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ORIGINAL ARTICLE

Vibrational properties of harp soundboard with respect to its multi-layered structure

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Abstract The vibrational properties of a harp soundboard were investigated with respect to its multi-layered structure. The surfaces of harp soundboards are usually reinforced with veneer; however, this reduces the specific dynamic Young's modulus (E'/ρ) and significantly increases the internal friction (Q^{-1}) of soundboards. Since smaller E'/ρ and greater Q^{-1} values impart a smaller acoustic conversion efficiency, the attachment of veneer is predicted to reduce the amplitude of the sound produced, as suggested by harp makers. The vibrational properties of veneer-reinforced wood are elucidated using a multi-layered model comprising base wood, a glue layer, veneer and a varnish layer. The results of calculations suggest that a thinner veneer attached with minimal glue would increase the sound amplitude.

Keywords Harp · Soundboard · Vibrational properties · Veneer · Multi-layered model

Introduction

A harp is a popular string instrument used in various genres of music. There are many types of harps; the modern "grand harp" illustrated in Fig. 1a is the biggest one. A harp comprises about 48 strings connected to a wooden soundboard, which converts the vibration of the strings into audible sound by its flexural vibration. Many acousticians have dealt with the vibration of string and soundboard, and sound radiation from the soundbox of the harp [1–5]. In addition, the vibrational properties of solid wood have been well investigated by wood scientists [6, 7]. However, little attention has been paid on the unique "plywood-like" structure of harp soundboard.

In general, the sound radiated from a wooden board is dominated by its vibrational properties along the grain, because the acoustic conversion efficiency (ACE) of wood is maximized in its fiber direction [6]. The ACE is usually defined as $\sqrt{E'/\rho^3}/Q^{-1}$, where ρ, E', and Q^{-1} are the density, dynamic Young's modulus, and internal friction of the material, respectively. It has been experimentally [6] and theoretically [7] proved that a higher ACE correlates with a greater overall power level of sound from wooden boards. The harp soundboard is usually made of spruce wood with its fiber direction aligned perpendicular to the length of the harp, as shown in Fig. 1b. In this case, the sound of harp is primarily determined by the flexural vibration of its soundboard in the width direction.

In small harps, a single wooden board is strong enough to support the tensile force of the strings. However, in grand harps, the strong force of the strings (12–20 kN) [4] can cause serious cracks of the soundboard along its width, *i.e.*, in the fiber direction. Therefore, the longitudinal direction of the soundboard, *i.e.*, the radial direction of the wood, is usually reinforced with a thin veneer, as shown in Fig. 1c.

Although the veneer overlay provides effective reinforcement to prevent the failure of the base wood, it causes another problem: many harp makers claim that the veneer significantly reduces the amplitude of sound. This problem may be caused by a reduction in the ACE of the soundboard in its width direction. Since the ACE in the radial direction is much smaller than that along the fiber direction

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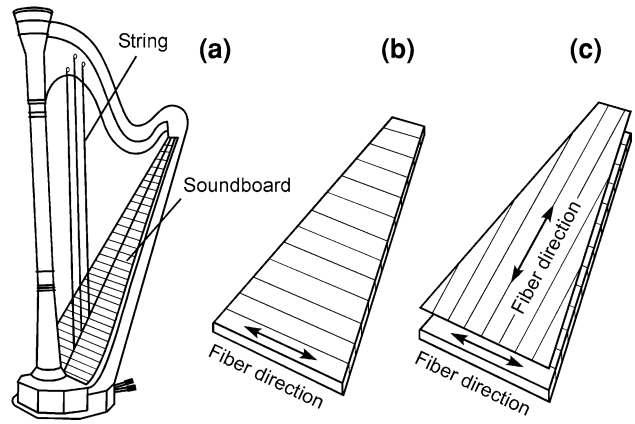

Fig. 1 **a** Appearance of a grand harp, **b** fiber alignment of the base wood, and **c** fiber alignment of a veneer-reinforced soundboard

[6], it is possible that the veneer dampens the flexural vibration of the soundboard in its width direction. However, few studies have focused on the vibrational properties of these plywood-like soundboards, probably because the plywood is not a usual material for the soundboard of traditional string instruments.

In this paper, we describe the vibrational properties of a harp soundboard with respect to its multi-layered or plywood-like structure. The results are analyzed using a multi-layered model in which the viscoelastic properties of the adhesive and varnish are taken into consideration.

Materials and methods

Wood samples

Sitka spruce (*Picea sitchensis*) wood selected for the harp soundboard was used as the base material. It was cut into strips with dimensions of 200 mm (L longitudinal direction) × 15 mm (R radial direction) × 2.9–10.0 mm (T tangential direction). On the other hand, sliced veneer of Sitka spruce with dimensions of 200 mm (R) × 15 mm (L) × 0.8–1.0 mm (T) was used for surface reinforcement. The thickness of those specimens was chosen by considering the structure of real soundboards. All specimens were conditioned at 25°C and 60% relative humidity (RH) for at least 1 month prior to the experiments.

Veneer attachment

Sliced veneers were attached to the edge grain (LR) surface of the strips using a honeymoon-type adhesive (Konishi Co. HB10). The curing agent was first applied to the surface of the strips and maintained at 25°C and 60% RH for 1 day until the solvent evaporated. Meanwhile, the base resin was applied to the surface of the veneer using a hand roller. The amount of applied resin, being based on its uncured weight, was controlled to be 100, 200, 300 and 400 g/m^2. The veneers were then attached to the strips, and pressed at room temperature for 1 h under a pressure of 0.1 MPa. Five specimens were employed for each testing condition.

Sample varnishing

A polyurethane lacquer (PU, Otani Paint Manufacturing Co. High-gross type) that is typically used for harp soundboards was applied to the LR surface of the wood specimens with a paintbrush. This varnishing process was repeated 1–4 times to vary the amount of applied lacquer from 100 to 400 g/m^2. Five specimens were employed for each testing condition.

Resin plates

To determine the vibrational properties of the adhesive and lacquer resins, they were spread onto a flat polytetrafluoroethylene plate and cured at room temperature. The process was repeated until a sufficient thickness of 1 mm for the adhesive resin and 3 mm for the PU resin was achieved. The resin plates were then cut into strips with dimensions of 10 × 80 mm.

Vibrational measurements

After conditioning at 25°C and 60% RH for 1 month, the dynamic Young's modulus (E') and internal friction (Q^{-1}) of the wood specimens were determined via the free–free flexural vibration method [8]. A thin piece of 3 × 10 mm iron was attached to the end of a specimen, and the specimen hung by silk threads was vibrated by a magnetic driver. The amplitude of vibration was detected using an eddy-current sensor, and the signal passed through a band-pass filter (NF Electronic instruments, Type 3611) was observed by a FFT analyzer (Ono Sokki Co., CF-4220A). The E' and Q^{-1} values were calculated from the resonance frequency of the first mode vibration and the width of the resonance curve, respectively. The resonance frequency ranged between 300 and 1500 Hz.

The E' and Q^{-1} values of the resin plates were measured using cantilever flexural vibration method at 25°C and 60% RH. A thin iron piece of 3 × 10 mm was attached to the end of a specimen, and the other end was fixed by a metal clamp. The free end of the specimen was then tapped lightly by a finger, and the excited vibration was detected by an eddy-current sensor. The E' value was determined by the resonance frequency of the free vibration, and Q^{-1} from the decrement curve. The resonance frequency ranged from 50 to 300 Hz.

Results and discussion

Effect of reinforcement with veneer

Table 1 lists the average E'/ρ and Q^{-1} values of materials tested. In this paper, the vibrational properties of reinforced and/or varnished specimens are always normalized by those of base wood determined before the attachment of veneer and varnishing to eliminate the natural variations in the vibrational properties of wood.

As in real harp soundboards, the thickness of the base wood (t_0) varied between 2.9 and 10.0 mm while that of the overlaid veneer (t_1) remained almost constant at 0.8–0.9 mm. Figure 2 shows the relative values of E'/ρ and Q^{-1} as a function of the relative thickness of the veneer (t_1/t_0). A thicker veneer resulted in smaller E'/ρ and greater Q^{-1} values. Those changes include the effects of adhesive, but it should be noted that the amount of adhesive was constant (200 g/m^2) in this case. Therefore, it is evident that the veneer significantly reduces the ACE of the soundboard. These data provide empirical support for harp makers' intuitive knowledge that the application of a veneer reduces the amplitude of sound. This adverse effect must be greater at higher frequencies because thinner base wood is usually used in the upper position of the soundboard, which covers the higher frequency range. Essentially, the overlaid veneer may act as a high-cut damper in soundboards. To maintain higher ACE, it is advisable to use a thinner veneer for the reinforcement of soundboards.

The effect of adhesive

In soundboards reinforced with veneers, a continuous layer of adhesive (glue layer) is present between the base wood and veneer. Even a very thin glue layer significantly affects the flexural vibration of the soundboard because it is located near the surface of the soundboard and its viscoelastic properties completely differ from those of wood. Figure 3 exhibits the relative values of E'/ρ and Q^{-1} for veneer-reinforced wood plotted against the amount of adhesive applied. In this case, the amount of adhesive varied from 100 to 400 g/m^2 while the thickness of base wood and veneer remained constant. The E'/ρ value was significantly reduced by the attachment of veneer, but it did not depend on the amount of adhesive. For the E'/ρ of soundboard, the effect of adhesive is much slighter than that of veneer. On the other hand, the Q^{-1} value increased linearly with increasing amount of adhesive, *i.e.*, increasing thickness of the glue layer. This suggests that the amount of glue should be minimized to maintain a higher ACE for veneer-reinforced soundboards.

The effect of varnishing

Varnishing is an effective method of stabilizing the performance of wooden instruments because it impairs the moisture sorption and desorption of wood. However, artisans suggest that the varnish layer should be as thin as possible because it degrades the sonority of the sound. This adverse effect can be explained by the reduction in ACE due to varnishing, as described in a previous paper [9, 10]. Varnish resin is usually an amorphous polymer and has lower E'/ρ and higher Q^{-1} values than wood; therefore, it reduces the E'/ρ and increases the Q^{-1} of wood in the fiber

Table 1 Average experimental values of density (ρ), dynamic Young's modulus (E') and internal friction (Q^{-1}) of materials tested

	ρ (kg/m^3)	E' (GPa)	Q^{-1}
Wood			
L direction	420	14.3	0.0068
R direction		0.936	0.0206
Adhesive	1200	2.6	0.189
Varnish	1200	2.5	0.050

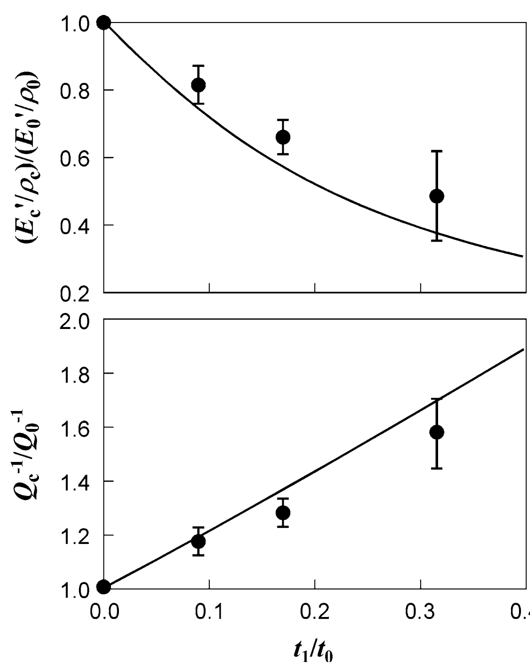

Fig. 2 Relative values of E'/ρ and Q^{-1} of veneer-reinforced wood as a function of the relative thickness of veneer (t_1/t_0). *Filled plots* experimental values, *solid lines* calculated values. The *bars* indicate standard deviation. All samples were unvarnished and the amount of glue for the attachment of veneer was 200 g/m^2

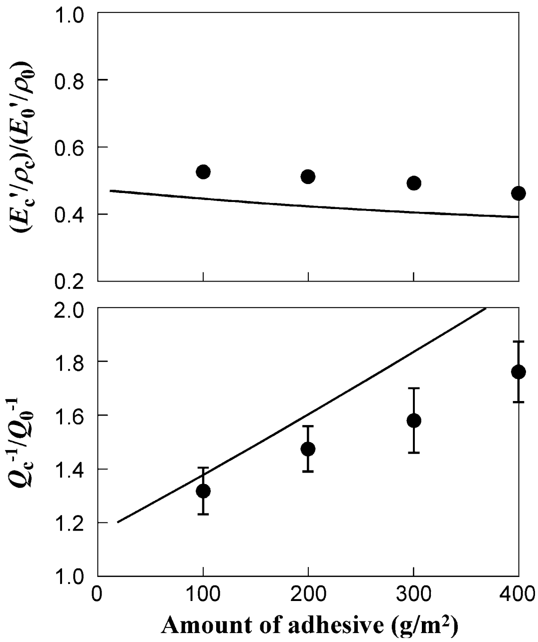

Fig. 3 Relative values of E'/ρ and Q^{-1} for veneer-reinforced wood plotted against the amount of adhesive. *Filled plots* experimental values, *solid lines* calculated values. The *bars* indicate standard deviation. Some plots *without bars* indicate that the standard deviation was smaller than the size of plot. All samples were unvarnished and the relative thickness of veneer (t_1/t_0) was 0.27

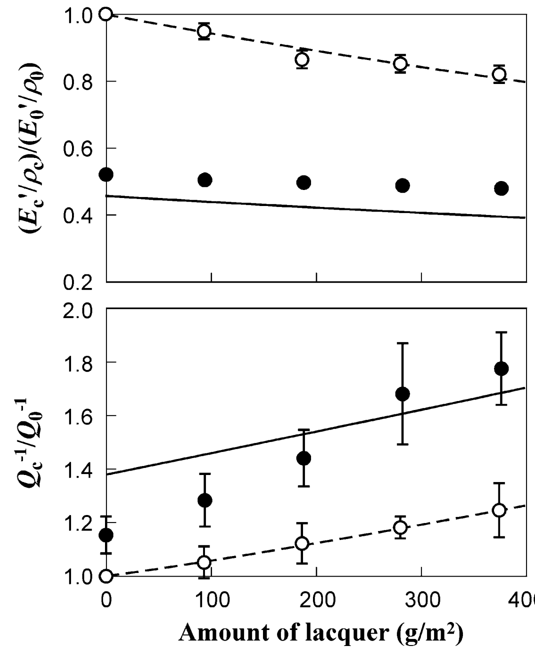

Fig. 4 Relative values of E'/ρ and Q^{-1} for unreinforced and veneer-reinforced wood plotted against the amount of lacquer applied. *Open plots* unreinforced specimens, *filled plots* veneer-reinforced specimens, *broken lines* calculated values for unreinforced specimens, *solid lines* calculated values for veneer-reinforced specimens. The *bars* indicate standard deviation. Some plots *without bars* indicate that the standard deviation was smaller than the size of plot. The amount of glue for the attachment of veneer was 100 g/m^2 and the relative thickness of veneer (t_1/t_0) was 0.27

direction. Figure 4 shows the relative values of E'/ρ and Q^{-1} for varnished wood plotted against the amount of lacquer applied. Again, the vibrational properties of the varnished specimens are normalized by those of "naked" specimens. Therefore, the results in Fig. 4 include the effects of veneer and adhesive as well as those of varnishing. In both the unreinforced and veneer-reinforced wood, thicker varnishing resulted in lower E'/ρ and higher Q^{-1} values. As suggested by artisans, the varnish layer should be minimized to increase the amplitude of sound.

Analysis using a multi-layered model

To elucidate the vibrational properties of plywood-like harp soundboard, we analyzed the experimental results using the multi-layered model illustrated in Fig. 5. The harp soundboard is approximated by a multi-layered composite (c) consisting of base wood (0), an adhesive layer (a), overlaid veneer (1), and a varnish layer (v). In reality, some of the lacquer and adhesive penetrates into the porous wood surface to form additional layers [9]. However, this effect is considered to be negligible in the present calculation and it is assumed that the adhesive and lacquer resins form flat and continuous layers without penetration into the wood. The ρ and flexural Young's modulus (E) of the composite are expressed by the following equations:

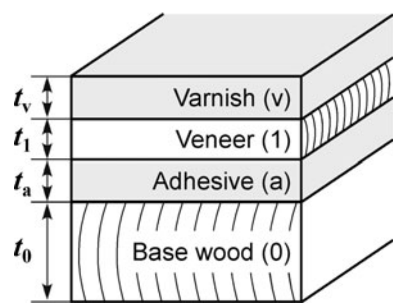

Fig. 5 A multi-layered model to calculate the vibrational properties of a harp soundboard

$$\rho_c = \frac{\sum_{j=1}^{n} \rho_j A_j}{A_c} \tag{1}$$

$$E_c = \frac{\sum_{j=1}^{n} E_j I_j}{I_c}, \tag{2}$$

where A and I represent the cross-sectional area and second moment of inertia of each layer, respectively. The I value of the nth layer (I_n) is given by

$$I_n = I'_n + a_n^2 A_n, \tag{3}$$

where I'_n is the second moment of inertia of the nth layer, and a_n is the shift of the neutral plane by the combination of different materials. When Eq. (2) is expanded to represent complex Young's modulus ($E^* = E' + iE''$), the dynamic Young's modulus (E_c') and internal friction (Q_c^{-1}) of the composite can respectively be described by

$$E_c' = \frac{\sum_{j=1}^{n} E_j' I_j}{I_c} \quad \text{and} \tag{4}$$

$$Q_c^{-1} = \frac{E_c''}{E_c'} = \frac{\sum_{j=1}^{n} E_j' I_j Q_j^{-1}}{\sum_{j=1}^{n} E_j' I_j} \tag{5}$$

The experimental values listed in Table 1 were used as basic parameters of local components, and the thickness of glue and varnish layers was calculated from the amount of adhesive and lacquer, their resin contents, and their densities in dry state. The calculated values are compared to the experimental values in Figs. 2, 3, 4 via lines. Despite the simplicity of the model and the natural variations in wood properties, agreement with the experimental data was fairly good.

It was inferred from the calculations that the lower E' and greater Q^{-1} values of veneer in the R direction are the major reasons for the reduced ACE of veneer-reinforced soundboard. An additional factor was the amount of adhesive, *i.e.*, the thickness of glue layer, which contributes to the reduction in ACE especially when the Q^{-1} of the glue layer is much greater than that of wood. For more effective sound radiation, it is advisable to minimize the thickness of veneer and amount of adhesive. Additionally, the use of epoxy or similar cross-linking resins will give better results because their Q^{-1} values are lower than that of honeymoon-type glue currently used. The adverse effects of varnishing were less significant than those of veneer and adhesive because the Q^{-1} value of the PU lacquer was smaller than that of the adhesive resin and comparable to that of wood in the R direction.

In any cases, the ACE of harp soundboard is more or less reduced by the conventional veneer reinforcement. For further development of harp soundboard, it is worth reconsidering its designing from the very beginning. As one of many options, carbon fiber-reinforced structure will be proposed in a following article.

Conclusions

The attachment of veneer resulted in a significant reduction in E'/ρ and a marked increase in Q^{-1} of wooden soundboard in its width direction, *i.e.*, the direction of the fiber of the base wood. These adverse effects were mainly due to the smaller E'/ρ and greater Q^{-1} values of the overlaid veneer. In addition, larger amounts of glue and varnish induced a greater reduction in E'/ρ and increase in Q^{-1}. These results all correlate with artisans' knowledge that veneer-reinforcement and varnishing reduce the sonority of harps. The experimental results were clarified via calculations on a multi-layered model consisting of base wood, a glue layer, veneer, and a varnish layer.

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