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## Relationships between longitudinal and radial *Picea genera* sound vibration parameters

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**Abstract** Longitudinal sawn wood are usually selected as samples in the study of sound properties of a musical instrument board. But in real production, radial sawn timber are cut and are also widely used as vibration component. Therefore, it is very important to evaluate the vibration properties of the board in the round, especially for the sound radiation characteristic of radial sawn timber and its relationship to longitudinal sawn timber. However, for the national and international experts, researches on radial sawn timber and its role and function in sound emission have not yet been developed. This paper describes a study of seven important spruces that grow up in the Sichuan and Heilongjiang provinces of China, and one *Picea sitchensis* specimen from North America. Under the high bending vibration mode, resonance frequency and other parameters of longitudinal and radial wood were tested. Analysis result disclosed the relationship between longitudinal and radial wood vibration property. An important conclusion of wood for musical instruments with proper anisotropy, fine toughness, and weak shear of longitudinal and radial vibration was inducted.

**Keywords** *Picea genera* wood, longitudinal, radial, vibration property, relationship

### 1 Introduction

Like other elastic materials, wood has the property to be stimulated to radiate a vibration wave by tapping it or applying a circle force. This is the origin of its sound. As we

know, wood is an important material for use as the resonance board in musical instruments. The quality of the instrument is not only dependent on the processing technique of the craftsman, but also depend on the sound characteristic of the selected material (Zhang, 1990a, 1990b, 1991a, 1991b; Li, 1994). Therefore, it is of great significance to develop a study on the vibration property of wood to improve the manufacturer's skill and the quality of the musical instrument. In the common efforts of international and domestic scholars on this field, many parameters and testing methods have been evaluated and analyzed to describe the vibration properties. These efforts provide a scientific basis to judge these properties objectively (Shen and Liu, 2001; Shen et al., 2001; Shen, 2003).

As an anisotropic material, wood has obvious directions and orders in cell shape, cell alignment, and micro-fiber arrangement in the  $S_2$  layer of the secondary cell wall. The physical mechanics would be different in longitudinal and in radial (Liu, 1984) sawn wood. Evaluating the properties combining the two directions was considered. Usually, the longitudinal wood specimen is selected to study vibration property. It was found that wood with a high specific dynamic *MOE*, sound radiation coefficient, and lower loss tangent has good vibration property (Norimoto, 1982; Ono and Norimoto, 1983; Norimoto et al., 1986). In real production, however, radial sawn timber is cut and also widely used as vibration component. Therefore, it is very important to evaluate the vibration properties of the board in the round, especially for the sound radiation characteristics of radial sawn timber and its relationship to longitudinal sawn timber.

However, for the national and international experts, researches on radial sawn timber on its role and function in sound emission have not yet been developed. This experiment will study seven important spruces that grow up in the Sichuan and Heilongjiang provinces of China, and one *Picea sitchensis* specimen from North America. Under the high bending vibration mode, resonance frequency and other parameters of longitudinal and radial wood were tested. Analysis result will disclose the relationship between

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longitudinal and radial wood vibration properties.

## 2 Materials and methods

### 2.1 Materials

Most of the spruce specimens were harvested from Sichuan and Heilongjiang provinces in China. No.31 Sitka spruce, which was sampled by Tokyo University in Japan, was used as control (See Table 1).

**Table 1** Spruce collection list

No.	Wood Species	Diameter /cm	Harvest Place
1	<i>Picea complanata</i>	66	Meigu County, Sichuan
2	<i>Picea complanata</i>	50	Meigu County, Sichuan
3	<i>Picea balfouriana</i>	62	Luhuo County, Sichuan
4	<i>Picea balfouriana</i>	62	Luhuo County, Sichuan
5	<i>Picea asperata</i>	54	Maerkang County, Sichuan
6	<i>Picea purpurea</i>	80	Maerkang County, Sichuan
10	<i>Picea likiangensis</i>	54	Muxiang County, Sichuan
11	<i>Picea likiangensis</i>	62	Muxiang County, Sichuan
14	<i>Picea purpurea</i>	54	Maerkang County, Sichuan
21	<i>Picea jezoensis</i> var. <i>komarovii</i>	35	Dailing, Heilongjiang
22	<i>Picea koraiensis</i>	40	Dailing, Heilongjiang
31	<i>Picea sitchensis</i>	>80	Canada

After air seasoning the samples to equilibrium moisture content for three months, they were sawn separately in the heartwood and sapwood. The basic dimension of each specimen was 300 mm (longitudinal section) × 30 mm (radial section) × 10 mm (tangential section) and 300 mm (radial section) × 30 mm (longitudinal section) × 10 mm (tangential section). All sample surfaces were planed smoothly after air conditioning. Then they were equilibrated to MC 12% at 20°C temperature, and 65% relative humidity.

### 2.2 Experiment method and parameters' calculation of the vibration property

First, the sample was hung horizontally on the 1st wave node by an elastic thread. Then, it was hit on the middle or the end by a small wooden hammer. The receiver, a highly sensitive, wide range and low noise microphone, was placed under the specimen. After the signal was received going through the preamplifier, filter and FFT analyzer in order, it was collected by an A/D converter. Finally, the discrete wave signal data of vibration was transferred into a computer. Using computer software to process the data, the resonance frequency of the first, the second and even high vibration mode was presented. Based on these data, precise dynamic *MOE* ignoring shear and rotor inertia was calculated. The principle and the method of the software computation are described as follows:

a. 32,000 equal interval data that were collected by the FFT analyzer each time were of the free attenuation type.

Interval was auto adjusted by resonance frequency and the number of wave analysis. Numerical value of the peak in each wave was determined by the computer. Peaks were  $P_1, P_2, \dots, P_j, P_{j+1}, \dots, P_n$ . Their sequence were  $x_1, x_2, \dots, x_j, x_{j+1}, \dots, x_n$ .

b. Dynamic *MOE* of the corresponding specimen can be calculated by the resonance frequency ( $f_i$ ) using the formula below.

$$f_i = 1/T = 1/\{[(X_n - x_1)/(n-1)] \times B\} = (n-1)/[B \times (X_n - x_1)] \quad (1)$$

where  $T$  is each cycle of vibration and  $B$  is data collected interval ( $\mu$ s).

$$E_i = (48 \times \pi^2 \times \rho \times L^4 \times f^2)/(m^4 \times T^2) \quad (2)$$

where  $\rho$  is the density,  $L$  is the length,  $T$  is the thickness, and  $m$  is the coefficient of the corresponding vibration mode.

c. Calculation of the coefficient of logarithm attenuation  $\delta$ , loss tangent  $\tan \delta$

The coefficient of logarithm attenuation  $\delta$  is usually calculated based on the amplitude  $A$  by formula (3).

$$\delta = \ln(A_1/A_2) = \ln(A_2/A_3) = \dots = \ln(A_i/A_{i+n}) / n \quad (3)$$

But in this paper, another accurate method was used.  $\{0, 1, \dots, n-1\}$  was considered as an independent variable group. Dependent variable group  $\{\ln(A_1/A_2), \ln(A_2/A_3), \dots, \ln(A_1/A_n)\}$  was used for regression analysis. The slope of the regression formula was read as the coefficient of logarithm attenuation  $\delta$ . Then the loss tangent  $\tan \delta$  was calculated by formula (4).

$$\tan \delta = \delta / \pi \quad (4)$$

d. Using the dynamic *MOE* calculated under different vibration mode, data were further processed by the software edited with reference to the Timoshenko bend-vibration theory and Goens, Hearmon calculation method. Dynamic *MOE* and shear modulus  $G$  were figured out eliminating the flexibility error caused by shear stress and moment of inertia.

e. Other vibration properties, such as specific dynamic *MOE* ( $E/\rho$ ), coefficient of sound radiation  $R(\sqrt{E/\rho^3})$  and  $E/G$  can be deduced using dynamic *MOE*,  $\tan \delta$  and  $\rho$  obtained from step a to b.

## 3 Results and discussion

### 3.1 Comparison of the longitudinal and radial vibration parameters of the specimen

Based on the vibration theory, the shear modulus of a material is small to reduce the shear effect in high frequency, while the dynamic *MOE*, which impact the toughness and vibration ability, is preferably high (Sobue, 1986). The loss tangent is another index that describes the internal friction,

which can represent the vibration efficiency (Liu, 1998). The data of the test were analyzed according to the above explanation. The ratio of the dynamic *MOE* to shear modulus and the ratio of the energy consumption in longitudinal to radial were adopted to describe the anisotropy of the vibration. The variety of the property for eight species in these two directions is shown from Fig. 1 to Fig. 5. Performance of the test materials was compared visibly.

From Fig. 1, the specific value of *P. var. complanata*, *P. likiangensis*, *P. purpurea* and *P. sitchensis* are more than 20. It is proved that the toughness of these species is better;

shear does not have a great influence on them. Among these species,  $E_L/G_{RT}$  performance of *P. jezoensis* is the best, while the *P. var. balfouriana* is the poorest.

In comparison to the longitudinal direction, *P. jezoensis* was the most seriously affected by shear in the radial direction, while *P. koraiensis* Nakai was the least affected. Corresponding to  $E_L/E_R$ , high anisotropy was shown on different species especially to dynamic *MOE* of the *P. jezoensis*, while that of the *P. var. balfouriana*, *P. purpurea* Mast. were poorer than others. From  $\tan\delta_L/\tan\delta_R$ , internal friction in radial direction was generally higher than that in the longitudinal

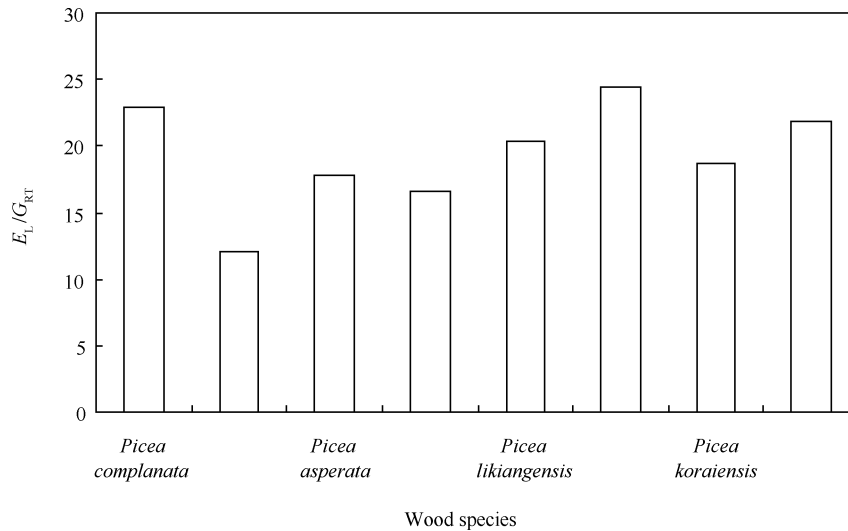


Fig. 1 Comparison of  $E_L/G_{RT}$  for different wood species

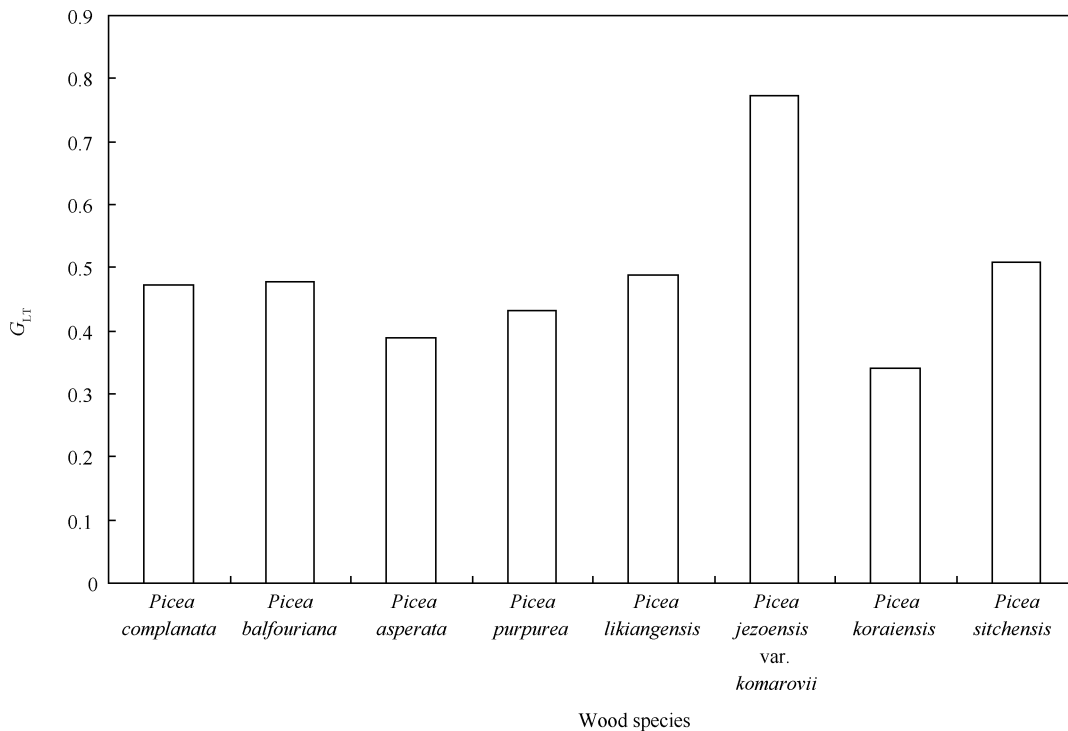
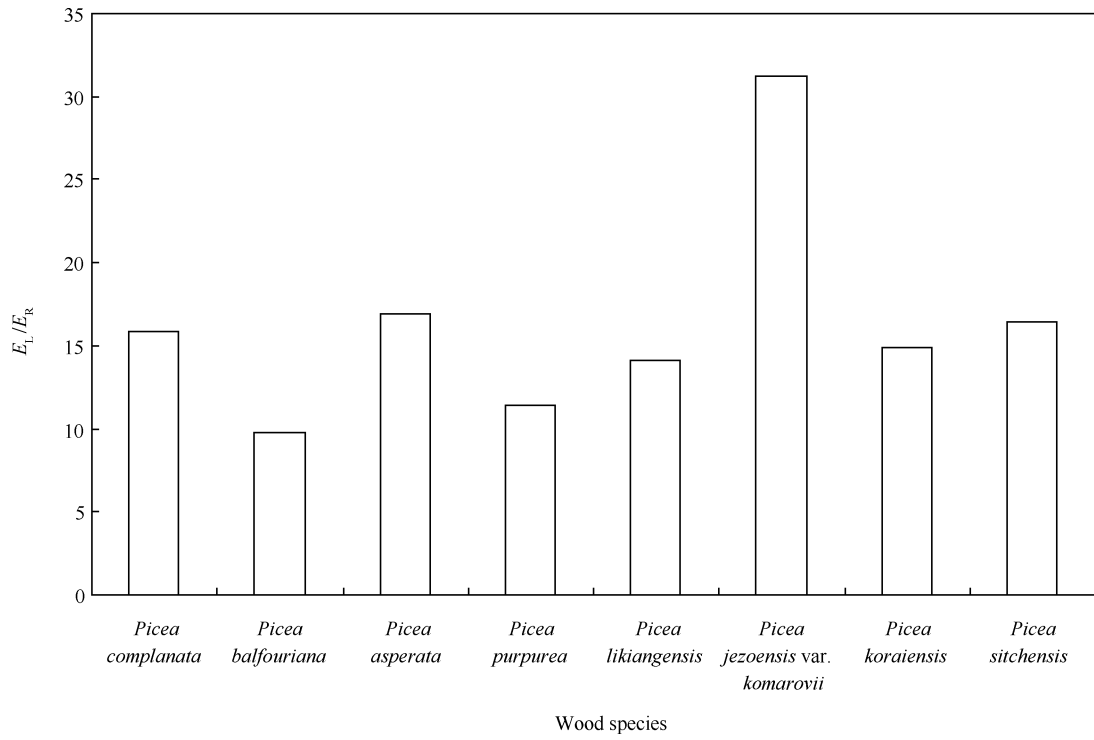
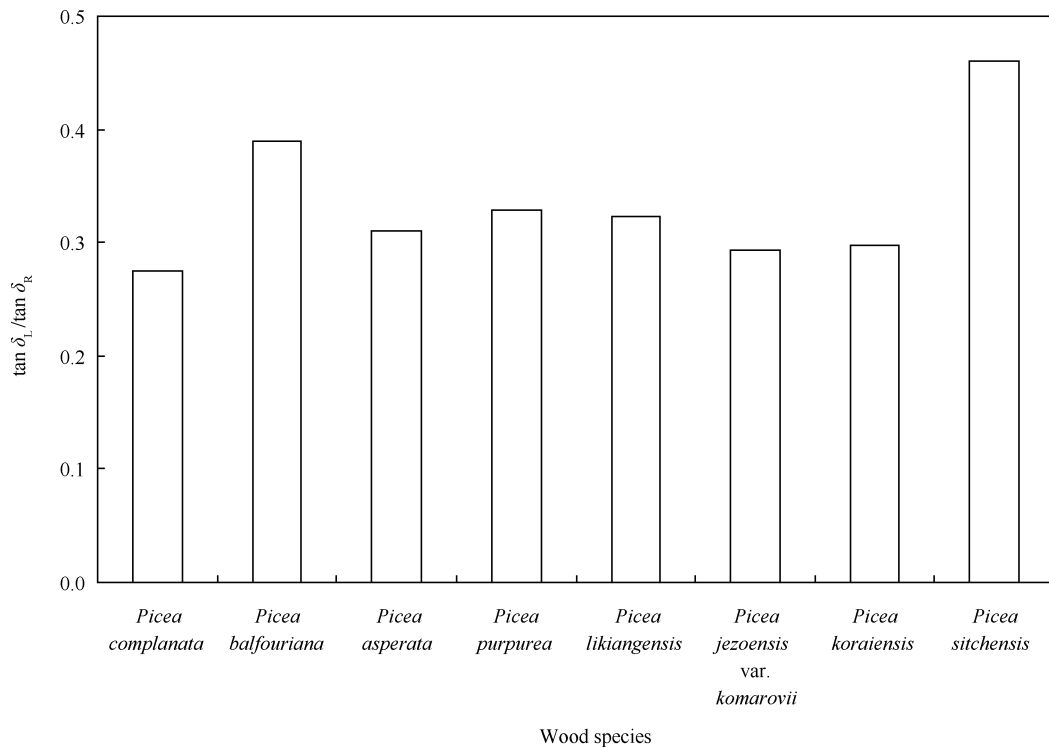


Fig. 2 Comparison of  $G_{LT}$  for different wood species



**Fig. 3** Comparison of  $E_L/E_R$  for different wood species



**Fig. 4** Comparison of  $\tan \delta_L / \tan \delta_R$  for different wood species

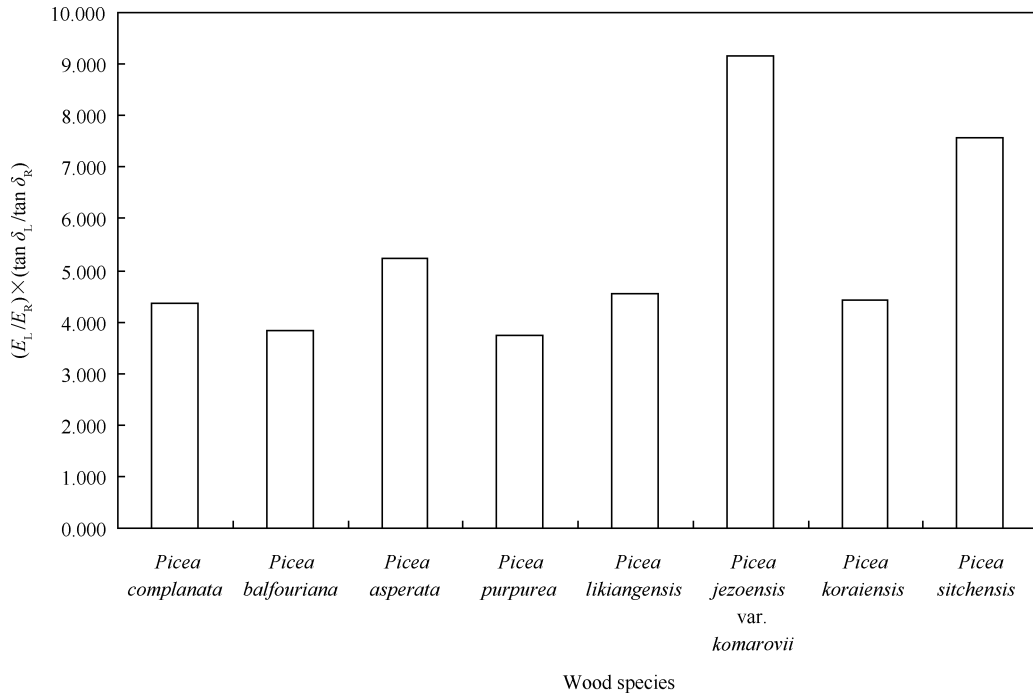


Fig. 5 Comparison of  $(E_L/E_R) \times (\tan \delta_L / \tan \delta_R)$  for different wood species

direction. It can be explained by wood structure.  $\tan \delta_L / \tan \delta_R$  for *P. sitchensis*, *Picea* var. *balfouriana* was higher than others.

Relationship between species and the  $(E_L/E_R) \times (\tan \delta_L / \tan \delta_R)$  is shown on Fig. 5, which reflects the general character of wood anisotropy from Fig. 1 to Fig. 4. Considered factors of  $E_L/E_R$  and  $\tan \delta_L / \tan \delta_R$ , vibration property of *P. jezoensis* and *P. sitchensis* Carr. was better than others.

### 3.2 Comparison parameters of longitudinal and radial vibration

The ratios of longitudinal to radial property are used as the physical quantity for representing the materials' anisotropy. Potential connection explosion may find a way to further evaluate the sound quality of wood. The correlation coefficient of longitudinal and radial vibration is illustrated in Table 2. Except for the poor correlation coefficient of  $G_{LT}$  to  $\tan \delta_L / \tan \delta_R$ , and  $E_L/G_{RT}$  to  $\tan \delta_L / \tan \delta_R$ , others have strong internal relationships.

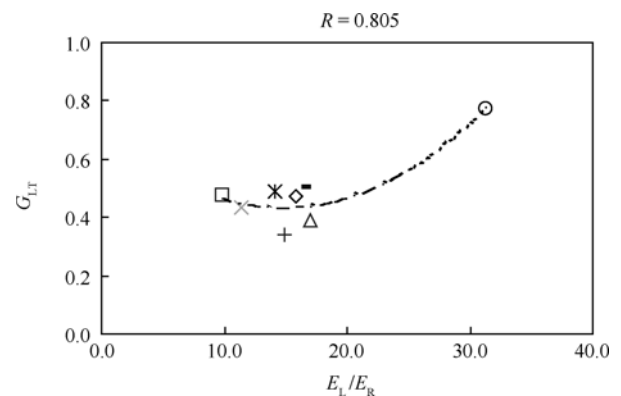
Table 2 Correlative coefficient of vibration parameters between wood longitudinal and radial direction

Comparison of vibration parameters between wood longitudinal and radial direction	$G_{LT}$	$E_L/G_{RT}$
$E_L/E_R$	0.805	0.741
$\tan \delta_L / \tan \delta_R$	0.006	0.256
$(E_L/E_R) \times (\tan \delta_L / \tan \delta_R)$	0.790	0.683

#### 3.2.1 Relationship between $E_L/E_R$ and $G_{LT}$

$E_L/E_R$  is the ratio of the longitudinal dynamic MOE to the radial. As the ratio is increased, the anisotropy of the material is exhibited evidently.  $G_{LT}$  is another property to indicate the shear in radial vibration. According to the vibration theory, a material with low shear modulus will reduce the effect on high frequency. Therefore, the suitable wood material for musical instruments should have proper  $E_L/E_R$  and low  $G_{LT}$ .

From Fig. 6, *P. sitchensis*, *P. complanata*, *P. likiangensis*, *P. asperata* and *P. koraiensis* could meet the requirement. *P. jezoensis* var. *komarovii* had the highest  $E_L/E_R$  and  $G_{LT}$ ,



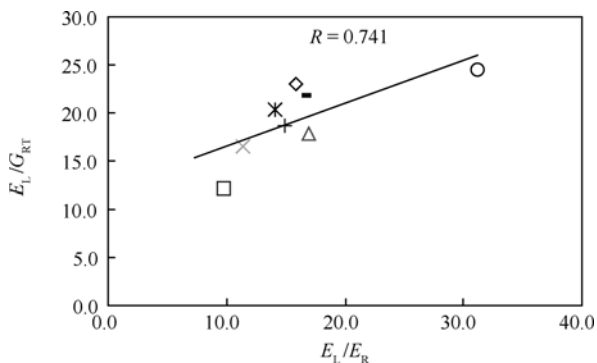
◇ *P. complanata* □ *P. balfouriana* \* *P. likiangensis* × *P. purpurea*  
△ *P. asperata* ○ *P. jezoensis* var. *komarovii* + *P. koraiensis* - *P. sitchensis*

Fig. 6 The relationship between  $E_L/E_R$  and  $G_{LT}$  of different wood species

which meant strong anisotropy would easily cause shear in radial vibration, because they had high variation of annual ring width and latewood percentage in this direction (Mario et al., 1983; Yoshitaka et al., 1997). The anisotropy of *P. balfouriana* and *P. purpurea* was poor. These phenomena were the same as the previous study.

### 3.2.2 Relationship between $E_L/E_R$ and $E_L/G_{RT}$

As  $E_L/E_R$  increases,  $E_L/G_{RT}$  increases linearly with it. They have a high positive regression coefficient. According to the conclusion obtained before, a material with proper anisotropy, better toughness and low shear in longitudinal vibration would have good vibration property, which makes it suitable for making musical instruments. The species above the line on the left (see Fig. 7), including *P. sitchensis*, *P. complanata*, *P. likiangensis*, *P. koraiensis* and *P. asperata* can meet the requirement.

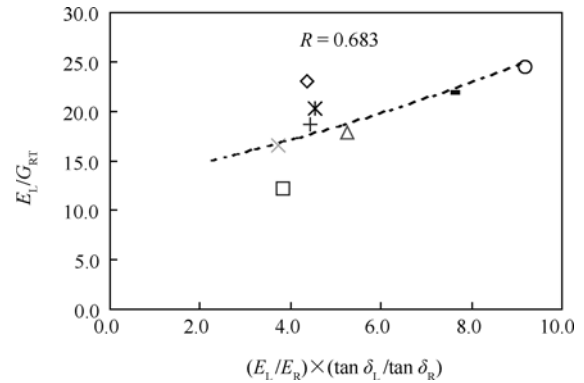


◇ *P. complanata* □ *P. balfouriana* \* *P. likiangensis* × *P. purpurea*  
△ *P. asperata* ○ *P. jezoensis* var. *komarovii* + *P. koraiensis* - *P. sitchensis*

**Fig. 7** The relationship between  $E_L/E_R$  and  $E_L/G_{RT}$  of different wood species

### 3.2.3 Relationship between $(E_L/E_R) \times (\tan \delta_L / \tan \delta_R)$ and $E_L/G_{LT}$

As an important property,  $\tan \delta/E$  is usually used to describe the energy loss in every cycle of vibration (Liu et al., 2001). As it increases, the energy loss in one cycle is broadened, which is adverse to sound radiation. In this test, the synthetic property  $(E_L/E_R) \times (\tan \delta_L / \tan \delta_R)$  was used to reflect the characteristics of wood anisotropy. In Fig. 8, the positive regression relationship, which had a high coefficient, between  $(E_L/E_R) \times (\tan \delta_L / \tan \delta_R)$  and  $E_L/G_{RT}$  is shown. The species with proper anisotropy in the middle of the line, i.e., *P. sitchensis*, *P. likiangensis*, *P. complanata*, *P. koraiensis*, *P. asperata* are suitable for use in musical instruments, since they incurred a weak shear in longitudinal vibration.



◇ *P. complanata* □ *P. balfouriana* \* *P. likiangensis* × *P. purpurea*  
△ *P. asperata* ○ *P. jezoensis* var. *komarovii* + *P. koraiensis* - *P. sitchensis*

**Fig. 8** The relationship between  $(E_L/E_R) \times (\tan \delta_L / \tan \delta_R)$  and  $E_L/G_{RT}$  of different wood species

## 4 Conclusions

1. Among the tested species, *P. jezoensis* var. *komarovii*, *P. complanata*, *P. likiangensis*, *P. sitchensis* were less affected by shear in longitudinal vibration. These materials also had good toughness, while *P. balfouriana* was seriously affected by the shear.

In the radial direction, *P. jezoensis* var. *komarovii* was affected by the shear, while *P. koraiensis* was not. Of the species, the dynamic MOE of *P. jezoensis* var. *komarovii* illustrated a strong anisotropy, while *P. balfouriana*, *P. purpurea* did not show this. Generally, *P. jezoensis* var. *komarovii* and *P. sitchensis* are considered as having better vibration qualities in radial direction than others.

2. In contrast to  $G_{LT}$  and  $\tan \delta_L / \tan \delta_R$ ,  $E_L/G_{RT}$  and  $\tan \delta_L / \tan \delta_R$  had a loose correlation. The other correlations between longitudinal and radial property were tight. The regression coefficients were more than 0.68.

3. Based on the correlation of longitudinal and radial vibration property, samples with proper anisotropy, good toughness, and low shear modulus are suitable for use in musical instruments, i.e., *P. sitchensis*, *P. complanata*, *P. likiangensis*.

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