Acoustic Converting Efficiency and Anisotropic Nature of Wood

Hideo AIZAWA*1, Eiichi OBATAYA*1, Teruaki ONO*2 and Misato NORIMOTO*1

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It is accepted that both the acoustic converting efficiency and the degree of anisotropy of wood are important factors for the sound board of musical instruments1,2). In this paper, the relationship between these factors were clarified experimentally and theoretically. The specific dynamic Young’s modulus (E'/ρ) and the loss tangent (tan δL) in the longitudinal (L) direction, and the dynamic shear modulus (G') and the loss tangent (tan δT) in the LT plane (T: tangential direction) for 101 kinds of woods were measured by using flexural and torsional vibration methods.

There was a negative correlation between E'/ρ and tan δL as shown in Fig. 1. This fact indicates that smaller mean microfibril angles give larger E'/ρ and lower tan δL values3). Fig. 2 shows the relationships between the ratio of loss tangents (tan δT/tan δL) and that of elastic moduli (E'/G'). Relatively large E'/G' and tan δT/tan δL values of wood reflect its anisotropic nature. Fig. 3 shows the relationship between (E'/G') (tan δT/tan δL) and √E'/ρ/tan δL. The former reflects the degree of anisotropy and the latter relates to the acoustic converting efficiency (√E'/ρ/tan δL). There was a positive correlation between them. These acoustic properties can be calculated by using a uniaxial cell wall model in which amorphous isotropic matrix is disposed in parallel along the axis of cellulosic fibrils inclining at θ to the L direction of wood4). The E'/ρ, tan δL, G'/ρ and tan δT can be expressed by

\[ \frac{E'}{\rho} \approx \frac{\nu}{\rho_w} \left( \frac{1}{E_{w1}} + \frac{\theta^2}{G_{w12}} \right)^{-1}, \quad \text{tan } \delta_L \approx \left( \frac{E_{w1}}{E_{w1} + G_{w12}} + \frac{G_{w12}}{G_{w12}} \right)^{-1}, \]

\[ \frac{G'}{\rho} \approx \frac{\nu}{\rho_w} \left( \frac{\sin^2 2\theta}{E_{w1} + \cos^2 2\theta} \right)^{-1} \]

and

*1 Laboratory of Property Enhancement.
*2 Faculty of Engineering, Gifu University.
Fig. 1. The relationship between the loss tangent (tan $\delta_L$) and the specific dynamic Young’s modulus ($E'/\rho$) in the longitudinal direction of wood. Note: O, Experimental values; solid line, the regression line of experimental values ($r=-0.632$); dotted line, calculated values.

$$\tan \delta_L \times 10^3$$

$E'/\rho$ (GPa)

Fig. 2. The relationship between the ratio of loss tangent (tan $\delta_S$/tan $\delta_L$) and that of elastic moduli ($E'/G'$) of wood. Note: O, Experimental values; solid line, the regression line of experimental values ($r=0.648$); broken line, calculated values.

$$\tan \delta_S \approx \left( \frac{E_{w2}}{E_{w2}^2 + G_{w12}} \frac{\sin^2 2\theta}{\sin^2 2\theta + \cos^2 2\theta} \right) \left( \frac{\sin^2 2\theta}{E_{w2}} + \frac{\cos^2 2\theta}{G_{w12}} \right)^{-1},$$

where $\nu$ is the volume fraction of $S_2$ layer, $E_{w1}$ and $E_{w2}$ are the Young’s moduli of the cell wall in the parallel (1) and perpendicular (2) to the axis of fibrils, $G_{w12}$ is the shear modulus.
of the cell wall in the 1–2 plane, \( \rho_w \) is the density of the cell wall, respectively. Single and double primes indicate the dynamic modulus and loss modulus, respectively. According to the law of mixtures, \( E_{w1}', E_{w1}'' \), \( E_{w2}', E_{w2}'' \), \( G_{w12}' \), and \( G_{w12}'' \) can be expressed by

\[
E_{w1}' = \varphi E_f + (1 - \varphi)E_m, \quad E_{w1}'' = (1 - \varphi)E_m', \quad E_{w2}' = E_m' \left(1 + \frac{\varphi}{1 - \sqrt{\varphi}}\right), \quad E_{w2}'' = (1 - \varphi)E_m'' \left(1 + \frac{\varphi}{1 - \sqrt{\varphi}}\right) \tan \delta_m, \quad \text{and} \quad G_{w12}' = G_m' \left(1 + \frac{\varphi}{1 - \sqrt{\varphi}}\right) \tan \delta_m, \quad G_{w12}'' = G_m'' \left(1 + \frac{\varphi}{1 - \sqrt{\varphi}}\right) \tan \delta_m,
\]

where \( E_f \) is the Young's modulus of fibrils along the axis, \( \varphi \) is the volume fraction of fibrils, \( E_m' \), \( G_m' \), and \( \tan \delta_m \) are the Young’s modulus, shear modulus and loss tangent of the matrix, respectively. Values of \( \varphi = 0.84 \), \( E_f = 134 \text{ GPa} \), \( \varphi = 0.5 \), \( E_m = 2 \text{ GPa} \), \( G_m = 0.77 \text{ GPa} \), and \( \tan \delta_m = 0.015 \) were adopted. Dotted lines in Figs. 1–3 show the calculated values. The calculated values in Fig. 3 predicted that smaller microfibril angles give higher values of acoustic converting efficiency as well as higher degrees of anisotropy.

References