Effect of Environmental Humidity on the Acoustic Vibration Characteristics of Bamboo

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Abstract: Bamboo musical instruments, such as bamboo flute and Ching-hu (Beijing opera fiddle), can generate a crisp and melodious sound closely related to the delicate multiscale pore structure of bamboo. Bamboo is a natural hydrophilic material, and its acoustic vibration characteristics are highly sensitive to changeable environmental humidity levels. Herein, we investigated the acoustic vibration characteristics of bamboo under three conditions: constant relative humidity (status I), changeable relative humidity (status II), and subjected to water extraction (status III). Three typical parameters were selected as evaluation indicators of bamboo acoustic vibration characteristics, namely, specific dynamic elastic modulus \( E'/\rho \), loss tangent \( \tan\delta \), and acoustical converting efficiency (ACE). The outer bamboos (OB) had higher \( E'/\rho \) and ACE but lower equilibrium moisture content (EMC) and \( \tan\delta \) than the inner bamboos (IB). Under status I, bamboo showed the maximum \( E'/\rho \) and ACE and the minimum \( \tan\delta \) at 35% RH (relative humidity) and about 6% MC. Compared with the bamboo under status II, the bamboo under status I retained higher \( E'/\rho \) and ACE and lower \( \tan\delta \). However, the bamboo under status (III) reached the maximum \( E'/\rho \) and ACE and the minimum \( \tan\delta \). The bamboo musical instrument is made of bamboo with proper removal of water-soluble extractives and high fiber volume fraction and stored in a stable relative humidity environment of 35%, which has suitable acoustic vibration characteristics.

Keywords: bamboo; acoustic vibration characteristics; humidity; specific dynamic elastic modulus \( E'/\rho \); loss tangent \( \tan\delta \)

1. Introduction

Bamboo is an excellent material for natural musical instruments due to its special fiber cell arrangement, porous structure, and chemical composition distribution. A large range of natural materials, in addition to bamboo, have traditionally been used for musical instruments. For example, wood is also the preferred material for a variety of applications ranging from musical instruments to construction. Bamboo and wood are especially suitable for musical instruments applications because they have many common characteristics, such as similar cellular and chemical composition, orthogonal anisotropy, and easy processing. However, there are also some differences. Bamboo culm is generally a hollow structure with transverse diaphragms at regular intervals, positioned at the nodes, separating the culm into the internodes. In addition, bamboo has no growth rings and transverse ray tissue similar to wood [1,2]. The microstructure of bamboo and wood is closely related to its acoustic vibration characteristics. For example, too many rays in wood have a negative effect on its acoustic quality, and the smaller the microfiber angle, the greater the crystallinity and the greater the anisotropy of bamboo and wood, the better the acoustic vibration characteristics [3–5].
Another common feature that is peculiar to bamboo and wood and germane to their use in musical instruments is that they are also highly sensitive to moisture change; almost all its physical and mechanical properties are affected by its moisture content (MC), particularly below the fiber saturation point. Increasing MC can weaken the mechanical properties of bamboo [6–9]. Significantly changeable environmental humidity can induce changes in the acoustic vibration characteristics of bamboo musical instruments, such as vibration efficiency, tone color, and sound stability. Therefore, the influence law of environmentally relative humidity (RH) on the acoustic vibration characteristics of bamboo, as well as the mechanism involved, need to be explored to promote the green and sustainable development of the bamboo musical instrument industry and the organic combination of material science and culture and art.

The water in bamboo can be categorized into three types: (1) free water existing in the cell cavity and interstitial space, (2) absorbed water between the microfibrils of the cell wall, and (3) chemical water. The absorbed water exerts the strongest effect on the acoustic vibration performance of bamboo. The water in the environment can dynamically change from a monolayer to a multilayer with multiple adsorption sites on the bamboo cell wall by hydrophilic groups (such as hydroxyl and carboxyl groups) and capillary action, macroscopically exhibiting a dynamic change in MC with an altered external environmental RH, which is the moisture absorption and desorption [10,11]. These moisture absorption and desorption behaviors exert important effects on the performance and service life of bamboo musical instruments. When the relative humidity of the use and storage environment changes, the bamboo musical instrument tends to become deformed or cracks because of shrinkage and swelling.

The moisture absorption and desorption behaviors of bamboo are mainly affected by its morphology (cell type, arrangement and distribution mode, and pore structure) and chemical composition [12–15]. The morphological structure and chemical composition of bamboo cells vary depending on the type, age, and position of bamboo (such as the inner or outer bamboos, root, or tip) [16–19]. All cells in bamboo are strictly aligned in a longitudinal direction, and there is no transverse cell tissue. Parenchyma cells and vascular bundles were the main components of bamboo, and vascular bundles consisted of vessel and fiber cells that surrounded vessels. Parenchyma cells (50%) and fibers (40%) account for most of the cell composition of bamboo, and the number of fibers increases from the inner to the outer layer along the thickness of the culm wall. The parenchyma cell wall consists of an ultramicroscopic wall structure with a typical loose–tight layer change; it is a complex cross-linked structure composed of cellulose, lignin, and hemicellulose. The fiber cell wall is composed of a multilayer composite structure with alternating wide and narrow layers from several to dozens of layers; it is mainly composed of rigid skeleton-functional cellulose microfibrils, amorphous hemicellulose penetrating between the skeleton materials, and the cross-linked lignin filled in the cellulose frame [20,21]. Among the aforementioned chemical components, hemicellulose exhibits the highest hygroscopicity, followed by cellulose (mainly amorphous region of cellulose) and then lignin. Compared with fibers, parenchyma cells have less crystalline cellulose (not hygroscopic) and more hemicellulose. Thus, the inner layer of bamboo exhibits higher hygroscopicity compared with the outer layer of bamboo due to its high concentration of parenchyma cells and low concentration of crystalline cellulose. Parenchyma cells typically contain starch and large cavities, whereas fibers have a thick wall and small cavities. Differences in the morphology and chemical composition of bamboo fibers and parenchyma cells cause differences in moisture absorption response. This study aimed to determine the acoustic vibration characteristics of bamboo under different relative humidity levels by applying the resonance method. The microstructure and chemical composition of bamboo were investigated by combining scanning electron microscopy (SEM), X-ray microtomography (μ-CT), X-ray diffraction (XRD), and other techniques, revealing the response law of the acoustic vibration behavior of the bamboo gradient structure to humidity.
2. Material and Methods

2.1. Materials

*Moso* bamboo aged 4 years was harvested in Hongtian Town, Yong’an City, Fujian Province. The bamboo culm was cut from 1.8 to 3 m above the ground (bottom of bamboo) and divided into 2 pieces (120 mm L × 1.5 mm R × 10 mm T) from the inner (IB) and outer (OB) layer along the thickness of culm after removing the innermost and outermost layers. A total of 25 IB and OB samples were obtained, respectively (Figure 1).

![Figure 1](image-url)

**Figure 1.** Samples preparation for bamboo properties test and characterization under different statuses. (a) Schematic of the standard sample preparation; (b) relative humidity treatment under three conditions; (c) device for testing the acoustic vibration characteristic via the resonance method; (d) field emission scanning electron microscopy observation, determination of fiber volume fraction, and porosity analysis by μ-CT.

2.1.1. Adjusting for Constant Relative Humidity (Status I)

The equilibrium moisture content (EMC) under constant relative humidity (RH) was used to evaluate the moisture absorption of bamboo samples. The air-dried bamboo samples were divided into 4 groups with 5 replicates. One group consisted of bamboo samples in the absolutely dried state, which were oven-dried at 103 °C for more than 24 h. The samples were then weighed every 2 h until the weight change was within 0.002 g. The samples in the other three groups were placed in a constant-temperature-and-humidity chamber with RH levels set to 35%, 65%, and 85%; the temperature (T) was set to 20 °C for more than 2 weeks until weight change was within 0.002 g (Figure 1b). The MC was then calculated, and the acoustic vibration performance was evaluated.

2.1.2. Adjusting for Changeable Relative Humidity (Status II)

A total of 5 OB samples and 5 IB samples were oven-dried to a moisture content of approximately 0% before placing in a humidity chamber at different RH levels of 35%, 65%, and 85% for multistep moisture absorption. The samples were weighed, and their acoustic vibration performances were evaluated at specific time points (3, 7, 14, 20, 25, and 30 h) and in the final equilibrium state during RH adjustment.
2.1.3. Water Extraction (Status III)

The air-dried samples (5 each of the OB and IB samples) were immersed in 18 °C distilled water at room temperature until weight change was within 0.002 g. The samples were placed in a humidity chamber with different RH levels (35%, 65%, and 85%) until the weight change was within 0.002 g. The samples were weighed, and their acoustic vibration performance at specific time points (that is, 3, 7, 14, 20, 25, and 30 h) and in the final equilibrium state were evaluated during RH adjustment.

2.2. Characterization

2.2.1. Acoustic Vibration Characteristics

The vibration performances of the IB and OB samples were measured using the single-cantilever method at 23 °C and 65% RH. The equipment used was manufactured by Beijing East Institute of Noise and Vibration Technology with a 10 mv/μm eddy current displacement sensor and the unit set as μm. During the test, one end of the sample was fixed, whereas the other end was pasted with a conductive aluminum foil; the free end was excited manually to generate free damping vibration. The vibration signal was detected and collected by the eddy current displacement sensor close to the sample. The software DASP was used to capture signals for further analysis. Time-domain signals were transformed into frequency-domain signals by Fourier transform spectroscopy (Figure 2) for data analysis and processing.

Figure 2. Schematic of Fourier transform with the time-domain signal to the frequency-domain signal and the principle of the half-power bandwidth method. (a) Time-domain spectrum; (b) frequency-domain spectrum; (c) Fourier transform; (d) half-power bandwidth method.

Specific dynamic elastic modulus ($E'/\rho$) and loss tangent ($\tan\delta$) are representative indicators of acoustic vibration characteristics, and acoustical converting efficiency (ACE) is a parameter for the overall estimation of acoustic characteristics. The half-power bandwidth method is used to determine the first-order natural frequency ($f$) and loss tangent ($\tan\delta$) of the sample. The natural frequency is used to calculate the dynamic elastic modulus ($E'/\rho$) and the ACE (Figure 2). Generally, high $E'/\rho$ and ACE and low $\tan\delta$ indicate high vibration efficiency, a small vibration energy loss, and excellent acoustic vibration characteristics [22,23]. The dynamic modulus of elasticity is calculated using Equation (1):
\[ E' = \frac{48\pi^2 M f^2 l^4}{1.875^4 L b t^3} \]  

where \( M \) is the weight of the sample (kg), \( L \) is the length (m), \( b \) is the width (m), \( t \) is the thickness (m), \( f \) is the measured natural frequency of the sample (Hz), and \( l \) is the length of the free part of the cantilever (m).

\( E'/\rho \) represents the average dynamic elastic modulus of the cell wall of the bamboo or wood along the grain. The larger the \( E'/\rho \), the higher the vibration efficiency of the material. \( E' \) is the dynamic modulus of elasticity (GPa), and \( \rho \) is the density (g/cm³).

\( \tan\delta \) represents the ratio of heat loss energy to the energy stored in the medium in each vibration cycle. The lower the \( \tan\delta \), the higher the vibration efficiency, the slower the attenuation speed, and the fuller the sound.

\( ACE \) (m⁴/kg) characterizes the efficiency of converting vibration energy into sound energy. The larger the \( ACE \), the better the overall acoustic vibration characteristics of bamboo. \( ACE \) is calculated using Equation (2):

\[ ACE = \frac{R}{\tan\delta} = \frac{\sqrt{E'/\rho^3}}{\tan\delta} \]  

\( R \) is the sound radiation quality constant (m⁴/kg/s), which represents the ability to radiate sound power to the surrounding air.

2.2.2. Determination of Fiber Volume Fraction

The vascular bundle embedded in the parenchyma cells was assumed to be straight and complete. The fiber area was calculated using an optical microscope (INF INFINITY3-6URC) to obtain a clear cross-sectional image of the sample, combined with the Image Pro Plus 6.0 graphics processing software (Media Cybernetics, Silver Spring, MD, United States). The fiber volume fraction of each bamboo piece was calculated using Equation (3):

\[ V_f = \frac{S_f \cdot 100}{S} \]  

\( V_f \) is the fiber volume fraction of each bamboo piece (%), \( S_f \) is the fiber area, \( S \) is the total area of the cross-section observed.

2.2.3. X-ray Micro-CT

High-resolution X-ray μ-CT (Nano Voxel-3000, Sanying Precision Instrument Co., Ltd, Tianjin, China) was conducted under the following conditions: voltage, 60 kV; current, 100 μA; pixel matrix, 1920 × 1536; and resolution, 2.4 μm. Each sample measuring 4.0 mm (T) × 4.0 mm (L) × 1.0 mm (R) was scanned for 90 min. The Arigin 3D software (v2.0.0, Arigin Medical, Shanghai, China) was used to calculate the three-dimensional pore structure and the percentage of pores in the samples.

3. Results and Discussion

3.1. Acoustic Vibration Characteristics of Bamboo under Constant Relative Humidity (Status I)

The EMC, \( E'/\rho \), \( \tan\delta \), and \( ACE \) of the samples under constant relative humidity are shown in Figure 3. With RH at 35%, IB and OB showed the highest \( E'/\rho \) (IB = 11.44; OB = 16.47) and \( ACE \) (IB = 165.97; OB = 229.09) and the smallest \( \tan\delta \) (IB = 0.033; OB = 0.027); meanwhile, a rebound trend was observed as MC increased. OB showed higher values of \( E'/\rho \) and \( ACE \) than did IB, but lower \( \tan\delta \).
The adsorption site is related to the content of hygroscopic chemical components. The main hygroscopic chemical components in bamboo include cellulose, hemicellulose, and lignin. Hemicellulose is generally considered more hygroscopic than cellulose and lignin because of the high contents of hydrophilic groups in it (-OH, C=O). Many studies have been conducted on the chemical compositions related to hygroscopicity for bamboo. Compared with the inner bamboo layer, the outer bamboo layer contains more cellulose and lignin and less hemicellulose [24,25]. Variations in the chemical components between IB and OB lead to their differences in hygroscopicity.

The MC and capacity of bamboo are not only related to the number of absorption sites in the noncrystalline regions of cellulose and hemicellulose, but its complex multiscale pore structure also plays a vital role. The multiscale pore structure of bamboo can be classified into three types. Pores (micropores) smaller than 2 nm, which exist between the cellulose molecular chains in the cell wall; slit-like pores (mesopores) in the cell wall, measuring 2–50 nm, mainly formed by lignin and hemicellulose filled with cellulose microfibrils, and tubular pores, more than 50 nm in diameter (large pores, Figure 4), including intercellular pores, cell cavities, and pits [18,26]. When water molecules are adsorbed on the surface of bamboo cell walls, they not only penetrate the capillary pores (macropores) in the cell wall, but they also penetrate into the inner surface of the cell wall (mesopores); moreover, they even penetrate the molecular chains in the cell wall (micropores) [25]. In the current study, in the three states, IB presented a higher EMC than that of OB, which was related to their porosity (Figure 5a–d). OB showed a higher fiber volume fraction (23.5%) than that of IB (12.8%) (Figure 6a). The parenchyma cells with thin walls and large cavities showed greater porosity and internal surface area than those...
of solid bamboo fibers (Figure 6b). Therefore, it is considerable to appropriately reduce the content of more hygroscopic parenchyma cells should appropriately reduce to improve the size and acoustic stability of bamboo musical instruments.

Figure 4. Scanning electron microscopy (SEM) images of the partial pore structure of bamboo.

Figure 5. Three-dimensional (3D) micro-CT images of the inner (IB) and outer (OB) bamboos. Stereogram and the XZ, XY, and YZ cross-sectional views of IB (a) and OB (b); (c) and (d) 3D reconstruction images (yellow) and pore distribution (green) of IB and OB, respectively.
3.2. Acoustic Vibration Characteristics of Bamboo under Changeable Relative Humidity (Status II)

The relationships between the MC-$E'/\rho$ and MC-$\tan\delta$ of the IB and OB moisture absorption with RH ranging from 35% to 85% are depicted in Figure 4. As shown in the figure, in the initial stages of moisture absorption (MC < 3%), the $E'/\rho$ curves exhibit a decreasing trend. However, with an increase in MC (>5%), the curves present a plateau (MC = 3%–5%) following the linear decrease. Meanwhile, $\tan\delta$ exhibits the opposite trend. After the earliest rapid increase, $\tan\delta$ reaches the highest value at 2%–3% MC and then gradually decreases. When $\tan\delta$ reaches its lowest value at 5%–6% MC, it shows a linear increase with an increase in MC (>6%). The MC of IB is higher than that of OB during the aforementioned moisture absorption process, which is consistent with the test result under constant relative humidity.

The $E'/\rho$ and ACE of bamboo under status II for MC adjustment were lower, whereas the $\tan\delta$ values were higher than those of bamboo under status I. The $E'/\rho$ and ACE of bamboo under status II decreased to 1.9%–10.7% and 1.1%–37.7%, respectively, and the $\tan\delta$ values increased to 1.3%–17.2%, relative to those of bamboo under status I (Figure 7).

Under the stable relative humidity and hygroscopic condition, the stable MC of the IB and OB at stable 35% RH were 6.08% and 5.86%, respectively. The samples in this state reached the maximum $E'/\rho$ and ACE and minimum $\tan\delta$, consistent with previous studies. When the MC was about 6.5% (±1.7%), the loss tangent reached the minimum value. It then exhibited an overall linear increase with increasing water content until the MC reached about 20%. The increase in the rate of $\tan\delta$ as the MC increased slowed down. $E'/\rho$ presented the opposite trend; meanwhile, the minimum $\tan\delta$ and the maximum $E'/\rho$ have very close corresponding MC [27–30].
Under the moisture absorption condition of gradually increasing relative humidity, the $E'/\rho$ and $\tan\delta$ of bamboo changed asynchronously with increasing MC, which is consistent with previous studies [31–34]. In the initial state of absolute dryness, the hydroxyl groups on the cellulose molecular chain of the bamboo cell wall formed a tight hydrogen bond, causing the molecular chain to twist and generate drying stress. After being in low relative humidity, the entry of moisture-absorbed water molecules tends to destroy the hydrogen bonding formed between the cellulose molecular chains in the dry state, restoring parts of the hydroxyl groups and absorbing water molecules. This occurrence causes the noncrystalline cellulose and matrix to swell and the cellulose molecules to become stretched and reoriented. Consequently, an instantaneous disturbance of the microfibril angle is generated inner bamboos, which instantaneously increases the internal friction within the internal macromolecular layer, decreasing $E'/\rho$ and increasing $\tan\delta$ [28,30,35,36].

Wei et al. [25] used dynamic water vapor sorption combined with the H-H model (Figure 8) to explore the moisture absorption mechanism of bamboo. The results indicated that the increase in MC (<4%) at low relative humidity levels (RH < 20%) was mainly attributable to the monolayer on the primary active sites (Figure 9a). With an increase in relative humidity (20% < RH < 95%), the multilayer absorbed on secondary sites by hydrogen bonding or van der Waals forces began to dominate the adsorption process, especially when RH > 60% (Figure 9b). At 35% RH, the moisture content of the monolayer was exactly close to the saturation state. The moisture content of bamboo was almost entirely attributable to the multilayer adsorption, with subsequently increasing RH. Under high relative humidity (RH > 95%), water condensation was generated by the capillary system composed of various pore structures in bamboo, resulting in a rapid increase in MC (Figure 9c,d).

![Figure 8](image8.png)

**Figure 8.** Hygroscopic mechanism of bamboo from the H-H model. Equilibrium moisture content (EMC), monolayer (Mo), and multilayer (Mu) adsorption curves at 25 °C as functions of relative humidity (RH). Reprinted from Ref. [25].

![Figure 9](image9.png)

**Figure 9.** Moisture absorption mechanism of the gradient bamboo fiber and multiscale pore structure under different relative humidity levels.
The water absorbed by the amorphous region of cellulose and hemicellulose in microfibril was released due to drying, resulting in the formation of new hydrogen bonds within and between molecules, resulting in the reduction in the distance between them, which results in a distortion of the overall spatial structure of microfibril. This occurrence prompted an increase in the microfibril angle and the porous appearance of the molecular chains, decreasing $E'/\rho$ and increasing $\tan\delta$ (Figure 10a). At 35% HR, bamboo with ~6% MC (IB: 6.08%, OB: 5.86%) reached the saturation state of the monolayered water adsorption and the initial stage of multilayered water adsorption (Figure 10b). The amorphous cellulose molecular chains were completely stretched because of the moisture absorption and swelling of the amorphous cellulose. The pores between the cellulose molecular chains disappeared, and the minimized microfibril angle prompted the cell wall to reach the most stable and strongest state. Therefore, under this special MC state, bamboo exhibited the largest $E'/\rho$ and ACE and the smallest $\tan\delta$. When the MC of bamboo continued to increase (>6%), the excess of the multilayered absorbed water acted as a plasticizer and caused a decrease in cohesion between molecules, as well as an increase in friction and internal friction. These occurrences adversely affected the acoustic vibration characteristics of bamboo (Figure 10c).

![Figure 10. Moisture absorption response model of the bamboo cell wall.](image)

Under a stable MC state, which was attained with a changeable RH adjustment, both $E'/\rho$ and ACE were smaller than that under a constant RH, whereas $\tan\delta$ was larger. This observation is related to the instantaneous effect generated by the instability of bamboo under the changing relative humidity [37]. The relative humidity of the environment decreases (the drying process) or increases (the moisture absorption process), causing instability to instantaneously increase the loss tangent. This increase in amplitude is determined by the differences in relative humidity (before and after the change) and adsorption rate [38,39]. The amplitude is gradually stabilized over time, demonstrating the occurrence referred to as “physical aging” [40,41].

In summary, the instantaneous effect generated by instability under a rapid change in environmental humidity causes the deterioration of the sound quality of bamboo and wood musical instruments, deformation of the instruments, and structural damage [42–
45]. Therefore, bamboo and wood musical instruments should be stored and maintained in an environment with relatively stable humidity as much as possible.

3.3. Acoustic Vibration Characteristics of Bamboo Subjected to Water Extraction (Status III)

The IB and OB after water extraction were adjusted to a stable MC at different 3 RH levels: 35%, 65%, and 85% (the temperature was set to 20 °C). The resultant $E'/\rho$, $\tan\delta$, and ACE values of the samples under three statuses are shown in Figure 11. As shown in the figure, the bamboo subjected to water extraction (status III) for 1 week had the highest $E'/\rho$ and ACE and the lowest $\tan\delta$, among the three types of bamboo samples. The bamboo under status III showed increases of 0.4%–5.6% in $E'/\rho$ and 30.8%–64.5% in ACE and a decrease of 3.1%–19.5% in $\tan\delta$, relative to those of bamboo under status I.

![Figure 11. Acoustic vibration characteristics of bamboo under three statuses.](image)

This finding indicates that the water-soluble extractives in bamboo negatively affect its acoustic vibration characteristics. The extracts in bamboo mainly contain starch (total 2%–6%, including 2% soluble starch), protein (1.5%–6%), and fat (2%–4%), among others
In the current study, soluble starch was the main extract obtained via water extraction, which mostly existed in the parenchyma cell cavities of bamboo (Figure 12a) and had no structural reinforcement for the mechanical properties of cell wall components. Thus, the bamboo treated by water extraction neither significantly changed its volume (Figure 12b) nor reduced its elastic modulus (The extracts of some wood samples formed a structural bond with the cell wall, and the removal of such extracts could weaken its mechanical and acoustic properties [47–50]); however, it showed reductions in weight (Figure 12c) and density (Figure 12d). This process promoted the improvement of certain parameters, such as $E'/\rho$ and ACE, that positively influenced the acoustic vibration characteristics. Meanwhile, with the dissolution of water-soluble starch and sugars in the parenchyma cells of the bamboo, the channels for the transmission of water and sound vibrations in the bamboo were dredged. After drying, the molecular spacing of such bamboo will be reduced compared with that before extract, and the fibril, microfibrils, and microcrystal in the cell wall will be closer to each other due to more complete water loss. Consequently, orientation in the cell wall increased, improving the acoustic vibration efficiency of the bamboo. Reed [51] and bamboo [52], after water extraction, also exhibited a slight increase in $E'/\rho$ and a significant decrease in $\tan\delta$, indicating higher stability in an environment with changeable relative humidity levels. However, excessive removal of water-soluble extractives can reduce the loudness, richness, and softness of the sound produced by a reed instrument. That is probably why Iranian luthiers traditionally soak the soundboard material in warm water for a certain period before the musical instrument is manufactured. Moreover, extracts such as starch and protein in bamboo parenchyma cells also render bamboo vulnerable to insect pests and molds during storage and use, causing damage to the appearance and structure of bamboo musical instruments, which exerts a strong effect on its acoustic performance.

Figure 12. Variations in water-soluble extractives of parenchyma cells ((a) before extraction, (b) after extraction), weight (c) and density (d) of bamboo before (IB and OB) and after (IB’ and OB’) extraction.
Therefore, proper removal of water-soluble extractives in bamboo can simultaneously improve the acoustic vibration characteristics of musical instruments produced from bamboo in response to changes in environmental humidity and the durability of mildew and insect resistance.

4. Conclusions

The instability of humidity has an instantaneous superimposition effect on the acoustic vibration behaviors of bamboo. Compared with constant relative humidity, changeable relative humidity more adversely affected the acoustic vibration characteristics of bamboo. The $E'/\rho$ and ACE of bamboo under changeable relative humidity status were reduced by 1.9%–10.7% and 1.1%–37.7%, respectively, whereas $\tan\delta$ increased by 1.3%–17.2%, relative to those of bamboo under constant relative humidity.

The fiber volume fraction of bamboo, as well as optimum moisture content, has a positive effect on its acoustic vibration performance. The acoustic vibration characteristics of the outer bamboo were better than those of the inner bamboo, which show a higher hemicellulose content, larger number of parenchyma cells, and higher porosity. The inner and outer bamboos reached the maximum $E'/\rho$ values of 11.44 and 16.47 and the maximum ACE values of 165.97 and 229.09, respectively, at 6% MC and 35% RH; meanwhile, the minimum $\tan\delta$ values of the inner bamboos and the outer bamboos were 0.033 and 0.027, respectively. When the cell wall is at 6% MC, it only adsorbed the monolayer water to saturation for bamboo, leading to the maximum orientation of the molecular chain of cellulose.

Water extraction is a simple technique of removing water-soluble extractives, which effectively improves the acoustic vibration characteristics and durability of bamboo. Relative to those of bamboo under changeable relative humidity, the $E'/\rho$ and ACE of bamboo subjected to water extraction increased by 0.4%–5.6% and 30.8%–64.5%, respectively, whereas $\tan\delta$ decreased by 3.12%–19.54%.

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References
1. Wegst, U. Wood for sound. Am. J. Bot. 2006, 93, 1439–1448. https://doi.org/10.3732/ajb.93.10.1439.
2. Wegst, U. Bamboo and wood in musical instruments. Annu. Rev. Mater. Res. 2008, 38, 323–349. https://doi.org/10.1146/annurev.matsci.38.060407.132459.
3. Obataya, E.; Ono, T.; Norimoto, M. Vibrational properties of wood along the grain. J. Mater. Sci. 2000, 35, 2993–3001.
4. Brancheriau, L.; Baillères, H.; Détienne, P.; Gril, J.; Kronland, R. Key signal and wood anatomy parameters related to the acoustic quality of wood for xylophone-type percussion instruments. J. Wood Sci. 2006, 52, 270–273. https://doi.org/10.1007/s10086-005-0755-2.
5. Shen, J. Study on relationships between Picea Species structures and Vibration properties. Ph.D. Thesis, Northeast Forestry University, Harbin, China, 2001.
6. Jiang, Z.; Wang, G.; Tian, G.; Liu, X.; Yu, Y. Sensitivity of several selected mechanical properties of Moso bamboo to moisture content change under the fiber saturation point. BioResources 2012, 7, 5048–5058.
7. Wakchaure, M.R.; Kute, S.Y. Effect of moisture content on physical and mechanical properties of bamboo. *Asian J. Civ. Eng.* 2012, 13, 753–763.
8. Wang, H.; Wang, H.; Li, W.; Ren, D.; Yu, Y. Effects of Moisture Content on the Mechanical Properties of Moso Bamboo at the Macroscopic and Cellular Levels. *BioResources* 2013, 8, 5475–5484. https://doi.org/10.15376/biores.8.4.5475-5484.
9. Low, I.M.; Che Latella, B.A. Mapping the structure, composition and mechanical properties of bamboo. *J. Mater.* 2006, 28, 1969–1976. https://doi.org/10.1007/s10557-006-0238.
10. Zhang, X.; Zhang, J.; Yu, Y.; Wang, H. Investigating the water vapor sorption behavior of bamboo with two sorption models. *J. Mater. Sci.* 2018, 53, 8241–8249. https://doi.org/10.1007/s10853-018-2166-y.
11. Liese, W. Research on bamboo. *Wood Sci. Technol.* 1987, 21, 189–209. https://doi.org/10.1007/BF00351391.
12. Chen, G.; Wu, Y. Lignocellulosic Chemistry; China Light Industry Press: Beijing, China, 1980.
13. Silva, E.; Walters, M.C.; Paulino, G.H. Modeling bamboo as a functionally graded material: Lessons for the analysis of affordable materials. *J. Mater. Sci.* 2006, 41, 6991–7004. https://doi.org/10.1007/s10853-006-0232-3.
14. Habibi, M.K.; Samaei, A.T.; Gheshlaghi, B.; Lu, J.; Lu, Y. Asymmetric flexural behavior from bamboo’s functionally graded hierarchical structure: Underlying mechanisms. *Acta Biomater.* 2015, 16, 178–186. https://doi.org/10.1016/j.actbio.2015.01.038.
15. Lin, Q.; Huang, Y.; Yu, W. An in-depth study of molecular and supramolecular structures of bamboo cellulose upon heat treatment. *Carbohydr. Polym.* 2020, 241, 116412. https://doi.org/10.1016/j.carbpol.2020.116412.
16. Monteiro, S.; Margem, F.; Braga, F.; Luz, F.; Simonassi, T. Weibull analysis of the tensile strength dependence with fiber diameter of giant bamboo. *J. Mater. Res. Technol.* 2017, 6, 17–22. https://doi.org/10.1007/s40281-017-0339-z.
17. Choudhury, D.; Sahu, J.K.; Sharma, G.D. Moisture sorption isotherms, heat of sorption and properties of sorbed water of raw bamboo (*Dendrocalamus longispathus*) shoots. *Ind. Crops Prod.* 2011, 33, 211–216. https://doi.org/10.1016/j.indcrop.2010.10.014.
18. Zhang, S.; Liu, R.; Lian, C.; Luo, J.; Fei, B. Intercellular pathways in internodal metaxylem vessels of moso bamboo (*Phyllostachys edulis*). *IAWA J.* 2019, 40, 1–13. https://doi.org/10.1163/22941932-40190237.
19. Liu, Y.; Zhao, G. Wood-Based Materials Science; China Forestry Publishing House: Beijing, China, 2004.
20. Chen, G.; Luo, H.; Yang, H.; Zhang, T.; Li, S. Water effects on the deformation and fracture behaviors of the multi-scaled cellular fibrous bamboo. *Acta Biomater.* 2018, 65, 203–215. https://doi.org/10.1016/j.actbio.2017.10.005.
21. Obataya, E. Effects of natural and artificial ageing on the physical and acoustic properties of wood in musical instruments. *J. Cult. Herit.* 2016, 27, S63–S69, https://doi.org/10.1016/j.jculher.2016.02.011.
22. Liu, Z. Vibrational Characteristics of Wood for Resonance Board and Acoustic Quality of National Instruments; China Science Publishing & Media: Beijing, China, 2016.
23. Farvardin, F.; Roohnia, M.; Lashgari, A. The effect of extractives on acoustical properties of Persian silk wood (*Albizia julibrissin*). *Maderas Cienc. Tecnol.* 2015, 17, 749–758. https://doi.org/10.4006/S0022-193X20150000065.
24. Chen, X.; Deng, L.; Wei, X.; Li, M.; Wang, G.; Chen, F. Measuring the damping performance of gradient-structured bamboo using the resonance method. *Forests* 2021, 12, 1654. https://doi.org/10.3390/f12121654.
25. Wei, X.; Wang, G.; Smith, L.M.; Jiang, H. The hygroscopicity of moso bamboo (*Phyllostachys edulis*) with a gradient fiber structure. *J. Materials Res. Technol.* 2021, 15, 439–436. https://doi.org/10.1016/j.jmrt.2021.10.038.
26. Papadopoulos, A.; Hill, C.A.S. The sorption of water vapour by anhydride modified softwood. *Wood Sci. Technol.* 2003, 37, 221–31. https://doi.org/10.1007/s00226-003-0192-6.
27. Kollmann, F.; Krech, H. Dynamic measurement of damping capacity and elastic properties of wood. *Eur. J. Wood Prod.* 1960, 18, 41–54. https://doi.org/10.1007/BF02615616.
28. Suzuki, M. The effects of water-sorption and temperature on dynamic Young’s modulus and logarithmic decrement of wood. *Mokuzai Gakkaishi* 1962, 8, 13–18.
29. Fukada, E. The vibrational properties of wood. II. *J. Phys. Soc. Jpn.* 1951, 6, 417–421. https://doi.org/10.1143/JPSJ.6.417.
30. Obataya, E.; Norimoto, M.; Gril, J. The effects of adsorbed water on dynamic mechanical properties of wood. *Polymer* 1998, 39, 3059–3064.
31. Gerhardts, C.C. Effect of moisture content and temperature on the mechanical properties of wood: An analysis of immediate effects. *Wood Fiber 1982*, 14, 4–36.
32. Guitard, D.; ElAmri, F. Modèles prévisionnels de comportement élastique tridimensionnel pour les bois feuillus et les bois résineux. *Ann. Sci. For.* 1987, 44, 142–145.
33. Brémaud, I.; Gril, J. Moisture content dependence of anisotropic vibrational properties of wood at quasi equilibrium: Analytical review and multi-trajectories experiments. *Holzforschung* 2020, 75, 313–327. https://doi.org/10.1515/hf-2020-0028.
34. Hunt, D.G.; Gril, J. Evidence of a physical ageing phenomenon in wood. *J. Mater. Sci. Let.* 1996, 15, 1580–1582. https://doi.org/10.1007/BF01855620.
35. Fukada, E. The vibrational properties of wood. I. *J. Phys. Soc. Jpn.* 1950, 5, 321–327. https://doi.org/10.1143/JPSJ.5.321.
36. James, W.L. Effect of temperature and moisture content on internal friction and speed of sound in Douglas-fir. *For. Prod. J.* 1961, 11, 383–390.
37. Brémaud, I.; Gril, J. Transient destabilisation in anisotropic vibrational properties of wood when changing humidity. *Holzforschung* 2021, 75, 328–344. https://doi.org/10.1515/hf-2020-0029.
38. Gril, J. Une Modélisation Du Comportement Hygro-Rhéologique Du Bois À Partir De Sa Microstructure. Ph.D. Thesis, Polytechnic school, University of Paris VI, Paris, France, 1988; p. 268.
39. Sasaki, T.; Norimoto, M.; Yamada, T.; Rowell, R.M. Effect of moisture on the acoustical properties of wood. *Mokuzai Gakkaishi* 1988, 34, 794–803. (In Japanese)
40. Dlouha, J.; Gril, J.; Clair, B.; Almeras, T. Evidence and modelling of physical aging in green wood. *Rheol. Acta* 2009, 48, 333–342. https://doi.org/10.1007/s00397-008-0325-9.
41. Struik, L.C.E. Physical aging in amorphous polymers and other materials. *Dr. Ann. New York Acad. Sci.* 1977, 279, 78–85. https://doi.org/10.1111/j.1749-6632.1976.tb39695.x.
42. Fioravanti, M.; Goli, G.; Carlson, B. Viscoelastic and mechano-sorptive studies applied to the conservation of historical violins: A case study of the Guarneri “del Gesù” violin (1743) known as the “Cannone”. *J. Cult. Herit.* 2013, 14, 297–303. https://doi.org/10.1016/j.culher.2012.08.004.
43. Goli, G.; Fioravanti, M.; Busoni, S.; Carlson, B.; Mazzanti, P. Measurement and modelling of mass and dimensional variations of historic violins subjected to thermo-hygrometric variations: The case study of the Guarneri “del Gesù” violin (1743) known as the “Cannone”. *J. Cult. Herit.* 2012, 13, S154–S160. https://doi.org/10.1016/j.culher.2012.04.007.
44. Borland, M.J.; Borland, M.J. The Effect of Humidity and Moisture Content on the Tone of Musical Instruments. Ph.D. Thesis, University of Waterloo, ON, Canada, 2014; p. 161. Available online: http://hdl.handle.net/10012/8253 (accessed on 16 February 2022).
45. Torres, J.A.; de Icaza-Herrera, M.; Castaño, V.M. Guitar acoustics quality: Shift by humidity variations. *Acta Acust. Unit. Acust.* 2014, 100, 537–542. https://doi.org/10.3813/AAA.918733.
46. Yu, W.J. *Surface Performance Characteristics and Mechanical Properties of Bamboo*; Chinese Academy of Forestry: Beijing, China, 2001.
47. Matsunaga, M.; Sakai, K.; Kamitakahara, H.; Minato, K.; Nakatsubo, F. Vibrational property changes of spruce wood by impregnation with water-soluble extractives of Pernambuco (*Guilandina echinata* Spreng.) II. Structural analysis of extractive components. *J. Wood Sci.* 2000, 46, 253–257. https://doi.org/10.1007/BF00776458.
48. Matsunaga, M.; Obataya, E.; Minato, K.; Nakatsubo, F. Working mechanism of adsorbed water on the vibrational properties of wood impregnated with extractives of Pernambuco (*Guilandina echinata* Spreng.). *J. Wood Sci.* 2000, 46, 122–129. https://doi.org/10.1007/BF00777358.
49. Golpayegani, A.; Brémaud, I.; Gril, J.; Thevenon, M.F.; Pourtahmasi, K. Effect of extractions on dynamic mechanical properties of white mulberry (*Morus alba*). *J. Wood Sci.* 2012, 58, 153–162. https://doi.org/10.1007/s10086-011-1225-7.
50. Alves, E.S.; Longui, E.L.; Amano, E. Pernambuco wood (*Caesalpinia echinata*) used in the manufacture of bows for string instruments. *IAWA J.* 2008, 29, 323–335. https://doi.org/10.1163/22941932-90000190.
51. Obataya, N. Acoustic properties of a reed (*Arundo donax L.*) used for the vibrating plate of a clarinet. *J. Acoust. Soc. Amer.* 1999, 106, 1106–1110. https://doi.org/10.1121/1.427118.
52. Inokuchi, Y.; Fushitani, M.; Kubo, T.; Sato, K. Effects of water extractives on the moisture-content dependence of vibrational properties of Bamboo. *Mokuzai Gakkaishi* 1999, 45, 77–84. (In Japanese)