

# Improved Methodology of Measuring Water Content of Wood by a Vibration Technique

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## Abstract

A method of measuring water content of wood is introduced. This method uses a vibration technique. A shaker driven by swept sine signals was used for the accurate measurement of vibration. A cylindrical wood was used as a sample to verify our method of measuring the water content. The resonance frequencies of the wood sample decreased as its water content increased. Also, we performed an experiment of measuring the vibration of a tree to explore the feasibility of applying the method to the measurement of tree water content. The circumferential mode that is independent of the height of a tree was identified using a white oak tree.

*Key words:* Acoustic measurement, circumferential mode, laser Doppler vibrometer, Non-destructive measurement.

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## Introduction

The industrial production of wood involves the thermal drying process. This process requires huge amount of energy considering the capacity of the water content of wood. The water content of wood in the pre-drying stage varies depending on the condition and a period of time in which the wood has been left. Wood with lower water content requires shorter drying period than that with higher water content. Therefore, measuring the water content of wood before the drying process should reduce the energy consumption.

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Extensive studies have been conducted on the water content of wood (sawn timber). The velocity of sound in timber has been used to determine the water content of wood (Mishiro, 1996a, 1996b; Wang and Chuang, 2000). However, this method can be used when water content is less than approximately 30%, which is below the fiber saturation point. Young's modulus has been an another indicator (Tonosaki and Saito, 2000; Guan et al., 2002). Other methods include determining the dielectric constant at microwave frequency (Kabir et al., 1998) and the drill resistance method (Lin et al., 2003). The water content of living trees is rarely measured; however, Kamaguchi et al. (2000, 2001) determined the water content of living trees by the manual hitting method.

In this paper, we report an improved methodology for measuring the water content of wood by using a vibration technique. The water content of wood alters their physical properties such as Young's modulus and density. Since the resonance frequencies of a tree are related to the above-mentioned physical properties, we can expect that these frequencies depend on the water content. The resonance frequencies can be measured non-destructively by using a vibration technique. The method uses an electronic excitation method. A shaker driven by swept sine wave signals and a laser Doppler vibrometer (LDV) were used for the accurate measurement of the vibrational spectrum of wood. The relationship between the water content and a resonance frequency was verified by using a cylindrical wood sample. We also report the preliminary experiments to explore the feasibility of using the above-mentioned method for measuring the water content of living trees.

## Materials and methods

### *Measurement of the water content of wood*

The resonance frequencies of wood  $f$  depend on its elastic modulus (Young's modulus)  $E$  and density  $\rho$  as follows:

$$f \propto \sqrt{\frac{E}{\rho}}. \quad (1)$$

If the water content increases, the resonance frequencies decrease because Young's modulus decreases and the apparent density increases. Therefore, we can conclude that the resonance frequencies depend on the water content of wood. Conversely, the water content can be determined by measuring the change in the resonance frequencies.

A wood sample was used to verify the above-mentioned method. The sample was a cylinder of *Cryptomeria japonica* D. Don (Japanese cedar or Sugi). It was 100 mm in diameter and height. The sample was immersed in water under vacuum and then dried gradually at room temperature to prepare a sample with different water contents. The dry base water content was determined as follows:

$$\frac{w - w_0}{w_0} \times 100 \quad (\% \text{ d.b.}) \quad (2)$$

where  $w$  and  $w_0$  are the weight of the sample in the wet and dried state, respectively. The vibration in the sample with different water content was measured using the experimental setup described in Fig. 1. A vibration shaker (513-B; EMIC Corp., Tokyo) was used to generate vibrations in the wood sample. The dynamic range of the shaker was up to 10 kHz. The vibration in the sample was measured with a laser Doppler vibrometer (LDV, LV-1720; Ono Sokki Co. Ltd., Yokohama). The signals from the LDV were FFT-analyzed and the spectrum of the vibration was obtained.

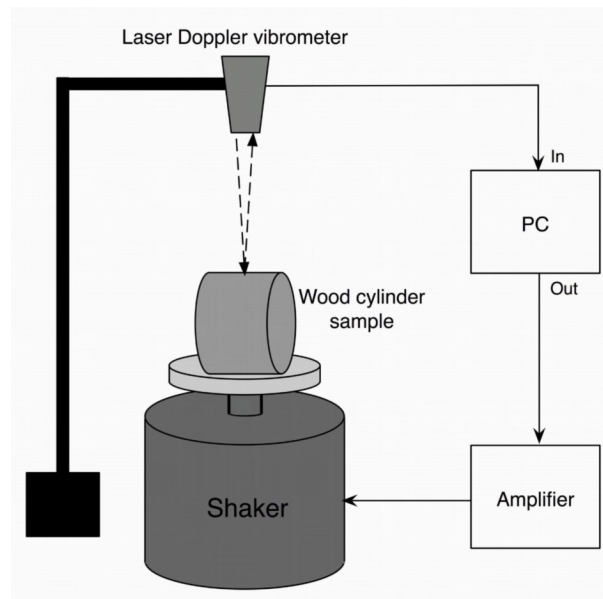


Fig. 1. Experimental setup for measuring the change in the resonance frequency of a cylindrical wood sample at various water contents. Excitation was applied to the sample with a shaker driven by swept sine wave signals. The vibration in the sample at the opposite side of the excitation was measured by a laser Doppler vibrometer.

#### *Vibration measurement of Quercus myrsinaefolia*

We here describe the preliminary experiment to explore the feasibility of using above-mentioned method for measuring the water content of living trees. Various vibration modes exist in a tree. The longitudinal mode, lateral mode, and circumferential mode are described in Fig. 2. In the longitudinal and lateral modes, the

vibration propagates along the length. On the other hand, in the circumferential mode, it propagates along the circumference of the cross-section of a tree trunk or branch. For measuring vibration in trees, we focused on the circumferential mode because it is independent of the height and fruit mass of a tree. It depends only on the circumferential length, while the longitudinal and lateral modes are dependent on the height and fruit mass of a tree. The circumferential mode has been used for the detection of internal decay of trees (Axmon et al., 2002, 2004).

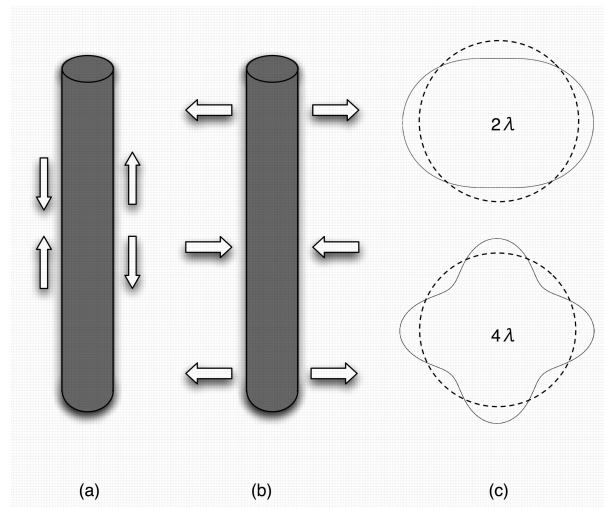


Fig. 2. Various vibrational modes of a tree: the longitudinal mode (a), the lateral mode (b), and the circumferential mode (c). For the circumferential mode, the second order (circumference =  $2\lambda$ ) and the fourth order (circumference =  $4\lambda$ ) have been presented, where  $\lambda$  is the wave length of the circumferential mode.

A *Quercus myrsinaefolia* (white oak) tree, approximately 4 m in height and 0.36 m in circumference, was used since its smooth surface was suitable for the vibration measurement. The experimental setup is described in Fig. 3. A small vibration shaker (G21-002; Shinken Co. Ltd., Tokyo) was used to generate vibrations in the tree trunk. The dynamic range of the shaker was up to 10 kHz. Swept sine signals of up to 10 kHz were used to drive the shaker. The vibration in the tree trunk at the opposite side of the excitation point was measured with the LDV. The height of the measurement point was 0.5 m above the ground. Vibration data of the tree were transformed to spectrum data by fast Fourier transformation (FFT). To determine the mode shape and to confirm the circumferential mode, the tree trunk vibrations were measured at nine points along the circumference as shown in Fig. 4. In this measurement, the shaker induced excitation at an observed resonance frequency in the spectrum.

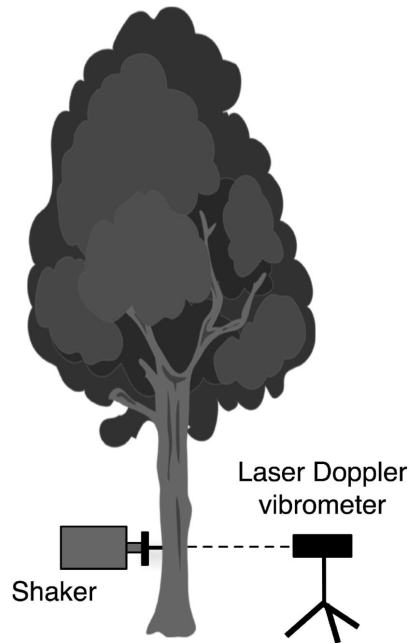


Fig. 3. The experimental setup for measuring the circumferential mode of a white oak tree. A shaker driven by swept sine wave signals was used for inducing excitation in a tree trunk. The vibration in the trunk at the opposite side of the excitation point was measured using a laser Doppler vibrometer.

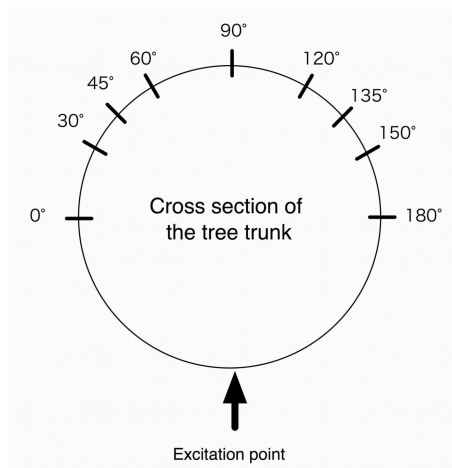


Fig. 4. The arrangement of the measurement points for identifying the mode shape of the white oak tree trunk. This picture shows the cross-sectional view of the tree trunk. The excitation was generated by a shaker driven by a single frequency signal. The vibration in the trunk in the radial direction was measured using a laser Doppler vibrometer.

## Results

### *Water content measurement of a wood sample*

Figure 5 (a) shows the spectra of the cylindrical wood sample at various water contents. The second resonance frequency of the sample was plotted against the water content (Fig. 5 (b)). These results indicate that the resonance of the sample decreased as the water content increased. This result was in agreement with the theoretical prediction. The resonance frequency varied by approximately 600 Hz with a corresponding change in the water content by 60% d.b.

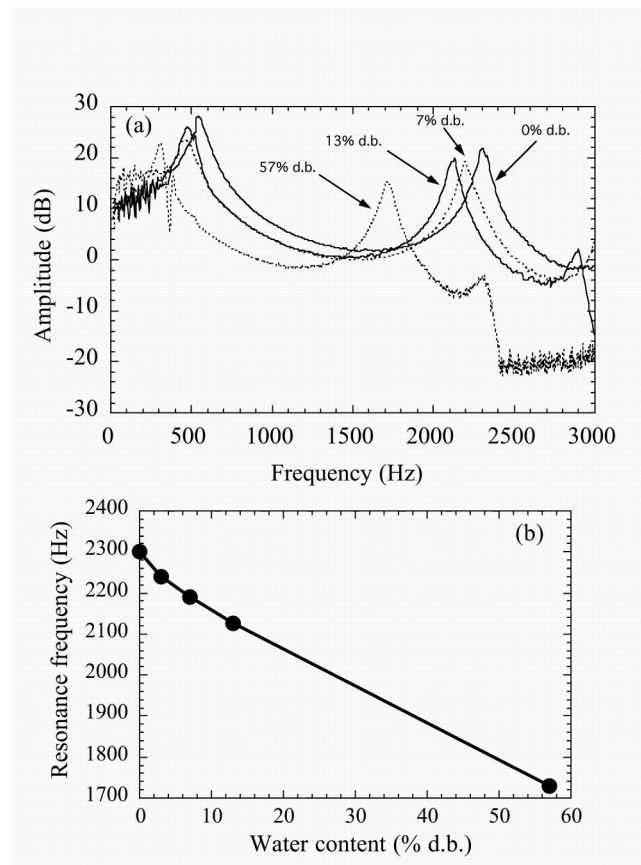


Fig. 5. (a) The spectra of cylindrical wood sample at various water contents. (b) The relationship between the resonance frequency and the water content.

### *Measurement of the circumferential mode of *Quercus myrsinaefolia**

Figure 6 shows a vibrational spectrum of the trunk of a white oak tree with a height of 4 m. There was a resonance with a clear peak and height of amplitude at 4318 Hz. Higher resonances were also observed at 6950 Hz and 8880 Hz.

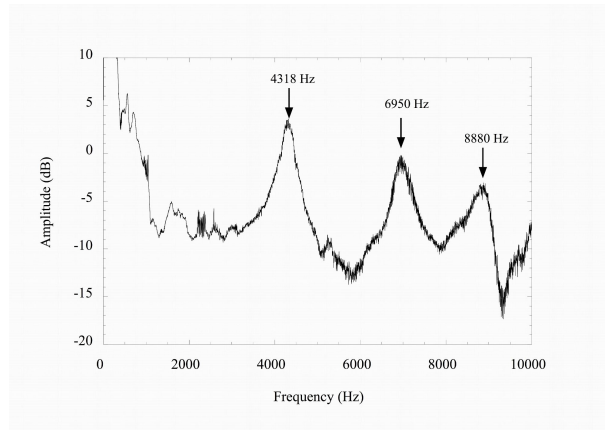


Fig. 6. The spectrum of the vibration in a white oak tree trunk. A clear resonance was observed at 4318 Hz and is indicated by an arrow. Higher resonance modes were also observed.

The mode shape was measured to confirm if the observed mode was a circumferential mode (Fig. 7 (a)). The vibration shaker gave sinusoidal vibrations at 4318 Hz; the lowest resonance peak was observed at this frequency. Two points at which the amplitude was local minimum were observed in the observation range of 0 to 180°. These points were supposed to be the nodes. The result indicates that the mode shape corresponded to the second order circumferential mode whose wave length was half the circumference as shown in Fig. 7 (b).

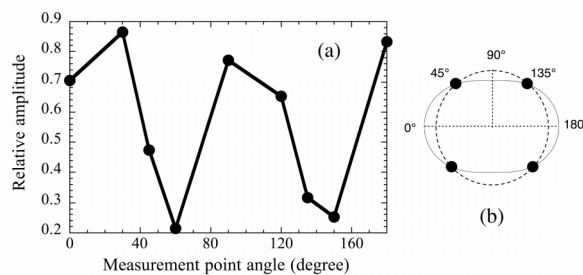


Fig. 7. (a) The mode shape of a white oak tree trunk. The vertical scale represents the relative amplitude of vibration to the excitation amplitude. Two points at which the amplitude was local minimum were observed. These points were supposed to be the nodes of the second order circumferential mode. (b) The mode shape of the second order circumferential mode. The black points represent the nodes.

## Discussion

An improved method of measuring the water content of trees was introduced in this study. A shaker driven by swept sine wave signals and an LDV were supposed to facilitate the accurate determination of the vibrational spectrum of wood as compared with the manual impact method. Our experiment with a wood cylinder sample showed that its resonance frequency was a function of the water content (Fig. 5). This result was in agreement with the theoretical prediction. The experimental result strongly supports that the water content can be determined by measuring the change in the resonance frequencies. Our result also showed that the water content above the fiber saturation point can be measured, although a previous method using the sound velocity (Mishiro, 1996a, 1996b) was limited to a 30% water content (below the fiber saturation point). Guan et al. (2002) suggested that the method using the sound velocity was effective for trees with a large difference in the water content of the late and early wood parts. However, if the difference is small, Young's modulus would be nearly constant. Therefore, it may be difficult to measure the water content above the fiber saturation point by using this method.

Electric resistance type and capacity and radio-frequency power loss types of water content meters are widely used in the wood industry. However, they are not efficient in determining the water content of large sections of wood with steep moisture gradients (Mishiro, 1996b). Time domain reflectometry (TDR) is widely used (Nadler et al., 2003); however, it damages tree surfaces because a hole needs to be drilled. Kamaguchi et al. (2000, 2001) have measured the water content of living trees. However, their results showed some scattering in their measurement. This may be due to the manual excitation method using a hammer. The manual method for constant excitation is difficult and depends on the person performing it. On the other hand, our method using a shaker driven by swept sine wave signals was able to generate precise excitations and enabled the accurate determination of the resonance frequency of wood.

Our preliminary experiments with a tree imply that our method can be used to measure the water content of trees. The circumferential mode of a tree was identified (Fig. 6, 7). The mode is advantageous to measure the vibration of trees because the mode only depend on their diameter. The water content of trees depends on the climate, moisture content of the soil, and daily variation in transpiration. It is important to measure the changes in the water content of trees not only for understanding tree physiology but also for practical irrigation scheduling in orchards. For instance, mandarin orange trees are planted in hilly areas where manual irrigation is difficult. Suppression of water intake by irrigation control increases the sugar content of orange fruits.

Irrigation scheduling is generally based on monitoring the soil water content. There has been increasing interest in the use of the methods that depend on plant responses



to water deficits (Jones, 1999, 2004). Leaf water potential could be an indicator of water deficit. However, it fluctuates with changes in environmental conditions such as temperature and humidity (Jones, 2004). The xylem water potential and stem water potential are more useful indicators of water status. Naor et al. (1995) have used the changes in stem diameter and stem water status to monitor irrigation. However, none of the plant-based methods are well suited for the automation of irrigation scheduling (Jones, 2004). Our method can be applied to automatic irrigation systems for fruit trees, roadside trees, etc.

The determination of resonance frequency needs to be more accurate for living trees than for wood because the range of the water content in living trees is expected to be smaller than that obtained in the wood in this experiment. In addition, the manual impact method using a hammer is not appropriate for measuring the vibration of a thin branch of a tree that is supposed to provide water content closely related to its leaf water potential. Electrical excitation methods such as our method are more suitable for measuring the vibration in thin tree branches.

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