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ACOUSTICAL LETTER

Classical guitar top board design by finite element method modal analysis based on acoustic measurements of guitars of different quality

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1. Introduction

Only good-quality wood of the *Picea* genus is used to make the top plates and soundboards of wooden musical instruments. It is becoming increasingly difficult to obtain such wood because of limited environmental resources. In addition, wood quality varies widely as wood is a biomaterial, and the tone of wooden musical instruments is strongly dependent on humidity. To resolve these issues, we have developed a composite of polyurethane foam reinforced anisotropically with carbon fibers for use as musical instrument soundboards [1,2]. Experimental folk guitars were built by a musical instrument maker using top boards of this composite, and the results of auditory appraisal by guitar experts indicated that it had sufficient potential for use as a substitute material for soundboard construction [3]. Furthermore, in our previous study [4], the effects of the physical properties of folk guitar top boards were investigated by FEM (finite element method) modal analysis, and the results showed that the relationship between frequency and mode number could be freely controlled by adjusting those properties.

As the next stage of these studies, we planned to also apply our composite to a classical guitar. This study was performed to enable the free design of the top boards of classical guitars to obtain excellent acoustic characteristics, on the basis of the composite's main advantage that it is possible to freely control its physical properties.

To achieve our purpose, we investigated the following in this study.

(1) The differences in acoustic characteristics between classical guitars according to quality.
(2) Whether our frequency-mode number curves obtained by FEM modal analysis can show point (1) above.
(3) The effects of each bracing strut on frequency–mode number curves for each quality.

2. Test guitars

Three high-quality classical guitars, designated A, B, and C in decreasing order of quality, built by the same musical instrument maker were examined. The wood used for the top boards of these guitars was European spruce in A and B and Yezo spruce in C. The bracing patterns of each top board are shown in Fig. 1. The number of bracing struts glued in a fan shape was different in each top board, and the top boards of B and C also had oblique crossing bracing. The top board of A had a thickness distribution of 3.0 mm at the center part and 2.0 mm at the end, and those of B and C had thicknesses of 2.8 mm and 2.6 mm, respectively.

3. Experiment and analysis

3.1. Experimental procedures

The frequency characteristics and transient characteristics of each classical guitar were measured by the tapping method. Briefly, sound emitted by tapping the bridge with an impulse hammer making a small pendulum motion was detected with a condenser microphone set up 30 mm from the center of the guitar's sound hole. Output signals of the impulse hammer and condenser microphone were sent to a Fast Fourier Transform (FFT) analyzer, and the frequency characteristics of each guitar were measured in the form of a transfer function. The tapping sound was also sent to a real-time octave band analyzer and the transient characteristics were measured by obtaining 1/3-octave band power spectra every 2 ms for 2 s. During these measurements, the strings were bound with cotton to prevent them from vibrating.

3.2. FEM modal analysis

Modal analysis of the top boards was performed using the FEM program, ANSYS [4]. Analysis models had the same shape and size as the top plates of the measured classical guitars. Tetrahedral elements were used as meshing models, and top board models had about 15,500 nodes. In the calculation, physical values of density, Young's moduli in three directions perpendicularly intersecting each other, and shear moduli and Poisson's ratios in three planes of references were used as typical values of wood [5]. For each quality top board, the effect of each bracing strut was investigated by varying the slope of frequency-mode number curves with and without gluing.

4. Results and discussion

4.1. Transient characteristics determined by tapping method

The variations in rise time T_r with frequency in overall values are shown in Fig. 2(a) [6]. From the figure, the rise occurred earlier in the quality order of A, B, and C. The slowest rise time of C was due to the large bracing struts glued diagonally and the highest number of bracing struts among the instruments examined. There was little difference between

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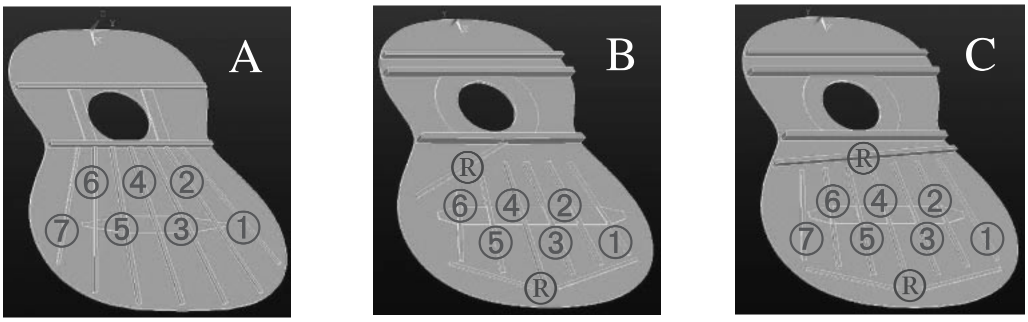

Fig. 1 Top boards of a classical guitar. A: highest quality, B: intermediate quality, C: lowest quality.

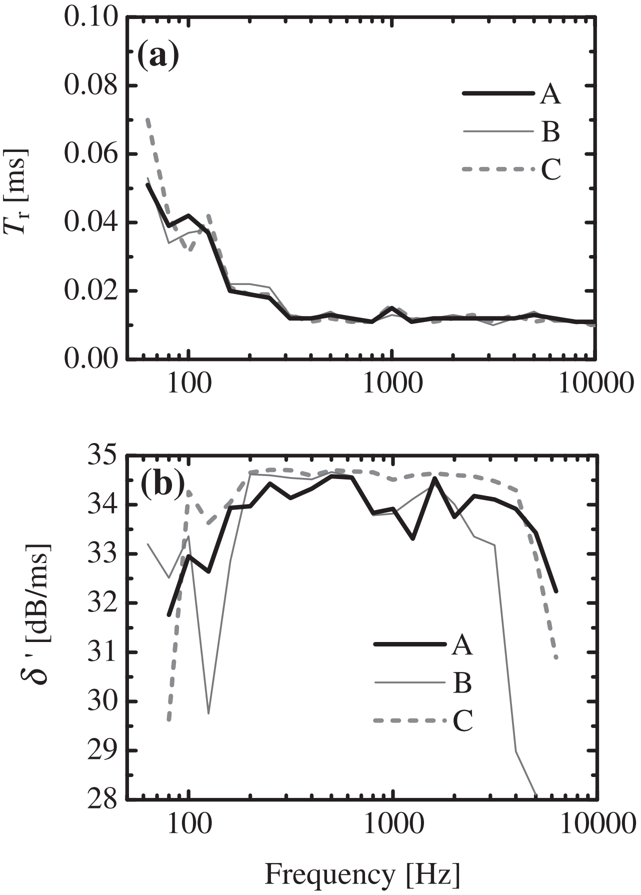

Fig. 2 Transient characteristic. (a) Variations of rise time with frequency. (b) Variations of decrement rate with frequency.

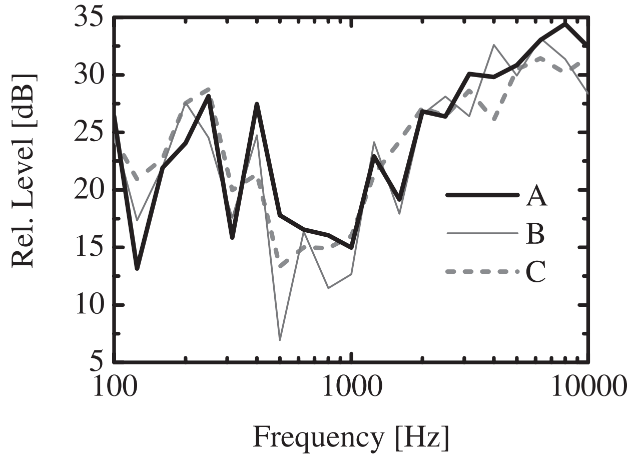

Fig. 3 Frequency response by 1/3 octave analysis.

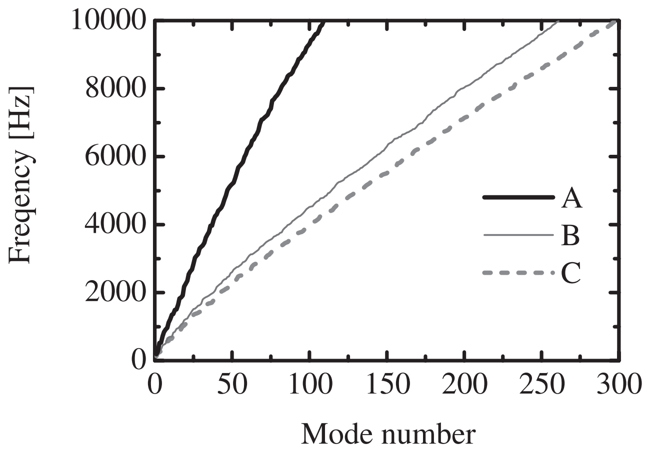

Fig. 4 Relationship between eigenfrequency and mode number by FEM analysis.

guitars in the middle–high frequency range. The variation of decrement rate δ' with frequency is shown in Fig. 2(b) [6]. The δ' of guitar A was slightly smaller in the middle frequency range than those of the other instruments. The δ' of B and C decreased abruptly in the low and high frequency ranges, while A showed no such characteristic but was characterized by the smallest degree of variation.

4.2. Frequency characteristics determined by tapping method

The frequency characteristics are shown in Fig. 3 as 1/3-octave bands. As shown in the figure, the level of C was highest under 300 Hz and lowest above 3 kHz, while the level of A was lowest under 300 Hz and highest above 3 kHz. There were negligible differences in level between B and A in the frequency range of 1 to 6 kHz, above which the level of A became higher than that of B.

4.3. Relationship between frequency and mode number by FEM modal analysis

The frequency–mode number curves of top boards determined by modal analysis are shown in Fig. 4 and can be compared with Fig. 3. In Fig. 4, the curves obtained had

Table 1 Effect of bracing on frequency-mode number curves.

Glued bracing	slope variation of frequency-mode number curve [%]								
	C			B			A		
	0–3k [Hz]	3k–7k [Hz]	7k–10k [Hz]	0–3k [Hz]	3k–7k [Hz]	7k–10k [Hz]	0–3k [Hz]	3k–7k [Hz]	7k–10k [Hz]
①	0.6	0.0	−0.2	0.9	0.7	−0.7	0.0	0.1	0.1
②	0.8	0.0	−0.1	1.2	0.9	−0.5	0.0	0.0	0.1
③	0.6	−0.1	−0.3	1.3	1.1	−0.5	0.0	0.1	0.3
④	0.7	−0.1	−0.5	1.1	1.0	−0.8	0.0	0.1	0.0
⑤	0.7	0.0	−0.4	0.8	0.8	−0.4	0.0	0.1	0.3
⑥	0.4	0.0	−0.1	0.6	0.7	−0.4	0.0	0.1	0.2
⑦	0.6	0.1	−0.2				0.0	−0.1	−0.1
Ⓡ	0.8	−0.3	−3.2	1.9	1.1	−1.0			

higher slope in the order of increasing quality and the characteristics shown in Fig. 3 correspond roughly to them, considering that the vibration amplitude became smaller with increasing mode number.

Consequently, it is expected that in these classical guitars, the difference in acoustic characteristics according to quality can be revealed by our FEM analysis.

4.4. Effects of each bracing pattern determined by modal analysis

The effects of each bracing strut on the frequency–mode number (*f-mn*) curves of the top boards were investigated based on the variation of *f-mn* slopes with the removal of each bracing strut from the full bracing pattern, divided into three frequency ranges of 0–3 kHz, 3–7 kHz, and 7–10 kHz. The effects are shown in Table 1. The table shows the percentage of variation of the *f-mn* slope upon gluing on each bracing strut. Fan and diagonal bracings are shown by circled numbers and circled R, respectively, as shown in Fig. 1.

In C, upon gluing on each bracing strut, all the *f-mn* slopes in the fan bracing showed a small increase in the 0–3 kHz range with little change in the 3–7 kHz range and a slight decrease in the 7–10 kHz range. It was predicted that the *f-mn* slope would increase owing to the increase in the bending rigidity of the top board upon gluing on the bracing struts; however, the simulation showed that the *f-mn* slope decreased in the high frequency range. Therefore, it was estimated that the increase in rigidity in top boards upon gluing on the bracing struts contributed to the *f-mn* slope in the low frequency range, and the increase in the weight of the top boards upon gluing on the bracing struts showed a greater contribution in the high frequency range. The *f-mn* slope in the diagonal bracing increased slightly in the 0–3 kHz range and showed slight and marked decreases in the 3–7 kHz and 7–10 kHz ranges, respectively. In B, the *f-mn* slope variation showed the same tendency as in C; all the *f-mn* slopes in B increased in the 0–3 kHz range and showed a slight increase in the 3–7 kHz range with a slight decrease in the 7–10 kHz range. The *f-mn* slope in diagonal bracing increased in the 0–3 kHz range with a smaller increase in the 3–7 kHz range and decreased in the 7–10 kHz range. In A, all the *f-mn* slopes increased very slightly in all frequency ranges. Moreover, the bracing effect in B and C was the greatest near the center of each top board.

The highest *f-mn* slope of A was due to the thickness distribution; therefore, A had a small number of bracing struts and the bracing effect was the smallest. B and C did not have a thickness distribution, but the diagonal bracing caused the *f-mn* slopes to increase in the low frequency range but decrease in the high frequency range. Therefore, in B and C, the low frequency range was improved by gluing the diagonal bracing struts into place. Furthermore, the bracing effect in B and C was the greatest near the center of the top board because this is where the top boards have the longest bracing.

From the results obtained in this study, it was found to be probable to make top boards for classical guitars of high quality and/or individual characteristics using not wood but composites.

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