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3aMU4. Wood for Guitars

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Numerous famous luthiers have used low grade salvaged timber and non-wood products to demonstrate that how a guitar is designed to exploit available materials is more important than using prime tonewoods. The material properties of timber are highly variable and are not the single figures frequently quoted in reference books. Within-species material properties can vary by a factor of two. Consequently, there is significant overlap of the material properties of one species with others, implying that wood species substitution is possible with little acoustical impact if the component is designed and built to acoustical tolerances rather than dimensional tolerances. However, species selection remains a significant factor in designing guitar components, primarily for structural rather than acoustical reasons. The woods chosen have to survive long-term loading without excessive distortion over time whilst still allowing the radiating surfaces to vibrate freely. Important parameters include Young's modulus, density, stability with humidity variation, heat bendability, and hardness. The author considers wood for soundboards, braces, backs, sides, necks, fretboards, and bridges. Guitars designed to acoustical criteria (rather than dimensional criteria) where the effects of different stiffnesses and densities of species are minimised, sound very similar.

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Introduction

Numerous reputable builders, including Bob Benedetto, Bob Taylor and Roger Bucknall[1] have built guitars out of low grade salvaged woods and have claimed that they sound just fine. The Martin Guitar Company builds guitars with backs and sides made from high pressure laminates with composite fretboards, materials of a type more commonly found surfacing kitchen workbenches. These guitars are ranked alongside their wooden counterparts in acoustical performance. The great Antonio de Torres proved his point in 1862, by building a guitar with papier-mâché back and sides. Further, nobody can tell the materials that a guitar is made from in blind listening tests. So, does it matter what timbers are used in guitar construction?

The answer, for fine acoustic guitars, is unequivocally yes. A guitar is a highly stressed instrument that has to perform both structurally and acoustically, but it is primarily for structural reasons that timber selection matters. The woods chosen have to survive long term loading without excessive distortion over time whilst still allowing the radiating surfaces to vibrate with a high degree of mobility. This paper introduces the author's design criteria and then examines the desirable woods properties and suitable species for a variety of guitar components including braces, tops, backs, sides, necks and bridges.

Design criteria for fine acoustic guitars

Acoustical Criteria

It has been a centuries long challenge to design and build guitars that are both highly responsive and highly musical. As the responsiveness and sensitivity of the instrument is increased (assessed by measuring a guitar's monopole mobility[2]), it becomes increasingly difficult to ensure that notes are of similar volume and duration all over the fretboard (i.e. there are no "wolf" notes)[3] and increasingly difficult to ensure that all notes play in-tune to the equally tempered scale.

A typical guitar frequency response curve to 500Hz is shown in Fig. 1. There are numerous peaks in the response curve, corresponding to modal resonances of the guitar body, but the most significant are the first three. These correspond to the modes of vibration shown in Fig. 2. If the correct frequency relationship between these peaks is not observed then uneven response, wolf notes and out of tuneness will result.

Each peak represents an admittance peak, where the energy from the string has high admittance to the soundboard of the guitar. If the peak is too high, the vibrational energy of the string at that frequency is rapidly drained, resulting in a note that is immediately loud but of short duration. It sounds "clunky". This is the guitar "wolf note". Further, due to the nature of coupled resonators (the string and the soundboard) the frequencies of the coupled resonances "repel" each other compared to where the uncoupled resonant frequencies would naturally lie[4]. The effect of this is that the string frequency is shifted away from the body resonant frequency and that the corresponding note will no longer be in tune to the equally tempered scale. The frequency shift can be as much as 30 cents, approximately 1/3 of a semitone, which is clearly audible, resulting in a dissonance when that note is sounded in an otherwise accurately pitched chord.

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[1] In 1993 Bob Benedetto used construction grade knotty pine on an arch top guitar with a back of weather-checked maple. In 1995 Bob Taylor used top wood from a 2x4 ("pine, fir or hemlock") and back wood from an oak pallet salvaged from a dumpster. Roger Bucknall (Fylde Guitars) routinely uses top wood of Oregon pine from distillery washback vessels and back and side wood salvaged from oak whisky casts for his "singe malt" guitars. All claim that the instruments sound just as good as any guitar constructed from prime tonewoods.

[2] Monopole mobility is defined as $1/\sqrt{(Km)}$, where K is the equivalent stiffness of the soundboard assessed by measuring the unit static deflection of the monopole mode at its antinode under a given load and m is the equivalent mass of the soundboard determined by measuring the uncoupled frequency of the $T(1,1)_2$ mode (uncoupled by plugging the sound hole) where $f=1/2\pi\sqrt{(K/m)}$. Details are contained in *Contemporary Acoustic Guitar Design and Build*, Vol. 1, pp1-89 to 1-91; T. A. Gore and G. Gilet; Pub. Trevor Gore, 2011.

[3] J. C. Schelleng, *The Violin as a circuit*, J. Acoust. Soc. Am. 35(3) Mar, 1963

[4] J. P. Den Hartog, *Mechanical Vibrations*, p89; McGraw Hill, 1934; O. Christensen & B. Vistisen; *Simple model for low frequency guitar function*, J. Acoust. Soc. Am. 68(3) Sept, 1980.

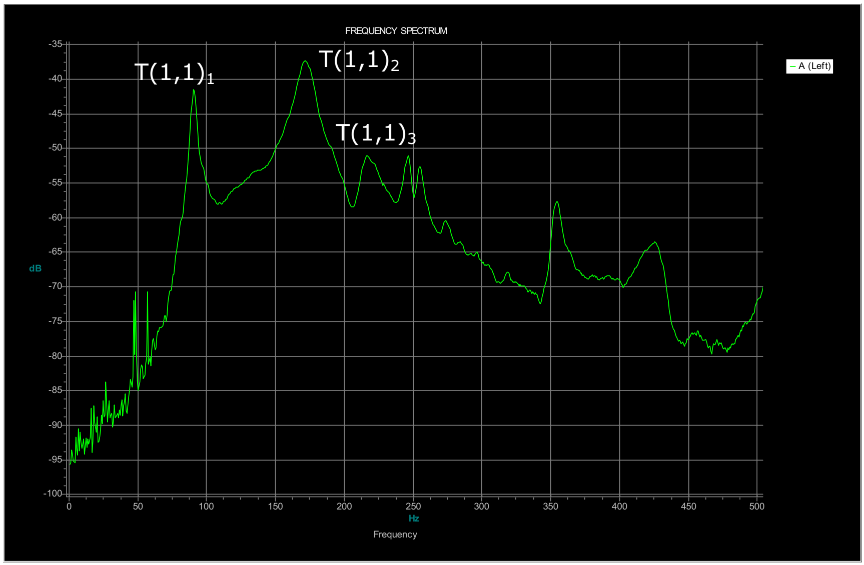
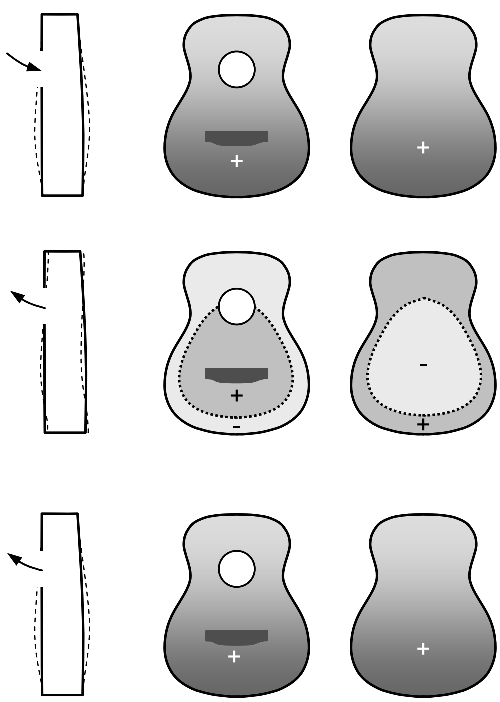


Fig. 1 *Frequency response of a steel string guitar elicited by tap testing. The guitar is held as if being played, is tapped 10 times in multiple places around the soundboard and bridge with the taps recorded using a single microphone approximately 1 metre in front of the sound hole. Whilst the taps are not calibrated for force and taps are in more or less random positions, the procedure gives remarkably repeatable results, always with the peaks at the same frequencies, which is the matter of prime interest here.*



$T(1,1)_1$ coupled main air resonance
Net sound radiation phase is negative with respect to $T(1,1)_2$
Typical frequency ~100Hz

$T(1,1)_2$ coupled main top resonance
Net sound radiation phase is defined as positive
Typical frequency ~190Hz

$T(1,1)_3$ coupled main back resonance
Net sound radiation phase is positive with respect to $T(1,1)_2$
Typical frequency ~240Hz

Fig. 2 *The first three modes of vibration of an acoustic guitar with a "live" back. The T(1,1) monopole mode (one antinode counted across the top of the guitar and one counted down) occurs three times, but at different frequencies and different phasing of the top, back and air in the sound hole. The $T(1,1)_3$ mode is heavily suppressed in non-live back instruments and the third peak in* Fig. 1 *disappears.*

As sensitivity (monopole mobility) increases, the problems are exacerbated, with most guitar builders avoiding the problem by ensuring that monopole mobility remains suppressed, Fig. 3 and Fig. 4.

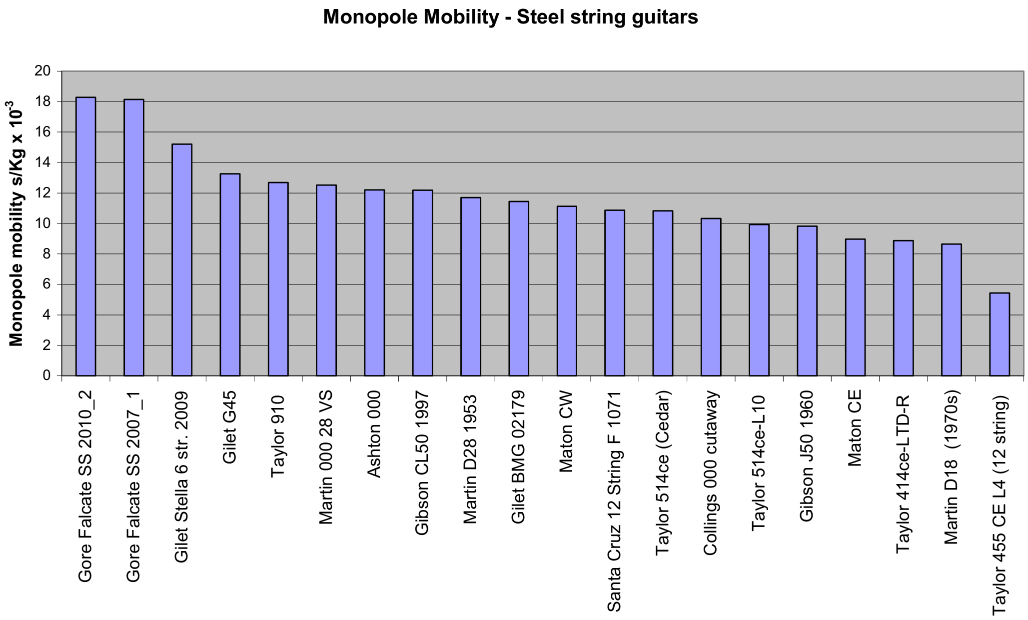


Fig. 3 *Monopole mobility for a variety of steel string guitars. The best factory built guitars have a monopole mobility of ~12 s/Kgx10^{-3}, only around $^{2}/_{3}$ ^{rds} the value associated with responsive guitars, which record mobilities above 18 s/Kgx10^{-3}. The recorded values correlate well with the perceived loudness of the instrument*

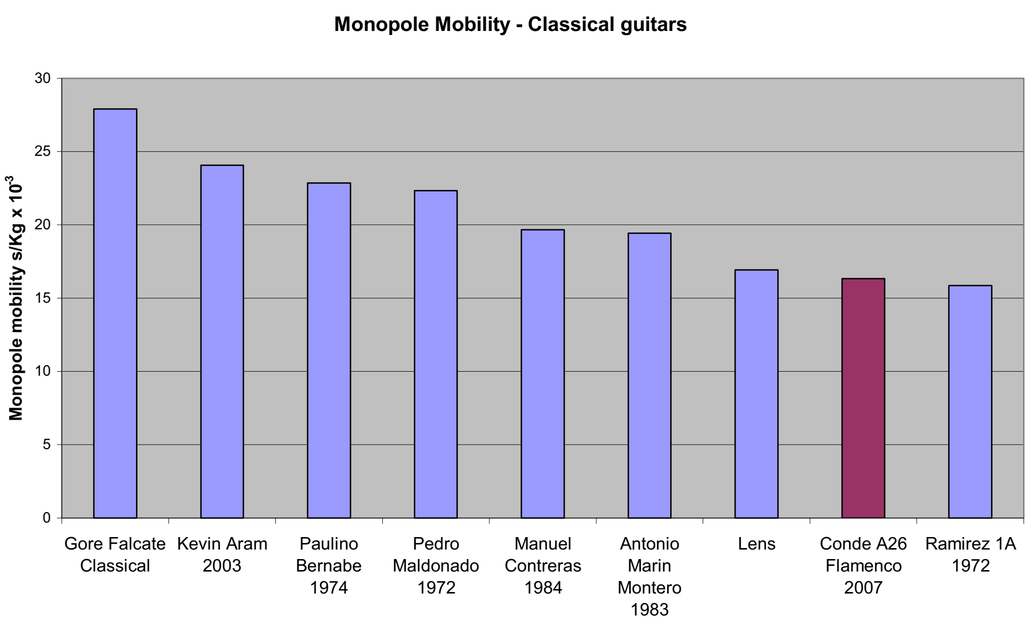


Fig. 4 *Monopole mobility for a variety of fine classical guitars (and one flamenco guitar). Soundboard structural issues can be expected above ~35 s/Kgx10^{-3}. The Gore, Bernabe, Maldonado, Contreras, Montero and Ramirez all had $T(1,1)_2$ resonances pitched precisely midway between scale tones*

These phenomena immediately suggest a number of design criteria if a responsive guitar is not to have wolf notes and intonation problems:

i) The guitar body main resonant frequencies (peaks in admittance) should not be positioned on scale tones, or that note when sounded will be both clunky and off-pitch.

ii) The $T(1,1)_1$ resonant frequency and the $T(1,1,)_2$ resonant frequency which typically have around an octave separation in a guitar should NOT be placed exactly an octave apart, as two harmonics of a sounded note will have admittance and intonation problems.

iii) The $T(1,1)_3$ resonant frequency (if it exists) should not be positioned too close to the $T(1,1)_2$, or the $T(1,1)_2$ will be severely attenuated and/or the guitar will sound "out of focus". Introducing a $T(1,1)_3$ resonance attenuates the $T(1,1)_2$ peak, which can alleviate over-admittance of that mode and introduce an extra peak in the response curve that both increases the gain-bandwidth product and makes for a more interesting sound[5]. The author's preference is that the $T(1,1)_3$ resonance be pitched ~4 semitones higher than the $T(1,1)_2$.

These criteria demand that both the soundboard and the back of the guitar be designed to mobility and modal resonance objectives.

Structural Criteria

Along with the vibrational criteria which need to be satisfied, some critical structural criteria require resolution.

The two main types of structural failure in guitars are neck distortions rendering the instrument unplayable and soundboard distortions which result in compromised musicality eventually leading to catastrophic failure of the soundboard or the bridge peeling off.

The neck-body joint and surrounding structure can be a significant initiator of playability issues, often to do with design rather than material choices. However, the design aspects are beyond the scope of this paper. Nonetheless, neck distortions are frequently due to inappropriate selection of neck shaft and fretboard materials.

Excessive soundboard distortions are inevitably a result of a combination of design and material choice issues. A criterion preferred by the author is to ensure that the bridge under load does not exceed a rotation of 2° relative to its unloaded condition. This figure produces a reasonable compromise between acoustic mobility and structural integrity. Rotations greater than 2° look visually excessive with the resulting distortion being a precursor to the bridge peeling off. Rotations of much less than 2° result in insufficient soundboard mobility if a guitar is to be judged as being in anyway responsive. A compounding problem is that the initially elastic deflections increase over time to become plastic deformations. This cold creep phenomenon has led commercial manufacturers to over-build their guitars to avoid this problem, but there are other solutions.

Guitar construction frequently involves the joining together of very different species of wood. Of itself, this is not necessarily a problem. However, if the woods have significantly different coefficients of dimensional change with moisture content, distorting forces can be induced into the structure. In some circumstances the distortion is of significance and in these cases the wood's response to humidity change has to be taken into account.

Important material properties

The material properties of timber are very variable and are not the single figures frequently quoted in reference books. Within-species material properties can vary by up to a factor of two. Consequently, there is significant overlap of the material properties of one species with others, rendering absolute comparisons of one species verses another only in any way valid if a statistical approach is taken. In individual cases, it is quite possible to

[5] Matthews and Kohut; *Electronic simulation of violin resonances*, J. Acoust. Soc. Amer. 53; 6, 1973.

find samples of one spruce species with identical properties to those of another spruce species, implying that wood species substitution is eminently possible.

The relative importance of the various material properties varies by component.

Neck woods, for example, need to be strong and stiff; fretboard woods need to be hard for wear resistance and stable with humidity changes so that the neck/fretboard structure does not become a hygrometer, deflecting with every change in humidity.

Backs and sides are traditionally made of the same species of wood, though other than for aesthetic reasons there is no reason why this should be so. Species used for sides need to be heat bendable if traditional construction techniques are used, whereas this is not a requirement for back panels.

However, the success of a guitar depends largely on the strings' ability to accelerate the inertia of the soundboard, and the soundboard structure having its main monopole resonance, the $T(1,1)_2$, in a fairly tightly defined band (so that the guitar sounds in-genre) which is determined by the soundboard's mass and stiffness. Guitar builders consequently tend to seek top woods of low density and high relative stiffness. The bridge transmits string vibrations to the soundboard, and, as low inertia is important for high acceleration (and good sound radiation) if follows that a low inertia bridge is beneficial.

This leads us to a determination of the most important material properties which then governs the choice of wood species to be used for each component. The material properties of specific interest are:

Young's modulus
Density
Stability with humidity variation
Heat bendability (which also seems to correlate with a wood's susceptibility to cold creep)
Hardness

Some luthiers would argue that the wood's damping properties are also critically important, especially for top and back woods. However, this property is very hard to measure routinely in an accurate, repeatable and comparable way. Provided the wood does not respond like the proverbial "piece of wet cardboard", most luthiers can create a respectable instrument from available timber. It would seem that design issues and the type of finish used on the guitar have much greater impact than whether a piece of wood possesses typical or superior damping characteristics.

Wood for braces

Braces in a guitar serve two main purposes: to limit the soundboard's deflection due to the bending moment applied by the static string loads, and to control how the soundboard subdivides into separate vibrating areas. How the second matter is handled is arbitrary, depending on the acoustical preferences of the builder, but the first matter is non-negotiable if the instrument is to survive the applied string loads. So our concern here is principally with the first matter.

Spruce has been the wood of choice for guitar braces for over a hundred years and a relatively simple analysis will demonstrate why this is the case. To illustrate the point, a possible alternative wood, in this case Western redcedar, has been chosen for comparative purposes. The significant material properties are tabulated below (Table 1), these values being for specific samples tested by the author.

	Density (kg/m^{3})	Young's Modulus (GPa)	Modulus of Rupture (MPa)
Sitka Spruce	450	12.5	70
Western Redcedar	320	6.2	54

Table 1 *Material properties for two competing brace materials*

Consider a beam (brace) being deflected by a bending moment, Fig. 5.

For a brace of rectangular cross section, width a and height b, the second moment of area I is

$$I = \frac{ab^3}{12} \qquad \text{Equ. 1}$$

The stress σ in a section of a beam a distance y from the neutral axis under applied bending moment M is given by

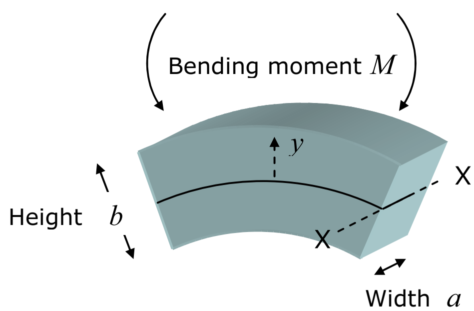
$$\sigma = \frac{My}{I} \qquad \text{Equ. 2}$$

Young's modulus E is the ratio of stress σ to strain ε in a material and so is a measure of the material's stiffness,

$$E = \frac{\sigma}{\varepsilon} \qquad \text{Equ. 3}$$

and so

$$\varepsilon = \frac{My}{EI} \qquad \text{Equ. 4}$$



Neutral axis X-X is at depth $b/2$

Fig. 5 *Rectangular beam (brace) under a bending moment*

The maximum stress and strain levels are in the outer fibres of the brace. To achieve the same maximum strain level in a cedar brace compared to a spruce brace of the same dimensions the brace deflection must be kept the same. But the cedar brace is only 6.2/12.5 times the stiffness of the spruce brace due to the ratio of the Young's moduli, so under a given applied moment M the cedar brace will deflect more (i.e. the strain ε will be greater). This can be rectified by increasing the width of the cedar brace by the ratio of the Young's moduli, so if the spruce brace is of width a, the cedar brace must be made to be 12.5/6.2 = 2.02a wide, in which case it will increase in mass by a factor of 2.02 also. However, the ratio of the density of cedar to spruce is 320/450=0.71, so the overall increase in mass of the cedar brace is 2.02 x 0.71 = 1.43 times the mass of the spruce brace for equivalent stiffness and peak strain level. Further, the cedar brace only has 54/70 = 0.77 of the modulus of rupture (MOR) of the spruce brace, so the cedar brace is operating much closer to its failure point. In fact, for a typical steel string guitar, with spruce braces operating at ~40% of MOR, a cedar brace of the same dimensions would be operating at ~130% of MOR and would fail. The analysis holds irrespective of the shape of the brace.

As it turns out, there are no other common softwoods or hardwoods that can rival the stiffness, strength and density performance of spruce, which is why the spruces have become the ubiquitous choice for guitar brace material. As Young's modulus is approximately linearly related to density for the spruces it is of little consequence which species of spruce is chosen. Skilled guitar builders tend to select the lowest density and highest stiffness samples from the rather broad within-species variability. However, because stiffness is related to the brace's height cubed (Equ. 1), it pays to choose low density samples of the species selected as a given flexural rigidity (EI) can be achieved for a lower overall mass.

Wood for soundboards[6]

The soundboard is the guitar's primary sound radiating surface. For the purposes of practicality, once the braces have been designed to satisfy a static deflection criterion (as well as some arbitrary soundboard sub-division control criteria) and thus have a corresponding vibrational response, the soundboard can be designed to have a particular dynamic response which, by superposition, augments the given vibrational response of the bracing system.

A wood's sound radiation coefficient[7] provides a guide to the species to select for a soundboard. The sound radiation coefficient (sometimes called radiation ratio) combines factors indicating how easy a material is to bend (E) with factors indicating how easy it is to accelerate (ρ) and so gives a measure of the acoustical power that can be produced by a driven vibrating plate before damping losses are taken into account.

$$Sound\ radiation\ coefficient = \frac{c}{\rho} = \sqrt{\frac{E}{\rho^3}} \quad (Speed\ of\ sound\ c = \sqrt{\frac{E}{\rho}})$$

Values measured by the author are provided in Fig. 6.

The author's approach to soundboard design is to work the thickness of the soundboard such that, irrespective of the material properties of that particular piece of wood, it always has the same vibrational response. The soundboard's thickness is determined using a development of the principles outlined by Hearmon[8], having previously determined the density of the wood sample to be used and its elastic constants by using a development of the dynamic method described by Caldersmith[9]. The procedure is described in detail by Gore and Gilet[10]. Consequently, any decent piece of guitar wood can have its thickness worked so as to deliver a particular vibrational performance that yields a target $T(1,1)_2$ frequency in the completed instrument. This eliminates performance variations due to varying material properties and as a consequence largely eliminates the differences usually attributed to different species of tone wood. A more conventional practice is to work the thickness of the soundboard wood to a specific target dimension, which results in considerable variation in the $T(1,1)_2$ frequency due to variations in material properties, with these variations often being attributed to the wood species (as opposed to material properties, which in conventional lutherie are seldom measured).

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[6] Photographs of wood species for guitar components can be found in Appendix 1

[7] J. C. Schelleng, *The Violin as a circuit*, J. Acoust. Soc. Am. 35(3) Mar, 1963; Wegst Ulrike G. K. *Wood for Sound*. American Journal of Botany 93(10) 1439-1448, 2006

[8] R.F.S. Hearmon,*The fundamental frequency of vibration of rectangular wood and plywood plates*, 1946 *Proc. Phys. Soc.* 58 78-92.

[9] G. Caldersmith, *Vibrations of Orthotropic Rectangular Plates II*, Acustica 73, 1991

[10] Gore and Gilet, *Contemporary Acoustic Guitar Design and Build*, Vol. 1; p4-58 to p4-61; Pub. Trevor Gore, 2011.

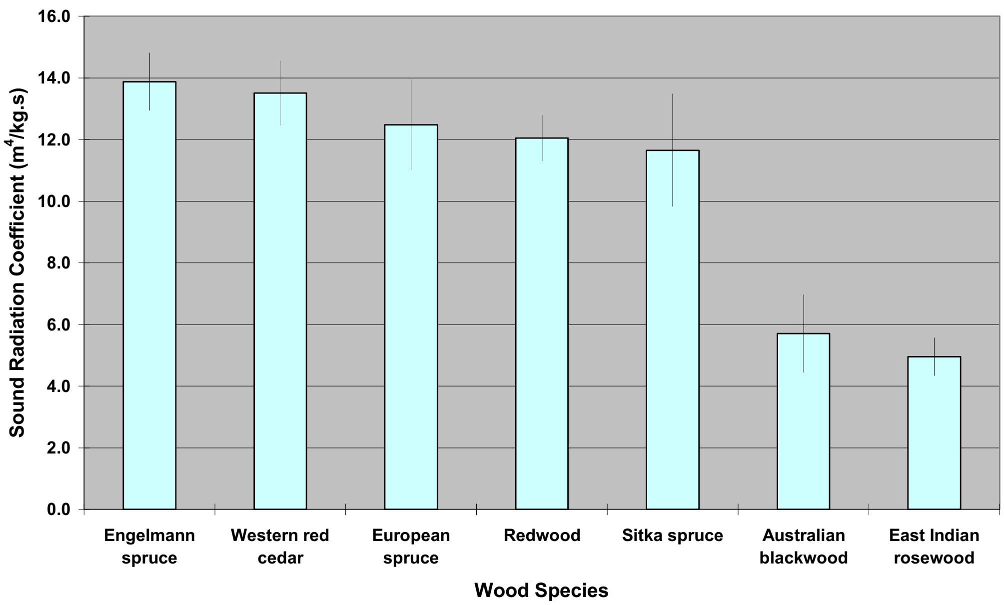

Fig. 6 *Mean sound radiation coefficient (bars), ± 1 standard deviation (lines) for a variety of species. These values are representative of select wood used by the author and may not necessarily be representative of the species*.

The author's approach to soundboard design results in soundboards that have consistent vibrational properties but have different masses. Preferred soundboards are those of low mass. Fig. 7 shows the range of top panel masses obtained using different species of top wood. Low mass tops respond more actively to string excitation and so produce louder guitars. However, this is only discernable if the guitar is of a successful, responsive design. Most mass-produced guitars do not fall into this category.

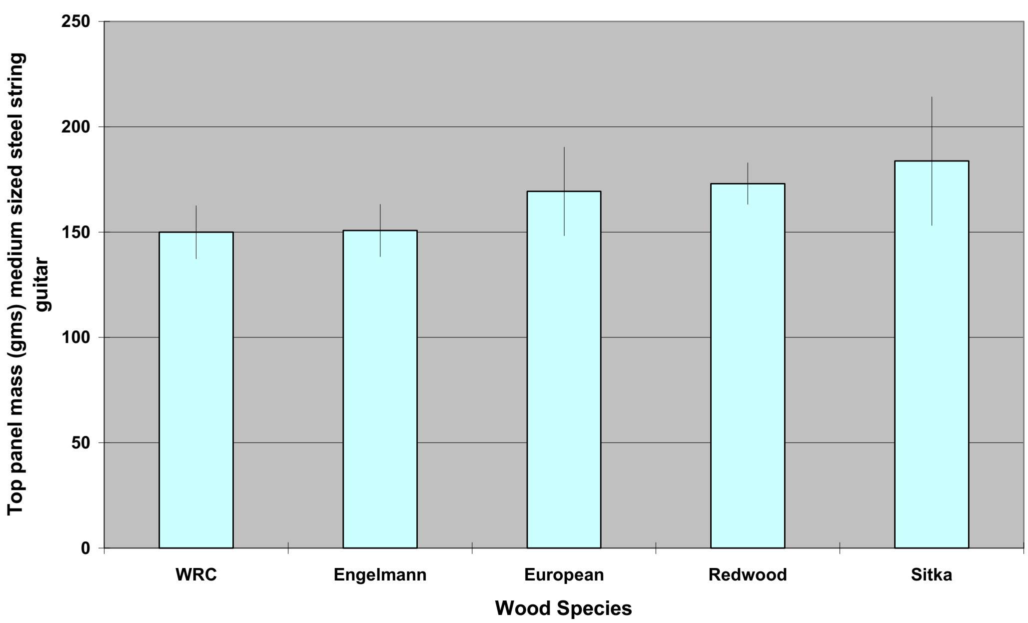

Fig. 7 *Means (bars) and ±1 standard deviation (lines) for the mass of the top panel of a medium sized steel string guitar using different top woods. These values are representative of select wood used by the author and may not necessarily be representative of the species*

One would expect the rankings of the top masses to fall in the reverse order of the rankings for the sound radiation coefficient, and they nearly do. Western redcedar and Engelmann spruce have swapped order. The reason for this is that the sound radiation coefficient as computed uses only the long-grain Young's modulus, whereas the method utilised to determine the thickness of the panel utilises both the long-grain, cross-grain and shear modulus. The difference is primarily due to Western redcedar being relatively stiffer across the grain.

Provided the soundboard is attached to a consistent "chassis", the residual variation in sound, which contributes to the overall allure of a particular instrument, remains largely uncontrolled and is attributed by the author to a function of the sound spectral absorption and radiation of the particular piece of wood used, a property that is not easily measured and is poorly substituted by the occasional measurement of the damping characteristics of the wood (measurement of Q or logarithmic decrement being the most frequently used parameters), Fig. 8. Wood with low damping has a low value for logarithmic decrement.

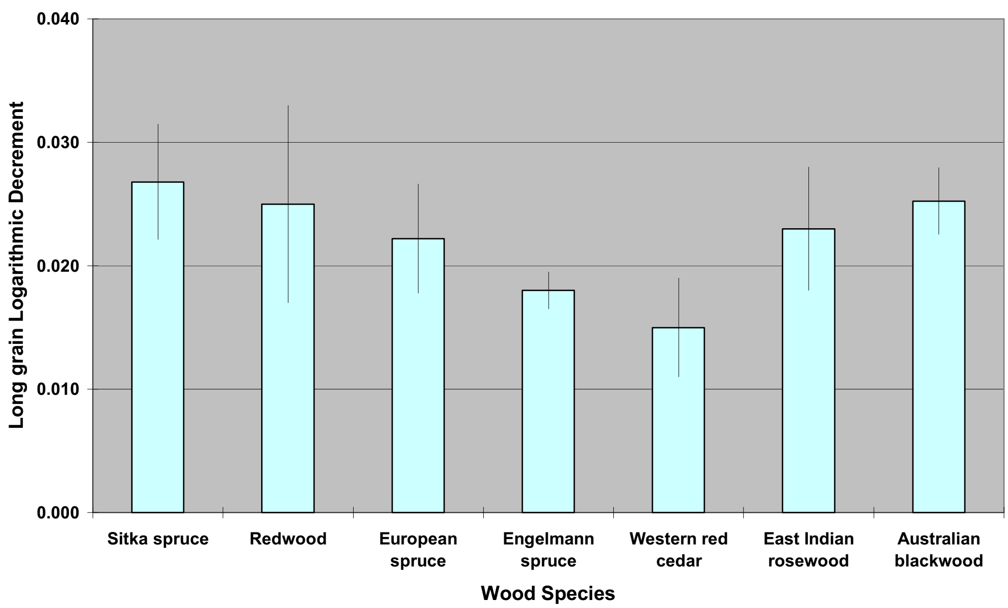

Fig. 8 *Means (bars) and ±1 standard deviation (lines) for logarithmic decrement, a rough measure of the damping characteristics of various wood species. These values are representative of select wood used by the author and may not necessarily be representative of the species*

The author's view therefore, is that a description of the acoustical differences between wood species is largely a description of the residual variation in sound caused by the nature of sound spectral absorption and radiation of the particular piece of wood used, which leads to the rather general comments below about how different woods sound. This residual variation is not the making or breaking of a good guitar, which is primarily determined by its design rather than species choices. However, it can, for some listeners, be the difference between a good guitar and a truly great instrument. Truly great instruments are exceedingly rare and whilst their tonalities can be very different there is frequently a consensus amongst listeners of all levels of experience as to the quality and desirability of the sound. It must never be forgotten, however, that no one to the author's knowledge can consistently identify the species of wood used in a guitar's construction in blind listening tests. One must also pose the question "Is the perceived sound of the wood coloured by the context in which it is used or has the sound of the wood determined its application?" The following discussion regarding Sitka spruce illustrates this point.

Sitka spruce (picea sitchensis)

By far the most common type of factory-made guitar is the Dreadnought style, often touted as a general-purpose guitar, but best suited for flat-picking playing styles where the instrument is strung with medium gauge strings and played hard with a plectrum to be heard over the banjo frequently found in the same band. The most commonly used top wood is Sitka spruce. Sitka spruce is, on average, one of the hardest and strongest spruces which is well suited to this application. It is also plentiful and therefore relatively inexpensive in the qualities required for guitar making, which also helps explain its popularity with guitar factories. Using the wood in this context, the guitar has a round sound, stronger in the string's lower harmonics, which is largely a function of the guitar's design, the strings used and the playing style. However, this sound has come to be associated with the wood, and therefore Sitka spruce is claimed to have a "strong fundamental"[11]. With the passage of time, in the steel string guitar community, this has become somewhat of a benchmark against which other woods are compared.

Engelmann spruce (picea engelmannii)

Compared to Sitka spruce, Engelmann spruce is lower density, lower stiffness and lower hardness. If directly substituted at the same thickness for Sitka spruce, the finished guitar will sound "darker", maybe even somewhat muddy, a result of the lower Young's modulus producing a soundboard with a lower $T(1,1)_2$ frequency, (Fig. 9). However, this can easily be rectified by increasing the thickness of the top very slightly, so stiffening it, to bring the $T(1,1)_2$ frequency back to target. The outcome is a guitar which is more sensitive because it will have a lower top mass due to Engelmann spruce's lower density, Fig. 7. Engelmann spruce also has a low logarithmic decrement (less damping), Fig. 8. Used in a well thought out design, Engelmann spruce will produce a very sensitive, responsive, balanced guitar. It is the author's preferred wood when a white-topped finger-style guitar is required. Because of the wood's ability to deliver low mass, low damping top panels, it is a very suitable wood for the soundboards of classical guitars also.

Due to its low hardness, Engelmann spruce is susceptible to indentation and marking both during construction (a consideration for the luthier) and in use.

European (Norway, German) spruce (picea abies)

European spruce is generally stiffer, denser and harder than Engelmann spruce (to which it bears a close visual resemblance) but not quite as dense or hard as Sitka spruce, whilst it may be a little stiffer. Whilst the tabulated differences (Table 2) between the various spruce species are small, these differences can certainly be felt as the wood is worked with hand tools. Its most notable difference from Sitka and Engelmann (for the samples the author has tested) is that the ratio of cross-grain to long-grain stiffness is higher. For Sitka this ratio is ~.075, for Engelmann it is ~.1 and for European it is typically .12 - .14. The author has not been able to establish whether this is of any acoustical significance. Structurally, there is a primarily cosmetic benefit as the resulting higher cross-grain stiffness of the panel means that there is less "print through" of the brace pattern visible on the outside of the guitar in the largely grain-aligned bracing patterns used on many classical guitars. To the author's ears, there is very little difference tonally between Engelmann and European spruce. However, careful use of Engelmann spruce results in a soundboard of lower mass, higher mobility and consequently a more responsive guitar. European spruce, under shellac (French polish) finishes to a beautiful ivory sheen that is not replicated by other "white" top woods.

[11] Luthiers Mercantile International Inc. Handbook-Catalogue, Section 9, p7; 1993.

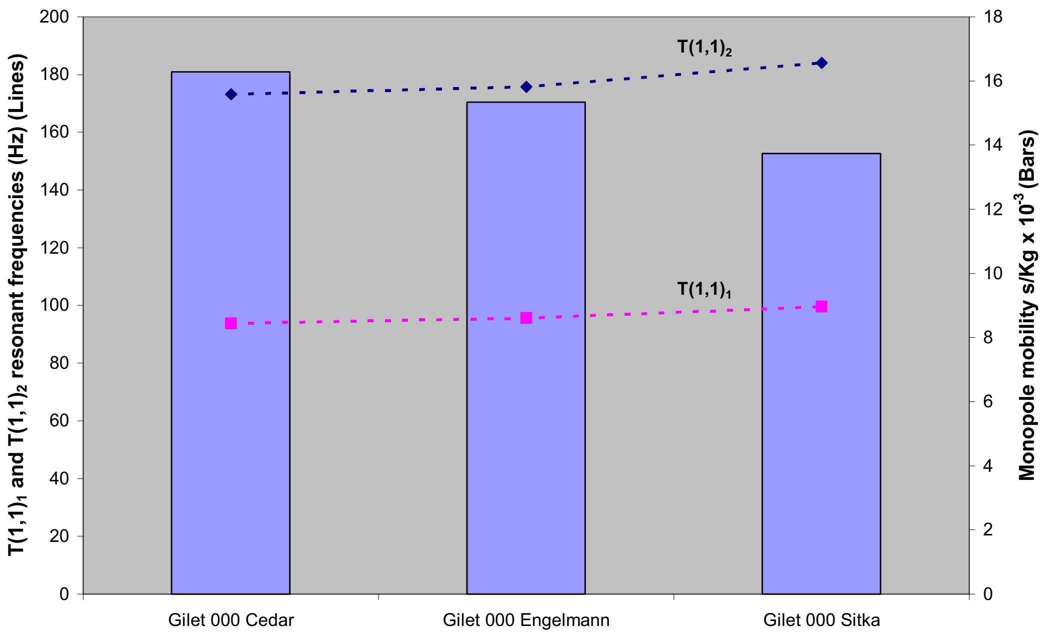

Fig. 9 *Monopole mobility(bars) and first two resonant frequencies of three guitars built under strict dimensional control, varying only in the choice of top wood. Dimensions and material properties of all other components were otherwise maintained as constant as practicable[12]. Young's modulus for the tops were 6.8GPa, 9.3GPa and 11.2GPa (Inta[12])*

Softwood Species	Long-grain Young's Modulus (GPa)	Density (Kgm^{-3})	Janka Hardness*	Long-grain Logarithmic Decrement
Sitka	11.1-15.7	400-520	2.1-2.3	0.022-0.031
Engelmann	9.3-13.2	340-425	1.8-2.0	0.016-0.019
European	11.5-16.7	400-500	1.9-2.1	0.018-0.267
Redcedar	5.4-8.3	325-350	1.5-2.0	0.011-0.019
Redwood	10.0-13.0	400-450	2.0-2.2	0.017-0.033

Table 2 *Properties of various woods used in guitar tops. * Data sourced from Bootle[13]. Other ranges given are ~± 1 standard deviation from the mean of the samples measured, and are indicative of the wood used by the author but not necessarily indicative of the species.*

Redwood (sequoia sempervirens)

Amongst luthiers who measure these things, redwood is notoriously variable in its material properties. This variability is not reflected in the tabulated data here as the samples measured had already passed a rigorous selection process prior to purchase. Redwood can be brittle, splitting easily along the grain, but is also more dimensionally stable with humidity changes than the majority of spruces. A very acceptable steel string guitar can be made with a Redwood soundboard, but there are no characteristically differentiating tonal features to the author's ears. If an exceptionally responsive steel string guitar is required, or a classical guitar, Redwood would not be a first choice wood due to its higher density and lower stiffness compared to some of the alternatives. Under a finish, well quartered redwood with its rich red/brown colour can look exceptional for those preferring darker faced guitars.

[12] R. Inta, *The acoustics of the steel string guitar*, PhD thesis, University of New South Wales, 2007
[13] K.R. Bootle, *Wood in Australia*, Appendix 3; McGraw Hill Sydney, 1983

Western Redcedar (thuja plicata)

Western redcedar (which is a cypress rather than a cedar, despite its taxonomy) is a soft, low density, relatively low stiffness wood with very low damping. Whilst its Young's modulus is more typically in the 6.0 GPa region, the author has measured samples as stiff as 9.5 GPa, albeit with densities in the higher range of those tabulated. Its sound radiation coefficient indicates that it is a superior wood for soundboards, despite its relatively low strength and stiffness, and this is indeed the case. If substituted at the same thickness for a spruce soundboard, like Engelmann spruce substituted for Sitka, it will sound darker. This has given redcedar a reputation as being tonally "dark" or "warm", mainly a consequence of the lowered $T(1,1)_2$ resonance (Fig. 9) that results from using timber with a lower Young's modulus. If the thickness of a top panel is increased to compensate, however, redcedar can produce a sound comparable with spruce. Steel string guitars with redcedar tops designed for finger picking can be truly responsive, outstanding instruments with great tonal pliability.

Redcedar is more frequently used for classical guitars for which it is well suited. It has a unique distinction from the spruces in that, in the experience of the author and many others, a redcedar faced guitar immediately has a more mature sound than a similarly aged spruce faced guitar. Spruce guitars can frequently take a number of years for their sound to fully develop. It is not at all clear why this is the case, however there is speculation that it is possibly a function of the anelasticity of wood[14].

Wood for backs and sides

A broad range of wood species as well as papier-mâché, plywood, composites and high pressure laminates have been used for the backs and sides of guitars. Of itself, this very fact gives a clear indication that perfectly acceptable instruments can be made irrespective of the species choice, with visual, cost or sustainability factors taking precedence.

For the luthier using traditional building methods a clear requirement is that the wood is heat bendable, which, for those skilled in the art, disqualifies very few woods.

A luthier can chose whether or not to design the guitar with a "live" back, where the back of the guitar is treated as a secondary vibrating surface to augment the tonality of the soundboard. If a non-live back option is selected, the back is left stiff and heavy and it is acoustically immaterial which wood species is used. If the live back option is selected, the back panel must be pitched at the correct frequency relative to the top and must have a sufficiently high monopole mobility to effectively couple with the top. The advantages of a live back have previously been discussed.

The detailed behaviour of the back of the guitar and how it couples to the soundboard via the air cavity and sides is complex and outside the scope of this paper. However, the author has determined both experimentally and by mathematical modelling[15] that suitable design criteria for a live back panel in the completed instrument is that it delivers a $T(1,1)_3$ resonant frequency ~4 semitones higher in pitch than the $T(1,1)_2$ and that to couple effectively with the top, the back's monopole mobility must be greater than $\sim 7.0 \times 10^{-3}$ s/Kg.

The mobility criterion makes the selection of back woods more restrictive. Rather dense woods, for example the rosewoods (*Dalbergia spp.*), and Macassar ebony, are popular choices for backs and sides. However, the mobility criterion effectively imposes an overall mass criterion for the back and consequently a density criterion for the wood in the back panel. If a very dense wood is used for a live back (e.g. African blackwood (*Dalbergia melanoxylon*), Macassar ebony (*Diospyrus celebica*) with densities of greater than 1000kg/m^3 the back has to be made only half as thick as a live back made from wood with a density of ~500kg/m^3 and the same bracing pattern. As the denser woods can be comparatively brittle, very thin back panels are rather fragile. Consequently, the author finds timbers lying in the density range 550kg/m^3 to 800kg/m^3 the most convenient to work with.

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[14] R. Inta, *The acoustics of the steel string guitar*, PhD thesis, University of New South Wales, 2007

[15] T. A. Gore and G. Gilet, *Contemporary Acoustic Guitar, Design and Build*; Vol 1, p2-40 to p2-41; Pub. Trevor Gore, 2011.

"Rosewood" vs "Mahogany"

Most listeners will be able to discern a difference between a steel string guitar with "rosewood" back and sides (*Dalbergia latifolia*) and a similar guitar with "mahogany" back and sides (*Swietenia macrophylla*). Different people describe the difference in different ways. To the author, the difference is heard as more midrange and longer sustain in the rosewood guitar compared to less midrange in the mahogany guitar.

A similar distinction is easily heard between a flamenco guitar (typically cypress back and sides) and a classical guitar (typically rosewood back and sides). The distinction exists even when the soundboards and other general dimensions are close to identical.

So what is the root cause of this difference?

For the author, the difference is due primarily to the overall mass of the structure that the soundboard is attached to, which is largely governed by the density of the wood species chosen for the back and sides. This can easily be demonstrated by constructing a guitar which has the facility for extra mass to be added to the sides of the guitar, (Fig. 10). The effect of adding mass is to reduce the frequency of the $T(1,1)_2$ resonance (Fig. 11) and increase the in-phase radiating area of the top, Fig. 12. Acoustically, the outcome is that the lower mid range is enhanced, effectively turning a low mass "mahogany" back and sides structure into a higher mass "rosewood" structure with the recognised auditory effect.

Back and side woods can be classified into low and high density groups approximating the densities of generic "mahogany" and generic "rosewood" with obvious transitional species, Table 3. Other properties of a selection of woods are shown in Table 4.

"Mahogany" range		"Rosewood" range	
Species	Density kg/m^3	Species	Density kg/m^3
Cypress	465	East Indian Rosewood	790
Koa	560	Purpleheart	880
Honduran Mahogany	590	Brazilian Rosewood	890
Big leaf maple	605	Madagascar Rosewood	950
Sapele	620	Bloodwood (Satine)	990
Black Walnut	640	Cocobolo	1100
Tasmanian Blackwood	700	Macassar Ebony	1120
Padauk	700	African Blackwood	1200

Table 3 *Densities of various hardwood species used for backs and sides of guitars, classified by density into a "Mahogany" range and a "Rosewood" range. Densities quoted are means of relatively small samples. The species range can be ±30-50% of these values.*

Hardwood Species	Long-grain Young's Modulus (GPa)	Density (Kgm^{-3})	Janka Hardness*	Logarithmic Decrement
EIR	9.8-15.6	740-840	10.0-12.5	0.018-0.028
Brazilian	12-14'	880-900	10.5-13.0	-
Blackwood	11.5-16.4	630-900	5.0-8.5	0.023-0.028
Satine	18-19'	990-1100	12.0-15.0	-
African Padauk	10.7-12'	570-750	4.0-5.0	-
Walnut	11-13'	540-590	4.5-5.9	0.017-0.023
Macassar Ebony	18-26'	900-1100	11.5-13.0	-

Table 4 *Properties of a variety of hardwoods used for guitar backs, sides and bridges.*
** Data sourced from Bootle[16]. ' Indicates small sample size*

[16] K.R. Bootle, *Wood in Australia*, Appendix 3; McGraw Hill Sydney, 1983

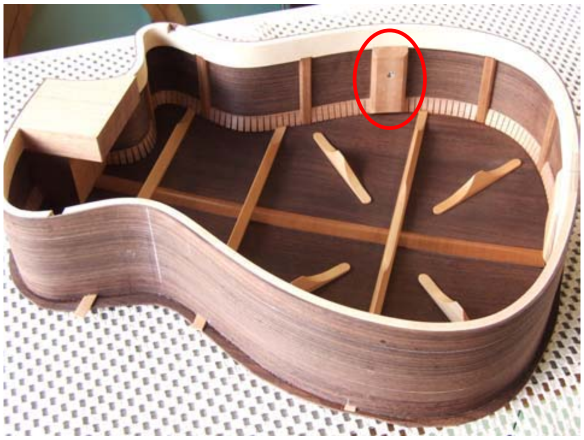


Fig. 10 *Mass attachment point (circled)*

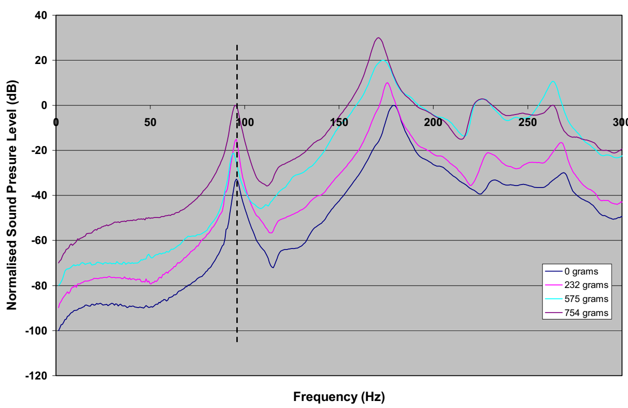


Fig. 11 *Shift in $T(1,1)_2$ frequency with added side mass. The $T(1,1)_1$ frequency remains constant. Each sucessive plot is displaced 10dB for clarity*

Fig. 12 *The left picture shows the* $T(1,1)_2$ *mode (main top) at 175Hz with no side mass added. The right picture is the same guitar with 335gm added to the side of the guitar in the lower bout, treble side. The node line has moved outboard, particularly on the treble side which results in an audible acoustical difference. The resonant frequency was reduced to 171.6Hz.*

Wood for necks and fretboards

Neck woods

The neck is a long, slender structural member under axial compression and bending as a result of string tension. The heavier the strings, the greater the string tension required and thus the neck has to resist more bending and more compression. The neck, however, is generally a composite structure comprising the neck, fingerboard and truss rod, so the neck wood has to be considered in this context. The better designs of truss rod add only bending forces to the neck with no additional compressive force and are adjustable from the body end so as not to weaken the headstock area.

A stable neck can be manufactured from a wide range of woods. Further, if reasonable wood is chosen, the author's experience has been that it is unnecessary to complicate the manufacture of the neck by using multiple laminates of either wood or composites to add stiffness and stability to the neck. Adding carbon fibre to the neck does not seem to produce any audible advantage whilst adding significantly to the build complexity.

The properties required of neck woods are long term stability under load and humidity variations, and ease of carving. The traditional choices are Honduras mahogany (*Swietenia macrophylla*) for a steel string guitar and "Spanish cedar" (*Cedrela odorata* – neither Spanish nor a true cedar) for a classical guitar. Australian Queensland maple (*Flindersia brayleyana*), which is not a true maple, is a very good neck wood. It is not unduly dense and carves very well, whilst possessing good strength and stability. Likewise, another excellent neck wood is New Guinea rosewood, (*Pterocarpus indicus*), of the same family as the padauks. It is stiff and stable but has a rather variable grain structure.

Critical to the success of a guitar neck assembly is that it remains stable over time as relative humidity changes. This cannot be achieved if the fretboard and neck woods have significantly different coefficients of dimensional change with moisture content.

Fretboard woods

Hardness, abrasion resistance, stability and the ability to hold a fret are the desirable properties when selecting fretboard woods. These properties are usually associated with high density and high stiffness in compression, which are also favourable properties.

The conventional choice of fretboard wood is made between the ebonies and the rosewoods. Ebony is the most highly prized, good pieces being uniformly black against which the frets and any inlay work contrast well. However, African ebony *(Diospyros crassiflora*) especially is not very dimensionally stable and is so stiff that it has the capability to bend the whole neck with humidity changes. It has a tendency to check and can be very brittle which is problematic when removing old frets. Being extremely stiff in compression, the fret slots need to be bevelled on the fretboard face in order to allow the fret to be effectively seated without undue force. Macassar ebony (*Diospyros celebica*) is a better choice for fretboards as it is more stable, having similar stability to the rosewoods. Whilst often stripy, when oiled the wood becomes (and stays) a uniform black. The ebonies are generally regarded as being more abrasion resistant than the rosewoods, but on fretted instruments this is less of a consideration than it is on violin family instruments. The ebonies provide a smoother finish due to the absence of large pores, a property that some players value highly. An alternative wood that meets the requirements for fretboards is Satine or Bloodwood (*Brosimum rubescens*). It is a rich red colour which will remain red if kept clean and is as hard or harder than the ebonies. It is more stable and has very small pores, and so works to a very smooth, hard surface.

The rosewoods (*Dalbergia spp.*) vary from dark purple/brown for East Indian rosewood (*D. latifolia*) to brick red for Vietnamese rosewood (*D. bariensis*). The within-species variation in material properties is considerable, with hard examples of most species being available. *D. latifolia* is generally on the softer side with Madagascar (*D. baronii*), Brazilian (*D. nigra*) Vietnamese (*D. bariensis*) and Amazon (*D. spruceana*), being harder.

The author has not been able to attribute any particular acoustical properties to particular neck woods, fretboard woods or combinations thereof.

Bridge Woods

The bridge is a piece of wood that does many jobs. Most obviously it holds the saddle, terminates the strings and transfers the strings' vibrations to the top. Less obvious (to most people) is the fact that it is also a massive cross-grain brace seated right in the middle of the top of the guitar and so has a profound effect on the vibrational behaviour of the guitar, and consequently affects the sound of the guitar considerably[17].

The mass and long-grain stiffness of the bridge are therefore major design variables. But one also has to consider other attributes like the hardness of the wood (so that strings won't cut right into it) and its cross-grain strength and stiffness so that it will effectively support a saddle without the front of the saddle slot sagging forward or even splitting away.

The traditional choices are the ebonies and the rosewoods, but these woods, on the necessary gluing footprint, produce a bridge that is too heavy for the author's preferences. Having tested numerous species, the woods that rate well balancing stiffness, density and hardness are padauk (*Pterocarpus sp.*), walnut (*Juglans nigra*) and Tasmanian blackwood (*Acacia melanoxylon*). It is still important, however, to select low density samples. Samples can usually be found with a near enough colour match to the fretboard material, if the builder deems that detail important. Some padauk can start life a bright orange/red colour, as can some rosewoods, but both will tone down over time to a rich brown colour. Walnut has a brown/grey cast which can be easily polished to match the browner rosewoods or stained to match the ebonies. Tasmanian blackwood has a more golden colour in its natural state, but its colour and grain structure are very variable.

The overall mass of the bridge is a critical design factor in both tailoring the sound of the guitar (the bridge mass heavily influences the resonant frequency of the $T(1,1)_2$ mode) and in determining its responsiveness (it significantly influences the monopole mobility).

Fig. 13 shows the equivalent mass of the $T(1,1)_2$ mode for various steel string guitars. The figures were calculated by evaluating m in the monopole mobility formula.[18]

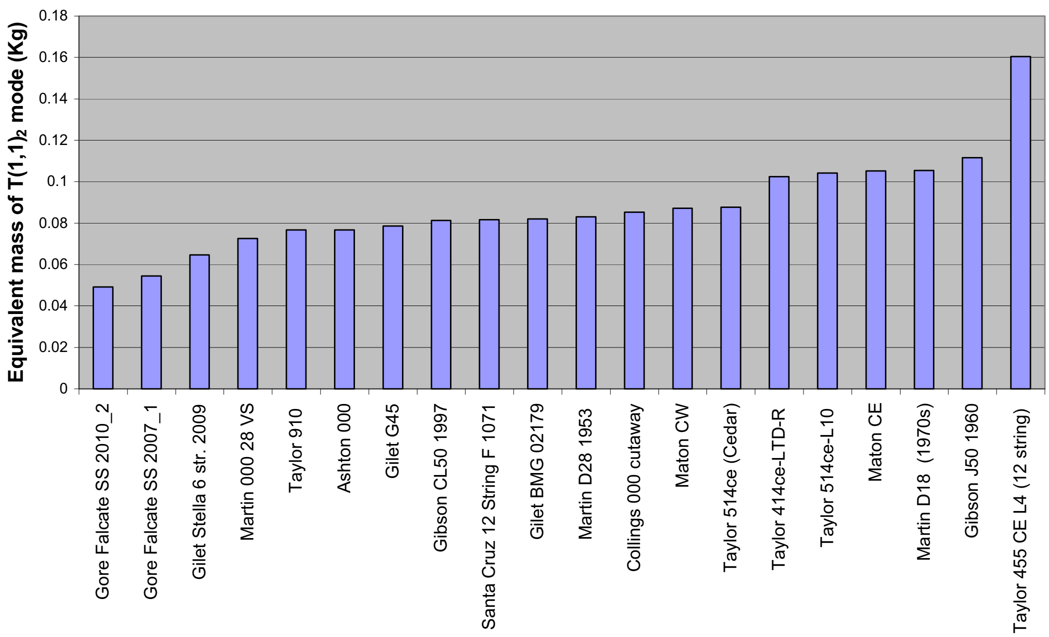


Fig. 13 *Equivalent mass of the $T(1,1)_2$ mode, steel string guitars*

[17] B. E. Richardson and G Roberts, *The adjustment of mode frequencies in guitars,* Proc. Stockholm Music Acoustics Conference, Pub. Royal Swedish Academy of Music, 46 (2) 285-302, 1983; E. Jansson *Acoustics for violin and guitar maker,* Kungl Tekniska Hogskolan, 4th Ed. 2002.
[18] See Footnote 2

Increasing the mass of the bridge translates immediately into increased equivalent mass of the top. Measurements (Fig. 14) indicate that for a guitar with an original monopole mobility of 11.1×10^{-3} s/Kg the increase in the effective mass of the top is ~45% of the actual bridge mass added. More responsive guitars are likely to reflect a higher percentage change. To bring the guitar back to a target $T(1,1)_2$ frequency, extra stiffness would have to be added, which of course requires extra structure and consequently further extra mass and a resulting significant decrease in monopole mobility.

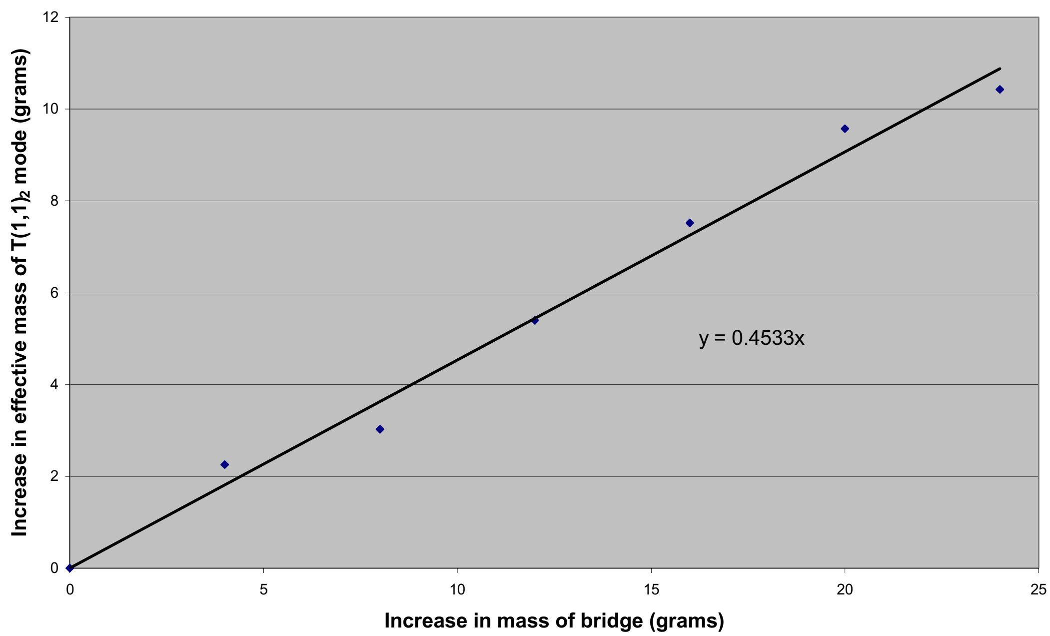


Fig. 14 *Increasing the mass of the bridge of a steel string guitar by substituting brass bridge pins for plastic pins increases the effective mass of the* $T(1,1)_2$ *mode by ~45% of the increase in bridge mass*

Bridge masses measured by the author prior to the assembly of some reasonable quality mass produced steel string instruments range from 20 to 35 grams, with bridge pins and saddles adding at least a further 5 grams. The wide range is due to the bridge height being used to compensate for neck angle variations whilst maintaining a constant saddle protrusion. This is a typical example of building to dimensional tolerances rather than acoustical tolerances. Other authors have suggested 35-60g as being a suitable range for a responsive steel string guitar[19] and 15-25g for a classical guitar[20]. The author keeps the mass of steel string bridges in the range 15-20g and classical bridges in the range 12-15g. It is challenging to build conventional looking bridges much lighter than this without risking too frequent failure.

Whatever else a steel string guitar might have going for it, a bridge in the mass range 35-60g almost certainly condemns it to acoustical mediocrity. It certainly could not be called a responsive guitar.

[19] E. Somogyi, *The responsive guitar,* p103; Pub. Luthiers Press 2009
[20] J. S. Bogdanovich, *Classical guitar making*, p 276; Sterling Publishing Co., Inc. New York, 2007

Conclusion

Specific woods types have specific attributes that make them best suited for making particular guitar components. Softwoods from the spruce and cedar families will be the preferred wood for soundboards, for example, for a long time to come. However, the street lore attributing specific types of sound to specific species of a genus is seldom justified. Wood properties are so variable within species that they substantially overlap between species and across genera. Guitars designed to acoustical criteria (rather than dimensional criteria) where the effects of different stiffnesses and densities of species are minimised, sound very similar. There are no known reports where species used in guitar building are successfully identified in blind listening tests. The residual differences that can be heard may be attributable to the sound spectral absorption and radiation of the particular piece of wood used, a property that is not easily measured and is poorly substituted by the occasional measurement of the damping characteristics of the wood. Once the density and Young's modulus of particular species is accounted for by careful acoustical design the residual differences are very subtle, yet can be important enough to ensure that some luthiers continue the romantic search for that "holy grail" of woods.

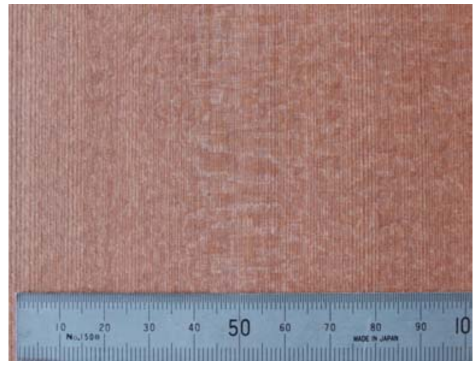
Acknowledgements

Many thanks to Gerard Gilet of Gilet Guitars, Sydney for access to some of his fine instruments, including the matched set of three 000 sized guitars. Thanks also to Rick Falkiner of The Guitar Centre for allowing access to his fine collection of classical guitars built by Spanish master luthiers. Jeff Mallia of Mallia Lutherie provided access to many of the steel string guitars measured in these tests, for which I am extremely grateful.

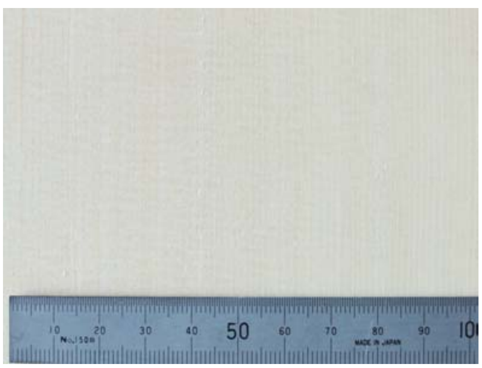
Appendix 1. Photographs of wood samples

All samples were freshly planed. No finish is applied.

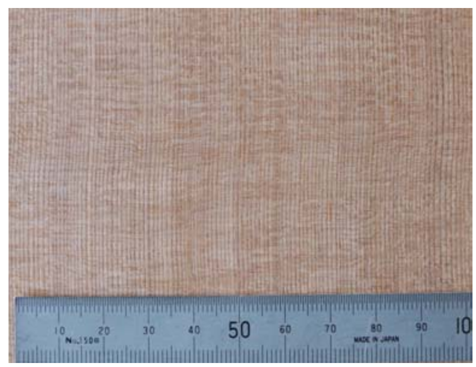
Sitka spruce
(picea sitchensis)



Redwood
(sequoia sempervirens)

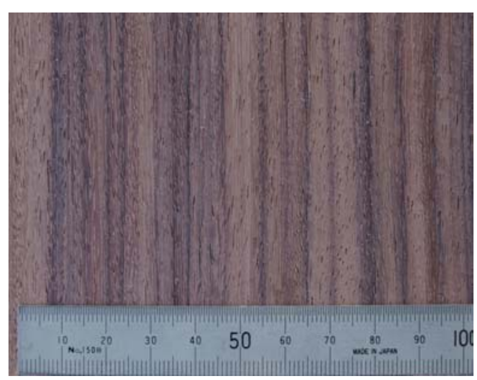


Engelmann spruce
(picea engelmannii)



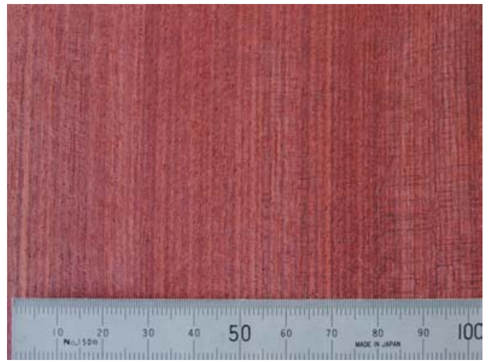
Western redcedar
(thuja plicata)

European (Norway, German) spruce
(picea abies)



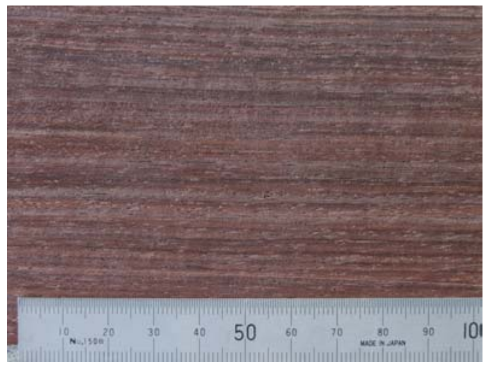
East Indian rosewood
(dalbergia latifolia)

Honduran mahogany
(swietenia macrophylla)



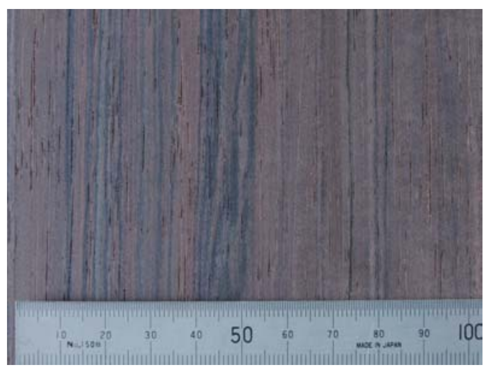
Bloodwood or Satine
(brosimum rubescens)

Queensland maple
(flindersia brayleyana)



Amazon rosewood
(dalbergia spruceana)

New Guinea rosewood
(pterocarpus indicus)



Brazilian rosewood
(dalbergia nigra)

Black walnut
(juglans nigra)

African ebony
(diospyros crassiflora)

Tasmanian blackwood
(acacia melanoxylon)

Vietnamese rosewood
(dalbergia bariensis)