J. Acoust. Soc. Jpn. (*E*) **20**, 2 (1999)

Transient response of wood for musical instruments and its mechanism in vibrational property

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(*Received 2 June 1998*)

The tapping sound of wood, which included sitka spruce and maple used for musical instruments, and isotropic materials was analyzed into power spectra every one milliseconds and their transient characteristics were investigated. The variations of 1/3-octave band power spectra with time were visualized in three dimensions. The rise time T_r and the decrement rate were investigated at each 1/3-octave band. The T_r decreased rapidly with increasing frequencies up to the first mode resonance regardless of the materials, and then the variation of T_r depended on the materials. The former depended only on frequency and the latter on flexural resonance intensity. Sitka spruce used for soundboards showed the high level up to the middle frequency range and then, decreased considerably the level by increasing considerably the internal friction and showed the fastest rising characteristic in the high frequency range. This characteristic in the high frequency range was attributed to the shear effect in which sitka spruce was the greatest.

Keywords: Transient response, Time-frequency analysis, Visualization, Rise time, Decrement rate

PACS number: 43. 75. De

1. INTRODUCTION

The tones of such musical instruments as violin family, guitars and pianos are definitely affected by the materials used. Therefore, the frequency characteristics of the materials used are indispensable for the study on the materials for musical instruments, and moreover, it is necessary to supply not only steady characteristic but also transient characteristic. However, the former has exclusively been investigated and the latter has hardly been investigated.

In the author's previous paper, the frequency characteristics under forced vibration in wood, which included sitka spruce and maple for musical instruments, and isotropic materials, which were for comparison, were investigated.[1] In this study, in order to investigate their transient characteristics, the time-frequency analysis of tapping sound has been carried out by using a real time octave band analyzer. It is the purposes of this study to visualize the results of time-frequency analysis, *i.e.* the power spectrum variation with time, in three dimensions and to investigate the rise time and the decrement rate as a function of frequency and to clarify the mechanism of the frequency characteristics.

2. EXPERIMENTAL

Samples were the boards used in the author's previous paper on frequency responses of wood[1] and the boards of an alumina ceramics (Al_2O_3) and a soda glass with the same shape and dimension as them. They were shown in Table 1.

A tapping apparatus used in this experiment was shown in Fig. 1. The details had been described in

Table 1 Characterization of test boards by vibration methods.

	ρ g/cm^3	f_{1L} Hz	f_{1R} Hz	E_L GPa	E_R GPa	Q_L^{-1} $\times 10^3$	Q_R^{-1} $\times 10^3$	G_{LR} GPa	$(E_L/\rho)^{1/2}$ $\times 10^3$ m/s	E_L/G_{LR}
Sitka spruce 1	0.536	1,049.4	231.7	16.9	0.842	6.67	19.4	0.965	5.62	17.5
Sitka spruce 2	0.482	1,022.7	269.0	14.4	1.02	7.33	18.2	0.864	5.47	16.7
Hemlock	0.479	733.6	174.5	12.3	0.705	6.27	22.4	0.909	5.07	13.5
Maple	0.668	616.6	231.2	11.8	1.64	10.9	19.9	1.74	4.20	6.78
Mahogany	0.595	641.7	237.1	10.8	1.49	7.01	14.3	1.18	4.26	9.15
Matoa	0.753	743.3	219.5	19.2	1.66	7.27	22.3	1.26	5.05	15.2
Acrylic resin	1.18	458.0		5.25		58.1		1.91	2.11	2.75
Soda glass	2.49	968.7		72.6		1.98		31.0	5.40	2.34
Aluminum	2.69	1087.7		70.9		1.02		27.2	5.13	2.61
Alumina Cer.	3.91	2197.0		375		0.152		164	9.79	2.29

* ρ: density, f_1: flexural resonant frequency at the first mode, E : Young's modulus, G: shear modulus, Q^{-1}: internal friction, L: direction along grain, R: direction across grain, LR: regularly grained plane. The E and Q^{-1} in isotropic materials are the values in their rectangular bars.

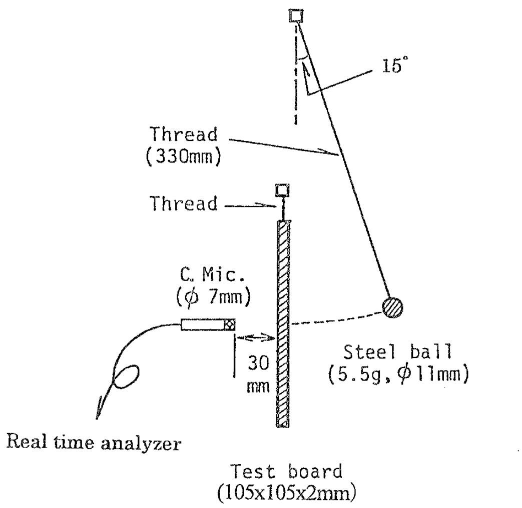


Fig. 1 The apparatus for measuring tapping sound.

the author's previous paper.[2] The tapping sound signal was inputted to a real-time octave band analyzer and analyzed into 1/3-octave band power spectrum every one milliseconds for one second, and so 1000 spectrum patterns were stored every one tapping signals. The analyzed frequency range was 25 Hz–20 kHz of 30 bands. The indicated values of sound pressure level (SPL) were calibrated by using a sound level calibrator.

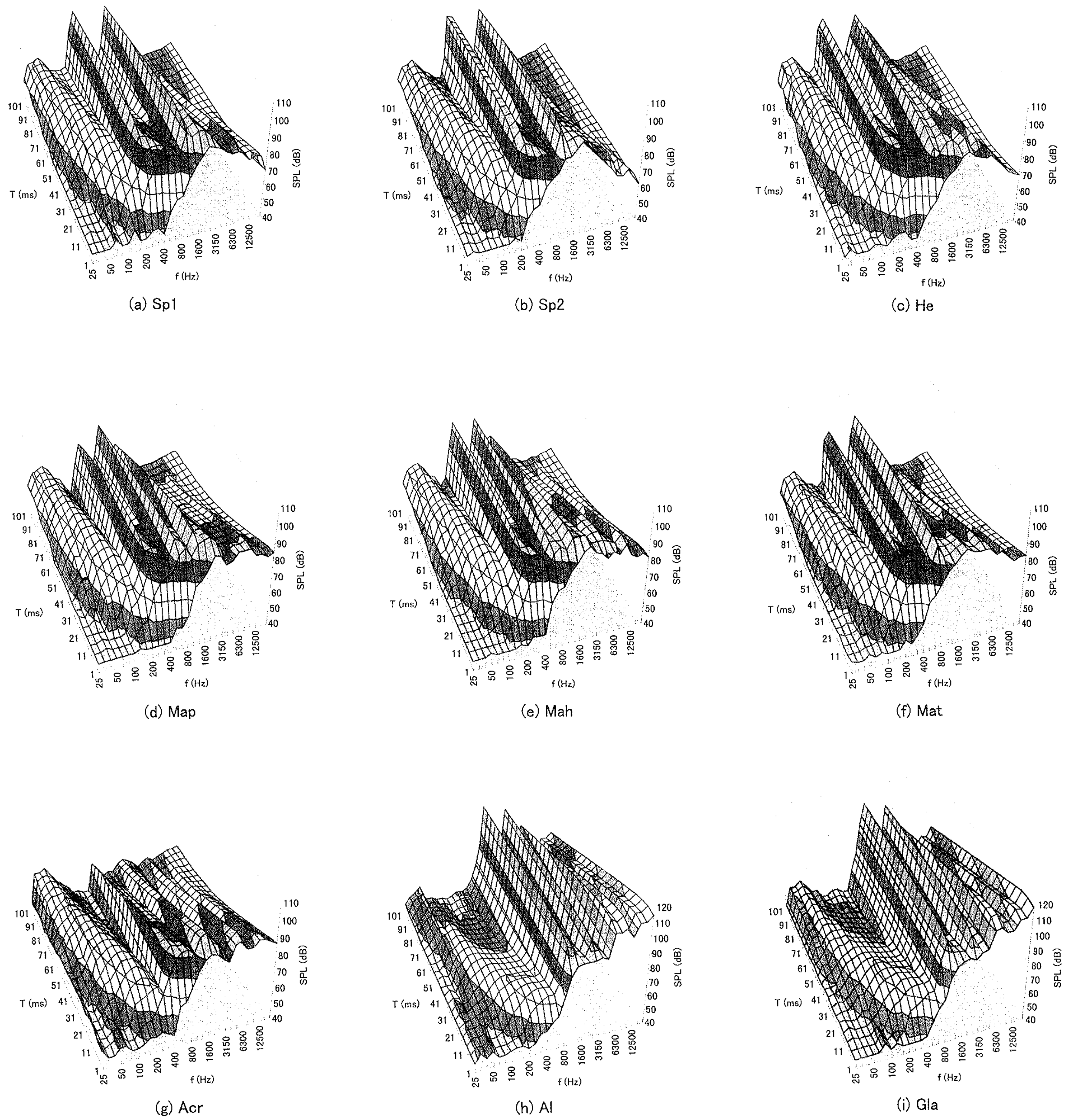
The Young's modulus, E, and the internal friction, Q^{-1}, of the boards and bars with free both ends were measured by using a flexural vibration at the first mode. The shear modulus in LR (regularly grained) plane, G_{LR}, and the torsional internal friction, Q_t^{-1}, of the boards with free both ends were measured by using a torsional vibration at the first mode.[1] 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 flexural and torsional internal frictions were calculated using the peak frequency and the half-value width in resonance curves, respectively.

3. RESULT AND DISCUSSION

3.1 Visualization of Power Spectrum Variation with Time in Tapping Sound

The results of time-1/3 octave band analysis in tapping sound were drawn in 3-D graph so that the power spectrum variations with time could be seen at a glance. The results at every five milliseconds were shown in Fig. 2. In the figures, Sp is sitka spruce, He hemlock, Map maple, Mah mahogany, Mat matoa, Acr acrylic resin, Al aluminum, Gla soda glass and Cer alumina ceramics.

Some mountain ranges were observed in all the figures and they represented resonance at each vibration mode. The results of the characterization of test boards by vibration methods were shown in Table 1. From the table, in the figures on wood, the broad and low mountain occurring at the lowest frequency was the first mode resonance in direction across grain, R_{1R}, and the sharp and high mountain occurring at the second lowest frequency was that in direction along grain, R_{1L}. In the softwood of sitka spruce and hemlock, the SPL decreased greatly with increasing frequencies in the high frequency range, and in the hardwood of maple, mahogany and



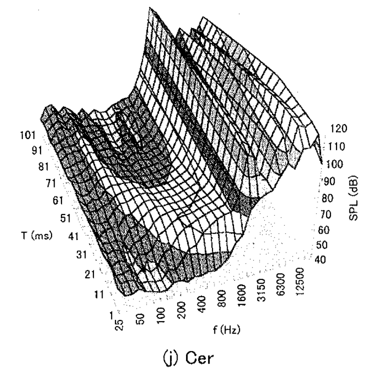


Fig. 2 The variation of 1/3-octave band power spectra with time of consecutive 5 ms periods in tapping sound. (a) sitka spruce 1 (Sp1), (b) sitka spruce 2 (Sp2), (c) hemlock (He), (d) maple (Map), (e) mahogany (Mah), (f) matoa (Mat), (g) acrylic resin (Acr), (h) aluminum (Al), (i) soda glass (Gla), (j) alumina ceramics (Cer).

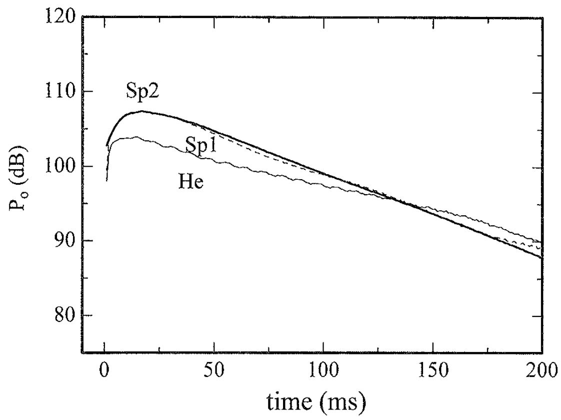


Fig. 3 The rising curve of overall SPL (P_0) in softwood. Legends are the same as those of Fig. 2.

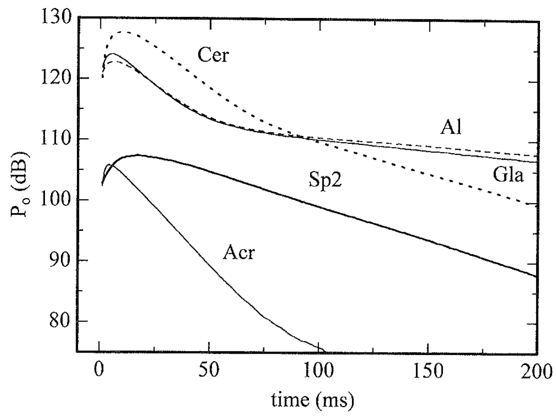


Fig. 5 The rising curve of overall SPL (P_0) in isotropic materials. Legends are the same as those of Fig. 2.

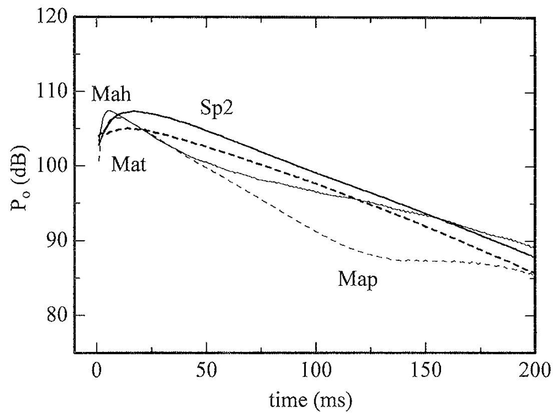


Fig. 4 The rising curve of overall SPL (P_0) in hardwood. Legends are the same as those of Fig. 2.

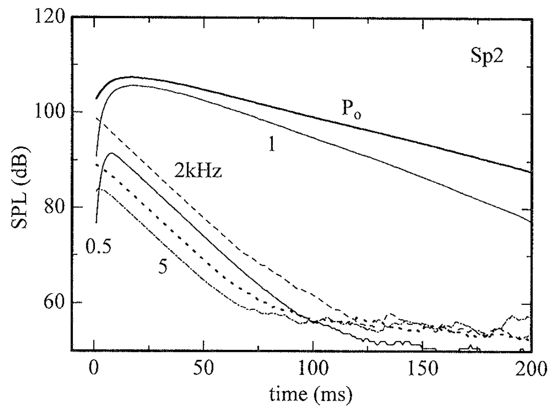


Fig. 6 The rising curve of 1/3-octave band SPL in sitka spruce 2 (Sp2). Numbers in this figure show the center frequencies of 1/3-octave bands.

matoa, it decreased slightly. In the acrylic resin, all the mountains were broad. In the aluminum, glass and ceramics, there were no mountains in the low frequency range and all the mountains occurring at frequencies above around 1 kHz were high and sharp and their ridges were very gentle in slope. According to their characteristics, they can be divided into four groups of softwood, hardwood, plastics and the others.

3.2 Rising Curves of Sound Pressure Level

The rising curves of overall SPL (P_0) for softwood, hardwood and isotropic materials were shown in Figs. 3–5. The rising curves of SPL at 1/3-octave bands of 0.5, 1, 2, 3.15 and 5 kHz for sitka spruce 2, maple, acrylic resin and aluminum were shown in Figs. 6–9 : these are the frequency compositions in Figs. 3–5 and the longitudinal sections in Fig. 2. The values measured every 1 ms were plotted in the figures.

The P_0 rising curve in Sp2 was almost the same as that in Sp1 from Fig. 3, and the individual difference was small. The P_0 values of softwood and acrylic resin decreased linearly with time from Fig. 3 and Fig. 5. This reason is because the SPL values of each frequency composition decreased uniformly, from Fig. 6 and Fig. 8. From Fig. 4 on hardwood, the P_0 value of Mat decreased linearly in the same manner as softwood ; however, these of Map and Mah decreased nonlinearly, that is, after decreasing greatly, they decreased gently. From Fig. 5, all the variations of Al, Gla and Cer belonged to the type of the latter. From Fig. 7 and Fig. 9,

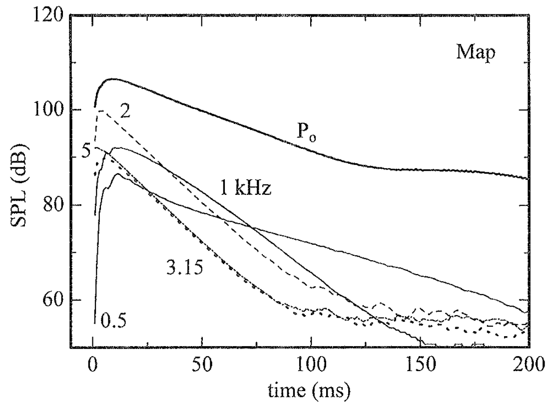


Fig. 7 The rising curve of 1/3-octave band SPL in maple (Map). Legends are the same as those of Fig. 6.

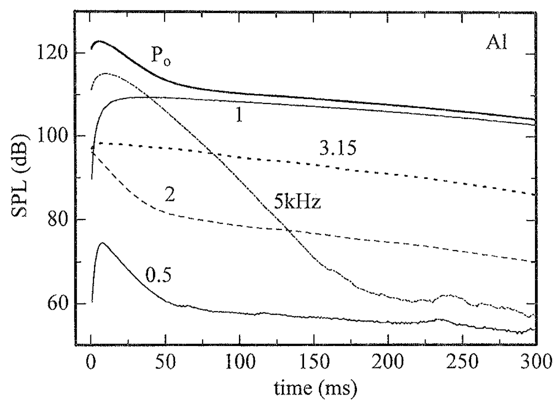


Fig. 9 The rising curve of 1/3-octave band SPL in aluminum (Al). Legends are the same as those of Fig. 6.

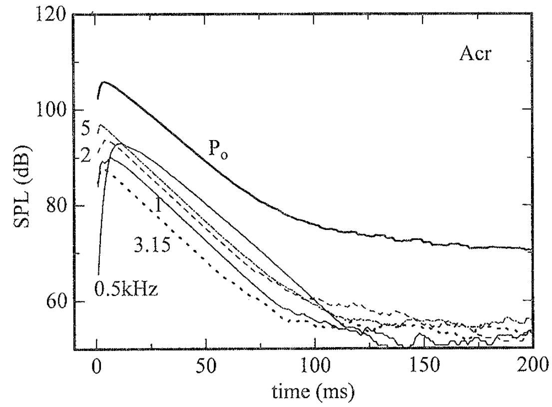


Fig. 8 The rising curve of 1/3-octave band SPL in acrylic resin (Acr). Legends are the same as those of Fig. 6.

the reason why the Map and the Al have such rising curve is because the main component shifted from the high frequency component decreasing greatly to the low frequency component decreasing gently as the time went. Thus, it was found that each material had clearly the characteristics of the spectrum and of the spectrum variation with time. The P_0 value has been used as an easy measure for the quality evaluation of musical instrument materials. However, it is a total value, and so it simply represents sound volume and/or acoustical conversion efficiency. From above facts, the P_0 value, which does not include the informations on the spectrum and the spectrum variation, is not cut out for a measure of the quality evaluation.

From Figs. 3–5, the rising of P_0 in Sp was the latest. From Fig. 6, this reason is because the main component of P_0 in Sp always was 1 kHz band including R_{1L} with low decrement which signified long time constant. Because, time constant τ is related to Q^{-1} and logarithmic decrement δ by the following equation :

$$\tau=\frac{2}{\omega Q^{-1}}=\frac{2\pi}{\omega\delta}, \qquad (1)$$

where ω is angular frequency. There has been the opinion that the rising becomes earlier according to the increase of longitudinal wave velocity (V_l), which is calculated from the relation of $V_l=\sqrt{E/\rho}$. This is grounded on the fact that materials with high V_l have high eigenfrequencies (f_r) (*i.e.* short periods) from the relation of $f_r \propto \sqrt{E/\rho}$. From Table 1, the Sp and the Cer certainly have high f with high V_l. However, their risings in P_0 and main component were later and different from the opinion. From Eq. (1), this reason is because the rising rate depends on not only frequency but also internal friction, and so V_l represents the propagation velocity of wave and does not signify the rising rate. The detailed discussion on the mechanism to determine the rising rate is found in next section.

3.3 Variations of Rise Time and Decrement Rate with Frequencies

From the rising curves at each band, the rise time T_r and the decrement rate δ' were investigated as a function of frequency. The T_r decreased rapidly with increasing frequencies, so the figures of the logarithms of T_r were drawn. The T_r values in Sp and Map and those in Acr and Al were shown as a function of frequency in Fig. 10 (a) and Fig. 11 (a), respectively. The δ' values in them were shown as a function of frequency in Fig. 10 (b) and Fig. 11

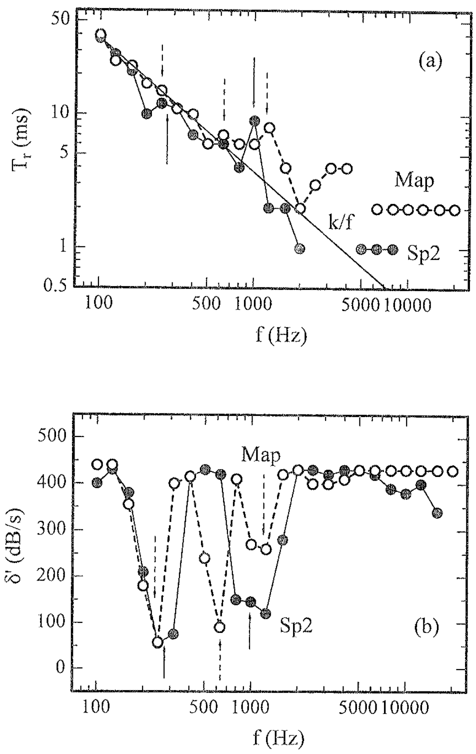


Fig. 10 The variations of rise time (T_r) and decrement rate (δ') with frequencies in sitka spruce 2 (Sp2) and maple (Map). A straight line is $T(s)=k/f$ ($k=3.7$), which is set to the T_r value at 100 Hz in sitka spruce 2. Arrows show resonance points.

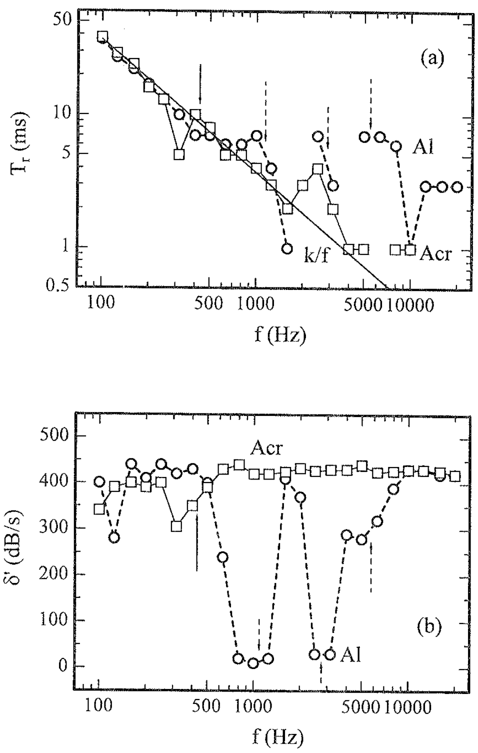


Fig. 11 The variations of rise time and decrement rate with frequencies in acrylic resin (Acr) and aluminum (Al). Legends are the same as those of Fig. 10.

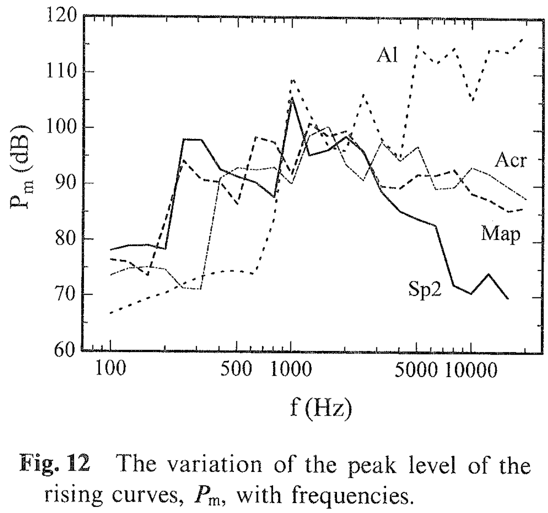


Fig. 12 The variation of the peak level of the rising curves, P_m, with frequencies.
Legends are the same as those of Fig. 2

(b). From the figure (a), the T_r decreased linearly with increasing frequencies up to around 1 kHz, depending hardly on the materials, and then the variation of T_r with frequency depended greatly on the materials. The straight line of $T(s)=k/f(k=3.7)$, which was set to the initial value of Sp2, was shown in the figures (a). As seen in the figures, the measured points of each material agreed well with the straight line in the range of frequencies under around 1 kHz. As shown by arrows in the figures (a) and (b), high T_r was accompanied by low δ'. From Table 1, these are resonance points. Consequently, it was found that only frequency (or period) determined the T_r in the range of frequencies under the lowest mode resonance, f_1.

The frequency at which the measured points of T_r deviate from the straight line is above f_{1L}, f_1 in direction along grain. The reason why the T_r at f_{1L} is high is because the time constant at R_{1L}, which is strong, is long. On the other hand, the T_r at f_{1R}, f_1 in direction across grain, is lower because the R_{1R} is weaker than the R_{1L}, and it is inconspicuous. As Q^{-1} ($\propto\delta'$) links up with amplitude, T_r should depend also on amplitude. Then, the peak level of the rising curves, P_m, was investigated at each band and the frequency characteristic of P_m was shown in Fig. 12. From the figure, the P_m in Sp2 decreased greatly with increasing frequencies above 1 kHz band, and that in Map decreased small. From Fig.

Table 2 Comparisons of the flexural resonant frequency, f_{1b}, and internal friction, Q_b^{-1}, in rectangular isotropic bars and those, f_{1p} and Q_p^{-1}, in square isotropic plates.

Material	ρ g/cm^3	f_{1b} Hz	f_{1p} Hz	Δf_1 Hz	Δf_1 %	Q_b^{-1} $\times 10^3$	Q_p^{-1} $\times 10^3$	ΔQ^{-1} $\times 10^3$	ΔQ^{-1} %
Acrylic resin	1.18	378.5	458.0	79.5	21.0	58.1	51.3	−6.8	−11.7
Soda glass	2.49	885.8	968.7	82.9	9.35	1.98	1.96	−0.016	−0.8
Aluminum	2.69	936.1	1087.7	151.6	16.2	1.02	1.43	0.41	40.2
Alumina Cer.	3.91	1950.4	2197.0	246.6	12.6	0.152	1.64	1.49	979

* $\Delta f_1 = f_{1p} - f_{1b}$, $\Delta Q^{-1} = Q_p^{-1} - Q_b^{-1}$, rectangular bar size: 105 (l)$\times$16(W)$\times$2(t) mm, square plate size: 105$\times$105$\times$2(t) mm.

10, in both of Sp and Map, the decrement rates are high in the high frequency range; however, it is observed in Map that there is weak resonance in the high frequency range. H. Meinel showed that the increase of Q^{-1} with increasing frequencies in Sp was greater than that in Map,[3] and his result supports this viewpoint. From Fig. 11 and Fig. 12, the Acr is high in decrement rate and low in level, in all the frequency range and is a little drop in level in the high frequency range, and the Al is strong in higher mode resonance and very high in level in the high frequency range. Low Q^{-1} accompanying high amplitude (*i.e.* high SPL) makes T_r high. Therefore, in the range of frequencies above f_{1L}, it can be explained that the T_r values in the Sp and the Acr are lower than those in the Map and the Al, respectively. However, though being the highest in Q^{-1}, the Acr lies between the Sp and the Map in T_r and contradicts with the above explanation. In an isotropic material forming a square board, degeneration occurs to its flexural resonance in directions perpendicularly intersecting each other, and it is estimated that this is the reason. Then, from the measurements for the rectangular bars and square boards of isotropic materials, which had equal length and thickness, the degeneration effects on f_1 and Q^{-1} were investigated and the results were shown in Table 2. From the table, it was observed that the following was caused by degeneration: 1) All the f_1 of boards increased in appearance and the rate increased with decreasing weight. 2) The Q^{-1} of boards decreased or increased in appearance, and the decreasing rate increased with decreasing weight and the increasing rate increased with increasing weight. From these facts, the above contradiction observed in the Acr to be light can be qualitatively explained. Consequently, the intensity of resonance determines the T_r in the range of frequencies above f_{1L}.

3.4 Mechanism of Frequency Characteristics in Wood for Soundboards

In elastic bodies, according to the increase of flexural vibration frequency, the shear deformation component of flexural deformation increases. The shear effect is greater in the materials having the higher value of the elastic modulus ratio of E/G. From the author's previous papers,[4,5] the increase of Q^{-1} and the decrease of apparent Young's modulus in wood in the high frequency range are due to the shear effect and sitka spruce having the high value of E_L/G_{LT} (LT: flat grain plane) is great in the rising of Q^{-1} and the falling of apparent Young's modulus, in the high frequency range. On the other hand, in isotropic materials, the value of E/G is low and the shear deformation component is small even at the higher modes in flexural vibration and the bending deformation is the principal component of flexural deformation. Therefore, in isotropic materials, the increase of Q^{-1} and the decrease of amplitude in the high frequency range are small. This is the cause producing the differences in the high frequency range characteristics of SPL and internal friction between the materials. Generally, it has been required for the materials of soundboards that the value of E_L/ρ is high and the value of Q_L^{-1} is low, that is, the value of sound conversion efficiency $(E_L/\rho)/Q_L^{-1}$ derived using them is high. Since there is a negative high correlation between E_L/ρ and Q_L^{-1}, these conditions make the time constant increase and make the rising late. However, sitka spruce has not only the values of high E_L/ρ and low Q_L^{-1} but also the high value of E_L/G_{LT}; therefore, sitka spruce is high in the level up to the middle frequency range and then, decreases considerably the level by increasing considerably the Q_L^{-1} and is the fastest in the rising in the high frequency range. It is guessed that such frequency characteristic matches well with human auditory sensation.[6] On the other hand, it is obvious that isotropic materials having the low value of E/G can not produce such characteristics. Since it is practically accepted that the sitka spruce wood is the most suitable for the soundboard of instruments, its characteristics clarified here should be the standard in making new materials for soundboards.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Mr. Y. Nakao of Kawai Musical Instruments Mfg. Co., Ltd. for providing test wood boards.

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