Carbon Fiber vs. Wood as an Acoustic Guitar Soundboard

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PHYS 207 term paper

Introduction

Virtually all stringed instruments have been built out of wood since stringed instruments were first conceived in ancient Egypt. Guitar making is one of the few modern markets where 50-year old technology is considered to be most desirable. However, with advances in carbon-fiber epoxy composites and other synthetic materials in the last few years, guitars made with manufactured materials now have sound quality comparable to conventional wooden guitars.

Background

Acoustics of the Guitar

The sound a listener hears from a guitar comes from different sources. Most of the low frequencies (80-150 Hz) comes from the interactions of the air cavity with the top and back of the guitar. The lowest resonant frequency is called the helmholtz frequency, and is primarily a function of the volume of the guitar body and the diameter of the soundhole (Rossing, 2002).

Much of the sound in the 150 to 1000 Hz range is determined by the overall size and stiffness of the soundboard of the guitar. A small portion of sound is contributed by the back plate, depending on how the guitar is held. The material, the bracing pattern, and the geometry all define the sound of a guitar in this range.

In the higher acoustic range (greater than 1kHz), it becomes difficult to characterize what makes up the tone. In conventional wooden guitars, damping of the wood increases quickly (Decker, 1999). Other factors include local stiffness of all the bracing, the stiffness and internal damping of the soundboard, the adhesives used, the stiffness of the neck, properties of the bridge and strings, and basically everything else on the guitar. Although everything makes a difference, not everything makes a noticeable difference. For this reason, no analysis was conducted above 1kHz.

For the purpose of this paper, I will consider mainly the tone of the guitar in the lower-mid acoustical range from 80-1000 Hz. This is reasonable because the entire playing range of the guitar fits within this range. The open strings are tuned to 84, 110 147, 196, 247, and 330 Hz and the highest possible note is 986 Hz.

Overview of Carbon Fiber

Carbon fiber composites were pioneered in the 1960s and have found major use in light and stiff aircraft structures. Over the years, the market has expanded into the sports and auto areas. Carbon fiber begins as a polymer which is extruded into very fine threads (on the order of 5 microns in diameter). These threads are bunched together into groups of 3000 or more, then woven into fabrics. The fabric can then be laminated in different ways and infiltrated with epoxy to make it stiff.

Carbon fiber has been used in musical instruments since the mid-1970's for prototype and limited production models. A guitar with a carbon fiber top plate was presented at meetings of the Acoustical Society of America as early as 1975 (Haines, Chang, Hutchins 1975). In the mid 1990's, Rainsong guitars began producing carbon fiber guitars, but in limited volumes (Decker, 1995). Several years later, Rainsong developed a new construction technique know as projection tuned layering (Decker, 1999), which eliminates the need for internal bracing of the soundboard of composite guitars. Composite acoustic guitars have also been found to provide very good tone with electronic pickups (Gerkin, 1999).

Discussion

A Yamaha FG401 acoustic guitar was chosen as a representative conventional wooden guitar for the purposes of this analysis. A carbon fiber guitar was designed and built (J. Hiller, S. Probert, 2006) within the Department of Mechanical Engineering to closely emulate the modal frequencies of the FG401 guitar top (See Figure 1). The body was designed and built without internal bracing in a manner similar to projection tuned layering.

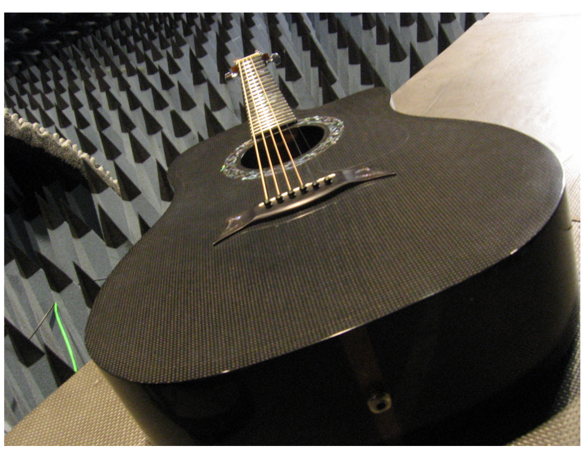

Figure 1: Completed carbon fiber acoustic guitar

Computer Modeling

As a part of designing this guitar, computer models were analyzed to determine the optimum layup parameters for the carbon fiber composite body to emulate the conventional wooden guitar sound. To do this, a composite guitar was first modeled in 3D, then imported into ANSYS, a finite element program. Finite element analysis programs output a wide variety of data based on the geometry, materials, and conditions imposed on the model. For instance, they will calculate the modal shapes and frequencies of the guitar top based on the material properties of the exact layup being examined. After performing tests to correlate finite element results with actual physical tests, layup parameters were optimized to the design requirements.

Unfortunately, the boundary condition of the top where it joins the sides of the guitar is not well known. Although the position of the edge can be considered fixed, the angle is not necessarily constrained. Therefore, both fixed (rigidly clamped) and free (hinged) rotational boundary conditions were considered. Thus, the computer models did not output exact modal frequencies, but a range. The first four mode shapes for the hinged-edge case as calculated by ANSYS are shown in Figure 2.

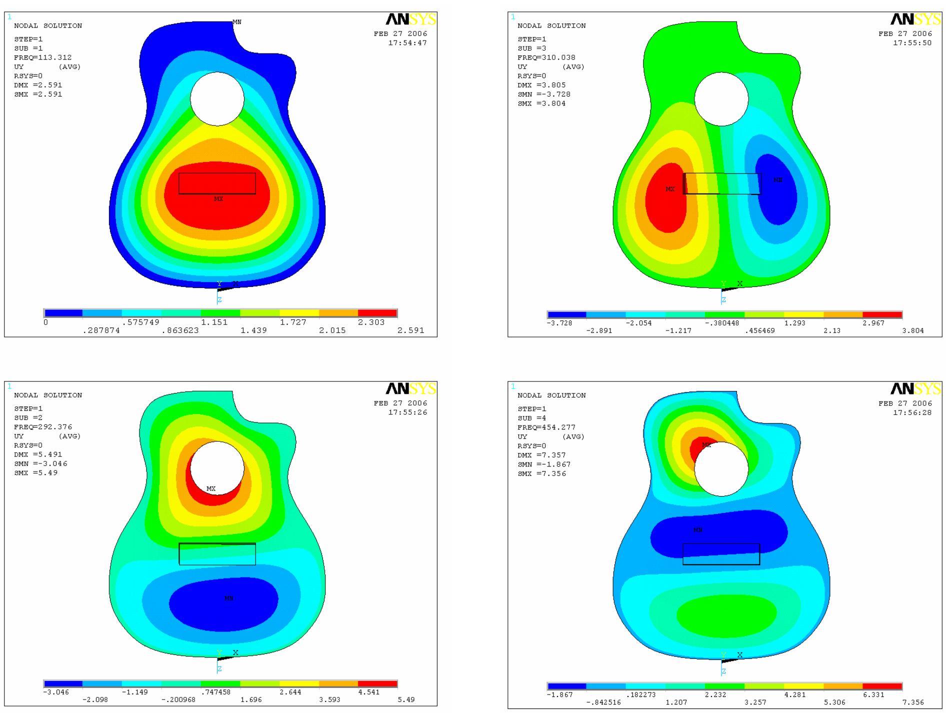

Figure 2: First four mode shapes of a composite guitar soundboard

In the final iteration, the first five calculated modal frequencies for the soundboard in the hinged and fixed condition are shown in Figure 3. A "P" factor of 0.5 (halfway between fixed and hinged conditions) was assumed and the computer model was manipulated to minimize the error between the FG401 data and the P=0.5 case. Exact agreement could not be obtained because the bracing of wooden guitars changes the relative modal frequencies, but errors were minimized to an average of 10%.

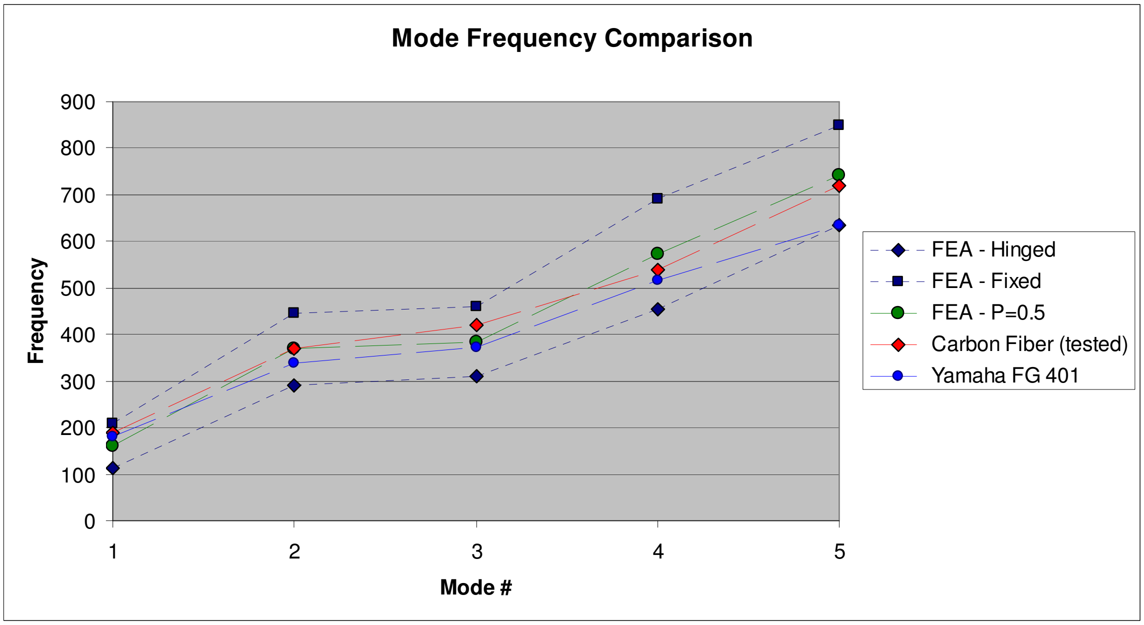

Figure 3: Mode frequency comparison. Average difference between FEA (P=0.5), FG401, and carbon fiber guitars was around 8 percent.

Comparison Data

Once construction of the carbon fiber guitar was complete, analysis was conducted directly comparing it to the Yamaha acoustic guitar. The acoustic response of the soundboard of both guitars was tested using a PolyTek OFV 2600 laser vibrometer. This instrument allows very precise, touch-free sensing of vibrations, but only at a single point. Use of holographic interferometry would be needed to actually view the mode shapes of the finished guitar (Jansson, 1971), but unfortunately no such equipment was available.

Free response

First, the transient response of both soundboards was analyzed. The strings were damped so that they did not vibrate and affect the raw resonances of the body. The laser vibrometer was then focused on a central spot on the soundboard, slightly off-center to pick up portions of all the lower modes. The soundboard of the guitar was then mechanically excited by tapping it either with a finger or a rigid mallet. Tapping with the finger brings out the lower modes (less than 500Hz), while the mallet excites the higher modes more. The response of both guitars to finger-tapping excitation is shown in Figure 4.

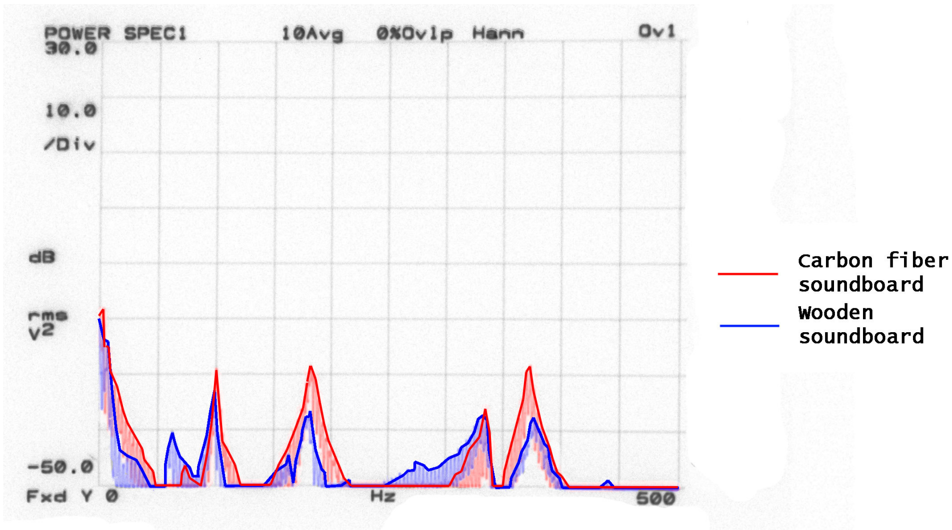

Figure 4: Frequency response of carbon fiber vs. wood soundboards

The first and most obvious observation is that all the major peaks have very similar frequencies. Thus, the carbon fiber guitar was successful in emulating the modal frequencies of the wooden Yamaha guitar. The first main peak at 100HZ is the helmholtz resonance. Since this is a function of the volume of the guitar and the diameter of the soundhole (which were kept the same between the two guitars), it makes sense that these peaks are very similar. The peaks just below this (at 65/80Hz) are the beam bending mode of the guitar, where the whole guitar (including the neck) is bending like the first mode of a beam. Since the carbon fiber guitar is stiffer, the peak occurs at higher frequency and is less intense. Both values are within typical ranges for this mode given by French and Hosler (2001).

The peaks at 190, 370, and 420Hz are the first 3 modes of the soundboard (Results for the first 5 modes are shown in Figure 3). The average difference in the modal frequencies between the FEA analysis and the actual carbon fiber guitar was 7 percent. Average difference between the two guitars was 8 percent.

The shape of the peaks in Figure 4 gives some clue about the timbre of the sound. The peaks of the wooden soundboard are somewhat more spread out, which gives the guitar a more mellow sound. The carbon fiber soundboard has narrower, more uniform peaks which gives it a crisper sound. In addition, the peaks of the carbon fiber soundboard are generally higher, which means the guitar is louder, or more efficient at transferring the energy to the soundboard.

Forced response

In addition to the transient response, both guitars were analyzed by recording the response of the top to the plucking of each open string. This shows the transmissivity of the soundboard to each note as it is actually played, which yields the overall response of the guitar while playing. The results for all 6 strings are overlaid and shown for the FG401 in Figure 5 and for the carbon fiber guitar in Figure 6.

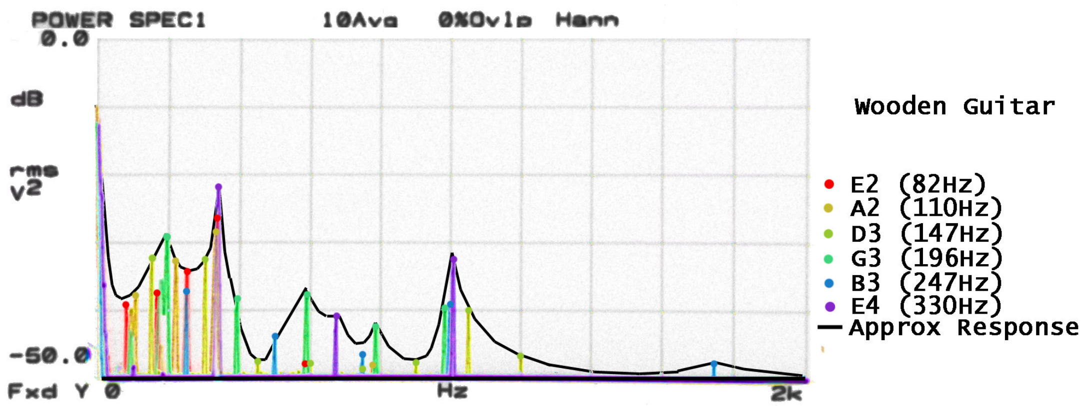

Figure 5: Response of Yamaha FG401 to plucked open strings

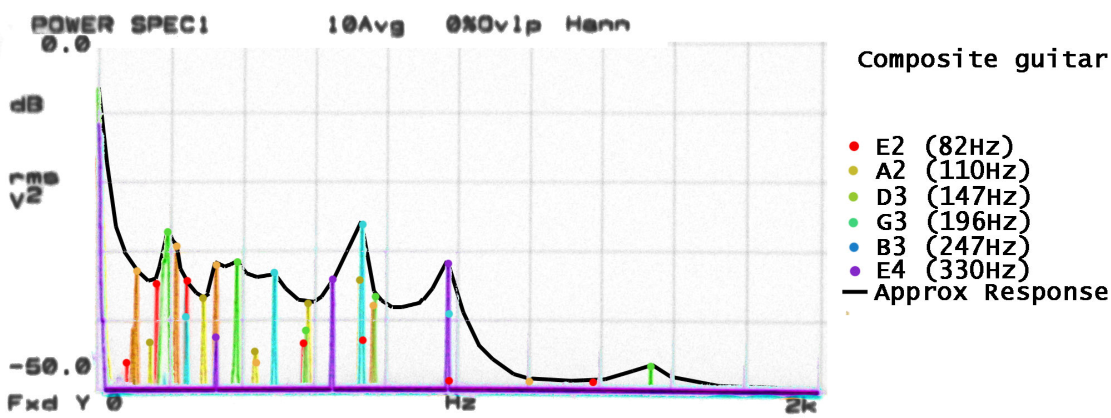

Figure 6: Response of carbon fiber guitar to plucked open strings

Not surprisingly, there are noticeable peaks at the transient resonances of the guitars. The first and second modes are the most obvious, at approximately 200 and 370Hz. The resonances tend to die out at around 1kHz, further verifying the assumption made earlier to disregard higher frequencies in the design of the soundboard. Over the 0-1kHz range, the composite guitar seems to have a more constant response, which is desirable. In the future, a frequency sweep could be done to obtain a more complete curve.

On a side note, this is an excellent experimental verification of musical interval addition. For example, the 3rd harmonic of the E2 string very nearly coincides with the fundamental of the B3 string. This is because the B3 is one octave plus one fifth above the E2. Also, the imperfections of equal temperament can be seen at the 7th harmonic of A2 vs the 4th harmonic of G3 in Figure 6 at 770Hz. Although these notes theoretically should coincide, they are off by about 10 Hz (30 cents).

Conclusions

Based on experimental (and auditory) evaluation, carbon fiber has been demonstrated to be comparable to wood for use in an acoustic guitar body. From a listeners point of view, the carbon fiber guitar has a pleasant sound that is a little more focused and crisp, with significantly more sustain than the wooden guitar. The lower modal frequencies can be accurately measured and were found to compare favorably with those of the wooden guitar it was designed to sound like. In addition, it has been shown that computer models can predict the basic acoustics of a carbon fiber guitar with reasonable accuracy, which has great implication for the future of tailoring the sound of an acoustic guitar to each musician's preference.

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