Comparison of Several Nondestructive Evaluation Techniques for Assessing Stiffness and MOE of Small-Diameter Logs[1]

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ABSTRACT

Many of the forests in the United States have large areas that contain trees of small diameter, mixed species, and undefined quality. Because these areas are overstocked, they are at risk from attack by insects, disease, and uncontrollable wild fires. Therefore, it is essential to find cost-effective products for the fiber from these trees. A critical need for this situation is the development of nondestructive technologies for evaluating the potential quality of stems and logs obtained from trees in such ecosystems. Static bending, transverse vibration, and longitudinal stress wave techniques are frequently used to assess the modulus of elasticity (MOE) of lumber. Excellent correlations between MOE values obtained from these techniques have been shown to exist. The objective of this research was to investigate the use of these techniques to evaluate the flexural stiffness and MOE of small-diameter logs. A total of 159 red pine and jack pine logs were obtained from Northern Michigan in the United States and assessed nondestructively using these techniques. Statistical comparisons between stiffness and MOE values obtained from each technique were then examined. Results of this study demonstrated that strong relationships exist between the log properties determined by longitudinal stress wave, transverse vibration, and static bending techniques. This indicates that any of these techniques can be used to sort small-diameter logs with reasonable accuracy.

INTRODUCTION

Many decades of inappropriate management practices, or lack of management altogether, have resulted in large areas of forest stands that are overstocked with small-diameter trees of mixed species. These stands are typically low in value, and the return from material harvested will not cover the costs of needed management treatments. A specific example is the Interior West region of the United States, where 39 million acres of ponderosa-pine-type forest have lost ecological integrity due to major changes in vegetative structure and composition. These changes have been caused by control of fire in an ecosystem where historically there were frequent, low-intensity, stand maintenance tires. Exclusion of fire has led to the current conditions of high risk of attack by insects, disease, and wildfires. Restoration, either mechanical or through prescribed fires, can cost $150 to $500 per acre. It is essential to

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find cost-effective products that can be produced from the materials available in these stands so that needed management operations such as thinning can be implemented to improve the condition of these stands. Economical and value-added uses for these materials can help offset forest management costs, provide economic opportunities for many small, forest-based communities, and avoid future loss caused by catastrophic wildfires. Among the issues of great concern for engineering applications of these materials are the variability and predictability of their strength and stiffness. A critical need is cost-effective technology for evaluating the potential quality of stems and logs obtained from trees in such ecosystems.

In the forest products industry, a variety of nondestructive evaluation (NDE) techniques are now being used to assess the engineering properties of structural lumber. Static bending, transverse vibration, and longitudinal stress wave techniques are frequently used to assess the modulus of elasticity (MOE) of lumber (Jayne 1959; Kaiserlik and Pellerin 1977; Pellerin 1965; Ross and Pellerin 1994; Ross et al. 1991, 1996; Schad et al. 1995). Commercial equipment that uses these techniques is readily available. The objective of this research was to investigate the use of these three techniques to evaluate the stiffness and MOE of small-diameter logs.

MATERIALS AND METHODS

A flow chart that outlines the experimental procedures is shown in Figure 1. First, a sample of small-diameter trees were selected from stands and harvested to obtain logs. Physical properties (diameters, moisture content, and density) of logs were then measured. This was followed by a sequence of nondestructive tests using longitudinal stress wave, transverse vibration, and static bending techniques to obtain the MOE and flexural stiffness of these logs. Statistical analyses were then used to examine the relationships between log properties determined by different techniques.

In this study, 159 small-diameter logs, including 109 jack pine (*Pinus banksiana* Lamb.) and 50 red pine (*Pinus resinosa* Ait.), were nondestructively evaluated. These logs came from trees that were grown on the Ottawa National Forest and the Lake Superior State Forest in Northern Michigan.

The jack pine logs used in this study were obtained from an overage stand of jack pine that was beginning to show signs of deterioration. Ranger district personnel are able to visually identify four categories of trees in this type of stand: live healthy trees (merchantable live), live trees that are showing signs of being under stress (suspect), trees that are dead but still containing merchantable material (merchantable dead), and dead trees that have deteriorated to the point of having no merchantable material (unmerchantable dead). The national forest is using commercial salvage sales to treat considerable acreage of these jack pine stands. To be able to properly estimate the value of these stands, better information on the value of each of the four categories of trees is needed. Trees in each of these categories were selected for this study to address this need. The estimated ages of the jack pine trees ranged from 50 to 70 years old. The diameter at breast height (DBH) of sampled trees ranged from 5.0 to 12.2 in. (127 to 310 mm).

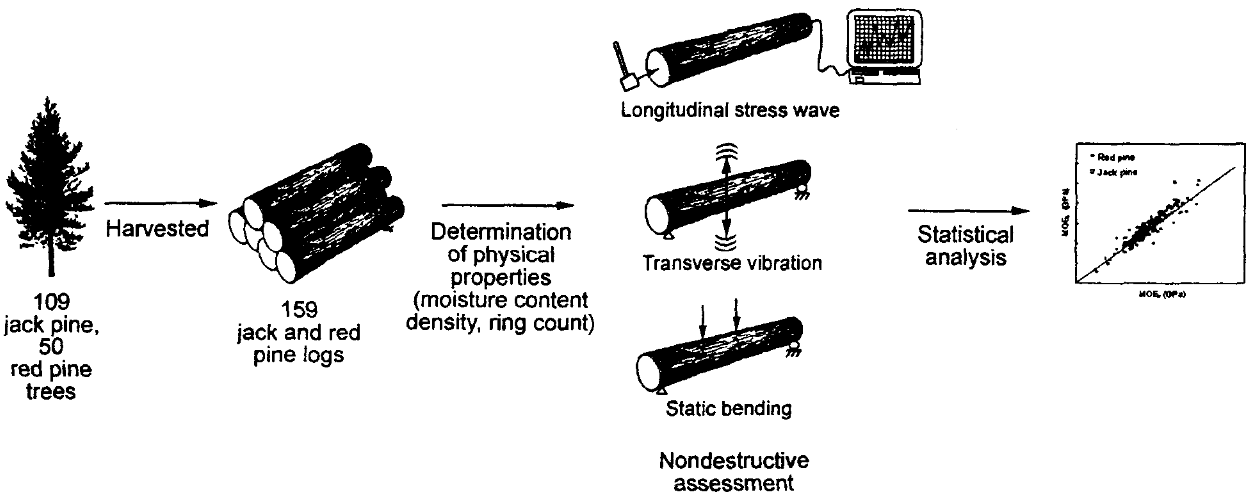

Figure l-Experimental procedure.

Red pine logs were obtained from 38-year-old research plots that had stocking level as the main treatment. The objective of the original study was to examine the growth of red pine over time at various stocking levels and correlate volume yield with financial yield at the different initial stocking levels. Plots at five stocking levels were available, 220, 320, 420, 620, and 820 trees per acre. Ten trees were harvested from each of the five plots. The DBH of sampled trees ranged from 4.70 to 11.50 in. (119 to 292 mm).

After these sampled trees were harvested, a 16-ft- (4.88-m-) long butt log was bucked on-site from each sample tree and was then transported to the Forestry Sciences Lab, USDA Forest Service, North Central Research Station in Houghton, Michigan, for various nondestructive testing.

Upon arrival at the Forestry Sciences Lab, a 2-ft- (0.61-m-) long section from each end of the butt log was then cut and sent to the USDA Forest Service, Forest Products Laboratory, in Madison, Wisconsin, for pulping studies. The remaining 12-ft- (3.66-m-) long logs were then used for this study. To determine moisture content (MC) of sampled trees, we cut three cookies from butt, middle, and top of each tree. Green weight and ovendry weight of these cookies were then obtained and used to determine tree MC. For each 12-ft (3.66-m) log, the green weight and the diameters of both ends were measured to obtain the green density and the moment of inertia of the log.

Each log was first evaluated using a longitudinal stress wave technique to obtain an estimate of dynamic modulus of elasticity (MOE_{sw}) of the log. An accelerometer was attached to one end of the log. A stress wave was introduced to the log through a hammer impact on the opposite end, and the resulting stress wave was recorded using a personal computer. A detailed description of the instrumentation and analysis procedures can be found in a previous article (Ross et al. 1994), and a discussion of its application to large specimens is included in Schad et al. (1995). From stress wave measurement, the stress wave speed (C) in a log was then determined. Dynamic modulus of elasticity (MOE_{sw}) was calculated with

$$MOE_{sw} = C^2 \rho \tag{1}$$

where ρ is the density of a log.

After stress wave tests, the logs were vibrated using a transverse vibration technique. A digital oscilloscope and an accelerometer were used in this test. The log under test was supported at one end by a knife-edge support and at the opposite end by a point support. The accelerometer was located in the middle of the log and glued on the upside surface. At that spot, the bark was removed or polished to improve the contact between the accelerometer and the log. The log was then set into excitation by impacting the middle part of the log with a rubber hammer. The free vibration response of the log was observed in the oscilloscope. The signal observed was a series of pulses with a gradually decreasing (decaying) amplitude. The vibrational parameter measured was natural frequency. The value for the dynamic modulus of elasticity (MOE_v) of logs was calculated from

$$MOE_v = \frac{f_r^2 W L^3}{2.46 I g} \tag{2}$$

where MOE_v is dynamic modulus of elasticity (lb/in^2 (Pa)), f_r is resonant frequency (Hz), W is log weight (lb (kg)), L is log span (in. (m)), I is log moment of inertia (in^4 (m^4)), and g is acceleration due to gravity (386 in/s^2 (9.8 m/s^2)).

Static bending tests were then performed on the logs to obtain the flexural stiffness (EI) and static modulus of elasticity (MOE_s) of these logs. Measuring MOE of a member by static bending techniques has been widely considered as the foundation of lumber grading and NDE of wood and wood-based materials. However, this technique is rarely used to evaluate the MOE of logs as a standard method. Consequently, no standard testing procedure exists for testing small-diameter logs. However, we assumed the MOE_s of logs to be the real MOE for logs and used it to evaluate the dynamic MOE of logs determined by stress wave and transverse vibration techniques. A Metriguard (Pullman, WA) Model 312 Bending Proof Tester was used to conduct static bending tests on all logs. The testing machine was originally designed for proof loading dimensional lumber. To test logs, we modified the two end supports to fit to the geometrical shape of small-diameter logs. The modified supports allow testing logs with a maximum diameter of 12 in. (305 mm). The span between two supports was set as 115.5 in.

(2.93 m). The distance from loading point to the nearest support was 38.5 in. (0.98 m), one-third of the span. A load was applied to the log through two bearing blocks. Deflection was measured in the central region, a zone of pure bending without shear deformation. The log under test was first preloaded to 100 lb (445 N), and the deflection was set to zero. This procedure was mainly used to improve the contact between log, supporters, and bearing blocks and eliminate the effect of bark on the deflection measurement. The log was then loaded to 0.2-in. (5.08-mm) deflection. The practical load value corresponding to this deflection was then recorded. Log static MOE (MOE_s) was then calculated:

$$MOE_s = \frac{Pa(3L^2 - 4a^2}{48\delta I} \quad (3)$$

where P is load, a is distance from the end support to the nearest load point, L is log span, δ is midspan deflection, and I is log moment of inertia.

RESULTS AND DISCUSSION

Physical characteristics

The average diameters of the butt logs obtained from the trees ranged from 4.4 to 10.2 in. (112 to 259 mm) for red pine and from 4.67 to 10.99 in. (119 to 279 mm) for jack pine. This is a typical diameter range of small-diameter timber (Wolfe 2000). For both species, the average MC exceeded the fiber saturation point (about 30%). However, red pine logs apparently have much higher MC than jack pine logs. The individual values ranged from 88.2% to 144.6% for red pine logs and from 31.2% to 65.0% for jack pine logs. The low MC level for jack pine logs was a result of the fact that the samples included live, suspect, and dead trees. Suspect and dead trees had already lost a lot of moisture by the time they were harvested. Therefore, the MC of some logs obtained from dead trees was close to or even lower than the fiber saturation point.

Also, red pine logs have higher density than jack pine logs. The density values for red pine logs ranged from 48.0 to 56.5 lb/ft^3 (0.77 to 0.90 g/cm^3), and those for jack pine logs ranged from 28.66 to 53.73 lb/ft (0.46 to 0.86 g/cm^3). The lower value and large range of density for jack pine logs was also due to the fact that the samples included suspect and dead trees.

Jack pine logs are different than red pine logs in cross-sectional stem shape and straightness of logs. Red pine logs are mostly round-shaped and very straight. Whereas some jack pine logs have a more irregular shape (not round in cross section) and a curved stem, which could introduce errors in the determination of density and moment of inertia of these logs.

Modulus of elasticity of logs

The static MOE (MOE_s) of logs ranged from 0.45 to 1.21 × 10^6 lb/in^2 (3.10 to 8.34 GPa) with a mean value of 0.80 × 10^6 lb/in^2 (5.52 GPa) for red pine. The range for jack pine logs was 0.17 to 1.48 × 10^6 lb/in^2 (1.17 to 10.20 GPa) with a mean value of 0.81 × 10^6 lb/in^2 (5.58 GPa). It was found that the stress wave technique produced higher estimates of MOE for both species. For red pine logs, the mean MOE_{sw} is 11.8% and 18.8% greater than its vibrational and static counterparts, respectively. For jack pine logs, the mean MOE_{sw} is 21.6% and 24.7% greater than its vibrational and static counterparts. We believe that the higher value of MOE_{sw} could be related to the wave propagation mechanism, dimension of logs, and the MC of wood in logs.

In previous studies (Wang 1999, Wang et al. 2000), we found that the stress wave behaved differently in logs than in small, clear wood and lumber because of the relatively larger size. Stress waves traveled faster in the outer portion of the wood (mature wood) when it was propagated through a log in the longitudinal direction. This led to a higher stress wave speed on a log and increased the value of MOE_d, which in turn overestimated the MOE of the log. It was also found that the diameter to length ratio could be a critical factor that may affect the stress wave behavior in logs. Quantitative analyses of the overestimation in MOE_{sw} of logs have not been reported.

Compared with MOE, of logs, the dynamic MOE of logs determined from transverse vibration technique (MOE_v) is much closer to static MOE of logs. The MOE_v of red pine logs ranged from 0.58 to 1.22 × 10^6 lb/in^2 (4.00 to

Table 1–Results of linear regression analyses of various MOE of red pine and jack pine fogs[a]

Species	MOE *y*	MOE *x*	*a*	*b*	r^2	*r*	S_{yx}	F[b]	
Red pine									
	MOE_v	MOE_{sw}	-2.7076	1.3100	0.77	0.88	0.545	162.1	***
	MOE_s	MOE_{sw}	-4.1270	1.4740	0.75	0.87	0.653	143.1	***
	MOE_s	MOE_v	-0.9947	1.1105	0.95	0.97	0.304	835	***
Jack pine									
	MOE_v	MOE_{sw}	-0.2190	0.8167	0.58	0.76	1.104	142.4	***
	MOE_s	MOE_{sw}	-0.4437	0.7883	0.60	0.77	1.032	150.9	***
	MOE_s	MOE_v	0.2929	0.8782	0.85	0.92	0.635	567.1	***
Combined									
	MOE_v	MOE_{sw}	0.3298	0.7748	0.55	0.74	1.036	182.9	***
	MOE_s	MOE_{sw}	0.0611	0.7555	0.53	0.73	1.040	172.4	***
	MOE_s	MOE_v	0.0839	0.9175	0.86	0.93	0.565	946.9	***

Linear regression model $y = a + bx$ (columns *a*, *b*, r^2, *r*, S_{yx}).

[a]MOE_{sw}, modulus of elasticity (MOE) of a log determined by stress wave method; MOE_v MOE of a log determined by transverse vibration method; MOE_s, MOE of a log determined by four-point static bending; r^2, coefficient of determination; *r,* correlation coefficient; S_{yx} standard error of estimate.
[b]***Highly significant (0.01 confidence level) by F-test.

8.40 GPa), and the range for jack pine logs was 0.25 to 1.47 × 10^6 lb/in^2 (1.72 to 10.14 GPa). The mean value of MOE_v of logs was about 7% greater than the mean MOE_s of logs for both species.

Modulus of elasticity relationships

Statistical analysis procedures were used to examine the relationships between the various MOE of red pine and jack pine logs. The results obtained from regression analyses are presented in Table 1.

The correlations among various MOE could be represented by linear regression models ($y = a + bx$). The results of the comparison between three different techniques are reported in terms of correlation coefficients that reflect the possible reliability of the method for prediction purposes. The square of the correlation coefficient expresses the percentage of the total variability explained by the regression line.

In general, the dynamic MOE (MOE_{sw} and MOE_v) of logs was very closely correlated with the static MOE (MOE_s) for both red pine and jack pine logs. The correlation coefficients were found to be 0.87 (MOE_{sw} and MOE_s) and 0.97 (MOE_v and MOE_s) for red pine logs. Those for jack pine logs were 0.77 (MOE_{sw} and MOE_s) and 0.92. The linear regression analyses indicated that the developed regression models were statistically significant at the 0.01 confidence level.

Figure 2, 3, 4, and 5 show the relationships of dynamic MOE predicted by stress wave technique to dynamic MOE predicted by transverse vibration technique and static bending MOE for both species. It was apparent that the red pine logs produced a better correlation (r = 0.87 to 0.88) than the jack pine logs (r = 0.76 to 0.77). This could be attributed to the geometrical differences between the two species. It was evident that irregular shape (not round in cross section and curved in stem) of some jack pine logs could introduce errors in diameter measurements, thus causing errors in density and MOE determination, especially in MOE_{sw} determination.

The relationships between MOE_v and MOE_s of red pine and jack pine logs are shown in Figure 6 and 7. The results from transverse vibration tests demonstrated that a significant improvement had been achieved in comparison to the results from stress wave tests. In regard to the relationship of MOE_v to MOE_s, it was found that two species could be

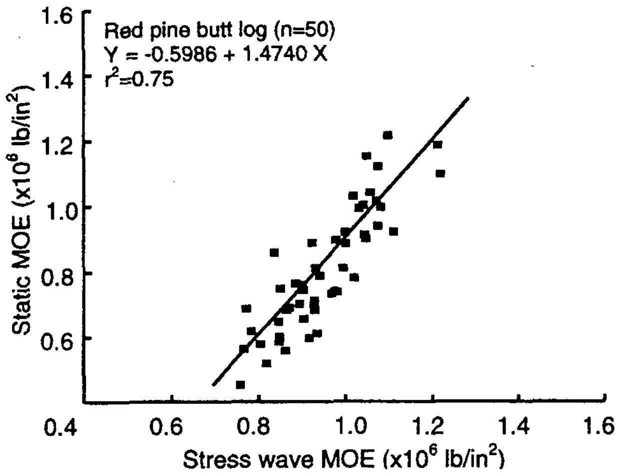

Figure 2–Relationship of MOE_{sw} to MOE_s for red pine logs.

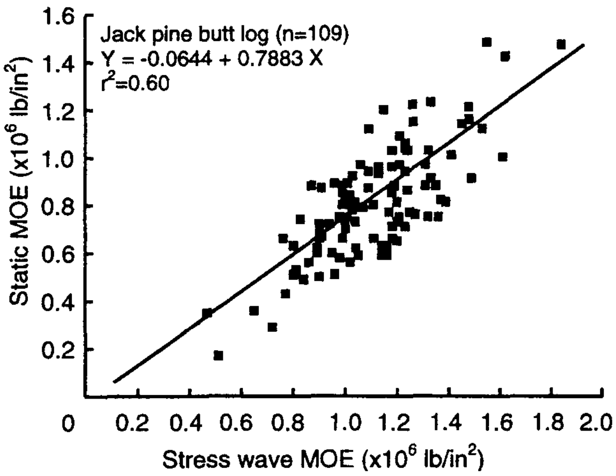

Figure 3–Relationship of MOE_{sw} to MOE_s for jack pine logs.

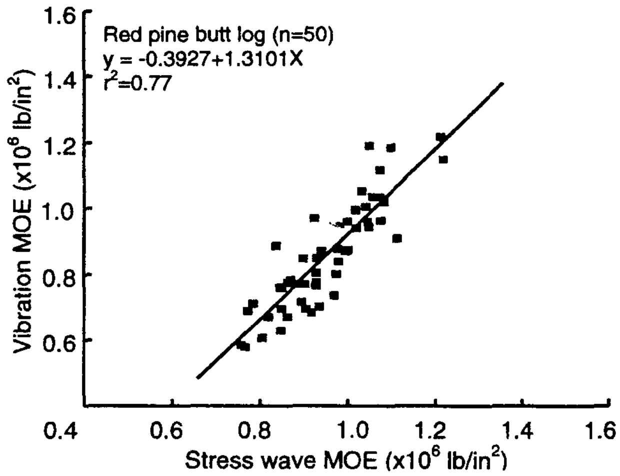

Figure 4–Relationship of MOE_{sw} to MOE_v for red pine logs.

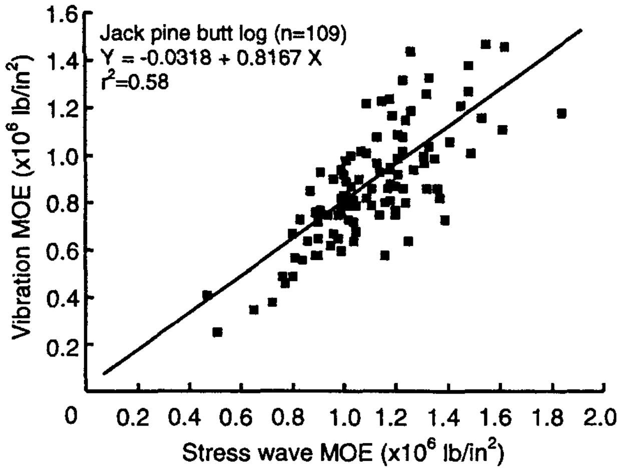

Figure S-Relationship of MOE_{sw} to MOE_v for jack pine logs

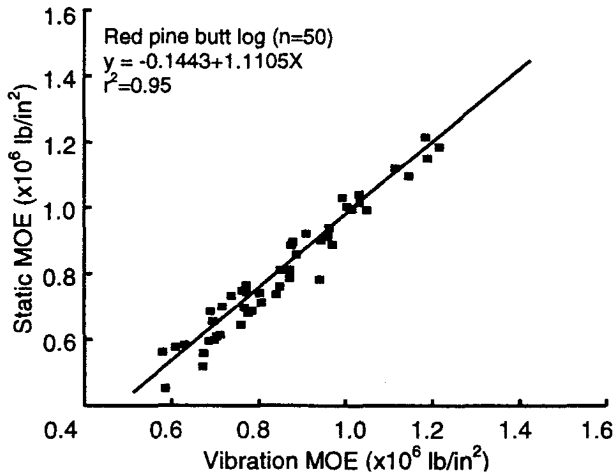

Figure 6–Relationship of MOE_v to MOE_s for red pine logs

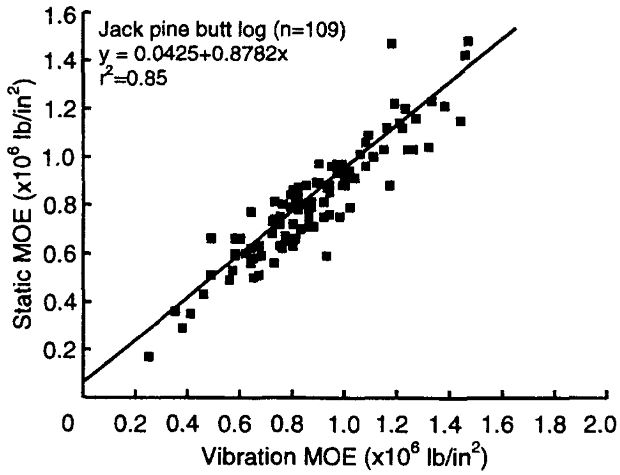

Figure 7–Relationship of MOE_v to MOE_s for jack pine logs.

combined and represented as a single population. The correlation coefficient relating the MOE_v to MOE_s was 0.93. This value indicates clearly that the variation caused by these two species does not affect the relationship.

Flexural stiffness relationships

Of the parameters that can be measured nondestructively, e.g., density, appearance, MOE, and stiffness, stiffness is used most frequently to predict the strength of wood materials. Therefore, it is important to know the relationships between the stiffness determined by these three techniques.

Flexural stiffness is expressed as the product of the moment of inertia (I) and modulus of elasticity (MOE) in bending. For logs, the moment of inertia is given by

$$I = \frac{\pi d^4}{64} \quad (4)$$

where d is the average diameter of a log.

When the MOE of logs is determined by these techniques, the various flexural stiffness of logs can be easily calculated.

The relationships between various log stiffness (stress wave EI, vibration EI, and static EI) are shown in Table 2 and Figure 8, 9, and 10. Red pine and jack pine logs showed no distinction in regard to the stiffness relationship. Therefore, we combined these two species together and treated them as a single population.

Table 2–Results of regression analyses of flexural stiffness (EI) of logs determined by different techniques[a]

			Regression model $y = a + bx + cx^2$ or $y = a + bx$					
Species	y	x	a	b	c	r^2	r	Syx
Combined	EI_v	EI_{sw}	5.13	0.9035	-0.00049	0.97	0.98	18.03
	EI_s	EI_{sw}	11.68	0.7530	-0.00028	0.94	0.97	23.37
	EI_s	EI_v	-1.83	0.9434	—	0.94	0.97	22.83

[a]EI_{sw}, stiffness of log determined by longitudinal stress wave technique; EI_v, stiffness of log determined by transverse vibration technique; EI_s, stiffness of log determined by four-point static bending; r^2, coefficient of determination; r, correlation coefficient; S_{yx}, standard error of estimate.

The results revealed that the correlations between these nondestructively determined stiffness values were extraordinarily strong. In Figure 8 and 9, the stiffness from transverse vibration and static bending tests were plotted as a function of stress-wave-determined stiffness. Compared with the MOE relationships, the correlations between stress wave technique and the transverse vibration and static bending techniques have been improved significantly in terms of flexural stiffness. Regression analyses indicate that a second-order polynomial regression model ($y = a + bx + cx^2$) could best fit the experimental data. The correlation coefficients were 0.98 (stress wave EI and vibration EI) and 0.97 (stress wave EI and static EI). The developed regression models accounted for 97% and 94% of observed behavior.

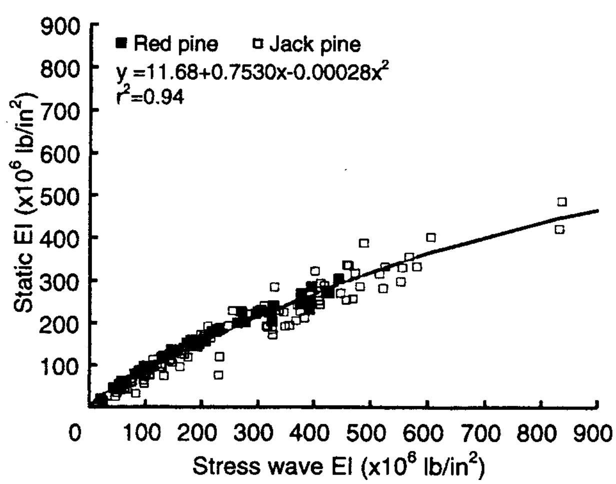

Figure 8–Stress wave EI versus static EI.

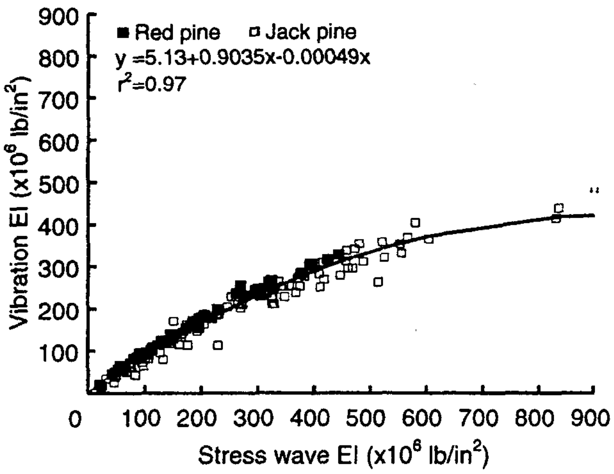

Figure 9–Stress wave EI versus vibration EI.

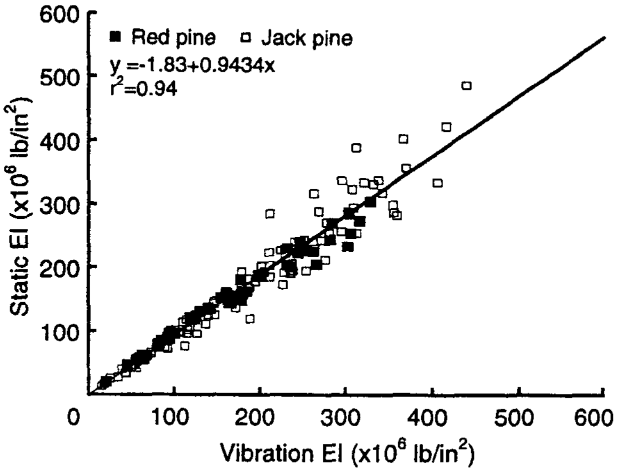

Figure 10–Vibration EI versus static EI.

Figure 10 shows the comparison between transverse vibration and static bending techniques in terms of flexural stiffness of logs. Just as for the MOE relationship, a linear regression model was found to be the best fitting function to the experimental data. The correlation coefficient was 0.97, indicating that 94% of observed behavior has been accounted for.

CONCLUSIONS

Based on the results of these experiments, it can be concluded that small-diameter red pine and jack pine logs can be successfully evaluated by longitudinal stress wave, transverse vibration, or static bending techniques. The dynamic MOE (MOE_{sw} and MOE_v) of logs was found to be well correlated with the static MOE for both species.

The experimental results indicated that the stress wave technique is sensitive to the geometrical imperfections of logs. Round and straight logs will produce better correlation between MOE_{sw} and MOE_s. The results from transverse vibration tests demonstrated that a significant improvement had been achieved compared with the results of stress wave tests. In regard to the relationship of MOE_v and MOE_s, transverse-vibrational parameters were found to be less sensitive to the geometrical imperfections of logs than stress wave parameters. Red pine and jack pine logs therefore could be combined and represented as a single population in the prediction model.

Extraordinarily strong relationships were found between various nondestructively determined log stiffness. Compared with the MOE relationships, the correlations between the stress wave technique and the transverse vibration and static bending techniques were improved significantly in terms of flexural stiffness.

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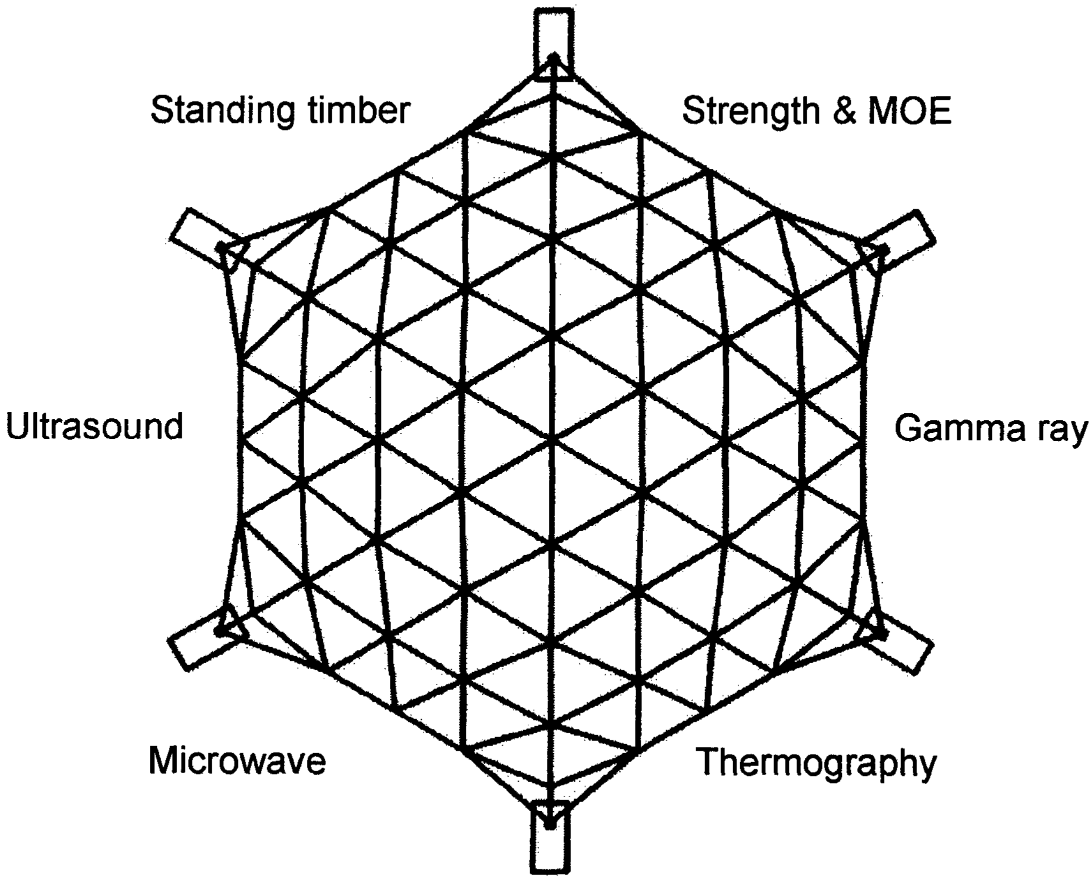

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