of the tree, would be interested. We also would like to find out if this biological defect (compression wood formation) is enough important to be characterized and differentiated from normal wood by analyzing ultrasonic signal changes.

2. Experimental procedure

2.1 Species selection

Three disks of spruce (Picea abies) with 10 cm thickness were taken from freshly cut tree. Spruce as a resonant wood is used in acoustical research. [9]. This species with a uniform and homogenous tissue restricted to 95% of longitudinal tracheids, is sensitive to the formation of compression wood [10]. Compression wood can be visually detected by naked eye as well as instrumentally by anatomical experiments and consequently the variations can also easily be understood [11]. To prevent moisture decrease, the samples were kept in plastic cover. An additional disk with 5 cm thickness was prepared for physical and anatomical experiments. Figure 1 shows the distance between pith and bark was divided to 4 cm in every disk. More than 80 cubic samples (2×2×10, radial × tangential × longitudinal) were taken from all disks. Samples with compression wood were finally separated from normal wood by anatomical and visual inspection.

2.2 Equipment setup

The electrical signal was sent through the cubic samples by direct transmission technique. For this purpose, the rolling transducers with a frequency bandwidth centered on 300 kHz transmitted signals with wavelength of 5 and 15 mm in transversal and longitudinal directions of samples respectively. The specific elastomer covered probe wheels was used as a coupling media. The refined processing signal was then computed to measure wave parameters (phase velocity, group velocity, attenuation coefficient as well as acoustic radiation). More details
can be found in SaadatNia et al, (2011) research [7]. All cubic samples were conditioned at 20 °C and 65% relative humidity to reach average moisture content of 12%.

Figure 1. Schematic diagram for sampling procedure from the tree

3. Results

Figure 2 (left) shows the radial variations of phase and group velocities along three main orthotropic directions, from the pith to the bark, for normal and compression wood. An increasing tendency of phase velocity was observed in the longitudinal direction of normal and compression wood. Besides, the values measured for compression wood were lower than those for normal wood. For normal wood the minimum value of 3700 m/s was observed near the pith and reached a value of 4300 m/s toward the outside near the bark. While for compression wood, phase velocity varied from 3000 to 3500 m/s in distance between pith and bark. This phenomenon was not evident for radial direction and had constant value of 1400 m/s for both normal and compression wood. The tangential direction showed a high value of 1300 m/s in compression wood and that was greater than a value of 900 m/s for normal wood. Figure 2 (right) compares the group velocity variations, as an index of energy flow, in different directions of normal and compression specimens. Slow increase of group velocity, comparing with the trend of phase velocity, exhibited that the interaction between spruce structure and group velocity is insignificant. For normal and compression wood, these values kept constant around 550 and 453 m/s in radial and tangential directions respectively. The transversal variations of attenuation coefficients and acoustic radiation were illustrated in Figure 3 through longitudinal, radial and tangential directions for both normal and compression wood. In contrast with what observed for phase velocity, there is a tendency for attenuation coefficients to decrease from the pith toward the bark. The minimum value of attenuation coefficient (137 dB/m) was measured for longitudinal direction of compression wood, (left) while the given value was recorded around 140 dB/m in longitudinal direction of normal wood. On the other hand, for radial direction, the maximum value of attenuation coefficient was found 300 dB/m for specimen near the pith and as soon attained a value of 245 dB/m for specimen near the bark. In addition, the attenuation coefficient of normal and compression wood in tangential direction had values of 450 and 253 dB/m and kept
decreasing toward the outside and reached values of 275 and 160 dB/m respectively. The radial variation of acoustic radiation was not significant in distance between pith and bark and had constant values of 11.4 and 8.9 for normal and compression wood respectively. However, the acoustic radiation in longitudinal direction of compression wood was significantly higher than that measured for normal wood. The values of acoustic radiation in radial and tangential directions show the given orthotropic directions had no significant effect on this parameter. In other words, the radial and tangential directions are not reliable for detecting compression wood by using this parameter of wave.

Figure 2. Transversal variations of phase velocity (left) and group velocity (right) in distance between pith and bark through orthotropic directions of normal and compression wood (NW: normal wood, CW: compression wood, L: longitudinal, R: radial and T: tangential directions)

Figure 3. Transversal variations of attenuation coefficient (left) and acoustic radiation (right) in distance between pith and bark through orthotropic directions of normal and compression wood (NW: normal wood, CW: compression wood, L: longitudinal, R: radial and T: tangential directions)
Regression analyses presented in Table 1 show the correlation coefficients between different ultrasonic wave parameters and wood density for both compression and normal wood. Since the relationship between wave parameters and wood density was not significant in radial and tangential directions, we have just presented the correlations in the longitudinal direction (Fig 4). A negative correlation was found between acoustic radiation and density, which was highly significant at 1% confidence level ($r = -0.95$, $-0.82$ for normal and compression wood respectively). The regression results show that the linear regression model between density and phase velocity was also significant at 1% confidence level ($r = -0.78$) for normal wood while the weaker relationship was observed between phase velocity and compression wood density where it was significant at 5% confidence level and not strong enough ($r = -0.50$). In contrast, group velocity and attenuation coefficient had no significant correlation with density for normal wood specimen while these wave parameters significantly correlated with the density of compression wood ($r = -0.65$, $r = 0.60$, group velocity and attenuation coefficient respectively).

Table 1. Correlation coefficients between ultrasonic wave parameters and wood density of normal and compression wood

<table>
<thead>
<tr>
<th></th>
<th>$V_p$</th>
<th>$V_g$</th>
<th>$\alpha$</th>
<th>AR</th>
<th>$\rho$</th>
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<tr>
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<tr>
<td>$V_p$</td>
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<td>0.92**</td>
<td>-0.78**</td>
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<tr>
<td>$V_g$</td>
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<td>0.24</td>
<td>-0.14</td>
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<tr>
<td>$\alpha$</td>
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<td>0.14</td>
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<tr>
<td>AR</td>
<td></td>
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<td>-0.95**</td>
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<tr>
<td>$V_p$</td>
<td>0.49</td>
<td>-0.14</td>
<td>0.82**</td>
<td>-0.50*</td>
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<tr>
<td>$V_g$</td>
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<td>-0.65**</td>
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<tr>
<td>$\alpha$</td>
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<td>0.60*</td>
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<tr>
<td>AR</td>
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<td>-0.82**</td>
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$V_p$: phase velocity, $V_g$: group velocity, $\alpha$: attenuation coefficient, AR: acoustic radiation, $\rho$: Density

(*: significant at 1%, **: significant at 5%)
4. Discussion

For a better understanding of the variations of different wave parameters with increase the distance between pith and bark, anatomical and physical properties of normal and compression wood should be considered (Figure 5). Spruce has a uniform and homogenous tissue with 95% of longitudinal tracheids with length of 1.5 to 4.5 mm which provide continuous path for wave propagation. It is of interest to compare this continuous path in longitudinal direction with transversal directions where the annual rings constitute early wood with lighter density and late wood with greater density. This inhomogeneity in wood structure produces stop bands for propagated wave and makes a complicated situation for wave movement in radial and tangential directions [12,13]. This shows why the maximum values obtained for longitudinal direction. Fig5 Presented transverse variations of anatomical and physical properties of normal and compression wood while tree ages and gets bigger in diameter. It can be obviously seen, in early age of tree, juvenile wood is produced with shorter tracheids length, lower density was well as greater microfibril angle but as time goes by, cambium layer produced mature wood with longer elements, thicker wall as well as higher density. These changes emphasize a kind of improvement in cellular development. The average values of tracheids length was 2.65 mm for compression wood while this value was 3.06 mm for normal wood. In contrast, wall thickness and wood density were 6.85 µ and 553
kg/m$^3$ respectively for compression wood and higher than those measured for normal wood (6.01 $\mu$ and 385 kg/m$^3$). The important role of anatomical changes on radial variations of wave velocity was illustrated by Hassegawa et al (2011) [4]. In an isotropic material, group velocity as an index of energy flow, is closely related to phase velocity [14]. But in wood as an orthotropic and inhomogeneous material, the values of group velocity are completely different from phase velocity. The lower group velocity values observed in compression wood were due to the shorter tracheids and the higher density comparing with normal wood. The trend of acoustic radiation for normal and compression wood clearly shows that this parameter is not sensitive to the position in spruce disk and had a constant value while increasing distance between pith and bark. Since the acoustic radiation is the ratio of velocity to density, the lower values of that were obtained because of the higher density in compression wood (43% more than normal wood). Wave attenuation is also sensitive to the fiber orientation, growth rings as well as the microfibril angel. The anisotropic and orthotropic structure of wood greatly affects the attenuation of wave even more than phase velocity. So this behavior cusses a complicated interaction between wood properties and attenuation coefficient. For this reason some researchers believe that attenuation coefficient is not a good parameter for analyzing acoustical behavior and more various wave parameters should be considered [6,15]. Probably an increase in density and modulus of elasticity of compression wood affects anisotropic behavior of wood samples and decreased attenuation coefficient values in radial and tangential directions. Our results clearly show that acoustic radiation and phase velocity were more correlated with density in comparison with group velocity and attenuation coefficient. This result can logically be explained because group velocity and attenuation of wave are directly related to the energy flow of propagated wave through the medium and energy index can weakly be affected by wood properties. As depicted, acoustic radiation and phase velocity decreased linearly with increasing density for both compression and normal wood but the interaction between density and wave parameters is not clear. Some researcher found a negative correlation between density and sound velocity while the others reported a positive relationship between them. Mishro observed no significant relationship between wood density and wave velocity[16,17,18,19]. However Schwarze et al, who investigated on acoustical behavior of spruce, found a negative relationship not only between density and wave speed but also between wood density and acoustic radiation[11].
Figure 5. Radial variations of wood properties from the pith to the bark in normal and compression wood

5. Conclusion
Our experimental results were looking for the trend of variation of different wave parameters in distance between pith and bark for both normal and compression wood of spruce samples. Phase velocity was greatly sensitive to the position of samples in spruce disks. The maximum values were found near the bark and the minimum values measured for samples around the pith. By using empirical relation between dynamic modulus and sound velocity \( E = \rho v^2 \), it could probably be estimated that the outer samples are better for construction materials need more strength. Most of wave parameters were significantly unaffected by wood properties in radial and tangential directions. To detect compression wood and assess wood quality, measuring wave parameters in transversal orthotropic direction is not reliable. It was also drawn that acoustical behavior of compression wood were weaker than normal wood. Acoustic radiation and phase velocity strongly correlated with density while wave parameters based on the index of energy flow (group velocity and attenuation coefficient) not well correlated with wood characteristics. Finally it is suggested to avoid lumbers containing compression wood.
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References


