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Frequency responses of wood for musical instruments in relation to the vibrational properties

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The frequency response and the Young's modulus, shear modulus and internal friction were measured for square boards with regularly-grained planes in several kinds of wood, which included Sitka spruce for stringed instrument top plates and maple for back plates, and for square boards in an acrylic resin of plastics and an aluminum of metals. The Sitka spruce was the highest in response frequency, higher in sound power level, the greatest in level variation and the greatest in level drop with increasing frequencies above 1 kHz, and it had the response pattern of high level in the range of middle frequencies. In contrast, the maple had the response pattern of low and almost flat level as a whole. In order to have such frequency responses, it was necessary that wood for top plates had not only the excellent vibrational properties in the direction along grain but also the strong anisotropy in regularly-grained plane, and that wood for back plates had the characteristics opposite to those of wood for top plates.

Keywords: Soundboard, Frequency response, Young's modulus, Internal friction, Anisotropy

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1. INTRODUCTION

In stringed instruments such as violin family and guitar, the sound radiation source is mainly a top plate and in pianos it is a soundboard. Materials used for them have been restricted to Picea genus wood of German spruce, Akaezomatsu, and Sitka spruce, and the wood boards with straight grain and without defects of nodes, cracks, *etc.* have been used as the materials of good quality. Materials used for back plates of violin family have been restricted to wood of maple, and the wood boards with fine appearance have been used. The piano soundboard has the structure that ribs of a wood bar are gluded across grain to the above wood board with regularly-grained planes, *i.e.* longitudinal-radial (*LR*) planes. The top plate, *i.e.* soundboard, of violin family has been made by giving violin shape, f holes, a bass bar, thickness distribution and an arch to the above wood boards with *LR* planes, and the timbre has been produced. From this fact, in stringed instruments, the frequency characteristic of the solid wood board for soundboards is the base of the timbre of top plates. On the other hand, it is influenced directly by the wood quality determining the acoustical properties. Consequently, it is necessary to find the difference in frequency characteristic between wood boards used for soundboards and the other wood boards and to make clear the mechanism how it is produced by the difference in acoustical property.

The timbre which is desirable for violins has been found by many studies on the frequency characteristics of violin bodies.[1] On the other hand, in order to find the reason why the above kinds of wood have been used as the materials for musical instruments, their vibrational properties in the direction along grain, *i.e.* longitudinal (*L*) direction, exclusively have been investigated, and the general opinion for it has been almost established: Wood for soundboards has higher specific Young's modulus and lower internal friction in L direction,[2] and wood for back plates has less vibrational properties in L direction and fine appearance. However, the vibrational properties in the direction across grain, *i.e.* radial (R) direction, must also contribute to the frequency characteristic because of the board with LR planes. Therefore, it is necessary to find the role of it and the effect of anisotropy. However, there have hardly been investigations on them.

In this study, the frequency response under forced vibration and the Young's modulus, shear modulus and internal friction in L and R directions were measured for square boards in several kinds of wood which included wood for the body plates, and from the features of them the mechanism of frequency responses was investigated.

2. FLEXURAL VIBRATION OF ORTHOTROPIC PLATES

Generally, the equation of motion in rectangular plates with grain parallel to the length is shown as follows:[3]

$$D_L\frac{\partial^4 w}{\partial x^4}+2D_{LR}\frac{\partial^4 w}{\partial x^2\partial y^2}+D_R\frac{\partial^4 w}{\partial y^4}+\rho\frac{\partial^2 w}{\partial t^2}=0 \quad (1a)$$

$$D_L=\frac{E_L h^3}{12(1-\sigma_{LR}\sigma_{RL})} \quad (1b)$$

$$D_R=\frac{E_R h^3}{12(1-\sigma_{LR}\sigma_{RL})} \quad (1c)$$

$$D_{LR}=D_L\sigma_{RL}+2D_K \quad (1d)$$

$$D_K=\frac{G_{LR}h^3}{12} \quad (1e)$$

in which w=displacement, x=position in L direction, y=position in R direction, D_L and D_R=flexural rigidity, D_{LR}=rigidity in LR plane, D_K=torsional rigidity in LR plane, h=thickness, ρ=density, E=Young's modulus, G=shear modulus, σ=Poisson's ratio.

From Eq. (1), the angular frequency ω is derived as the following equation:

$$\rho h\omega^2=\frac{A^4 D_L}{a^4}+\frac{B^4 D_R}{b^4}+\frac{2CD_{LR}}{a^2b^2} \quad (2)$$

in which a=side length in L direction, b=side length in R direction; A, B and C=constants depending on boundary conditions and vibration modes. The flexural vibration is influenced by shear deformation at the higher order mode and the increase of eigenfrequency with increasing the mode order decreases by degrees, and so at the higher order mode, the shear effects in LT plane (flat grain plane) and RT plane (end grain plane) should be taken into account for the eigenfrequency in L direction, ω_L, and the eigenfrequency in R direction, ω_R, respectively.[4,5]

3. EXPERIMENTAL

3.1 Samples

Materials for samples were Sitka spruce (*Picea sitchensis*), which was used for musical instrument soundboards, and hemlock (*Tsuga heterophylla*) of softwood, maple (*Acer saccharum*), which was used for violin back plates, mahogany (*Swietenia* spp.) and matoa (*Pometia pinnata*) of hardwood, acrylic resin of plastics and aluminum of metals. From these materials, samples of square boards with $105\times105\times2(t)$ mm, which were smaller and different in shape in comparison with practical body plates, were made in order to make easy the preparation and the measurement but to serve the purposes in this study. The wood samples had a side parallel to grain. The board numbers were two in Sitka spruce and one in the other. In the boards of acrylic resin and aluminum, degeneration occurred to their flexural resonances because of square and isotropy, and the Young's modulus and the internal friction could inexactly be measured. Then, their rectangular bars with $105(l)\times16(w)\times2(t)$ mm, whose length (l) and thickness (t) were the same as those of the sample boards, were made for the measurements. The number of each bar was one.

3.2 Measuring Methods

3.2.1 Frequency response curves

An apparatus for measuring the frequency response was shown in Fig. 1. A square plate

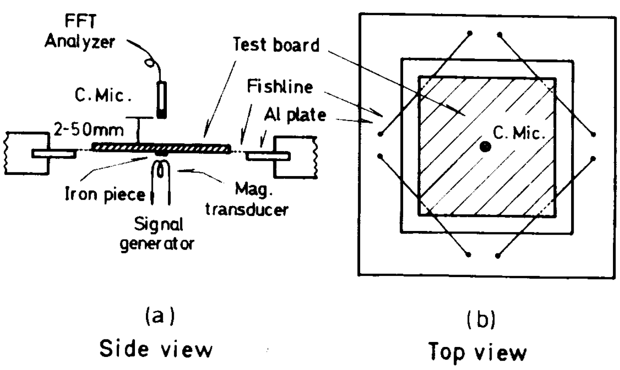

Fig. 1 An apparatus for measuring frequency responses.

vibrating flexurally radiates sound at modes having a loop at the center, that is, at modes of symmetric with respect to planes perpendicular to the plate at the middles. And, for the purpose of finding the essential acoustic characteristics of a board material, it is more desirable that the boundary condition is free, though practical body plates are fixed at edge. Accordingly, an aluminum square frame with fishlines strained at four corners was fixed horizontally and the test board with an iron piece glued to the center was put on the fishlines. The electromagnetic transducer of a driver was faced with the iron piece keeping the gap of 1 mm, and the sine wave sweeping the frequency range of 0.1-10 kHz was inputted to the transducer and the board with approximately free edges was drived. The sound radiating from the boards was detected by a condenser microphon set up in height of 2 mm or 50 mm from the center and was inputted to a FFT analyzer. The sweep time of the sine wave, whose source was the signal generator in the FFT analyzer, was five minutes. The condition of measurements in the FFT analyzer was Hanning in window function and was 2,048 points in sampling number.

The effect of the difference in distance (l_{bc}) between the board and the microphon on the envelope of frequency responses was investigated by taking the difference in level between 1/3 octave responses at $l_{bc}=2$ mm and $l_{bc}=50$ mm. The two examples were shown in Fig. 2. In the figure, the power level at $l_{bc}=50$ mm is 0 dB of a standard shown by a dotted line. The envelope at $l_{bc}=2$ mm, which naturally had higher ratio of S/N, rose in the range of low frequencies, in which the effect was observed.

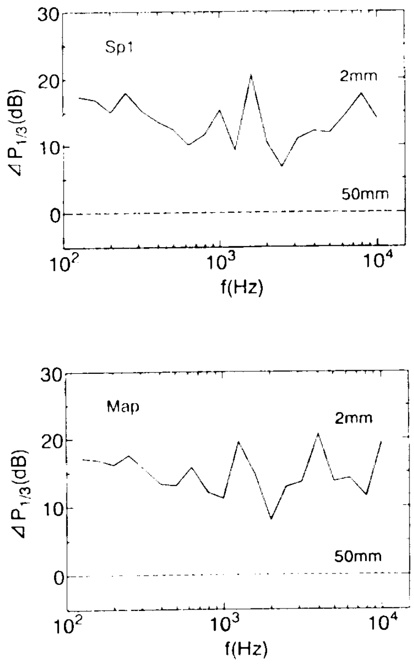

Fig. 2 The effect of distances (l_{bc}) between a board and a microphon on 1/3 octave responses. Legend: Sp: Sitka spruce; Map: maple; dotted line: 0 dB of the standardized power level at $l_{bc}=50$ mm.

3.2.2 The Young's modulus and internal friction by flexural vibration and the shear modulus and internal friction by torsional vibration

The Young's modulus (E) and the flexural internal friction (Q^{-1}) for the boards and bars with free both ends were measured by using a flexural vibration at the first mode. The shear modulus in LR plane (G_{LR}) and the torsional internal friction in LR plane (Q_t^{-1}) for the boards with free both ends were measured by using a torsional vibration at the first mode: The boards with iron pieces glued to two corners forming the extremities of one diagonal were fixed with an edge at the middle in L direction which was a vibration node and electromagnetic transducers for a driver and a detector were faced with the iron pieces, and the boards were excited by the driver at one corner and the vibration was detected by the detector at the other corner. All the measurements were made in a room maintained at a temperature of 20-25°C and a relative humidity of 50-60%.

The Young's and shear moduli and the internal friction were calculated using the peak frequency and the half-value width in resonance curves, respectively. The shear modulus G_{LR} was calculated using the following equation[6]:

$$G=\frac{\rho(1+u^2)l^2}{g(u)}f^2 \tag{3a}$$

$$u=\frac{w}{h}\left(\frac{G'}{G}\right)^{1/2} \tag{3b}$$

$$g(u)\approx 1-\frac{192}{\pi^5}\frac{1}{u}\tanh\frac{\pi}{2}u \tag{3c}$$

where, l = length (in L direction), w = width (length in R direction), G' = shear modulus in a cross section along length (G_{LT}).

4. EXPERIMENTAL RESULTS

4.1 Frequency Response Curves

The experimental results of frequency responses were shown in Fig. 3. In each figure in Fig. 3, the

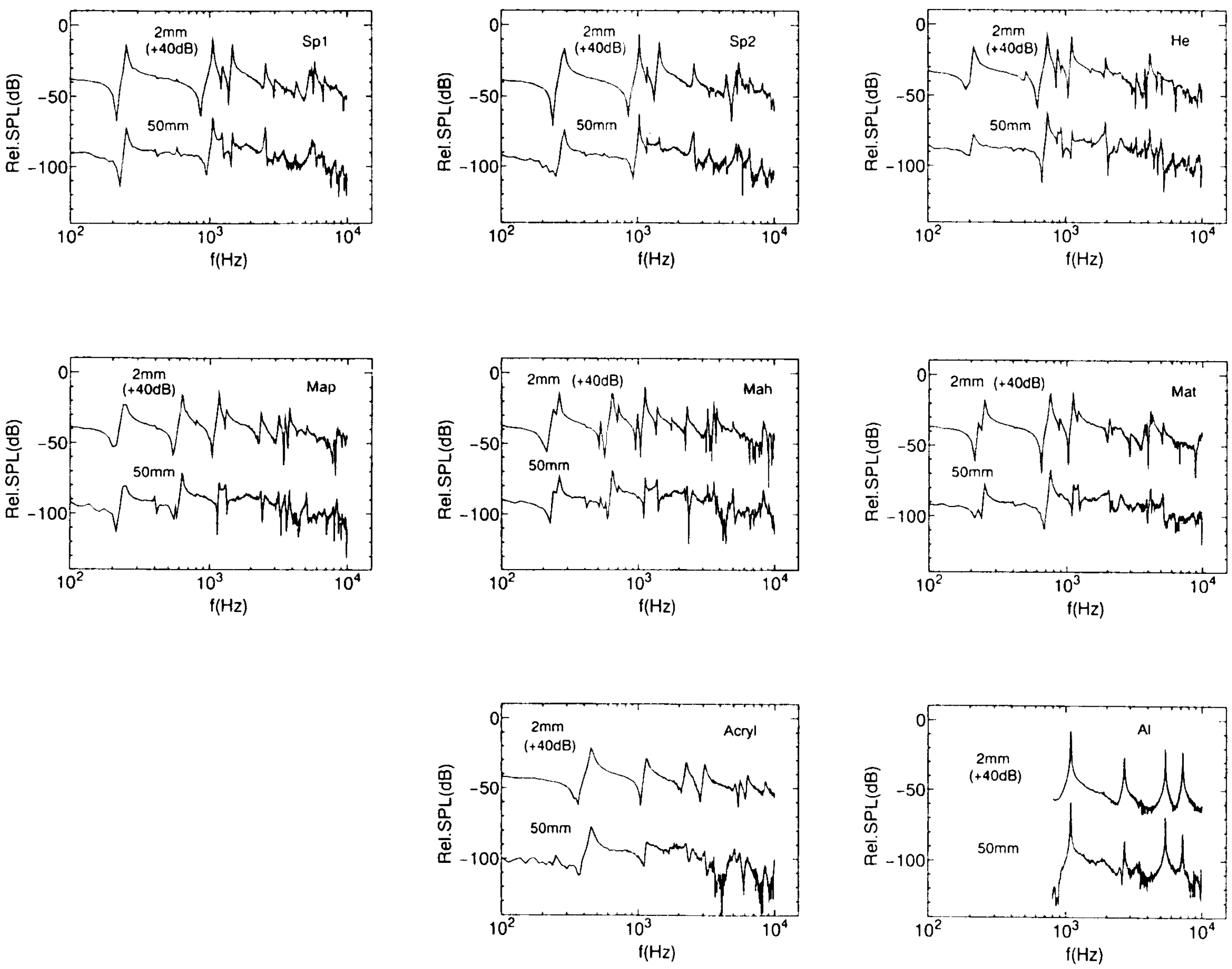

Fig. 3 Frequency responses. Legend : Sp : Sitka spruce ; He : hemlock ; Map : maple ; Mah : mahogany ; Mat : matoa ; Acryl : acrylic resin ; Al : aluminum.

upper curve and the under curve are the results at $l_{bc}=2$ mm and $l_{bc}=50$ mm, respectively, and 40 dB was added to the value of the former. The figures of the upper row, the middle row and the lower row are the response curves for the softwood, the hardwood and the acrylic resin and aluminum, respectively. The overall power level P_0 in Fig. 3 was shown in Table 1. In the table, the P_{01} and the P_{02} are the overall power levels at $l_{bc}=2$ mm and $l_{bc}=50$ mm, respectively.

From the figure and the table, it was observed that each material had the following features: (1) The acrylic resin is smaller in peak number, smaller in level variation and the lowest in P_0. (2) The aluminum is the highest in response frequency, the smallest in peak number, the sharpest in peak, the greatest in level variation and comparable to wood in P_0. (3) The softwood has a peak in the range of low frequencies, and it is greater in level variation than the hardwood, wider in interval between peaks, higher in P_0 and greater in level drop with increasing frequencies above 1 kHz. In the Sitka spruce for soundboards, they are more remarkable. (4) The hardwood has a peak in the range of low frequencies, and it is smaller in level variation, narrower in interval between peaks, lower in P_0 and smaller in level drop with increasing frequencies above 1 kHz. In the maple for back plates, they are more remarkable.

4.2 Young's Modulus, Shear Modulus, Flexural Internal Friction, and Torsional Internal Friction

The experimental results of Young's modulus (E) and flexural internal friction (Q^{-1}) were shown in Table 1. In the table, the subscripts of L and R

Table 1 Characterization of test boards by flexural vibration and torsional vibration methods.

Specimen	ρ g/cm³	f_{L1} Hz	f_{R1} Hz	E_L GPa	E_R GPa	Q_L^{-1}	Q_R^{-1}	P_{01} dB	P_{02} dB	f_t Hz	G_{LR} GPa	Q_t^{-1}
Sitka spruce 1	0.536	1,049.4	231.7	16.9	0.842	0.00667	0.0194	−44.2	−59.0	241.0	0.965	0.0153
Sitca spruce 2	0.482	1,022.7	269.0	14.4	1.02	0.00733	0.0182	−44.1	−60.0	240.7	0.864	0.0157
Hemlock	0.479	733.6	174.5	12.3	0.705	0.00627	0.0224	−41.9	−57.1	192.3	0.909	0.0130
Maple	0.668	616.6	231.2	11.8	1.64	0.0109	0.0199	−47.5	−63.5	229.7	1.74	0.0153
Mahogany	0.595	641.7	237.1	10.8	1.49	0.00701	0.0143	−44.8	−60.3	205.1	1.18	0.0127
Matoa	0.753	743.3	219.5	19.2	1.66	0.00727	0.0223	−46.4	−61.5	184.5	1.26	0.0173
Acrylic regin	1.18	450.0		5.25		0.0514		−54.2	−69.4	226.0	1.91	0.0620
Alminium	2.69	1,087.5		70.9		0.00105		−47.5	−58.9	563.9	27.2	0.00160

* P_{01} and P_{02} are overall power levels at 2 mm and 50 mm between a board and a microphon, respectively.

show a longitudinal direction and a radial direction, respectively, and f_{L1} and f_{R1} show the flexural resonant frequency at the first mode in L direction and that in R direction, respectively. The Sitka spruce had lower ρ, higher E_L and lower Q_L^{-1}, and these results agreed with the general opinion for the physical properties which were desirable for wood for soundboards, and correspondingly the Sitka spruce had higher P_0. So, it was confirmed that the opinion was valid, and that Sitka spruce was suitable to the materials for soundboards. The maple had higher ρ, lower E_L and the highest Q_L^{-1}, and correspondingly it had lower P_0. Maple's results were contrary to Sitka spruce's ones, so it was estimated that wood sounding poorly was suitable to the back plate. On the other hand, between the Sitka spruce and the maple, the relationship in E_R size was contrary to that in E_L size. The acrylic resin had the lowest E and the highest Q^{-1}, and correspondingly it had the lowest P_0. The aluminum had the highest E and the lowest Q^{-1}, and it was contrary to the acrylic resin in size of E and Q^{-1}.

The experimental results of shear modulus (G_{LR}) and torsional internal friction (Q_t^{-1}) were shown in Table 1. In the table, f_t is a torsional resonant frequency about the axis along L direction. From the table, the Sitka spruce had lower G_{LR}, and conversely the maple had the highest G_{LR}.

5. DISCUSSION

5.1 Acoustical Factors

Many kinds of acoustical factors calculated from measured values were shown in Table 2. In specific Young's modulus in L direction (E_L/ρ), the Sitka spruce was the highest and the maple the lowest. On the contrary, in specific Young's modulus in R direction (E_R/ρ), the Sitka spruce was lower and the maple higher. In comparison with the E_L/ρ of wood, the E/ρ values of acrylic resin and aluminum were much lower and comparable, respectively. The variation of $(E/\rho)^{1/2}$, which showed sound velocity, with materials naturally was similar to that of E/ρ.

The Sitka spruce had higher E_L/Q_L^{-1} and lower E_R/Q_R^{-1}. The maple was the reverse of the Sitka spruce in the size of these values. The E/Q^{-1} of acrylic resin was much lower than the E_L/Q_L^{-1} of wood, and it was comparable to the E_R/Q_R^{-1} of the maple. The E/Q^{-1} of aluminum was much higher

Table 2 Acoustical factors of test boards.

Specimen	E_L/ρ (km/s)^2	E_R/ρ (km/s)^2	$(E_L/\rho)^{1/2}$ km/s	$(E_R/\rho)^{1/2}$ km/s	E_L/Q_L^{-1} $\times 10^3$ GPa	E_R/Q_R^{-1} $\times 10^3$ GPa	E_R/E_L	Q_R^{-1}/Q_L^{-1}	E_L/G_{LT}
Sitka spruce 1	31.6	1.57	5.62	1.25	2.57	0.0434	0.0497	2.94	17.5
Sitka spruce 2	29.9	2.12	5.47	1.46	1.97	0.0562	0.0709	2.49	16.6
Hemlock	25.8	1.47	5.08	1.21	1.99	0.0315	0.0571	3.61	13.6
Maple	17.7	2.45	4.21	1.57	1.08	0.0823	0.139	1.83	6.83
Mahogany	18.1	2.50	4.26	1.58	1.54	0.104	0.138	2.04	8.69
Matoa	25.4	2.21	5.04	1.49	2.66	0.0745	0.0867	3.10	15.2
Acrylic regin	4.46		2.11		0.102		1.0	1.0	2.75
Alminium	26.6		5.16		67.5		1.0	1.0	2.61

* E_L/G_{LT} was calculated as $G_{LT}=G_{LR}$.

and 30 times as large as the E_L/Q_L^{-1} of Sitka spruce.

The Sitka spruce had lower E_R/E_L. The maple had the highest E_R/E_L and the lowest Q_R^{-1}/Q_L^{-1} reverse to the Sitka spruce. These quantities show the anisotropy of E and Q^{-1} in the ratio of R direction to L direction. Therefore, it means that the lower the E_R/E_L and/or the higher the Q_R^{-1}/Q_L^{-1}, the stronger the anisotropy. Consequently, from the table, the softwood has stronger anisotropy.

The values of E_L/G_{LT} were calculated using the measured values of G_{LR} in stead of G_{LT} because of $G_{LT}\approx G_{LR}$ from other researcher's data.[6] The Sitka spruce had the highest E_L/G_{LT}, and conversely the maple had the lowest E_L/G_{LT}. From the same data, it is observed that the difference in E_R/G_{RT} value between Sitka spruce and maple is larger than that in E_L/G_{LT} value. Both acrylic resin and aluminum had much lower E/G values of 2-3. This is the feature of isotropic materials. The increase of E/G values has the effect that the increase of eigenfrequency with increasing vibration mode order decreases more greatly.

Each value of the other wood lay between values of the Sitka spruce and the maple. Thus, these results in L direction agree with former results, and those in R direction and anisotropy are new findings.

5.2 Relationships of Acoustical Properties, Acoustical Factors and Anisotropy to Overall Power Level

For wood boards, correlations of the acoustical properties and the acoustical factors to the overall power level P_0 were investigated, and the results were shown in Table 3. There were high negative correlations of the ρ and the Q_L^{-1}, which were reasonable, no correlation of the E_L and the high negative correlation of the E_R, which was new finding. These relationships were shown in Figs. 4-6. In the figures, r and a solid line show the correlation coefficient and the regression line, respectively. There were high positive correlations of the $(E_L/\rho^3)^{1/2}$,[7] the $(E_L/\rho)/Q_L^{-1}$,[2] the $(E_L/\rho)^{1/2}/Q_L^{-1}$ and the $(E_L/\rho^3)^{1/2}/Q_L^{-1}$.[8] The relationship of $(E_L/\rho^3)^{1/2}/Q_L^{-1}$ was shown in Fig. 7. The quantity of $(E/\rho^3)^{1/2}$ $(=(E/\rho)^{1/2}/\rho$: sound velocity per density) has been proposed as an acoustic radiation damping factor, and the quantity of $(E/\rho^3)^{1/2}/Q^{-1}$ combining it and Q^{-1} also has the same meaning.

Table 3 Correlations of the overall power levels to the acoustical properties and the acoustical factors in wood boards with LR planes.

	l_{bc} mm	ρ	E	Q^{-1}	E/ρ	$(E/\rho)^{1/2}$	$(E/\rho^3)^{1/2}$	E/Q^{-1}	$(E/\rho)/Q^{-1}$	$(E/\rho)^{1/2}/Q^{-1}$	$(E/\rho^3)^{1/2}/Q^{-1}$	E_L/G_{LT}
L	2	−0.847	−0.161	−0.792	0.504	0.513	0.815	0.290	0.711	0.789	0.922	0.472
	50	−0.757	−0.020	−0.864	0.558	0.567	0.775	0.435	0.781	0.863	0.922	0.545
R	2	−0.847	−0.895	0.063	−0.757	−0.761	−0.477	−0.679	−0.422	−0.308	0.202	
	50	−0.757	−0.883	0.126	−0.820	−0.824	−0.315	−0.701	−0.492	−0.377	0.084	

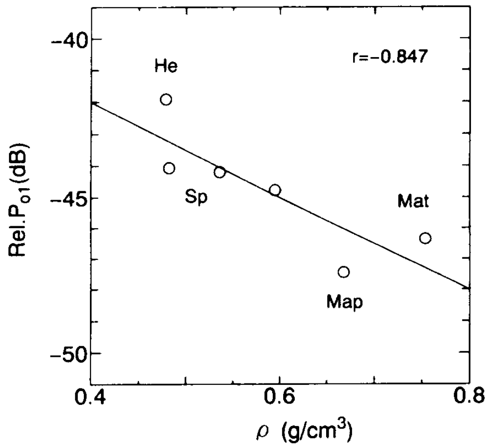

Fig. 4 The relationship between the overall power level P_{01} at $l_{bc}=2$ mm and the density ρ. Legends are the same as those of Fig. 3.

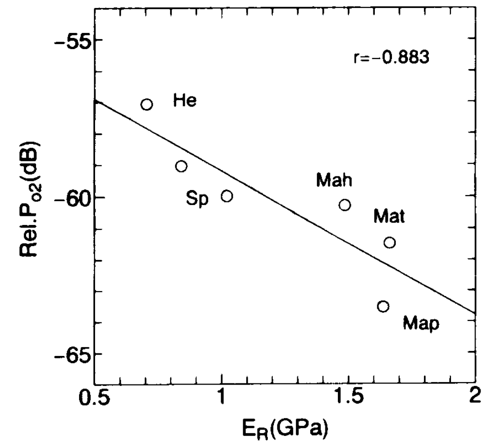

Fig. 5 The relationship between the overall power level P_{02} at $l_{bc}=50$ mm and the E_R. Legends are the same as those of Fig. 3.

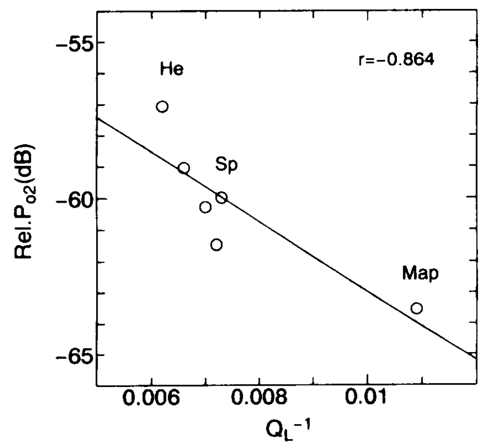

Fig. 6 The relationship between the overall power level P_{02} at $l_{bc}=50$ mm and the Q_L^{-1}. Legends are the same as those of Fig. 3.

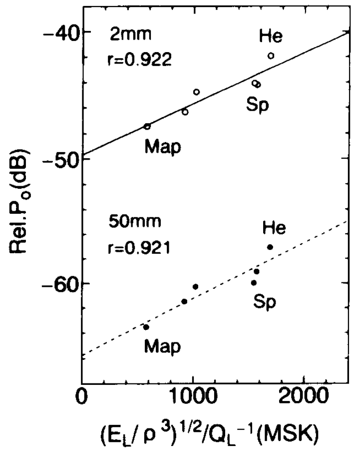

Fig. 7 The relationship between the overall power level P_0 and the $(E_L/\rho^3)^{1/2}/Q_L^{-1}$. Legends are the same as those of Fig. 3.

Table 4 Correlations between the overall power level and the anisotropy of E, Q^{-1} and E/Q^{-1} in wood boards with LR planes.

l_{bc} mm	E_R/E_L	Q_R^{-1}/Q_L^{-1}	$(E/Q^{-1})_{R/L}$
2	−0.671	0.660	−0.663
50	−0.733	0.751	−0.739

* $(E/Q^{-1})_{R/L}=(E_R/E_L)/(Q_R^{-1}/Q_L^{-1})$

Both correlations of the $(E/\rho^3)^{1/2}/Q^{-1}$ to the P_0 at $l_{bc}=20$ mm and the P_0 at $l_{bc}=50$ mm were the same and the highest, and both slopes of the regression lines were almost the same, and it was the best as an acoustical factor. The $(E/\rho^3)^{1/2}$ can become an easy measure for the quality assessment of acoustic materials. There were high negative correlations of the E_R/ρ, the $(E_R/\rho)^{1/2}$ and the E_R/Q_R^{-1}, and these results are new finding.

The correlations of the P_0 to three kinds of anisotropy of E, Q^{-1} and E/Q^{-1} in the ratio of R direction to L direction, *i.e.* E_R/E_L, Q_R^{-1}/Q_L^{-1} and $(E_R/E_L)/(Q_R^{-1}/Q_L^{-1})=(E/Q^{-1})_{R/L}$, were investigated, and the results were shown in Table 4. All the correlation coefficients of P_{02} were higher than those of P_{01}. Both correlations of the E_R/E_L and the $(E/Q^{-1})_{R/L}$ were high negative, and that of the Q_R^{-1}/Q_L^{-1} was high positive. These results are new finding and mean that the stronger the anisotropy, the stronger the sound radiation.

Torsional vibration is not excited for the test boards in this experiment, however, G_{LR} depends on E_L and E_R. Then, the correlation between the G_{LR}

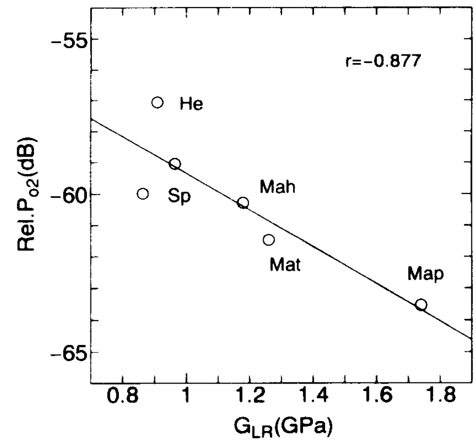

Fig. 8 The relationship between the overall power level P_{o2} at $l_{bc}=50$ mm and the G_{LR}. Legends are the same as those of Fig. 3.

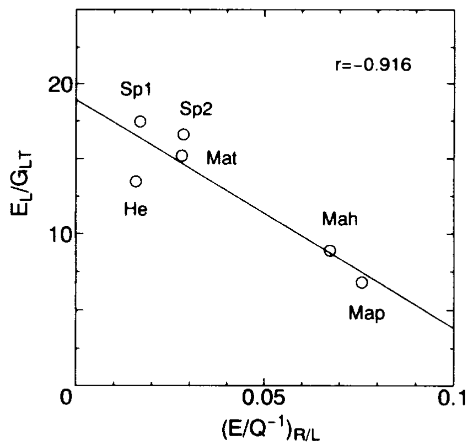

Fig. 10 The relationship between the E_L/G_{LT} and the $(E/Q^{-1})_{R/L}$. Legends are the same as those of Fig. 3.

Table 5 Correlations between the G_{LR} and E_L/G_{LT} and the anisotropy of E, Q^{-1} and E/Q^{-1} in wood boards with LR planes.

	G_{LR}	E_L/G_{LT}
E_R/E_L	0.806	−0.907
Q_R^{-1}/Q_L^{-1}	−0.646	0.671
$(E/Q^{-1})_{R/L}$	0.814	−0.916

* $(E/Q^{-1})_{R/L}=(E_R/E_L)/(Q_R^{-1}/Q_L^{-1})$

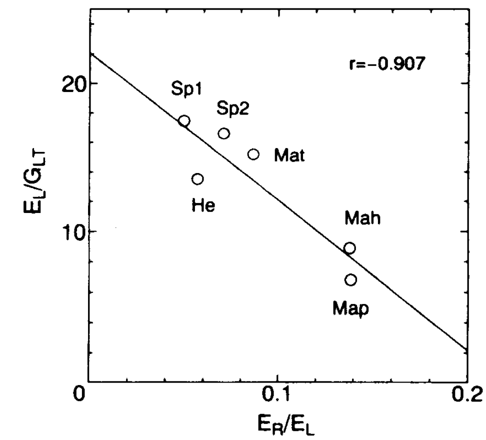

Fig. 9 The relationship between the E_L/G_{LT} and the E_R/E_L. Legends are the same as those of Fig. 3.

and the P_o was investigated, and the correlations of the G_{LR} to the P_{o1} and the P_{o2} were $r=-0.871$ and $r=-0.877$, respectively and were high negative. The relationship between the G_{LR} and the P_{o2} was shown in Fig. 8. This result persuades the fact that the top plates have been tested by the bend and the twist made by the artisans. Furthermore, the correlations of the G_{LR} and the E_L/G_{LT} to three kinds of anisotropy of E_R/E_L, Q_R^{-1}/Q_L^{-1} and $(E/Q^{-1})_{R/L}$ were investigated and the results showed that to the E_R/E_L and the $(E/Q^{-1})_{R/L}$, the correrations of G_{LR} and E_L/G_{LT} were high positive and very high negative, respectively, which were shown in Table 5. The relationship of the E_L/G_{LT} to the E_R/E_L and that to the $(E/Q^{-1})_{R/L}$ were shown in Fig. 9 and Fig. 10, respectively. Therefore, as the degrees of anisotropy in LR plane increase, the G_{LR} decreases and the E_L/G_{LT} increases. The results derived from Fig. 8 and Table 5 agree with that of Table 4. In addition, from the reason mentioned at Section 5.1, it is estimated that the increase of E_R/G_{RT} with increasing the degrees of anisotropy in LR plane is greater than that of E_L/G_{LT}.

Consequently, with the decreases of ρ, E_R, Q_L^{-1} and G_{LR} and the increases of E_L and Q_R^{-1}, the P_o and the E_L/G_{LT} increase. This can be condensed as following: As the ρ decreases and the degrees of anisotropy of E and Q^{-1} in LR plane increase, the P_o and the E_L/G_{LT} increase.

5.3 Third-Octave Band Analyses

In order to find the features of frequency responses for the material for musical instruments, the response curves of Fig. 3 were analyzed into 1/3 octave bands, and the results were shown in Fig. 11 comparing the result of the Sitka spruce (Sp1), which was shown by a dotted line, with the results of the others. From the figure, the following were observed for each material: (1) Two boards of

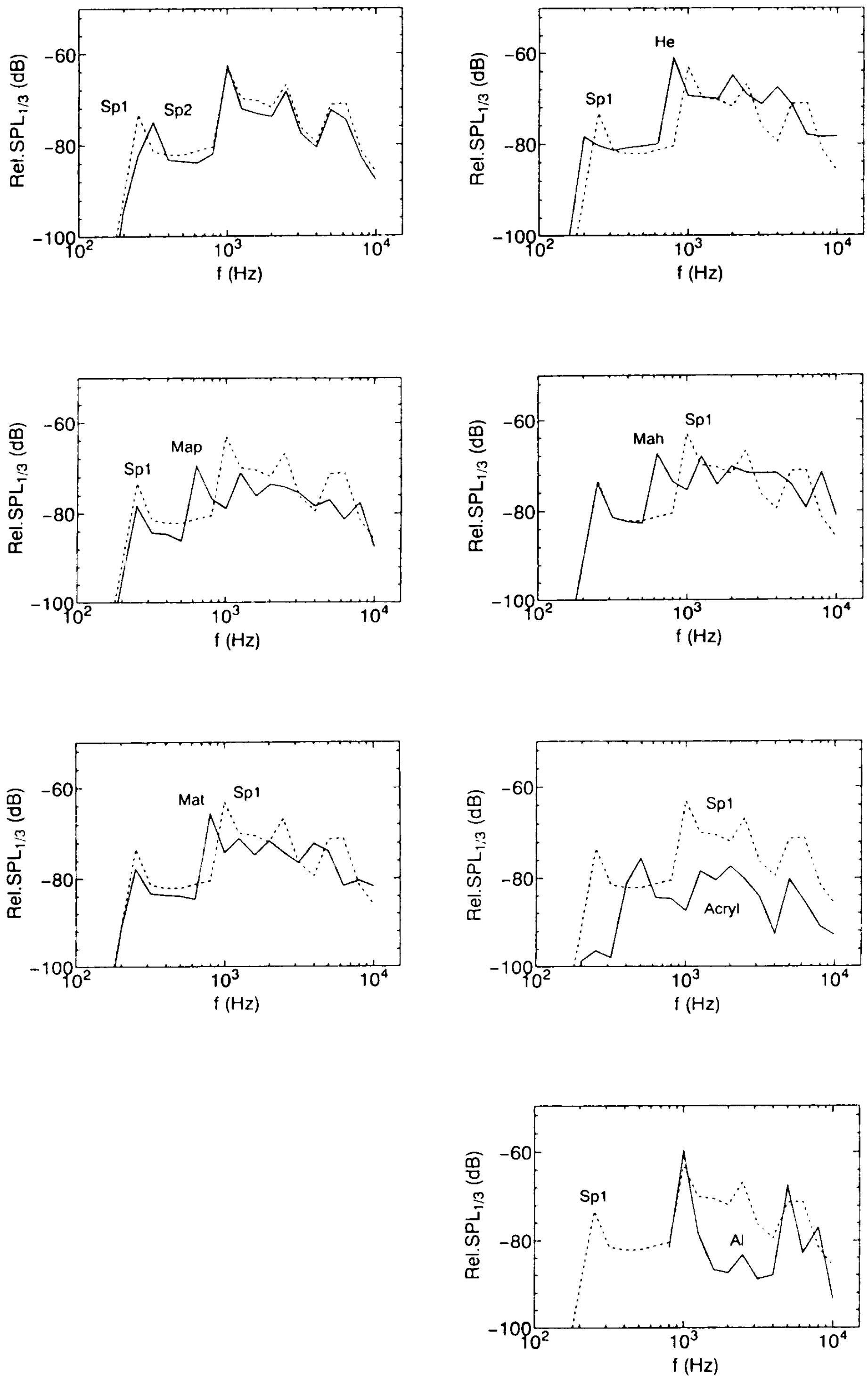

Fig. 11 Comparisons of the 1/3 octave response at $l_{bc}=50$ mm in Sp1 with that in the other materials. Legend: dotted line: 1/3 octave response of Sp1; the other legend: See Fig. 3.

Sitka spruce are very similar and the individual difference is very small. (2) The acrylic resin is much lower in level and narrower in response frequency range because of the lowest response frequency being higher. (3) The aluminum is much greater in level variation and much higher in the lowest response frequency. (4) The hemlock is lower in response frequency, slightly higher in level and smaller in level drop with increasing frequencies above 1 kHz. (5) The maple is lower in response frequency, the lowest in level and the smallest in level variation. (6) The mahogany is lower in response frequency, similar in level and smaller in level variation. (7) The matoa is lower in response frequency, slightly lower in level and similar in level drop with increasing frequencies above 1 kHz.

Thus, both acrylic resin and aluminum are quite different from all the wood in 1/3 octave response pattern, and they are unsuitable for the materials for stringed instruments. Of all the wood, the Sitka spruce used for soundboards is the highest in response frequency, higher in level, the greatest in level variation and the greatest in level drop with increasing frequencies above 1 kHz, and it has the characteristic of high level in the range of middle frequencies. The maple used for back plates has the characteristic of low and almost flat level as a whole. From these results, the Sitka spruce is quite different from the maple in response pattern and they are in contrast. B. A. Yankovskii investigated using impulsive excitation the spectral characteristics of high quality violins and the typical averaged spectra in third-octave bands for violins with various qualities of timber, and he showed that high quality violins had a mountain spectral pattern and bad quality violins had a flat spectral pattern.[9] The results in this experiment agreed with his results in content. From this result, the response curve showed by the small boards of Sitka spruce is the base of the frequency characteristic required for top plates, and the timbre of top plates is produced by giving several geometric processes mentioned in this introduction to the wood boards having such basic frequency characteristic; therefore, the quality of wood for soundboards can be judged by the response curve of small boards.

5.4 Mechanism of Frequency Responses

From Eq. (2), the variation of eigenfrequencies with vibration mode order is proportional to $(E/\rho)^{1/2}$. Therefore, it is found that the interval of peaks becomes wider with increasing $(E/\rho)^{1/2}$ values. From Table 1, the first peak and the second peak in Fig. 3 are the resonance at the first mode in R direction and that in L direction, respectively, and so the many peaks at frequencies above f_{L1} are the resonances at higher modes of them.

From the above facts and the experimental results, the mechanism of frequency responses obtained in this experiment can be explained as following: (1) In isotropic materials, with increasing $(E/\rho)^{1/2}$ values, the response becomes higher in frequency, higher in level and rougher in variation because of the decrease of internal friction and the expansion of peak intervals. This is the case of metals such as aluminum. And, with decreasing $(E/\rho)^{1/2}$ values, the response becomes lower in frequency, lower in level and gentler in variation because of the increase of internal friction and the reduction of peak intervals. This is the case of plastics such as acrylic resin. From these frequency responses, an isotropic material is unsuitable for soundboards. (2) In orthogonal materials, the L direction having high E and the R direction having low E respond to high frequencies and low frequencies, respectively, and such boards can respond to wide range frequencies without the expansion of the interval between peaks. And, with increasing E_L/ρ, the response level increases and the level drop in the range of high frequencies becomes larger because of the increase of shear effects. Wood is an orthotropic and porous material, and Picea genus of all wood is lighter in weight, the highest in E_L/ρ, smaller in Q_L^{-1} and the strongest in anisotropy. Therefore, Picea genus has the response pattern of high level in the range of middle frequencies. This is the mechanism how wood of Picea genus satisfies the conditions required for the materials for soundboards. And, this is the answer to the question of why wood and also limited wood have been used for musical instrument soundboards.

Consequently, it can be concluded that the features of frequency responses for each material in this experiment are attributed to their following physical properties: (1) The acrylic resin has much lower E, much higher Q^{-1} and the isotropy. (2) The aluminum has much higher E, higher $(E/\rho)^{1/2}$, much lower Q^{-1} and the isotropy. (3) The softwood has lower ρ, higher $(E_L/\rho)^{1/2}$, lower Q_L^{-1} and the stronger anisotropy in LR plane. In the Sitka spruce, the properties are the strongest. (4) The hardwood has the acoustical properties opposed to those of the softwood. In the maple, the properties are the strongest. (5) The other species of wood have the acoustical values lying between those of the Sitka spruce and the maple.

5.5 The Other Conditions Required for a Wood Board for Soundboards

It is required that wood for soundboards has not only high P_0 but also high strength in L direction for tolerating the tension of string. Then, from the viewpoint of flexural rigidity, the conditions required for a wood board for soundboards were considered.

High P_0 means large amplitude, *i.e.* large deflection, at a constant radiation area, while as flexural rigidity EI (I: geometrical moment of inertia) increases, deflection decreases. In rectangular section, $I=bh^3/12$ (b= width and h= thickness), so from EI, it is desirable that E is made high and h is made small. When the flexural rigidity $E_b I_b$ of 'b' board is equalized to the flexural rigidity $E_a I_a$ of 'a' board with the same width and length, the following equation is derived:

$$\frac{E_b}{E_a}=\left(\frac{h_a}{h_b}\right)^3 \tag{4}$$

When E_b is made high, h_b can be made small according to above equation. E is proportional to ρ from the calculation equation, so E is high at high ρ or high E/ρ. The ρ had a negative correlation to the P_0, because high ρ means high weight, so it is required that the ρ is low. On the other hand, the E_L/ρ had a positive correlation to the P_0. Therefore, wood having low ρ and high E_L/ρ satisfies above conditions. This result is compatible with the results of sections 5.2 and 5.4. In addition, in this experiment, the difference in flexural rigidity of the test boards is equivalent to the difference in E_L of them, because their size is almost the same. Therefore, it is expected that the E_L has a negative correlation to the P_0; however, the E_L had no correlation as shown in Table 3. This result can be explained by the facts that the E_L depends on both factors of the ρ and the E_L/ρ which have a negative correlation and a positive correlation to the P_0, respectively.

From other researcher's data, not only LR plane but also flat grain (LT) plane have strong anisotropy. On the other hand, however, in the degree of swelling and shrinkage, tangential (T) direction is the largest and R direction is smaller; therefore, in the board with LT plane, the deformation caused by humidity variation is the largest and many troubles of warp and separation etc. occur. The board with LT plane has this defect and has never been used for soundboards. The board with LR plane is the most desirable also in this point.

Consequently, when summarizing the results obtained in this study, it is required that wood for soundboards has low ρ, high E_L/ρ, low Q_L^{-1} and the stronger anisotropy in LR plane. Wood of Picea genus satisfies these conditions and has been made skillfully use of the characteristics to soundboards and is the best material for soundboards at present. This result is useful for the development of new materials for soundboards.

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