Fine Tuning

By Alan Carruth

I've been working toward a rational understanding of guitar acoustics for nearly as long as I've been making guitars (more than twenty years now). It's probably a task that will never be completed. The hall mark of a good guitar is the breadth of its response and that comes from the complex way it behaves when driven by the strings.

Up until fairly recently it took a well-equipped laboratory to get useful information on the response of a guitar. Before the middle 1960's almost nothing was known about real guitars and theorists proposed various models “in the dark.” A good model started to emerge in the middle '70s. As the price of measurement equipment, and particularly computers, has fallen in recent years there has been a steady increase in the information available to builders and an improvement in the theoretical framework to make sense of it.

So far, the best results in understanding the guitar have come about through the application of “formant theory.” Essentially this says that the tone of the instrument is shaped by its various normal resonance modes. Each resonance can be characterized by its frequency response, the shape and phase relationship of the vibrating areas and the ease with which it can be driven by the strings. In theory, if you knew all of these things about every resonance of the guitar, you could predict what it would sound like for any note you played on it.

In practice this becomes very difficult. For one thing, there are an awful lot of these resonances. It is usually possible to find 15-20 resonances on the top or back of the guitar between 100-1000 Hz, and there are so many above 1000 Hz that they “run together” and are difficult to distinguish except by laser holography. If you add in the resonances of the air inside the box the picture becomes more complicated still. In many cases these resonances work together (“couple”), which adds still more complexity. Simplified computer models have been constructed of the guitar, using the lowest few resonances to explore their influence on the tone of the instrument and they have given useful insights. We can now distinguish objectively between, “poor” and “good” guitars to some extent. However, it is still true that we don't yet know what the difference is between a “good” and a “great” guitar.

Fortunately, by combining the approaches of the scientist and the traditional luthier, it is quite possible to consistently build very good instruments. Although the lowest few resonances are similar from one instrument to the next, small but measurable and controllable differences in them can make a lot of difference in the tone of the guitar. By understanding where they come from and the way they work together one can gain a head start on the “great” sound one is after.

Frequency Always Hertz

It is handy to divide the response of the guitar into a number of frequency ranges and talk about them separately. They are, of course, not separate in the real instrument, but each range seems to influence the tone in a certain way. I call them the “low range” from the lowest notes up to about 200 Hz., the “low mid-range” from 200-400, the “upper mid-range” from 400-1000 and the “high range” from 1000 Hz on up. This is pretty arbitrary and they overlap a lot, but it's useful.

The low range covers the lowest notes of the guitar, up to about the open G string. In this range the guitar acts much like a “bass reflex” loudspeaker with the top, soundhole and the enclosed air volume cooperating to determine the response. The most important resonance here is the so-called “Helmholtz” air resonance, or the “A-zero” mode. This involves pumping air in and out of the soundhole and is the same sort of mode one hears when blowing across the mouth of a soda bottle. The air pressure inside the box rises and falls in the same way at all points at any given time and pushes on the walls. The body flexes slightly, moving like a balloon that is being inflated and deflated a little bit many times every second. Thus, the flexibility of the top, and even the back and sides, can be very important in this resonance. If the walls of the guitar were perfectly rigid, this air mode would generally happen at about 120-140 Hz, but with the flexibility of the top and back it is lowered in frequency to around 90-110 Hz in most guitars.

It is this mode that gives the “fullness” to the lowest notes of the guitar, by making it possible for the instrument to radiate some of the fundamental of those notes. Most people prefer guitars in which this mode is a few semitones higher than the lowest note to which the instrument is tuned. If it is too low in frequency, the power will already be falling off on the lowest notes as one plays up the scale, and the low range will be uneven or possibly “tubby.” If it is too high, then the lowest notes will sound “nasal” or “tight.”

The lower mid-range actually covers the notes from the open G string to about the G on the high E string. A broad, tall peak in the output in this range seems to be the key to a full tone. If this family of resonances is too narrow or isolated from the peaks above and below it, the tone can be “thin.” This peak is primarily caused by the so-called “main top resonance. If the “main back” resonance is close enough to it in frequency it will help to make this peak broader, but if it is too close a “wolf note” will result. Note that on some types of guitars, notably Flamencos, it seems desirable that this peak be somewhat isolated, as it contributes a certain “cut” or “projection” to the tone that is useful.

A number of wood and air resonances contribute to peaks in the output of the guitar in the upper mid range, between 400-1000 Hz; roughly the notes of the high E string. These seem to give a lot of the “color” to the tone of the guitar by their presence. If these peaks are tall and narrow with sharp dips in between, the tone tends to be “brighter”, while a more uniform level gives an “even” but possibly less “interesting” tone.

Not too much is known specifically about the resonances above 1000 Hz. These contribute to the overtones of all the lower notes. In general it seems important that there be a number of them and it is probably particularly helpful to have resonances in the 2000-4000 Hz range where human hearing is most sensitive. Many people feel that this may be the most important range of the guitar, but it is also the one in which we have the least direct control over what happens.

I’m in the Mode for Glitter

I have been exploring this over the past several years, looking at “tap tone” spectra and “glitter patterns” of a great many guitars, old and new, of all sorts. Tap tones are obtained by hanging the guitar up so that it can move freely and tapping on the bridge with a small hard plastic ball. The strings are damped so that they will not ring and add their own peaks to the mix. The tap is recorded with a microphone attached to a computer and the resulting sound file is broken down mathematically to yield the power output at every frequency. This can be printed out as a chart. Assigning these tap tone peaks to particular resonances is done in part by looking at “glitter patterns.”

Ernst Chladni found that by sprinkling sand on a metal plate and bowing the edges he could form patterns at the resonance frequencies. The sand bounces off the active areas and gathers along the lines that separate them which he called “nodes.” These days we use an electronic signal generator to drive the resonances and “glitter” to form the patterns. Air resonances can be pinpointed with a decibel meter, or a small probe microphone inserted into the body of the guitar that can find the antinodes (regions of large pressure change) and nodes (where the acoustic energy is represented as flow) of the air modes.

The lowest several vibration modes of the top and back of the guitar are always pretty symmetrical, even when the bracing is not. All guitars tend to have similar modes, but each type of guitar (steel string, classical and archtop) tends to have the modes in a particular order and it seems to be the order of modes that gives them some of their characteristic timbre.

The lowest mode of a top or back plate will almost always involve a single large area moving in and out like a piston or loudspeaker and it is this mode of the top that accounts for most of the radiated sound of the guitar. It is thus important that this mode be as “free as possible. To do this, a luthier will try to make the top as light as possible and only as stiff as it needs to be to withstand the pull of the strings and give the desired timbre.

The main back mode, if it occurs at a frequency close enough to the main top mode, can reinforce it and it is thus helpful to tune it as well. The back is usually heavier than the top and moves less, so this is a secondary contributor to the sound, but it can make a noticeable difference, particularly in the bass range. Sometimes the lowest "bar mode" of the whole instrument (which is sometimes referred to as the "neck mode") will occur in the frequency range of the A-0 mode and this can also effect the tone of the lowest notes as well as the "feel" of the guitar.

Between them, the main top and back modes usually make up the low midrange output peak. In some cases the second bar mode of the body/neck system can enter the picture. Above that frequency the greater weight of the back means that it has progressively less direct influence on the sound. However, it has been shown that a very heavy back can actually "steal" enough energy from the top to decrease its output. The top is the most important source of the upper mid-range peaks that give the instrument its "color." The glitter patterns become more and more asymmetric as one goes higher in frequency as well; asymmetries in the bracing pattern and even in the wood stiffness and mass distribution become more and more important. If the bracing is too heavy, relative to the thickness of the top, it can "quench" a resonance, restricting it to a smaller area than it could have or cutting down its activity. This decreases both tone color and overall volume in the final sound. It is thus important to achieve a balance in stiffness between the top and its bracing. One benefit of tuning the main back resonance is that it allows for a slightly thicker top which will better balance the bracing, and thus give a more colorful tone.

Radiation is Good for You

One thing that can contribute to the tone of the instrument is the way it radiates sound. Low frequency modes, like the A-0 and main top modes, tend to put out sound in all directions. As you move higher in frequency there are more areas vibrating for any given resonance, and half of them will be moving in the opposite sense from the other half: while one area is moving away from you the one next to it is moving toward you. If these two areas are the same size and move with the same amplitude they will cancel out any sound radiation along the node line that divides them. They will send out two "beams" of sound at some angle, depending on the exact geometry of the case. With more modes the picture becomes much more complicated, and very small changes from one area to the next can make a lot of difference in the way the tone is produced. It seems as though this is one of the big differences between the "live" and "recorded" tone of the acoustic guitar.

…and a High Fiber Wood Diet

In all of this the strength of the top must also be considered. The torque and pull of the strings on the bridge will eventually collapse the top if it is not heavy enough. The critical area seems to be between the bridge and the soundhole and the most successful traditional bracing patterns have the braces converge there. As the torque falls off near the edges of the top less wood is needed, and the top can be tapered in thickness. This reduces the weight and frees up the main top mode. The bracing also can be tapered toward the edge to balance the top thickness and stiffness.

It's widely recognized that wood choice can have an effect on the tone of the guitar. Some of these effects can be fairly easily related to measurable properties of the wood, such at its stiffness/weight ratio, the ratio of long-grain to cross-grain stiffness, and the “damping factor” (the amount of energy that is lost in the wood as it vibrates). In general, the lighter the top of the instrument can be made while still retaining sufficient stiffness the better. This is why spruces of various sorts have long been used for instrument tops; in general spruces have the highest strength/weight ratio of any common wood. Cedar and redwood can have a higher stiffness/weight ratio (as can balsa!), but they tend to lack the toughness of spruce, and so are not as strong. Western Red Cedar tends also to have lower losses than most spruces and this can help to give it a tone with more treble. There is a lot we don't know about wood and tone. Often woods that have very similar mechanical properties can have different acoustic ones and we don't know why. For example, Sitka spruce and Red spruce are very similar on the whole mechanically but react much differently when used as guitar tops.

For back and side woods, the usual choices seem to emphasize moderate to high density, hardness and low damping. Low damping seems to be especially important on classical guitars. A material with high damping will tend to absorb more of the high frequencies and classical guitar strings tend to have less energy in the high partials anyway. The damping of the back wood seems to make less of a difference in the tone of steel string guitars.

Damping also seems to be influenced by the balance between bracing and plate stiffness. Rather small imbalances seem to be enough to cause noticeable differences in timbre. Part of the skill of the traditional luthier is to find some means of feeling the balance of stiffness. Modern methods of “plate tuning” take a lot of the guesswork out of it, and make it possible to work with a much wider range of woods.

Larger guitars can move more air than smaller ones, all else being equal, and tend to have lower resonance frequencies. The down side is that the broader top span must be braced more heavily in order to be stiff enough to take the string tension. At some point the gain in area is offset by the increased weight.

The Shape and Things to Come

The shape of the guitar should have an effect on the internal air modes but not much work has been done on that . There is every reason to believe that it would be productive to do so.

In short, there is a lot we don't know about the acoustics of the guitar. What we do know is very helpful in making better instruments out of a wider range of woods.