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Interdigital capacitance sensing of moisture content in rubber wood

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ABSTRACT

A low-cost, repeatability, and linearity interdigital capacitive transducer is proposed with an explanation of experimental results. The probe is in the form of a printed circuit board (PCB) with configuration of two interpenetrating comb electrodes, which is different from the configuration of the moisture content sensors available in the market and literature. The moisture contents of the tested rubber wood samples were in the range of 6–70%. The change in capacitance of sensing probe due to the change of moisture content inside rubber wood was detected by the modified bridge circuit. The performance of this sensor is 2% accuracy error with 0.98% precision error.

1. Introduction

The Southern part of Thailand is one of the largest rubber plantation region in the world. Over 65% of the rubber wood production in Thailand is shipping abroad. China is the world largest consumer of rubber wood. The rubber wood demanded by China has continually to be raised, totaling more than 1 billion USD in 2015 (Heemmuden, 2016). The rubber wood is raw material for sawmills and wood product factories, such as furniture, kitchenware and wooden toy factories.

Rubber wood is characterized by its hygroscopic nature. Like all porous materials, this enables wood to take in water from the air and store it within the cell membrane and cell cavities. The hygroscopic behavior of rubber wood describes the adsorption and desorption of moisture to maintain equilibrium depending on the surrounding climate in particular relative humidity and temperature. The dimensional changes of wood due to changes in moisture contents (shrinkage, swelling) are different in the three material axes (longitudinal, tangential or radial). Shrinkage and swelling are more significantly pronounced in radial and tangential direction than in longitudinal direction as shown in Fig. 1. Therefore the required final moisture content (MC) of a product made from rubber wood varies from 6 to 16% depending on its intended applications. Therefore, moisture content of rubber wood is an important factor influencing its physical and mechanical behaviors. The quality of rubber wood from drying process is depended on the intrinsic moisture content.

Rubber wood moisture content can be determined by gravimetric method as shown in Eq. (1)

$$\%MC = \frac{m_w - m_0}{m_0} \times 100 \tag{1}$$

where m_w is mass of wet wood and m_0 is mass of oven drying wood.

A traditional method, which is the oven drying method for the moisture content measurement is to perform weight and size measurements before and after removing the water content of the sample. It is considered as a reference method. However, this method has disadvantages since it is the destructive method and time consuming. Recently, multiple methods and technologies have been investigated to determine the moisture content in wood more rapidly, nondestructively, and precisely. The measurement of moisture content in wood is based on one of several technologies: infrared, microwave, X-ray, radar, conductive and capacitive.

Near infrared technique uses reflectance and absorbance principles to calculate the moisture content (Defo et al., 2007; Adedipe and Dawson-Andoh, 2008). The water absorbs certain wave-lengths of light. The higher the moisture content, the higher the amount of light absorbed. The filtered beam is directed onto the surface of the sample. A portion of the light is reflected back to a detector. Moisture content can be calculated from the amplitude ratio of the reflected wavelengths of the sample beam and the reference beam. In another method, a calibration curve is constructed to determine the relationship between absorbed light and moisture content. However, the infrared method can only measure the moisture content of thin films or layers of material, paper, and other thin materials since this noncontact method detects only the material's surface moisture. Therefore, effects of the material's particle size, particle shape, particle surface characteristics, and color may make high errors in measurement.

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Fig. 1. The dimensional changes of wood due to changes in moisture contents.

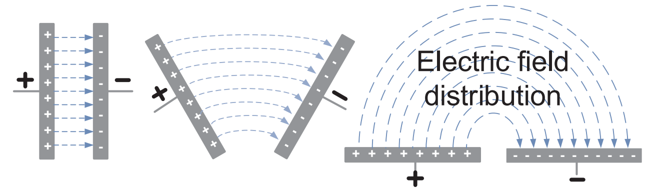

Fig. 2. The operating principle of an interdigital capacitive sensor (Mamishev et al., 2004).

Microwave method (Kraszewski and Kulinski, 1976; King et al., 1992; Schajer and Orhan, 2006; Hansson et al., 2005; Vallejos and Grote, 2009) transmits microwaves at a material and then calculates the energy losses emitted from the material and speed variation due to microwave propagation from the material to the moisture content. This technique is based on transmission. An emitter and a receiver are mounted opposite of each other in the process, so they can shine through the material. For this reason, the measuring setup of this method depends on the space between emitter and receiver. This method cannot be installed on steel equipment in a very narrow location because the sensor can confuse reflections from the steel with those from rubber wood.

X-ray method (Roels and Carmeliet, 2006) measures the moisture content in material with irradiation of X-ray beams into the rubber wood. This method estimates the speed losses of the beams after they pass through the rubber wood's water molecules. This method is extremely expensive and not frequently applied in drying rubber wood process like the other methods.

Radar technology (Hans et al., 2015a, 2015b) monitors wood moisture content with the measurement of the travel time through the sample and early time amplitude of the radar signal. The moisture content of wood with infinite media often cannot be measured by this method. The wood size effects on an accuracy of the measurement.

These reviewed methods are used to measure moisture content in rubber wood in the laboratory, but not in the practical measurement because they are not convenient to determine the moisture contents of a large number of contact points in the wood. In addition, the equipment of each method is expensive.

To measure electrical properties of rubber wood (resistance or capacitance) correlated to moisture content is an alternative method widely used in the rubber wood industry. A resistance method (James, 1963) uses two electrodes inserted directly into the material to measure its resistivity. As moisture content increases, the rubber wood's electrical resistance decreases. The resistance could vary between several hundred kΩ when wet to more than several thousand MΩ when dry. However, it requires either a superficial application of electrodes or to puncture electrodes into the lumber at different places. Moreover, the measurement in range of very low moisture content is probably errored.

The capacitive sensing in industrial applications has gained increasing attention in the last decades (Brasseur, 2003) due to its simple and low cost. The technique is suitable to evaluate moisture content in wood, wood chip, and wood pellets (Fuchs et al., 2008, 2009; Moser et al., 2008; Pan et al., 2016; Moron et al., 2016; Solar, 2016) because of the high relative permittivity of water ($\varepsilon_r \approx 80$). Dry wood has low relative permittivity. The relative permittivity of rubber wood is typically between 2 and 3.5. Nevertheless, the rubber wood can contain more than 50% water relative to its total mass, causing significant changes in permittivity (Moser et al., 2008). The variation of the material permittivity due to change of moisture content can be measured as a value of capacitance when the test material is placed between two electrodes.

This paper describes the design and implementation of the sensor for measurement of the moisture content in rubber wood based on a printed circuit board (PCB) with configuration of two interpenetrating comb electrodes. The theoretical method used to calculate the capacitance of the interdigitated transducer is discussed. The modified bridge network was designed and fabricated to measure the change in capacitance of the moisture content in rubber wood. The difference between the moisture content and air dielectric constant of liquid is sufficient to be used as a basic for measurement of moisture content in rubber wood. This technique can also be applied for moisture content monitoring in the drying process of rubber wood. The experimental results are found to have good repeatability and linearity. Therefore, the sensor is cost effective, easy to use, and portable with rapidly measurement and non-destructive method.

2. Principle of transducer

The interdigital capacitive sensor is a coplanar structure comprising of multiple interpenetrating comb electrodes. The operating principle of the sensor is similar to the rule of two parallel plate capacitors. The parallel plate capacitor is transformed to the interdigital capacitive sensor as shown in Fig. 2. When both electrodes were excited by the different electric potential to generate fringing fields between electrodes these electric fields traveled from positive electrode to negative electrode passing the material contacting on the electrode. Thus, the material dielectric properties affect the impedance between electrodes. The sensor behaves as a capacitor in which the capacitive reactance becomes a function of material properties. The fringing capacitance measured between the electrodes varies with the dielectric constants, which varies with the moisture contents in material. Therefore measurement of the capacitive values for the material property measurement can be operated. The applications of interdigital capacitive sensor are widely used in chemical sensor (Kitsara et al., 2007), strain gauge (Li et al., 2007), food inspection (Syaifudin et al., 2009a) humidity sensors (Lei et al., 2011), biosensor applications (Radke and Alocilja, 2005; Varshney and Li, 2009) concrete moisture content measurement (Alam et al., 2010), etc.

The configuration of interdigital capacitance is illustrated in Fig. 3. The performance of interdigital capacitance can be optimized by investigation of the optimum numbers of negative electrodes (Syaifudin et al., 2009a, 2009b). The physical aspects of electrode format are up to the arrangement of different numbers of positive and negative electrodes within the sensing area. The numbers of electrodes pairs have strong effect on sensing signal to fabricate probe with uniform electric field distribution and measurable output signal. Therefore, this probe gives high sensitivity. For this reason, the structure of the interdigital capacitance is resembled the comb with multiple electrodes, which can achieves the higher capacitance than other types of capacitance. This

Fig. 3. Interdigital capacitance.