Wood Sci Technol (2012) 46:979–990
DOI 10.1007/s00226-011-0460-9

ORIGINAL

Observation of interference effects in air-coupled ultrasonic inspection of wood-based panels

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Received: 5 May 2011

Abstract The air-coupled ultrasonic inspection method is a widely applied non-destructive measuring technique in the wood-based panel industry. The technology is mainly applied to detect panel delaminations by analyzing the transmitted signal. Recent research deals with the use of ultrasonic techniques not only for the qualitative but also for the quantitative characterization of wood-based panels. To achieve a fundamental understanding of the behavior of ultrasonic waves in wooden panels, it is necessary to study the mechanisms that affect ultrasonic transmission and velocity during testing. Impedance and attenuation effects have been examined in previous studies. This article focuses on the interferences of ultrasonic waves. The interferences can be detected in experiments where the ultrasonic transmission is tested against the panel thickness. The results are verified with a mathematical model that explains the interferences due to multiple reflections inside the tested panels. By fitting

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the experimental data to the model predictions, the ultrasonic velocity and attenuation can be determined. So far, interference effects have not been considered for the non-destructive testing of wood-based panels. This research is a contribution to a better understanding of the mechanisms influencing the air-coupled ultrasonic methods.

Introduction

Air-coupled ultrasonic inspection is a common and widely applied non-destructive measuring technique in the wood-based panel industry. With air as the coupling medium, the ultrasonic measurements are taken online. This method allows the user to detect panel delaminations right after the pressing process and to control the production process in real time.

In an air-coupled through-transmission system, the ultrasound propagates through air, the tested sample and air again. In each layer, the ultrasonic waves are attenuated, and at each interface, they may be refracted, reflected and converted to other wave forms. The particular physical effects are mainly described by Krautkraemer and Krautkraemer (1986), Millner (1987), Kuttruff (1988), Rose (1999), Vary (2007). Information about air-coupled ultrasound as a non-destructive measuring tool was published by Buckley (2000) and Stoessel (2004).

Related to the detection of delaminations in wood-based panels, most research on ultrasound has been carried out by Kruse (1993), Niemz et al. (1999) and Bucur (2006). Other studies examined whether ultrasonic testing methods can be applied for the characterization of wood-based panels. Especially, the ultrasonic velocity was tested for a correlation with internal bond strength perpendicular to the plane of the board (Burmester 1968; Kruse et al. 1996; Bekhta et al. 2002) but also the influences of density (Niemz and Aguilera 1995) and particle type (Hilbers et al. 2009) on velocity were examined. Between the ultrasonic attenuation and internal bond strength, no correlation was found (Kruse 1993; Greubel and Plinke 1995; Schafstall 2001; Hasener and Thoemen 2003). The influence of density and particles on the ultrasonic attenuation was further discussed by Vun (2003), Hilbers et al. (2010) and Sanabria et al. (2010).

The interference effect is a phenomenon that is mainly known from optics where it is applied for Fabry-Pérot interferometers and used to control and measure the wavelengths of light (Hernandez 1986; Neumann et al. 2007). For ultrasound, the interferences in layered media have been examined in general by Brekhovskikh (1980). They have mainly been found due to varying frequencies and in other media than air and wood (Jackins and Gaunaurd 1986; Guyott and Cawley 1988; Rose 1999). So far, the interferences have not been considered for the air-coupled ultrasonic testing of wood-based panels.

Materials and methods

Theory

With air-coupled ultrasonic testing methods, acoustic waves propagate through three different layered media. The physical phenomena that occur during this inspection method are described by Brekhovskikh (1980).

A monochromatic plane acoustic wave that is incident on an interface between two media is split into a reflected and a transmitted wave. The transmitted wave is split again at the second interface and so on. Inside the second media, the wave propagates by reflections from one side to the other. To each side, a sequence of waves is transmitted. These waves superimpose each other and generate the entire signal which can be calculated as demonstrated below.

Figure 1 illustrates the incidence of an ultrasonic wave on a plane solid layer with the thickness d at an arbitrary angle. The authors examined the particular case where the surrounding layers $n = 1$ and $n = 3$ are the same media, in this case air. The air layers and the solid layer $n = 2$ are characterized by the sound impedance Z_n, which is a product of their material properties, density ρ_n and velocity c_n:

$$Z_n = \frac{\rho_n \cdot c_n}{\cos \theta_n}. \tag{1}$$

The angle θ_1 of the incident wave is determined by the experimental setup. According to Snell's law, the incident angle and the angles of refraction θ_2 and θ_3 are related to each other by the wave number k_n:

$$k_1 \cdot \sin \theta_1 = k_2 \cdot \sin \theta_2 = k_3 \cdot \sin \theta_{3.} \tag{2}$$

Taking the attenuation, expressed by the coefficient α, inside the solid material into consideration the wave number becomes complex:

$$k_2 = \frac{\omega}{c_2} + i\alpha. \tag{3}$$

The wave number in z direction, parallel to the panel thickness, also becomes complex and is related to k_2 by:

$$k_{2z} = k_2 \cdot \cos \theta_2. \tag{4}$$

Under the assumption that longitudinal waves are not being converted into other wave modes (transversal waves), the transmission coefficient T_T of the ultrasonic wave amplitude can be determined:

$$T_T = \frac{4 \cdot Z_1 \cdot Z_2}{(Z_1 + Z_2)^2} \frac{1}{\mathrm{e}^{-i \cdot k_{2z} \cdot d} - \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \cdot \mathrm{e}^{i \cdot k_{2z} \cdot d}}. \tag{5}$$

Fit procedure

To verify the experimental data, a fit function is developed using the procedure FindFit of the software package Mathematica© by Wolfram Research Inc (Champaign, USA).

Due to the large impedance difference between wood-based panel and air, the expression V_{12} from Eq. 5 is approximately equal to 100%:

$$\left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 = V_{12}. \tag{6}$$

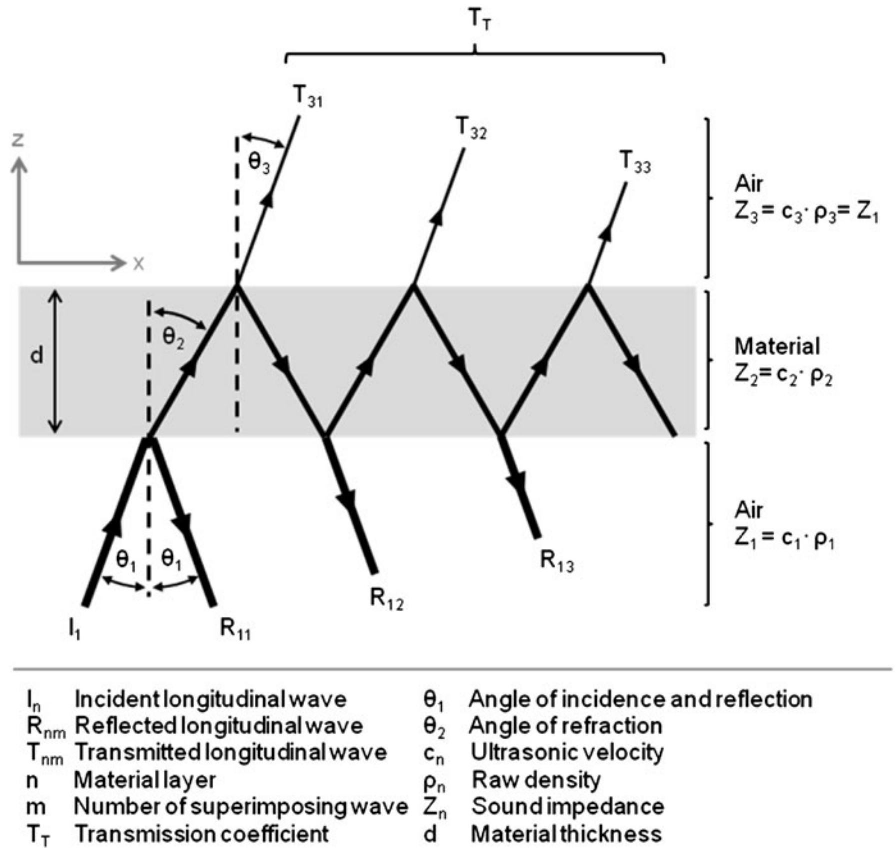

Fig. 1 Multiple reflections and transmissions in layered media

Consequently, V_{12} is kept constant, equal to one, and the following fit function $T(d)$ is developed:

$$T(d) = \frac{a}{\mathrm{e}^{-ik_{2z}d} - \mathrm{e}^{ik_{2z}d}}. \tag{7}$$

This function $T(d)$ is fit to the measured ultrasonic amplitude versus the wood-based panel thickness d with the fit parameters a, $\mathrm{Re}(k_{2z})$ and $\mathrm{Im}(k_{2z})$, the real and the imaginary part of the wave number in z direction.

With these fit parameters, the ultrasonic velocity and the attenuation inside the wood-based panel can be determined. Therefore, k_{2z} needs to be converted to k_2 by using Eqs. 2–4:

$$c_2 = \frac{\omega}{\mathrm{Re}(k_2)} \tag{8}$$

$$\alpha = \mathrm{Im}(k_2). \tag{9}$$

Experiments

For the experimental part of this work, three different wood-based panels, namely medium-density fiberboard (MDF), particleboard (PB) and oriented strandboard (OSB), were manufactured in a laboratory press. The industrially produced fibers consisted of 95% *Pinus sylvestris* L., and the strands were 100% *Pinus sylvestris* L. For the surface particles, 90% softwood (*Picea abies* L. and *Pinus sylvestris* L.) and for the core particles 90% *Pinus sylvestris* L. were used.

According to the experimental design, one fiberboard of 40 mm thickness and 500 kg/m^3 nominal density, one particleboard of 60 mm thickness and 600 kg/m^3 and one strandboard of 40 mm thickness and 700 kg/m^3 nominal density were produced. All boards were processed under identical conditions. For each sample, the surface and the core layer were mixed separately in a drum blender with a standard urea formaldehyde resin (BASF Kaurit 405, 10% dry solid content based on oven-dry mass of wood) and an ammonium-nitrate catalyst (3% based on dry solid content of adhesive). Considering the surface and core layer, the resinated fibers, particles or strands were manually and randomly formed into forming boxes of 600 × 400 mm^2. The mat was predensified and then moved into a computer-controlled hydraulic laboratory hot-press where the pressing process started immediately.

After conditioning the boards in a standard climate (20°C/65% relative humidity), they were trimmed to a size of 500 × 300 mm^2 to exclude the density decline at the edges. All wood-based panels were sanded symmetrically to a final thickness of 40 and 60 mm, respectively.

The density profile was determined with a measuring device using gamma radiation by Raytest Isotopenmessgeräte (Straubenhardt, Germany).

For the experiment, the boards were symmetrically sanded in 1-mm increments, with 0.5 mm on each side. After each sanding step, the ultrasonic transmission was measured with the testing system UPU 3000 from GreCon (Alfeld, Germany). The ultrasonic device was installed on a metal frame in the laboratory. The transmitter contains a piezoelectric ceramic where a 50-kHz pulse of 0.4 ms is generated. With an angle of 12°, the pulse propagates through air, is refracted into the tested material and travels through another air layer to the receiver on the opposite side of the material. The receiver is adjustable in height to maintain a constant distance to the testing material (Erhard et al. 1976). The receiver converts the transmitted wave into an analog electric signal ranging from zero to ten Volts.

All boards were measured at eight defined positions, and the average value was calculated.

Results and discussion

Experiments

First, the density profile perpendicular to the panel plane was tested. All panels show a distinct profile with a difference of 300–400 kg m^{-3} between the surface and the core layer (Fig. 2). Due to the increased density in the surface layers, the acoustic impedance is higher than in the core layer. Hilbers et al. (2010) show that the transmission is reduced with increasing acoustic impedance. However, the

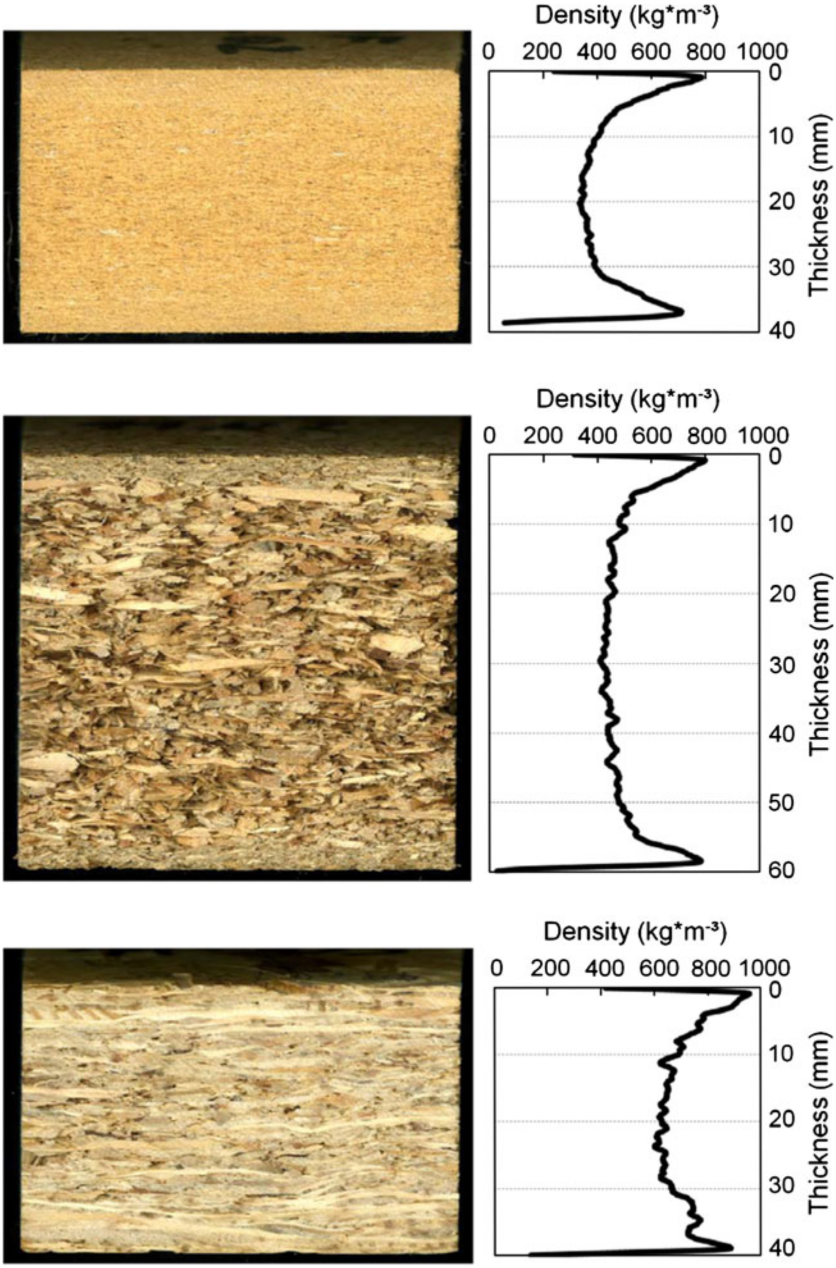

Fig. 2 Density profile of fiberboard (*top*), particleboard (*center*) and strandboard (*bottom*)

denser surface layers were sanded away by reaching a thickness of 25 and 45 mm, respectively.

The ultrasonic signal was tested against the thickness of the different wood-based panels. The results that are presented in Fig. 3 show the same trends for all panel types. First, pronounced oscillations of the transmitted signal are observed; second, the range between maxima and minima decreases with increasing thickness, and third besides the oscillations, a decreasing trend with increasing thickness is detected.

The entire signal T_T is a composition of the transmitted waves T_{nm} resulting from the multiple reflections inside the panel (Fig. 1). Due to the theory of Brekhovskikh (1980), the oscillations are interpreted as the interferences of the reflections during one ultrasonic pulse. The interferences become constructive for certain panel thicknesses. In this case, the transmitted waves T_{nm} are in phase with each other. Respectively, they become destructive if the waves are out of phase.

Three effects that influence the ultrasonic propagation in this application may be discussed here.

First, it was examined whether the ultrasonic pulse of 0.4 ms is long enough to cause multiple reflections. The angle of refraction of the ultrasonic signal (Eq. 2), its velocity inside the panel and the panel thickness determine the number of transmitted waves T_{nm}. For three examples of typical wood-based panels (6-mm high-density fiberboard (HDF), 19 mm MDF, 40 mm PB), Fig. 4 presents the number of transmitted waves T_{nm} the entire signal T_T is composed of. It is shown that the applied pulse generates several transmissions being capable to cause the observed interferences—even in panels of high thickness and low density.

Second, according to Snell's law, the ultrasonic waves with an incident angle of 12° are refracted with a certain angle into the panel. As a result of this, the ultrasonic waves are dislocated from the original path the further they travel. Consequently, the detection with the fixed receiver becomes difficult for those transmitted waves resulting from reflections with higher order. The dislocation is illustrated in Fig. 4, too.

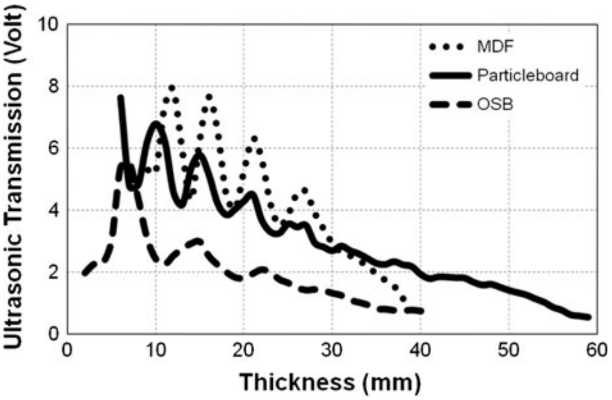

Fig. 3 Measured ultrasonic transmission against thickness of different wood-based panels

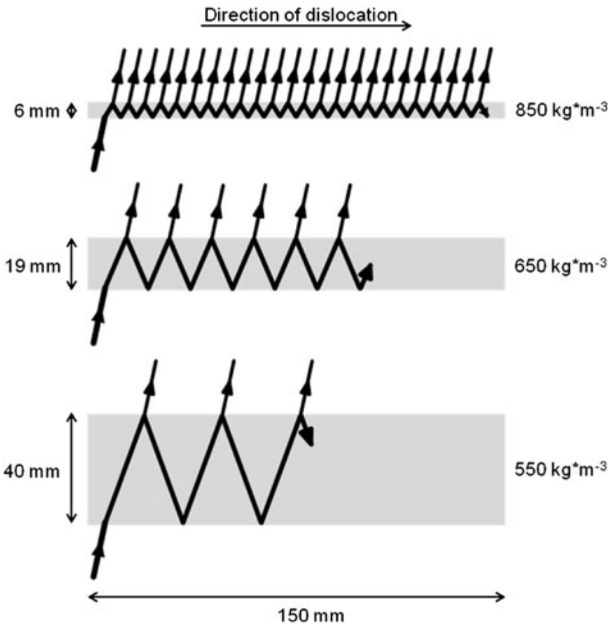

Fig. 4 Examples of multiple transmissions as a function of panel thickness and density—HDF (*top*), MDF (*center*), PB (*bottom*)

Third, besides the longitudinal waves that are examined in this paper, transversal waves are generated at the interface for oblique incident ultrasonic pulses. The superposition of longitudinal and transversal waves generates plate waves that propagate in the panel plane. The velocity and direction of these waves are different from those of longitudinal waves. The interested reader can find detailed information on this topic in the corresponding literature (Rose 1999; Drury 2005; Workman et al. 2007).

Fit procedure

To verify the interference theory, the experimental data are fit with the function described in Eq. 7. For particleboard and OSB, the best-fit curve was applied over the entire thickness. For MDF, the function showed the best result between a thickness of 13 and 30 mm. Figure 5 illustrates the calculated curves and the measured values for each panel type.

The experimental data are reproduced well by the applied function. Except for low thicknesses, the absolute values show good results. The small deviations between fit curves and the experimental data may be discussed:

Besides the described influence of density on the ultrasonic transmission, voids and particles that give wood-based panels a heterogeneous character cause variations in the ultrasonic signal and cannot be considered in the fit model.

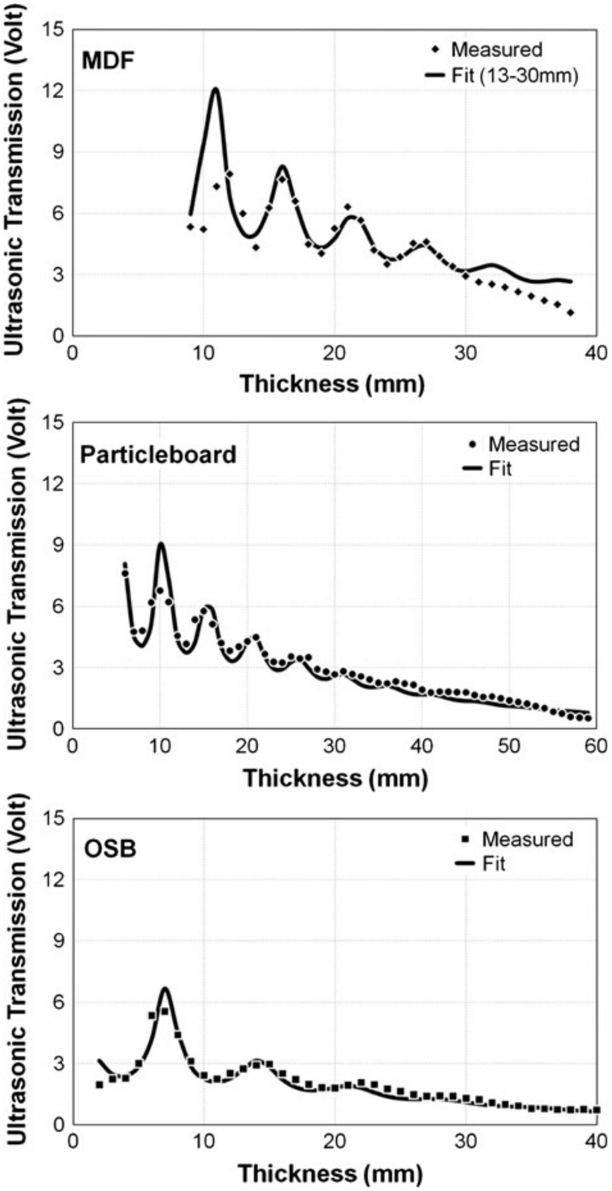

Fig. 5 Comparison of measured and calculated ultrasonic transmission for different wood-based panels

For the thickness measurements, a distance of 1 mm was chosen to verify the interference model. For an exact reproduction of the interference peaks, a higher resolution would be necessary. Nevertheless, the oscillations of the ultrasonic signal are represented well.

Table 1 Fit parameters and calculated ultrasonic velocity and attenuation for tested wood-based panels and thicknesses

Parameter	MDF (9–38 mm)	Particleboard (6–59 mm)	OSB (2–40 mm)	MDF (13–30 mm)
$\mathrm{Re}(k_{2z})$ (m^{-1})	554.9	604.7	437.2	583.5
$\mathrm{Im}(k_{2z})$ (m^{-1})	45.93	40.00	49.80	38.83
a (V)	11.23	8.51	4.86	11.07
Calculated ultrasonic velocity ($\mathrm{m\ s}^{-1}$)	536	496	659	512
Calculated ultrasonic attenuation ($\mathrm{dB\ cm}^{-1}$)	3.77	3.31	3.97	3.21

According to Eqs. 8 and 9, the fit parameters a, $\mathrm{Re}(k_{2z})$ and $\mathrm{Im}(k_{2z})$ are used to calculate the ultrasonic velocity and the attenuation inside the panel (Table 1). For MDF, the parameters are presented for both tested thickness ranges.

In summary, the results show that the fit procedure is an adequate tool to simulate the experimental data and calculate the relevant ultrasonic parameters.

Conclusion

In this work, the occurrence of interference effects by pulsed air-coupled ultrasonic waves in wood-based panels was examined. In dependence of the thickness of the panels, an oscillating signal was detected and explained by the interferences of the multiple reflections inside the tested panels. According to the theory by Brekhovskikh (1980), the interferences are verified with a best-fit model and used to determine the main ultrasonic parameters velocity and attenuation.

So far, this effect has not been considered for the testing of wood-based panels before. Besides the impedance and attenuation mechanisms, interferences can affect the detected signal considerably. The parameters panel thickness and density as well as the ultrasonic velocity and the incident angle have an effect on the interferences and need to be regarded when analyzing the detected signal. The results of this research are a contribution to the full understanding of the behavior of ultrasonic waves in wood-based panels and in future the air-coupled testing method may be a promising tool to characterize wood-based panels during the production process.

However, the blister detection is not affected by interferences as defects reduce the signal significantly, even in the case of constructive interferences.

The fit procedure allows calculating the important ultrasonic parameters velocity and attenuation. The method and the realistic data that are presented in this publication contribute to the study of wood-based panels by non-destructive testing methods.

Acknowledgments We would like to express our appreciation to everyone who supported this project. Especially, GreCon contributed with their equipment, financial support and experience. Testing material was provided by Kronopol (Zary, Poland), Rauch (Markt Bibart, Germany), Glunz (Nettgau, Germany) and BMU (Hörstel-Bevergern, Germany). The work was partially funded by the Swiss National Science Foundation.

References

Bekhta P, Niemz P, Kucera LJ (2002) Untersuchungen einiger Einflussfaktoren auf die Schallausbreitung in Holzwerkstoffen. Holz Roh- Werkst 60(1):41–45

Brekhovskikh LM (1980) Waves in layered media. In: Frenkiel NF, Temple G (eds) Applied mathematics and mechanics. Academic Press, London

Buckley J (2000) Air-coupled ultrasound—a millennial review. 15th World conference on nondestructive testing, Roma

Bucur V (2006) Acoustics of wood. Springer, New York

Burmester A (1968) Untersuchungen über den Zusammenhang zwischen Schallgeschwindigkeit und Rohdichte, Querzug- sowie Biegefestigkeit von Holzspanplatten. Holz Roh Werkst 4(26):113–117

Drury JC (2005) NDT fundamentals: ultrasonics, part 3. Refraction and mode conversion. Insight-Wigston then Northampton 47(1): 44–46

Erhard A, Rathgeb W, Wüstenberg H, Kuhlow B (1976) Einfluss des Ankoppelspalts auf den Schallübergang bei der Ultraschallprüfung mit Schrägeinschallung. Materialprüfung 18(9):4

Greubel D, Plinke B (1995) Nondestructive strength tests on particleboards with ultra-sonic measuring techniques. Holz Roh Werkst 53(3):193–200

Guyott CCH, Cawley P (1988) The measurement of through thickness plate vibration using a pulsed ultrasonic transducer. J Acoust Soc Am 83(2):9

Hasener J, Thoemen H (2003) Ultrasonic and density profile parameters—how useful are they for statistical process modeling? 7th European panel products symposium. Llandudno/United Kingdom

Hernandez G (1986) Fabry-Perot interferometers. Cambridge University Press, Cambridge

Hilbers U, Thoemen H, Niemz P (2009) Measurement of ultrasonic velocity in wood based panels. COST 49: final conference, Nantes, France

Hilbers U, Thoemen H, Hasener J, Fruehwald A (2010) Effects of material density and particle type on the ultrasonic transmission through wood based panels. Wood Sci Technol. doi:10.1007/s00226-011-0436-9

Jackins PD, Gaunaurd GC (1986) Resonance acoustic scattering from stacks of bonded elastic plates. J Acoust Soc Am 80(6):1762–1776

Krautkraemer J, Krautkraemer H (1986) Werkstoffprüfung mit Ultraschall. Springer, Berlin

Kruse K (1993) Untersuchungen verschiedener Einflussgrößen auf die zerstörungsfreie Werkstoffprüfung von Holzwerkstoffen mittels Ultraschall. Universität Hamburg, Fachbereich Biologie, Hamburg

Kruse K, Broeker F-W, Frühwald A (1996) Zusammenhang zwischen Querzugfestigkeit, Rohdichteprofil und Ultraschallgeschwindigkeit von Spanplatten. Holz Roh Werkst 54:295–300

Kuttruff H (1988) Physik und Technik des Ultraschalls. S.Hirzel Verlag, Stuttgart

Millner R (1987) Ultraschalltechnik. Fachbuchverlag Leipzig, Halle

Neumann N, Ebermann M, Hiller K, Kurth S (2007) Tunable infrared detector with integrated micromachined Fabry-Perot filter. SPIE—The International Society for Optical Engineering, vol 6

Niemz P, Aguilera A (1995) Untersuchungen zur Schallausbreitungsgeschwindigkeit für ausgewählte Holzarten Chiles. Holz Roh Werkst 53(1):187–191

Niemz P, Kucera LJ, Schob M, Scheffler M (1999) Experimentelle Untersuchungen zur Erkennung von Defekten in Holz mittels Ultraschall. Holz Roh Werkst 57(2):96–102

Rose JL (1999) Ultrasonic waves in solid media. Cambridge University Press, Cambridge

Sanabria S, Hilbers U, Sennhauser U, Wenker J, Thoemen J, Niemz P, Neuenschwander J (2010) Imaging of in-plane density distribution in particleboard with air-coupled ultrasound sound speed measurements and X-ray mat scanning. Holzforschung (submitted)

Schafstall B (2001) Qualitätsüberwachung bei der Produktion von MDF mittels Ultraschall. Universität Hamburg, Fachbereich Biologie, Hamburg

Stoessel R (2004) Air-coupled ultrasound inspection as a new non-destructive testing tool for quality assurance. Universität, Fakultät Maschinenbau, Stuttgart, vol 150

Vary A (2007) Ultrasonic characterization of material properties. Nondestructive testing handbook—ultrasonic testing. In: Moore PO, Workman GL, Kishoni DC (eds) The American Society for Nondestructive Testing, vol 7, pp 305–356

Vun RY (2003) Ultrasonic characterization of engineering performance of oriented strandboard. Louisiana State University, vol 186

Workman GL, Alers GA, Allen TL, Bar-Cohen Y, Bruton FA, Chang FH, Khuri-Yakub BPT, Moles M, Monchalin JP, Rose JL (2007) Generation and detection of ultrasound. In: Moore PO (ed) Nondestructive testing handbook: ultrasonic testing. ASNT, Columbus, vol 7, pp 61–141