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Prediction of ultrasonic wave velocity in particleboard and fiberboard

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Abstract Ultrasonic wave velocities were determined at parallel and perpendicular to manufacturing direction and at the interval angles of 15° in clockwise and counterclockwise directions of particleboard and fiberboard. The experimental results were compared with the predicted values using some empirical formulae such as Hankinson and Jacoby equations. The results showed that the ultrasonic wave velocity were the highest in parallel direction in particleboard and fiberboard and decreases with increase of angle and the lowest values occurred in perpendicular direction. The predicted ultrasonic velocity using Hankinson and Jacoby equations are in close agreement with the measured values. Relationship between ultrasonic wave velocities and particles and fibers angle could be successfully presented by cubic and quadratic regression equations as well.

Introduction

Fiber and particles shape and alignment greatly affect the mechanical and anisotropic properties of particleboard (PB) and fiberboard (FB) panels, thanks to the high proportion of the fibers and particles in the composite panel and the orthotropic nature of the particles themselves. Generally, despite the random alignment of the fibers and particles, most of the fibers and particles are aligned parallel to production (manufacturing machine) direction. Furthermore, since ultrasonic wave velocity is greatly affected by the grain directions and grain angles in wood [1–3], the particles and fibers alignment affects the ultrasonic wave velocity in as the ultrasonic velocity is higher in parallel to production direction of PB and PF [4–8]. Hence the ultrasonic technique as a nondestructive, simple, fast, portable and flexible method was widely considered to be appropriate for evaluating the physical and mechanical properties of wood based composites including various static elastic and strength properties. The success of the ultrasonic technique for wood based panels such as PB and FB is primarily related to an understanding of ultrasonic wave propagation mechanism [9]. Therefore, considering to significance of particles alignment efficiency on ultrasonic wave velocity, it seems necessary to study of this efficiency and to predict this properties at different angles. The results considerably are useful in engineering design and performance.

The Hankinson's formula [10], an empirical equation developed bye the U.S. Army in 1921, is well known to predict strength properties of wood from grain angle:

$$N = (P \times Q)/(P \sin^n \theta + Q \cos^n \theta) \quad (1)$$

where N is strength property at an angle θ, P is strength property parallel to grain, Q is strength property

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perpendicular to grain, n is an empirically determined constant and θ is grain angle. It was also used successfully to estimate ultrasonic velocity in wood [11, 12] and oriented strand board (OSB) [6].

The relationship between ultrasonic wave velocity and grain angles has also been presented by the Jacoby equation (2) which can be written as:

$$V_\theta = V_0 \cos^n \theta + V_{90} \sin^n \theta \qquad (2)$$

where V_θ is the ultrasonic wave velocity at an angle θ from the grain direction, V_0 is the ultrasonic wave velocity parallel to grain, V_{90} is the ultrasonic velocity perpendicular to grain, and n is an empirically determined exponent. An attempt has also been made for estimating the ultrasonic properties from flack's angle by Wang and Chen [6].

The estimation of ultrasonic wave velocity in PB and FB from the particles and fiber angle using Hankinson and Jacoby equations could also be possible. An attempt has also been made for estimating the ultrasonic velocity from particles and fibers angle using statistical regression analysis. Through regression analysis of the data, two equations with the highest correlation coefficients were selected. Thus the purpose of this study is to develop a means for mathematically estimating and predicting the ultrasonic wave velocity in PB and FB.

Materials and method

Three full size commercial PB and three full size commercial FB panels were randomly selected for testing. Characteristics of manufacturing process and boards are given in Table 1. A disc of the diameter of 160 cm was prepared from each board. The discs were conditioned at 20 ± 2 °C and 65 ± 2% RH for two weeks. The parallel and perpendicular to production (manufacturing) directions were considered 0° and 90° angles and noted as particles and fibers angle. The through transmission ultrasonic method was carried out by using a commercial ultrasonic tester (Sylvatest Duo) of 16 kHz pulsed longitudinal waves. Two exponential piezoelectric conical transducers were used for transmitting and receiving the pulses. The measurements were taken from 0° to 90° at an interval of 15° in clockwise (CW) and counterclockwise (CCW) directions (Fig. 1). The transmission time of the pulses through the specimen was digitally displayed and manually recorded. Transmission time was measured to a time resolution of ±1 μs. The ultrasonic velocity was calculated by dividing the specimen length by the transmission time. The moisture content of specimens during measurement were 12 ± 1% for PB and 11 ± 1% for FB.

Table 1 Characteristics of manufacturing process and boards

Properties	Board	
	Fiberboard	Particleboard
Species	Mixture of Iranian forest hardwoods	Mixture of Iranian forest hardwoods
Structure	S1S (Smooth 1 Side)	3-layers
Resin	–	UF
Press type	Multi-opening presses	Multi-opening presses
Thickness (mm)	3	17
Density (g/cm^3)	0.75	0.63

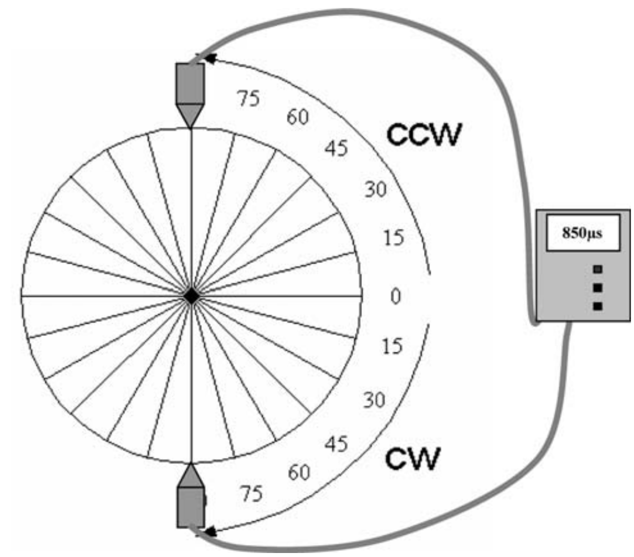

Fig. 1 Method for ultrasonic wave velocity measurement

Results and discussions

The predicted ultrasonic velocities using different equations and regression analysis along with experimental data at different angles are presented in Figs. 2–5. It is generally assumed that since ultrasonic wave velocity is a function of dynamic modulus of elasticity (MOE), the relationship between velocity and particles and fibers angle would conform to Hankinson's formula.

Average Absolute Errors (AAE) method was used to determine the best Hankinson and Jacoby equations for predicting ultrasonic wave velocity from the particles and fibers angle following the method of Armstrang et al. [11] and Kabir [12]. The calculated AAE percentage in CCW and CW are presented in Table 2.

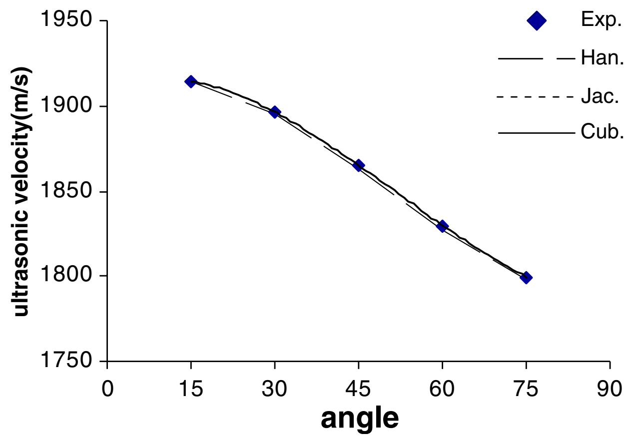

Fig. 2 Experimental and predicted ultrasonic wave velocity using different equations in CCW direction of PB

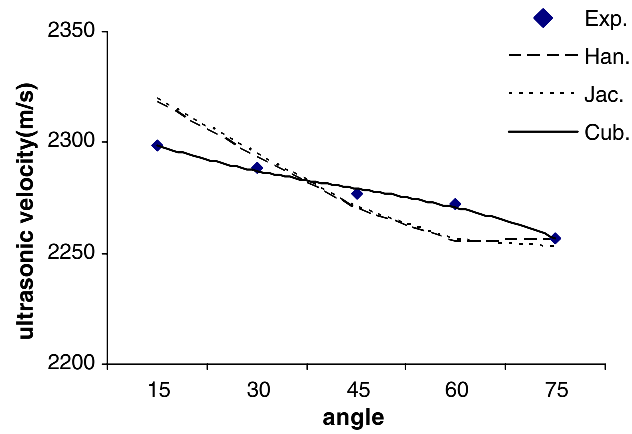

Fig. 5 Experimental and predicted ultrasonic wave velocity using different equations in CW direction of FB

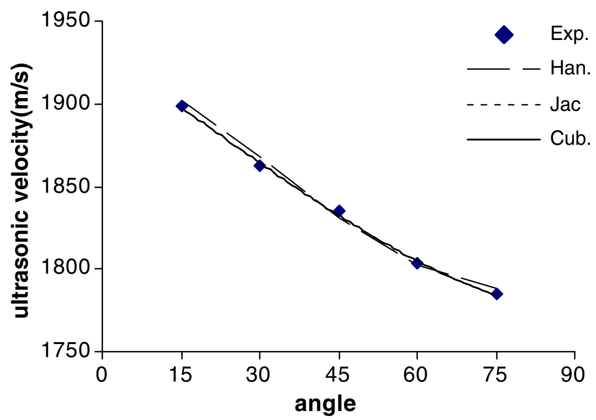

Fig. 3 Experimental and predicted ultrasonic wave velocity using different equations in CW direction of PB

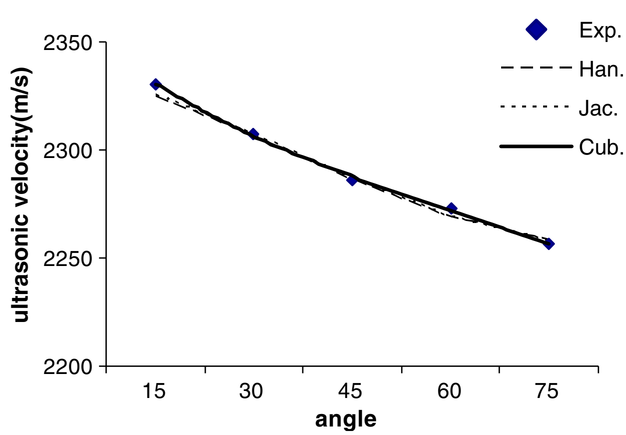

Fig. 4 Experimental and predicted ultrasonic wave velocity using different equations in CCW direction of FB

Table 2 Average Absolute Error (AAE) percentage for the ultrasonic wave velocity

Angle	PB				FB			
	CCW		CW		CCW		CW	
	Han.	Jac.	Han.	Jac.	Han.	Jac.	Han.	Jac.
15°	0.07	0.05	–0.20	–0.17	0.24	0.23	–0.87	–0.91
30°	–0.40	–0.47	–0.27	–0.14	0.04	0.01	–0.20	–0.26
45°	–0.39	–0.52	0.20	0.43	0.01	–0.02	0.31	0.27
60°	0.14	0.01	0.02	0.27	0.21	0.19	0.73	0.71
75°	0.40	0.34	0.22	–0.08	–0.10	–0.09	0.04	0.17

The negative sign in these tables means that the predicted value is greater than the average experimental value. It is observed from Figs. 2–5 that Hankinson and Jacoby equations fitted very well for ultrasonic velocity in PB and FB and the predicted ultrasonic wave velocities are in good agreement with experimental results. The AAE values are found below 1% when the particles and fibers angle increases from 15° to 75° (Table 2). Kabir [12] found that Hankinson equation fitted very well for ultrasonic velocity (AEE values below 10%) in different planes (LR, LT and RT) of rubber wood, but Jacoby equation predicted well only at an angle greater than 50° in LR and LT planes (well fitted for RT).

The exponent n in each equation of Hankinson and Jacoby was determined empirically for the best fitted data and the values are presented in Table 3. The value of the n exponent for Hankinson and Jacoby equation is 2.0 in both direction of CW and CCW in PB and FB. Kabir [12] obtained an n exponent between 1.6 and 2.0 for ultrasonic wave

Table 3 Calculated and predicted values of n for different types of equation

	PB				FB			
	Hankinson		Jacoby		Hankinson		Jacoby	
	Calculated	Predicted	Calculated	Predicted	Calculated	Predicted	Calculated	Predicted
CCW	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
CW	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

Table 4 Quadratic and cubic equations for ultrasonic wave velocity from angle in PB and FB

		Quadratic equation	Cubic equation
CCW direction	PB	$-0.009\ \theta^2 - 1.167\ \theta + 1935.9$ $r^2 = 0.9965$	$0.0004\ \theta^3 - 0.0677\ \theta^2 + 1.1436\ \theta + 1911.2$ $r^2 = 1$
	FB	$1.4516\ \theta^2 - 26.979\ \theta + 2355.6$ $r^2 = 0.9372$	$-0.4498\ \theta^3 + 5.4994\ \theta^2 - 37.594\ \theta + 2363.2$ $r^2 = 0.9982$
CW direction	PB	$0.0094\ \theta^2 - 2.7616\ \theta + 1937.6$ $r^2 = 0.9984$	$0.0001\ \theta^3 - 0.0072\ \theta^2 - 2.1059\ \theta + 1930.6$ $r^2 = 0.9987$
	FB	$-0.3257\ \theta^2 - 8.1118\ \theta + 2306.5$ $r^2 = 0.9829$	$-0.7336\ \theta^3 - 6.2763\ \theta^2 - 25.424\ \theta + 2318.9$ $r^2 = 0.9904$

velocity by Hankinson formula in different planes of rubber wood. The author obtained these values between 1.6 and 2.8 for Jacoby equation.

In addition to the prediction of the n exponents, these values were calculated by substituting the measured ultrasonic wave velocity data in different angles into Hankinson and Jacoby equations. The calculated n values are given in Table 3. The calculated and predicted n values are the same, 2, in both equations and both directions of CCW and CW.

Wang and Chen [6] calculated the optimal n values for ultrasonic wave velocity to be 1.8–2.1 and 2.8–3.2 in several kinds of the full piece size oriented strand board (OSB) by Hankinson and Jacoby equations, respectively.

Regression analyses indicate that cubic and quadratic equations provide the best fit of data with higher r^2 (Table 4). The usefulness of the regression equations for predicting studied properties from particles and fibers angle are determined by r^2 values. It is found from Table 4 that the cubic and quadratic equations can be used to estimate ultrasonic wave velocity from the particles and fibers angle. The high values of r^2 show that these parameters could be successfully calculated from particles and fibers angle by using the above mentioned equations. Generally the r^2 values in cubic equation were found to be higher than in quadratic for this reason only cubic equation were shown in the figures.

Armstrang et al. [11] found that the second-order parabolic and hyperbolic equations with r^2 ranging 0.97 and 0.99 can be used for estimating ultrasonic wave velocity from the grain angles in wood. Kabir [12] also reported similar equations for rubber wood.

As the results shows the ultrasonic velocity is the highest in production direction (0°) of PB and FB and decreases with increase of angle and the lowest value of ultrasonic velocity occurs at 90°. It shows most of particles and fibers are aligned parallel to production direction. The effect of the particles and fibers alignment on ultrasonic wave velocity of PB and FB is similar to the effect of the grain direction on the ultrasonic velocity in solid wood. Ultrasonic wave velocity in grain direction (longitudinal direction) of wood is the highest and it decreases rapidly by deviation of grain angle from longitudinal direction and reaches a minimum through grain perpendicular direction [2, 3, 13]. Similar results were obtained for OSB by Wang and Chen [6].

Furthermore, the anisotropy of PB an FB were studied by the ratio of V_0/V_{90}. These ratios were obtained 1.07 and 1.03 for PB and FB, respectively. Wang and Chen [6] reported higher values for OSB (2.9–3.2). Bucur et al. [8] obtained the same ratio for ultrasonic wave velocity to be 1.09, 1.21 and 1.01 for medium density fiberboard (MDF), OSB and chipboard, respectively. The difference between V_0 and V_{90} depends on the geometry and alignment of fibers and particles. A higher difference means more anisotropy property and better geometry and alignment. It means PB and FB are relatively in plane isotropic the contrary of solid wood that shows highly orthotropic behavior.

Conclusions

The ultrasonic wave velocity at different angles to manufacturing direction of PB and FB can be predicted using empirical equations of Hankinson and Jacoby and also with cubic and quadratic regression equations. The predicted ultrasonic wave velocity show good agreement to measured values in both CCW and CW directions of PB and FB using the Hankinson and Jacoby equations. The calculated and predicted n exponents by each equation are equal for ultrasonic wave velocity. Cubic and quadratic equations can also be used for estimating ultrasonic properties from particle angle having high r^2 values.

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