Front. For. China 2009, 4(4): 382–387
DOI 10.1007/s11461-009-0064-9

ORIGINAL ARTICLE

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A comparative study on the velocities of stress wave propagation in standing *Fraxinus mandshurica* trees in frozen and non-frozen states

Abstract In order to improve the accuracy and reliability of identifying wood defects and to realize the maximum wood utilization of trees, we employed an experimental method to test the stress wave propagation velocity in standing *Fraxinus mandshurica* trees selected from the Harbin Forest Experimental Station in winter. Thirty standing trees in good conditions were taken as test specimens and stress wave propagation velocities were measured using a FAKOPP Microsecond Timer in trees in both fall and winter. The test data were processed with the aid of Excel and SPSS software. The results show that 1) the velocities in longitudinal and radial stress wave propagation in frozen *F. mandshurica* trees were much higher than those in the non-frozen trees; 2) there was a highly positive correlation between longitudinal stress wave propagation velocity in frozen and non-frozen states, with a correlation coefficient of 0.82, as well as a positive correlation between radial stress wave propagation velocity in frozen and non-frozen states with a correlation coefficient of 0.87; 3) in the frozen state, the longitudinal stress wave propagation velocity was significantly affected by the moisture content (MC) of standing tree, while it was not obvious in the non-frozen state and 4) the radial stress wave propagation velocity was not significantly affected by MC in either frozen or non-frozen state.

Keywords stress wave, *Fraxinus mandshurica*, frozen state, non-frozen state, propagation velocity, moisture content

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Received August 12, 2008; accepted December 24, 2008

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1 Introduction

A nondestructive testing method of wood based on stress waves has been developed rapidly in recent years. Research has shown that nondestructive stress wave techniques have good prospects of application in both the detection of internal defects in wood and the protection of trees (Duan et al., 2002; Wang et al., 2007). Simple time-of-transmission measurements are utilized in nondestructive stress wave testing experiments in order to determine the speed of stress waves. The method detects internal symptoms of disease or wood decay through variation of the velocities of stress wave transmission in the wood (Ross et al., 1992, 1994; Wang et al., 2002, 2003, 2004, 2007; Yang and Wang, 2005a, 2005b). A series of investigations has been conducted on the relationship between the stress wave velocity or transmission time and the mechanical properties of wood (Burmester, 1965; Yamamoto et al, 1998; Ross et al., 1997, 2001, 2005; Wang et al., 2001, 2002). Also, the assessment of structural conditions of moisture-affected wood members in service was studied (Wang et al., 2001, 2002; Brian et al., 2004). Especially, the relationship between the moisture content of wood and the longitudinal stress wave velocity has been involved in most studies (Brian et al., 2004; Han et al., 2006).

These investigations have shown that most of the objects detected using stress waves were either trees growing under normal temperatures or processed wood samples, and many studies have been conducted to analyze the factors affecting the velocities of stress wave propagation under these conditions. However, no studies have been applied in frozen standing trees. Given the particular climate and local timber production methods in northeastern China, most of the trees are harvested during cold winters and immediately processed in a frozen state. During winters, standing trees are in a condition of dormancy, in which case the mechanical properties and moisture content (MC) of standing trees are quite different from those during their growth state. It is clear that stress wave propagation velocities in frozen standing trees are different from those under normal temperatures. In order to obtain effective and reliable indications of the basic data concerning stress wave propagation in standing trees during winter, the longitudinal stress wave velocities in both frozen and non-frozen standing trees need to be further investigated. Accordingly, the accuracy of stress wave nondestructive evaluation (NDE) of wood will be enhanced by analyzing the different velocities during each season and clarify the relative properties that have an apparent impact on these velocities at various levels.

The main objective of our study was to test the live transmission speed of stress waves and moisture content of *Fraxinus mandshurica* in both frozen and non-frozen states in order to document scientific proof for increasing the utilization efficiency of woods during winter. *F. mandshurica* is one of the major fast-growing hardwood species in northeastern forests and is widely distributed in the northeast of China.

2 Materials and methods

2.1 Materials

Thirty standing trees of *F. mandshurica* in good condition were randomly selected from the Harbin Forest Experimental Station. The diameters at breast height (DBH) ranged from 19.9 to 31.5 cm and stems were absolutely straight with few knots. The measured indicators, such as stress wave propagating velocity and MC, were tested at the prevailing temperature of the surroundings, ranging from −20°C to −5°C in January 2008. Similar survey procedures were also adopted in October 2008 at temperatures from 15°C to 20°C on the selected trees.

2.2 Methods

Time of propagation (TOP) of stress waves in standing tree was determined by a FAKOPP Microsecond Timer, which measured the time of stress wave propagation between two transducers. Two pins of the Timer were screwed into the xylem. One screw head was connected to a pulse sensor and the other head was hit by a hammer (Figs. 1 and 2). Stress waves can be started by the impact of the hammer. The time in both radial and longitudinal directions of the standing trees were measured. The angle between the transducer pin and fibers was fixed between 45° and 60°. Readouts are not reliable if the angle is larger than 60°.

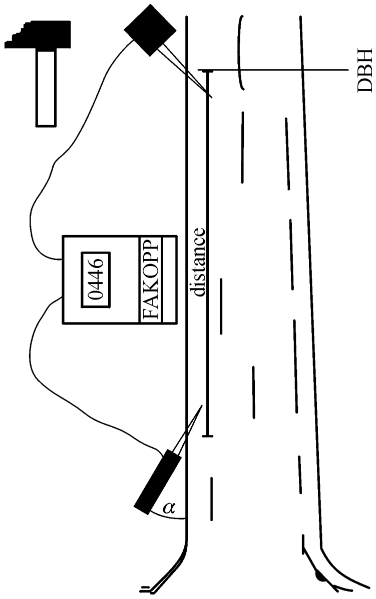

Fig. 1 Setup for velocity measurements in longitudinal direction

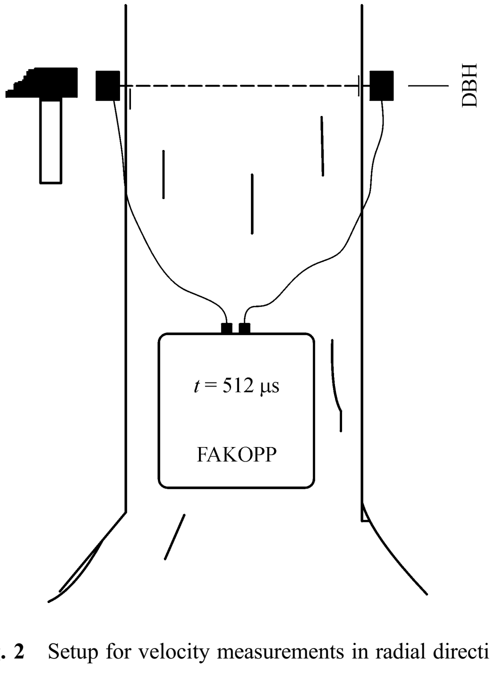

Fig. 2 Setup for velocity measurements in radial direction

For each tree specimen, a label was printed on the tree bark at a height of 200 cm. Then, two pins of the transducer were screwed into the xylem at about 50 and 150 cm above the butt. The DBH of the tree was measured with a caliper. The distance between the two pins was measured with a steel ruler after fixing the two pins. Finally, the longitudinal time of propagation of stress wave was established after striking the start end of the transducer. Average TOP values of more than six strikes, conducted in three different directions in order to obtain precise records, were calculated. The radial TOP values of stress waves across the stem were obtained in the same way. Calipers were used to determine the DBH of the specimens. At length, digital lumber MC instruments (ST-85 and KT-80) were used to measure the MC at breast height of the standing trees. It is also important to note that the gears of the digital lumber MC instruments can be manually changed according to the prevailing temperature of the environment. Also, the error of the FAKOPP caused by the temperature is merely a system error, which can be easily adjusted.

3 Results and analyses

3.1 Descriptive statistics of results

Thirty standing trees were measured in this experiment. A pair of longitudinal times of propagation of stress wave was measured in zygomorphic orientation of each tree, respectively. Corresponding MC was also measured in zygomorphic orientation. Therefore, 60 pairs of values of longitudinal velocities and MC were obtained. The experimental data, measured in frozen (winter) and non-frozen (fall) states, were processed by statistical software. The longitudinal stress wave propagation velocities (LV), radial stress wave propagation velocities (RV) and moisture content (MC) were analyzed by SPSS (Statistical Product and Service Solutions) after being arranged and calculated by Excel. Descriptive statistics of the specimens are shown in Table 1.

As shown in Table 1, the longitudinal velocities ranged from 3935.74 to 4610.04 m/s with an average value of 4270.97 m/s in standing frozen *F. mandshurica* trees, while the LV of the non-frozen trees ranged from 3491.66 to 4498.63 m/s with an average value of 3970.83 m/s. The radial velocities of trees in the frozen state ranged from 1469.12 to 2303.60 m/s with an average of 2006.28 m/s, while the RVs in non-frozen trees ranged from 1107.27 to 1817.75 m/s with an average value of 1558.01 m/s. The moisture content of standing trees in frozen state ranged from 22.60% to 37.50% (average 29.8%) and from 51.50% to 67.50% (average 57.7%) in the non-frozen state. The stress wave longitudinal velocity in the fall was about 4.5% lower than that in winter and the radial velocity was about 8.6% lower, while the moisture content was about 20% higher.

3.2 Analyses of variance (ANOVA) on stress wave velocities and MC

Both longitudinal and radial velocities as well as MC in the two states met the parametric assumptions required for one-way ANOVA, which was established through normal distribution tests and tests of homogeneity of variances, as shown in Table 2.

As shown in Table 2, with a probability of $\alpha < 0.000$, the mean square value of the between groups was far greater than that within groups, which indicates that the difference of the time of stress wave propagation and MC between frozen and non-frozen trees was greater than those within groups caused by random errors. Therefore, we can draw the conclusion that both longitudinal and radial velocities as well as MC in winter were markedly different from those in the fall. Velocities in trees in the frozen state were obviously higher than those in the non-frozen state. The mean difference of LV was about 300 m/s with a

Table 1 Basic description of test results

parameters		*N*	means	std.	std. error	95% CID
DBH/cm		30	23.8	3.47	0.67	22.8–25.55
LV/($\mathrm{m\cdot s^{-1}}$)	fall	60	3970.83	246.61	45.02	3878.75–4062.92
	winter	60	4270.97	182. 60	34.63	4210.62–4352.28
RV/($\mathrm{m\cdot s^{-1}}$)	fall	60	1558.01	194.35	35.48	1485.44–1630.58
	winter	60	2006.28	208.28	38.03	1928.45–2084.00
MC/%	fall	60	57.70	2.12	0.59	56.49–58.91
	winter	60	29.80	4.21	0.77	28.22–31.37

Note: *N* is the number of cases, std. is standard deviation and 95% CID is the 95% confidence interval for differences

Table 2 ANOVA of stress wave velocities

parameters		SS	*df*	MS	*F*	*p*
LV/($\mathrm{m\cdot s^{-1}}$)	Bg	1.4×10^{6}	1	1.3×10^{6}	28.7	0.000
	Wg	2.7×10^{6}	58	4.7×10^{4}		
RV/($\mathrm{m\cdot s^{-1}}$)	Bg	3.0×10^{6}	1	3.0×10^{6}	74.3	0.000
	Wg	2.4×10^{6}	58	4.1×10^{4}		
MC/%	Bg	1.1×10^{4}	1	1.1×10^{4}	795.3	0.000
	Wg	8.3×10^{2}	58	14.4		

Note: Wg is within group, Bg is between groups, SS is sum of squares, *df* is degrees of freedom, MS is mean square, *F* is the *F* value and Sig. is the level of significance.

standard deviation of 299 m/s, and the mean difference of RV was about 448 m/s with a standard deviation of 311 m/s. Therefore, the differences in both longitudinal and radial velocities as well as in MC between the two states were significant.

3.3 Correlations and regression analysis

Excluding the data of a sample of 10 groups by Casewise Diagnostics of SPSS, from comparisons among the remaining 50 samples, the longitudinal stress wave velocities in the frozen trees were, in a statistical sense, significantly related to moisture content of trees in the same state, with determination coefficient of 0.80. Any effect of MC on longitudinal velocity in the non-frozen state was not evident. Also, there was no marked correlation between radial stress wave velocity and MC in either frozen or non-frozen states of standing trees given their low correlation coefficient. There was, however, a highly positive correlation between both longitudinal and radial velocities in frozen and non-frozen states, with determination coefficients of 0.80 and 0.67, respectively. The regression models and R^2 for the velocities in both frozen and non-frozen states are shown in Table 3.

Table 3 Regression models and correlation coefficients for the velocities

	velocities in winter (Y)	R^2	N
LV_W–MC_W	$Y_L = 5422.37 - 38.64MC$	0.80^{**}	50
LV_W–LV_F	$Y_L = 478.75 + 0.92X_L$	0.67^{**}	30
RV_W–RV_F	$Y_R = -114.29 + 1.11X_R$	0.70^{**}	30

**: Correlation is significant at the 0.01 level (2-tailed). LV_F is longitudinal velocities in the fall, LV_W is longitudinal velocities in winter, RV_F is radial velocities in the fall, RV_W is radial velocities in winter and MC_W is moisture content in winter. Only 30 pairs of values of RV and LV were chosen to establish regression models because of avoidance of repetition.

Each group of measurements was considered normally distributed, passing the K-S test, given the process of distribution tests of wave stress velocities. Obviously, there were significant linear relationships in both longitudinal and radial velocities in frozen and non-frozen states. Regression analyses were also conducted between longitudinal velocities and moisture content both from trees in a frozen state (scatter plots are shown in Figs. 3, 4 and 5). Figure 3 shows a linear relationship between LV_F and LV_W, with a regression equation of $Y_L = 478.75 + 0.92X_L$ ($R^2 = 0.67$, significant at $\alpha = 0.01$, $N = 30$). The regression equation obtained between RV_W and RV_F was $Y_R = -114.29 + 1.11X_R$ ($R^2 = 0.70$, significant at $\alpha = 0.01$, $N = 30$) (Fig. 4). MC had a great impact on the longitudinal stress wave velocities in the frozen state as shown in Fig. 5. Without considering other factors, it can be stated that the relation between moisture content and the longitudinal velocity in the frozen state is $Y_L = 5422.37 - 38.64MC$ ($R^2 = 0.80$, significant at $\alpha = 0.01$, $N = 50$).

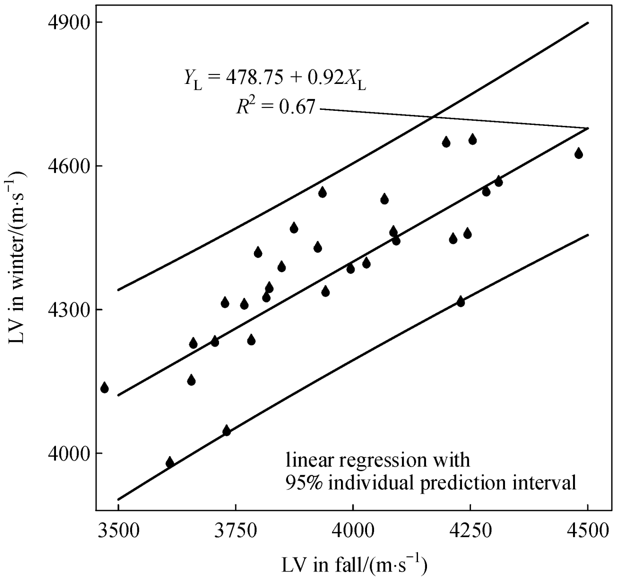

Fig. 3 Comparison between longitudinal stress wave propagation velocities in *Fraxinus mandshurica* in frozen and non-frozen states

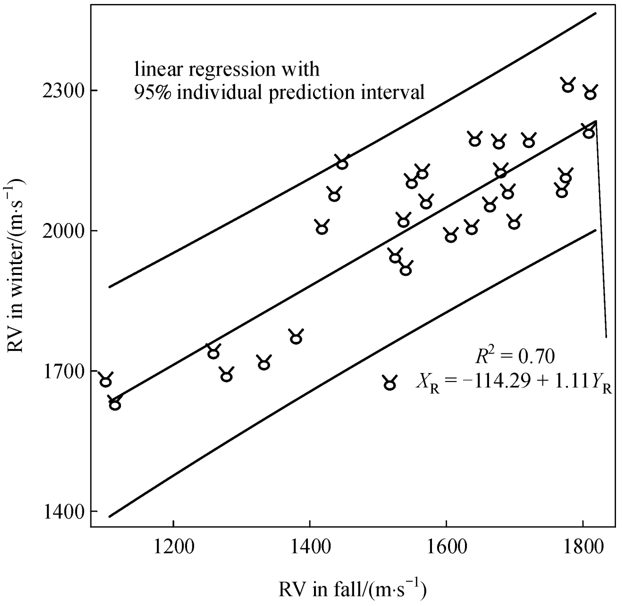

Fig. 4 Comparison between radial stress wave propagation velocities in *Fraxinus mandshurica* in frozen and non-frozen states

We found that the MC of standing trees in the frozen state were under the fiber saturation point (30%–40% MC). In this case, the effect of moisture content on the longitudinal stress wave velocity was significant. Because of heavy transpiration and illumination, the moisture content of standing trees in the fall is always over the fiber saturation point. With MC over the fiber saturation

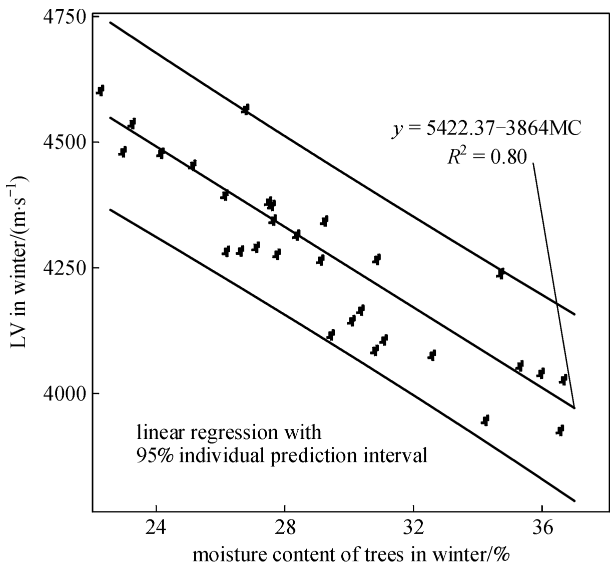

Fig. 5 Comparison between longitudinal stress wave propagation and moisture content of frozen *Fraxinus mandshurica* trees

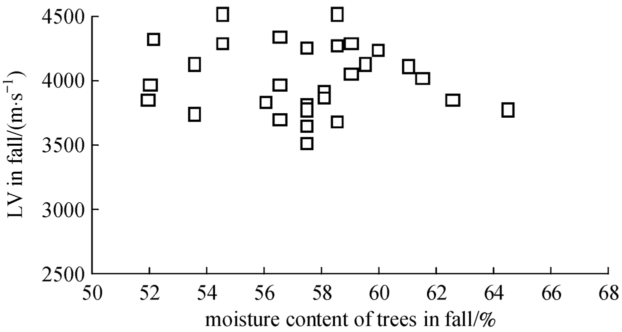

Fig. 6 Relation between longitudinal stress wave propagating and moisture content of *Fraxinus mandshurica* trees in a non-frozen state

point, the longitudinal stress wave velocity does not change all that much because the fibers are largely responsible for wave propagation. It is in this way that the lack of a statistically insignificant relationship between longitudinal velocities and MC in the non-frozen state can be explained (Fig. 6).

At the low outdoor temperatures and dormancy of trees, the moisture content of trees in the winter is under the fiber saturation point. Accordingly, MC exerted a significant effect on the longitudinal stress wave propagation velocity. Possible effects of DBH and radial velocities on longitudinal velocity in both frozen and non-frozen states were not observed in our study.

4 Discussion and conclusions

Stress wave velocities and MC in standing trees in both frozen and non-frozen states are clearly different. Longitudinal and radial velocities in the frozen state are, respectively, 300 and 448 m/s higher than those in the non-frozen state, while MC is 20% lower in the non-frozen state. A positive correlation was observed between the longitudinal velocities in frozen and non-frozen states, with a coefficient of determination of 0.64. In addition, a negative correlation was observed between longitudinal velocity and MC in frozen state with a coefficient of determination of 0.80, while MC exerted only a small effect on longitudinal velocity in the non-frozen state. It is really obvious that in both frozen and non-frozen states, neither MC nor DBH have any significant effect on radial velocity. Also, the effect of radial velocity on longitudinal velocity is not significant.

Because of the variation in MC and density of trees as well as the different light conditions during the seasons with attendant changes in growth parameters, stress wave velocities in standing trees are affected (Liu, 2004; Tao and Jin, 2005). In the frozen state, longitudinal velocity of stress wave propagation decreases as the MC increases. Longitudinal velocities in frozen standing trees are higher than those in non-frozen trees, which is confirmed by our theoretical explanations. These conclusions can be used to improve accuracy of NDE and efficiency of wood utilization from our comparisons and investigations.

Acknowledgements This study was financially supported by the China National Key Project (No. 2006BAD18B07) and the National Science Foundation of China SFC Project (Grant No. 30671643).

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