Analysis and study on acoustical quality of a piano soundboard based on ANSYS

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Abstract

Basing on the theory of finite element method and modal analysis， the models of a bare plate and a piano soundboard are established in the ANSYS separately， then the two models' natural frequency and mode shape are calculated and compared. What is more， the influences of density and thickness on the piano soundboard's modal frequency are discussed. The result reflects that the piano soundboard's modal frequency is higher than the bare plate's and the piano soundboard vibrates in more complicate way. At the same time, it is found that the piano soundboard's modal frequency turns to be larger when the thickness turns to be larger and turns to be smaller when the density turns to be larger.

Keywords: ANSYS, force analysis, piano soundboard, sound quality, experimental study

1 Introduction

The piano acoustical quality is decided by the soundboard to a great extent, and the soundboard acoustical quality is decided by the wood. In the producing, wood selection for piano soundboard is depending on the subjective evaluation of technician for the moment. This method of wood selection is inefficient. It does not satisfy the requirement to produce the excellent piano soundboard [1].

This research selected nine Picea wood and provided technique parameters by measuring the sound vibration data of the instrument wood. In order to establish the objective method of wood selection for piano soundboard and objective evaluation method of vibration properties of piano resonant board, this research analyzed and differentiated the comprehensive vibration properties of the samples of Picea glehnii, Picea jezoensis, Picea likiangensis var. linzhiensis, and Picea sitchensis by the comprehensive coordinate method and comprehensive marking method. According to the results of differentiation, it selected two groups of samples used for producing the resonant boards from every species respectively, and the distinction between the both groups of every species was obvious. It analyzed the vibration properties base on the vibration theory of resonant board.

The piano acoustical quality is decided by the soundboard to a great extent. [2] In the producing, the Technician evaluates and chooses the wood for piano soundboard subjectively for the moment. It is inefficient, large error, and insufficiency of the scientific foundation. It does not satisfy the requirement to produce the excellent piano soundboard in the condition of volume produce.

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 in 2002. The soundboard is a thin plate about 8mm thick and made of spruce strips of 80 to 100mm width, which are usually glued together edge to edge.

2 Vibration properties

Mechanism.

After reviewing the current status of piano study, a number of key issues with regard to the dynamic vibration, mechanics and acoustics of piano were investigated in this thesis.

The interaction between piano bow and strings is very complicated. Through the analysis of the Helmholtz motion of strings, the traditional stick-slip friction string vibration model and modern string vibration theory, a pendulum frictional vibration model was developed in this thesis. By taking account of the energy conversion and the vibration period in the bow-string vibration system, the vibration behavior of piano string can be modelled more accurately in the proposed model.

In order to understand the physics of a bowed piano string and develop an accurate model experimental measurement of the bowed string motion is crucial. In this thesis, a high-speed photography based non-contact optical measurement system was designed to measure the string motion without interference for movement when plucking or bowing a string fitted in a piano. Through a novel optical system design and setting up an artificial marker on the string, the instantaneous motions of the marker in the X-Y and X-Z planes were simultaneously recorded in every single image. The string vibration was videoed using a single high-speed video camera, generating more than 10,000 sequential images. [3] An image processing algorithm based on the Hough transform were developed to extract the marker position from a recorded image at sub-pixel resolution. All the recorded sequential images were processed automatically using the developed image processing algorithm, to track the three-dimensional motion of the marker. Experimental results showed that the proposed measurement system can accurately track the piano string motion and trajectory. The tracked motion verified the predicted Helmholtz motion of the bowed string. The designed measurement system and image processing algorithm provide a potential experimental tool for studying the mechanism of piano string vibration. First order modal cloud picture of soundboard is shown in Figure 1.

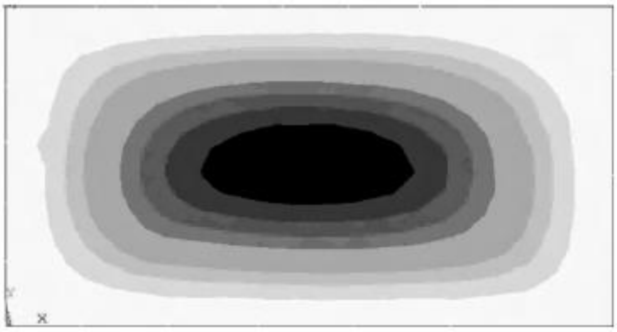

FIGURE 1 First order modal cloud picture of soundboard

Experements.

The dynamic response of a piano is often divided into a deterministic region and a statistic region. However, the statistic region is not well understood. The bridge role in the dynamic response was firstly analyzed through four theoretical models: the deterministic-statistical division model, the convolution model, the modal model, and the dynamic contact vibration model. The bridge mobility under in-plane and out-of-plane excitations was then explored based on the dynamic contact vibration model for a real bridge and a solid plate bridge. Theoretical analysis and numerical results showed that the bridge mobility is not only affected by the bridge geometrical structure and material, but the interaction among the strings, bridge and the front plate also plays a vital role. Especially, the contact vibration boundaries in the two contact interfaces: strings-bridge, and bridge feet-top plate, have a great impact on the bridge mobility and as a result on the piano dynamic response, helping us gain an further understanding to the statistic region in the dynamic response of a piano.

The resonance boards are shown in Figure 2. The resonance of board with dimensions 1408mm×937mm×8mm is made of 18 to 22species of wood plate. Eight resonance boards were made from the woods of Picea in this study. After their vibrational properties were mesured, weight piano were made using these resounance boards.

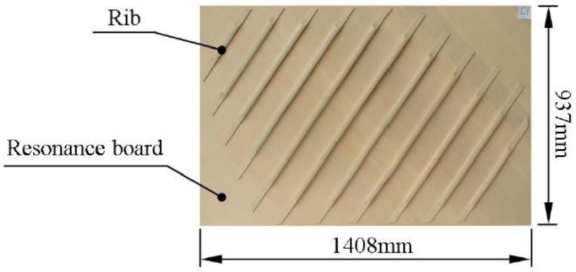

FIGURE 2 The resonance board

In order to verify the theoretical and numerical findings on bridge mobility, a novel experimental system was designed on the basis of a piezoelectric dynamometer for bridge mobility analysis in this thesis. [4] The dynamic forces in three directions acted on the front plate by the bridge when bowing a string with finger slurring on the finger board were recorded through the experiment system, and frequency responses were further analyzed. Experimental results confirmed the impact of contact vibration boundaries on the bridge mobility, which were discovered in the finite element simulation.

$$f_r(m,n) = \frac{1}{2\pi}\sqrt{\frac{D_{11}\dfrac{a_1(m,n)}{a^4} + \dfrac{a_2(m,n)}{b^4} + 2D_{12}\dfrac{a_3(m,n)}{a^2b^2} + 4D_{66}\dfrac{a_4(m,n)}{a^2b^2}}{\rho h}}\,. \tag{1}$$

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 D11, D22 and D12 and tensional ridigity D66 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. The moduli of elasticity of the resonance board in the x- and y- directions were obtaines using Equation 2.

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

Where $f(m, n)$ is the resonant frequency (Hz), h, a, and b are the height (m), length (m), and width (m), respectively, of the sample, p is the density.

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

where u is Poisson's ratio in the x- direction and y- direction, C is the longitudinal sound velocity and the vibration transmission velocities in the two directions are calculated with the values of E and v for the different directions.

Based on the obtained theoretical and experimental findings on the vibration mechanism and mechanics of piano, the influence of the piano structures, materials, and interaction among different parts on the sound quality were further analyzed, and the ways and methods to improve the piano sound quality were proposed.

3 Piano materials

The comprehensive vibration properties of the samples of every species were analyzed and differentiated respectively by the comprehensive coordinate method and comprehensive marking method. According to the results of differentiation, two groups of samples used for producing the resonance boards in every species were selected respectively, and the distinction between the both groups was obvious (the No.1 and No.2 groups of samples respectively, correspond to the No.1 and No.2 piece of resonance board, correspond to the No.1 and No.2 piano). The vibration properties of resonance board were analyzed base on the vibration theory of thin plate. After the pianos were producing, the acoustical qualities of pianos were evaluated by the subjective method, objective method, and psycho-physiological index method. On the basis of the comprehensive analysis of the correlation between vibration properties of the resonance board and the acoustical quality of pianos, the objective evaluation method of the resonance board of piano and the objective selection method of wood used for soundboard were established.

$$f = \frac{f}{k} + \left(\frac{f_0 - f}{k} \cos w_0 t + \frac{V_B}{w_0} \sin w_0 t \right). \qquad (4)$$

The samples of wood used for resonance board were glued to resonance board. The foundation theory of vibration of piano resonance board was analyzed, and the frequency equation of free vibration was acquired. The MOE, velocity of longitudinal wave of resonance board on the x (MOEX, V) and y (MOEy, Vy) direction were computed by the frequency equation and longitudinal wave transmittal equation. The results were: the MOEX, MOEy, V, Vy of the No.2 piece of resonance board (correspond to the No.2 group of wood samples) are larger than the No.1 (correspond to the No.1 group of wood samples) in every species; for all resonance boards, the MOEy, Vy are larger than MOEx. The mechanical properties of the 450 grain samples in the edge of the resonance board were analyzed, and the results were same to the resonance board. [5]

The soundboard is the resonance board that the ribs were glued on it. The influence of ribs on the sound transmit velocity of piano resonance board was analyzed. The result shows that the ribs can enhance the sound transmit velocity on the radius direction of resonance board. The response time of vibration on the radius direction is near to that on the longitudinal direction. That is because the ribs enhance the sound transmittal velocity on radius direction of resonance board.

The acoustical quality of the pianos was evaluated by the subjective and objective method. The experts of subjective evaluation were engaged in piano performance and education many years. The indexes of objective evaluation were loudness, sound length, dynamic range, and tone. The results of evaluation were: the acoustical quality of the No.2 piano was more excellent than the No.1 piano in the same species. Correlation between the MOE of the resonance board and the acoustical quality of the piano is shown in Figure 3.

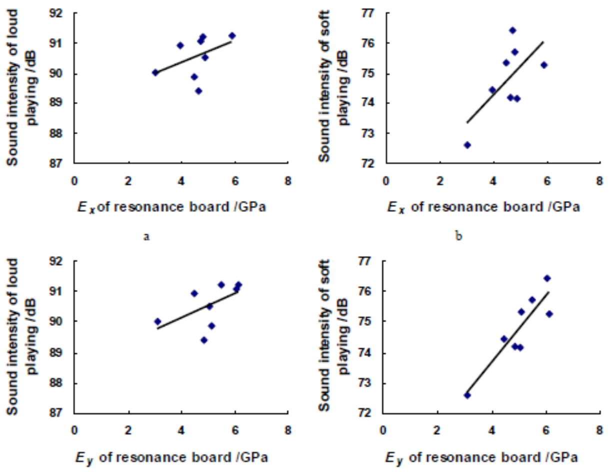

FIGURE 3 Correlation between the MOE of the resonance board and the acoustical quality of the piano

The influence of the piano music on psycho-physiological reaction (the main indexes are Heart Rate Variability, Blood Pressure Variability, Skin Temperature, and Respiration Frequency) of the subjects who are undergraduate without the background of musical training were analyzed. Compared with the resting state, the subjects' physiological reaction was changed when they enjoyed the piano music. The subjects' sympathetic nerves activity decreased, and the parasympathetic nerves activity increased, but the equilibrium was not broke. The synthetically presentation was that the activity of autonomic nervous system was weakening, and the subjects were more comfortable than they were resting. Then the differentiation of the influence of two pianos music of the same species on the subjects' physiological reaction was analyzed. The results show: when the subjects were enjoying the music of the No.2 piano the sympathetic nerves activity of the subjects decreased, the parasympathetic nerves activity increased, and they were more comfortable than that the No.1 piano of the same species. Correlation between the MOE of the beam sample and the acoustical quality of the piano is shown in Figure 4. Recorded dynamic forces exerted on the piano plate by bridge when plucking is shown in Figure 5.

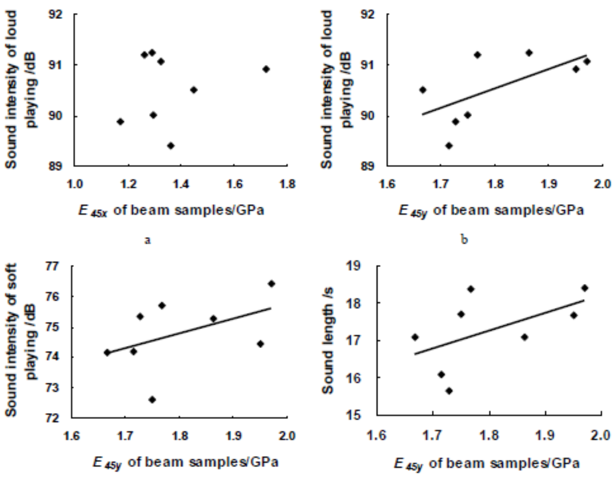

FIGURE 4 Correlation between the MOE of the beam sample and the acoustical quality of the piano

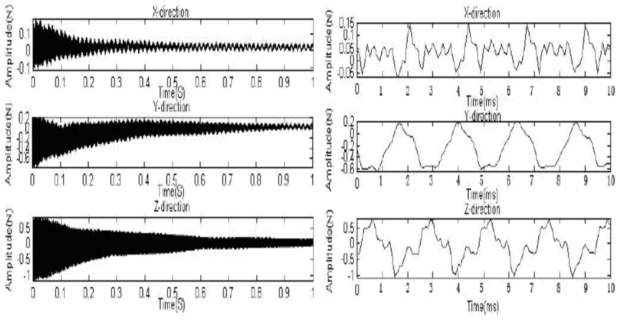

FIGURE 5 Recorded dynamic forces exerted on the piano plate by bridge when plucking

The correlation between the vibration properties of resonance board (MOEX, MOEy, V, Vy), MOE of the 450 grain sample in the edge of the resonance board (MOE45X, MOE， response time of vibration of soundboard(Ti time of longitudinal direction, time of radius direction) and the score of subjective evaluation, indexes of objective evaluation of piano acoustical quality were analyzed. The correlation between subjective evaluation score, objective evaluation indexes and the vibration properties in the y-direction of resonance board were more significant than that in the x-direction. That may be related to the strings array frame. Because the strings axis in high and intermediate frequency region is near parallel to y-direction and the angle between strings axis and y-direction in low frequency region is smaller than that between strings axis and x-direction of the soundboard. The correlation between subjective evaluation score, objective evaluation indexes and the response time of vibration of soundboard in the radius direction were more significant than that in the longitudinal direction of wood. So, the acoustical quality of piano is improved with the MOE (MOEX, MOEy), velocity of longitudinal wave of resonance board increased, especially in the y-direction. If the discrepancy between T and TR is abated with TR reduced, the piano acoustical quality is improved.

$$T = \frac{1}{w_0}\left(\pi + 2\arctan\frac{V_b k}{w_0(f_0 - f)}\right) + \frac{2(f_0 - f)}{V_b k}. \quad (5)$$

The objective evaluation method of wood used for piano resonance board is: the MOE of the resonance boor the 45“grain sample in the edge of the resonance board is measured, especially the y-direction; And the velocity of longitudinal wave transmittal, or response time of vibration of soundboard is measured, especially the y-direction velocity or the response time of vibration in the radius direction of the soundboard (TR). [6]

$$\frac{\partial^2 y}{\partial t^2} - c\frac{\partial^2 y}{\partial x^2} = f(x,t). \quad (6)$$

The objective selection method of wood used for piano soundboard is: the comprehensive vibration properties of wood used for piano soundboard are computed by comprehensive coordinate method and comprehensive marking method, and the indexes include wood longitudinal and radius (or 45“direction of grain) vibration properties. String array on the soundboard is shown in Figure 6.

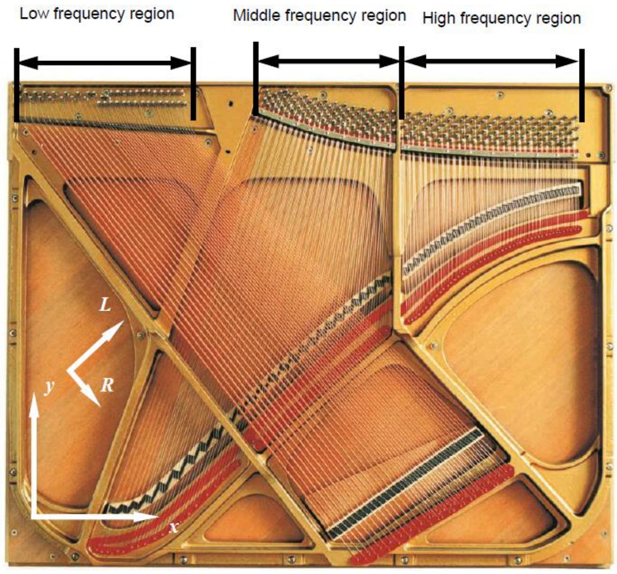

FIGURE 6 String array on the soundboard

4 Conclusion

The results were summarized as follows.

According to the vibration parameters of experiments, the relationship between small-size and full-size instrument wood samples were analyzed. The results showed that if the vibration parameters of small-size were large, the corresponding parameters of full-size were large. The vibration parameters of full-size instrument wood can be forecasted by the small-size samples.

On the basis of studying exploring on the vibration properties measurement of full-size wood samples, it measured the vibration properties of full 一 size wood used for resonant board of piano. The comprehensive vibration properties of samples of Picea glehnii, Picea jezoensis, Picea likiangensis var. linzhiensis, and Picea sitchensis were analyzed and differentiated by comprehensive analysis methods. And finally, it selected two groups of samples for producing the resonant board of piano, and that the distinction of vibration properties between the first groups and the second groups was obvious in every species.

It analyzed the foundation theory of vibration of piano resonant board, and the frequency equation of free vibration was acquired. The MOE, velocity of longitudinal wave of resonant board on the length direction (MOEx)and the width direction (MOEy) direction were computed on the basis of the frequency equaion and longitudinal wave transmittal equation. And the results were: the MOEX, MOEy, Vlx, VLy of the first resonant board are larger than the second in every species; for all resonant boards, the larger.

The objective selection method of wood used for piano soundboard is the comprehensive vibration properties of wood used for piano soundboard were computed by comprehensive coordinate method and comprehensive marking method, and the indexes include not only wood radial but also wood longitudinal vibration properties.

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