Ciência da Madeira (*Braz. J. Wood Sci.*), Pelotas, v. 02, n. 02, p. 64-74, Novembro de 2011
ISSN: 2177-6830

INFLUENCE OF MOISTURE CONTENT, SPECIFIC GRAVITY AND SPECIMEN GEOMETRY ON THE ULTRASONIC PULSE VELOCITY IN *Eucalyptus grandis* Hill ex Maiden WOOD

Leandro Calegari[1]; Darci Alberto Gatto[2]; Diego Martins Stangerlin[3]

Abstract: The use of ultrasound for the characterization of mechanical and physical properties is a well-defined technique for homogeneous materials such as metals. However, its application on heterogeneous and anisotropic materials like wood is more problematic. This study analyzes the influence of moisture content, specific gravity, and effect of specimen cross-section on ultrasonic pulse velocity in *Eucalyptus grandis* Hill ex Maiden. To do so, specimens of fixed length and height (3 and 25 cm, respectively) and varying width (5; 10 and 15 cm) were confectioned in order to obtain distinct base-height ratios: 1.67, 3.33, and 5. These specimens were dried in oven and monitored to determine the ultrasonic pulse velocity taking into account the longitudinal direction of the wood. Results indicated the moisture content as the main influence factor, and the specific gravity was revealed as having minor influence, whereas the base-height ratio of the specimens showed no statistically significant influence.

Keywords: wood acoustic properties; nondestructive testing; timber quality; plane face transducers.

INFLUÊNCIA DO TEOR DE UMIDADE, MASSA ESPECÍFICA E GEOMETRIA DOS CORPOS DE PROVA NA VELOCIDADE DO PULSO ULTRASSÔNICO EM MADEIRA DE *Eucalyptus grandis* Hill ex Maiden

Resumo: O uso do ultrassom para a caracterização das propriedades físicas e mecânicas é uma técnica bem definida para materiais homogêneos, como metais. Entretanto, sua aplicação em materiais heterogêneos e anisotrópicos, como a madeira, é mais problemática. Este trabalho analisou a influência do teor de umidade, massa específica e efeito da secção

[1] Forest Engineer, Ph.D., Adjunt Profesor of Forest Engineering Academic Unit, Center of Health and Rural Technology, Federal University of Campina Grande - Campus of Patos, PB, Brazil, <calegari@cstr.ufcg.edu.br>.
[2] Forest Engineer, Ph.D., Adjunt Profesor of College of Wood Industrial Engineering, Engineering Center, Federal University of Pelotas, Pelotas, RS, Brazil, <darcigatto@yahoo.com>.
[3] Forest Engineer, M.Sc., Assistant Profesor of Institute of Agricultural and Environmental Sciences (ICAA), Federal University of Mato Grosso (UFMT) – Campus of Sinop, Sinop, MT, Brazil, <diego_stangerlin@yahoo.com.br>.

Recebido em: 15/03/2011 e aceito em: 10/08/2011.

transversal do corpo de prova sobre a velocidade do pulso ultrassônico em madeira de *Eucalyptus grandis* Hill ex Maiden. Para isso, confeccionaram-se corpos de prova de altura e comprimento fixo (3 e 25 cm, respectivamente) e largura variada (5; 10 e 15 cm), a fim de obter distintas relações base-altura: 1,67; 3,33 e 5. Estes foram secos em estufa e monitorados para a determinação da velocidade do pulso ultrassônico considerando o sentido longitudinal da madeira. Os resultados acusaram o teor de umidade como sendo o principal fator de influência, sendo que a massa específica apresentou influência secundária, enquanto que a razão base/altura dos corpos de prova não apresentou influência estatisticamente significativa.
Palavras-chave: propriedades acústicas da madeira; ensaios não destrutivos; qualidade da madeira; transdutores de faces planas.

1 INTRODUCTION

Ultrasonic waves correspond to acoustic waves of frequency above 20 kHz, undetectable by the human ears, but, because of their high frequency, they may propagate into directed beams and, similar to the light, they may reflect when they find a discontinuity or flaw in the medium of propagation.

The determination of the propagation velocity of ultrasonic waves (ultrasonic pulse velocity) through wood represents an important practical application of acoustic properties in this material. In this sense, the use of ultrasound is an important tool with potential for classification of structural pieces of wood, which helps in the increase of quality and competitiveness (PUCCINI, 2002; BARTHOLOMEU et al., 2003).

The ultrasonic pulse velocity in a certain medium is directly related to the dynamic elasticity modulus (Ed) and inversely related to the specific gravity (SG) of this medium. Since these parameters (Ed and SG) also suffer some influences, ultrasonic pulse velocity is influenced by various factors (BUCUR, 2006). In wood, among the factors that perceptively influence the ultrasonic pulse velocity are fiber dimensions, frequency of rays, moisture content, specific gravity, reaction woods, grain angle, presence of flaws (knots and cracks), specimen geometry, medium conditions (temperature and relative air humidity), and the procedures used to take the measures, such as frequency and type of transducer (MISHIRO, 1996; FEENEY et al., 1998; GRUNDSTRÖM, 1998; SIMPSON, 1998; CARRASCO; AZEVEDO JÚNIOR, 2003; NESVIJSKI, 2003; BRASHAW et al., 2004; BALLARIN; NOGUEIRA, 2005, DYK; RICE, 2005; OLIVEIRA et al., 2005a; OLIVEIRA et al., 2005b; OLIVEIRA; SALES, 2006; CALEGARI et al., 2007; STANGERLIN et al., 2010).

Lumber grading by nondestructive testings is of major interest for timber industry. Studies carried out from 1988 on have shown good correlations among static destructive testing (static bending) and dynamic non-destructive testing (ultrasonic) and, taking this idea as a starting point, such correlations began being used for lumber classification using ultrasonic pulse velocity (BARTHOLOMEU et al., 2003).

The NBR 15521 (ABNT, 2007), the first Brazilian technical standard regulation that involves the application of ultrasound in woods, standardizes lumber classification using ultrasonic pulse velocity, which may be used in labs, sawmills, and factories. Due to the influence of many different factors, the NBR 15521 (ABNT, 2007) is restricted to sawn pieces of dicotyledonous wood, taken from adult trees, with specific gravity varying from 0.45 to 1.1 $g.cm^{-3}$, and in a parallel direction to the grain. Such a technical standard also establishes the frequency of the transducer with reference both to the length of piece and the correction of ultrasonic pulse velocity with wood moisture.

Considering that the quantification of the influences becomes very important for the analysis of results obtained in the most diverse application practices (e.g.: flaw detection, classification of wood, strength predictor in timber and large wood structures), this study aims at examining the influence of moisture content, specific gravity, and the effect of specimen cross-section on the ultrasonic pulse velocity in *Eucalyptus grandis* Hill ex Maiden wood.

2 MATERIAL AND METHODS

Eucalyptus grandis Hill ex Maiden wood was obtained from a sawmill located in Pelotas, state of Rio Grande do Sul, Brazil. This wood was collected from three trees, recently cut down and converted into planks (3 cm thick).

Using these portions of boards with no flaws, specimens of 25 cm in length, with a variable width (5; 10 and 15 cm), were confectioned in order to obtain different base-height ratios: 1.67, 3.33, and 5. Ten specimens for each base-height ratio were confectioned, all of which were dried in an oven at 80°C.

During the drying process, specimens were removed from the oven individually for the determination of the ultrasonic pulse velocity in the longitudinal plane of wood and, simultaneously, of its mass, which was immediately reinstated.

The ultrasonic pulse velocity was measured using a portable ultrasonic non-destructive testing (PUNDIT) meter, equipped with plane face transducers that generate waves of volume, at a frequency of 50 kHz. The transmitting transducer and the receiving transducer were placed facing each other with the specimen in between. The travel time (transmitting time) was recorded as displayed on the meter screen. The ultrasonic pulse velocity was measured by Equation 1.

$$\text{Upv} = \frac{\text{L}}{\text{T}} \qquad \text{(Equation 1)}$$

Where: Upv = ultrasonic pulse velocity ($m.s^{-2}$); L = length of the specimen (m); T = travel time of the pulse through the specimen (s).

Simultaneous determinations (ultrasonic pulse velocity and mass) were taken from wet specimens (moisture content above 30%) until they were completely dry (moisture content equal to 0%). For mass determination, an analytical balance was used. Based on the dry mass, the moisture content corresponding to the exact time of determination of the ultrasonic pulse velocity was calculated. Finally, specimens were placed in an acclimatized room until they reached equilibrium moisture content of 12% and, then, their specific gravity was estimated.

Experimental results were analyzed by regression analysis. Linear models were selected to better estimate the dependent variable ultrasonic pulse velocity (Upv) based on independent variables such as moisture content (MC), specific gravity at 12% moisture ($SG_{12\%}$), and base-height (b/h) ratio, considering a 5% error probability. Later on, graphics comparing the effects of variables were generated.

3 RESULTS E DISCUSSION

Results indicated an increase of the ultrasonic pulse velocity with the progression of the drying process. Like the moisture content, the specific gravity also had significant influence. On the other hand, the base-height ratio of the specimens did nor show any statistically significant influence (Table 1).

Table 1. Statistical model and variance analysis of moisture content (MC) influence, specific gravity at 12% of moisture ($SG_{12\%}$), and base-height (b/h) ratio of specimens at ultrasonic pulse velocity (Upv) in *Eucalyptus grandis* Hill ex Maiden wood.
Tabela 1. Modelo estatístico e análise de variância da influência do teor de umidade (MC), massa específica a 12% ($SG_{12\%}$) e razão base-altura (b/h) dos corpos de prova em função da velocidade do pulso ultrassônico (Upv) na madeira de *Eucalyptus grandis* Hill ex Maiden.

Equation				$R^2_{adjusted}$ (%)	S_{yx}
Upv = 4688.78 - 37.6084 MC + 944.403 $SG_{12\%}$ - 5.44661 b/h				72.6	151 $m.s^{-1}$
Source	Degree of freedom	Sum of squares	Mean square	F-Ratio	P-Value
MC	1	6.319 x 10^6	6.7319 x 10^6	295.17	0.0000**
$SG_{12\%}$	1	292025.0	292025.0	12.80	0.0005**
b/h	1	6201.65	6201.65	0.27	0.6031 NS
Model	3	7.03013 x 10^6			

** = significant at 5% probability; NS = not significant.

The magnitude of influence of each variable can be observed by comparing Figures 1, 2, and 3, since they have the same range of values of the dependent variable (4000 to 5000 $m.s^{-1}$).

3.1 Effects of moisture content on ultrasonic velocity

Considering the moisture content from the dry wood (MC= 0%) up to the fiber saturation point (MC= 30%), a great influence of humidity on the ultrasonic pulse velocity was observed in an inverse relationship (Table 1 and Figure 1).

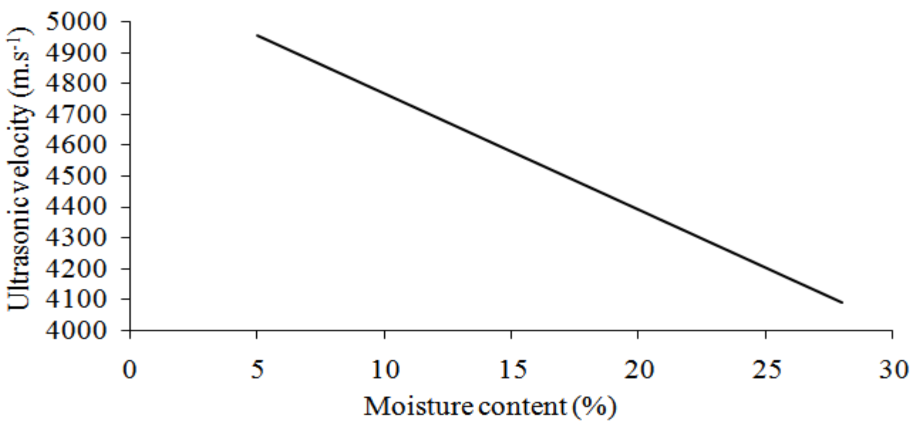

Figure 1. Influence of moisture content on ultrasonic pulse velocity in *Eucalyptus grandis* Hill ex Maiden wood. Diagram created from the equation presented in Table 1, with the specific gravity and the base-height ratio (0.5 $g.cm^{-3}$ and 3.33, respectively) kept constant.
Figura 1. Influência do teor de umidade na velocidade do pulso ultrassônico na madeira de *Eucalyptus grandis* Hill ex Maiden. Diagrama criado a partir da equação apresentada na Tabela 1 com a massa específica e a razão base-altura (0,5 $g.cm^{-3}$ e 3,33, respectivamente) mantidas constantes.

The increase of the ultrasonic pulse velocity due to the reduction of moisture content - especially for moisture contents values lower than the fiber saturation point (FSP) - has contributed to various research works (e.g.: SIMPSON, 1998; PUCCINI, 2002; WANG et al., 2003; BRASHAW et al., 2004, OLIVEIRA et al., 2005a; CALEGARI et al., 2007).

The reduction of wood moisture content causes an increase of the dynamic elasticity modulus (Ed) and, consequently, a reduction of the ultrasonic pulse velocity (Upv), since these variables (Ed and Upv) are inversely related. Therefore, the ultrasonic velocity decreases drastically with the increase of MC from 0 to FSP, and, from this point (MC > FSP) on, the variation becomes small, as it occurs with the elastic properties of the wood.

When moisture is reduced, strength increases, and vice versa. This increase is due to changes in the cell walls, which become more compact. Their structure units come closer together and the attractive forces between chain molecules become stronger (TSOUMIS, 1991).

The ultrasonic pulse velocity is bigger in solid materials (cell wall) when compared to liquids (water). As for moisture content above the FSP, there is presence of water both in empty cells and in cell walls, which means that attenuation is greater when compared to moisture contents below the FSP, in which water occurs only in cell walls. Therefore, in this latter case, the amount of water is lower and, hence, the ultrasonic pulse velocity is greater.

3.2 Influence of specific gravity on ultrasonic velocity

Studies show distinct influences of specific gravity on ultrasonic pulse velocity: increasing, decreasing or not influencing it (MISHIRO, 1996; WANG et al. 2003; OLIVEIRA; SALES, 2006; CALEGARI et al., 2007). In the present case, the first situation occurred (Table 1 and Figure 2).

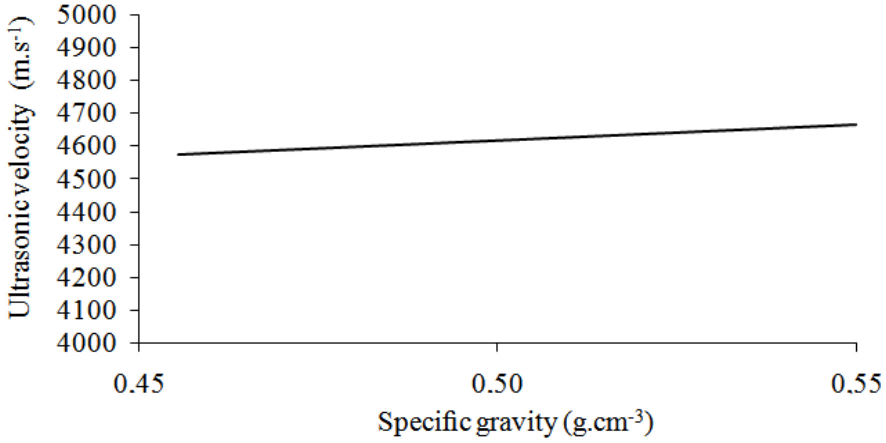

Figure 2. Influence of specific gravity on ultrasonic pulse velocity in *Eucalyptus grandis* Hill ex Maiden wood. Diagram created from the equation presented in Table 1, with the moisture content and the base-height ratio (14% and 3.33, respectively) kept constant.
Figura 2. Influência da massa específica na velocidade do pulso ultrassônico na madeira de *Eucalyptus grandis* Hill ex Maiden. Diagrama criado a partir da equação apresentada na Tabela 1 com o teor de umidade e a razão base-altura (14% e 3,33, respectivamente) mantidas constantes.

Referring to the *Eucalyptus grandis* wood, Oliveira; Sales (2006) also observed an increase in the ultrasonic pulse velocity with the increase of specific gravity. On the other hand, Calegari et al. (2007) found an inverse behavior.

Woods with high specific gravity present small cell lumens and thick walls, which favor the propagation of ultrasonic waves. Because of this, the largest ultrasonic pulse velocities are reached usually in woods with larger specific gravity. However, the increase of the specific gravity may be caused by the largest cellulose deposition in the inner layer of cellular walls. This deposition causes a more significant increase in the rigidity values than in the values of specific gravity. In that way, even if there is an increase of the specific gravity, the ultrasonic pulse velocity does not decrease, therefore it is compensated by the increase of rigidity (CARRASCO; AZEVEDO JÚNIOR, 2003).

Although most studies relate the ultrasonic pulse velocity directly with the specific gravity of wood, a more complete explanation would involve its anatomical constitution: wood with low specific gravity but with long cellular elements may present a higher ultrasonic pulse velocity when compared to wood with a high specific gravity but with short cellular elements. This way, longer cellular elements favor an increase of the ultrasonic pulse velocity, regardless its specific gravity (BUCUR et al., 2002).

3.3 Effects of specimen cross-section (ratio b/h) on ultrasonic velocity

A tendency of reduction of the ultrasonic pulse velocity with the increase of base-height ratio of specimen was observed, although not statistically significant (Table 1 and Figure 3).

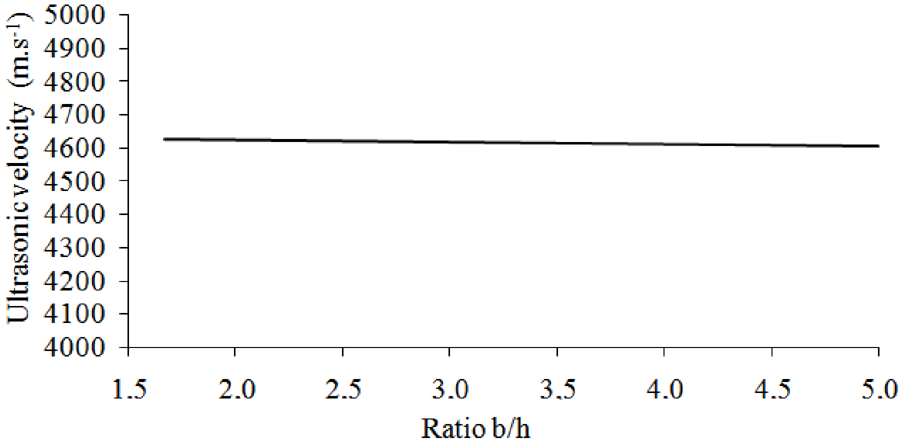

Figure 3. Not statistically significant of b/h ratio on the ultrasonic pulse velocity in *Eucalyptus grandis* Hill ex Maiden wood. Diagram created from the equation presented in Table 1, with the moisture content and the specific gravity (14% and 0.5 $g.cm^{-3}$, respectively) kept constant.

Figura 3. Ausência de significância estatística da razão b/h em função da velocidade do pulso ultrassônico na madeira de *Eucalyptus grandis*. Diagrama criado a partir a equação apresentada na Tabela 1 com o teor de umidade e a massa específica (14% e 0,5 $g.cm^{-3}$, respectivamente) mantidos constantes.

Studies on the influence of specimen geometry (length, width, and thickness) on the ultrasonic pulse velocity are shown by some authors (e.g.: BARTHOLOMEU et al., 2003; OLIVEIRA et al., 2005b, BUCUR, 2006). As to *Eucalyptus* sp. wood, Bartholomeu et al. (2003) described the variation of the ultrasonic pulse velocity as a function of the propagation distance (d), the wavelength (λ), and the ratio d/λ. For d/λ > 5, the velocity remained almost constant; however, for d/λ < 5, it decreased. When the same authors analyzed specimens with constant length and variable cross-section, they observed no reduction of the ultrasonic pulse velocity when specimen cross-section had a ratio bigger than 0.3, a factor that must be taken into account when structural lumber is analyzed.

Oliveira et al. (2005b) also report the variation of the ultrasonic pulse velocity in the cross-section of *Eucalyptus citriodora* Hook. Testings were carried out with initial cross-section of 12 cm x 12 cm, varying up to 12 cm x 1 cm, and constant length (50 cm). Results showed that the longitudinal ultrasonic pulse velocity decreased as the ratio between base and height (b/h) decreased.

Bucur (2006) discussed the influence of specimen length and specimen cross-section on the longitudinal ultrasonic pulse velocity measured for *Abies Alba* Mill. The ultrasonic pulse velocity was strongly reduced by the ratio width versus thickness with constant length. For the experiment with constant width and thickness, the ultrasonic pulse velocity was nearly constant when the ratio length versus width varied from 20 to 40. Below this limit, the longitudinal ultrasonic pulse velocity diminishes.

The reduction of ultrasonic pulse velocity due to increase of b/h ratio can be explained by different types of waves: when the dimensions of the piece are greater than the wavelength, propagation of pure bulk waves was observed and the piece started being penetrated by surface waves, which present a lower propagation velocity when compared to the volume waves (OLIVEIRA et al., 2005b; BUCUR, 2006).

It must also be considered that Bucur (2006) examined specimens with cross-section from 1 to 14, getting a reduction of 12% in the ultrasonic pulse velocity. On the other hand, in cross-section (b/h ratio) specimens varying from 1 to 12, Oliveira et al. (2005b) observed a reduction of the ultrasonic pulse velocity in about 4%. In the present paper, there was a reduction in about 0.5%, due to the low cross-section variation (ratio b/h from 1.67 to 5), which can explain its lack of significant influence.

Due to the fact that the influence of variable b/h is not statistically significant, the statistical model can be simplified to Upv = 4679.4 - 37.5787 MC + 928.189 $SG_{12\%}$, with $R^2_{adjusted}$= 73%, and S_{yx}= 150.5 $m.s^{-2}$.

4 CONCLUSIONS

Moisture content was the main factor influencing the ultrasonic pulse velocity in *Eucalyptus grandis* Hill ex Maiden wood, in an inversely proportional rate.

Specific gravity to the moisture content at 12% had a secondary influence, with an increase in the ultrasonic pulse velocity directly related to this increase. However, its influence should be the subject of further studies taking into consideration the anatomical characteristics of the wood.

There was a tendency towards the decrease in the ultrasonic pulse velocity with the increase of the base-height ratio of the specimens, though it was not statistically significant.

Due to the influence of various factors on the ultrasonic pulse velocity in wood, the ultrasonic device has to be calibrated and/or results must be corrected for each situation in order to avoid loss in the accuracy of the method.

Keeping in mind the idea that the present study was based on some specific conditions, additional research has to be carried out taking into consideration other specimen with different size, so that these calibrations/corrections can be applied with security.

6 REFERENCES

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). **NBR 15521:** Ensaios não destrutivos - Ultra-som - Classificação mecânica de madeira serrada de dicotiledôneas**.** Rio de Janeiro, 2007.

BALLARIN, A. W.; NOGUEIRA, M. Determinação do módulo de elasticidade da madeira juvenil e adulta de *Pinus taeda* por ultra-som. **Engenharia Agrícola,** Jaboticabal, v. 25, n. 1, p. 19-28, 2005.

BARTHOLOMEU, A.; GONÇALVES, R.; BUCUR, V. Dispersion of ultrasonic waves in Eucalyptus lumber as a function of the geometry of boards. **Scientia Forestalis**, Piracicaba, n. 63, p. 235-240, 2003.

BRASHAW, B. K.; WANG, X.; ROSS, R. J.; PELLERIN, R. F. Relationship between stress wave velocities of green and dry veneer. **Forest Products Journal**, Madison, v. 54, n. 6, p. 85-89, 2004.

BUCUR, V. **Acoustics of wood.** 2.ed. New York: Springer-Verlag, 2006.

BUCUR, V.; LANCELEUR, P.; ROGE, B. Acoustic properties of wood in tridimensional representation of slowness surfaces. **Ultrasonics,** Amsterdam, v. 40, n. 1-8, p. 537-541, 2002.

CALEGARI, L; STANGERLIN, D. M.; SANTINI, E. J.; HASELEIN, C. R.; LONGHI, S. J.; CARMO, P. I. O.; SILVA FILHO, L. C. P.; GATTO, D. A. Monitoramento do teor de umidade de madeiras de *Pinus elliottii* Engelm. e *Eucalyptus grandis* W. Hill ex Maiden, sob diferentes temperaturas de secagem, através do ultra-som. **Ciência Florestal,** Santa Maria, v. 17, n. 4, p. 399-408, 2007.

CARRASCO, E. V. M.; AZEVEDO JÚNIOR, A. P. Avaliação não-destrutiva de propriedades mecânicas de madeiras através de ultra-som - fundamentos físicos e resultados experimentais. **Cerne,** Lavras, v. 9, n. 2, p. 178-191, 2003.

DYK, H. V.; RICE, R. W. Ultrasonic wave velocity as a moisture indicator in frozen and unfrozen lumber. **Forest Products Journal,** Madison, v. 55, n. 6, p. 68-72, 2005.

FEENEY, F. E.; CHIVERS, R. C.; EVERTSEN, J. A. KEATING, J. The influence of inhomogeneity on the propagation of ultrasound in wood. **Ultrasonics,** Amsterdam, v. 36, n. 1-5, p. 449-453, 1998.

GRUNDSTRÖM, F. **Non-destructive testing of particleboard with sound and eigen frequency methods.** 1998. 60 f. Master's Thesis (Mechanical Engineering Master's Program) - Luleå University of Technology, Institute of Skellefteå, 1998.

MISHIRO, A. Effect of density on ultrasonic velocity in wood. **Mokuzai Gakkaishi,** Tokio, v. 42, n. 9, p.887-894, 1996.

NESVIJSKI, E. G. Dry point contact transducers: design for new applications. **The e-Journal of Nondestructive Testing,** v. 9, n. 9, Berlin: NDT.net, 2003. Available in: <www.ndt.net/article/v08n09/nesvi/nevsi.htm>. Accessed in: 20 dez. 2010.

OLIVEIRA, F. G. R.; CANDIAN, M; LUCCHETTE, F. F.; SALGON, J. L.; SALES, A. Moisture content effect on ultrasonic velocity in *Goupia glabra*. **Materials Research,** São Carlos, v. 8, n. 1, p. 11-14, 2005a.

OLIVEIRA, F. G. R.; MILLER, K. P.; CANDIAN, M.; SALES, A. Influência da seção transversal na velocidade ultra-sônica na madeira de *Eucalyptus citriodora*. **Cerne**, Lavras, v. 11, n. 2, p. 197-203, 2005b.

OLIVEIRA, F. G. R.; SALES, A. Relationship between density and ultrasonic velocity in Brazilian tropical woods. **Bioresource Technology**, v. 97, n. 18, p. 2443-2446, 2006.

PUCCINI, C. T. **Avaliação de aspectos de qualidade da madeira utilizando o ultra-som.** 2002. 139f. Doctoral Dissertation (Doctoral Program in Agricultural Engineering) - Universidade Estadual de Campinas, Campinas, 2002.

SIMPSON, W. T. Relationship between speed of sound and moisture content of red oak and hard maple during drying. **Wood and Fiber Science**, Pennsylvania, v. 30, n. 4, p. 405-413, 1998.

STANGERLIN, D. M.; GATTO, D. A.; MELO, R. R.; CALEGARI, L.; VIVIAN, M. A.; CASTELO, P. A. R.; BELTRAME, R. Uso do ultrassom para estimativa das propriedades mecânicas da madeira de *Peltophorum dubium*. **Ciência da Madeira,** Pelotas, v. 01, n. 02, p. 44-53, 2010.

TSOUMIS, G. **Science and technology of wood:** structure, properties, utilization. New York: Van Nostrand Reinhold, 1991.

WANG, S.Y.; LIN, C.J.; CHIU, C.M. The adjusted dynamic modulus of elasticity above the fiber saturation point in Taiwania plantation wood by ultrasonic-wave measurement. **Holzforschung**, Berlin, v. 57, n. 5, p. 547-552, 2003.