The Viscoelastic Properties of Wood Used for Musical Instruments II*,**

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Abstract——In order to make clear the relation between the acoustic properties and the fine structures of wood, the present paper deals with the dynamic mechanical and dielectric properties in relation to the angle of micellar orientation and the degree of crystallinity estimated by X-ray measurements of wood using for the musical instruments (Sitka spruce) and other few wood species (Hinoki, Sugi and Hoonoki).

The dynamic elastic modulus, loss modulus, dielectric constant and loss factor for Sitka spruce were large in magnitude for its specific gravity compared with the other species. The mean angle of micellar orientation and the half width in the distribution function of spiral angle for Sitka spruce were the smallest among the coniferous wood species used. The crystallinity indexes calculated from transmission method for Sitka spruce and Hinoki were smaller than those for Sugi and Hoonoki. From these results, it may be concluded that the principal cause which the dynamic elastic and loss modulus for Sitka spruce are large in magnitude for its density is due to its small angle of micellar orientation and/or its uniformity in the gross structures.

Introduction

Hither to the studies on the dynamic mechanical properties of wood used for the musical instruments have been made by FUKADA[1,2,3], TATEMITI[4], HOLZ[5,6,7], AOKI and YAMADA[8]. These papers deal with the dynamic properties as functions of frequency, density and the width of annual ring. It may be considered, however, that the acoustic properties also depend profoundly on the fine structures, i. e. the structures of microfibrils, micelles and supramolecular aggregates.

As sound and key boards of piano and in organ building, Sitka spruce has been mainly used. The timber cut from the outer portions of mature trees has a fine silky texture and mostly straight grain, and is remarkably free from defects. The average density in the seasoned condition is about 0.43 g/cm^3. The timber from nearer the center of the tree is typically of coarser texture with a tendency to spiral grain[9,10].

The strength of Sitka spruce is exceptionally high for its weight[9,10]. Furthermore, as reported in the previous paper[8], the values of dynamic elastic and loss modulus of Sitka spruce in longitudinal direction are larger than the other species for its specific gravity. This fact was also reported by AKIYAMA[11]. It may be considered, therefore, that the superior mechanical properties of Sitka spruce is attributed to the various structures mentioned above. In this paper, to obtain more information on the relation between the acoustic properties and the structures, the degree of crystallinity, the angle of micellar orientation and the dielectric properties of Sitka spruce and other few species are compared.

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Experimental

For the dynamic mechanical measurements Sitka sptuce (*Picea sitchensis* CARR.) as wood samples were used and their dimensions were $0.5\times0.5\times3.4\sim4.7$ cm. The measurements were made at 20 ± 1°C, 55 ± 5 % R. H. by using a composite oscillator at 60 kHz. The instruments and the methods were all the same to the ones refered in the previous paper[8].

For the dielectric experiments dry Sitka spruce, Sugi (*Cryptomeria japonica* D. DON) and Hinoki (*Chamaecyparis obtusa* ENDL.) were used and their dimensions were $5.0\times5.0\times0.1$ cm. The measurements were made over the frequency range from 300 Hz to 1 MHz and over the temperature range from -70°C to room temperature, and the inductive-ratio-arm bridge was employed as the measuring device. The values of dielectric constant ϵ' and loss factor ϵ'' were calculated from the following equations.

$$\epsilon'=C_xt,$$

$$\tan\delta=\frac{G_x}{wC_x},$$

$$\epsilon''=\epsilon'\tan\delta,$$

where C_x and G_x are the capacity and the conductance of the sample, w is the angular frequency, and t is the thickness of the specimen.

For the X-ray analysis Sitka spruce, Sugi, Hinoki and Hoonoki (*Magnolia obovata* THUNB.) were used and their dimensions used for the measurements of the angle of micellar orientation were $0.1\times0.5\times1.0$ cm. For the determination of crystallinity index the discs prepared by pressing wood powder of 300 mg passed a 100 mesh screen under a pressure were used. The measurements were made at room temperature. As X-ray diffractometer, Rota flex (Rotating anode X-ray generator, Rigaku Denki Co. Ltd.) was employed. The angle of micellar orientation was calculated by the following relations[12,13].

$$D=\sin\alpha\cdot I,$$

$$\cos\alpha=\cos\theta\cos\varphi_i \quad (\alpha>\theta),$$

$$\cos\alpha=1-(1-\cos\varphi_i)\cos^2\theta \quad (\alpha<\theta),$$

where D is the distribution function of the spiral angle, α is the spiral angle, I is the interference intensity, φ_i is the rotational angle and θ is the Bragg's angle, respectively. The crystallinity indexes were determined by the Durantia's method[14].

Results and Discussion

1. Dynamic mechanical properties.

In Table 1, the specific gravity ρ, the width of annual ring, and the dynamic properties of wood are shown. The dynamic properties at 60 kHz for Sitka spruce in longitudinal direction (L-direction) as a function of ρ are illustrated in Fig. 1. In these figures, the results reported in the previous paper[8] are included for comparison. The closed circles represent the wood species using for the musical instruments, while the open circles the other species, and the solid line represents the regression line obtained by staticical analysis. The dynamic elastic modulus E' and loss modulus E'' for Sitka spruce and Yezo spruce, which are used as sound and key boards of piano, were larger in magnitude than those of the other species for their density, while on the loss tangent $\tan\delta$ the inverse trend was observed. KRÜGER and ROHLOFF[15] reported

Table 1. Specific gravity, the width of annual ring B and dynamic mechanical properties of wood in L-direction at 60 kHz.

Species	ρ	E' dyne/cm²	tan δ	E'' dyne/cm²	B (cm)
Sitka spruce*	0.48	1.46×10^{11}	1.29×10^{-2}	1.87×10^{9}	0.08
Stika spruce**	0.39	1.05	1.48	1.55	0.27
Stika spruce**	0.42	1.19	1.29	1.54	0.15
Stika spruce**	0.44	1.36	1.24	1.69	0.07
Stika spruce**	0.46	1.45	1.36	1.97	0.05
Yezo spruce**	0.75	1.74	1.05	1.83	
Itayakaede**	0.39	1.29	1.26	1.62	
Balsa	0.15	0.35	3.19	1.11	
Kiri	0.21	0.37	1.96	0.85	
Sugi (sapwood)	0.36	0.86	1.43	1.27	
Kusunoki	0.45	0.63	1.71	1.04	
Yamaguruma	0.50	1.01	1.44	1.45	
Ichii	0.51	0.84	1.59	1.34	
Hoonoki	0.51	1.43	1.15	1.65	
Buna	0.56	1.00	1.62	1.62	
Keyaki	0.69	1.19	1.38	1.63	
Shirakashi	0.74	2.01	1.00	2.01	
Isunoki (sapwood)	0.95	2.22	0.98	2.18	
Isunoki (heartwood)	1.04	2.36	0.76	1.80	

* Nihon Gakki Co. Ltd.
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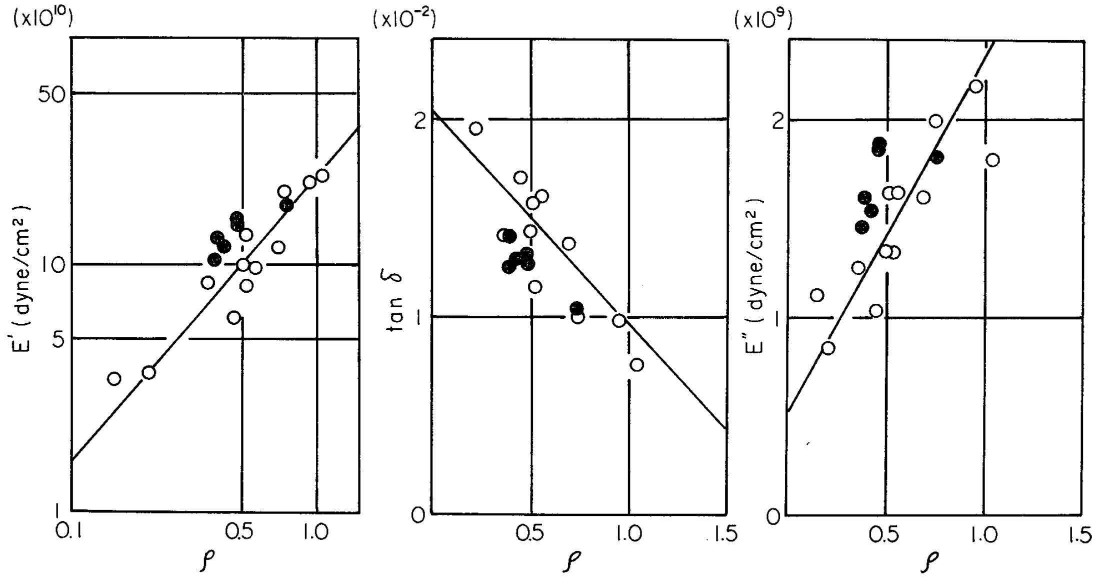

Fig. 1. E', E'' and tan δ for wood as a function of ρ.
●: Wood species using for musical instruments, Solid lines: regression lines.

the similar results, i. e. the values of logarithmic decrement for spruce in L-direction are small for their density compared with the other species. However, it is reported that E' and E'' of Sitka spruce in the transvers direction are almost equivalent in magnitude to other species comparing with corresponding ρ[8]. These results suggest that the dynamic properties in L-direction

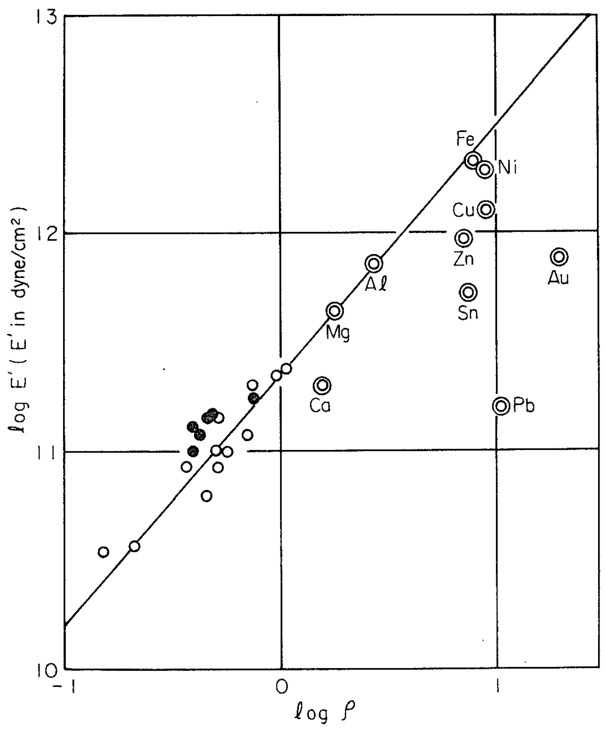

Fig. 2. $\log E'$ as a function of $\log \rho$.
○: Wood species (●: Wood species using for musical instruments), ◎: metals.

may profoundly depend on the structures, both gross and fine structures mentioned in the introduction.

MATSUMOTO[16] described that the propagation velocity of sound into L-direction of wood is close that of metals; for example 3900, 5300 m/s for Toneriko and Mominoki, and 3900, 5000 m/s for Cu and Fe respectively, although the specific gravity of wood is about $\frac{1}{20} \sim \frac{1}{10}$ times of those of metals, and then the radiative decrement of sound, which plays a significant role on the acoustic properties, is more marked than in metals. To compare the dynamic properties of

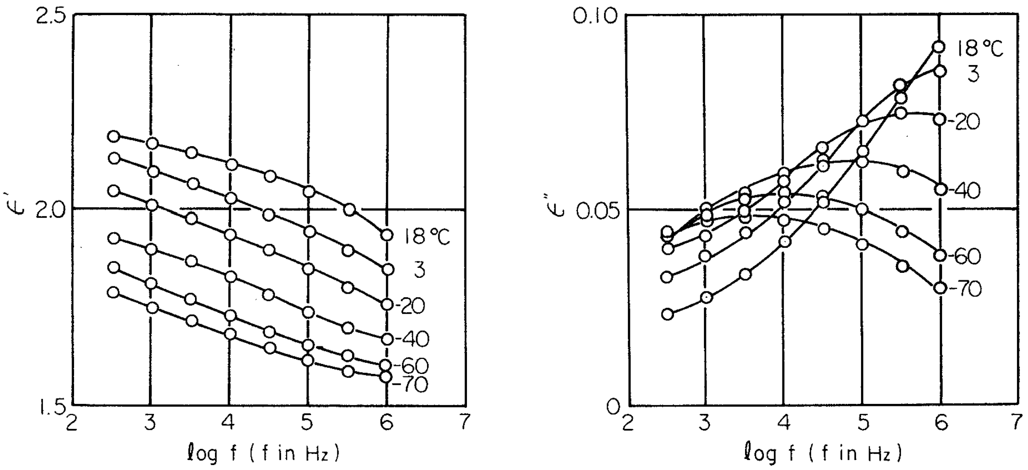

Fig. 3. Dielectric dispersion and absorption curves for Sugi in L-direction at respective temperatures.

wood in L-direction with those of metals[17,18], E' as a function of ρ are plotted in Fig. 2, in which the open and closed circles represent wood species and metals, respectively, and the solid line shows the regression line for wood species. It is interesting that the values of E' for the

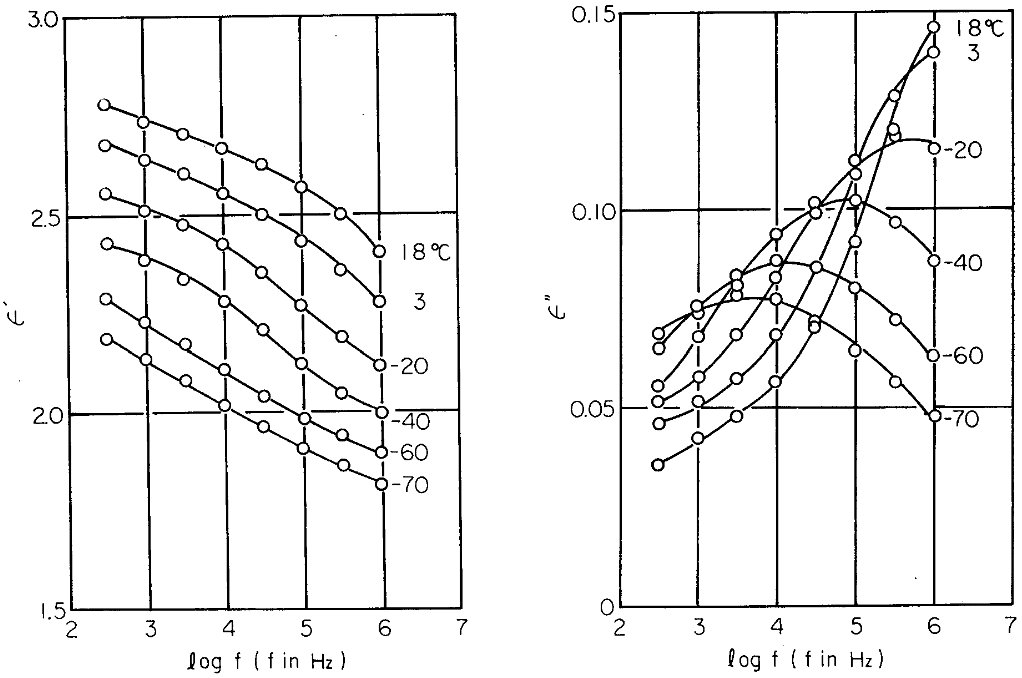

Fig. 4. Dielectric dispersion and absorption curves for Sitka spruce in L-direction at respective temperatures.

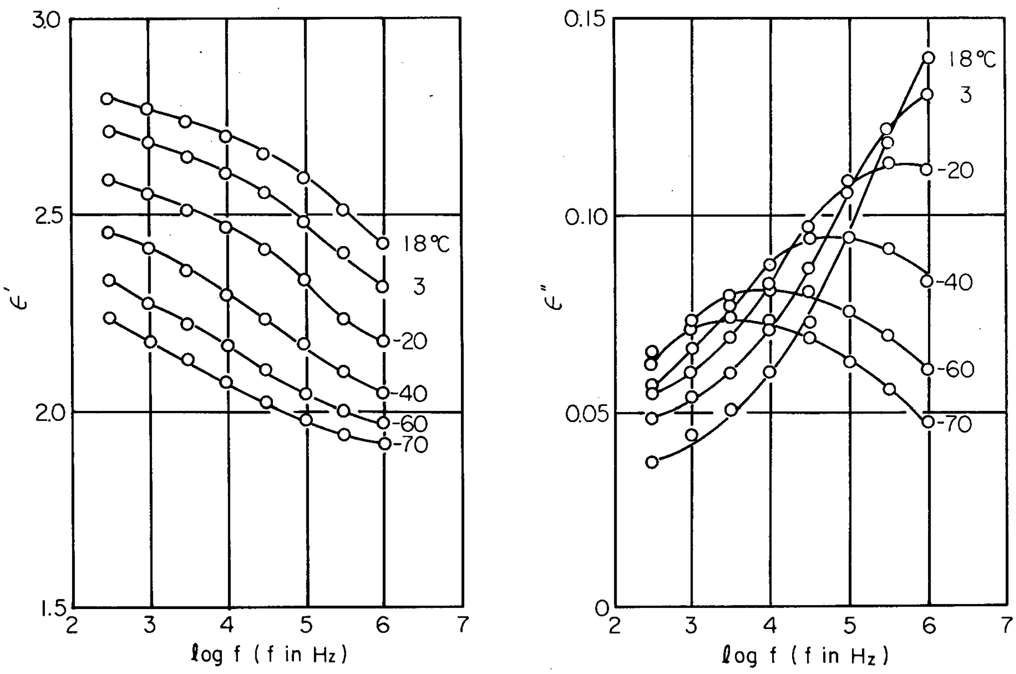

Fig. 5. Dielectric dispersion and absorption curves for Hinoki in L-direction at respective temperatures.

metals using for musical instruments, for example Al and Fe, can be ploted on the regression line.

2. Dielectric properties.

The dielectric dispersion and absorption curves for dry Sitka spruce, Sugi and Hinoki in L-direction are shown in Figs. 3 through 5. The values of ϵ' increased with increasing temperature and with decreasing frequency. The maximum values of ϵ'' increased with increasing temperature, and the frequency corresponding to ϵ'' maximum shifted to lower frequency range with decreasing temperature. It is reported that this absorption is due to the motion of CH_2OH

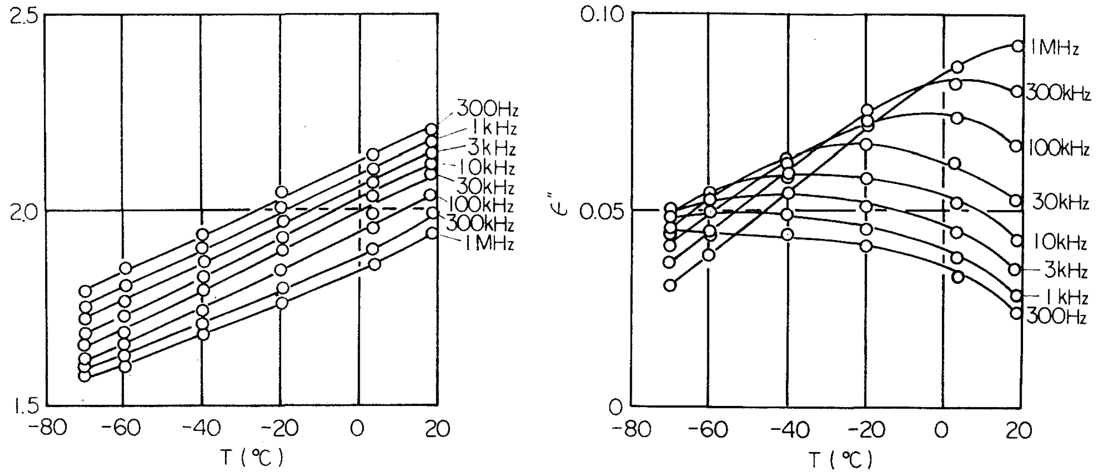

Fig. 6. Dielectric constant and loss factor of dry Sugi in L-direction as a function of temperature at respective frequencies.

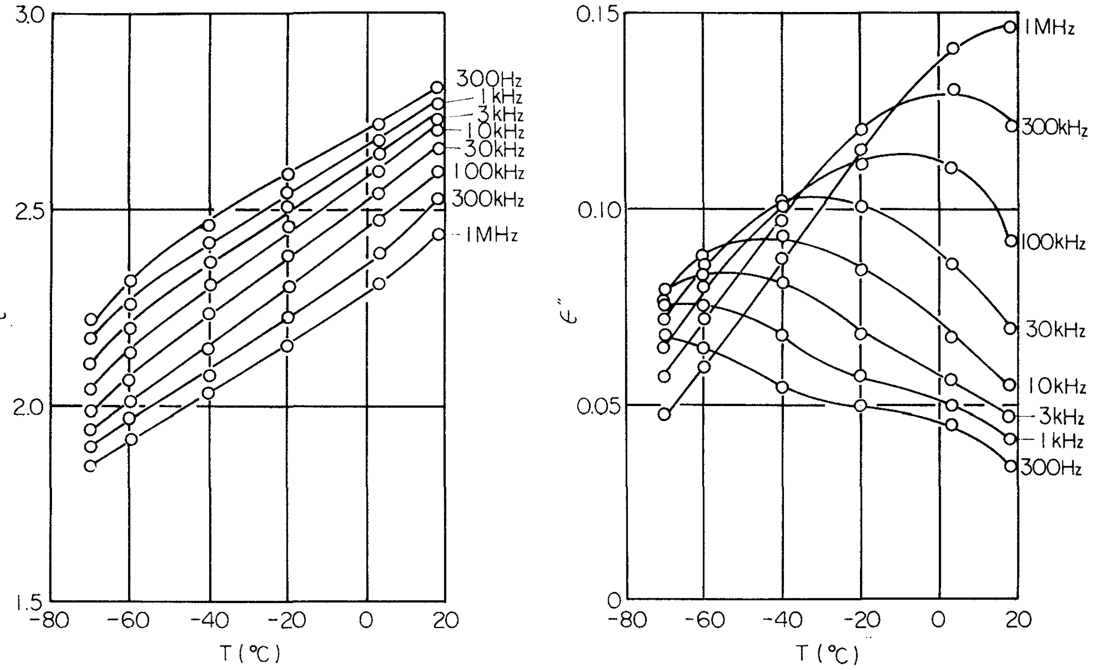

Fig. 7. Dielectric constant and loss factor of dry Sitka spruce in L-direction as a function of temperature at respective frequencies.

groups in the non-crystalline region of wood substance[19]. The same trend were also observed for Hinoki.

The dielectric constant ϵ' and loss factor ϵ'' of dry Sugi, Sitka spruce and Hinoki in L-direc-

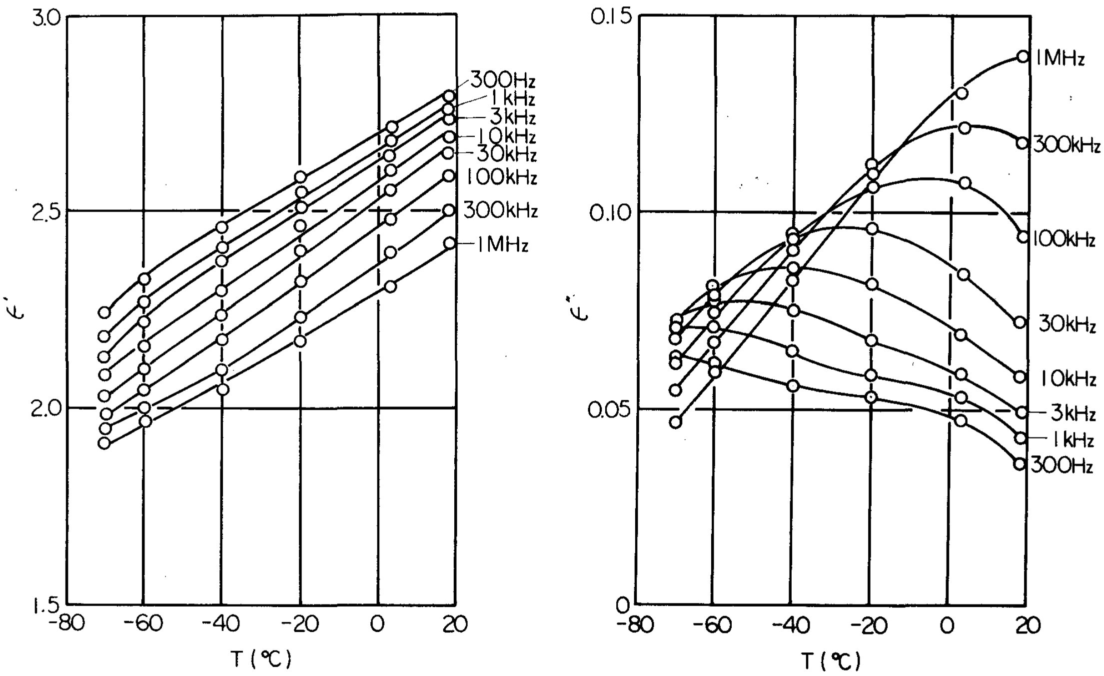

Fig. 8. Dielectric constant and loss factor of dry Hinoki in L-direction as a function of temperature at respective frequencies.

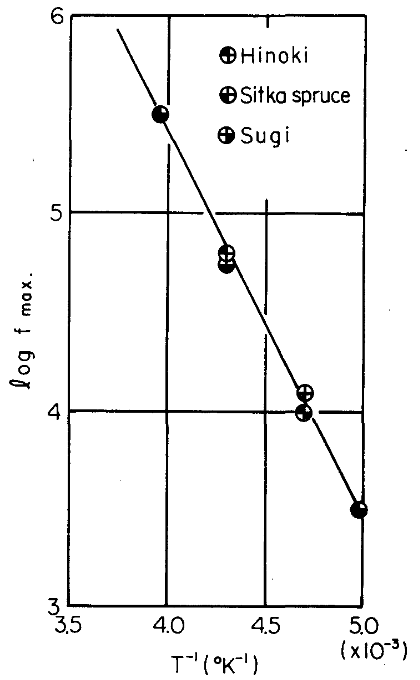

Fig. 9. $\log f_{max}$ vs, T^{-1} curve for Sugi, Sitka spruce and Hinoki.

tion as a function of temperature at respective frequencies are shown in Figs. 6 to 8. The values of ϵ' decreased with increasing frequency and with decreasing temperature. The maximum value of ϵ'' increased with increasing frequency and the temperature corresponding to ϵ'' maximum shifted to lower temperature range with decreasing temperature. At low frequencies another absorption was observed in the temperature range of -40 to 18°C. It may be expected that this absorption is associated with the motion of CO-groups in lignin[20].

In Fig. 9 the log f_{max}, which represents the frequency corresponding to the dielectric loss factor maximum, versus the reciprocal of absolute temperature T^{-1}, for Sugi, Sitka spruce and Hinoki are shown. From the slope of the straight line, the values of the apparent energy of activation[21] were calculated as about 9.6 Kcal/mole. The Cole-Cole's plots for Sugi, Sitka spruce and Hinoki in L-direction at -40 and -60°C are shown in Fig. 10. The dispersion magnitude

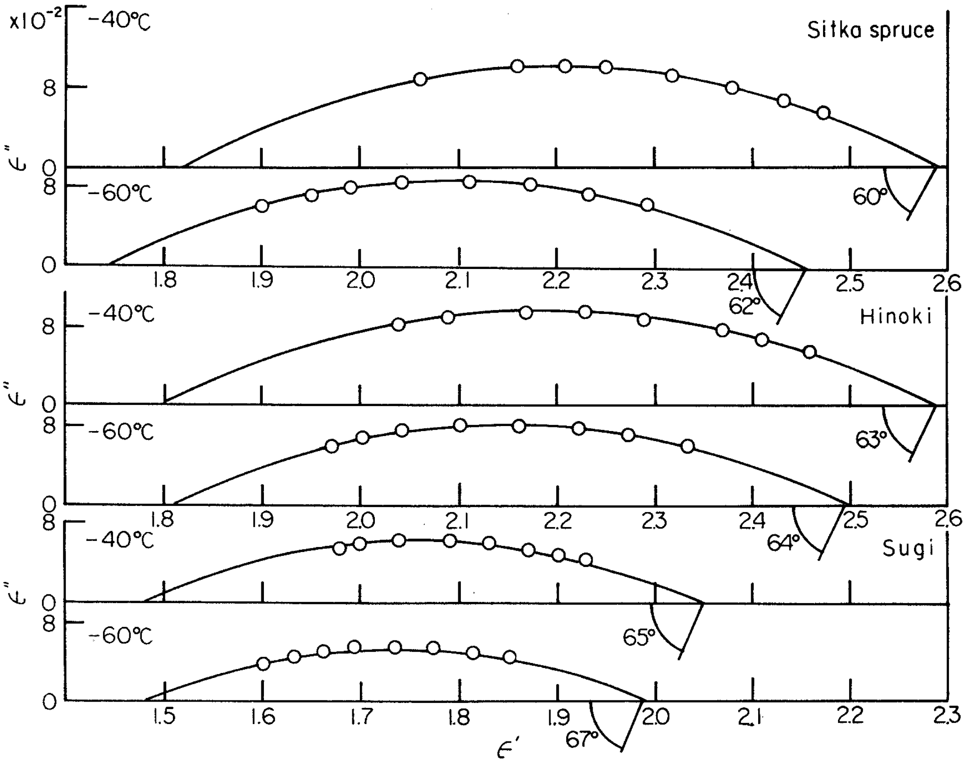

Fig. 10. Cole-Cole's plots for Sugi, Sitka spruce and Hinoki in L-direction at —40 and —60°C.

Table 2. The dispersion magnitude $(\epsilon_0' - \epsilon_\infty')$ and $\frac{\pi}{2}\cdot\alpha$ calculated from Cole-Cole's plots for three species.

Species	ρ	Temp. (°)	$(\epsilon_0' - \epsilon_\infty')$	$\frac{\pi}{2}\cdot\alpha$
Sugi	0.34	—60	0.51	67
		—40	0.57	65
Sitka spruce	0.45	—60	0.71	62
		—40	0.76	60
Hinoki	0.49	—60	0.68	64
		—40	0.79	63

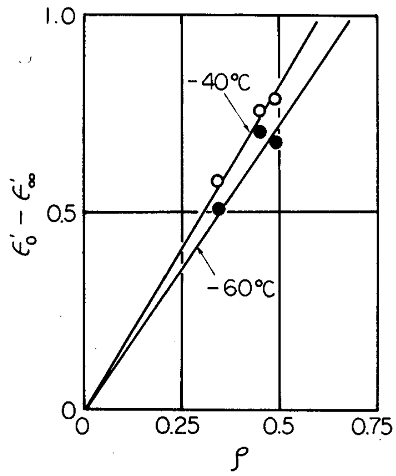

Fig. 11. ($\epsilon_0' - \epsilon_\infty'$) vs, ρ curve.
○ : −40°C ● : −60°C

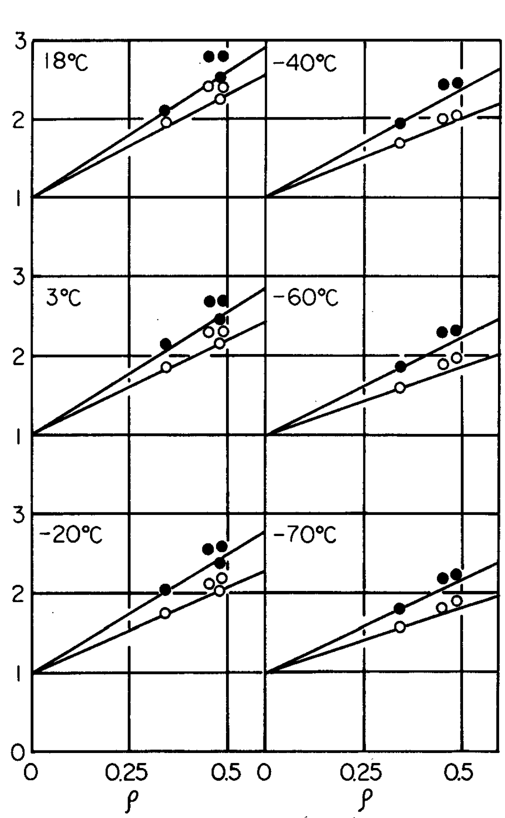

Fig. 12. Relationship between dielectric constant and specific gravity at respective temperatures.
○ : 1 MHz, ● : 300 Hz.

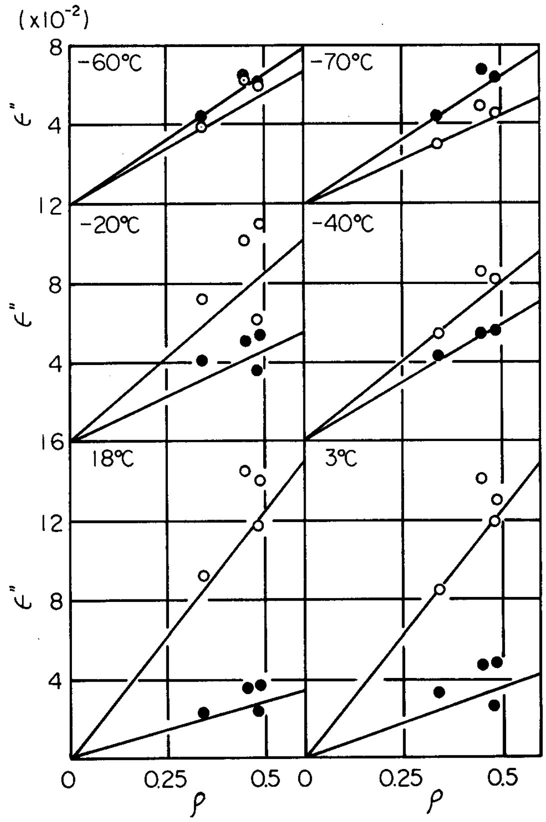

Fig. 13. Relationship between dielectric loss factor and specific gravity at respective temperatures.
○ : 1 MHz, ● : 300 Hz

$(\epsilon_0'-\epsilon_\infty')$ and $\frac{\pi}{2}\cdot\alpha$, which measure the distribution of relaxation times, at various temperatures are shown in Table 2. The dispersion magnitude $(\epsilon_0'-\epsilon_\infty')$ and $\frac{\pi}{2}\cdot\alpha$ increased with increasing temperature, and then it is clear that the distribution of relaxation times becomes nallower with temperature. In Fig. 11 the relation between the dispersion magnitude $(\epsilon_0'-\epsilon_\infty')$ and ρ is shown. $(\epsilon_0'-\epsilon_\infty')$ for Sitka spruce was greater in magnitude than the others for its density.

In Fig. 12 the dielectric constant at 300 Hz and 1 MHz over the temperature range of 18 to -70°C for four species in L-direction are presented as a function of ρ. The values of ϵ' at 18°C for Sitka spruce were large for its density comparing with the other species. However, with decreasing temperature they come nearer in magnitude to those of others. The dielectric loss at 300 Hz and 1 MHz over the temperature range of 18 to -70°C for four species in L-direction as a function of ρ is shown in Fig. 13. The values of ϵ'' for Sitka spruce were generally larger than those of others, but compared with corresponding ρ, the values of ϵ'' for Sitka spruce come nearer to those of others with increasing temperature at 300 Hz and with decreasing at 1 MHz. These results can be easily explained by considering the frequency and temperature dependence of ϵ' and ϵ''.

Generally, ϵ' and ϵ'' may increase in magnitude with increasing non-crystalline content, since the dipoles in non-crystalline region contribute mainly to ϵ' and ϵ'' in the frequency and temperature ranges used. On the other hand, these values may also increase with decreasing the angle of micellar orientation, since it is reported that the stable orientational positions for each CH_2OH group exist along the directions of microfibrils. Furthermore, it may be expected that wood having uniform macroscopic structures has large values of ϵ' and ϵ''. Then, from the results on the dielectric measurements, it may be concluded that Sitka spruce has large amount of non-crystalline fraction and/or small angle of micellar orientation and/or more uniform gross structures compared with other ones.

3. X-ray studies.

In order to make clear the relationship between the acoustic properties and the fine structures of wood in more detail, both the angle of micellar orientation and the degree of crystallinity

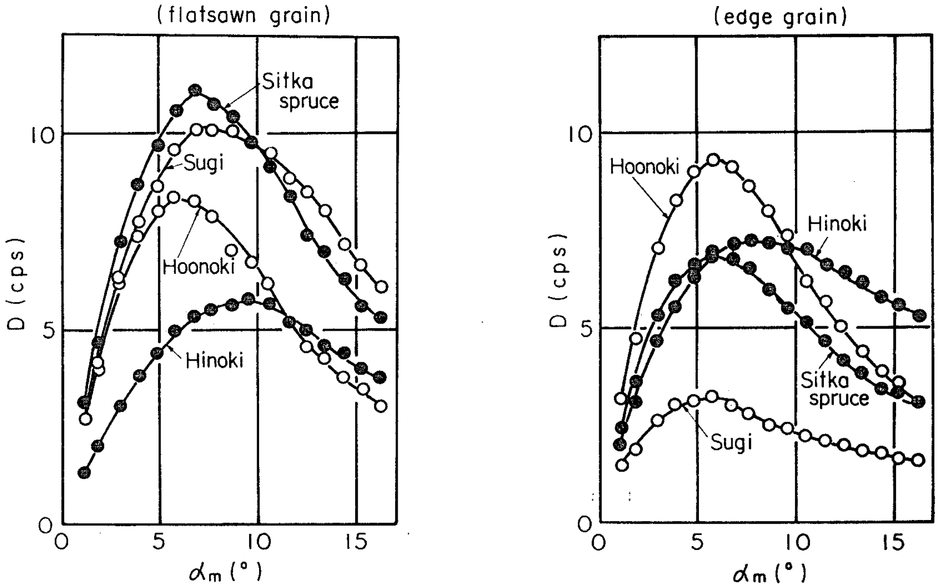

Fig. 14. Distribution of α_m, D, for four species in flatsawn and edge grain.

were determined from X-ray measurements. The distribution function of spiral angle D as a function of the angle of micellar orientation for wood species in edge grain and flatsawn grain is shown in Fig. 14. The mean angle of micellar orientation $\bar{\alpha}_m$ and the half width Δ in the distribution function of spiral angle are given in Table 3. $\bar{\alpha}_m$ for Hinoki is largest among four species. While $\bar{\alpha}_m$ for Sitka spruce is the smallest among coniferous wood species used. Δ for Sitka spruce are smaller than those of other coniferous wood species. From these results, it seems that Sitka spruce has generally small $\bar{\alpha}_m$ and Δ compared with other coniferous wood species used in this paper.

Table 3. The mean angle of micellar orientation $\bar{\alpha}_m$ and the half width in the distribution function of spiral angle Δ.

Species	flatsawn grain		edge grain	
	$\bar{\alpha}_m$ (°)	Δ (°)	$\bar{\alpha}_m$ (°)	Δ (°)
Sugi	7.6	>14	5.7	15
Sitka spruce	6.8	14	5.7	13
Hinoki	9.6	15	8.0	>15
Hoonoki	6.8	12	5.7	12

Table 4. The values of crystallinity index for four species.

Species	ρ	Crystallinity index (%)	
		Transmisson method	Reflection method
Sugi	1.2	40	50
Sitka spruce	1.2	36	52
Hinoki	1.2	36	50
Hoonoki	1.1	48	51

On the other hand, the crystallinity index for four species is shown in Table 4. The crystallinity indexes for Sitka spruce and Hinoki calculated from the results measured by transmisson method were smaller than those for Sugi and Hoonoki, although these values from reflection method were almost equivalent to those of four species.

From these results, it may be concluded that the principal cause which the dynamic elastic and loss modulus for Sitka spruce are larger in magnitude than those of the other species for its specific gravity is due to its small angle of micellar orientation and/or its uniformity in the gross structures.

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