Predicting Wood Quality of Green Logs by Resonance Vibration and Stress Wave in Plantation-Grown *Populus* ×*euramericana*

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Abstract

A cost-effective estimation of wood quality of hardwood green logs is needed. The purposes of this study were to investigate and compare two nondestructive acoustic methods to predict the wood quality of green logs from a poplar I-72 (*Populus* ×*euramericana* cv. I-72/58 ''San Martino'') plantation. After log measurements, small clear wood specimens were cut and air dried to 12 percent moisture content. The static bending modulus of elasticity (MOE) of small clear wood specimens was about 15 and 20 percent greater than the dynamic MOE of green logs based on resonance vibration (E_{fr}) and stress wave (E_{sw}). However, good correlations (R) between E_{fr} and E_{sw} of logs and bending MOE of 0.806 and 0.848 ($P < 0.001$), respectively, were observed. Significant correlations were also found between the E_{fr} and E_{sw} of logs and the modulus of rupture and compressive strength parallel to grain (σ_c) of small clear wood specimens ($P < 0.001$). The results indicate that both acoustic techniques were effective predictors of wood quality, although the stress wave method was found to be more accurate and reliable than the resonance vibration method. The longitudinal changes of strength properties with tree height could be tracked by these two methods.

Nondestructive evaluation (NDE) techniques have been developed during the last several decades for a wide range of materials and have been extensively applied to evaluate the quality of different kinds of wood and wood products (Kaiserlik and Pellerin 1977, Resch 2005). Recent acoustic-based NDE research has focused mainly on determining whether portable and cost-effective acoustic techniques can be developed to estimate the quality of wood from logs and standing trees (Brashaw et al. 2009).

China currently has the largest area of fast-growing plantation forests in the world, with an estimated area of 61.7 million hectares (Chinese State Forestry Administration 2010). The main supply of wood shifted from natural forests to plantation forest stock after 1998, when the Natural Forest Conservation Program was implemented in China. To advance the understanding of the plantation quality and the potential for use in value-added products, it is necessary to assess how wood properties relevant to such products are impacted by the wood growth characteristics. Application of effective acoustic NDE techniques to predict the growth characteristics from plantation wood is a crucial step in improving the plantation quality and optimizing wood use in the forest products industry.

For conifer species, several previous studies have shown the useful relationship not only between the acoustic-based modulus of elasticity (MOE) of logs and the static bending properties of lumber (Aratake et al. 1992, Ross et al. 1997) or small specimens (Yin et al. 2010) cut from logs, but also between the acoustic-based MOE of standing trees and the elasticity properties of logs (Iki et al. 2006, Wang et al. 2007, Ishiguri et al. 2008), lumber (Ishiguri et al. 2008), or small specimens (Wang et al. 2001) cut from standing trees. To date, few studies have focused on the acoustic prediction

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of wood quality from logs or standing trees of hardwood in comparison with softwood species (Wang et al. 2004). Poplar is one of the most important commercial hardwood plantation species in China. Timber use from poplar plantations plays an important role in alleviating the pressure of meeting the rapidly increasing demands for wood products because it is highly valued for a diverse range of products. However, a cost-effective estimation of wood quality is lacking, and consequently there are wide disparities between the estimated value and the actual value when the logs are harvested and used by the wood processing industry.

Therefore, the first purpose of this study was to assess whether acoustic methods, in general, can predict the strength properties of logs from a plantation of poplar I-72 (*Populus* ×*euramericana* cv. I-72/58 ''San Martino''), which is one of the major poplar species prevailing in the bottomland area of the Yangzi River of southern China. Two acoustic methods based on resonance vibrations and stress waves were examined. The second purpose was to compare the two acoustic methods' ability to accurately predict log quality attributes for optimizing value-added wood applications. The dynamic elastic properties were studied by two methods: (1) dynamic MOE based on resonance vibration (E_{fr}) and (2) dynamic MOE based on stress wave (E_{sw}). The relationships between E_{fr} and E_{sw} for logs and the static bending MOE, the modulus of rupture (MOR), and compressive strength parallel to grain (σ_c) of small clear samples cut from the same logs are discussed in this article.

Materials and Methods

Materials

The experimental site of a 16-year-old I-72 poplar plantation with a planting intensity of one tree per 3 by 10-m plot is located at the Nangeng forestry farm (30°50′N, 169°90′E, and 15-m altitude), Anqing city, in the Anhui Province of China. A total of 15 healthy sample trees were collected (Table 1). After noting the north- and the south-facing stem surfaces, each sample tree was cut into four logs about 2.4 m in length at heights of 1.3, 3.7, 6.1, and 8.5 m from ground level. Two logs were abandoned because of visual defects (decay and large knots). The ends of each log were coated with pitch to minimize moisture loss. After all 58 marked logs were conveyed to the laboratory in Beijing, one 150-mm-thick disk, to be used for fresh wood moisture content (MC) measurement, was taken from the butt of each log. The green density of the remaining 2.20-m length of log was determined from the bulk weight and volume and used for the calculation of dynamic elasticity properties.

Measurement of dynamic elasticity properties

Two nondestructive methods for estimating dynamic elasticity properties were applied to the green logs. In brief, a hammer was used to excite the resonance vibration of the log in the longitudinal direction; the fundamental resonance frequency was then measured by a fast Fourier transform analyzer (AD-3542, 10-Hz resolution; Fig. 1a). Equation 1 was used to determine E_{fr}.

$$E_{fr} = 4 \times \rho \times l^2 \times f^2 \qquad (1)$$

Table 1.—Growth characteristics of 15 sample trees.[a]

Characteristic	Mean ± SD
Tree height (m)	23.8 ± 1.22
Clean length (m)	11.2 ± 1.96
DBH (cm)	33.6 ± 2.12
MC (%)	
Sapwood	113 ± 34.9
Heartwood	174 ± 27.3

[a] DBH = diameter at breast height; MC = moisture content.

where E_{fr} = dynamic modulus of elasticity of log based on resonance vibration, ρ = green density of log, l = length of log, and f = fundamental resonance frequency of log.

For the stress wave method, two spikes, each instrumented with accelerometers and connected to the stress wave equipment (Fakopp FRS-06/00, 1-μs resolution), were nailed in the xylem (sapwood) of the north and south faces at a 45° angle with the longitudinal axis of the log, as shown in Figure 1b, to simulate the measuring state of the standing tree. The head of one spike was then struck with a hammer to create a longitudinal stress wave. The propagation velocity of the stress wave in the log was then detected by the accelerometer on the other spike, and the E_{sw} of the log was determined using Equation 2. The average value determined from striking the spike on the north and south faces was assumed to be the E_{sw} of the log based on the stress wave approach.

$$E_{sw} = \rho \times v_{sw}^2 \qquad (2)$$

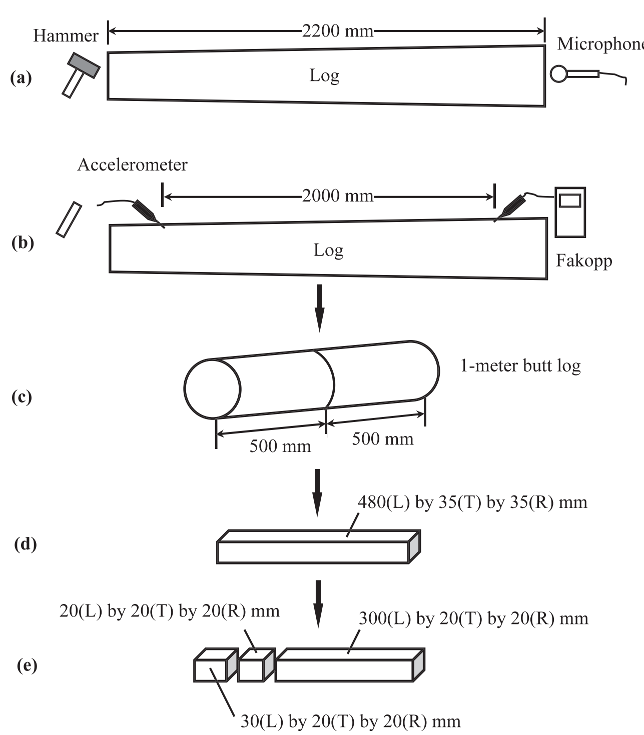

Figure 1.—Acoustic and static experimental setup. (a) Measurement of resonance vibration, (b) measurement of stress wave, (c) sawing sketch for extracting 1-m log, (d) extraction of rough small specimen, and (e) sawing of small clear specimen.

where E_{sw} = dynamic modulus of elasticity of the log based on stress wave, ρ = green density of the log, and v_{sw} = stress wave velocity propagated in the log.

Measurement of density and strength properties

After completing the measurements of dynamic elasticity properties, one 1-m butt section (Fig. 1c) was obtained from the log for preparation of a small clear specimen. Each butt section was then cut into two halves along the east–west direction. Using a cutting scheme similar to the one described in Yin et al. (2010), as many small rough specimens (35 by 35 by 480 mm, tangential by radial by longitudinal; Fig. 1d) as possible were sawn from all halves of the butt section. A total of 1,125 pieces of small rough specimens were obtained for further testing. After 4 months of air drying, the small rough specimens were planed and finished into 20 by 20 by 400-mm pieces. From these, a total of 443 pieces free from any visual defects were cut into three small clear wood specimens (Fig. 1e): (1) one 20 by 20 by 300 mm for bending testing, (2) one 20 by 20 by 20 mm for air-dried density measurement, and (3) one 20 by 20 by 30 mm for compression testing. Because of the limited log diameter and the presence of knots and other defects, the number of small clear wood specimens obtained from each log varied from 5 to 12 pieces. The small clear wood specimens were then conditioned to an equilibrium MC of approximately 12 percent by storing in a constant environment room maintained at 20°C and 65 percent relative humidity. The log property was taken to be the average value from across all the small specimens cut from the same log. This average value was used for comparing the two NDT methods.

Strength properties testing on the small clear wood samples was conducted according to national Chinese Standards (China State Bureau of Technical Supervision [CSBTS] 1991a). The GB1936.2 standard third-point loading method over a 240-mm span was used to determine the static bending MOE Two load points spaced 80 mm apart were set between two supports. A deflectometer mounted on an alloy aluminum frame was suspended from the specimen neutral axis over the outer supports to measure the midspan deflection relative to the support points. However, for MOR testing, the GB1936.1 standard center point loading was used over the same 240-mm span (CSBTS 1991b). Compressive strength (σ_c) was measured following the GB1935 standard (CSBTS 1991c). Following destructive testing, a full cross-section block was immediately cut near the failure location from each specimen. MC was then determined by the oven-drying method, and the results were used to adjust, if necessary, the bending and compression testing results to that at 12 percent MC.

Data statistical analysis

One-way analysis of variance (ANOVA) was used for comparison analyses. Correlation coefficients between E_{sw} and E_{fr} of log and static strength properties (MOE, MOR, and σ_c) of small clear wood specimens were also calculated to examine their relationships. Statistical analysis was performed using the SAS programs (SAS Institute Inc. 9.0).

Results and Discussion

Acoustic evaluation on green logs

For both sapwood and heartwood in green logs, the individual and average MCs (Table 1) were much higher than the fiber saturation point (>30%). The percent difference between the average MCs of heartwood and sapwood was 54 percent. As shown in Table 2, the coefficient of variation for the average E_{fr} and E_{sw} in green logs was 19.3 and 17.3 percent, respectively. Although the average value of E_{fr} was about 4.2 percent larger than that of E_{sw}, the difference between the dynamic MOE of logs determined by these two acoustic methods was not statistically significant at the 0.05 level. It was observed that the mean v_{sw} from the north segment was 1.2 percent greater than that from the south and that the mean E_{sw} from the north segment was 2.3 percent greater than that from the south; however, these differences were also not statistically significant ($P > 0.05$).

Static strength properties of small clear wood specimens

Table 3 summarizes the results of the air-dried density and strength properties of small clear wood specimens cut from logs. The average air-dried density had a 5.8 percent coefficient of variation. The average value of the bending MOE ranged from 6.01 to 14.6 GPa with a 20.8 percent coefficient of variation. It was observed that the average MOE obtained from static bending was approximately 15 and 20 percent greater than that from the resonance vibration method and the stress wave method, respectively. The ANOVA results showed that the differences between the bending MOE and dynamic MOE of logs by both of the acoustic methods were statistically significant ($P < 0.05$). The difference between the average bending MOE from small clear specimens and the E_{fr} of the log agreed with that from an earlier study (Yin et al. 2010).

However, the static MOE of the small clear wood specimens was found to be higher than the E_{sw} of green logs, a result inconsistent with the conifers in previous research (Wang et al. 2001, Yin et al. 2010). Contrary to the current study on poplar I-72, Yin et al. (2010) reported a significant variance between the average E_{fr} and E_{sw} in

Table 2.—Dynamic elasticity properties of 58 green logs.

Dynamic properties[a]	Mean ± SD
Green density (kg/m^3)	1,000 ± 75.4
f (Hz)	673 ± 53.5
E_{fr} (GPa)	9.64 ± 1.86
v_{sw} (m/s)	
N	3,087 ± 256
S	3,049 ± 230
N/S	3,068 ± 235
E_{sw} (GPa)	
N	9.35 ± 1.71
S	9.14 ± 1.62
N/S	9.25 ± 1.62

[a] f = the resonant vibration frequency; E_{fr} = dynamic modulus of elasticity based on resonant vibration; v_{sw} = stress wave velocity; E_{sw} = dynamic modulus of elasticity based on stress wave; N = north segment; S = south segment; N/S = average value of north and south segments.

Table 3.—Air-dried density and strength properties of small clear wood specimens.

Mechanical properties[a]	Sample size	Mean ± SD
Air-dried density (kg/m^3)		
N	219	488 ± 31.3
S	224	494 ± 30.9
N/S	443	491 ± 28.5
MOE (GPa)		
N	219	11.1 ± 2.47
S	224	11.1 ± 2.26
N/S	443	11.1 ± 2.31
MOR (MPa)		
N	219	83.0 ± 9.88
S	224	81.2 ± 9.32
N/S	443	82.1 ± 8.67
σ_c (MPa)		
N	219	42.3 ± 6.15
S	224	42.5 ± 5.72
N/S	443	42.4 ± 5.66

[a] MOE = modulus of elasticity based on static bending; MOR = modulus of rupture based on static bending; σ_c = compressive strength parallel to grain; N = north-facing segments; S = south-facing segments; N/S = average value of north- and south-facing segments.

green logs from a Chinese fir (*Cunninghamia lanceolata*) plantation and noted that E_{sw} had a much higher value than E_{fr} and static MOE. Gerhards (1975) reported an MC of between 15 and 150 percent a higher static bending MOE than E_{sw} for wood cut from the sapwood of a hardwood species sweetgum (*Liquidambar styraciflua*). This was attributed to the difference of the wood structure between hardwoods and softwoods; however, other studies showed much higher E_{sw} values than the bending MOE of air-dried small clear wood specimens of several hardwood species (Smulski 1991, Luo et al. 2008). Because of these inconsistencies, further study of more tree species is necessary to clarify the difference of dynamic elasticity properties between hardwoods and softwoods.

Moreover, Gerhards (1975) and Ross and Pellerin (1991) revealed that both v_{sw} and E_{sw} responded to wood MC increases below the intersection moisture content (IMC), defined as the MC level at which mechanical properties begin to change when drying from green conditions. The IMC differs from the fiber saturation point because of the combined influence of the mass of the water on the static and dynamic properties of the wood. When MC levels were above the IMC level, E_{sw} increased with MC levels, but v_{sw} remained nearly constant. It was observed that a much lower average MC was measured in the sapwood portion than in the heartwood of green logs of poplar I-72. The lower E_{sw} than E_{fr} and static MOE could be due to the MC in the sapwood portion being much closer to the IMC level than that in the heartwood portion of this species. Therefore, a relatively low value of E_{sw} was obtained when the propagation of stress waves was only collected in the sapwood portion in the present experiment, and a higher average E_{sw} would be obtained from measurements on both sapwood and heartwood.

It was found that there was no significant difference between the measurements of air-dried density, the bending MOE, MOR, and σ_c from the north and south segments of logs ($P > 0.05$). The result of bending MOE was consistent with the E_{sw} measured for the logs. The average value of bending MOR ranged from 62.4 to 102.5 MPa, with a 10.6 percent coefficient of variation, while the average σ_c ranged from 27.5 to 52.1 MPa, with a 13.3 percent coefficient of variation. Regression analyses suggested that the correlation coefficient ($R = 0.730$) between bending MOE and MOR of small clear wood specimens was highly significant at the 0.001 confidence level.

Relationship between dynamic and static strength properties

Regression analyses were applied to quantify the prediction of dynamic elasticity properties of green logs to strength properties of small clear wood specimens obtained from the logs. The relationships between the average value of E_{sw} measured on the north- and south- facing segments of the logs, the E_{fr} of the logs, and the bending MOE of small clear wood specimens are shown in Table 4 and Figure 2. The linear regression model between the E_{fr} of the logs and the MOE of small clear wood specimens taken from those same logs was significant at the 0.001 confidence level ($R = 0.806$). Moreover, a better relationship ($R = 0.848$) was observed between the E_{sw} of the logs and the MOE of small clear wood specimens from those logs (Table 4; Fig. 2b). This suggests that the stress wave method can provide a better prediction of static elasticity properties of the log than the resonance-based acoustic method in this work, although E_{sw} was measured in the xylem close to the log surface and E_{fr} was investigated by the vibration of the whole log. In addition, Figure 2d shows that the correlation coefficient between the E_{sw} of logs and the MOR of small clear wood specimens ($R = 0.550$) was slightly greater than that indicated between the E_{fr} of logs and the MOR of small clear wood specimens (Fig. 2c). The linear relationship between the E_{sw} of logs and the σ_c of small clear wood specimens ($R = 0.843$) was also found to be better than using the E_{fr} of logs (Figs. 2e and 2f).

The correlation between the dynamic MOE on a log as determined by stress wave measurements and the bending MOE of small clear wood specimens of poplar I-72 was better than that observed by Wang et al. (2004) and by Yin et al. (2010) on conifers. Correlation models have been developed recently between the velocity of stress wave in standing trees of several conifer species and dynamic MOE based on the resonance vibration in green logs cut from the same trees (Wang et al. 2007). Moreover, Iki et al. (2006) and Ishiguri et al. (2008) also reported statistically significant correlations between the stress wave velocity of standing trees and E_{fr} by longitudinal vibration in *Abies*

Table 4.—Correlation coefficients (R) between dynamic elasticity properties of green logs and static strength properties of small clear wood specimens.

Small clear wood specimens	Green logs[a]			
		E_{sw} (GPa)		
	E_{fr} (GPa)	N	S	N/S
MOE (GPa), N/S	0.806*	0.803*	0.844*	0.848*
MOR (MPa), N/S	0.540*	0.490*	0.579*	0.550*
σ_c (MPa), N/S	0.770*	0.820*	0.816*	0.843*

[a] Asterisk (*) indicates significant at 0.001 level.

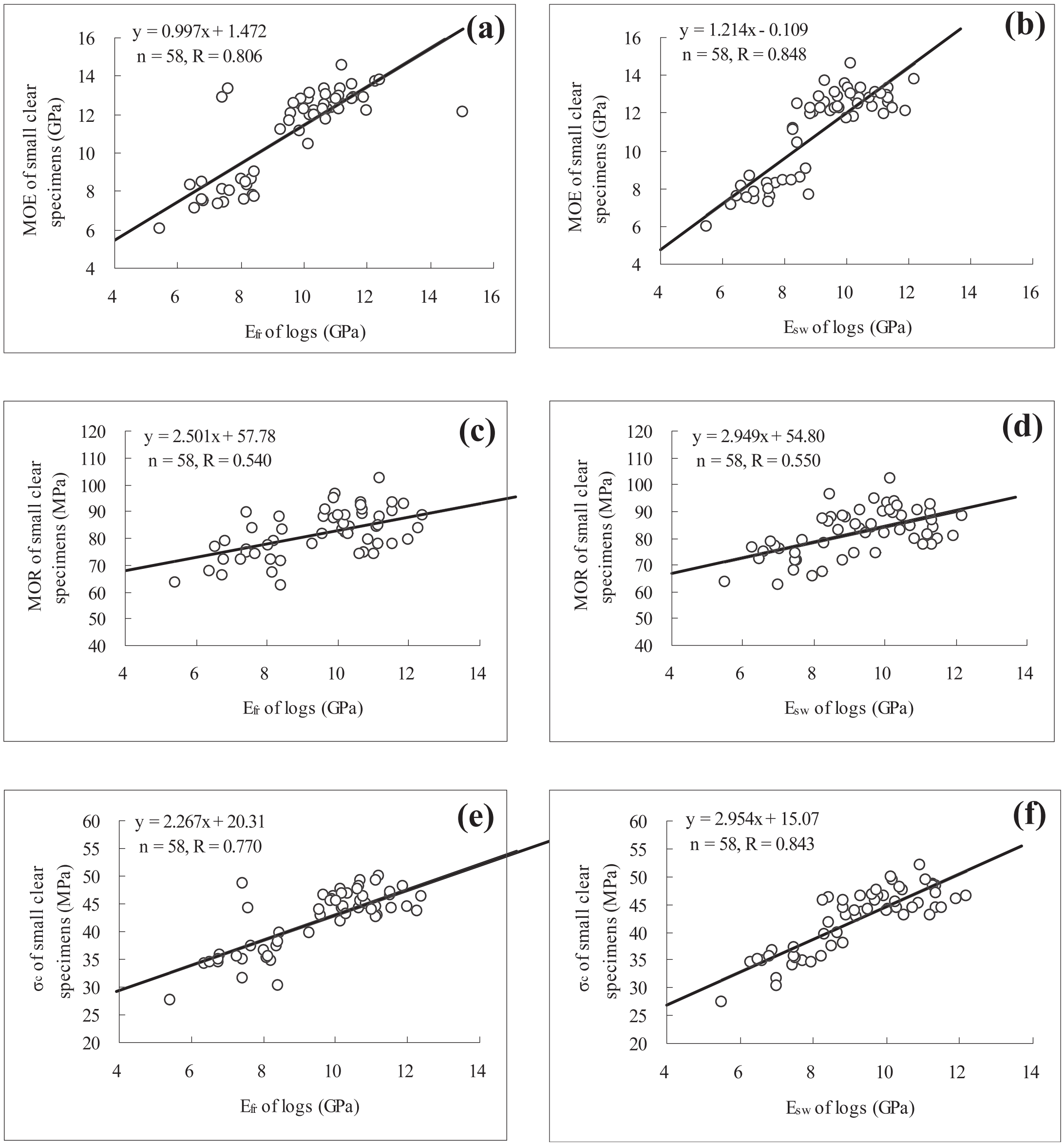

Figure 2.—Relationships between dynamic elastic properties and static strength properties. (a) Dynamic modulus of elasticity (MOE) based on resonance vibration (E_{fr}) of logs and MOE of small clear specimens, (b) dynamic MOE based on stress wave (E_{sw}) of logs and MOE of small clear specimens, (c) E_{fr} of logs and modulus of rupture (MOR) of small clear specimens, (d) E_{sw} of logs and MOR of small clear specimens, (e) E_{fr} of logs and compressive strength parallel to grain (σ_c) of small clear specimens, (f) E_{sw} of logs and σ_c of small clear specimens.

sachalinensis and *Larix kaempferi*. Based on the present study, it is concluded that not only MOE but also MOR and σ_c of small clear wood specimens cut from logs can be well predicted by E_{sw} of those same logs. Therefore, it is suggested that stress wave technology is a reliable method to predict the wood strength properties both of logs and standing trees in conifer and hardwood species. On the other hand, the resonance-based acoustic method has been reported previously to be a well-established NDT technique for long and slender wood members (Aratake et al. 1992, Wang et al. 2007, Yin et al. 2010). In the measurement of resonance frequency of longitudinal vibration, the acoustic pulse reflections stimulated in a log can provide a repeatable and accurate measurement. However, the present device used to assess the resonance vibration can only be applied to wood materials (e.g., logs) with cut ends. Furthermore, an effective method for exciting the longitudinal resonance vibration on the standing tree is lacking.

There are likely several reasons for differences between the measured static and dynamic elastic properties. In addition to variations in the transmission and reception of the signals for the resonance vibration and stress wave methods, growth characteristics (such as knots, wood grain), the uneven distribution of moisture, and density variations within a log could result in differences between the static and dynamic methods. It was shown that E_{fr} based on longitudinal vibration remained nearly constant over a wide range of MCs, although vibration frequency was found to decrease with MC level (Guan et al. 2002). As a result of the relatively constant properties of E_{fr} with MC, a good correlation was found between longitudinal vibration measuring and strength properties of small clear wood specimens. Moreover, the much higher and uneven distribution of MC in green logs of poplar I-72 would tend to introduce additional variability for the stress wave measurement and a reduced correlation with strength properties of air-dried small clear wood specimens, as compared with the results between E_{sw} and bending MOE of green lumber (Ross and Pellerin 1991).

For the present study, the stress wave method was used to measure the propagation speed on the north and south face of green logs, which is how the potential method was applied to measurements on the standing trees. A better correlation with the bending MOE and MOR of small clear wood specimens was observed using the E_{sw} determined from the south segments rather than the north segments (Table 4). However, with the E_{sw} measured on the north-facing segments of the logs, the correlation with the bending MOE, MOR, and σ_c of small clear wood specimens was lower than with the average value of E_{sw} from the north and south segments (Table 4). Although the stress wave estimation on the south segments showed slightly better prediction for both the bending MOE and MOR of small clear wood specimens than from the north segments, it is recommended that stress wave testing be conducted on two or more locations on the stem to reduce the effects of natural growth characteristics of the tree and to provide a more reliable prediction of the strength properties of logs and standing trees.

The results show that the bending MOE for small clear wood specimens obtained from logs could be predicted by E_{fr} and E_{sw} measurements of those same green logs. Furthermore, because the stress wave evaluation on logs showed better prediction for both the static bending MOR and σ_c of small clear wood specimens than the longitudinal resonance vibration, it suggests that the stress wave measurements can provide a reliable and accurate assessment of the potential wood quality of poplar I-72 logs.

Acoustic evaluation and static properties with tree height

The variation in the dynamic MOE of the green logs from the two acoustic methods and the bending MOE from small clear wood specimens was examined in relation to tree height (Table 5). The elasticity properties determined by dynamic and static methods were found to increase with tree height. The bending MOE increased rapidly, changing by 3.88 GPa on average from 1.3 to 3.7 m, then gradually by 0.6 GPa from 3.7 to 6.1 m, and finally by 0.43 GPa toward the 8.5-m height. For dynamic acoustic measurements, the E_{fr} and E_{sw} increase more gradually from 1.3 to 3.7 m (2.56 GPa for E_{fr} and 1.75 GPa for E_{sw}) than the bending MOE. As shown in Table 5, although there were no significant differences in E_{fr}, E_{sw}, and static MOE between the heights of 6.1 and 8.5 m, significant differences were found in those between the 1.3-m height and all other heights ($P < 0.05$). The consistent variation of dynamic and static bending MOE with tree height was reported in Chinese fir (*Cunninghamia lanceolata*; Yin et al. 2010), although the trend was different from that in poplar I-72. In this study, with changes in tree height, the variation in dynamic elasticity properties of logs determined by the acoustic methods followed the trend found for the bending MOE of small clear wood specimens. Therefore, these results suggest that the resonance vibration and stress wave could be applied to track longitudinal changes of strength properties along tree height.

Conclusions

The average bending MOE of small clear wood specimens obtained from static bending was 15 and 20 percent greater than that of green logs, determined by the resonance vibration and the stress wave method, respectively. Although the differences between the bending MOE and dynamic MOE of green logs by the two acoustic methods were found to be statistically significant ($P < 0.05$), there is a significant correlation between E_{fr} and E_{sw} in logs and the bending MOE, MOR, and σ_c of small clear wood specimens obtained from these same logs.

It can be concluded that both acoustic techniques are effective predictors of wood quality of green logs of poplar I-72 with wet heartwood, although the stress wave provides a more accurate and reliable evaluation of strength properties of logs than resonance vibration. The acoustic-based technique based on resonance vibration and stress waves could be applied to track the longitudinal changes of strength properties along tree height.

Acknowledgments

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Table 5.—Analysis of variance in dynamic and static elasticity properties among tree height levels.

	Tree height (m)[a]				
Property (GPa)	1.3	3.7	6.1	8.5	F probability
E_{fr}	7.53 A (0.86)	10.1 B (0.85)	10.5 B (1.40)	10.5 B (2.17)	<0.0001
E_{sw}	7.33 A (0.95)	9.08 B (1.12)	10.1 C (0.95)	10.4 C (1.20)	<0.0001
MOE	7.82 A (0.75)	11.7 B (1.30)	12.3 BC (1.31)	12.7 C (1.42)	<0.0001

[a] The significance level is 0.05. Values in parentheses represent standard deviations. Within a row, means followed by the same letter are not significantly different (Student-Newman-Keuls test).

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