Acoustic Testing and Sorting of Chinese Poplar Logs for Structural LVL Products

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The purpose of this study was to investigate the feasibility of using resonance-based acoustic technologies for sorting Chinese poplar logs for laminated veneer lumber (LVL) products. Representative poplar logs were sampled. Each log was first tested for acoustic velocity and then peeled into veneer. Each veneer sheet was subsequently dried and measured with a production-line veneer tester. LVL beams were made, and their stiffness was non-destructively measured by both time-of-flight (TOF) acoustic method and free-beam vibration methods. Based on the LVL dynamic modulus of elasticity (MOE) values, logs were sorted into several grades with known grade outturns. The results showed that there was a strong correlation between resonance-based acoustic velocities of logs and dynamic MOE of veneer and LVL. Thus, it is feasible to predict the stiffness of LVL products based on log resonance-based acoustic velocity measured. The resonance-based acoustic measurement is easy to use and reliable, which can help increase the grade outturn and in turn value recovery of Chinese poplar logs. It was estimated that the log grade outturns were approximately 31.1% for LVL grade 1, 38.6% for LVL grade 2, and 26.1% for LVL grade 3.

Keywords: Poplar; Log; Acoustic; Laminated veneer lumber (LVL); Modulus of elasticity (MOE); Grading; Non-destructive testing

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INTRODUCTION

China has the world's largest stock of fast-growing wood plantations. Among them poplar (*Populus euramericana* cv) is predominant. This species has been widely used for pulp, lumber, and plywood manufacturing. But its application is still restricted due to its low density, soft texture, and proneness to deformation and decay (Cai *et al*. 2012). Over the past decade, in order to meet the increased market demands for structural lumber, studies have been conducted to assess and modify the poplar wood to more accurately grade and enhance its physical and mechanical properties (Brashaw *et al.* 2009). As a result, this fast-growing wood can substitute for old-growth timber in applications such as parquets and floors, furniture parts, and posts and beams.

At present, old-growth timber resources are quickly becoming depleted, and log quality is continually decreasing from around the world. On the other hand, the demand of wood supply is increasing due to expanding population and increasing quality of life. To meet this challenge, utilization of fast-growing species has been seen as one of the feasible solutions. In China, laminated veneer lumber (LVL) made from poplar is mainly for non-structural use in competition with solid wood in the areas of furniture industry, house building components, packaging, and transportation. However, a visual inspection method based on diameter, knots, straightness, and decay is commonly used to sort poplar logs for different products. While the visual inspection is a simple non-destructive evaluation method (Galligan *et al.* 1977), it cannot reliably estimate log structural properties. For structural applications, the most important wood characteristics are the mechanical properties (Bowyer *et al.* 2007). In particular, modulus of elasticity (MOE) (which is related to stiffness) is one of the most important mechanical properties. This is the most frequently used indicator of the ability of material to support loads and resist bending deformation (Amishev and Murphy 2008, 2009). For structural applications of LVL such as I-joist flanges, headers, and beams, its bending MOE is normally a primary criterion. However, the correlation between the LVL product MOE and the log visual characteristics is generally weak, leading to logs being mis-sorted or ill-segregated and a waste of wood resources. With the visual method, it is impossible to grade the logs based on different end-use of LVL, leading to a substantially reduced value return from logs. Therefore, log grading is particularly important for improving the LVL mechanical properties and the yield of high-grade LVL products.

A static bending test is generally used to determine wood MOE, but preparation and evaluation of test samples have been time-consuming, expensive, and destructive (Raymond *et al.* 2007). So during the last decades, research has been focused on rapid, cheap, and cost-effective non-destructive evaluation (NDE) methods, such as: ultrasonic, stress wave, and vibration detection methods (Wang and Ross 2002; Cui *et al.* 2005; Yoshihara 2011; Wang *et al.* 2012), and these techniques have been commercialized for years (Wang *et al.* 2004c). However, there are inherent differences between static and dynamic estimates of wood MOE, and the static MOE is generally lower than the dynamic MOE (Ilic 2001; Raymond *et al.* 2007). Among various wood NDE methods, the acoustic technique has been seen as the best option for predicting the mechanical properties of wood, as the tools are robust, flexible, cheap, and cost-effective for field uses (Brashaw *et al.* 2004; Chauhan and Walker 2006), such as with the Metriguard Model 239A stress wave timer, the Fakopp tree-sonic microsecond timer, the James"V" meter, the Director ST-300™, and time-of-flight (TOF) acoustic technology. Those tools have also been used to detect wood internal defects and growth characteristics. Over the past several decades, wood researchers, especially in North America, have conducted many studies that assess the stiffness of various wood products with stress wave NDE. It was reported that there are strong correlations between stress wave attenuation and mechanical properties of log, lumber, LVL, and other wood products (Wang *et al.* 2002, 2007a). Recently, stress wave NDE of logs has been used to sort logs to achieve desired stiffness levels of lumber or veneer and thus to improve log grade outturns and value recovery (Ross *et al.* 1997; Wang *et al.* 2004a).

Earlier studies indicated that a high correlation exists between the yield of structural grades of lumber and acoustic velocity of logs processed as measured by acoustic techniques (Wang *et al.* 2001, 2002; Grabianowski *et al.* 2006; Wang *et al.* 2007b). Segregation of logs by resonance-based acoustic tool has already been used by some forest companies to improve the value of lumber recovery (Andrew 2003). This acoustic method is a well-established NDE technique for measuring long, slender wood members (Wang *et al.* 2004b; Mora *et al.* 2009; Achim *et al.* 2011). The acoustic velocities taken from logs at the log yard would represent a good first step towards improving decision-making early in the wood supply chain. The resonance-based acoustic technology can also be used to trace wood properties according to source and handling (Casado *et al.* 2012). However, in most wood grading studies involving standing tree, log, and lumber evaluations (Brashaw *et al.* 2004; Wang *et al.* 2008; Macdonald and Hubert 2002), very little has been done to reveal the inherent relationship between the log and its LVL products for segregating logs into different grades based on its stiffness. Assessing log quality in the mill, determining its most appropriate use, and consequently delivering it to the right location for processing are very important steps to improve end product stiffness, reduce production costs, and increase mill profits (Achim *et al.* 2011).

Needless to say, different tree species have different mechanical properties (Alteyrac *et al.* 2005) arising from diverse genetic, stand management, and growth conditions (*e.g.*, regional climate or soil characteristics). The mechanical properties of wood also vary within and between individual trees (Auty and Achim 2008). Within a log, wood properties vary from pith to bark and along the length of the stem (Sandoz 1993; Carter *et al.* 2006). Poplar is the most known fast-growing plantation species, but so far, virtually no research has been done on its suitability for structural LVL products and its end product based log grading. The main objective of this work was to investigate the property relationship between the poplar logs and their LVL products. Logs were sampled and obtained from the northern Jiangsu province in P. R. China and evaluated and sorted before entering into a LVL mill. The log sorting was performed one step prior to the log-to-product value chain. The specific objectives were to: 1) examine the relationships among dynamic MOE values of logs, resulting veneers, and LVL products measured by resonance-based, ultrasonic, and TOF methods, respectively, 2) explore the correlation of LVL MOE measured by the TOF acoustic method and free-beam vibration method and the static bending MOE, in order to verify the accuracy of the resonance-based acoustic technology, and 3) grade logs based on the requirements of LVL MOE in accordance with Chinese national LVL standard (*Chinese Standard: GB/T 20241*).

MATERIALS AND METHODS

Log Sampling, Veneer Processing, and LVL Manufacturing

A total of 238 poplar I-72 *(Populus euramericana* cv. I-72) logs were laid out and tested using the Director HM200™ resonance tool developed by Fibre-gen, New Zealand (Wang *et al.* 2007b) at a LVL mill located in Siyang County, Suqian City, Jiangsu Province, P. R. China. These logs were from the same batch of 8-year-old trees growing in Suqian City nearby. Then 13 representative poplar log samples in the length of about 2.52 to 2.59 m were randomly selected from them. After marking them sequentially, measurements were subsequently taken to record the length, large-end, and small-end diameters and weight of each log. The moisture content (MC) of logs obtained from the MC samples cut from them was from 65 to 78%, with an outside temperature between 23 and 28 ºC during the test.

The 13 logs were first debarked and cut into two 1250 mm long sections, then peeled with a BQ1513/7 single hydraulic double shaft rotary-peeling veneer lathe in one mill without conditioning. The target veneer thickness was 2.1 mm. The veneer sheets from each log were clipped to a dimension of 1250 mm x 260 mm, and stacked in sequence. Eleven veneer sheets were proportionally selected from bark (sapwood) to pith (heartwood) of the same log and numbered accordingly. They were then dried using solar energy first and further dried with a press dryer to achieve a target MC of 7 to 8%.

The main manufacturing process of LVL beams is described hereafter. Each LVL beam was assembled by 11 veneer sheets in the same grain direction. The adhesive used was phenol formaldehyde (PF), with formaldehyde and phenol molar ratio of 2:1. It had a viscosity of 210 mPa·s and a pH value of 10. Prior to hot pressing, each beam was cold pressed with a pressure of 1.0 MPa for 7 to 8 min. In total, 13 LVL beams were made with the following pressing parameters: temperature = 110 to 120 °C, pressure =1.6 MPa, and pressing time = 40 min. The dimension of LVL specimen at 8 to 10% MC was 1210 mm × 180 mm × 21.1 mm.

Resonance-based Acoustic Testing of Logs

The longitudinal acoustic velocity of poplar logs (2 to 40 m-long) was measured using the Director HM200™. Before testing, the log was laid flat on horizontal ground, and its length was entered in the tool with the head of the tool vertically pressed against one end of the log, ensuring that the sensor in a rubber bossing at the head of the tool achieved good contact with the end of the log. Then the end of log was hit by a steel hammer to induce stress waves (Fig. 1). The sensor picked up the acoustic wave signal based on a measure of the harmonic frequencies of a plane induced on the logs as it passed back and forth along the length of the log. The stress wave signal was immediately processed using a Fast Fourier Transformation (FFT) program to display velocity in meters per second (Wang *et al.* 2004b). The acoustic velocity based on a measure of the harmonic frequencies of a plane induced on the logs was determined from Equation 1 (Achim *et al.* 2011),

$$C_L = \frac{2fL}{n} \tag{1}$$

where C_L is the resonance-based acoustic velocity of the log (m/s), f_n is the natural frequency of the n^{th} harmonic of an acoustic wave signal (Hz), and L is the log length (end-to-end) (m).

Fig. 1. Resonance-based log acoustic test with Director HM 200™

Since the Director HM-200™ software outputs an average velocity of the log from its analysis of the whole wave signals it receives and the length of propagation back and forth will be basically equal (Carter *et al.* 2004) based on the assumption that the tested log can be assumed to be a slender rod, there is little effect regarding which end of the log is chosen or where the sensor is placed at the end and the hammer blow struck. Thus, resonance-based acoustic dynamic MOE of the log can be calculated using the one-dimensional equation,

$$E_D = \rho v^2 \tag{2}$$

where E_D is dynamic MOE (Pa), v is longitudinal wave velocity (m/s), and ρ is green density (Kg/m^3).

In this study, a total of 238 poplar logs were tested to obtain their acoustic velocities. During each test, three readings were collected from each log to derive the average velocity. The diameters at the two ends and weight of each of the 13 log samples were also measured to calculate ρ and E_D.

Ultrasonic Test of Veneer Sheets

Each veneer sheet was passed through a 2800 DME Digital Metriguard Veneer Tester. This tester calculates veneer dynamic MOE by measuring mean ultrasonic propagation time (UPT, us) along the length of each veneer sheet and density of each veneer sheet (Metriguard Inc. 2012). Generally, higher quality veneer has a lower mean UPT. Veneer temperature affects veneer grading, so temperature compensation is accomplished by use of an infrared thermometer that measures the temperature of each sheet. The density (or specific gravity) and MC are determined by using microwave and radio frequency technologies. All of these measurements can be done at a line speed up to 130 m/min.

LVL Testing

Time-of-flight (TOF) acoustic measurement

The acoustic velocity of the LVL specimens was measured using an FAKOPP 2D stress wave timer (Fakopp Enterprise Inc.). The vibration frequency of the LVL specimens was measured using a dynamic signal acquisition system. LVL stress wave propagation time, measured in ms, was calculated as the mode of 3 consecutive TOF readouts obtained from each LVL (Fig. 2).

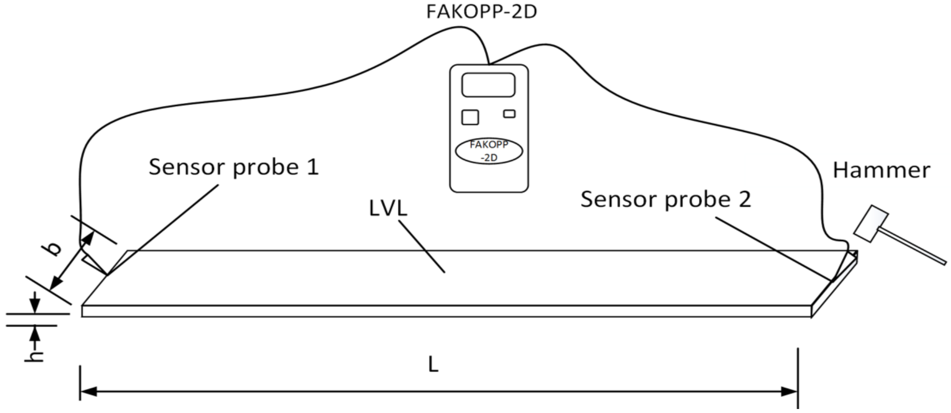


Fig. 2. Time-of-flight (TOF) acoustic measurement of LVL

The probes were positioned on each end of LVL specimen, at approximately 45 ± 5° with respect to the centerline of the LVL specimen. Stress waves were induced by striking the transmitting probe with a steel hammer. Before the test, the dimension and mass were measured to calculate density; then, dynamic stiffness in LVL specimen was calculated using the same formula as (2) after the acoustic velocity was calculated according to the stress wave propagation time and the length of the LVL specimen.

Free-beam vibration test

This test is also called a free-free flexural vibration test (Yoshihara 2011). The principle of free-beam vibration measurement is shown in Fig. 3. At first the LVL specimen was in a free-beam state, then hit with a rubber hammer to produce vibration. The accelerator on the end surface of the LVL specimen transforms the mechanical parameters (acceleration) into an electrical signal, and the signal data were acquired after filtering and amplifying.

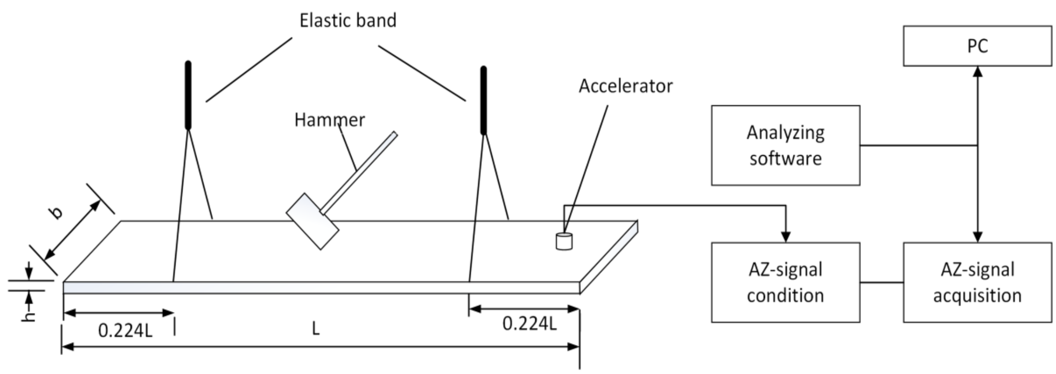


Fig. 3. Free-beam Vibration Measurement of LVL

Dynamic MOE of LVL specimens estimated from the fundamental frequency was calculated using the following equation (Zhang *et al.* 2011),

$$E_{D(fv)} = 0.9455 \rho f_0^{\,2} l^4 / h^2 \tag{3}$$

where $E_{D(fv)}$ is free-beam vibration MOE (Pa), ρ is green density (g/cm^3), f_0 is the fundamental frequency of oscillation (Hz), l is length of LVL specimen (mm), and h is height of LVL specimen (mm).

Static bending test

After completing the dynamic MOE measurements, three small specimens (20 by 20 by 500 mm) were sawn from each LVL sample in order to average the measurements. Static MOE of LVL specimens was obtained from the 3-points bending test using a Daojin AG-IC 10KN AUTOGRASDH machine (Daojin Inc., Japan). Prior to the test, the dimension and mass were measured at 11% MC. The specimens were loaded contiguously using center loading with span was 420 mm and tested to failure. Each one was tested. The formulas used to calculate static MOE are given in GB 1927~1943-1991(ATSPRC 1991).

RESULTS AND DISCUSSION

Dynamic MOE of Log, Veneer, and LVL

The testing results and physical properties of 13 poplar logs and the corresponding veneers and LVL products are listed in Table 1. The average of log (at 65-78% MC) resonance-based acoustic velocity was 3.05 km/s lower than the results of Douglas-fir log (3.77 km/s, unknown MC) obtained by Amishew and Murphy (2008). In addition, Wang and coworkers had tested the log velocity of Sitka spruce, W. hemlock, Jack pine, Ponderosa pine, Radiata pine, and a combination of these species (3.198, 3.004, 3.480, 1.982, 2.120, and 2.349 km/s, respectively); all of them were tested using HM200 (Wang *et al.* 2007a). All of these indicate that log acoustic velocity varies between species. In Table 1, it can be seen that LVL density (0.54 g/cm^3) was higher than that of veneer (0.44 g/cm^3) at a close MC range (the former was 8 to 10%, and the latter was 7 to 8%). This may be attributed to the hot pressing process and adhesive in LVL. Together with the higher acoustic velocity, the acoustic dynamic MOE of LVL (12.17GPa) is higher than that of veneer (10.05GPa, see Table 2). A statistical summary of MOE obtained from measurement on log, veneer, and LVL is presented in Table 2, which shows that the standard deviation and coefficient of variation (COV) for all 5 methods was in the same range of approx. 20%.

Table 1. Experimental Data obtained from Measurement on Log, Veneer, and LVL

Parameter		Log	Veneer	LVL
MC(%)	Max	78.0	8.3	10.1
	Min	65.3	7.2	8.2
	Mean	71.4	7.7	9.3
Density(g/cm^3)	Max	1.05	0.48	0.63
	Min	0.77	0.35	0.48
	Mean	0.93	0.44	0.54
Velocity(km/s)	Max	3.47	/	4.89
	Min	2.33	/	3.73
	Mean	3.05	/	4.42

The results of 13 total LVL beams obtained from TOF acoustic measurement and the dynamic MOE values of logs, veneers, and LVL are summarized in Table 2. The results show that average dynamic MOE measured from LVL beams by the TOF acoustic method (12.17 GPa, shown in Table 2) was generally higher than that measured from logs by the resonance-based acoustic method (8.73 GPa) and that of veneer specimens by the ultrasonic method (10.05 GPa) by 39.4% and 21.09%, respectively (Fig. 4).

Table 2. Statistical Summary of Data obtained from Measurement on Log, Veneer, and LVL

Parameter	Max	Min	Mean	Std. Dev.	COV(%)
Log acoustic MOE (GPa)	11.77	4.91	8.73	2.106	24.1
Ultrasonic veneer MOE (GPa)	12.30	6.40	10.05	1.96	19.51
TOF LVL MOE (GPa)	15.10	7.64	12.17	2.35	19.34
Free-beam LVL MOE (GPa)	15.66	7.41	12.60	2.79	22.16
Static LVL MOE (GPa)	14.31	5.24	10.71	2.99	27.9

The higher results for the acoustic method could be mainly due to the fact that log defects (knot, crack, decay, *etc.*) no longer exist in a contiguous zone where mechanical stresses could concentrate, and this effect greatly reduces the influence of the defects upon the stiffness, and makes the stiffness more uniform. The second reason is that the logs were measured in green condition, with 65 to 78% moisture content, which is much higher than LVL specimens with 5-6% MC. It is well known that with the increasing MC, the (static) MOE of wood decreases (Ross and Pellerin 1991; Sandoz 1993). Moreover, through adding adhesive and hot pressing, LVL products are much denser than the corresponding logs.

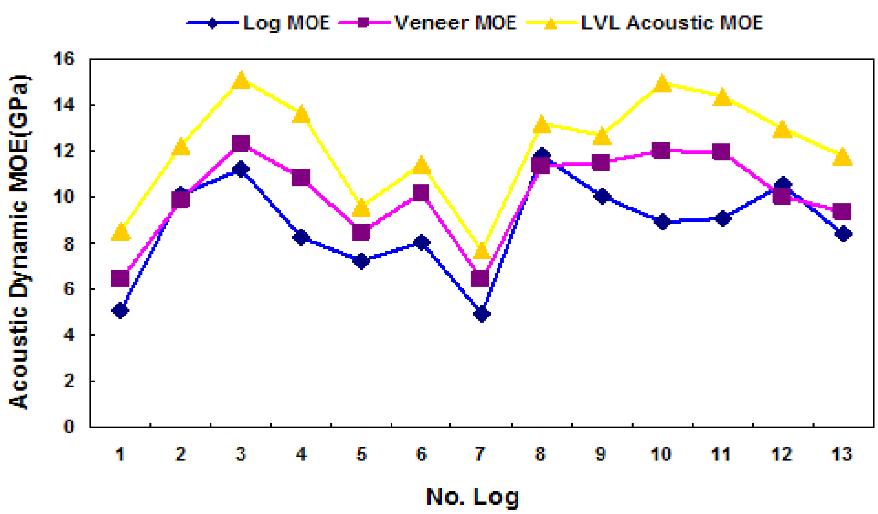
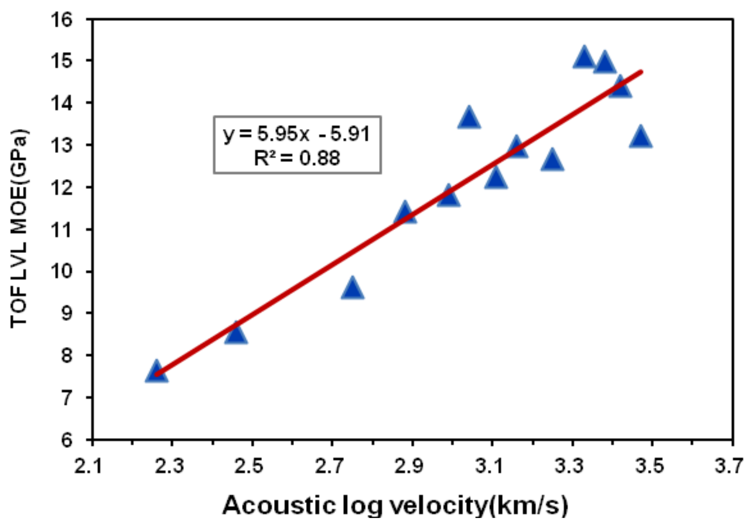


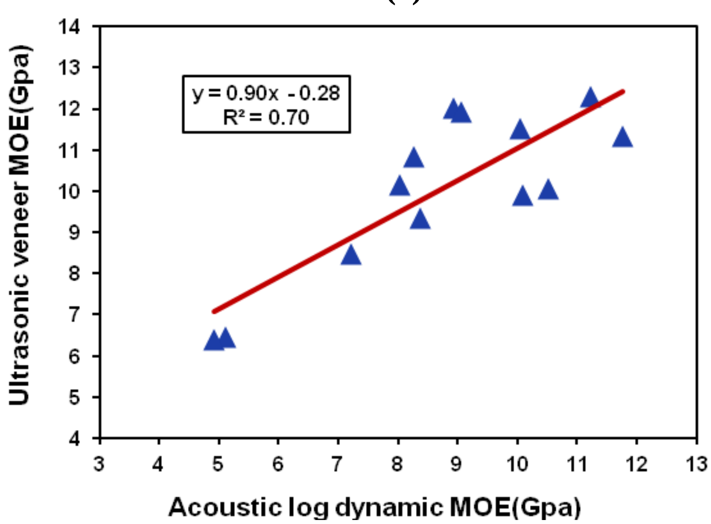
Fig. 4. Acoustic dynamic MOE of log, veneer, and LVL

Figure 5(a) shows the correlation between dynamic MOE values measured from LVL specimens and acoustic velocities measured from logs. Figure 5(c) shows the correlation between dynamic MOE values obtained from the log resonance-based acoustic test and the LVL TOF acoustic test. Regression analysis indicated that there were linear correlations between them giving a coefficient of determination (R^2) of 0.88 and 0.65, respectively at the significance level P of 0.001. So both the log resonance-based acoustic velocity and the dynamic MOE were judged to be good predictors of the LVL made from the processed logs.

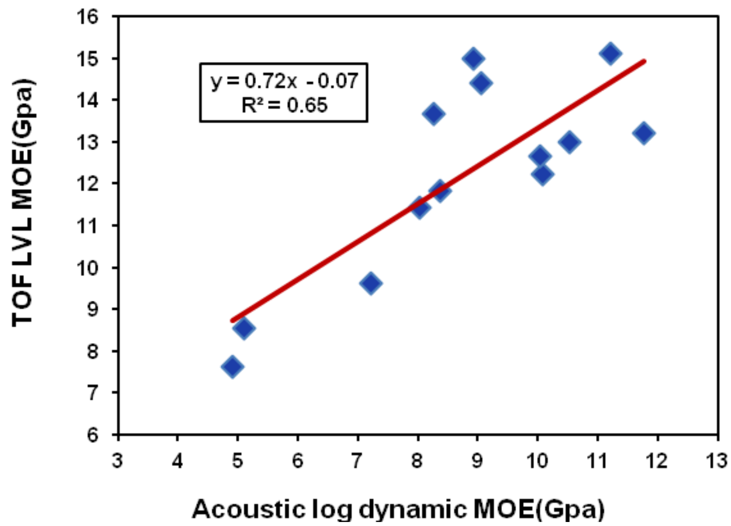
In this study, a value chain from logs to end products was present, namely, the MOE results for LVL were compared with the average MOE value of veneers from which the LVL beam was made, and the average MOE of veneers was compared with the MOE values of logs sampled for peeling. Figure 5 shows the relationships between dynamic MOE of logs, veneers, and LVL. Obviously, the correlation between dynamic MOE values of veneer sheets and LVL specimens was the strongest (R^2=0.93 at P of 0.001), the correlation between dynamic MOE values of veneer sheets and logs was moderately good (R^2=0.70 at P of 0.001), and the correlation between log and LVL dynamic MOE was the lowest but acceptable (R^2=0.65). The discrepancy could arise from the fact that each log was not completely converted to veneer due to the peeler core (Achim *et al.* 2011) unlike sawn lumber from round logs (Matheson *et al.* 2002; Carter *et al.* 2006). As a result, an LVL mill can still use the resonance-based acoustic method to sort logs based on their stiffness values as the correlation coefficient R is 0.81 at P of 0.001.



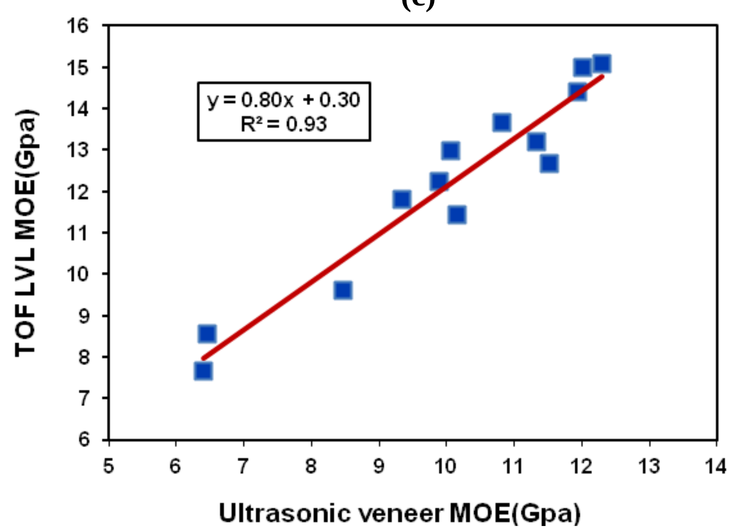
(a)



(b)



(c)



(d)

Fig. 5. (a) Relationship between LVL dynamic MOE and log acoustic velocity. **(b)** Relationship between dynamic MOE of log and veneer. **(c)** Relationship between Dynamic MOE of Log and LVL. **(d)** Relationship between dynamic MOE of log and veneer.

Relationship between LVL Dynamic MOE Measured by TOF Acoustic and Free-beam Vibration Methods

Figure 6 illustrates the comparison of LVL MOE values measured with the two methods. The experimental data indicated that LVL dynamic MOE values obtained from two measurements were basically the same, the exception being the large difference between the two kinds of dynamic MOE shown in No.6 and No. 13 for LVL (Fig. 6). Although there was no significant difference between the two ($p>0.05$), the free-beam vibration seemed to be slightly larger. In this study, LVL specimens in TOF and free-beam method tests were the same, and they were tested one after another at short intervals, so it can be thought that the density and MC of LVL were almost the same in both methods. So the reason for the slight difference between them could be that the free-beam vibration test involves a measurement of the flat-wise bending mode and the TOF is a measurement of the edge-wise bending mode. In general, due to the surface densification of LVL, the flat-wise bending MOE is slightly higher than the edgewise counterpart.

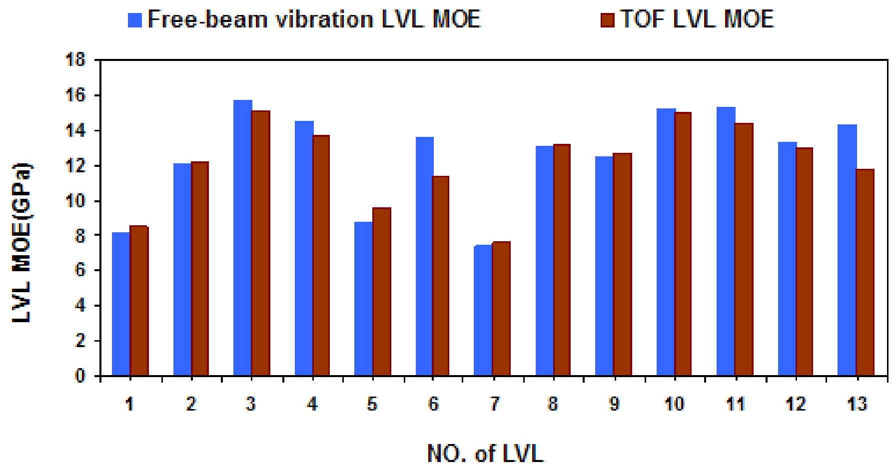


Fig. 6. Comparison of LVL MOE between vibration-based and TOF-based

The results of line regression analysis showed a strong correlation between those two methods of dynamic MOE measurements, giving an R^2 of 0.89 (at the significance level P of 0.001). The t-test showed that there was no significant difference in MOE obtained by those two methods. Thus, it can be concluded that both TOF acoustic and free-beam vibration methods are feasible for measuring LVL dynamic MOE and they can be effectively used for predicting the stiffness of LVL.

Relationship between LVL Acoustic Dynamic MOE and Static MOE

Figure 7 indicates a true correlation between LVL static bending MOE and dynamic MOE through the regression analysis. The static MOE was 12% lower than dynamic MOE (see Table 2), conforming to previous research (Raymond *et al.* 2007).

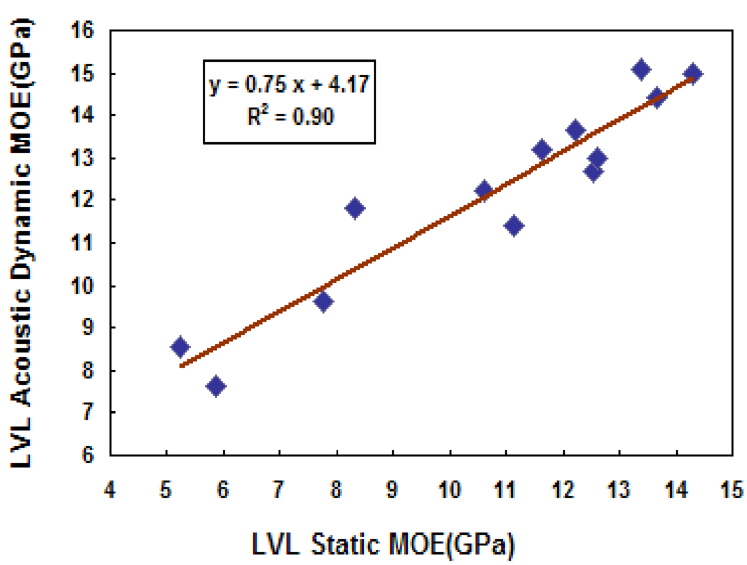


Fig. 7. Relationship between acoustic dynamic MOE and static MOE of LVL

In a study on the prediction of wood quality of poplar I-72 green logs, the static MOE of small clear wood specimens was 15 to 20% higher than the dynamic MOE of green logs (Yin *et al.* 2011). This result is contrary to the current results in this study. The MC of test materials is the main factor leading to the disagreement, as the TOF acoustic dynamic MOE increase along with the MC. It is clear that in Yin's study, the MC of the test materials varied widely, but in this study the specimens' MC in both methods were basically the same. So it can be concluded that the static MOE was lower than dynamic MOE for wood materials in the same condition. Furthermore, with this correlation R^2=0.90 at P of 0.001, which is nearly the same as the result (R=0.95) that has been established for Douglas-fir (Ross and Pellerin 1991), the resonance-based acoustic technology can be judged as being useful for assessing static MOE and could be optimized by fine tuning log acoustic velocity thresholds for log sorting.

Log Grading Based on LVL Dynamic MOE

Figure 8 shows the distribution of resonance-based acoustic velocities for 238 poplar logs. The average velocity of logs was 3.15 km/s with a standard deviation of 0.39 km/s. The variation in velocity can come from external factors (silvicultural practices and growing environmental, such as the regional climate, soil characteristics) combined with internal factors (age, MC, density, and inherent difference between logs that are assumed to be of a genetic origin).

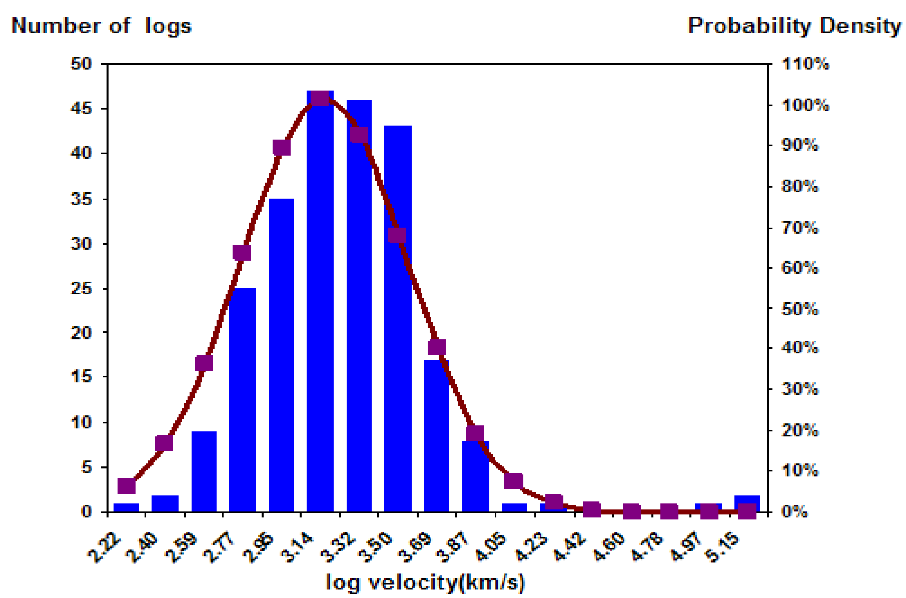


Fig. 8. Population distribution of log velocities

According to GB/T20241-2006 *"Laminated Veneer Lumber standard"*, the grade outturns of logs based on LVL TOF acoustic dynamic MOE (or LVL free-beam vibration dynamic MOE) were summarized (Table 3). There were four LVL grades with different MOE requirements. Based on the range of each LVL grade, the thresholds of log acoustic velocities were estimated to determine the number of logs, and in turn log grade outturns. It was estimated that the log grade outturns were approximately 31.1% for LVL grade 1, 38.6% for LVL grade 2, and 26.1% for LVL grade 3.

Further study to achieve more accurate log sorting, as well as the effects of log moisture content (MC) and temperature on log acoustic velocities for more accurate log sorting, and in turn dynamic MOE, needs to be undertaken.

Table 3. Log Grading Based on the Requirements of LVL Dynamic MOE

Chinese LVL grade	LVL MOE range		LVL TOF MOE (GPa)	Log acoustic velocity (km/s)	Number of logs	Estimated log grade outturns (%)
	Low	High				
1	>=140E		MOE≥14	>=3.35	74	31.1%
2	>=120E	<140E	12 < =MOE < 14	3.01-3.34	92	38.6%
3	>=100E	<120E	10 < =MOE < 12	2.67-3.00	62	26.1%
4		<100E	MOE<10	<2.67	10	4.2%

CONCLUSIONS

1. In this study, the feasibility of using resonance-based acoustic technology for LVL production was assessed using Chinese polar logs. Log acoustic velocity and dynamic MOE tested were found to correlate very well in these measurements. Dynamic MOE values estimated from log resonance-based acoustic measurements were in good agreement with those measured from veneers and small LVL samples. Hence, the inherent relationship between the end LVL products and logs was revealed. The results demonstrated that the acoustic technology is a promising and valuable tool in assessing log dynamic MOE and thus sorting logs at the early stage of log supply chain.
2. There was also a significant correlation between LVL dynamic MOE measured with TOF acoustic method and free-beam vibration method; both measurements could be used to make optimal grading decisions based on the standard requirements of LVL stiffness.
3. According to GB/T20241-2006, four classes of logs were sorted based on LVL dynamic MOE. It was estimated that the log grade outturns were approximately 31.1% for LVL grade 1, 38.6% for LVL grade 2, and 26.1% for LVL grade 3.

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