Development of Non-contact Ultrasound as a Sensor for Wood Moisture Content

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Abstract. Numerous handheld moisture meters are available for measuring moisture levels of wood and building materials for a vast range of quality control and moisture diagnosis applications. However, most methods currently available require physical contact of a probe with the test material to operate. The contact requirement of such devices has limited applications for these purposes. There is a tremendous demand for dynamic online quality assessment of in-process materials for moisture content (MC) measurements. In this paper, a non-destructive non-contact ultrasound technology was used to evaluate the effects of increasing temperature in two MC levels and of increasing MC in lumbers. The results show that the ultrasonic absolute transmittance and velocity parameters are directly correlated very well ($R^2 \geq 0.87$) with temperature for the two moisture levels in wood. At a constant temperature condition, however, the velocity is inversely correlated with MC. It was also found out that the distribution of MC along the length is marginally insignificant to both ultrasonic measurements. The transmittance measurement along the orthogonal thickness direction is insignificant above the fibre saturation MC; whereas, the velocity measurement is marginally significant. The study concludes a positive correlation and a good fit for this technology to advance into the development of an automated device in determining wood moisture levels, which will in turn be used to control the dynamics of wood drying-sterilization processes. Further calibration research is recommended to ascertain the constraints and limitations of the technology to specific wood species and dimension.

1.0 Introduction

There are a number of commonly used methods of measuring the moisture content (MC) of wood [1]. The most accurate method is the gravimetric method, also known as the "oven dry" method. The gravimetric method may be applied by assuming an oven dry specific gravity for a given species and subsequent weight and volume, measured physically. Resistance and dielectric methods are commonly used in handheld moisture meters. None of these methods are particularly well suited to monitoring the MC of wood products intended for drying or phytosanitary treatment. While the resistance and dielectric techniques can be adapted to continuous monitoring, neither technique is accurate at high moisture contents. The resistance method is very sensitive to surface moisture and is therefore ill-suited for continuous monitoring of the MC. The dielectric method is relatively inaccurate at high MC.

Sound can generally be thought to propagate through a material at a velocity and transmittance which is a function of physical material properties [2,3,4,5]. This behaviour has been utilized to determine wood physical properties using direct-contact ultrasound [6,7], but is not suitable for continuous processing. More recently, non-contact ultrasound (NCU) techniques have been utilized to evaluate wood material properties [8,9,10]. These studies indicate that NCU technology may be successful in measuring the MC of wood processed on a continuous basis. The development of the phenomenal high transduction in air [11] has open avenues for this non-contact mode, i.e., transmission of ultrasound through air without the need for a coupling medium like gel or water. This mode is ideal for continuous in-process monitoring.

Experiments were performed in support of this application using transmission NCU technology developed by The Ultran Group, State College, Pennsylvania, U.S.A. In this paper, the sensitivity of the NCU technology was tested to detect temperatures and moisture content in flat-sawn wooden pieces of processed lumber. Specifically, the objectives are to correlate the following:

(1) ultrasound parameters to the temperature change from 20°C to 60°C at two MC levels (50% and 130%).
(2) ultrasound parameters to the MC change from 25% to 150% at ambient conditions.
(3) ultrasound parameters to two orthogonal directions across the thickness and width.

2.0 Materials and Methodology

2.1 Specimen preparation

Lumber samples of red pine (*Pinus resinosa*) with different levels of MC were procured according to the experimental design summarized in **Table 1**. The lumbers were air-tight plastic wrapped and frozen for storage to retain the wood moisture level. The lumber specimens were sectioned and the zone marked in between central points of about 100 mm apart, forming the section for NCU and other physical measurements consistent for all specimens and test objectives. The MC at each point was evaluated using the gravimetric method based on the oven-dry and green weight measures. To achieve objective (1), the heating of the lumber was done using a microwave to a desired temperature level. Microwave was set at 0.95 kW with following exposure regimes: 5 min. for A2 (low MC) and 8 min. for B2 (high MC). The core temperature of the lumber was measured using a Ipitek, Lumitherm 500 fibre-optic temperature probe at the predetermined points. At each point, a small hole of 1.5 mm (1/16 in.) diameter was drilled at the centre of the thickness section to the centre of each NCU zone for the fibre-optic probe insertion. After the temperature dropped about 5°C, the probe was removed and the section was scanned. Objective (2) was accomplished at ambient conditions. The specimens were kept wrapped and conditioned to ambient conditions before scanning was done. In the same manner, the scanning of the thicker samples was done as in objective (3).

Table 1. Experimental design for the development of NCU moisture content of lumber.

Temperature	Sample Moisture Content %	Species	Lumber Dimension (mm)	Replicate
23 to 60 °C	53, 130%	Red pine	25x100x250	2 x 2
25 °C	25, 92.5, 150 %	Red pine	25x100x810	2 x 3
22 °C	27%	Red pine	100x100x810	2 x 1

2.2 Equipment and setup

Two high transduction 140 kHz, 50 mm active diameter, air-coupled transducers were used and excited at 400 volts using Ultran iPass system (**Fig. 1**). The transducers were aligned in a through the thickness transmission mode, spaced at about 85 mm and 200 mm of air column for the 25 mm thick and 100 mm thick lumber test specimens, respectively. The material thickness in the direction of transmission was determined at the point of measurements (designated as dm, measured in mm). The air velocity (Va, m/s) was measured using a special gas velocity transducer. The air temperature and relative humidity (RH) were recorded. The air column time-of-flight (ToF) is designated as the Ta (μs) and was precisely measured nearest to ns. Similarly at each predetermined point, the ToF measurements with the test specimen in between the transducers (designated as Tc) were taken. The velocity in the material (Vm) is computed as in Eq. 1.

$$Vm = \frac{dm}{\frac{dm}{Va} - (Ta - Tc)} \qquad \text{Eq. 1}$$

The signal amplitude at 0 dB gain was recorded as the Aa (mv). A gain of 64 dB was used for all test specimens, and the material amplitude was recorded as Ac. The absolute transmittance parameter (Am) was determined using Eq. 2.

$$Am = 20Log(Ac) - (20Log(Aa) + 64) \qquad \text{Eq. 2}$$

Fig. 1 The iPass Non-Contact Ultrasound system composed of variable frequency and pulse-width pulser, multi-channel receiver, and CPU for the evaluation of temperature and moisture content of lumber.

3.0 Results and Discussions

3.1 Correlation of ultrasound to temperature

The NCU tests involved the nominal 53% and 130% MC test groups with increasing temperature regimens. The average group thickness was quite consistent at 28.26 mm with only 1.2% coefficient of variations (CV). The specimen core temperature was increased from 30°C to about 60°C for both groups. The NCU velocity for the two groups are highly significant ($p<0.0001$) with an average of 1545 m/s (2.6% CV) and 1462 m/s (1.8% CV), respectively. Similarly, the NCU absolute transmittance has significant different ($p=0.048$) with an average of -82.3 dB (2.6% CV) for the 53% MC group and -71.4 dB (1.6% CV) for the 130% MC group.

The relationship of the average NCU velocity and transmittance to the increase of core temperature are shown in **Fig. 2**. In general, the velocity is directly related to the temperature, whereas, the transmittance is inversely related to the temperature. Both parameters correlate very well to the increase of temperature ($R^2 \geq 0.87$). The 53% MC group, however, has the higher correlation than the 130% MC group.

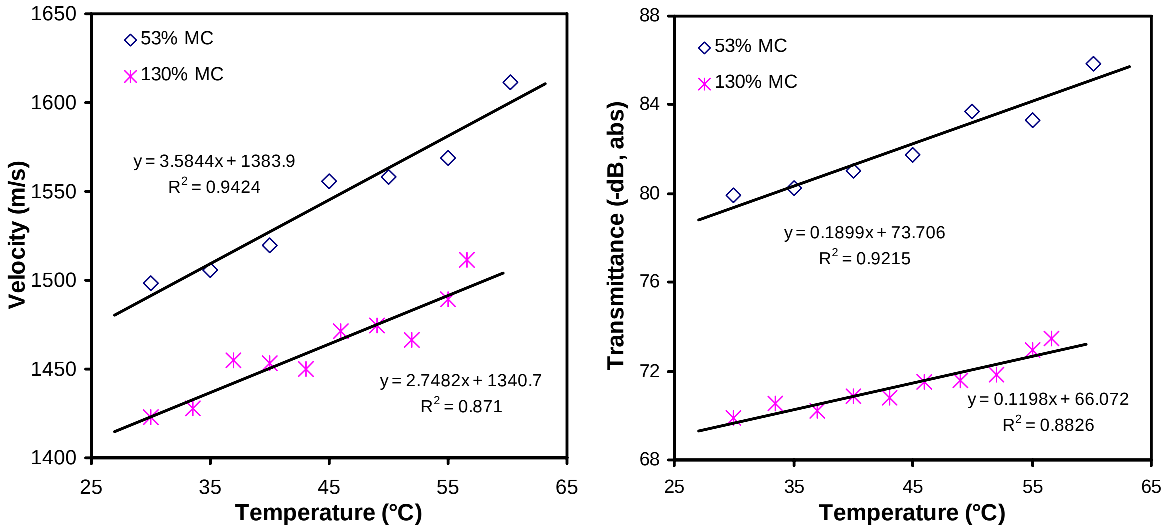

Fig. 2 Typical correlations of the NCU velocity (left) and abs. transmittance (right) versus temperature in 25x100x250-mm lumbers at 53% and 130% moisture contents levels.

These observations show both of the NCU velocity and transmittance parameters can be modelled for measuring temperature at a specified wood MC. However, more extensive, controlled experiments will be needed to fully calibrate the other MC levels of interest. Therefore, an estimate of material temperature may be necessary to isolate the sensor response with respect to MC, particularly below the fibre saturation point.

3.2 Correlation of ultrasound to moisture content

The NCU tests were done at 23°C laboratory room temperature and corresponding 53% RH on all the three MC test groups of average 27%, 95%, and 151%. The average group thickness was quite consistent at 28.46 mm (1.4% CV). The central points of measurements were separated by 100 mm along the length pf the sample. The NCU velocity and NCU transmittance for between the location points are both insignificantly different ($p=0.248$ and $p=0.774$, respectively), indicating the uniformity of the MC distribution along the length. However, they are both significantly different for between the test groups ($p=0.002$ and $p=0.014$, respectively). The group average NCU velocity values decrease with moisture content; respectively 1678 m/s, 1513 m/s, 1357 m/s (all at CV<4.12%) to the three moisture content groups. The group average NCU transmittance values decrease (-82.8 dB, -85.4 dB, -87.7 dB at CV<1.4%) with the three moisture content groups.

Fig. 3 shows the typical relationship of the NCU velocity and transmittance to the increase of moisture content in the three levels. In general, both the velocity and transmittance parameters are inversely related to the increase of moisture content. The velocity, however, has the higher correlation ($R^2=0.85$) than the transmittance.

These observations show both of the NCU velocity and transmittance parameters modelling potentials for measuring moisture content at a specified wood temperature. However, more extensive, controlled experiments will be needed to fully calibrate the other temperature of interest. Also, the optimization of the NCU sensors beam size is recommended to check both temperature and MC sensitivity and accuracy to the sample dimension.

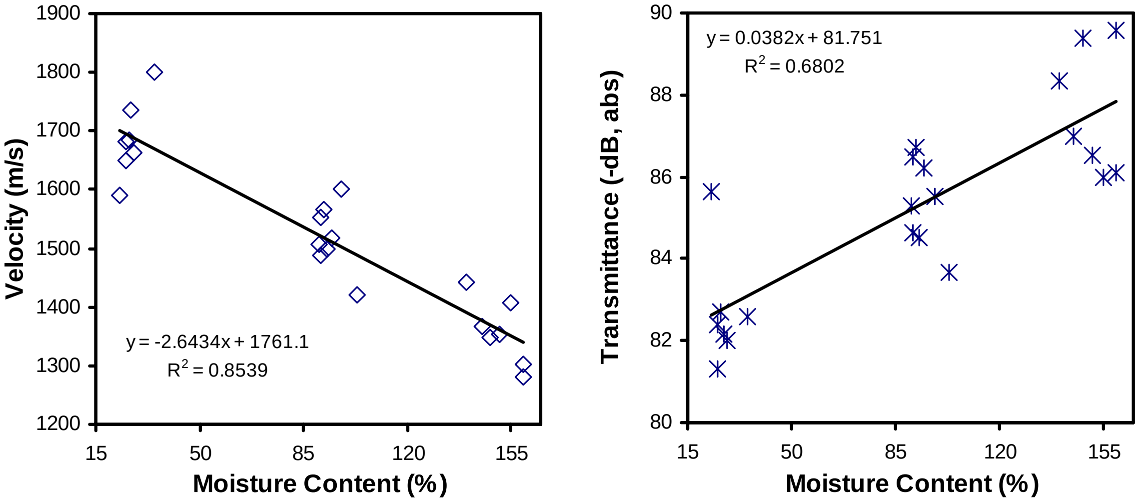

Fig. 3 Typical correlations of the NCU velocity (left) and absolute transmittance (right) versus moisture content in 25x100x810-mm lumbers at ambient conditions (23°C and 53% RH).

3.3 Correlation of ultrasound to scanning direction

The NCU tests were done on 100x100x810-mm lumber of average MC of 36.5%. The central points of measurements were separated by 100 mm in the cross section differed by direction of scanning, i.e., through the thickness or width. Using two-factor analysis of variance, the NCU velocity and NCU transmittance for between the location points are both marginally insignificantly different ($p\geq0.068$), again indicating the uniformity of the MC distribution along the length. In addition, the transmittance measurements are also insignificantly different ($p=0.11$) for between the thickness and width measurements (average value of -65.3 dB, CV of 1.9%); however, the velocity measurements (average of 1874 m/s, CV of 1.6%) are marginally significant ($p=0.057$). In general for moisture content at above the fibre saturation point, the moisture content distribution along the length and thickness/width is fairly consistent based on the ultrasound measurements. However, further in-depth study on other wood features is recommended.

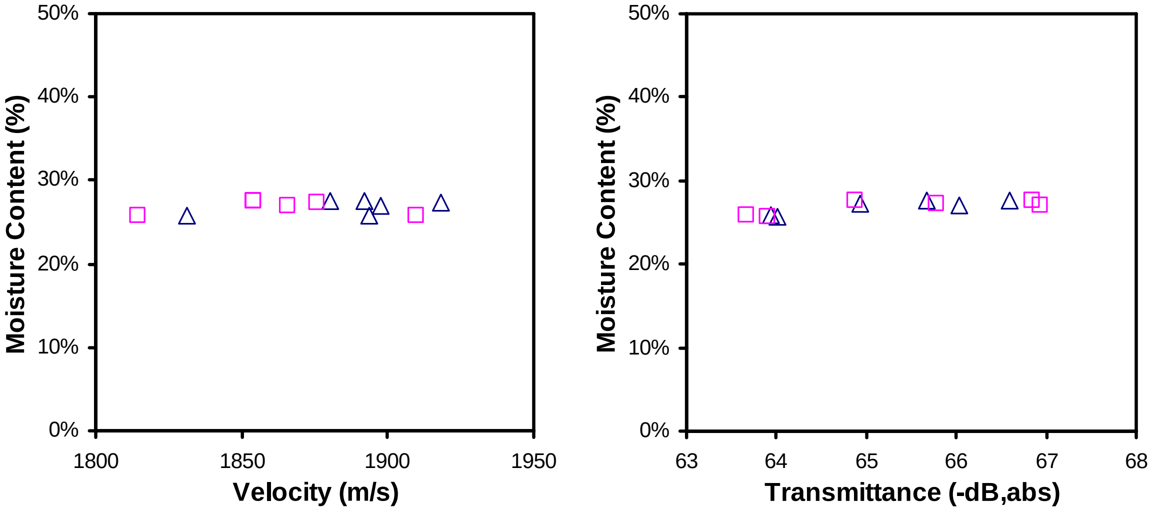

Fig. 4 Typical spatial distribution of the NCU velocity (left) and absolute transmittance (right) in 100x100x810-mm lumbers measured through the thickness (□)and width (Δ), respectively.

4. Conclusion

This study has shown that at high moisture content, the non-contact ultrasonic velocity is directly related with increasing temperature; in contrary, the NCU transmittance is inversely related with temperature. At a constant temperature condition, both of the NCU velocity and transmittance are inversely related with MC. It was also found out that the distribution of MC along the length is marginally insignificant to both of the ultrasonic parameters. Likewise, along the orthogonal thickness direction, the transmittance measurement is insignificantly different for above the fibre saturation MC. The velocity measurement, however, is marginally significant.

This study proved that this technology is feasible and a great potential in the development of an automated device in determining wood moisture levels, a mean to control the dynamics of wood drying-sterilization processes. Further research into multivariate calibration is recommended to ascertain the constraints and limitations of the technology with respect to specific wood species, features, test conditions, and dimension.

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