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# A Wood Viscoelasticity Measurement Technique and Applications to Musical Instruments: First Results

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## Abstract

*The viscoelasticity (damping) property of spruce wood was measured for the audio frequency range 20 Hz to 20 kHz and as a function of time when vibrated at 1 kHz. After less than one hour of vibration, the loss tangent of the spruce decreased by 6%.*

The Musée de la Musique in Paris retains in its collection many wooden stringed instruments from a number of regions and various historic times. Some are maintained in playable condition. Wood, as we know, has been used as an essential material for musical instruments in every country in the world. Because there are so many wood species, there is a wide variation of vibrational properties. For example, the genus *Picea* is used for the sounding boards of the violin family, and tropical woods are used for those of African harps. More than the effect of natural aging, wood instruments may degrade as a result of biological attack, radiation (from UV with natural light or heat transfer of absorbed artificial light), climatic variations, and constraints due to being in a playable state.

A significant challenge for the conservation of stringed musical instruments is their unpredictable behavior over a long period, considering that they are made of wood and subject to great stress due to string tension and/or humidi-

ty variations when they are played (sweat from musician contact, thermo-hygrometric variations during transport, etc.). These factors, along with the general aging of the wood, motivated us to find a quantitative criterion for protecting and conserving musical instruments.

Among the numerous factors that influence the quality of an acoustical musical instrument, the material property viscoelasticity (often referred to as damping) in the audio frequency range (20 Hz to 20 kHz) has been determined to have an important role in a number of studies [1], including recent experiments in composite design [2]. Moreover, viscoelasticity seems to vary during the playing time [3] and according to the moisture content [4]. This experience provided more motivation for the experiments reported here.

## ENVIRONMENTAL CONDITIONS DURING A CONCERT

Although climatic conditions are controlled in our museum to keep the temperature and

humidity as stable as possible, when a musical instrument is played during a concert, it is exposed to substantial variations of humidity due to transport and contact with the musician. Evidence of this is presented in Fig. 1, where humidity was measured with a small probe inside a violin before, during, and after a concert. The “concert effect” appeared clearly on the hygrometric variations during the playing (between 8:30 and 10:30 pm).

Moreover, as Hunt [5] has presented, sound quality can be improved by regular playing. Can viscoelastic behavior explain why a musical instrument would ring better after being played for some period, as reported by musicians? How are mechanical properties, such as damping, sensitive to these parameters (regular playing, climatic variations), and could there be conservation criteria?

Existing scientific devices have not provided answers to these questions regarding humidity and playing time, so we developed a tool to measure wood viscoelasticity in the 20 Hz to 20 kHz

spectral range and as a function of vibration time (simulating regular playing) and hygrometric variations.

## OVERVIEW OF VISCOELASTICITY MEASUREMENT

### Theoretical background

Most structural engineering materials are described, for small strains, by Hooke’s Law of linear elasticity: stress  $s$  is proportional to strain  $e$ , with a proportionality factor  $E$  called Young’s modulus. If the relationship between stress and strain depends on time or on frequency, the material exhibits a viscoelastic response. The viscoelastic behavior comes from three phenomena more or less neglected in the function of the material: damping due to the coupling of the material with the air; thermoelastic losses, which are very low for wood due to low thermal conductivity; and the internal friction between molecules.

The loss angle  $d$  is the phase angle between

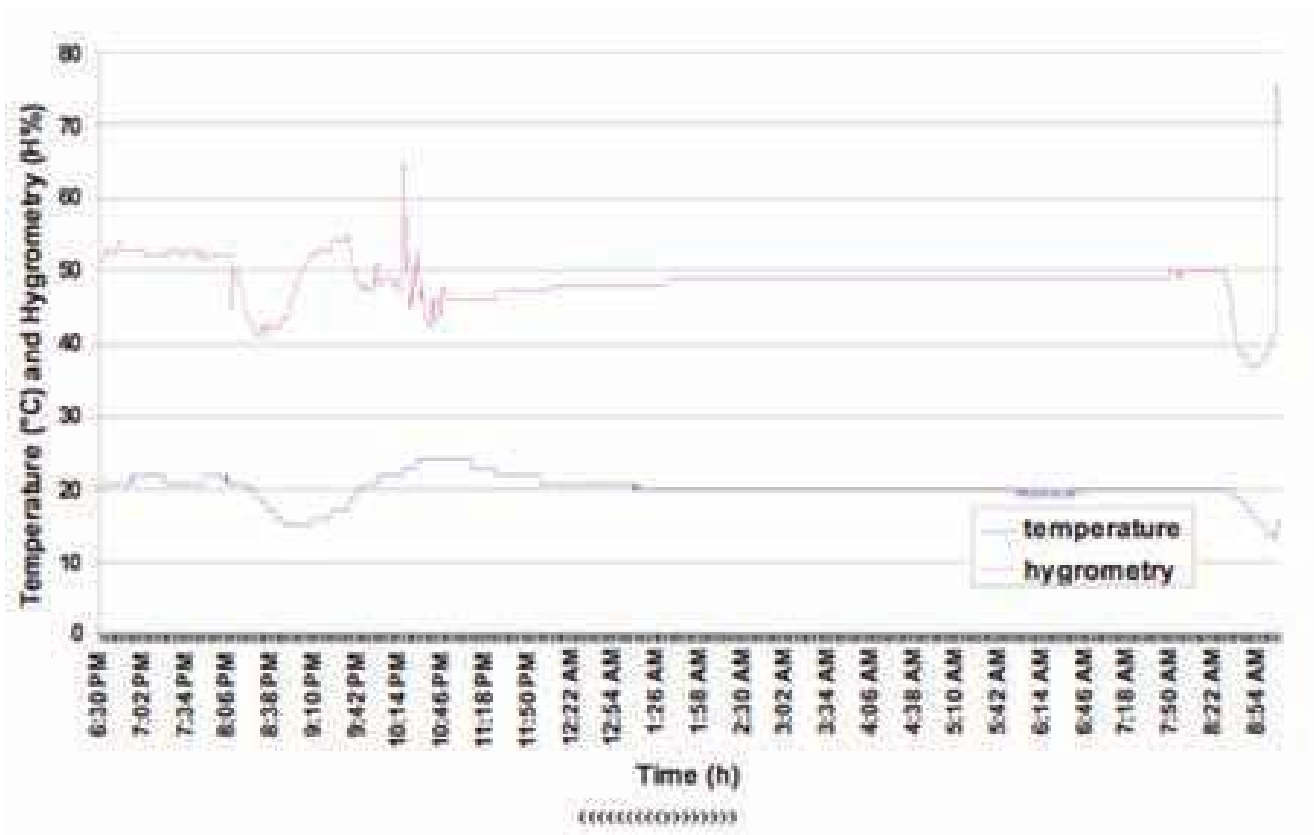


Figure 1. Temperature (lower curve) and relative humidity (upper curve) measured inside a violin before (including warmup), during a concert performance (8:30-10:30 pm), and over a prolonged time afterward.

stress and strain during sinusoidal deformation in time. The loss tangent  $\tan(d)$  is a measure of damping or internal friction in a linear material and is clearly defined in terms of observable quantities. It depends on no physical models.  $\tan(d)$  is the ratio of the imaginary part  $E''$  to the real part  $E'$  of the complex modulus  $E^* = E' + jE''$ . The quality factor  $Q$ , associated with the width of the resonant peak obtained by dynamic analysis, is given (for small  $d$ ) by  $Q \approx \tan(d)$  [6]. After removal of the excitation, if the vibration decays (e.g., due to material viscoelasticity), the *log decrement*  $\Lambda$ ,<sup>1</sup> in terms of amplitudes of successive cycles, can be measured. For small  $d$ ,  $\Lambda \approx p \tan(d)$  ([6]).

All these measurements provide information about the material stiffness or modulus in viscoelastic materials, which depends on frequency. Viscoelasticity in wood is studied to determine how musical instruments absorb acoustic vibrations with time. We chose, in this study, to measure directly the loss angle when a stress is applied on the sample because we need no analytical model about the wood species and structure—it's a direct measurement.

### Classical experimental configurations

Violinmakers are used to testing the wood quality factor with their hand and ear. The method most frequently used to estimate wood quality is striking a flat piece of wood and listening to the temporal decrease. In 1983 Giovanni Lucchi [7] developed a meter for measuring the velocity of sound in wood such as that used by bowmakers and violinmakers. It performs a damping measurement on a long beam with (hand-held) ultrasonic transducers that measure a global structure response. However, the “Lucchi Meter” does not perform a full measurement of the material property since the frequencies it uses are in the complex “middle frequency domain,” between waves and flexural motions. Nevertheless, the large database that has been accumulated with this device demonstrates the need for non-destructive measurement of wood to evaluate its quality before using it in musical instruments.

<sup>1</sup> The logarithmic decrement  $\Lambda$  is a measure of how rapidly the peak amplitude of the wave decays, i.e., how rapidly an oscillating circuit loses its energy.

Two principal techniques exist to measure viscoelasticity from the structure vibration. The vibration is either free or imposed. In the first case, the measurement is based on the logarithmic decrement of the amplitude. This method requires additional mass (cantilever beam) in order to explore a discontinuous frequency domain and supposes that viscoelastic properties do not depend upon the amplitude of the vibration (linear viscoelasticity). The damping is obtained by measuring the time dependence of the attenuation of the beam vibration (logarithm decrement method). Nevertheless, the interpretation of this test is based on the use of an approximation of the analytical solution for the deformation field in the specimen.

The second technique is based on measurements of the phase shift between the force, which results from the vibration, and the imposed displacement. This requires use of force and displacement transducers that do not perturb the measurement. Commercial viscosity test machines measure the loss angle applying a displacement at one end of a sample and providing the force at the other end, but instrumental resonances limit the frequency range of these devices below 1000 Hz.

Flexural modes, combined with free vibrations (first method), are often preferred for viscoelastic measurements on musical instruments [8-10]. They allow large displacements that can be easily measured. But, first, the flexural motion involves air movement in which some amount of the energy is dissipated, generally neglected (as shown in [11], the internal friction was greater than fluid dissipation in the case of woods). Second, the logarithmic decrement that is currently taken as a viscoelasticity indicator is, according to Lakes [6], proportional to the angle only for low values. Third, the cantilever beam needs a heavy reference body and a clamping system that have to be well characterized to avoid additional losses in joints.

In a general way, these methods require knowledge of the sample positioning and are bandwidth limited (from very low frequency until 3 kHz).

The main objectives of our research were to develop and utilize an experimental apparatus that takes advantage of these two approaches to measure viscoelasticity over the entire audio fre-

quency range, free of any analytical model, and to characterize the aging of wood instruments.

### Principle of the measurement device

Currently, measurements are not performed directly on instruments, but on samples of resonant wood (for violinmakers). The samples are cylindrical rods (55 mm long with 5 mm diameter) held in compression, under imposed vibration. A pre-stress insures that the specimen remains in compression, as could be a violin soundboard (the magnitude of vibration being small in comparison). The actuator and force transducers are identical piezoelectric PZT-type ceramics with a flat response in amplitude between 20 Hz and 20 kHz. The actuator imposes the motion on one extremity of the sample and the sensor provides force measurement (Fig. 2).

## MEASUREMENT

The theoretical development allowing the mathematical relation between Young's modulus (real and imaginary parts) and the tension measured with the force sensor will soon be published elsewhere. Presented here are (1) the results of the viscoelasticity measurements on resonant wood, in particular spruce, (2) the effect of humidity, and (3) the effect of vibration time on the viscoelasticity of wood.

## CALIBRATION

Since the signal amplitude and phase depended on electronic devices, a calibration procedure was needed. Aluminum 2017A was used as the reference material since it has no internal friction, i.e., no viscoelasticity. This measurement, repeated and averaged, led to a flat response for

this material for acoustic frequencies up to 18 kHz, as is evident in Fig. 3.

## RETICULATED SPRUCE

Some violinmakers use reticulated spruce because of the stability of its mechanical properties when exposed to variations in relative humidity. For this reason, this wood was selected for the present experiments. The length of the sample was 55 mm. As shown in Fig. 3, the measured viscoelasticity increased linearly between 20 Hz and 18 kHz, which is in accordance with the classical Kelvin-Voigt rheological model (William Thomson—the first Baron Kelvin—and Woldemar Voigt).

## PLAYING EFFECT

According to experience reported by musicians, the more an instrument is played, the better it rings. This raises the question of whether a musician becomes used to a particular instrument, or if the mechanical wood properties (implied in acoustical quality) are somehow modified by the playing. To try to answer this question, spruce wood samples (as used by violinmakers) were subjected to vibration at 1 kHz for seven hours. For this, the displacement transducer of our device was used to excite the samples to simulate the vibration generated by playing. Constant climatic conditions were maintained to measure only the effect of regular vibration on the damping.

Measurements of the loss tangent were repeated at periodic intervals. A rod of aluminum 2017A was tested first to verify the time stability of the electronic device. Since no loss angle variation was measured for this material,

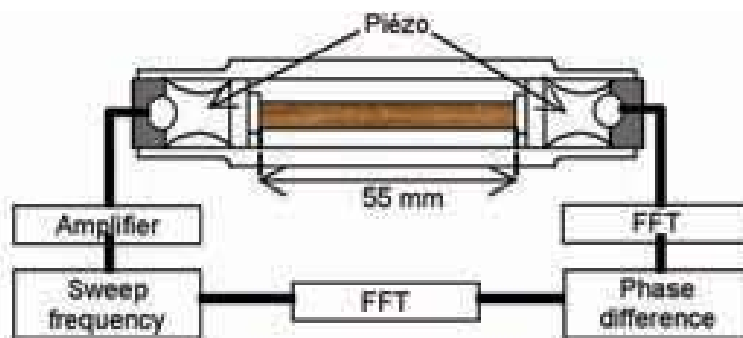


Figure 2. Schematic test apparatus used for measurements of viscoelasticity.

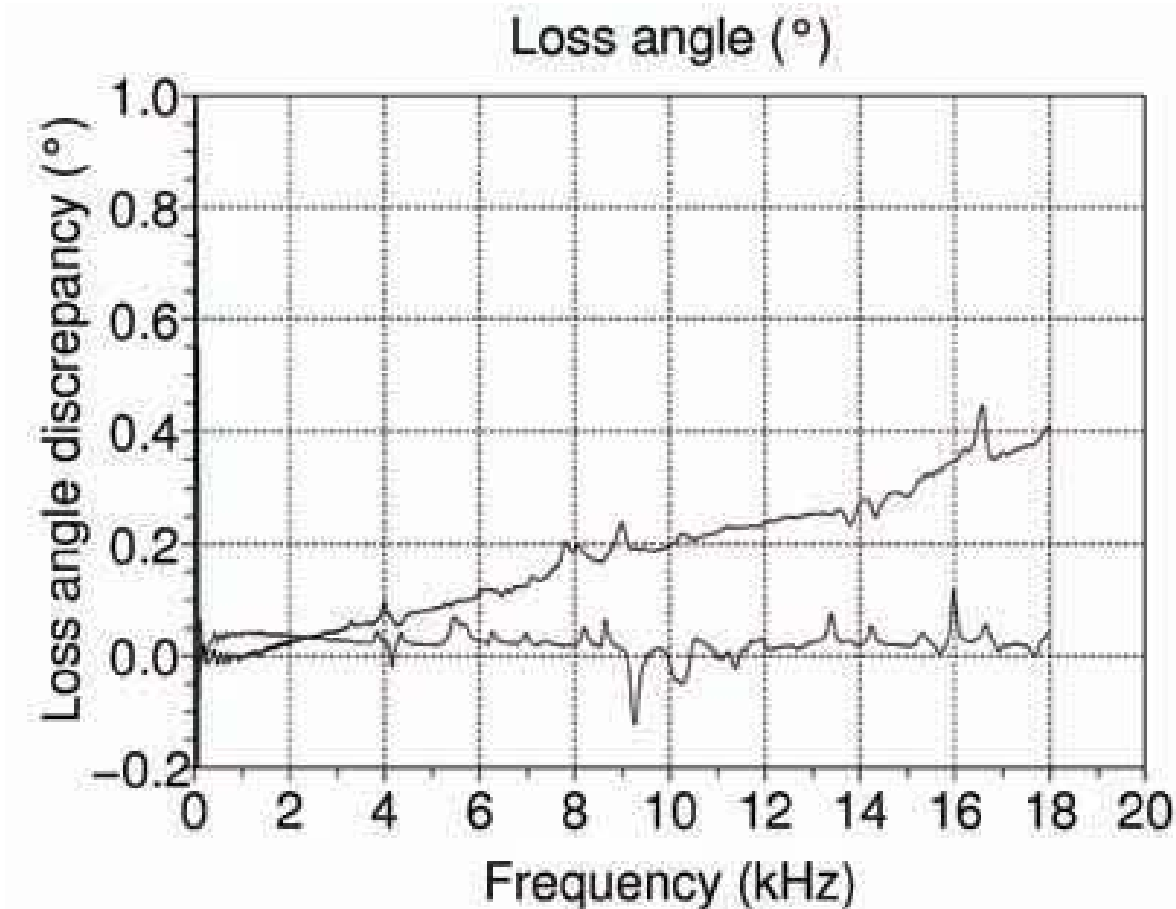


Figure 3. Loss angle versus frequency for aluminum 2017A (lower curve) and reticulated spruce (upper rising curve).

the sensors and the acquisition chain were considered as constant, as evident in Fig. 4.

Figure 4 is a graph of the loss tangent for spruce for exposure to 1kHz vibration versus time. After less than one hour of excitation, there was a significant decrease of the loss tangent (4% compared to the initial value). Thereafter, the normalized loss tangent continued to decline slowly (to the level of 6%), after which it was relatively constant during the vibration run. Finally, the variation of the loss angle was a decrease of 5%. Sobue [3] had proposed molecular rearrangement to explain the behavior of the loss tangent with respect to vibration run. It is possible that the vibration could deliver enough energy to break links between water molecules. If these links were broken, there would be less internal friction, which would explain the significant decrease in the loss tangent. The observed constant value in loss tangent between 150 and 300 minutes in Fig. 4

would correspond to an equilibrium state of the water molecules.

## HYGROMETRIC VARIATIONS

To validate the role of water molecules in the viscoelasticity of wood, the damping of spruce in different hygrometric states was measured. The spruce was the same as that used for making violins. The displacement imposed was a linear frequency modulation with constant amplitude and ranging between 20 Hz and 5 kHz. An initial experiment was performed on spruce before the drying process. Then the spruce samples were dried in an oven. The effect of the drying process was estimated by a mass measurement and the hygrometric equilibrium by weight stabilization. A second measurement was made after 1% mass loss. Measurement of the final state was obtained after 2% mass loss.

For each hygrometric state, measurements

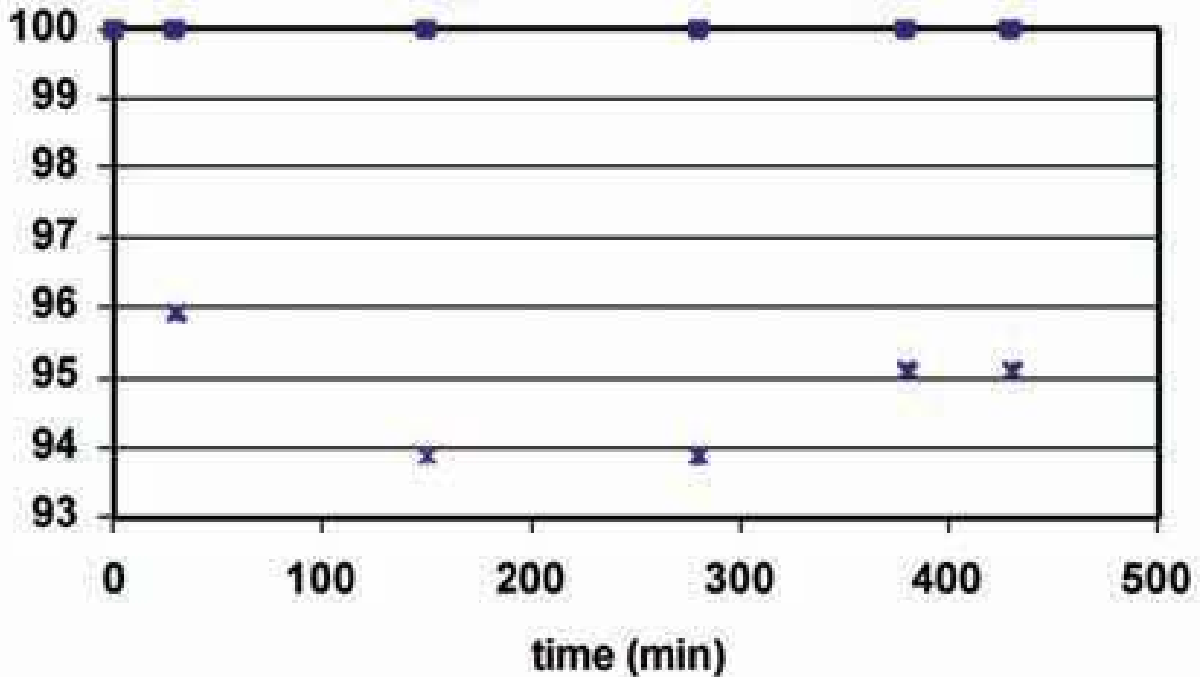


Figure 4. Variation of the loss tangent (normalized to time zero) for spruce (crosses) with run time for exposure to acoustic vibration at 1 kHz. As expected, no change was observed for the same tests of aluminum 2017A (squares), which also verifies the constancy of the measurement sensors.

of the viscoelasticity were performed with both spruce and aluminum, the latter as a reference. The results, presented in Fig. 5, reveal the effect of the relative humidity. The primary observation is that the frequency dependence of the loss tangent decreased when the mass decreased due to the drying process. When the samples were returned to their initial values of temperature and humidity, the measured viscoelasticity apparently returned to its initial value. So, this phenomenon appears to be reversible.

This result indicates that water molecules play a significant role in the damping, probably via internal friction. One speculation is that when a musician plays an instrument, the body warms the instrument, resulting in some drying.

## CONCLUSION

An experimental apparatus and procedures were developed to measure the viscoelasticity of wood over the entire audio frequency range (up to 18 kHz). Direct measurement of the loss angle for reticulated spruce indicated that the damping between 20 Hz and 20 kHz has a linear frequency dependence. Moreover, the absolute value of the damping appeared to be in accordance with

the classical value obtained at low frequency ( $0.05^\circ$  at  $\sim 1$  kHz). A second set of experiments indicated that wood damping is dependent on exposure time to vibration (1 kHz) and humidity. These two results indicate the possible role of water molecules in viscoelasticity of wood—a hypothesis proposed by Sobue [3].

Future viscoelastic tests are planned to determine the magnitude of damping in wood samples of different ages and for a large variety of samples.

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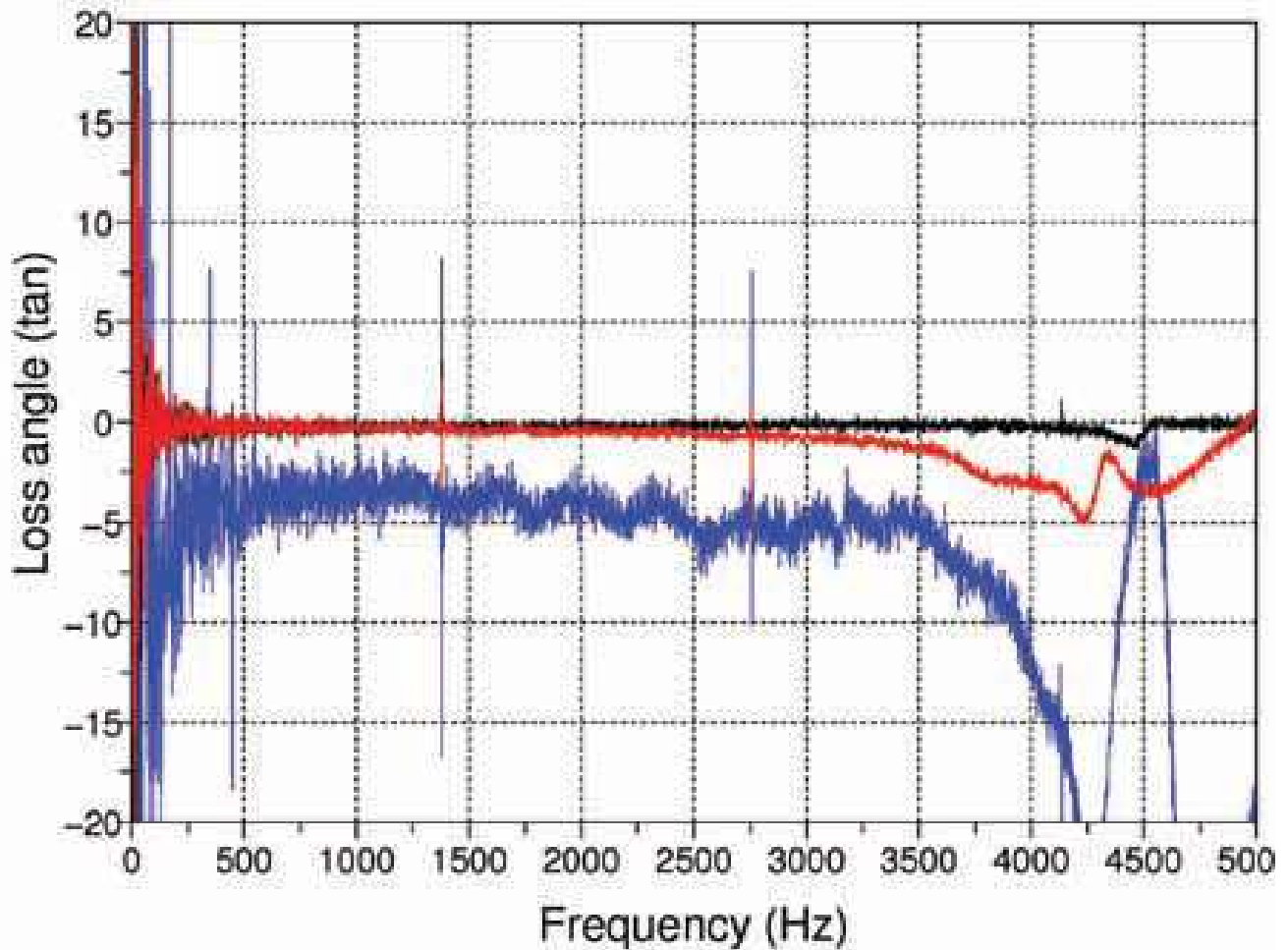


Figure 5. Loss angle tangent for spruce versus frequency for different hygrometric states: blue for initial state (12%), red after 1% mass loss, and black at the equilibrium (2% mass loss).

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