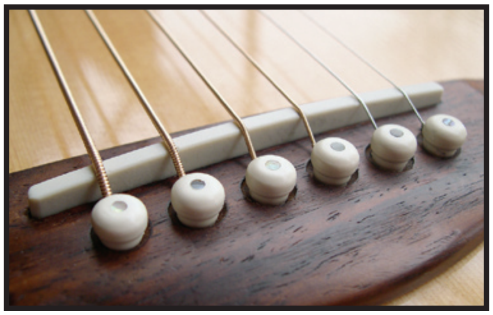
The Acoustics of the Guitar

The science behind acoustic guitar tone

What are the magical properties that make a quality guitar sound so spine-tingling good? When you strip away the tradition, the romance, and a little luthier voodoo, the answer is firmly grounded in science...



Acoustic guitars are fundamentally designed to convert the mechanical energy of string vibration into pressure waves that are transmitted to the ear through the air.

How does the guitar produce sound? A player plucks a string and sets the string into a complex pattern of vibration that consists of a fundamental and many partials. The string moves few molecules of air – certainly not enough to create pressure waves of a significant magnitude the ear could easily pick up. Very little of the sound heard from a guitar comes directly from the vibrating strings. Rather, the strings transmit the energy to the soundboard via the saddle. The saddle acts as a selective filter, allowing only some frequencies of the vibrating string through to the soundboard. The board imposes its own characteristics on the frequencies it receives, suppressing some and enhancing others. The air in the cavity and the structural members also influence the sound by interacting with the soundboard.

Let's take for an example an open string played on an acoustic guitar. When the string is plucked with a pick (or finger), the pick initially puts a kink into the string. With just a little more pressure, the string slides off the pick. Next, the kink traverses the length of the string, hitting the saddle. Here the kink transfers some of its energy through the saddle to the bridge, which then meters the energy to the flexible soundboard, or top, of the guitar. The kink is immediately reflected back toward the nut. Because the nut is set on the solid and stable neck, little of the kink's potency dissipates there.

The kink is reflected back and forth from nut to saddle. On each traverse, the kink transfers some energy through the saddle. The string finally comes to rest after transmitting all its energy to the soundboard and, to a lesser extent, to the air surrounding the string.

The speed with which the kink travels depends on the mass per unit length (the thickness) and the tension of the string. The combination of the speed of the kink with the distance it travels - that is, the length of the string - defines the rate of vibration. Thus, a kink that makes 440 round trips a second produces the A above middle C. This is the "A=440 hertz", or "A 440", known to all musicians and represents the fundamental tone of that string.

The guitar string actually vibrates in a much more complex manner than we have described so far. While oscillation at 440 hertz, the string is also vibrating in halves, near 880 hertz. Simultaneously, the string vibrates in thirds, near 1320 hertz; in fourths, near 1760 hertz; and so on. These various modes of vibrations are known as partials, overtones or harmonics.

Strings would like to oscillate as closely as possible to harmonic partials, or whole-number multiples of the fundamental. In practice, the partials do not occur at precisely those simple ratios, because strings have thickness (mass) as well as length, which lends them "inharmonicity," or an inability to vibrate harmonically.

Because the string has modes of vibration other than the fundamental, the saddle must deal with the energy of all the partial vibrations as well as the fundamental vibrations.

Here's where the saddle comes into play: The saddle tends to be discriminating. It governs the strength of the excitations produced by some partials and may deny others any access to the soundboard. It also meters the rate at which energy is transferred from the string to the board.

The efficiency with which the saddle-performs these chores depends on what is called the impedance match between the string and the soundboard. A perfect impedance match, with no obstruction or reflection from the saddle, would allow all the energy of the vibrating string to be transferred to the board at once. The result would be a loud and not too musical "bang", with no sustain. A poor impedance match would have just the opposite effect. It would take a long time for the energy or the vibration string to dissipate (sustain), but little sound would be heard.

The challenge is to balance the impedance of the strings with the guitar top, combined with the right musical filtering, provided by the saddle, to allow the *appropriate* frequencies to excite the soundboard (tone) while *denying access* to other frequencies and keeping them in the string (sustain).

The soundboard's efficiency depends on its shape, thickness, mass distribution and grain pattern as well as the characteristics of the bridge and the bracing glued to the underside of the soundboard. A good luthier will meticulously sculpt the bracing to "voice" the guitar.

The soundboard is like a loud speaker and can vibrate at the significant frequencies. But it also has eigenmodes, or normal modes of vibration, that occur at favored frequencies. At these frequencies, the soundboard resonates with much greater amplitude than at other frequencies and thus imposes its own characteristics on the energy imparted it by the vibrating string.

The sections of the soundboard that vibrate with the greatest amplitude are usually located away from the area directly beneath the vibrating saddle. You can observe this by the use of Chlandni Patterns*. This observation shows the importance of the proper impedance match between the strings and the soundboard. If the area where the string crosses the bridge moves a great deal, the energy of the vibrating string would be transferred too readily, resulting in musically undesirable sound.

Almost every location on the soundboard moves a fairly large amount at one or more frequencies. The entire board at one time or another participates in some modal behavior.

A modal analysis also uncovers a wealth of detail impossible to achieve through the use of Chlandni patterns alone. These details reveal that the back and sides of the guitar are actively involved in the vibrational motion. In fact, at some low frequencies, the amplitude of motion of the back rivals that of the soundboard.

The wood is not the only part of the guitar that moves. Because the instrument has a bottom, the whole forms a box enclosing a volume of air. When the soundboard moves, the air mass also vibrates. And like the board, the air had favored modes.

We do not know the precise interplay between of the air and wood. The air-cavity modes cannot contribute directly to the sound radiated from the guitar. But this is not to say the air modes are unimportant; the presence of the air can and does affect the behavior of the sound board.

The strings do not directly communicate with the air cavity; only the motion of the soundboard can excite an air mode. But the air can indirectly affect this process by influencing the motion of the board. The soundboard may excite an air mode in the absence of a resonance of its own if the soundboard can move with enough amplitude to excite the air mode's hot spot.

The air modes can also influence the board by behaving as a load or by acting as an internal spring. In addition, physical coupling can occur if the mode shapes of the board and air are similar and if their resonant frequencies are close. Together the air and soundboard interact to suppress some frequencies and enhance others.

There is one last source of coloration that gives the guitar its sound: the human ear. One of the characteristics of a good guitar chord it its strong bass. But the fundamental of a bass string is not particularly loud. If it were, the string would be vibrating with great amplitude, slapping against the soundboard and the other strings. How then does the ear perceive a distinctive, powerful bass?

The answer lies in the psycho physiological phenomenon called heterodyning, a useful term borrowed from electrical engineering. Bass strings have a rich structure of prominent partials. (Treble strings appear to oscillate with fewer partials than bass string because most of the high-frequency partials lie beyond human hearing.) The brain uses these partials to identify the bass notes of the guitar.

Take as an example the low E on the guitar. Although the fundamental is physically present in the vibrating string, it is a weak component of the collection of frequencies that reaches the ear. The brain, however, recognizes that the partials belong to the compact collection of closely related frequencies that make up the pitch of low E. It has no trouble supplying a frequency of its own. Heterodyning is the same process by which one can recognize a deep voiced friend talking on the phone, a device whose speaker is too small to vibrate strongly at the lowest frequencies of a voice.

The ear provides another sort of coloring as well. The auditory mechanism "hears" the high pitches of instruments very well, but in the bass register, it is quite inefficient. To compensate, musical instruments use far more energy to produce low pitched sounds than high pitched ones. For instance, a properly constructed guitar generates more power in the bass that in the treble. Interestingly, the net result is an even perception of sound level over the entire range of the instrument. ■

** Named for the German physicist Ernst F.F. Chlandni which can provide a graphic way of demonstrating the vibrational patterns of plates and membranes. To study the resonance of the guitar top visually, decorative glitter is spread evenly over the surface of the soundboard. When the sound board vibrates, the glitter bounces out of the regions that are moving and collect in areas where the soundboard is not vibrating. The glitter surrounds the areas of maximum motion.*