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Modeling and prediction of density distribution and microstructure in particleboards from acoustic properties by correlation of non-contact high-resolution pulsed air-coupled ultrasound and X-ray images

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ABSTRACT

Non-destructive density and microstructure quality control testing in particleboards (PBs) is necessary in production lines. A pulsed air-coupled ultrasound (ACU) high-resolution normal transmission system, together with a first wave tracking algorithm, were developed to image amplitude transmission G_p and velocity c_p distributions at 120 kHz for PBs of specific nominal densities and five particle geometries, which were then correlated to X-ray in-plane density images ρ_s. Test PBs with a homogeneous vertical density profile were manufactured in a laboratory environment and conditioned in a standard climate ($T = 20$ °C, RH = 65%) before the measurements. Continuous trends ($R^2 > 0.97$) were obtained by matching the lateral resolution of X-ray images with the ACU sound field radius ($\sigma_w^o = 21$ mm) and by clustering the scatter plots. $\rho_s \mapsto c_p$ was described with a three-parameter non-linear model for each particle geometry, allowing for ACU density prediction with 3% uncertainty and PB testing according to EN312. $\rho_s \mapsto G_p$ was modeled by calculating ACU coupling gain and by fitting inverse power laws with offset of ρ_s and c_p to material attenuation, which scaled with particle volume. G_p and c_p variations with the frequency were examined, showing thickness resonances and scattering attenuation. The combination of ACU and X-ray data enabled successful particle geometry classification. The observed trends were interpreted in terms of multi-scale porosity and grain scattering with finite-difference time-domain simulations, which modeled arbitrarily complex stiffness and density distributions. The proposed method allows for non-contact determination of relations between acoustic properties and in-plane density distribution in plate materials. In future work, commercial PBs with non-uniform vertical density profiles should be investigated.

1. Introduction

Particleboards (PBs) are popular in housing and furniture applications. They are produced by mechanically reducing wood material into small particles, applying adhesive to the particles and consolidating a loose mat with heat and pressure into a panel product [1,2]. The strength of PBs is influenced by, among others, adhesive bonding, particle geometry, resin content and density variations due to random particle deposition during mat forming [3]. According to the EN312 standard [4], the quality assurance of PBs requires control of a variety of parameters such as transverse tensile strength (internal bond), bending strength, elastic moduli and density, all of which provide complementary information about mechanical performance. The density of the panels is a major quality control parameter, since it correlates with strength and elastic moduli [5]. Significant density fluctuations have moreover a negative impact on mechanical performance, the EN312 standard specifies that the maximum density deviation should not exceed ±10% from the mean [4]. Current standardized density tests consist of gravimetric measurements in at least six 50 mm × 50 mm random control specimens cut out from the same panel with distances >100 mm between specimens [6,7]. For large production volumes <1% of produced panels are tested [8]. The development of a non-destructive continuous density monitoring method is therefore necessary to optimize PB production lines.

X-ray densitometry in PB is based on the quasi-linear regression between wood density and X-ray logarithmic attenuation [9–11]. Off-the-shelf continuous in-plane/horizontal density distribution (HDD) and vertical density profile (VDP) measurement systems are available. X-ray Computed Tomography (CT) enables three-dimensional density imaging and is applied to microstructure investigations [12–14]. γ-rays are also sensitive to density gradients in PB but require the use of a radioactive source [15]. Micro-

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wave dielectric measurements allow for on-line imaging of moisture content in PB, abnormal density due to e.g. air inclusions can also be detected [16].

Ultrasonic testing is a low-cost and non-hazardous alternative for non-destructive testing of PB. Ultrasonic velocity across the panel correlates with density, elastic properties and internal bond strength [17–21]. Ultrasonic amplitude allows monitoring of the bonding development of PB during hot-pressing [22]. With roller transducers, a significant correlation of internal bond strength with ultrasonic amplitude and PB mat temperature was observed shortly after the pressing [23]. For finished PBs (adhesive cured, panel cooled to room temperature), however, a significant correlation between ultrasound amplitude and internal bond strength could not be found [24,25]. Sufficient acoustic coupling has traditionally required the pressing or gluing of ultrasound transducers onto the inspected sample. Consequently, coupling pressure variations limit the reproducibility, scanning is generally not possible and particles can attach to the transducers [19]. Air-coupled ultrasound (ACU) is a novel technology that removes the aforementioned limitations and finds increasing applications in the inspection of wood and wood composites [19,26–35]. Industrial systems are available that continuously detect air voids, cracks and delaminations in wood composites, such as PBs but as well OSBs and fiberboards up to 100 mm thick. A significantly reduced amplitude for ACU waves coupled in normal transmission mode (NTM) is associated to defects [36]. However, ACU imaging of PB material properties has not been sufficiently investigated. An implementation of the method of [23] with ACU transducers has been proposed [37]. In another investigation, a continuous wave ACU system has been used to measure resonance frequencies in PB. The results were used to estimate the ultrasound velocity in control specimens, which was then correlated to strength, nominal density and VDP [19]. Similar regressions were performed for oriented strandboards (OSB) with a deconvolved-chirp ACU system that measures ultrasound velocity and amplitude [21]. Recently, the main attenuation mechanisms affecting ACU transmission through wood-based panels have been qualitatively described [38], and interferences of multiple reflected waves inside PBs have been examined [39].

In this work high-resolution pulsed ACU NTM scans were correlated to X-ray HDD images for PBs with specific nominal densities and particle geometries. Test PBs with a homogeneous density profile were manufactured in a controlled laboratory environment, in order to separately investigate the influence of density and particle geometry on the ACU wave propagation. The manufactured samples were conditioned in a standard climate before X-ray and ACU measurement. A first wave tracking algorithm simultaneously determined ultrasound velocity and amplitude. The correlation between ACU and X-ray images was maximized by matching their lateral resolution with a self-adjusted pre-smoothing method. Regression laws were determined between ACU parameters and HDD, which were used as calibration functions to perform ACU HDD prediction. The influence of the frequency on ACU parameters was also examined. Next, the PBs were classified according to particle geometry by combining X-ray and ACU data. Finally, the influence of the PB microstructure on ACU parameters was analyzed with finite-difference time-domain simulations.

2. Materials and methods

2.1. Sample preparation and optic characterization

A total of 30 PB samples of 350 mm × 120 mm × 19 mm were manufactured (Table 1). They were divided into five sample groups, corresponding to specific particle geometries (Fig. 1a). The particles were fractionated with a screening machine (Maier Zerkleinerungstechnik GmbH, Bielefeld, Germany). Specific screen mesh sizes define the particle geometries A–E (Table 1). Fine particles (groups A–B) are typically used in the surface layer (PBSL) and coarse particles (groups C–E) in the core layer (PBCL) production lines. For each sample group, two specimens #1 and #2 were cut out from a larger panel for each of three specific nominal board density (ND) levels (400, 600 and 800 kg m^{-3}). For sample group E-400 only one specimen #1 was available for measurement.

The particles (Rauch Spanplatten GmbH, Markt Bibart, Germany) consisted of 90% softwood and 10% hardwood. They were mixed in a drum blender with 12% urea formaldehyde resin, dry solid based on oven-dry mass of wood (Kaurit 350, BASF SE, Ludwigshafen, Germany), 1% ammonium-nitrate catalyst (based on dry solid content of adhesive) and 10% target panel moisture content. The relatively high resin content ensured a good bonding even for the smallest particles. A mat was manually formed, pre-densified and then pressed in a computer-controlled hydraulic laboratory hot-press down to a thickness of 21 mm with up to 25MN m^{-2}. A homogeneous VDP was obtained by slowly heating up the mat during the pressing (1 °C/min), from room temperature until a temperature over 100 °C was measured for some minutes in the core layer, in order to guarantee the complete curing of the adhesive. The temperature was controlled with a thermoelement driven into the mat at middle thickness. The platen temperature was on average 10 °C higher than the one measured at the mat core. The samples were then conditioned in a standard climate (T = 20 °C and RH = 65%), which was also used for storage. Finally, they were sanded to a thickness of 19.3 ± 0.2 mm [40]. The internal bond strength was measured according to EN319 [41] for random specimens cut out from similarly manufactured PBs and ranged between 0.4 and 1.5 MN m^{-2}, increasing with the density in agreement with [5].

The mean particle geometry was estimated from optic scans of the surfaces of the samples (Fig. 1b). More than 100 particles were manually marked and binarized in each image, and then fitted to ellipses using the particle analyzer from the ImageJ software [42]. The major axes in two orthogonal planes were used to define the particle dimensions (Table 1).

2.2. X-ray horizontal density imaging and γ-ray vertical density profiling

The HDD of the samples was imaged with an industrial online X-ray scanner (Dieffensor, Fagus-Grecon Greten GmbH & Co., Alfeld, Germany). X-ray fan beams were sent across the panel and were detected underneath by a 128 element detector (Fig. 2a). The detected radiation attenuation was calibrated to density values, following the Lambert–Beer law [10]:

$$\ln(I/I_o) = -(M\rho + N)d \quad (1)$$

Table 1
Particleboard sample definition and optic particle sizing results.

Sample group	Screen mesh size (mm)	Optic particle size[a] l, w, t (mm)	Optic particle volume[a] Π(mm^3)	Nominal board densities (kg m^{-3})	Use[b]
A	< 0.5	2, 0.96, 0.46	0.9	400, 600, 800	PBSL
B	0.5–1.5	2.5, 1.3, 0.75	2.4	400, 600, 800	PBSL
C	0.5–1.5	7.3, 1.5, 0.53	5.8	400, 600, 800	PBCL
D	1.5–3	11.3, 2.4, 0.77	20.9	400, 600, 800	PBCL
E	> 3	16.7, 3.6, 0.85	51.2	400, 600, 800	PBCL

[a] l: particle length, w: particle width, t: particle thickness (according to Fig. 1b).
[b] PBSL: surface layer particleboard, PBCL: core layer particleboard.