Influence of the Vibrational Properties of the Resonance Board on the Acoustical Quality of a Piano

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The vibrational properties of eight resonance boards made from *Picea glehnii*, *Picea jezoensis*, *Picea spinulosa,* and *Picea sitchensis* were analyzed. The modulus of elasticity and the vibration transmission velocity of the resonance board, the modulus of elasticity of the beam samples cut from the edge of the resonance board, and the vibration response time of the soundboard (T_L, T_R: times for the longitudinal and radial directions, respectively) were calculated. After the resonance boards were incorporated into the pianos, the sound intensity of loud (L_L) and soft playing (L_S), sound length (S), and the dynamic range of volume (V_d) were measured. Then the Influence of the vibrational properties of the resonance board on the acoustical quality of a piano was investigated preliminarily, and the results showed that the acoustical quality would improve notably with improvements in the vibrational properties in the y-direction of the resonance board, and that the T_R affected acoustical quality more obviously than did T_L.

Keywords: Wood; Resonance board; Vibrational properties; Piano; Acoustical quality

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INTRODUCTION

The piano is one of the world's most popular instruments. It has a very characteristic sound, a wide dynamic range, and a playing range of more than seven octaves. The soundboard is the main radiating structure of the piano, and its quality greatly affects the piano's acoustical performance (Jin 2002). The soundboard is a thin plate about 8 mm thick and made of spruce strips of 80 to 100 mm width, which are usually glued together edge-to-edge.

In order to analyze the vibrational properties of the piano soundboard, it is necessary to understand the manufacturing process of the soundboard and to know the vibrational parameters and measuring methods of the wooden plate, which is an anisotropic material. Sun (2004) discussed the manufacturing of the piano soundboard. In several studies, Liu and Han analyzed the natural frequency and other parameters of the soundboard of a small grand piano (Liu and Han 1991a,b; Liu 1991). Sobue and coworkers measured the elastic constants and complex Poisson ratios of wood as a two-dimensional anisotropic material using a plate-vibration technique (Sobue and Takemura 1979; Sobue and Kitazumi 1991). Nakao and coworkers measured the complex Young's modulus, the complex shear modulus, and the complex Poisson's ratio of wood by applying the vibration method of free-free beams and measuring the resonance frequencies of higher torsional vibration for wooden bars. These frequencies were then compared with frequencies obtained by applying St. Venant's torsion theory and thin- and thick-plate theories, taking into consideration the different elastic constants (Nakao *et* *al*. 1985; Nakao 1996). By applying plate vibration methods, Tonosaki and coworkers measured the vibration mode and dynamic loss in the longitudinal-radial plane of a 21.5-cm square plate of Sitka spruce, with free boundary conditions on the four edges (Tonosaki *et al*. 1985). Suzuki (1986) researched the vibration and sound radiation of the soundboard from a Steinway grand piano. Kindel and Wang (1987) made modal analysis measurements of two concert grand piano soundboards and researched a finite element model in order to describe the vibrational characteristics of these soundboards and thereby explore the possibility of using both techniques in the design of new soundboards. Giordano (1997) studied the behavior of the mechanical impedance in the musically important frequency range of 50 to 10^4 Hz and constructed a simple finite element model of the vibrational properties of the piano soundboard. The model includes the effects of elastic anisotropy and the ribs. Giordano (1998) then experimentally investigated the generation of sound by a piano soundboard by measuring the sound pressure, p, and the soundboard velocity, v_b, that is produced in response to a force applied at the bridge. The variation in the mass distribution of a soundboard can affect its vibrational properties and the sound quality of the piano. Xing *et al.* studied the effects of additional mass-blocks on a soundboard. The results showed a notable difference in the spectrum between mass-added cases and the original case at low frequencies, but little difference at high frequencies (Xing *et al*. 2007). It could be concluded that an additional mass-block greatly affects the energy of the low-frequency mode of a soundboard. The above works trace the continuous study of the soundboard, an important resonance component of the piano, over the past several decades. However, the relationship between the vibrational properties of the resonance board and the acoustical properties of the piano has been seldom investigated until now.

In order to investigate the relationship between the vibrational properties of the soundboard (resonance board) and the acoustical properties of the piano, the piano's acoustical properties need to be evaluated in terms of the resonance board's vibrational properties using both subjective and objective evaluation methods. The subjective evaluation method uses music or instrument experts who have a profound understanding of musical theory and sensitive hearing. For the objective evaluation method, the physical elements of a single tone of the piano are measured using specific equipment. However, the dynamic acoustical properties are difficult to evaluate when the piano is played.

In this paper, the vibrational properties of the resonance board were measured according to the vibration theory (Liu *et al*. 2008), and the acoustical properties of the piano were then evaluated objectively after the resonance board was incorporated into the piano. Additionally, the relationship between the resonance board's vibrational properties and the piano's acoustical properties was investigated preliminarily.

EXPERIMENTAL

Materials

The resonance board with dimensions 1408 mm × 937 mm × 8 mm is made of 18 to 22 species of wood plates (Fig.1). Eight resonance boards were made from the woods of *Picea glehnii*, *Picea jezoensis*, *Picea spinulosa*, and *Picea sitchensis* (two boards per species) in this study. After their vibrational properties were measured, eight pianos were made using these resonance boards.

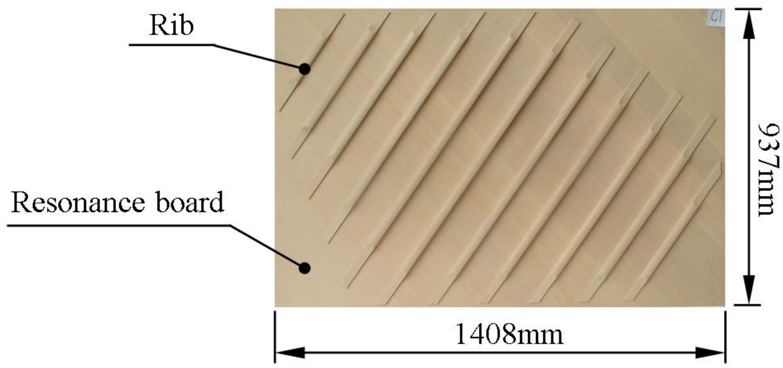

Fig. 1. The resonance board

Methods

Measurement of the vibrational properties of resonance boards

The vibration spectrum of each resonance board was measured using a CF5220 Multi-Purpose FFT Analyzer manufactured by Ono Sokki in accordance with the vibration theory of a thin plate. The flexural rigidities D_{11}, D_{22}, and D_{12} and torsional rigidity D_{66} were obtained from the frequency equation for free vibration (Equation 1) and from the resonant frequencies (2,0), (0,2), (1,1), and (2,2), which were identified from the vibration spectrum (Giordano 1998; Xing *et al.* 2007; Sobue and Katoh 1992; Hearmon 1961; Rossing and Fletcher 2004). The moduli of elasticity of the resonance board in the *x*- and *y*-directions were obtained using Equation 2,

$$f_r(m,n)=\frac{1}{2\pi}\sqrt{\frac{D_{11}\dfrac{\alpha_1(m,n)}{a^4}+D_{22}\dfrac{\alpha_2(m,n)}{b^4}+2D_{12}\dfrac{\alpha_3(m,n)}{a^2b^2}++4D_{66}\dfrac{\alpha_4(m,n)}{a^2b^2}}{\rho h}} \tag{1}$$

where $f_r(m,n)$ is the resonant frequency (Hz), h, a, and b are the height (m), length (m), and width (m), respectively, of the sample, ρ is the density (kg/m^3), D_{11}, D_{22}, and D_{12} are the flexural rigidities, D_{66} is the torsional rigidity, and α_i(m,n) is the coefficient for constants,

$$\begin{aligned}
E_x&=\frac{12}{h^3}D_{11}(1-\mu_x\mu_y)=\frac{12}{h^3}D_{11}\mu\\
E_y&=\frac{12}{h^3}D_{22}(1-\mu_x\mu_y)=\frac{12}{h^3}D_{22}\mu\\
\mu&=1-\mu_x\mu_y=1-\frac{D_{12}}{D_{22}}\bullet\frac{D_{12}}{D_{11}}=1-\frac{D_{12}^2}{D_{22}\bullet D_{11}}
\end{aligned} \tag{2}$$

where μ_x is Poisson's ratio in the *x*-direction and μ_y is Poisson's ratio in the *y*-direction.

The equation for the vibration transmission velocity of the resonance board (Rossing and Fletcher 2004) is,

$$C=\sqrt{\frac{E}{\rho(1-\mu^2)}}, \tag{3}$$

where C is the longitudinal sound velocity and μ is Poisson's ratio. The vibration transmission velocities in the two directions are calculated with values of E and v for the different directions.

Measuring the objective indices of piano acoustical quality

For the moment, it is difficult to objectively evaluate the acoustical quality of a musical instrument being played, but the physical factors of a single tone can be measured quantitatively. There are three physical factors that describe a single tone in physics: fundamental frequency, amplitude, and the frequency spectrum, which correspond to pitch, sound intensity, and tone, respectively, in music psychology. Although these factors of music psychology cannot be quantified easily, the acoustical properties can be measured and analyzed using the three physical factors. In brief, a single tone's pitch is a subjective feeling of the resonance frequency, loudness is a subjective feeling of the sound intensity, and tone is related to the frequency spectrum (the proportion of each harmonic component) (Han 2002). In this paper, the sound intensity during loud and soft playing, sound length, and dynamic range were measured.

The sound intensity of the musical instrument is the sound power, also referred to as the volume of sound, in units of decibels (dB). Generally, a musical instrument is considered better if it has greater sound intensity without distortion. The sound intensity is often different in different registers, but the sound intensity of a better musical instrument is more balanced in different registers. In this paper, the sound intensity was determined by playing the instrument both loudly and softly in a quiet environment, with five duplications for each key. Sound length is the attenuation time of the sound activated by the musical instrument, in units of seconds. The sound length of most musical instruments including the piano can be controlled by the musician. However, in the case of the piano, the sound length can reflect the damping property of the vibration system. Longer sound lengths indicate higher sensitivity and less damping of the vibration system. A lower damping coefficient would favor the continuation of sound energy. Sound length was measured in a quiet environment with a stopwatch as the key was tapped with the same power; there were five duplications for each key. The dynamic range of sound was calculated from the difference in sound intensity between loud playing and soft playing.

RESULTS AND DISCUSSION

The relationships between the vibrational properties of the resonance board and the sound intensity of loud playing, the sound intensity of soft playing, and the sound length were analyzed. The relationship between the vibrational properties of the resonance board and the timbre of the piano will be researched in other works.

Correlation Between the Modulus of Elasticity (MOE) and the Acoustical Quality of the Piano

The MOE (E) is an important parameter that expresses the vibrational properties of a resonance board. The vibrational energy that is transmitted from the string can be radiated maximally with a suitable value of E for the soundboard. The relationship between E (E_x, E_y: the x- and y-directions, respectively, of the MOE of the resonance board) in the two directions and the objective indices of the acoustical properties of the piano were analyzed (Fig. 2).

Figure 2 shows that a linear correlation existed, to a certain extent, between E_x and the sound intensities of loud and soft playing (L_L and L_S), but the correlations between E_y and L_L and L_S were more significant than those in the *x*-direction. The coefficients of correlation between E_y and L_L and L_S were 0.5490 and 0.8984, respectively, whereas they were 0.4328 and 0.6499 in the *x*-direction. However, the relationships between *E* and the sound length (*S*) and dynamic range (V_d) were not significant.

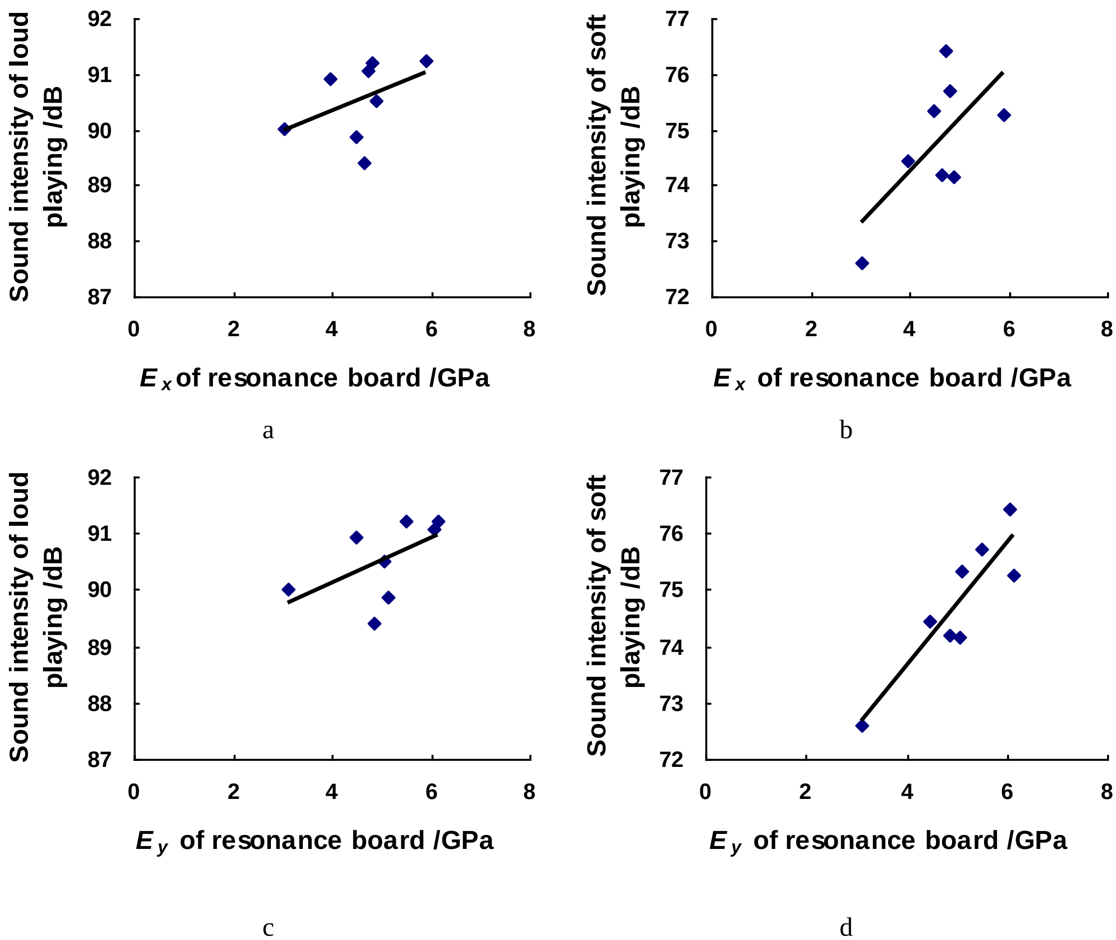

Fig. 2. Correlation between the MOE of the resonance board and the acoustical quality of the piano

Correlation between the Vibration Transmission Velocity and the Acoustical Quality of the Piano

The vibration transmission velocity (*C*) is another important parameter of the resonance board. A higher vibration transmission velocity can make the whole resonance board vibrate uniformly within a shorter time. That is, higher vibration transmission velocities improve the radiation of sound energy transmitted from a string. The relationships between *C* (C_x, C_y: vibration transmission velocity of the resonance board in the *x*- and *y*-directions, respectively) in the two directions and the objective indices of the acoustical properties of the piano were analyzed.

The correlations between C_x and L_L and L_S were not significant, but that there was a positive linear correlation between C_y and L_L and L_S, the coefficients being 0.6759 and 0.8735, respectively. However, the correlations between C and S and V_d were not significant.

Correlations between the MOE of Samples Cut from the Edge of the Resonance Board and the Acoustical Quality of the Piano

During manufacturing, each resonance board was sawed to a certain size. The MOEs of beam samples taken from the cutting residues were measured. The length direction of beam samples is 45° to the direction of wood grain and parallel to the x or y-direction of resonance board. As parts of the initial resonance board, the samples could be analyzed to obtain the vibrational properties for the resonance board. The relationships between the MOEs of the beam samples (E_{45}: E_{45x} and E_{45y} are MOE values for the resonance board in the x- and y-directions, respectively) and the objective indices of the acoustical properties of the piano were analyzed (Fig. 3).

Figure 3 shows that the correlations between E_{45x} and L_L, L_S, S, and V_d were not significant, but that those between E_{45y} and L_L, L_S, and S were to some extent positive and linear, with correlation coefficients of 0.6305, 0.5417, and 0.4675, respectively.

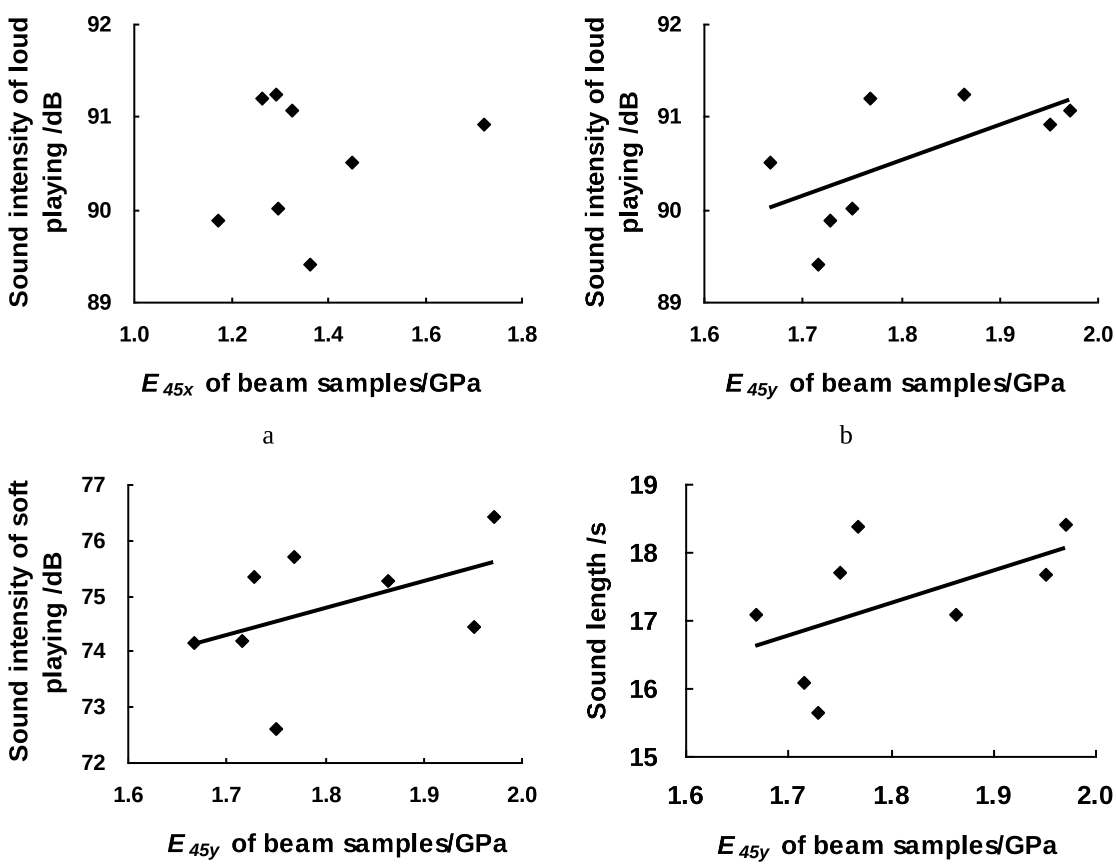

Fig. 3. Correlation between the MOE of the beam sample and the acoustical quality of the piano

Correlation between the Vibration Response Time and Acoustical Quality of the Piano

The soundboard is a resonance board affixed with ribs. The vibration response time of a piano's soundboard indicates the transmission velocity of vibration energy and the soundboard's ability to vibrate uniformly. The correlations between the vibration response time and the sound intensities of loud playing (L_L), soft playing (L_S), sound length (S_L), and the dynamic range of the volume (V_d) of the piano were analyzed (Fig. 4).

Figure 4 shows that the correlation between the vibration response time of the soundboard in the longitudinal direction (T_L) and the acoustical quality of the piano was not significant, but that the correlations between the vibration response time in the radial direction (T_R) and L_L, $L_{S,}$ and S were negative and linear with correlation coefficients of -0.8710, -0.3948, and -0.7311, respectively. This indicates that C, L_L, $L_{S,}$ and S decreased as T_R increased. The acoustical quality of the piano improved as T_R decreased. A lower T_R reduced the difference between T_R and T_L, leading to the even vibration of the whole soundboard in the shortest period of time.

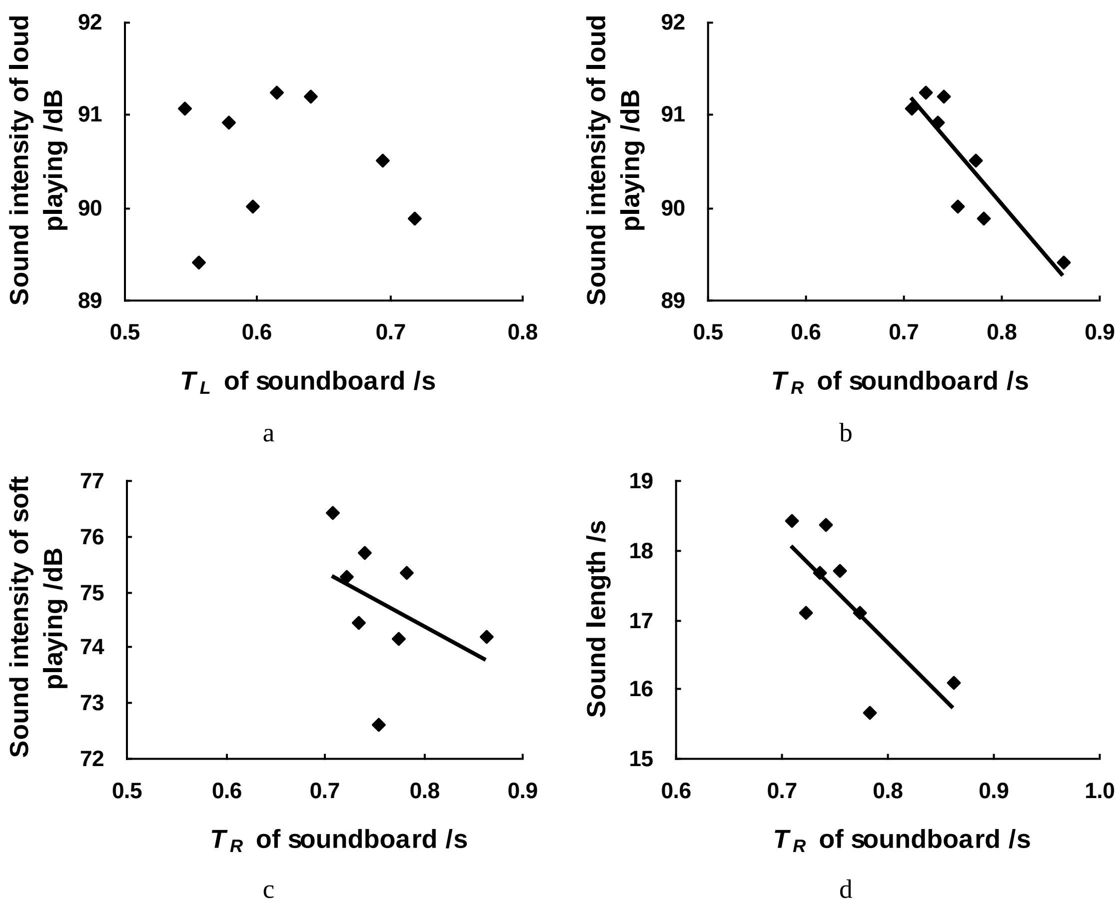

Fig. 4. Correlation between the vibration response time of the soundboard and the acoustical quality of the piano

Interestingly, the correlation between the vibration response time of the sound-board in the radial direction and the acoustical quality of the piano was stronger than that in the longitudinal direction. The anisotropy of wood that has a sound speed in the longitudinal direction higher than that in the radial direction leads to the uneven vibration of the soundboard. Therefore, the vibration response time in the radial direction of the soundboard affects the acoustical quality of the piano more significantly. The acoustical quality of the piano would improve if the difference between T_L and T_R were reduced. One function of the ribs is to improve the sound speed in the radial direction of the soundboard, which allows the whole soundboard to vibrate evenly in the shortest period of time.

The correlations between the vibration response times of the soundboard in the *x*- and *y*-directions and the acoustical quality of the piano were also analyzed but found to be insignificant. This indicates that before the whole soundboard vibrates evenly, the vibration wave is transmitted more quickly in the longitudinal direction than in the radial direction.

Comprehensive Analysis

From the above analysis it follows that the correlations between the acoustical quality of the piano and the vibrational properties in the *y*-direction of the resonance board are stronger than those in the *x*-direction. This may be related to the string distribution and arrangement on the soundboard. The string array frame is shown in Fig. 5.

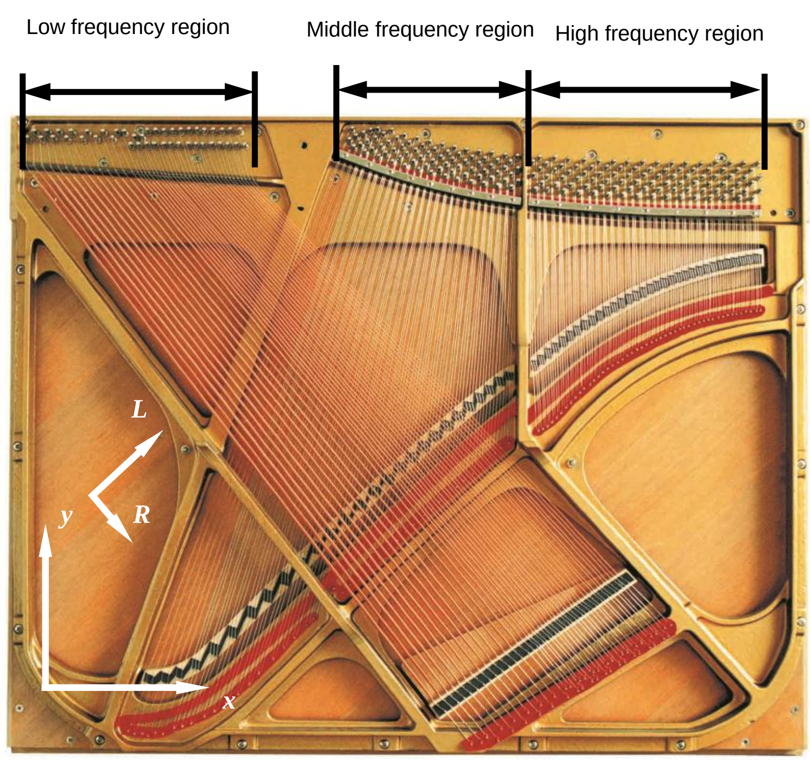

Fig. 5. String array on the soundboard

The high-, intermediate-, and low-frequency regions are distributed at the right, middle, and left of the soundboard (Fig. 5), respectively. All strings of the high-frequency region and some in the high region of the intermediate region are almost parallel to the *y*-direction of the soundboard. The angle between the strings and the *y*-direction of the soundboard increases as the strings approach the low-frequency region. Additionally, the angle is the largest in the low-frequency region, but still less than the angle between the strings and the *x*-direction. Therefore, the *y*-direction of the soundboard sustains most of the energy passed from the vibrating strings. The *y*-direction is activated first when the strings vibrate, after which the whole soundboard is then driven to vibrate. That is, the vibration properties in the *y*-direction are more important to the acoustical quality of the piano than are those in the *x*-direction.

CONCLUSIONS

1. The vibrational properties in the *y*-direction of the resonance board are positively correlated with the sound intensity of loud playing (L_L) and the sound intensity of soft playing (L_S). However, the correlations between the properties in the *x*-direction and L_L and L_S are not significant. Therefore, the piano's acoustical quality can be noticeably improved if the vibrational properties in the *y*-direction are improved.
2. The correlations between the vibrational properties of the resonance board and L_L and L_S are stronger than the correlations between the vibrational properties and sound length (c). The correlations between the vibrational properties and the dynamic range of volume are not significant.
3. The correlations between the vibration response time in the soundboard's radial direction (T_R) and L_L, L_S, and S of the piano are linear and negative to some extent and are stronger than those in the longitudinal direction (T_L). This indicates that the acoustical quality of the piano is affected more significantly by T_R than by T_L.
4. The correlations between the vibrational properties of the resonance board in the *y*-direction and acoustical quality of the piano are more significant than those in the *x*-direction. This may be related to the string array frame, as the string axis in the high- and intermediate-frequency regions is nearly parallel to the *y*-direction, and the angle between the string axis and the *y*-direction in the low-frequency region is smaller than that between the string axis and the *x*-direction of the soundboard. The results show that the parameters of the vibrational properties in the *y*-direction are more important to the acoustical quality of the piano.

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