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Review of the use of air-coupled ultrasonic technologies for nondestructive testing of wood and wood products

Yiming Fang [a,b,*], Lujun Lin [a], Hailin Feng [a], Zhixiong Lu [b], Grant W. Emms [c]

[a] School of Information Engineering, Zhejiang A & F University, Lin'an, China
[b] College of Engineering, Nanjing Agricultural University, Nanjing, China
[c] New Zealand Forest Research Institute Ltd., Rotorua, New Zealand

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ABSTRACT

Air-coupled ultrasonic (ACU) is a contactless ultrasonic measurement method which has become increasingly popular for material characterization. This is due to a growing number of advanced materials which cannot be contaminated during the testing processes by coupling agents utilized in conventional ultrasonic testing. This paper provides a review of the applications of ACU to wood and wood products. The ACU fundamentals, including principles, working modes and commercial transducers used for this purpose, is briefly described. The emphasis of this paper is on approaches of inspection and characterization. The applications of ACU to wood characterization with reference to wood quality aspects are summarized. Correlations between the ACU parameters (i. e. amplitude, velocity, and spectrum) and the wood properties (i.e. density, moisture content, strength, and stiffness) as well as the wood defects (i. e. knots, cracks, decay, insect damage, and delamination) are dealt with in detail. Finally, a discussion of apparent future research directions completes this review.

Contents

* Corresponding author at: School of Information Engineering, Zhejiang A & F University, Lin'an, China.

E-mail address: ymfang@zafu.edu.cn (Y. Fang).

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1. Introduction

Wood has been used for thousands of years as a cheap and renewable construction material. Today it will still be found widely in roof, interior doors, exterior cladding, furnishing, flooring, veneering, making of barrels and much more. In practice, it is necessary to characterize the wooden material based on properties, aiming to determine the most suitable use. Moreover, wood defects, such as knots, decay, insect damage, splits, and checks, can change the wood performance substantially and need to be characterized. Detection of these defects before further processing, preferably before the finishing steps, can achieve a considerable saving in manufacturing costs. Finally, wooden structures tend to deteriorate after long-term use due to both sustained load and fluctuations of temperature and humidity. These deteriorations reduce the strength of such structures, can cause safety hazards, and so have to be identified as early as possible. Therefore, there is an increasing demand to develop non-destructive integrity characterization methods for improving the quality of wood and wooden materials, both during production and utilization.

Many different techniques have been investigated (Bucur, 2013), including ultrasonic, radiography (Li et al., 2014), thermography (López et al., 2013), etc. Among these, ultrasonic measurements have been demonstrated to be an appealing tool for nondestructive characterization of wood and wooden materials. As a mechanical wave, ultrasonics is related to key parameters of wood materials, such as density, stiffness, strength, grain orientation, moisture content and defects like cracks, knots, and insect damage (Senalik et al., 2014). Compared with other methods (e.g. radiography, microwave), ultrasonic techniques are non-hazardous and safe and will not harm the medium to be tested nor the person performing the test. Moreover, ultrasonic-based methods are less expensive than most other methods (Blomme et al., 2002).

Conventionally, a liquid couplant (water, usually) or some type of gel or oil is essential for ultrasonic materials characterization in contact-mode coupling. Only in this way, can ultrasonic waves be transmitted with sufficient energy from the transmitter to the receiver, and through the sample under testing. Not only is this time consuming and inconvenient for testing a large number of wood cuts, but it is unacceptable or even not allowed due to the porous structure of wood materials. Therefore, the on-line implementation of contact ultrasonic methods are severely limited. The development of air-coupled ultrasonic (ACU) techniques has made ultrasonic methods more feasible for both materials characterization and defect detection (Buckley, 2000; Chimenti, 2014). It removes the inherent limitation of contact ultrasonics by using air as the coupling medium and provides an efficient, noncontact inspection resolution. Recently, ACU techniques have attracted much attention due to its excellent performance. A variety of materials have been investigated using ACU methods. Examples of materials include carbon-carbon composites (Castaings et al., 1998; Poudel et al., 2013), steel plate (Waag et al., 2015), paper (Saniman and Ihara, 2014; Stor-Pellinen and Luukkala, 1995), food products (Pallav et al., 2009), plant leaves (Sancho-Knapik et al., 2012), and concrete (Berriman et al., 2006; Chang et al., 2013). Buckley provided an extensive review on the developments of ACU transducers and its application in nondestructive inspection of industrial materials (Buckley, 2000). However, Buckley's review was written some time ago and there have been significant studies performed since then, and so the authors feel that it is in need of an update. Chimenti reviewed work relating to materials characterization and inspection using ACU methods (Chimenti, 2014). However, it did not specifically focus on the applications to wood and wood products.

ACU is quite suitable for characterizing wood and wood products because their lower mass density means a more favorable acoustic impedance for the transmission of ultrasonic waves (Chimenti, 2014). During the past decades, a large number of studies have been reported on the characterization and defect detection of wood and wood products. Many of them have led to the development of commercial nondestructive testing devices for wood industries. Now the ACU techniques are adequate for both static measurements in laboratory and on-line testing for industrial applications. The goal of this paper is to summarize the primary research and applications, and to provide recommendations for future research on this topic.

2. Fundamentals of ACU

2.1. Major advantages and challenges

ACU uses the surrounding air as the coupling agent between the sample and transmitter or between the sample and the receiver, instead of the typical ultrasonic gel or water. Based on analysis of the attenuation, velocity, or spectrum of the ultrasonic waves, the specific information related to wood properties can be obtained. The main advantage is that no couplant is needed like regular ultrasonic testing. The wooden samples would therefore not be contaminated during testing. Moreover, the absence of couplant allows for testing with high efficiency and high reproducibility (Sanabria et al., 2011b). ACU also allows for continuous scanning with arbitrary transducer orientation and step size, so that measurements can be taken over the whole surface of the test sample rather than at specific points.

The main disadvantage is that only a small fraction of the acoustic energy can be coupled into the specimen due to the large difference in impedance between air and wooden materials. The typical impedance for air is 415 Rayl, whereas wooden materials have typical impedances around 1.57×10^6 Rayl (Fleming et al., 2005). This impedance mismatch typically causes high reflection losses. It was reported that only 0.1 percent of the initial energy can be transmitted through one air/wood interface (Fleming et al., 2005). Also, the refraction of the ultrasonic waves as they enter the test sample will typically be extreme (Chimenti, 2014). With such acoustic impedances mismatch, a small deviation in the incident angle from the normal direction leads to great deviation of the beam into the material, which could prevent reaching the receiving transducer. Generally, the ultrasonic waves cannot propagate a long distance in the wooden sample because the amplitude of the waves tends to be extremely low after the strong interface reflection and the high refraction. Therefore, ACU techniques tend to be used to test wood specimens of small or moderate thickness (<30 mm) (Blomme et al., 2010). Fortunately, this problem has been overcome in recent years with increased emission energy, receiving transducer with high sensitivity (Chimenti, 2014), and optimized frequency for the specific application (Buckley, 2000). Recent research has extended ACU applications to 500 mm thick glulam (Sanabria et al., 2013a).

2.2. Working modes

In the field of wood characterization, ACU transducers can be aligned in different modes to excite and receive waves, including normal through-transmission, slanted through-transmission, pulse-echo, and plate wave. Fig. 1 illustrates the transducer arrangement in different modes.

ACU applications to wood and wood products were almost always done in the normal through-transmission mode (Hsu et al., 2010). As shown in Fig. 1(a), two transducers are used with