STABILIZATION OF ACOUSTICAL PROPERTIES OF WOODEN MUSICAL INSTRUMENTS BY ACETYLATION

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ABSTRACT

Because variable humidity affects the acoustic properties of wood, manufacturers of wood instruments must minimize dimensional changes caused by the absorption of water. Acetylation reduces the moisture content of the cell wall, thereby increasing the stability of the acoustic and dimensional properties of wood under conditions of changing humidity. The acetylation of wood slightly reduces sound velocity (by about 5%) and also reduces sound absorption when compared to unreacted wood. Hence, acetylation does not change the acoustic converting efficiency.

Keywords: Dimensional stabilization, acoustical properties, acetylation, specific dynamic Young's modulus, internal friction.

INTRODUCTION

Wood is a hygroscopic material, so when the ambient humidity changes, the dimensions of wood products change too. This affects the tone quality of wooden musical instruments because as moisture content increases, the acoustic properties of wood, such as the specific dynamic Young's modulus (E'/γ) and internal friction (Q^{-1}), are reduced or dulled (James 1964; Sasaki et al. 1988). The absorption of water molecules between the wood cell-wall polymers acts as a plasticizer to loosen the cell-wall microstructure. The decrease in cohesive forces in the cell wall also enhances the deformation of wooden parts under stress. Stress may be due to forces in the strings of guitars and violins and the pin block in a piano.

Varnish applied to the wooden parts helps

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TABLE 1. *Description of test specimens.*

Test	Species	Specific gravity	Specimen	Dimensions (mm)[a]
Free-free vibration[b]	Sitka spruce	0.42	Longitudinal strips	180 by 20 by 3
			Radial strips	20 by 180 by 3
Clamped plate	Sitka spruce	0.43	Quarter-sawn plate	150 by 150 by 3.5
Creep	Maple	0.68	Longitudinal strips	120 by 14 by 1.8
Pin block	Maple	0.68	Longitudinal strips	125 by 125 by 14

[a] Longitudinal by radial by tangential.
[b] Free-free vibrational beam test.

stabilize the dimensional and acoustic properties of wooden musical instruments by delaying the absorption of moisture. However, excessive varnishing causes suppression of the sound level radiated from the top plate of the violin (Schelleng 1968). Another method, chemical modification of wood, can effectively reduce the hygroscopicity of wood (Rowell 1983). It has been known for almost 50 years that acetylation of wood reduces hygroscopicity and increases dimensional stability (Stamm and Tarkow 1947).

Acetylation, when applied to the wooden diaphragm of speakers, was shown to stabilize tone quality under conditions of changing humidity (Ono and Norimoto 1983). Acetylation also affects the vibrational properties of wood (Yano et al. 1986; Akitsu et al. in press).

Dynamic vibrational analysis can help determine how the acoustic properties of wood change when ambient humidity changes (Ono and Norimoto 1983, 1984). Dynamic Young's modulus (E′) divided by specific gravity (γ) measures the square of sound velocity, while Q^{-1} measures sound absorption or damping within the wood.

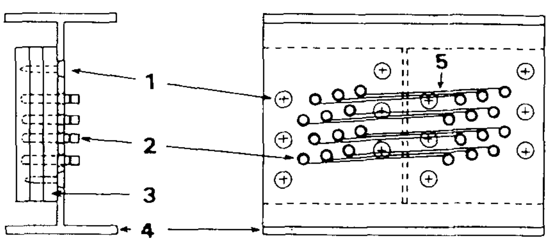

FIG. 1. Schematic diagram of simplified model of string-sustaining part used in the experiment. (1) wood screw, (2) tuning pin, (3) pin block, (4) iron plate, (5) string.

The purpose of this research was to determine the effects of acetylation on: (1) changes in E'/γ and Q^{-1}; (2) stabilization of acoustic properties of wood using a free-free vibrational beam test and an all-sides-clamped plate test; and (3) reduction of drops in tuned frequency caused by deformation of wooden parts under stress, using a full-scale model of the string-sustaining part of a piano pin block.

EXPERIMENTAL METHODS

Test specimens

The specimens for the free-free vibrational beam test were cut from a Sitka spruce (*Picea sitchensis* Carr.) wood block that had been selected for piano sound boards. These specimens and the specimens for the clamped plate, creep, and pin block tests are described in Table 1. The quarter-sawn Sitka spruce plates for the clamped plate test were prepared from a plate selected for a guitar sound board. Three specimens for the pin block test were cross-laminated with the longitudinal direction of the face specimens parallel to the strings, using a resorcinol resin to construct the pin block as shown in Fig. 1 (Yano et al. 1988).

Acetylation

The acetylation of the wood specimens (Rowell et al. 1986) involved chemical reactions in 120 C neat acetic anhydride for time spans ranging from 30 min to 4 h. Specimens were dried at 70 C in a vacuum for 10 days. Weight percentage gains (WPG) were determined from measurements of each specimen's dry weight before and after acetylation. Measurements for the longitudinal and radial strips ranged from 0.7 to 24.9, with 22.0 for the plates, 19.1 for the creep test specimens, and 18.7 for the pin blocks.

Acoustic properties

Flexural vibration with a free-free end condition [20 C, 65% relative humidity (RH)] was used to determine the specific dynamic Young's modulus and the internal friction of strips (Ono and Norimoto 1983, 1984). The acoustic properties at the first mode of vibration were measured before and after acetylation. E'/γ and Q^{-1} were measured from longitudinal specimens. To vary the resonance frequency of the specimens, we gradually cut their lengths (18 to 6 cm) and increased their vibrational mode (from the 1st to the 4th). Resonant frequencies ranged from 0.5 to 7 kHz. Ten replicate specimens were used and the results averaged.

The free-free flexural vibration technique used also determined how the acoustic properties of the strips changed when placed in a methyl methacrylate box with variable RH. For the equilibrium moisture content (EMC) experiment, sulfuric acid aqueous solutions of various concentrations controlled the RH level from 30% to 85%. For the nonequilibrium moisture content experiment, the dried specimens were placed in a vessel at 20 C, 95% RH, and acoustic properties were measured when the moisture content reached equilibrium. Finally, the specimens were moved back to the dry box containing silica gel, and acoustic properties were measured again until the moisture content reached equilibrium. Five replicate specimens were used and the results averaged.

Acetylated and unreacted plates, conditioned at 20 C, 65% RH for 10 days, were attached to a plexiglass frame using a cyano acrylate adhesive with a 5-mm wood frame overlap. The transverse sides of the frame were attached to a speaker having an 80-mm-diameter flat aluminum diaphragm. This assembly was placed in a glass vessel conditioned at 20 C, 95% RH, for 36 h. Before and after adsorption of moisture, the plate was excited by the speaker. A microphone placed 150 mm away from the center of the plate detected

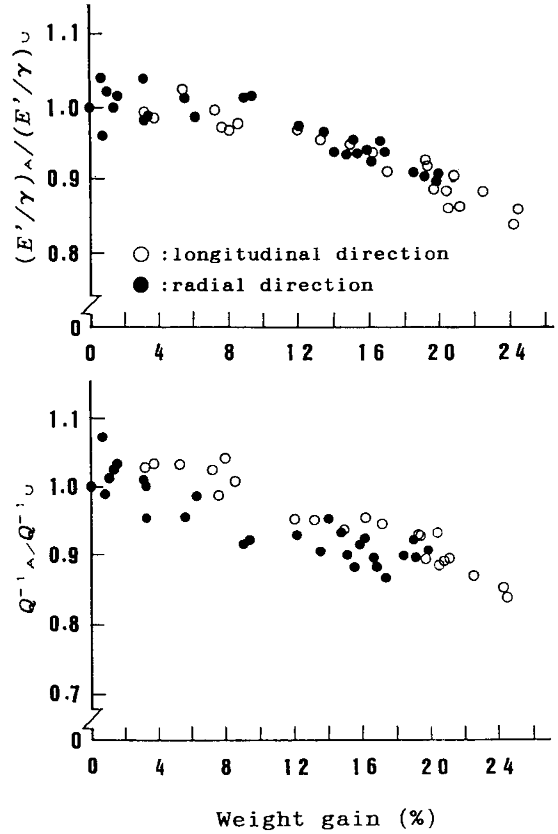

FIG. 2. Ratio of acoustic properties (20 C, 65% RH) after acetylation to before acetylation in longitudinal and radial directions versus acetyl weight percent gain.

sound radiation from the plate. A spectrum analyzer recorded the sound spectrum while the speaker received a relative amplitude of sound pressure level to white noise level. The Chladni's figure of the 1st mode of acetylated and unreacted wooden plates was photographed simultaneously by the use of fine silicic oxide powder. Triplicate samples were used and the results averaged.

Creep test

Ten specimens of each type were subjected to a bending moment at a distance of 60 mm between load points and a span of 100 mm. A linear variable differential transducer measured the deflection at the midpoint between supports. The load was 18.35 N, which cor-

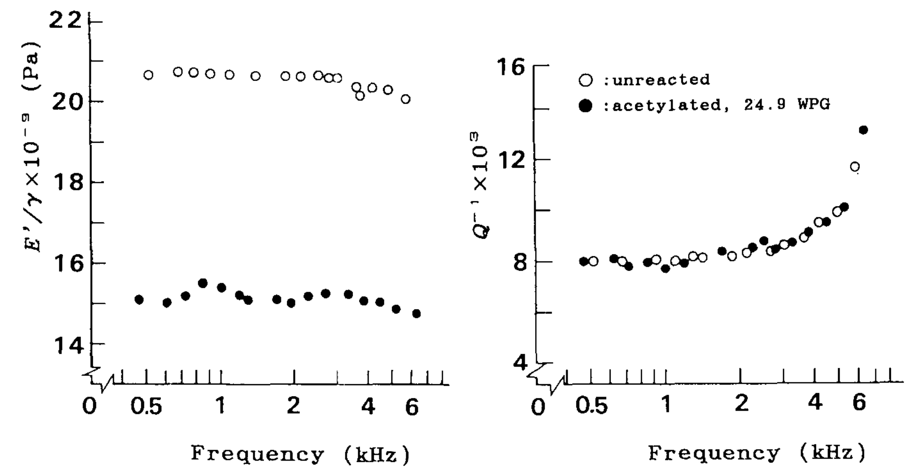

FIG. 3. Effect of acetylation on frequency dependence of E'/γ and Q^{-1} (20 C, 65% RH).

responds to stress levels of 16% and 14% of the bending strength (at 20 C, 65% RH) for unreacted and acetylated strips, respectively.

Resonance frequency of string-sustaining model

To measure the resonance frequencies of the strings, we used an acoustical pickup attached to the frame to detect their plucked vibration, feeding the signal (Fig. 1) into the spectrum analyzer. The resonance frequency was read to 0.32 Hz accuracy. Triplicate measurements were taken and the results averaged.

RESULTS AND DISCUSSION

Figure 2 shows the effect of treatment on E'/γ and Q^{-1} at 20 C, 65% RH, resulting from acetylation. The ratio of $(E'/\gamma)_A/(E'/\gamma)_U$ remained constant up to 8 WPG. As the degree of acetylation increased, the ratio decreased up to 15% and 10% in the longitudinal and radial directions, respectively. This was probably because very little cell-wall bulking took place up to 10 WPG; above 10 WPG, bulking became a significant factor. The ratio of $Q^{-1}{}_A/Q^{-1}{}_U$ decreased up to 15% in both longitudinal and radial directions as the degree of acety-

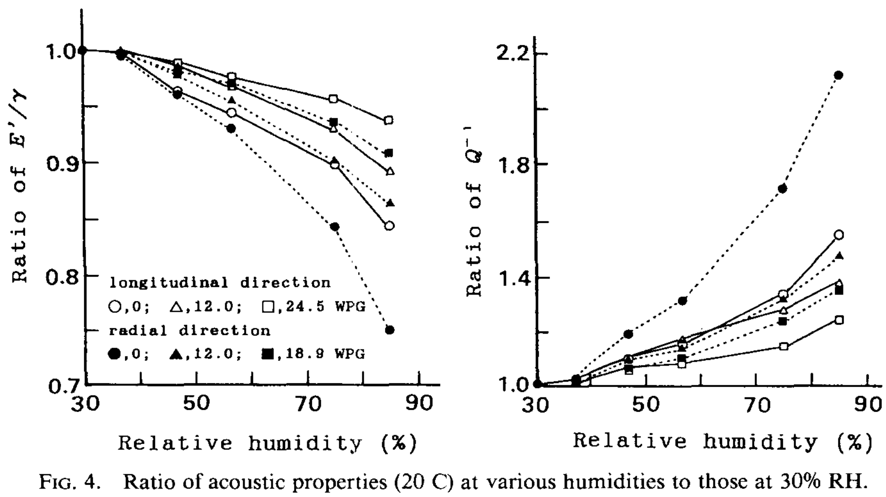

FIG. 4. Ratio of acoustic properties (20 C) at various humidities to those at 30% RH.

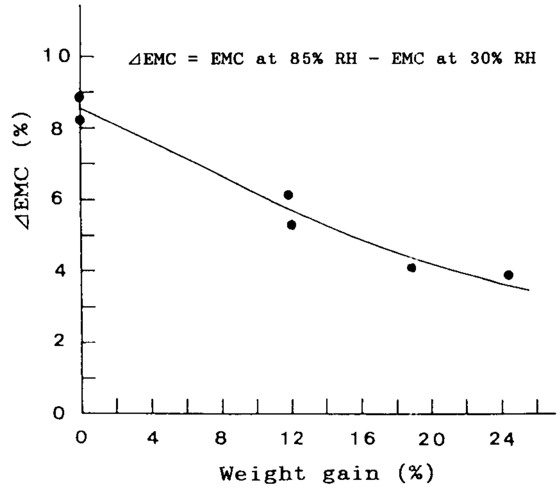

FIG. 5. Changes in equilibrium moisture content (EMC) at 20 C with acetylation.

lation increased. So, as weight gain resulting from acetylation increased, both sound velocity and sound absorption decreased.

Figure 3 shows the frequency dependence of E'/γ and Q^{-1} for acetylated and unreacted strips. The value of E'/γ decreased slightly while Q^{-1} increased greatly as the frequency increased. However, no differences in the frequency dependence were observed between acetylated and unreacted strips. The acoustic converting efficiency, which is related to the ratio of acoustic energy radiated from the musical instrument to the energy given by the string, is proportional to $\sqrt{E'/\gamma/(Q^{-1}\gamma)}$ (Tanaka et al. 1987; Yano and Matsuhisa 1991). The increase of air-dry specific gravity caused by acetylation of 23.9 WPG was 9.2%. This suggests that acetylation has a minor effect on the acoustic converting efficiency of wood for musical instruments in the audible frequency range.

Figure 4 shows the ratio of E'/γ and Q^{-1} with elevation of RH above 30% compared to the value at 30% RH. The ratio of E'/γ decreased while Q^{-1} increased with increasing RH for both control and acetylated specimens. However, the degree of the distortion of the acetylated specimens was about one-third that of the unreacted specimens in both longitu-

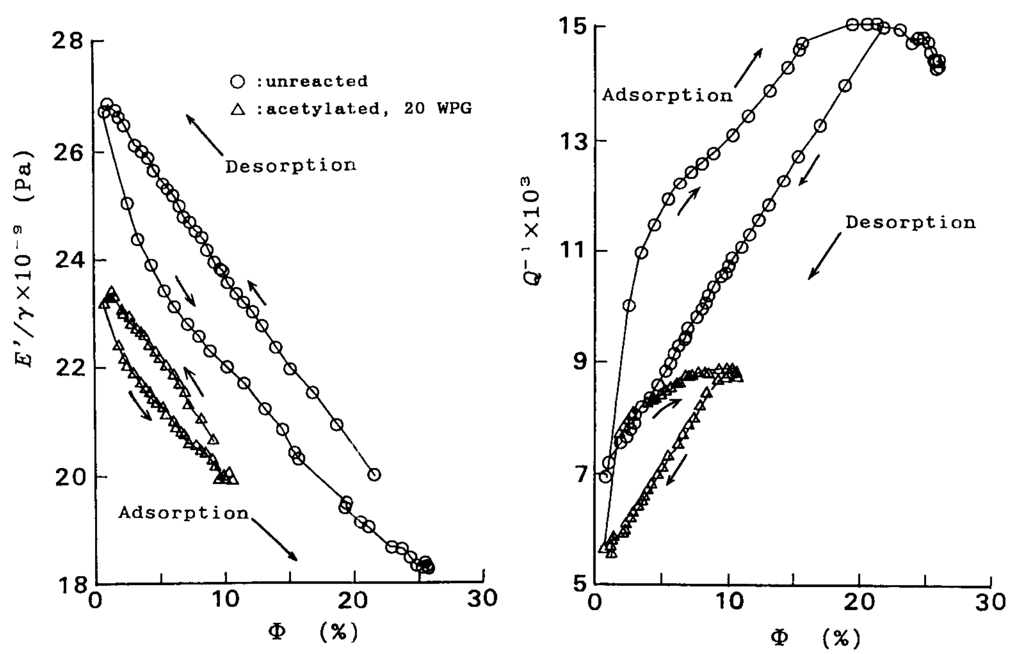

FIG. 6. Relationship between acoustical properties in longitudinal direction and average moisture content for unreacted and acetylated specimens.

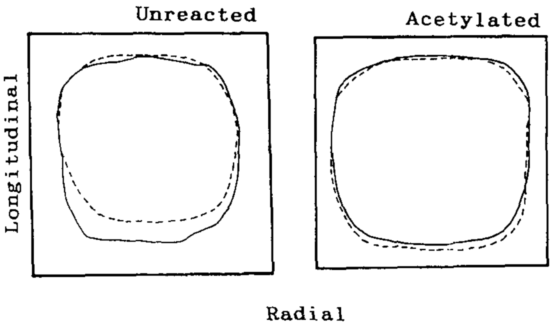

FIG. 7. Chladni's figures of all-sides-clamped plates at 20 C, 65% RH (solid line) and 20 C, 95% RH (dashed line).

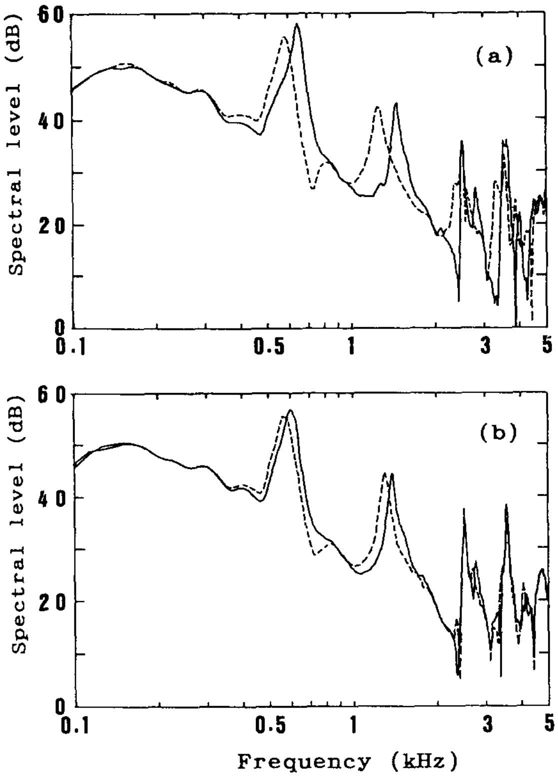

FIG. 8. Sound spectra of all-sides-clamped plates at 20 C, 65% RH (solid line) and 20 C, 95% RH (dashed line) for (a) unreacted and (b) acetylated specimens.

dinal and radial directions. Changes in humidity had a greater effect on radial properties than longitudinal, and acetylation stabilized these changes. Figure 5 shows the effect of acetylation in reducing EMC changes between 30% and 85% RH with a WPG of $\leq$24: EMC changes were reduced by $>$50%. The displacement of the hydrophilic hydroxyl group with a more hydrophobic bulky acetyl group decreased the amount of moisture being adsorbed and/or desorbed under the same humidity changes. This reduced changes in acoustic properties.

The effect of acetylation on acoustical properties was more pronounced in the nonequilibrium moisture condition. Figure 6 shows the changes in acoustic properties against average moisture content. Although acoustic properties changed more in the nonequilibrium moisture condition than in the equilibrium moisture condition, acetylation greatly suppressed these changes, especially in the process of adsorption, even though changes in average moisture content were constant.

Reducing cell-wall moisture increased the cohesive forces among wood constituents, causing them to resist dimensional changes as the humidity increases. Stabilizing both the physical dimensions and the internal cell-wall polymer conformation in wood used for musical instruments greatly affected their acoustic properties. As the RH increased from 30% to 85% at 20 C, the unreacted specimens swelled 1.28% in the radial direction, whereas the acetylated specimens swelled only 0.59% at a WPG of 18.5. When an instrument containing a wooden plate clamped at all sides is exposed to humidity changes, the mechanical restraint of the dimensional changes causes internal forces that can deform and actually destroy the instrument.

Internal forces due to changing from 65% RH to 95% RH caused changes in the Chladni's figure as shown in Fig. 7. The RH change only minimally changed the Chladni's figure for the acetylated plate. Acetylation also stabilized the sound spectra for the all-sides-clamped wood (Fig. 8). Although mutual interference between vibration modes in both plates complicated the sound spectra over 2 kHz, the change in the resonance frequency of the first peak from 65% to 95% RH was 14.5%

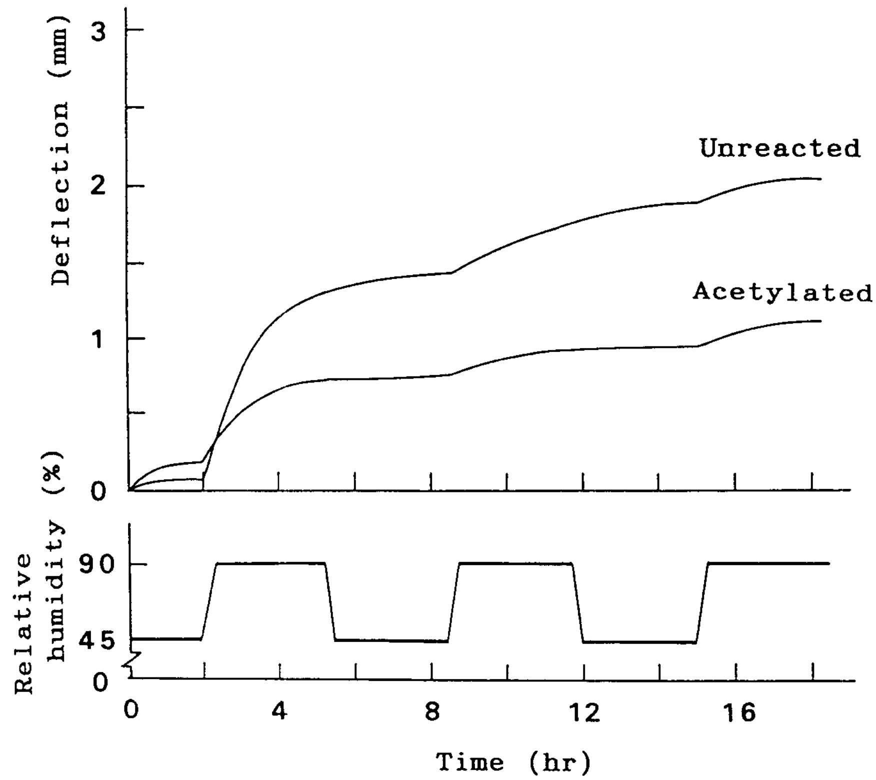

FIG. 9. Effect of acetylation on creep deflection compared to humidity cycling.

in the unreacted plate, while it was 6.2% in acetylated plate. Acetylation reduced the changes in resonance frequency to the same degree as in the free-free beam test, in spite of the restraints. The reduction in the peak level in the lower frequency range was smaller for the acetylated plate than for the unreacted plate as the RH increased.

It is well known that the adsorption and/or desorption of moisture enhances the deformation of wood under stress (mechano-sorptive behavior). Although the humidity change magnified the creep deflections (Fig. 9), acetylation greatly reduced them. This can be attributed to the decrease in hygroscopicity of the cell wall as well as to the reduction in the plasticizing effect of water on the cell-wall polymers.

To stabilize piano tones under humidity changes, a pin block must have dimensional stability. Since the string is under great tension, any movement of the tuning pin causes a reduction in the pitch of the vibrating string (Fig. 10). For this purpose, we investigated changes of the string's resonant frequency on a full-scale model of the string-sustaining part at the 72 key (G sharp) of the piano using acetylated and control cross-laminated wood pin blocks,

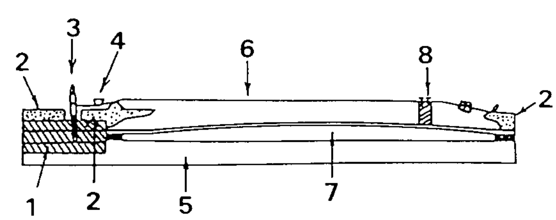

FIG. 10. Cross section of the string-sustaining part of a piano. (1) pin block, (2) iron plate, (3) tuning pin, (4) pressure bar, (5) wood brace, (6) string, (7) sound board, (8) bridge.

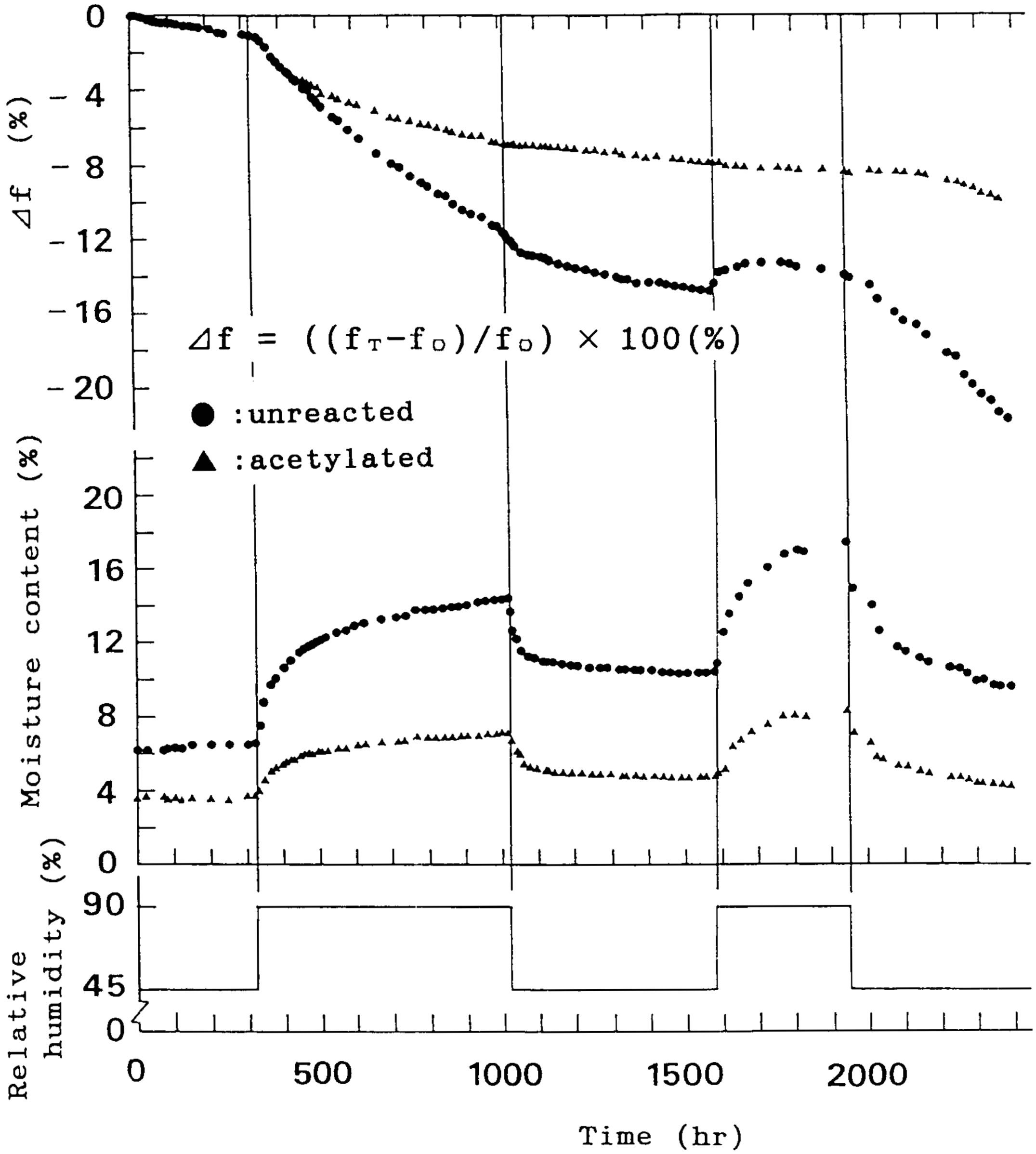

FIG. 11. Changes in resonant frequency and moisture content of acetylated and unreacted pin blocks, where f_0 and f_T represent average resonant frequencies of 12 strings at start of measurement and that after time T, respectively.

with humidity cycling. The decrement of the resonance frequency for the acetylated model was much less than that for the control blocks as the moisture content increased (Fig. 11). It is expected that a laminated acetylated pin block could be extremely effective in reducing the changes of resonance frequency in a piano.

CONCLUSIONS

The acetylation of wood slightly reduced both sound velocity (due to the decrease in E'/γ) and Q^{-1} (sound absorption) when compared to unreacted wood. Acetylation greatly reduced variability in the moisture content of the cell-wall polymer, thereby stabilizing the physical dimensions of wood and its acoustic properties. These tests did not determine whether acetylation enhanced sound quality. A violin and guitar in Japan and a violin in Sweden have been made from acetylated spruce, and actual changes in sound quality are presently being investigated.

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