

Effect of Moisture Sorption State on Vibrational Properties of Wood

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Abstract

The purpose of this study was to investigate the vibrational properties and corresponding anisotropy in wood during different states of moisture sorption. Samples of maple (*Acer* spp.) and red oak (*Quercus rubra* Michx.f.) were moisture conditioned by the adsorption process from an oven-dried state and by the desorption process from a water-saturated state. The dynamic modulus of elasticity (DMOE) and logarithmic decrement (δ) were examined as a function of grain orientation during moisture change processes and under constant moisture contents (MC). It was observed that regardless of species and grain direction, the DMOE and δ were lower and higher, respectively, during the moisture change process compared with those measured without a change in MC. The increase in δ value during adsorption was greater than that during desorption. These results suggest that wood in an unstable state shows lower elasticity and strength and higher damping properties than wood in an equilibrium state. Furthermore, results of this study demonstrate that a greater adsorption rate leads to greater destabilization during an adsorption process. The anisotropy in vibrational properties was found to vary between two species.

Wood is a complex biocomposite consisting of principally three structural components: cellulose, hemicellulose, and lignin. From the point of view of structure, wood is composed of elongated cells whose walls have a complex multilayered structure. In each layer, cellulose molecules are grouped together in long filaments called microfibrils embedded in a matrix substance composed of lignin and hemicelluloses with some amorphous cellulose around the surface of the microfibrils. As wood is a viscoelastic material, its mechanical properties are highly dependent on the elasticity of, as well as the internal friction within, the cell-wall polymers and matrix.

One convenient way of studying viscoelastic properties of wood is through vibrational analysis. A damped free vibration test was carried out with a cantilever beam vibration testing apparatus. The dynamic modulus of elasticity (DMOE) and internal friction (logarithmic decrement [δ]) measurements can be used to study the viscoelastic nature of wood. The DMOE is related to sound velocity and δ to sound absorption or damping within the wood so that, in themselves, both quantities are important as far as technological applications are concerned.

Because wood is a hygroscopic material, its physical and mechanical properties are highly affected by the change of its moisture content (MC). Since environmental conditions never remain stable and ambient relative humidity (RH) and temperature change continuously, repeated adsorption and desorption of moisture take place, and MC of wood seldom reaches an equilibrium level with the surroundings. It has been observed by several researchers that wood behaves

differently during adsorption and desorption, and some of its physical and mechanical properties are influenced by the state of sorption (Goulet and Hernández 1991; Hernández 1993a, 1993b; Obataya et al. 1998; Naderi and Hernández 1999; Chauhan and Aggarwal 2004; Takahashi et al. 2006). It is well known that under the same RH and temperature conditions, equilibrium moisture content (EMC) is found to be higher during desorption compared with adsorption and thus is described as the hysteresis effect.

Regarding the sorption hysteresis of wood, it is well known that the amount of moisture held by wood depends not only on the equilibrium of the RH but also on the direction from which the equilibrium is approached.

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Summarizing the explanation by White and Eyring (1947), the sorption hysteresis of water in cellulosic materials can be attributed to the irreversible uncoupling and recoupling of hydroxyl groups in the cellulose structure; that is, the uncoupling occurs during adsorption, and the recoupling occurs at relatively delayed stages in the desorption process. These delayed stages are due to the rigid structure of the cellulose chains in which a hydroxyl group barely recouples when a water molecule is desorbed. Consequently, the available sites for the adsorption of water are larger during the desorption process than during the adsorption process. In other words, water molecules bound directly to sites in the cellulose chain are larger during the desorption process than during the adsorption process.

In any event, the existence of sorption hysteresis suggests that in terms of the existing states of moisture, wood that is moisture conditioned during the adsorption process is different from wood that is moisture conditioned during the desorption process. It is interesting that such a difference in the existing state of moisture affects the vibrational properties of wood. The aim of this study was to investigate the effect of the state of moisture sorption on the vibrational behavior of wood. This was achieved by examining the DMOE and δ of wood during the moisture-conditioning process of adsorption and desorption.

Materials and Methods

Wood material

Maple (*Acer* spp.) and red oak (*Quercus rubra* Michx.f.) samples were tested in this study. The mean basic densities of maple and red oak based on oven-dried weight and green volume were 599.8 and 696.9 kg/m³, respectively. Two series of end-matched specimens were prepared from air-dried defect-free boards of each species, one for radial tests and the other for tangential tests (hereafter referred to as “LR” and “LT” specimens, respectively). The dimensions of LR specimens were 125 by 12 by 2 mm (length [L] by radial [R] by tangential [T]), and those of LT specimens were 125 by 12 by 2 mm (L by T by R).

Moisture conditioning

Samples for the vibration tests at constant MC were divided into five groups, each consisting of five samples. Air-dried specimens were moisture conditioned in three conditioning rooms (20°C; RH levels of 30%, 65%, and 90% ± 2%) for 4 weeks. Saturated samples were prepared by soaking air-dried samples in water for 4 weeks at room temperature. Oven-dried samples were dried using a constant-temperature drying chamber (24 h at 105°C). The EMCs of the samples are shown in Table 1.

Table 1.—Conditions for equilibrium moisture content (EMC) of samples.

Relative humidity (%)	Moisture conditioning	EMC (%)	
		Maple	Red oak
—	Oven dried	0	0
30	Controlled room air	5.9	6.3
65	Controlled room air	10.9	9.9
90	Controlled room air	17.2	14.6
—	Saturated with water	(30)	(30)

Five oven-dried specimens of each species were subjected to multistep adsorption in three rooms with relative humidity of 30, 65, and 90 percent. During the moisture sorption processes, specimens were taken out of the conditioning rooms at different times (2, 5, 10, 16, or 26 h) to determine their MC (Table 2) and vibrational behavior. After completion of the adsorption experiments, samples were saturated over distilled water for 10 days. These samples were subjected to multistep desorption mode in three rooms with relative humidity of 90, 65, and 30 percent; they were then placed in a desiccator containing P₂O₅ (0% RH). The specimens were weighed and measured for the vibrational properties at different times (2, 5, 10, 16, or 26 h) of each desorption process (Table 2).

Measurement of vibrational properties

The test samples that were moisture conditioned for 2, 5, 10, 16, or 26 hours were sealed with a polyethylene film to avoid changes in MC during the test. A cantilever beam vibration testing apparatus (Forest Products Laboratory, USA) was used for vibration tests under constant MC and during moisture changes. The specimen was gripped securely at one end and excited near the free end with a sharp flick from a shooting valve. The vibration was detected with a laser displacement transducer and recorded as a function of time. The frequency and amplitude attenuation were then used to calculate the DMOE and the δ of the cantilever samples.

DMOE can be calculated by the following equation (Turk et al. 2008):

$$\text{DMOE} = \frac{M}{L} \frac{12}{bt^3} (2\pi f)^2 \left(\frac{l^2}{1.875^2} \right)^2 \quad (1)$$

where

- M = mass of the specimen (kg),
- L = complete length of the specimen (m),
- b = base width of the specimen (m),
- t = thickness of the specimen (m),
- f = detected frequency of the first natural mode of vibration (Hz), and
- l = unclamped length of the cantilever beam (m).

As far as the internal damping is concerned, the law governing a damped vibration has the following form:

$$\chi = \chi_0 \exp(-ht) \times \cos(\omega t + j) \quad (2)$$

where h is the damping constant. The amplitude is a function of time, and it decreases toward zero.

A typical specimen free vibration response is shown in Figure 1. In order to determine the δ , the following equation can be used:

$$\delta = \ln \frac{\chi_n}{\chi_{n+1}} \quad (3)$$

Results and Discussion

Vibrational properties of wood at constant moisture contents

Figure 2 shows the DMOE and δ values of LR and LT specimens as a function of constant MC for maple and red oak. Each dot represents the averaged values for five

Table 2.—Conditions for moisture content (MC) changes of samples.

Change in relative humidity (%)	Moisture conditioning	Change in MC (%)	
		Maple	Red oak
0 → 30	Controlled room air	0 → 4.8	0 → 3.5
30 → 65	Controlled room air	4.9 → 10.3	3.9 → 8.2
65 → 90	Controlled room air	10.7 → 16.7	9.2 → 14.4
Saturated → 90	Controlled room air	(30) → 23.3	(30) → 22.0
90 → 65	Controlled room air	21.7 → 13.0	19.2 → 12.6
65 → 30	Controlled room air	10.6 → 6.8	9.9 → 6.5
30 → 0	P ₂ O ₅	5.2 → 0.7	5.0 → 0.6

samples, and the 95 percent confidence interval for the plots was less than 0.03 GPa and 0.006 for DMOE and δ , respectively. The DMOE reached a maximum from 0 to 6 percent MC and then decreased with increasing MC. The δ value decreased as the MC changed from 0 to 6 percent MC and then rose with increasing MC.

These results agree with those obtained by Kollmann and Krech (1960), James (1961, 1964), Suzuki (1962), Obataya et al. (1998), and Takahashi et al. (2006). In their research, the elastic modulus showed a maximum value, and δ showed a minimum value of about 5 to 8 percent MC. These phenomena can be explained by the hypothesis that in an oven-dried state, molecular chains in the amorphous regions of the cell wall are unnaturally distorted. In addition, microvoids exist between the molecular chains. This unnatural structure of the cell wall in an oven-dried state causes a smaller DMOE value and a greater δ value. With the increasing MC from the oven-dried state, water molecules are embedded in the microvoids, and the distorted molecular chains are rearranged. As a result, at about 5 to 8 percent MC, a more stable state for the cell-wall structure is obtained. Above 8 percent MC, water acts as a plasticizer that allows more molecular movement, and the cohesive forces between molecules are decreased, resulting in decreasing DMOE values and increasing δ values.

Beyond these common trends, the differences in both DMOE and δ are apparent between two grain orientations for maple and red oak. The DMOE and δ of LR samples were lower and higher, respectively, than those of LT samples for the maple specimens. However, the opposite trends were found for red oak. The variation of vibrational behavior between two species is probably because of the difference in the arrangement of the cell wall and the lumen in addition to the anisotropy of cell-wall substances.

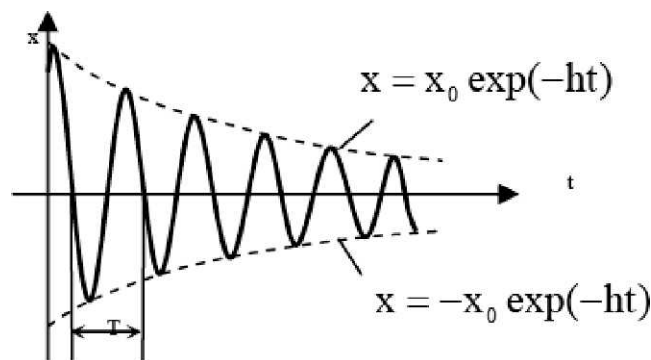


Figure 1.—A typical specimen free vibration response.

Changes in vibrational properties during moisture adsorption processes

Figure 3 shows changes in DMOE and δ values for the wood that was moisture conditioned by the adsorption process in both grain directions of maple and red oak specimens. The tests were carried out five times for each condition. Because the behavior of DMOE and δ with MC change was similar for all conditions, only one of the results is shown here. In each adsorption condition, regardless of species and grain direction, DMOE decreased in the early stage and then increased or flattened out in the higher MC ranges. This is attributed to the fact that the samples were more stabilized as MC changes finished in the later stages. The changing behavior of DMOE from the oven-dried state to approximately 5 percent MC (0% → 30% RH) was compared with that of the other two adsorption processes (30% → 65% and 65% → 90% RH). A remarkable decrease in DMOE with increasing MC was apparently observed in the former case. The adsorption rate should affect the decreasing behavior of DMOE because a greater adsorption rate leads to greater destabilization during an adsorption process (Takahashi et al. 2005).

The δ values of maple and red oak during the moisture adsorption processes for LR and LT samples are also presented in Figure 3. Regardless of species and grain direction, the δ value had a relative maximum at about 3 percent MC and then increased almost linearly with an increase in MC from around 5 percent MC. In the oven-dried state, the hydroxyl groups of the cellulose cell wall closed together, allowing the formation of weak cellulose-to-cellulose bonds. When adsorption of water then occurred in lower MC (less than 5% MC), a part of these weak bonds was broken down by entering water molecules, and some hydroxyl groups were released (Bowyer et al. 2003). Therefore, the reorientation of molecular chains may cause energy dissipation during the initial adsorption processes, resulting in an increasing δ value. In general, the δ value of wood increases with an increase of MC within the limits of the MC examined in this study.

With respect to the comparison of Figures 2 and 3, the DMOE and δ values during the adsorption processes were relatively lower and higher, respectively, than those of the samples measured at constant MC. This is because wood in a nonequilibrium moisture state shows a lower strength and higher damping properties than wood in the equilibrium state (Takahashi et al. 2004, 2005).

Changes in vibrational properties during moisture desorption processes

Representative results of DMOE and δ values of LT and LR samples for maple and red oak during the moisture

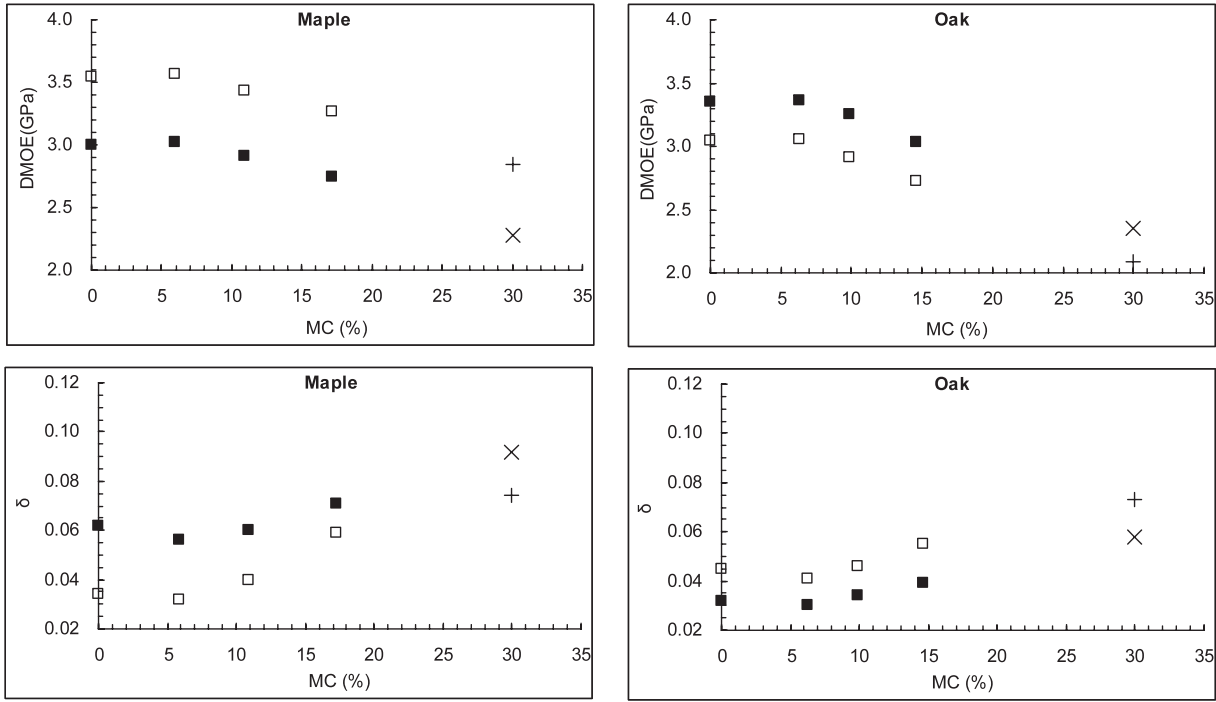


Figure 2.—Relationship between dynamic modulus of elasticity (DMOE), logarithmic decrement (δ), and constant moisture content (MC) for maple and red oak: vibrational tests at constant MC (■) and saturated with water (×) for radial test specimens; vibrational tests at constant MC (□) and saturated with water (+) for tangential test specimens.

desorption processes are shown in Figure 4. Regardless of species and grain direction, DMOE increases with decreasing MC without showing a maximum value. The DMOE during the desorption processes was lower than that in a stable state (Fig. 2) at a similar corresponding MC.

In Figure 4, δ decreases with a decrease in MC during the desorption processes. Furthermore, wood conditioned by desorption showed lower δ values than wood conditioned by adsorption (Fig. 3) regardless of the conditioning period. Considering the characteristics of the unstable state of

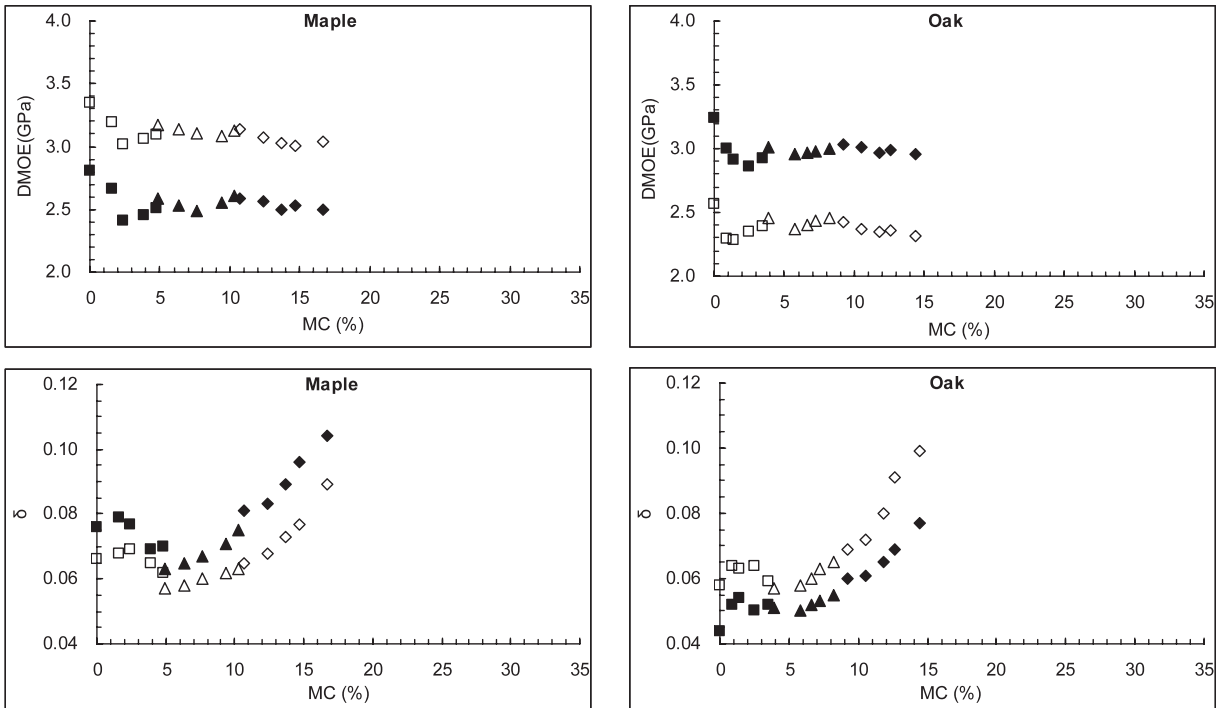


Figure 3.—Relationship between dynamic modulus of elasticity (DMOE), logarithmic decrement (δ), and moisture content (MC) during adsorption processes for maple and red oak: 0 → 30 percent relative humidity (RH) (■/□); 30 → 65 percent RH (▲/△); 65 → 90 percent RH (◆/◇); radial test samples (filled symbols); tangential test samples (open symbols).

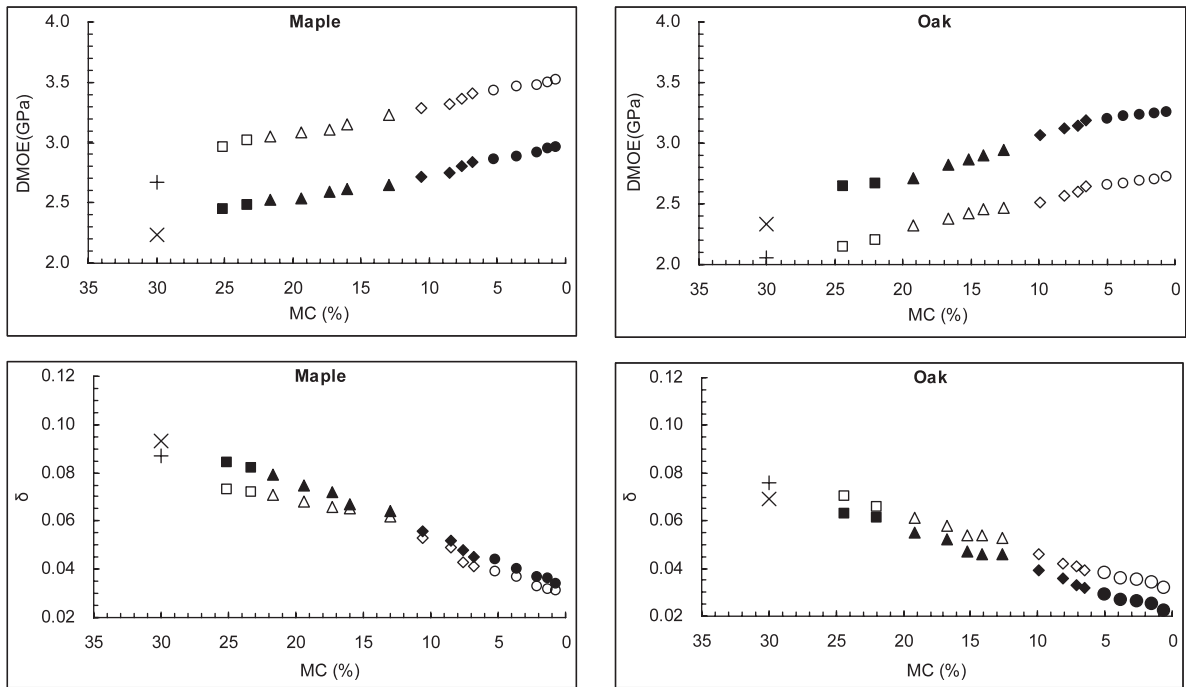


Figure 4.—Relationship between dynamic modulus of elasticity (DMOE), logarithmic decrement (δ), and moisture content (MC) during desorption processes for maple and red oak: saturated \rightarrow 90 percent relative humidity (RH) (\times /+, \blacksquare / \square); 90 \rightarrow 65 percent RH (\blacktriangle / \triangle); 65 \rightarrow 30 percent RH (\blacklozenge / \diamond); radial test samples (filled symbols and \times); tangential test samples (open symbols and +).

wood, this phenomenon can be attributed to the fact that wood that is moisture conditioned by adsorption is more unstable than wood that is conditioned by desorption. This interpretation is reasonable and can be explained as follows. Trees live in a state swollen by water, and this state is the most stable state for wood. During the drying process, a highly unstable state is induced. Such an unstable state is not easily modified by the adsorption of moisture. Accordingly, wood moisture that is conditioned by the adsorption process remains in a more unstable state than wood that is conditioned by the desorption process to the same MC (Ishimaru et al. 2001a, 2001b).

Conclusions

Vibrational properties of maple and red oak specimens were measured in the radial and tangential directions during moisture change processes and under constant MC. The results of the tests led to the following conclusions:

1. Regardless of species and grain directions, DMOE reached a maximum of 0 to 6 percent MC and then decreased with increasing MC for samples under constant MC. In each adsorption condition, DMOE decreased in the early stages of adsorption and then increased or flattened out in the higher MC ranges as a result of stabilization. During the desorption processes, DMOE increased linearly with decreasing MC. DMOE was lower during the moisture adsorption or desorption processes than for samples without a change in MC.
2. Regardless of species and grain directions, samples showed a minimum δ at approximately 6 percent MC and then rose with increasing MC under the constant MC state. Wood in a moisture sorption state showed a higher damping property than that in the MC stable state. The increase in δ value during adsorption was higher than

that during desorption. These behaviors can be interpreted to be the result of an unstable state caused by the existing state of moisture different from that in an equilibrium state.

3. The anisotropy in vibrational properties was found to be different between two species. The DMOE and δ of LR samples were lower and higher, respectively, than those of LT samples for the maple specimens, while the red oak showed opposite trends.

Acknowledgment

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