

# THE EFFECT OF STEAMING AND MOISTURE CONTENT CHANGE ON THE RESONANCE FREQUENCY OF WOOD

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## ABSTRACT

The vibrational characteristics of wood play an important part in the tonal characteristics of woodwinds and stringed instruments such as pianos and guitars. In this series of experiments, the effect of steaming on the peak or resonance frequency was assessed and compared to the resonance frequency of samples that were not steamed but had undergone moisture content changes. The results were clear. Steaming produced a significant shift in the peak frequency whereas measurements of peak frequency before and after moisture content change, without steaming, did not produce a significant change. The results of these experiments may affect the preparation of wood for use in musical instruments.

**Keywords:** Moisture content, wood, vibration characteristics.

## INTRODUCTION

The tones produced when a musical instrument is played are a complex combination of waves developed from the properties of the material, the characteristics of the instrument, and the skill of the musician. For centuries, certain species have been preferred by luthiers for the manufacture of musical instruments. Among those, spruce and maple are prominent for stringed instruments (Bucur 1995).

Treatments that change the vibrational characteristics of wood will also change the sound of the instrument when a musician plays it. During this series of experiments, the effect of steaming on wood was tested to see if the vibrational characteristics of the wood were changed by steaming. The hypothesis for these experiments was that dry wood that is exposed to steam and re-dried will resonate at a different frequency. The hypothesis was based on an understanding of the stresses that develop during the drying process, the action of steam

to relieve stresses, and the practices of some musical instrument makers.

Every material has one or more "natural" frequencies when an applied force causes it to vibrate. One of the natural frequencies is called the resonance frequency. Resonance can be defined as the comparatively large-amplitude vibration that results whenever the frequency of some driving force closely matches a natural oscillation frequency of the system on which it acts (Fletcher and Rossing 1991). Materials have a number of natural frequencies, which are directly related to their physical properties. In a string or a thin bar, the natural frequencies,  $f_n$ , are given by (Den Hartog 1985):

$$f_n = nc_l/2L \quad (1)$$

where:

$c_l$  is the velocity of the propagating waves in the bar ( $\text{ms}^{-1}$ )

$L$  is the length of the bar (m)

$n = 1, 2, 3, 4 \dots$  are the overtones of the fundamental frequency

The velocity of a wave in a bar,  $c_l$ , can also be written:

$$c_l = \sqrt{E/\rho} \quad (2)$$

where:

$E$  is the modulus of elasticity or stiffness ( $\text{Nm}^{-2}$ )

$\rho$  is the density of the material ( $\text{kgm}^{-3}$ )

Combining Eqs. (1) and (2) shows that the natural frequencies in a bar are related to the elasticity and the density of the bar:

$$f_n = \frac{n}{2L} \sqrt{\frac{E}{\rho}} \quad (3)$$

Since the resonance frequency is approximately equal to one of the natural frequencies, the resonance frequency of a bar is influenced by its length, its stiffness, and its density and the characteristics of the wood species or of the sample.

Of importance during this series of experiments were the stresses and strains that develop during the drying process. Removing moisture causes stress and strain within wood that tends to concentrate at the surfaces. Early in drying, the surfaces of wood undergo moisture loss and attempt to shrink. However, they are unable to do so because the moist interior does not shrink. The end result is that the surfaces undergo tensile forces and the interior is under compression. The tensile forces at the surface cause the cells and the cell components to shrink less than they would without the restraint of the moist interior. The surface of the wood, particularly across the grain, dries in the stretched condition known as set or casehardening. Later, as moisture is being lost from the interior of the wood, the stresses reverse, resulting in the surface layers of the wood being under compressive stress and the interior being under tensile stress. At the end of the drying process for wood, the resulting stress imbalance must be removed. In order to do so, wood is subjected to a conditioning pro-

cess in which steam and thermal energy are added to the environment re-wetting the surface, which then shrinks. As the wood redries, the strain imparted to the surfaces during the early part of the drying process is reversed (Simpson 1991).

#### MATERIALS AND METHODS

Flat-sawn 25-mm-thick by 15-cm-wide boards of sugar maple (*Acer saccharum*), originating from approximately the same location in northeastern Maine, were procured from a local sawmill. The green lumber was carefully dried in an environmental chamber by following a drying regime for maple (schedule T8-C3) published by Simpson (1991). The final moisture content of the wood was approximately 10%, and the samples were not conditioned after drying. After drying, the boards were machined into samples measuring 9.5 cm (L)  $\times$  7.6 cm (W)  $\times$  1.9 cm thick. After machining, the samples were labeled and placed in an environmental chamber set at 37.8°C and 54% relative humidity, which corresponds to a final moisture content of 9.2% for the wood (Simpson 1991). The samples remained in the chamber until their weights were constant.

Steaming of the samples was done in an unpressurized, unheated, metal cylinder that had a capacity to hold five samples simultaneously. Steam at approximately 105°C and having an unknown moisture content was introduced into the chamber, and the steaming was continued for approximately 24 h. The samples were then re-weighed and returned to the environmental chamber for re-conditioning to 9.2%. The moisture gain varied among the samples but was generally in excess of 10%.

Three additional moisture content conditions were used during these tests as described below. Samples conditioned to either 13.9% or 6.1% were done in an environmental chamber in accord with conditions defined by Simpson (1991). Samples dried to approximately zero percent moisture content were dried in a precision oven at 100°C for a period of 24 h.

Prior to resonance testing, all samples also

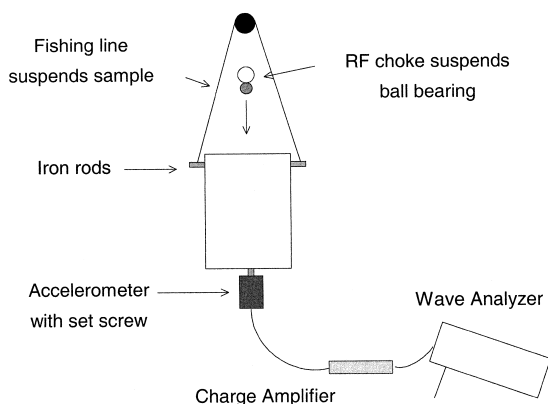


FIG. 1. Schematic diagram of testing apparatus.

had a hole drilled to a depth of approximately 0.75 cm on either side so that small iron rods could be inserted. The purpose of the iron rods was to allow the entire wood sample to be suspended from the experimental apparatus (Fig. 1). Suspending the sample in this manner allowed free rotation during excitation.

The apparatus from which the sample was suspended held the sample via a looping fishing line (Fig. 1). Directly above the sample was an RF choke, which was energized by a 4.7V DC power source and acted as an electromagnet. From the electromagnet, a metal ball ("exciter") weighing 0.355 grams was dropped onto the samples to generate vibration. Since the wood was driven by the ball's impact on its cross-sectional surface, sound energy traversed through the length of the sample (Fig. 1).

In order to measure the various frequencies of the sound waves propagating throughout the wood medium, a lightweight accelerometer (Bruel and Kjaer model 4370) was attached to the bottom end of the sample. The accel-

erometer was part of an assembly that included a small set screw inserted into the bottom of the wood to act as a "wave guide and a special connecting cord that went to an amplifier (Bruel and Kjaer model 2635). The captured vibration pattern then went to a Hewlett Packard 35070A wave analyzer, which performed a Fast Fourier Transform (FFT) on the data to show the various frequencies of the vibration. After multiple preliminary tests, parameters for the analysis system were chosen that emphasized the resonance frequency of the wood/sensor/support system (Table 1).

The procedure of dropping the ball and recording the resonance frequency was performed ten times for each sample at each protocol. The experimental design for the project is shown in Table 2.

## RESULTS

A typical waveform and associated FFT showing the peak frequency are shown in Fig. 2. The resonance frequency test results from all test protocols are summarized in Table 3. For Test protocol 1, the average frequency dropped by 0.219 kHz (pre-steam - post-steam) after steaming and reconditioning. The difference was significant at the  $\alpha = 0.01$  level ( $P$ -value  $\cong 0$ ). Figure 3a illustrates the change in resonance frequency between the pre-steam and post-steam conditions.

Test protocol 2 followed the protocol of Test 1, but after steaming and re-conditioning, the final moisture content (MC) was raised to 13.9%. After steaming and re-conditioning, the average difference in resonance frequency was 0.337 kHz. When the moisture content of the samples was raised to a 13.9% MC, without steaming, the observed resonance fre-

TABLE 1. Equipment settings for the experiments.

Settings for charge amplifier (Bruel & Kjaer Type 2635)		Settings for wave analyzer (HP - 35070A)	
Sensitivity	0.1-1 pC/m/s <sup>2</sup>	Trigger level	100 $\mu$ V
Gain	1	Range	1.0012 Vpk
Lower frequency limit	2 Hz	Frequency range	0-6.4 kHz
Upper frequency limit	30 kHz	Time	0-62.438 ms

TABLE 2. *Experimental design.*

Test	Conditions	Number of samples	Number of excitations at each level	Total excitations for each sample
1	Green → 9.2% → Steam → 9.2%	15	10	20
2	Green → 9.2% → Steam → 9.2% → 13.9%	5	10	30
3	Green → 9.2% → Steam → 9.2% → 6.1%	5	10	30
MC	Green → 9.2% → 0%	5	10	20

quency differed from the original pre-steam 9.2% level by 0.275 kHz, and from the post-steam 9.2% level by 0.062 kHz (Fig. 3b). The difference between the original pre-steam 9.2% MC resonance frequency and the post-steam 9.2% MC resonance frequency was significantly different ( $P$ -value  $\cong 0$ ). The difference in resonance frequency between the 9.2% MC post-steam frequency (Fig. 3b, bar 2) and 13.9% MC frequency (Fig. 3b, bar 3) was not significantly different at the  $\alpha = 0.01$  level.

Test 3 also followed the initial protocol of Test 1, but after the post-steam tests at 9.2% MC, the MC was lowered to 6.1%. As with Test protocols 1 and 2, there was a significant difference between the pre-steam 9.2% MC resonance frequency and the post-steam 9.2% MC resonance frequency ( $P$ -value  $\cong 0$ ). Changing the moisture content to 6.1% MC shifted the average resonance frequency to 3.367 kHz (SD = 0.269 kHz). The difference between the post 9.2% MC resonance frequency and the 6.1% MC resonance frequency, though, was not significant at the 0.01 level (Fig. 3c).

Neither Test protocol 2 nor Test protocol 3 showed a significant shift in the resonance frequency of wood when the moisture content was changed by 3–4%. To further illustrate the effect of moisture content versus the effect of steaming, ten samples were tested at 9.2% MC without steaming then dried (approximately 0% MC) and re-tested (Table 3). The resonance frequency did not change significantly when the moisture was removed (Fig. 3d).

Since density is related to the natural frequency of the wood (Eq. 3), density values were calculated from vernier caliper and balance measurements for a representative num-

ber (3–4) of samples of each Test and at each MC level. The results are shown in Table 4. The pre-steam and post-steam differences of Test protocol 1 were not significantly different ( $P$ -value  $\sim 0$ ). Among the other comparisons, all others had  $P$ -values less than 0.03 except the comparison between the post-steam values at 9.2% and the post-steam values at 6.1% moisture content which had a  $P$ -value of 0.23. The cause was related to one sample which distorted during drying, making measurement difficult.

#### DISCUSSION

Steaming clearly affects resonance frequency while moisture change without steaming did not significantly affect resonance. A broad explanation of the expected changes in frequency is found in Eq. (3), which indicates that the natural frequencies of the wood are related to the modulus of elasticity (stiffness), the density, and the length of the sample. Both the removal and the addition of moisture changed the resonance frequency (Fig. 3) but not significantly although both the sample density and, presumably, the stiffness were altered as the moisture content varied. Steaming the wood, without significantly changing its moisture content, altered the resonance frequency significantly as hypothesized. The statistically significant decrease in the resonance frequency can be attributed to the relief of stresses and the volume changes that occurred when steam was added to the system. The addition of steam relieves stresses and decreases density (Table 3) by increasing the volume more than the mass. A possible theoretical explanation for the shift in resonance frequency

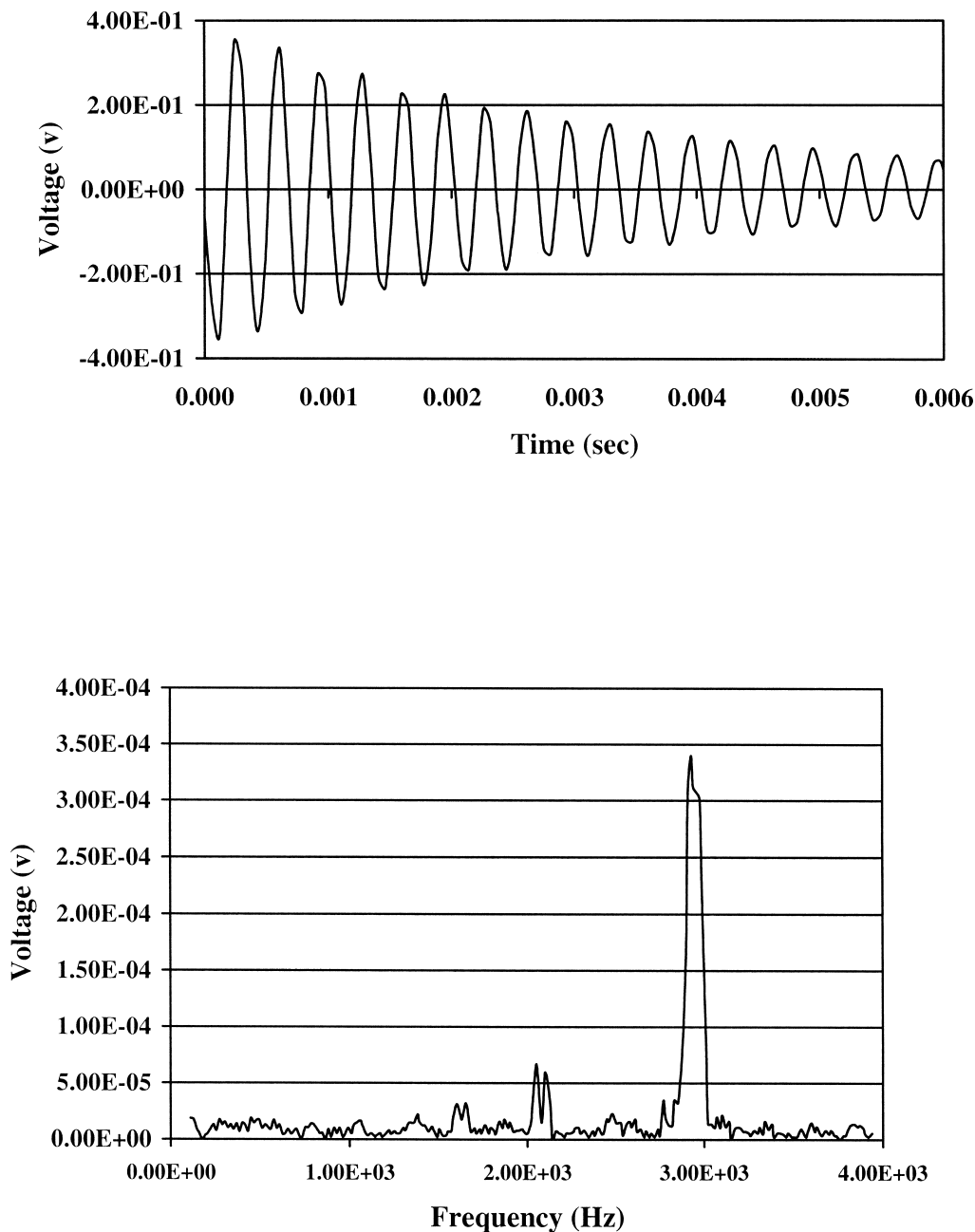


FIG. 2. Typical waveform (amplitude vs. time) and frequency response.

has been outlined by Flory (1953), who described changes in polymer entropy and enthalpy under various conditions; the standard approach has been adapted to the circumstances of these experiments as described below.

At the polymer level, the addition of steam, or enthalpy, probably changes the entropy of the polymers that comprise wood. As the polymer entropy or positions change, the vibrational characteristics of the wood also change.

TABLE 3. Mean resonance frequency values (kHz).

Test protocol	9.2% pre-steam	0% No steam reduction	9.2% post-steam	6.1% No steam reduction	13.9% No steam increase
1	3.906	—	3.688	—	—
2	3.651	—	3.314	—	3.375
3	2.607	—	3.285	3.367	—
MC	3.692	3.654	—	—	—

During the drying process, the polymers are stretched due to differential shrinkage stresses, and their entropy decreases due to an ordering of the polymer chain segments. The addition of energy to a system of polymers during drying can be modeled as:

$$dU = dq + dw, \quad (4)$$

where:

$dU$  is the change in the internal energy of a system,

$dq$  is the heat absorbed, and  
 $dw$  is the work done on the system

$dw$  can be expanded to incorporate elastic effects and pressure/volume work:

$$dU = dq - pdV + FdL, \quad (5)$$

where:

$pdV$  is pressure/volume work and  
 $FdL$  is the elastic work done.

During drying, work is done by differential

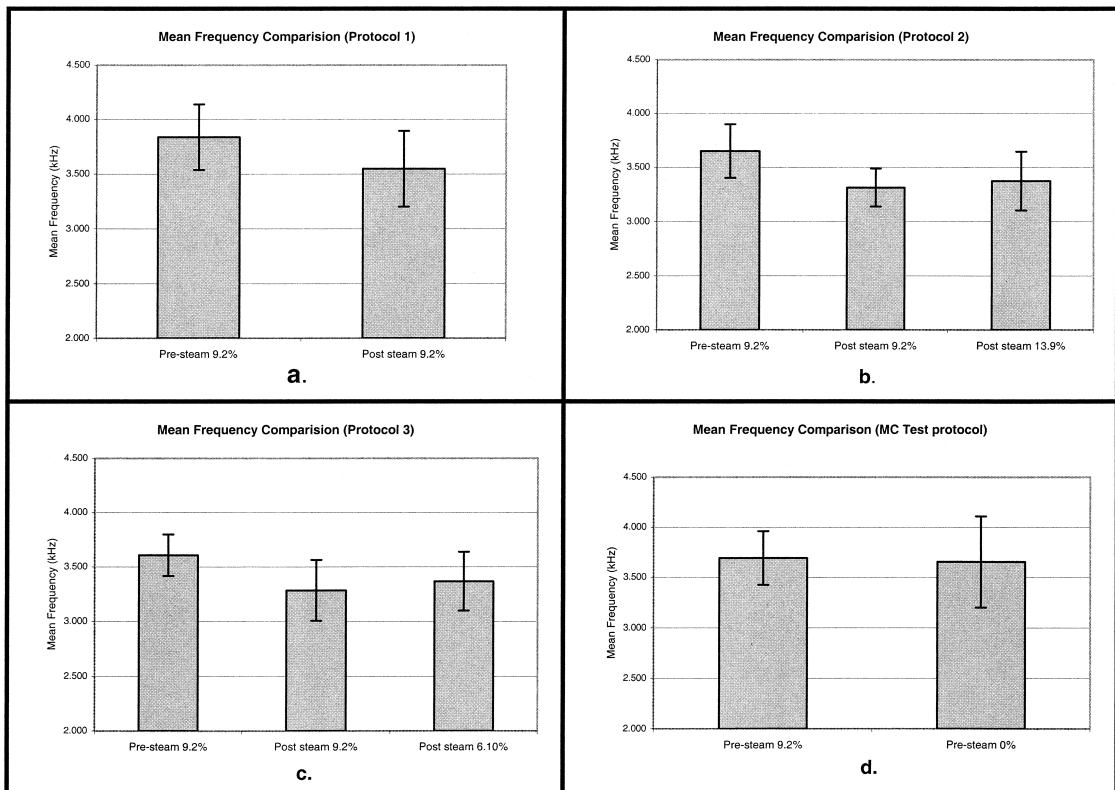


FIG. 3. Mean frequency values for the various protocols.



TABLE 4. Mean density values ( $\text{g cm}^{-3}$ ) for each test at each MC level

Test protocol	9.2% pre-steam	0% pre-steam	9.2% post-steam	6.1% post-steam	13.9% post-steam
1	0.744	—	0.723	—	—
2	0.724	—	0.703	—	0.711
3	0.753	—	0.729	0.720	—
MC	0.761	0.731	—	—	—

shrinkage stresses, and elastic strain occurs across the grain as the polymers within the wood undergo strain known as “set” or case-hardening. Ignoring the pressure-volume work in Eq. (5), the elastic work is equal to  $FdL$ :

$$dw = FdL \quad (6)$$

Energy is being added to the system through the action of heat supplied to dry the wood. The Gibbs free energy ( $G$ ) can be related to the enthalpy ( $H$ ), temperature ( $T$ ), and entropy ( $S$ ):

$$G = H - TS \quad (7)$$

Differentiating with respect to length at constant temperature and pressure, Eq. (7) becomes:

$$(\partial G/\partial L)_{p,T} = (\partial H/\partial L)_{p,T} - T(\partial S/\partial L)_{p,T} \quad (8)$$

The applied force,  $F$ , can be related to  $G$ , the Gibbs energy:

$$F = (\partial G/\partial L)_{p,T} \quad (9)$$

Thus,

$$F = (\partial H/\partial L)_{p,T} - T(\partial S/\partial L)_{p,T} \quad (10)$$

Consequently, the change in length of a polymer (strain) is related to the enthalpy and entropy of the polymer system. By changing those two variables, the length of the polymer will also be changed. In the drying process, the entropy of the polymers is reduced as the surface elongates due to the tensile forces at the surface during drying.

As wood dries, its surface is elongated and the final state of drying is that the outer surfaces are stretched, but under compression. In

steaming, enthalpy is increased by the addition of energy, the temperature is changed and, by Eq. (10), both the entropy and Gibbs energy are changed. That is, instead of becoming more ordered, the addition of heat and moisture makes the polymers more disordered, increasing entropy. As entropy increases, the number of statistical degrees of freedom in the polymer increases and the overall end-to-end distance of the polymer decreases. Consequently, the natural frequencies of the wood are changed, which also shifts the resonance frequency (Eq. 3). Simply adding or subtracting water vapor does not relieve internal stresses in wood, nor does it significantly alter the resonance frequency. However, the addition of steam at higher temperatures has a significant effect on the stresses within the wood.

## CONCLUSIONS

The addition of steam clearly changed the peak or resonance frequency of the wood under the conditions of these tests. Conversely, without the addition of steam, the peak frequency changed, although the changes were not statistically significant. While classical theory predicts changes in the natural frequencies of polymeric materials with changes in size and density, the changes in resonance frequency became significant only after prolonged steaming. The factors causing significant change probably derive from changes in polymer entropy resulting from the high temperature steaming and the relief of drying stresses in the wood, both of which are inter-related. Although not part of these experiments, a change in peak frequency indicates that the entire frequency spectrum has shifted

and the tonal properties made from wood undergoing the treatment would also change.

#### ACKNOWLEDGMENTS

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