FEATURE *Testing of Acoustic Stringed Musical Instruments: Part 3*

by M. French and D. Hosler

THE MECHANICS OF GUITARS

This is the third in a series of articles on testing musical instruments. The first article[1] introduced the subject and the second[2] described the basic mechanics of stringed instruments. This one deals specifically with mechanics and testing of the guitar. The fourth and final article will deal exclusively with violins. This article discusses acoustic guitars, since the mechanical properties of electric guitars (particular those with solid bodies) are generally a secondary contributor to the sound.

Guitars are currently manufactured in a wide range of sizes, designs and materials. As a result, specific descriptions cannot apply to many instruments as is possible with the more standardized violin. Even so, most guitars share the same basic features. The body is usually made of wood, though some popular models have significant portions formed from composite materials. The top is very thin and stiffened on the inside with surface mounted wood braces as shown in Figure 1. The neck is usually made of wood with a steel, aluminum or graphite reinforcement rod.

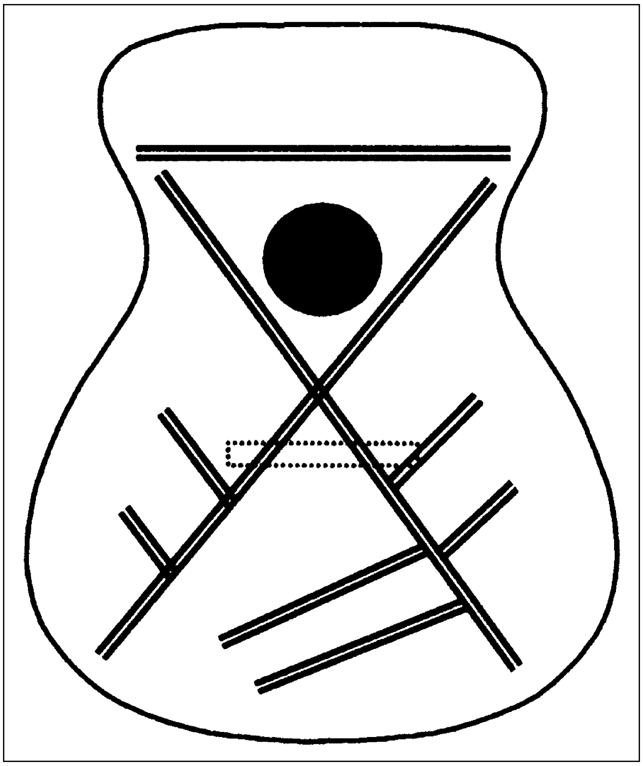

Fig. 1: A typical "X" bracing pattern

Structural Concerns

The structure of an acoustic guitar is a careful balance between stiffness and flexibility. It must be stiff enough to resist the tension of the strings without unacceptable deformations while still being flexible enough to deform in response to the string vibrations.

The only significant static loads on the instrument are from the strings. String tensions vary greatly with the material and diameter of the strings. Nylon strings are used almost exclusively on classical guitars and require relatively low tension in order to achieve proper pitch—typical tensions are on the order of 8–10 lbs/string. Steel strings can require tensions of 20 lb each. Note that the diameters of the six strings are usually different, with the higher pitch strings being smaller in diameter. Thus, the tension is on the same order for all six strings. Note also that the lower pitch strings are wound with wire, often bronze. The purpose is to increase the mass without requiring a heavier and unacceptably stiff load-carrying core.

The load carrying structure of the guitar can be divided between the body and the neck. The neck is essentially a cantilevered beam, though the boundary condition is only approximately clamped. The most interesting structural feature of the neck is the truss rod, an internal reinforcement used to increase the stiffness of the neck and sometimes to counteract the deformations due to string tension.

Adjustable rods appear in many different forms, but most use tension in a steel rod set into the neck to develop an internal force that counters deformation due to string tension. Some instruments use a non-adjustable reinforcement—often steel, but less often graphite. Some designs even combine the two, though they would seem to act at cross purposes. Classical guitars are usually built without truss rods, since the low string tension does not appreciably bend the neck.

The load carrying structure of the guitar body is much more elaborate. The top is usually made of thin solid wood or plywood. Thickness is usually in the range of .095″–.125″. The top is reinforced with wood braces glued to the inside of the top. Bracing designs vary greatly and are the subject of lively debate. Since they are one of the few structural elements of the guitar that can be modified after construction, trimming the braces is a common way of modifying the tone of completed guitars.[3]

One of the subtle features of steel string guitars is that they usually have curvature built into both the top and back plates to increase buckling resistance. These plates are manufactured in spherical forms with radii in the range of 15–50 feet. Typically, the back has a much shorter radius than the top and some tops are nearly flat. Classical tops and backs are usually flat.

The soundhole serves as a port for the enclosed air in the body, which is effectively a Helmholz resonator. It also pro-

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M. French (SEM Executive Board Member) is Senior Engineer, Robert Bosch Corporation, Braking Systems Division, Farmington Hills, MI. D. Hosler is affiliated with Taylor Guitars, El Cajon, CA.

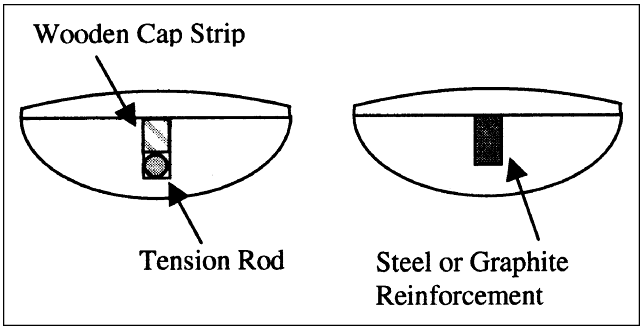

Fig. 2: Neck cross-sections

vides the only access to the interior of the instrument and is usually large enough to accommodate a man's hand. The soundhole is usually on the centerline of the instrument between the bridge and the neck (right about where the load path from the bridge to the neck would ideally be). Because if its location, the braces and top must transfer the string loads around it. A few guitars have been made with offset soundholes, at least partially in order to simplify the structural problems, however, they have not become particularly popular.

Modal Response

The dynamic response of the guitar structure is intended to couple easily with that of the strings. The standard tuning[4] for a 6 string guitar is E_2 A_2 D_3 G_3 B_3 E_4 (approximately 82, 110, 147 196 247 and 330 Hz respectively), though alternate tunings are regularly used. "Drop D" (DADGBE) and DADGAD are relatively common examples. It is very uncommon for guitars to have more than 24 frets. Since 24 frets correspond to 24 semi-tones and, thus, two octaves, the range of fundamental frequencies for guitars is approximately 80–1320 Hz.

The strings, by design, contain much of the kinetic energy of the system. In tests for which the instrument is strung, clearly, they should be tuned to correct pitch before any data is recorded. In addition, it has been the experience of one of us (DH) that using new, high-quality strings makes a very noticeable difference in subjective sound quality. Indeed, some professional musicians change strings daily.

Different bracing designs combined with different body geometry mean that the modal response of different instruments varies. However, the first few modes are generally similar. The following discussion thus applies to conventional designs excluding archtops.

In all cases with which the authors are familiar, the first mode of the freely suspended instrument is a beam bending mode. A typical example, shown in Figure 1, was measured from a Martin parlor guitar circa 1910. This mode has a frequency of 85 Hz. One of us (MF) has observed this mode on several different instruments and has found it between 65 and 85 Hz.

Both the structure and the enclosed air volume have resonant modes, though they are well coupled. The first body mode is usually closely related to the first air mode, designated A_0. This mode is often called the Helmholz resonance and clearly has the character of such a mode. Strictly speaking, though, it is not a true Helmholz mode, since the ideal Helmholz resonator has rigid walls. On a freely suspended guitar, the A_0 mode includes significant motion of both the top and back. For a typical full-size acoustic guitar, the A_0 mode may have a frequency on the order of 100 Hz. One of us (MF) has measured an A_0 mode at 100 Hz on the Taylor dreadnought shown in Figure 4. Similarly Rossing[5] reports a frequency of 102 Hz measured on a Martin D-28.

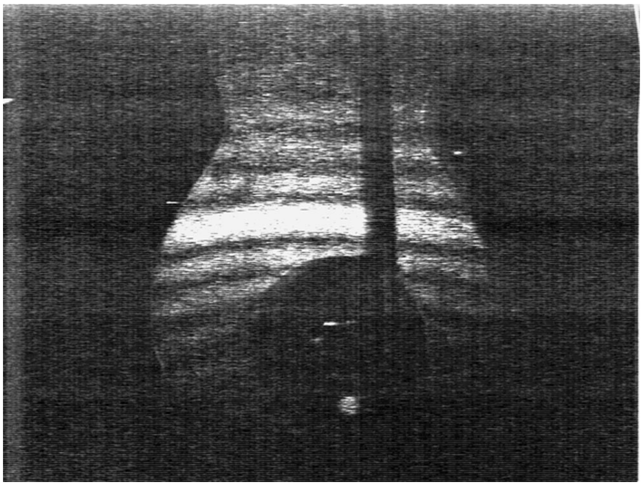

Fig. 3: Electronic speckle pattern interferometry image of body bending mode–1910 Martin

There are typically no node lines in this mode (other than at the edges) and the top and back move out of phase to alternately increase and decrease the cavity volume as shown in Figure 5.

For obvious reasons, this mode is sometimes called a breathing mode. A typical example from a Yamaha APX–SPLI steel string guitar[6] is shown in Figure 6. This instrument is slightly smaller than the typical full-sized instrument and exhibits this mode at 116 Hz.

Some investigators have partially buried instruments in sand to immobilize the sides and back. Occasionally, the tops are also at least partially immobilized in this way. Under these conditions, flexibility of the cavity walls is greatly decreased and the physics more clear match those assumed for the Helmholz resonator. Understandable, the increased impedance of the structural-acoustic system increases the natural frequency. Rossing[5] reports a measured frequency of 121 Hz for the Martin D-28 with the sides and back immobilized.

The next mode is typically one in which the top and back move in-phase so that the body volume does not change. When viewed from the top, this mode bears a strong resemblance to the A_0 mode with the primary difference being the phase relationship between the top and back. This mode is expected in the neighborhood of 200 Hz. For example, the Yamaha exhibits this mode at 224 HZ while Rossing reports a frequency of 193 Hz for the Martin D-28.

Fig. 4: Taylor Dreadnought Guitar

Testing Considerations

Test conditions are dictated by the light structure of the body of the guitar and the subtle nature of sound quality descriptions.

When testing any musical instrument, it is important to make sure the acoustic environment is suitable. The background noise should be low and the space in which the instrument is tested should be as free from acoustic resonances as possible. Ideally, acoustics testing should take place in a hemi-anechoic or fully anechoic space. The top and back of the instrument are designed to radiate efficiently in response to string vibrations and thus the reciprocal is also true—they vibrate readily in response to extraneous acoustic noise in the test environment.

Picking the right sensors is a prime concern for the test engineer. Surface mounted sensors are not attractive because they can add unacceptable mass to the very light structure. Miniature accelerometers can be used, though the sensitivity is often not high. In addition, any surface mounting method (wax, glue, etc.) is likely to concern the owner of any good instrument. Though expensive, optical methods are preferred for structural testing. Double exposure holograms, laser doppler vibrometers and electronic speckle pattern interferometers have all been used with success.[7,8]

Finally, there are signal processing considerations. Structural damping of guitars is almost always quite low and several seconds may be necessary to completely observe the impulse response when strings are not damped. Indeed, musicians seek instruments with good "sustain", i.e. low damping. When recording radiated sound, it is often necessary to use sample frequencies greater than 40 kHz in order to resolve the human hearing range of 20 Hz to 20 kHz. The result can be relatively long (by modal standards) data files.

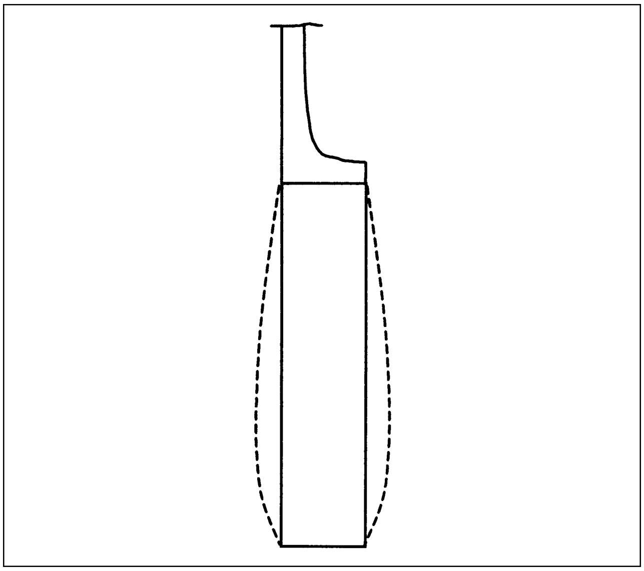

Fig. 5: Typical A_0 mode

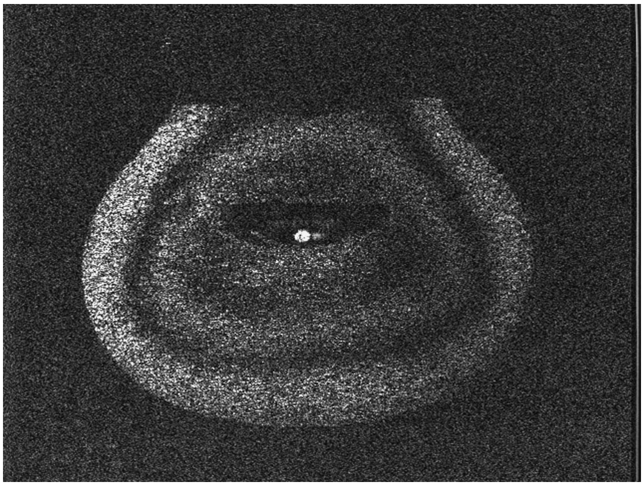

Fig. 6: Electronic speckle pattern interferometry image of A_0 mode

Sound Quality

Although sound quality is one of the most subjective areas one could discuss, it is also the very reason for efforts to understand the mechanics of guitars. This is where science and art walk parallel paths yet sometimes have difficulty meeting one another. Attempts to describe sound quality with numbers, graphs, and even words,[9–11] somehow fall short of the experience of listening itself. To the player, the combined qualities of an instrument must provide a vehicle for expression and inspiration. To the listener it is the projection of that talent and creativity that must be experienced. An instrument's ability to provide these things would be considered a realistic measure of sound quality.

It is often easier to describe what is bad than what is good when talking about sound quality. There are, however, a few concepts that have emerged over the years that are generally considered qualities of measurement or comparison for steel string acoustic guitars. The distinctive mix of these factors in a given instrument combine to produce what we describe as sound quality, tone or timbre. We commonly use words such as warm, bright, transparent or harsh to express those perceptions.

We have not broken these down into objective term, but have rather looked for something between the science and enjoyment perspective.

Sound Projection: The ability to project sound outward. The player and the audience can have very different listening experiences.

Note Clarity: The ability of individual notes to played and perceived well by both performer and listener along with the harmonic qualities expected in a given tone.

Sonic Balance: The ability to have an appropriately balanced mix of both highs and lows.

Sustain: The duration or length of a note from the time of being played.

Headroom: The ability of the instrument to express dynamics.

Material Translation: The ability of an instrument to reflect the known qualities or characteristics of the material (wood) it is made of. Specific materials are used for instruments partially because of the tonal qualities they impart.

The proportional or artistic combination of various factors in design, construction techniques, and materials, ultimately produces the mix of these qualities into what we perceive as distinctive sound quality.

Efforts to describe sound quality in objective terms are still far from authoritative.[9–11] Even the relationship between the modal response of a given instrument and its acoustic radiation poses challenges. As an example, Figure 7 shows the sound spectrum recorded from the Taylor Dreadnought playing a G-major chord. The individual notes are clearly resolved even though several of the peaks are not near measured natural frequencies.

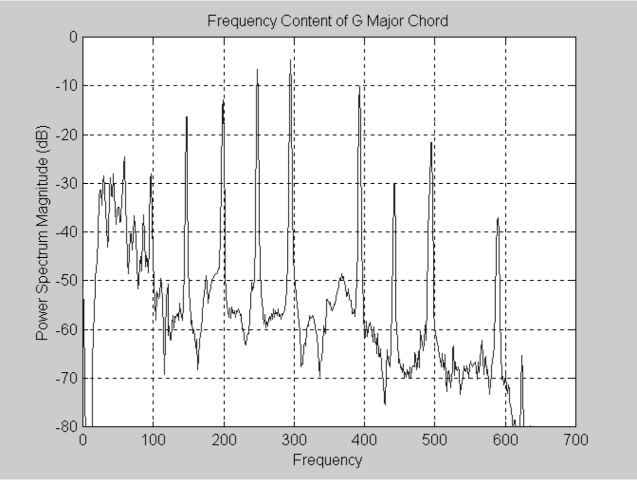

Fig. 7: Measured spectrum of Taylor Dreadnought playing G-major chord

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