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The effects of wood variability on the free vibration of an acoustic guitar top plate

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Abstract: A finite element model of a bare top plate with braces and a bridge plate was created using orthotropic material properties. The natural variation of the wood properties including dependence on moisture content was also determined. The simulated modes were then compared to experimentally obtained modes from top plate prototypes. Uncertainty analysis was also performed to determine the statistical bound of natural variability between wood samples. The natural frequencies of the model fall within the computed error bound. These results reinforce the importance of obtaining accurate material properties for acoustic guitar modeling.

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1. Introduction

The sound produced by acoustic guitars is a result of interactions of the guitar body and the strings. Although the strings create the main tones of the sound, the dominant acoustic radiation is from the vibration of the top plate. At low to mid frequencies, the radiation of the top plate strongly depends on its mode shapes and natural frequencies, which in turn depend on the material properties, edge boundary conditions, and geometry. To create an accurate model of an acoustic guitar, accurate material properties of the wood must be used.

To model the sound from guitars, several researchers have created computer models using finite element (FE) and boundary element (BE) methods. Torres and Boullasa[1,2] studied the top plate and bridge vibration and radiation characteristics using finite elements and the Rayleigh integral. The back plate was removed so that the top plate was not influenced by the air cavity. Elejabarrieta *et al.*[3] created a structural FE model of the plate, bridge, braces, neck, and sides and used acoustic finite elements to model the air cavity. Both Torres and Boullasa, and Elejabarrieta *et al.* compared their simulations to measurements of guitar mock-ups and found good agreement. Derveaux *et al.*[4] developed a full simulation of a guitar including strings, top plate, and cavity. The strings, top plate, air cavity, and surrounding air were all modeled with finite elements and the radiated sound given a plucked string was computed using a time-marching scheme. A similar but slightly more complicated computer model was created by Becache *et al.*[5] Although these results show great promise for simulating guitar sounds, they do not account for variability in the properties of the wood. Ezcurra published a short study on the influence of material properties but did not include variation in density or variation due to moisture content.[6] Additionally, the sample set from which the range of properties' values was obtained was not well-defined.

This paper presents the modeling of a free-free guitar top plate. A finite element model is created and the results are validated against measurements. The

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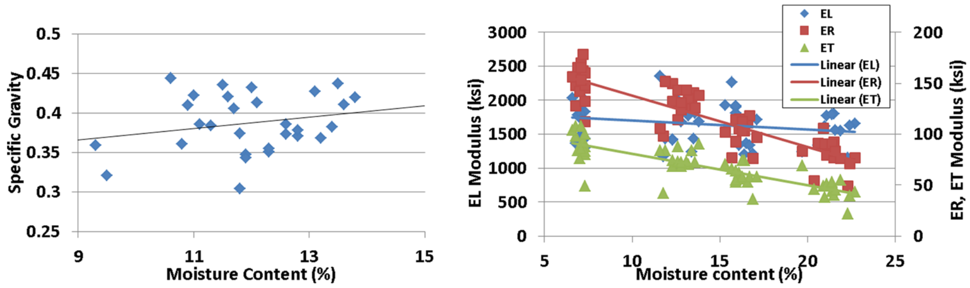

Fig. 1. (Color online) (Right) Sitka spruce modulus of elasticity as a function of moisture content. (Left) Sitka spruce specific gravity as a function of moisture content.

variability of the modal properties is also considered including the effects of moisture content. Uncertainty analysis is then performed based on the natural variability of the wood properties. These results reinforce the importance of obtaining and using accurate material properties to simulate the sound radiation of acoustic guitars

2. Top plate modeling

Wood is known to exhibit anisotropic behavior, meaning that the modulus of elasticity changes with the orientation of the material. For example, wood is typically much stiffer in the direction of its rings than in the directions perpendicular to the rings. The elasticity must be defined for three orthogonal directions, typically referred to as the radial, tangential, and longitudinal directions. The radial direction (R) points from the center of a log in a straight line toward the edge of the log at any angle. The tangential direction (T) points from the edge of the log in the direction perpendicular (90°) to radial (i.e., forms a tangent at the edge of the log). The longitudinal direction (L) points from the edge of the log in the direction of the upward growth of the tree. Wood can be modeled accurately as an orthotropic material, which is a special case of an anisotropic material.

The mechanical properties of wood that are most important for its vibration characteristics are density and elasticity, both of which vary with moisture content. There also exists a natural variation of these properties within the species. Natural variation in the wood properties will then cause variability in the top plate frequencies of vibration.

The material used for the top plates in this study is Sitka spruce. A study by the Forest Products Laboratory published the relationship between Sitka spruce properties and moisture.[7] The elastic moduli are shown in Fig. 1 (right) with linear curve fits, where the elastic modulus in the longitudinal direction (E_L) is over an order of magnitude higher than in the radial and tangential direction. Figure 1 also shows a downward trend in stiffness with increased moisture. As a note, 7% moisture is approximately the moisture of wood used in a modern acoustic guitar. The specific gravity of Sitka spruce, which is a measure of density, is shown in Fig. 1 (left) as a function of moisture content. The specific gravity increases with moisture content. The mean elasticity and density values at 7% moisture content are shown in Table 1 and

Table 1. Average material properties for Sitka spruce at 7% moisture per Ref. 7. The density was extrapolated based on the linear fit shown in Fig. 1.

EL = 1745 ksi	GLT = 125 ksi	vLT = 0.428
ET = 90 ksi	GLR = 124 ksi	vLR = 0.37
ER = 153 ksi	GTR = 6.5 ksi	vTR = 0.248
Density = 0.0127 lbs/in^3		

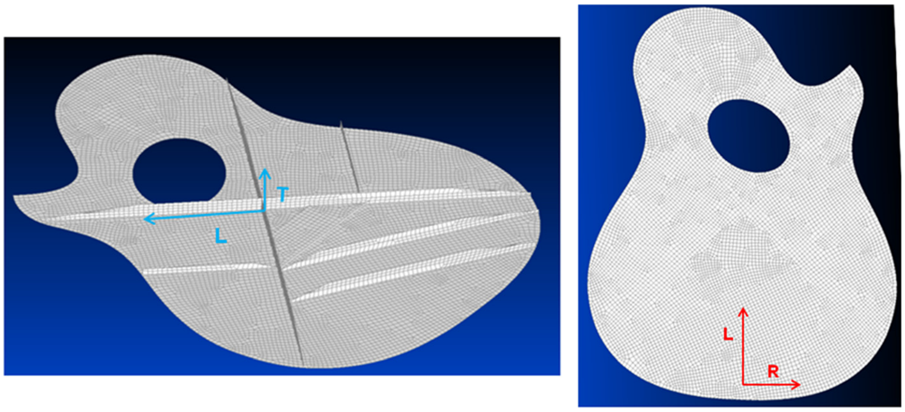

Fig. 2. (Color online) Finite element meshes shown from the (right) top and (left) bottom. The material directions are separately indicated for (right) the top plate and (left) the braces.

were used in the top plate models. Since the density values in the table are sparse and are not reported at low moisture, an extrapolated value was used. Updated values should be obtained in the future.

The top plate and bridge were modeled with shell elements with the appropriate material properties and orientations assigned to each element. The braces were modeled using shell elements oriented normal to the top plate with a base element and a thinner top element to account for the tapered width. The bridge and braces were offset to account for the thickness of the plate and then attached to the top plate with rigid connections. Figure 2 shows the top and bottom view of the finite element mesh. The material orientation of the top plate elements is shown in addition to the orientation for one of the cross braces. The material of the other braces is also oriented with the longitudinal direction along the length of the brace.

3. Experimental validation

A prototype of the guitar top plate was built and tested using experimental modal analysis. The measured and simulated modes shapes and natural frequencies are compared in Fig. 3 and show good agreement, validating the general accuracy of the estimated material properties and the structural modeling technique as a whole. The natural frequency simulations are slightly higher than the measured natural frequencies. This error may be reduced with a solid element representation of the braces.

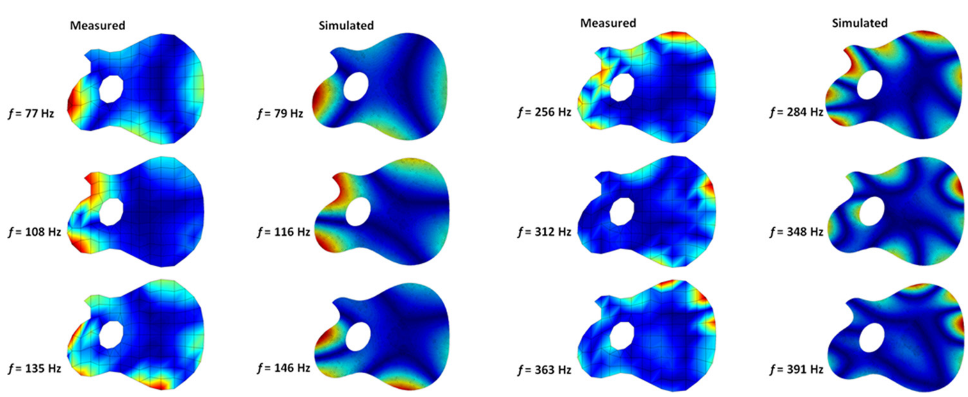

Fig. 3. (Color online) Comparison of measured and simulated modes shapes of the top plate.

4. Model uncertainty due to material property variability

An estimate of the uncertainty in the natural frequency of the guitar top plate can be based on the natural frequencies for a thin plate,

$$\omega = \sqrt{\frac{D}{\rho h}} k_m^2, \tag{1}$$

where k_m is the modal wave number, D is the flexural rigidity (proportional to Young's Modulus E), ρ is the mass density, and h is the panel thickness. Although the actual frequencies depend on anisotropic rigidities, isotropic theory may be used to assess uncertainty. For free boundary conditions, the dependence on E and ρ is the same. By taking the derivative of Eq. (1) and dividing by ω, we determine the non-dimensional relationship of the uncertainties to be

$$\frac{d\omega}{\omega} = \frac{1}{2}\frac{dE}{E} - \frac{1}{2}\frac{d\rho}{\rho} \tag{2}$$

by assuming that only E and ρ have variation and that they are not correlated. The standard uncertainty in natural frequency is achieved by taking the sum of the squares to obtain

$$df = f\sqrt{\left(\frac{1}{2}\frac{dE}{E}\right)^2 + \left(-\frac{1}{2}\frac{d\rho}{\rho}\right)^2}. \tag{3}$$

Using the standard deviation for the differential and the mean for the value (listed in Table 1), df equals approximately 10% of the predicted natural frequency. The mean and standard deviation are listed in metric units in Table 2.

However, Fig. 1 indicates that there may be some correlation between the elasticity and density since they both depend linearly on moisture content. As moisture content increases, E decreases, rho increases, and the aggregate effect decreases the resonance frequencies. In this case, a simple technique for estimating uncertainty given the correlation is

$$\frac{df}{f} = \text{stdev}\left(\sqrt{\frac{E}{\rho}}\right) \Big/ \text{mean}\left(\sqrt{\frac{E}{\rho}}\right), \tag{4}$$

which comes out to be $df/f = 0.08$. Since the published density values from Ref. 7 are sparse, all the density values in Fig. 1 were used for the mean and standard deviation estimates in Eq. (4) with corresponding values of E_L at the same moisture content. This assumes that the standard deviation does not change significantly with moisture content.

Figure 4 plots the percent difference in natural frequency for the measured and simulated top plate. The uncertainty margins of 68% (1 standard deviation) and 95% (2 standard deviations) are included indicating that the models are within bounds set by natural variation. This uncertainty margin may decrease if more data are collected to reduce the standard deviations in Table 2. It should also be noted that

Table 2. The mean and standard deviation of Sitka spruce material properties over all moisture content per Ref. 7 (converted to metric units).

	Young's modulus (GPa)	Density (kg/m^3)
Mean	11.355	386.97
Standard deviation	2.17	36.37

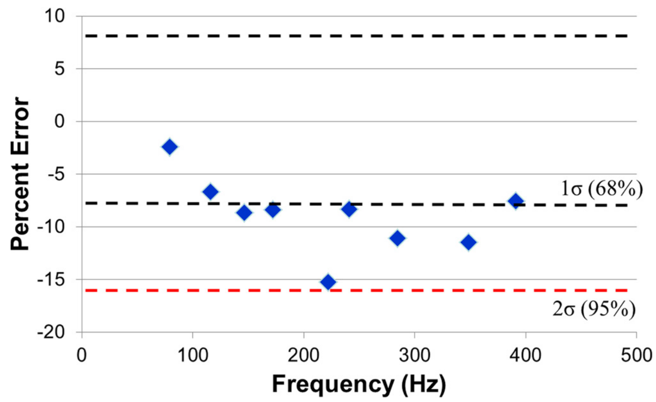

Fig. 4. (Color online) Percent error in the simulated natural frequencies. The 68% and 95% confidence intervals based on uncertainty analysis are also included.

additional variation could exist due to uncertainty in the moisture content of the wood at the time of measurement.

5. Conclusion

The modes of a free-free guitar top plate have been modeled using finite elements with orthotropic material properties. The variability of the wood properties was also considered including the effect of moisture content. The measured modes and natural frequencies compared favorably to measurement. Uncertainty analysis was then performed using the normal variance of the wood properties based on published values. These results indicate the importance of using accurate material properties in models of acoustic guitars.

Acknowledgments

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