The Guitar: History, Mechanics

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PRINCIPLES OF CLASSICAL GUITAR OPERATION

Two parts may be identified:

1) The excitation system – the strings.
2) The amplifier/resonator system, consisting of the instrument's sound body.

The strings provide a rich signal containing numerous frequencies that will be amplified by the soundboard, assuming it is constructed properly, as well as by other parts of the sound body.

All of these pieces and parts have their own natural frequency and act as resonators. As they are secured, attached, glued together, they act as coupled resonators.

The major challenge is amplifying all of the frequencies emitted by the strings, without emphasising or restricting some of them, specifically without over resonance or holes in the instrument's frequency response, which must be even for all notes and strive for this goal. If the soundboard amplifies one frequency, reinforced by the vibration of one of its constituent parts, this is called an over resonance. The opposite is also possible.

It is therefore possible to modify the constituent parts, all of the pieces in order to obtain an even response without damaging the qualities already acquired.

However, a new problem soon arises. The energy communicated by the thumb to the string may be reconstituted by the guitar in three seconds or in six seconds, depending on construction.

This leaves us with two extreme choices:

1) Build a lightweight guitar, with a maximum weight of 1,600 grams with a thin soundboard, similar to a drum skin. This will lead to large amplitudes but swift decay of sound, in part because the back and sides will also be very thin. This will deliver a strong bass and a generally rounded, dull and brief sound with a prominent attack.
2) Build a heavier instrument, with thicker plates, with a more heavily braced soundboard (properly reinforced) which resists, which "springs back", which is not blocked.
   With a well thought-out neck, the instrument as a whole will be balanced, allowing good oscillating potential. This leads to long sustain, maximum power and excellent output, but a clearer, shallower sound overall.

It must be noted that no part of the guitar can be modified without changing some aspect of its response, the guitar's sound, for better or for worse. Extremely careful observation is necessary in order to advance.

A technical data sheet must be drawn up for each instrument. Finally, it is the builder's sole responsibility to make the choices. He must be gifted with the ability to synthesise and a certain artistic flair.

There is no 'secret key' to designing or creating a guitar; there are thousands of things to know. There are no miraculous 'tricks', only experience, a great deal of experience, from which observations, teachings and solutions may be drawn.

Amongst the numerous problems faced by the luthier, some are difficult to grasp and partially evade scientific attempts to decipher them, placing them in the field of artistic endeavours (which itself is broad enough).

These experiments will focus on:

1. Power (from afar, close by).
2. Sustain.
3. The evenness of the sound level
4. The timbre (the quality and texture of the guitar’s voice, its colour).
5. The balance between treble and bass.
6. Easy or difficult playability of the instrument.
7. The homogeneity of sounds.
8. Degree of responsiveness and sensitivity.
9. Attack of the sound (noticeable or slight).
10. Contrast (more like a “harpsichord” or more like a “piano”).
11. Sympathetic resonances – present or absent.
12. Clarity or darkness of chords.

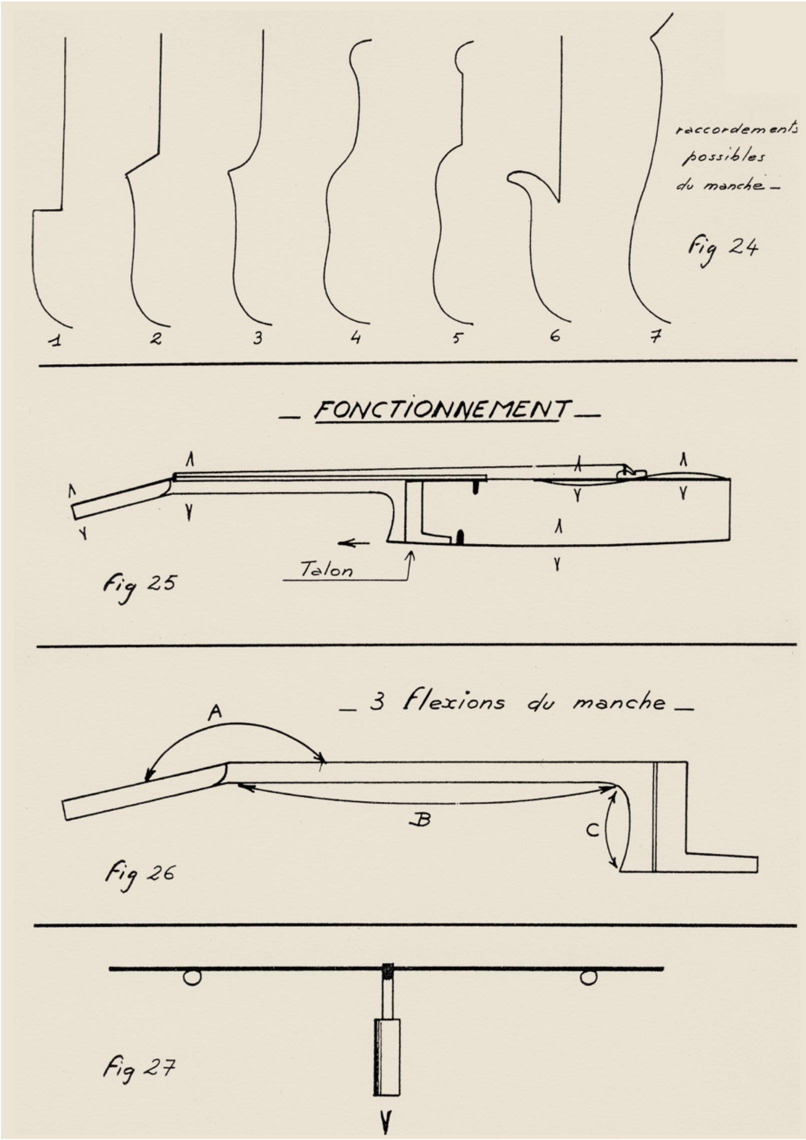
Ed.: On an undated paper posted on the wall in his studio, where all these criteria were listed, Friederich had added 2 others: 13) Presence of a fret buzz and 14) Intonation.

All of these elements constitute the primary characteristics of the instrument, but we will only examine some of them in detail in this article. Power and sustain in particular. In fact, the investigator will also assess other elements in the course of his research into power and sustain.

Which component parts of the instrument should be prioritised for study?
If we experiment on multiple parts at the same time, interpretation of results will be unreliable and difficult. In descending order of importance, we must examine:

1) The soundboard and its bracing; the choice of wood, thickness.
2) The neck; the type of wood, thickness.
3) The body; the sides, the back.
4) The bridge; its volume and shape, arching.
5) Glues and finishes.

The investigations presented below focus primarily on the system of 'Soundboard – Neck – Strings'. Also described are an experiment examining the roles of the soundboard and the back, and finally a historic perspective and the mechanics of guitar bridges.



SOUNDBOARD – NECK – STRINGS SYSTEM
Researching power – Testing a theory of functioning

(it is assumed that the majority of guitarists desire an instrument with good sustain with a less explosive initial attack, but which retains body in the subsequent seconds).

Upon release of the string – let's take the sixth string, Low E – after having created excess tension, meaning simultaneous movement of both soundboard and neck, via finger pressure on the string, we can observe a complex vibrational excitation of the instrument.

1) Direct excitation:
   The soundboard begins to oscillate upon release, vibrating in response to the string's excursions. The neck does the same, particularly the headstock (easy to verify by holding it between two fingers) at the other

extreme end of the string.
If the neck wood and heel are hard and rigid enough, and the back is flexible and lightly braced, the back will also move with the pull of the heel (*fig. 25)*. Movement which cannot exist without the presence of an arched, domed back.

The part of the soundboard (which is domed) behind the bridge is also subject to additional traction with each vibration of the string (which merge into a complex vibrational mode). These vibrations are instantly transmitted to the sides and the back by the materials used, which will reinforce certain frequency, leading to particular sound characteristics for a series of notes.

2) Indirect excitation: air resonances:
The vibrating air volume, created by soundboard displacement, will act on the back and sides at their fundamental frequencies, and project sound waves through the soundhole.
All of these vibrational modes combine and superimpose themselves to yield complex sounds with specific characteristics which the luthier tries to master.

The neck
Closer observation of the neck reveals three potential points of flexibility/bending that are the site of vibrational motion upon release of the string, combining instantaneously (*fig. 26).*

Let us examine two extremes. The neck may be constructed out:
- of a hard, heavy and rigid wood,
- or made of a flexible, lightweight wood,
- or simply be too thin, or too thick.

(A neck may be considered too thin if it bends under string tension, the relief, exceeds 0.4 mm. Past this value, phenomena such as string 'rattle' in the basses and 'snapping' in the trebles once past the sixth or seventh fret, requiring raising of the saddle).

A heavy, rigid neck: It is easy to imagine, therefore, that a neck that is too heavy and too rigid will inhibit the movement of the string upon its sudden release. It dominates the system and will prevent the swift development of lower frequencies, for example. Bass notes will be dry and lacking in mellowness. The neck acts as a filter.
This neck, with its anarchistic response, will also inhibit the soundboard, leading to difficult coupling, dulled response and finally, a loss of power.

A flexible, light or thin neck: The opposite situation, a very flexible or too thin neck, is equally problematic. When the finger applying pressure to the string creates additional tension, the weakest, most flexible point will move. In this specific case, the neck itself will pull forward rather than the soundboard, which will only move a minimal amount; this is not the goal strived for in guitar making.

The notion that creating movement in the soundboard is the only important thing, ensuring string action only manifests in the soundboard, is seductive. We see some luthiers use very robust necks on their guitars, or add internal stiffeners to the neck. The solution to this type of problem is often a compromise between the advantages and disadvantages.

The soundboard

The problem is complicated by the soundboard, situated at the other end of the string.

The soundboard too can be described conceptually in two extreme, different ways:

1) Soundboard that is too stiff. There is minimal movement, leading to a small sound which is dry and clear, with minimal amplitude and is difficult to play.
2) Soundboard that is too flexible. Large amplitudes favouring bass notes are obtained, with strong second harmonic, easy playability, mellow bass, but generally short sustain.

This oscillating system can be visualised and illustrated at a low cost, by placing a 5 mm x 5 mm stick of spruce on two small dowels spaced 40 cm apart (fig. 27). Attaching a 500 g weight at the centre the stick of spruce pulls it down slightly, and when released, a fairly rapid, sustained movement may be observed (the weight represents the effect of the strings on the soundboard). Next, by placing a stick of the same wood but thinner, only 3 mm thick, if we repeat the experiment we can observe a much slower, shorter movement with greater amplitude which closely mirrors the behaviour of a soundboard that is too flexible.

Soundboard and neck

Combining soundboards and necks yields two extreme scenarios:

1) Soundboard and neck are too stiff: Only the string stretches, nothing moves voluntarily, volume is pathetic, the sound is small, dry, with a poor, metallic timbre and lacking in bass.
2) Soundboard and neck are too flexible: A lot of bass, the guitar will have a soft touch (in a word, mushy). The sound will be generally short and dull, and attack will be characterised by string rattle and snap.

One could also combine a flexible neck and a stiff soundboard, or vice versa, which we have already described above. As with all aspects of lutherie, this is an artistic choice representing the maker's personality.

From one choice to the next, the personality of the luthier emerges.

The quest for power – for the equilibrium point in the 'soundboard – neck – strings' system – may be facilitated by measuring the flexibility of the neck and the soundboard separately and subsequently, with the instrument completed, repeating these measures with and without string tension as outlined in the paragraph 'Controlling flexibility'.

Comments
Luthiers of days past tensioned the strings of their instruments until they 'Rang out' and functioned properly. Modern day demands appear greater; obtaining a sound with good sustain and timbre, without weaknesses in any of the three and a half octaves requires in-depth research while maintaining fixed tuning to A 440 Hz.

In order to achieve optimal tuning and balance for soundboard, neck and strings, an adjustable neck may be employed, with an adjustable joint and two screws that rest on the soundboard. We personally built such a design, but found the variation available to be lacking.

Second solution: Adjust the soundboard after testing the instrument (only possible if bracing has been designed with this approach in mind).

Third solution: The system can be optimised by changing string tension.

A final observation relating to the wood that has been used in high-quality classical guitar necks for over a century: Spanish Cedar (Cedrela odorata) appears to have a rare property in addition to its stability and light weight. Its damping property (and sensitivity to impact) allows it to stop, to filter certain vibrations coming from the headstock which could be a nuisance if they travelled all the way to the sound box, overlapping vibrating frequencies emitted from the bridge. This wood therefore delivers a clean, neat, homogenic character to the sound, as well as contributing to a spontaneous sound due to its light weight.

WOOD SELECTION – TESTING
General considerations
Once the luthier achieves an excellent result through successive trials, a major problem arises: “How to precisely reproduce this instrument in terms of power, timbre, homogeneity, touch, etc...?” *(This relates to lutherie of the highest level).*

Woods are most often extremely variable, even within the same tree or within one board from said tree. There are a number of different ways to address this issue:

1) The optimist says to himself: “Chance will bring me pleasant surprises”.
2) The careful builder will think: “I like to control as many aspects as possible, experiment in order to improve areas in which my understanding is lacking, and be able to implement diverse and desirable changes.”
3) Alternatively, one might say: “Using the knowledge I have gained, I will attempt to construct homogenous guitars of very similar quality, with woods that often have very different characteristics”.

In any case, mistakes are very "unwelcome" and embarrassing, and the problem of wood selection arises.

Comments
The first experiment which comes to mind is obtaining soundboards that come from the same board *(difficult to realise, as most commercially available soundboards tend to be mixed up)*. Over the course of several years, one notes that the soundboards from the top of the tree trunk are tighter, stiffer. During the next sawing session, one takes care to number the soundboards, dividing the tree trunk into three or four sections of increasing rigidity and fineness of grain. Despite these efforts, results remain uneven.
The same observations can be made for necks, which when taken from the opposite sides of a board (in width), can vary significantly in terms of both weight and rigidity.

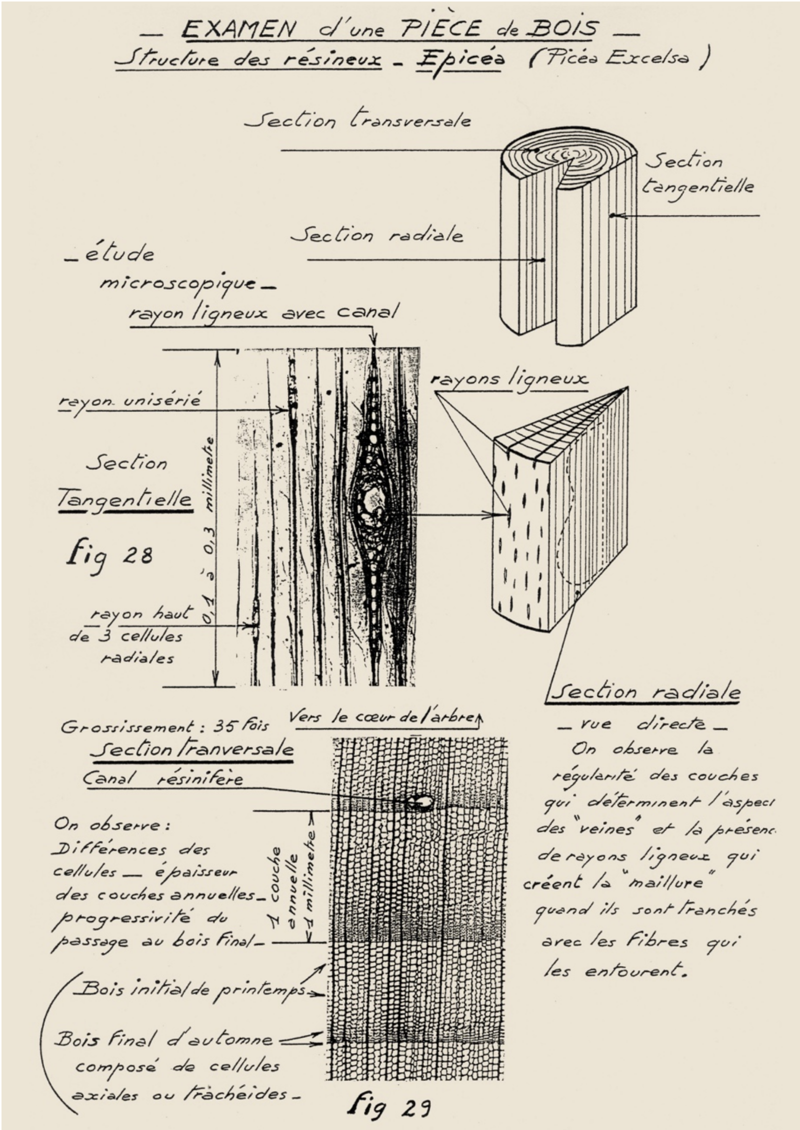
To move beyond a lutherie of chance, one must go further and systematically control and weigh every part, choosing exactly the same species of wood which yielded an interesting result.
(Thankfully, guitar making, with its multiple thin plates of wood used to construct the guitar, is well suited to tests and measures that are far more difficult for violin makers.)

We present a number of quick observations on the resinous woods used for soundboards (spruce in the example below) before providing more precise ideas about flexibility and calibration of various constituent parts, as well as examining the flexibilities that the instrument may present during the course of its construction and in its finished state.

Examination of a piece of resinous wood
The structure of spruce
These woods consist primarily of axial cells (lengthwise) which act as minuscule 'juxtaposed pipes' 1.5 to 4 mm in length. They often account for 90% of the wood's total volume.

There are also radial cells (radiating from the centre to the outside), which create the medullary rays.

There are two types of axial cells (tracheids) (fig. 29):
1) Cells formed at the beginning of the growing season (earlywood), with thin walls, which are elements that conduct sap.
2) Cells formed late in the growing season (latewood), thicker walled and flattened, which are the support elements and lend the wood rigidity and resistance.
   These close-packed cells define the annual rings and form the grain.



External factors (the meristem) will greatly influence structure and determine the proportion of earlywood and latewood cells. These factors include altitude, the tree's immediate environment, the terrain, rainfall.

We know that altitude (around 1,000 meters) often yields thin layered spruce, as the growing season is short. This generally leads to a heavy, strong grained wood.
The cells in the latewood are the spruce's natural reinforcement in a longitudinal direction.

Trees that have experienced regular growth over the two to three centuries required to create a beautiful tonewood are rare. Growth rings are irregular due to greater rainfall, or milder temperatures for one or more years. Felling a neighbouring tree immediately provokes enlargement of cellular layers. This is visible as areas of varying density across a board.

Along its radial axis, the tree has a multitude of medullary rays with a lenticular or extremely flattened cross-section, creating the 'cross frame' for the wood, its 'solid' reinforcement (figure 28). The medullary rays are not very tall, between 0.1 mm to 0.3 mm. They consist of cells with moderately thick walls. The rays, depending on their number and thickness, appear to contribute to radial rigidity, i.e. 'cross grain stiffness' (1).

(1) When asked about this hypothesis, the Technical Wood Office replied it was 'very likely'

An important comment arises: if one takes an off-axis board of spruce, one will no longer encounter whole medullary rays, but rather rays that have been broken, lending the board a certain lateral 'floppiness', a significant difference compared with a perfectly on-axis board taken from another part of the tree.

This leads to the following deduction: when buying woods, the presence of fine chatoyance when held up to the light indicates the presence of cleanly split medullary rays along with the 'fibres' surrounding them, indicating the board was taken from the centre of the tree and will present maximal 'cross grain' stiffness.

One notorious cause of irregularity in the mechanical properties of wood in general, and of spruce in particular, is that the wood fibres often don't grow perfectly parallel and vertically, resulting in constantly shifting directions of wood fibres throughout the board. In these cases, the wood fibre is considered 'cut', leading to extremely diverse mechanical properties from one piece of wood to the next.

For all of the reasons enumerated above, when one is selecting pieces of wood for bracing, for example (from a single board), one may note that pieces taken from a particularly hard, resinous part of the board will exhibit flexibility numbers, mechanical properties, that vary by a factor of up to three, meaning they can be up to three times as stiff as a piece taken from a softer area.

This lack of homogeneity poses a problem that can be resolved by controlling, measuring and sometimes weighing almost every component, allowing the luthier to choose those that exhibit the desired qualities.

These controls – flexibility of components – will relate to their weight, and for soundboards to their cross-grain compressibility. Compressibility that can be tested using a sample a few centimetres wide over the entire width of the joined soundboard. Compressibility replaces cross-grain flexibility, a measurement which is always difficult to obtain.

A soundboard that is highly compressible is a supple piece of wood, with low cross-grain stiffness, which will lead to a dulled response and a risk of rapid wood fatigue under string tension. Precise measurement of this value is interesting.

Device for measuring compression

The goal is to slide the cross-grain sample vertically into a case with walls that keep it squared.
Next, a weight of 10 kg per square centimetre (more or less) of sample is

applied to the end. The amount of compression is read using a dial gauge which must be integrated into the measurement apparatus. The soundboards will also be subjected to tap tuning by tapping the centre of gravity, potentially followed by frequency analysis of this impact in a laboratory *(described elsewhere in this bulletin)*.

Concepts of flexibility and assorted tests

A board flexed within its limits is subject to constrained forces of compression for the outer face, and traction for the inner face. These forces act most strongly on the surface fibres.

We observe a neutral fibre in the centre.

The deformation, the curvature of the piece can be calculated.

We also encounter the notion of the modulus of elasticity, or Young's modulus. Simply put, this represents the degree of rigidity for the wood, which will determine greater or lesser easing.

When building the guitar, we encounter many potential flexibilities that can be measured with a selection of simple devices created by the investigator.

Longitudinal flexibility

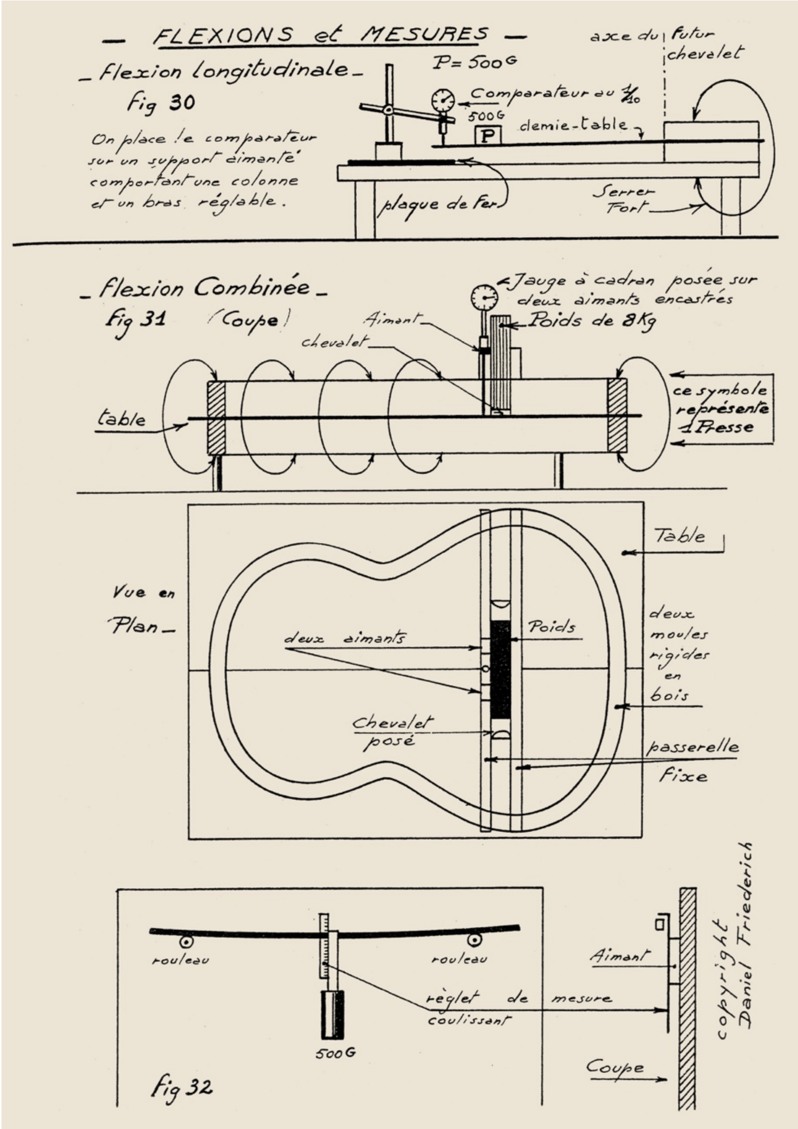
1)Take one of the two halves that will constitute the soundboard, dimensioned uniformly to a thickness of 3 mm, for example, and place it in the device (fig. 30) so that the folding axis will be situated precisely where the saddle would be. By applying a weight of about 500 grams at an adequate distance, the difference in flexibility can be measured either by using two metal rulers (one on each side, attached to a magnet, or using a dial gauge mounted to a support. We can call this longitudinal flexibility.

Combined flexibility

2) Once the soundboard is jointed and glued a more complete measurement can be obtained, providing a more realistic indication of flexibility or stiffness using a device (fig 31) consisting of two 'external moulds' of thick, rigid, non-deformable wood, with a cut-out precisely matching the guitar's shape.

By placing these two 'moulds' on top of one another and clamping them firmly in place (with the soundboard between them), it is possible to apply a weight of about 8 kg to the bridge location, and measure flexibility using a dial gauge The calliper will be attached to a bridge on one of the two transverse slats, between which the 8 kg weight will be inserted to rest on a bridge, positioned where it will be on the completed instrument.

This flexibility figure represents the resultant of the combined transversal and longitudinal rigidity, hence combined flexibility.



3) After the soundboard, we turn our attention to the various bracing components (fig 32). The flexibility of each brace can be measured easily by placing it on two small dowels spaced about 40 cm apart. A 500 grams weight can be hung from the brace and a dial gauge can be used to measure the maximum flexibility (you will be surprised by the significant variations between different pieces of wood).

4) The same setup can be used to measure flexibility for transverse braces, but deformation will be so minimal, a gauge measuring tenths of a millimetre should be used.

5) Bridge flexibility (the bridge is essentially a transverse brace) is also interesting. This allows testing a batch of items, randomly varying dimensions, or varying them systematically, one by one. Immobilise the bridge by clamping one of the wings firmly in a modified vice, and hang a 1,000 grams weight from the end of the other wing. Flexibility is measured using a dial gauge measuring tenths of millimetres.

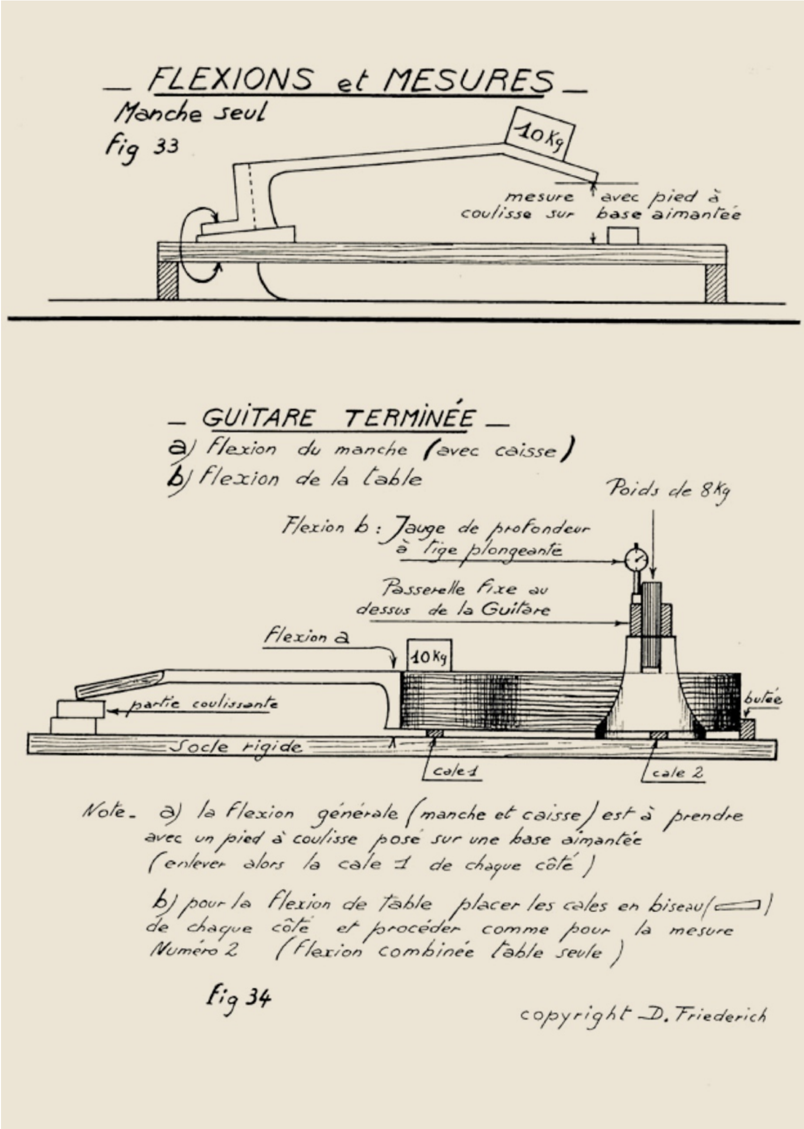
Bridges can also be evaluated for their tendency for torsion, an interesting notion if one tries to allow the bass and treble sides of the guitar to work independently. A bridge that is too thick, or made of wood that is too hard will only move as a single block, without any flexibility.

6) Flexibility of the roughly shaped neck (fig. 33). This important measurement should be made when a neck is rough cut, meaning rough shaped with headstock and heel block glued in place. By clamping the neck by the Spanish foot and placing a 10 kg weight on the headstock face, flexibility can be measured using a decent calliper. The calliper can be attached to a magnetic base.
The overall gross weight of the neck should also be recorded; a systematic record for all woods used for this purpose should be created.

7) Flexibility of the ebony fretboard. The method to use is similar to the one described under I for measuring soundboard flexibility (longitudinal flexibility). After immobilising one end of the fingerboard, a 1,000 grams weight is placed on a defined reference point, and flexibility is measured using a metal ruler or a dial gauge It goes without saying that all pieces of wood to be compared must be planed down to the same thickness.

8) Dimensional stability. In humid environments in tropical countries, or by the seaside, some guitars seem 'muffled'. One may assume certain woods used for soundboards are particularly hygroscopic. It is a well-known fact that certain extremely dense and resinous spruces resist impregnation with conservation products through immersion, and their saturation point is significantly lower than 28% for water – the average for this wood species.

9) Flexibility of the neck with and without string tension (fig. 34)
Once the instrument has been completed, and before varnishing, the behaviour of the neck when combined with the sound box can be checked by placing the guitar in an apparatus where it rests on three points, situated at the end of the headstock and at the two widest points of the lower bout (the contact point the headstock rests on will need to be flexible in order not to falsify the measurement). It is then easy to place a 10 kg weight between the 12th and 19th frets, and measure displacement using a calliper between the 11th and 12th frets.
Once the guitar is complete, this operation can be repeated with the strings tuned to pitch, and one will be surprised to note that some instruments display greater displacement with the strings tuned to pitch, raising questions of why.



10) Soundboard flexibility – strings tuned to pitch – strings slack.
Without changing the guitar's position on the apparatus, following the previous measurement, move on to the measurement concerning the soundboard’s flexibility once the guitar is complete. The 8 kg weight is inserted between the transverse slats (as described above) and applies weight to the bridge, positioned temporarily before varnishing.

The operation will be repeated once the bridge is glued in place, and again with the strings tensioned, allowing the luthier to observe the most significant movements when the strings are tensioned on certain instruments. In general, the guitar will have the lightest touch if the flexibility of the top exceeds 2 mm and if the flexibility of the neck also reaches the figures found under the previous section (N°9 in this section).

The wise luthier will learn from these different measurements. He will have to weigh the rough-sawn and then dimensioned soundboards, as well as the necks, backs, fingerboards and sides in order to build an instrument whose weight matches his wishes and plans.

Attack, the sound of fingers moving along the string is far less audible if the instrument is heavy. However, there is also a limit beyond with responsiveness, spontaneity and suppleness of sound find themselves altered (the margin is narrow).

At the end of the twentieth century, we do not feel it is not at all useless to spend two or three hours taking measurements and performing tests (and recording and archiving the findings) considering the overall build time of at least 100 hours required to create a quality guitar.

For the artistically inclined luthier, this careful approach and understanding of these mechanical elements will allow a greater flexibility and variety within his building; they are a weapon against the 'industrial aspects of the guitar' which attempt to thwart change. It is not wrong to think that past masters had already created a system of personal references that allowed them to secretly move forward on sure footing. *(We personally hope that these testing procedures constitute the most significant technical contribution possible within the context of this essay*).

A final note should be writ large:

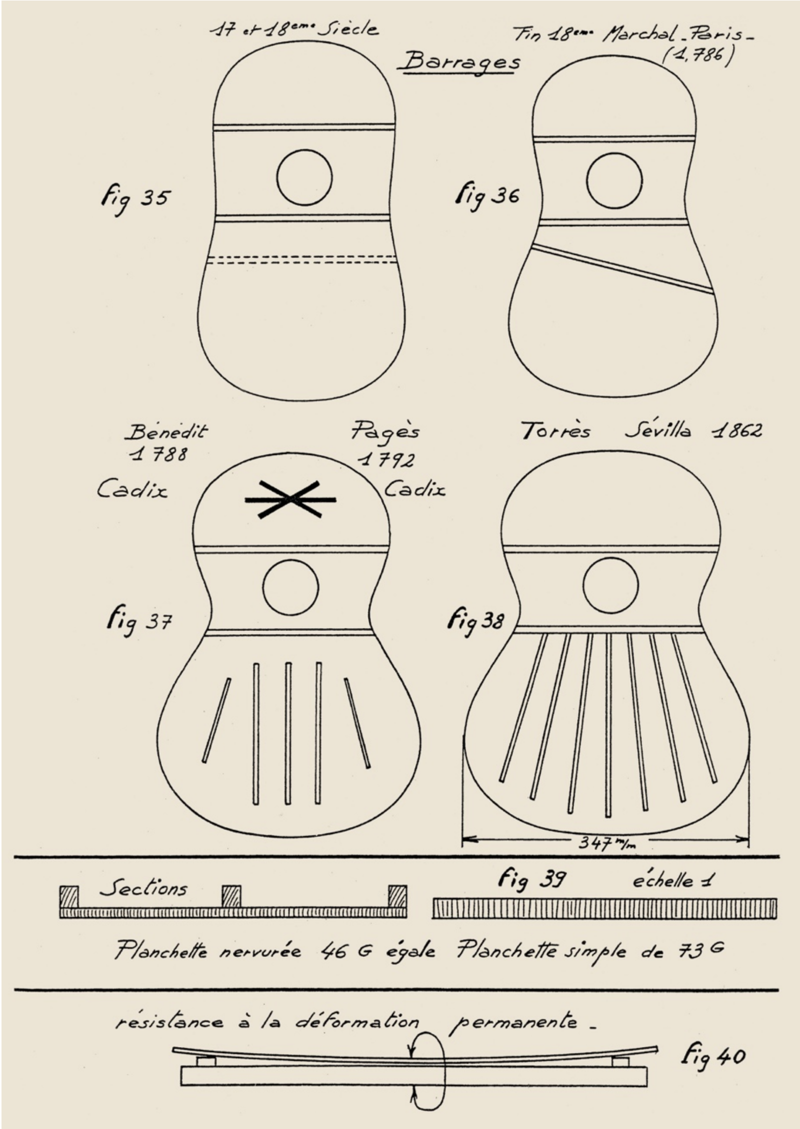
It is impossible to build two comparable instruments without using the same woods

Soundboards and bracings

In the 17th and 18th centuries, guitar soundboards were reinforced with nothing more than a brace placed at either side of the rosette (fig. 35). In exceptional cases, imitating the lute, a light brace was placed between the rosette and the bridge.

Towards the end of the 18th century, a number of experiments began appearing in France. Marchal placed an angled brace between the rosette and the bridge (fig. 36), but the breakthrough discovery for the birth of the modern guitar appears to have been made in Andalusia, in Cadix: Benedict in 1788 and Pages in 1792 were already employing a five-brace fan (fig. 37).
With this pattern, they discovered a revolutionary bracing system that would further differentiate and separate the guitar's tonal character from that of the lute, giving it the character we are now familiar with.

Antonio de Torres (1817 – 1892) must have been familiar with the guitars built by Pages, renowned in their time, and he accented the system by adding two further braces (fig. 38), and increasing the size from 35 to 36 cm for the maximum width of his guitars dated around 1860.



A little bit of research will show that this bracing pattern allows equivalent longitudinal rigidity and solidity while maximising transversal flexibility with less thickness. All that is required is to glue three braces on a softwood board 40 cm long and 2.6 mm thick (fig. 39), and it will become apparent that a board 5.2 millimetres thick is required to provide the same amount of flexibility, the same resistance, and will weigh 73 grams instead of 46 grams.

This significant weight gain will allow a more spontaneous response, a greater responsiveness, a greater maximum amplitude (more bass) and a longer sustain, because internal friction is less significant in a thinner section of wood.

Antonio de Torres's methods created a solid bass sound and a taste for the instrument that has lasted for over a century. In recent years, a slight shift in the opposite direction may be noted. (It must be remembered that the guitar has gained bass response since the end of the 16th century).
All luthiers are capable of building instruments with a generous bass response... the difficulty lies in building a guitar with a bass, midrange and treble response of equal quality.

THE ROLES OF WELL-DESIGNED SOUNDBOARD BRACING

1) Allows the implementation of a large number of vibrational modes and the amplification of many of the frequencies delivered by the rich string signal (the subdivision of the vibrating surface into sectors and areas by a bracing pattern allows the creation of complex vibrational modes not possible if the soundboard were a simple plank of wood).

2) Creating a pleasing, interesting, characteristic sound.

3) Bracing must hold up mechanically for the long term, withstanding the violent effects of torsion applied by the strings.

4) Must not be too rigid. This will quickly lead to a heavy touch and difficult playability. The sound will be dry, devoid of smoothness, mellowness and bass.

5) Must not be too flexible: this will yield a large, short sound, bassy and dull, with a very easy touch, but strings that 'slap' under the fingers, with a mushy sound in rapid runs; the instrument will easily be overdriven when played heavily.

6) Bracing must not lead to anarchistic responses within the system of 'neck – soundboard – strings'.

7) If necessary, minor touch-ups can be performed, to correct mistakes or make adjustments after testing.

8) The bracing pattern may limit the appearance of shrinkage cracking. This is an important function for reinforcing a piece of wood such as the soundboard, which is exposed to tension caused by drying out or swelling due to humidity.

The importance of the soundboard bracing pattern takes a long time to understand. It is well-established in terms of woods used and goal strived for. The best results are often found at the limits of resistance for these woods, making the longevity of the system extremely precarious.
Modern guitars have limited solidity reserves in terms of bracing, and are not designed to last 100 years with the same sound.

It is not only the bracing layout that defines the quality of the sound emitted. The properties of the soundboard wood itself, of the vibrating plate, are extremely important and will provide an initial colour to the sound; a particular, specific quality.

Each piece of wood, even within the same species, has a property that must be discovered. It takes skill to create a very warm, mellow sound full of character, but with enough darkness while providing opacity in chords, with multiple superimposed notes.

Another tree may deliver different qualities; sustain, clarity, biting brilliance - characteristics that will make the guitar more suitable for playing the work of Bach over that of Turina or Villa-Lobos. The guitar that can do everything does not exist and the luthier will have to either accept a compromise, of sell multiple guitars to his wealthier clients...this is often the case for renowned guitarists.

Using bracing adjustments, these different qualities can be balanced and adjusted sensibly (while exhibiting mastery, should one have the ambition).

Comment

In any case, we note that string vibration dissipates more or less swiftly for three reasons:

a) Opposition of air resistance to soundboard movements.
b) Internal frictions in the soundboard (which transforms the communicated energy into heat).
c) Internal frictions in the string.

Woods

Two species of resinous softwoods are of particular interest to luthiers:

1) European spruce (Picea Excelsa, Picea Abies), growing at an altitude of about 1,000 metres, provides wood with a solid texture.
2) Canadian Western Red Cedar (Thuja Plicata), growing in British Columbia, close to the Pacific Ocean, is a softer wood, more fragile and sensitive to shocks (a wood with low resilience) but which has the appealing quality of always being more flexible, more elastic in the longitudinal direction than spruce. It is also a wood with low damping.

These two resinous softwoods, extremely variable from one tree to the next, can be:

1) Damped or not (this means when a board that is considered 'damped' is lightly tapped, the sound of the tap is dull and rapidly dissipates, absorbed by the wood. If the wood is resonant, 'non-damped', the sound or hock of the tap yields a long, clear sound).
2) Heavy or lightweight.
3) Fibrous or clear grained.
4) Strong textured (like iron) or weak (like copper).
5) The grain may be straight, parallel, or skew.
6) The wood may be elastic or rigid.

Let us look at what we can expect from a damped, flexible and lightweight soundboard (soft and supple). Without correction using bracing, it will be very difficult to build a guitar with a clear, spontaneous, lively response with long sustain. The sound will be rather round and dull, dark with short sustain. The guitar will be easy to play, but easy to overdrive. A heavy and very hard soundboard wood will easily yield a hard, dry, metallic sound, with weak, bassy harmonics. The result will lack mellowness. The touch will be heavy, the sound quick and not very responsive.

The 'ideal' wood lies somewhere between these two extremes for most luthiers. We also note that some resinous woods have 'fibres' that are firmly interlocked and extremely solid. After ten years of use, we see minimal deformation, and the sound remains appealing and vigorous.

Other woods of the same species will have long left go, and the instrument no longer develops anything other than bass tones or a worse timbre. The central part of the soundboard will have been completely neutralized, broken down, 'brought to its knees'.

Note by Daniel Friederich, March 1997
On the subject of light woods, red cedar or spruce, weighing between 300 and 400 kg per cubic metre, I would like to add, after thirty years of experience, that this wood is interesting if the lateral stiffness is strong or fairly strong. Tops that are too flexible across the grain give less spontaneity, nervousness and definition in response, but often a lighter feel (with similar bracing, of course). This can be partially corrected with a crossbar under the bridge.

It is possible to gain an understanding of the wood's resistance to deformation by keeping a sample board lightly tensioned at its centre, with the two ends resting on small slats. After a year, the tension is release, and the board will straighten out – or not (fig. 40). The other option is to build a single guitar using this wood and observing what happens to it after one year.

Having wood fibres parallel to the thickness of the soundboard favour stability over time. If the fibres are cut, if there is runout, the board will not present a great deal of longitudinal resistance, and significant deformation will occur if uncorrected by bracing.

The difficulty for the builder who wants to be a creator is controlling all of the data we have described, and progressively integrating this knowledge.
The artistic design of an instrument is the most delicate aspect, given the level of mastery required and the numerous contradictions implied.
It is a perpetual series of choices that can engender some anxiety.

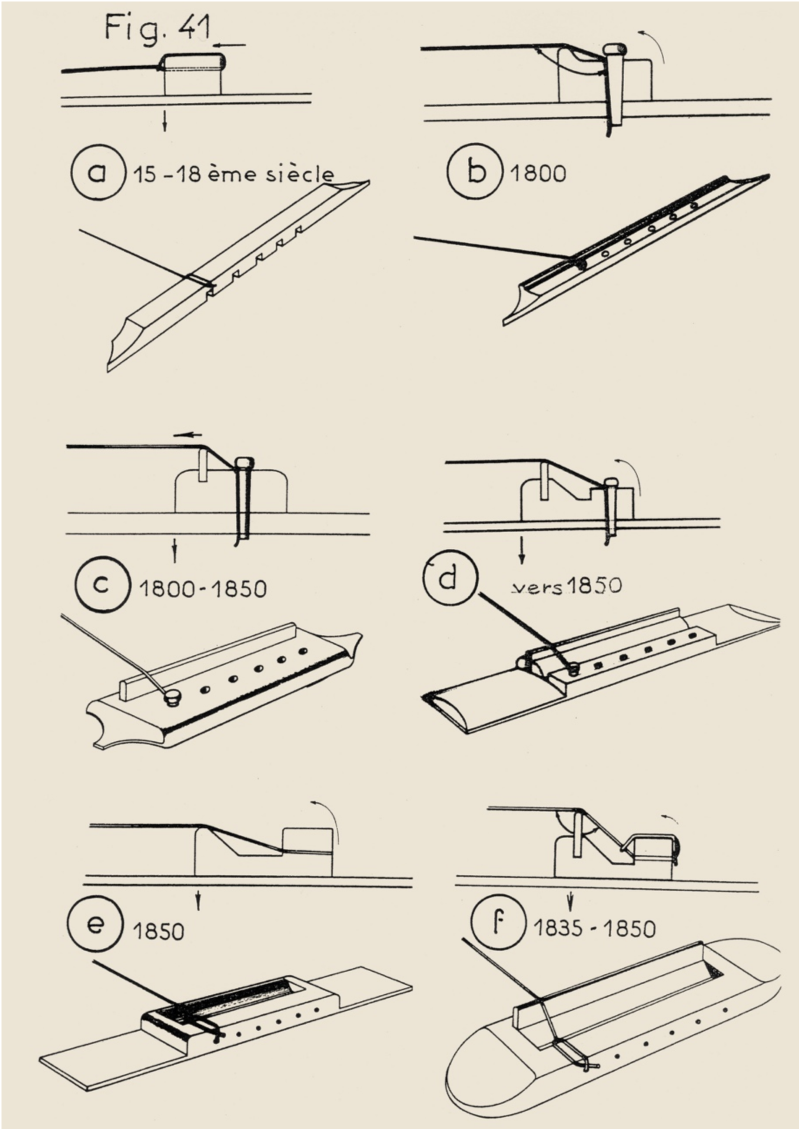
With each change, the instrument improves as the builder's understanding of the woods he has increases...but there are still many obstacles.

Here is an irritating contradiction: For soundboard, if one wants a rich sound with a strong personality, a wood must be selected that is hard enough and stiff enough in both directions, which will deliver well-defined resonant peaks. However, a damped wood with opposite characteristics will deliver a homogenous response, an even sound level.
A whole book would be necessary to address the problems posed by bracing and soundboards, so to end this chapter, let us define a golden rule:

“Obtaining a complex, rich sound with personality and character is impossible without a 'bracing' that is complex and personal and applied to a 'selected' top”

This is one of the secrets.

The bridge



The bridge transmits string vibrations to the soundboard. It is the final component to be glued during the construction process. For over one hundred years, its shape and structure have been refined to suit guitars played with fingers.

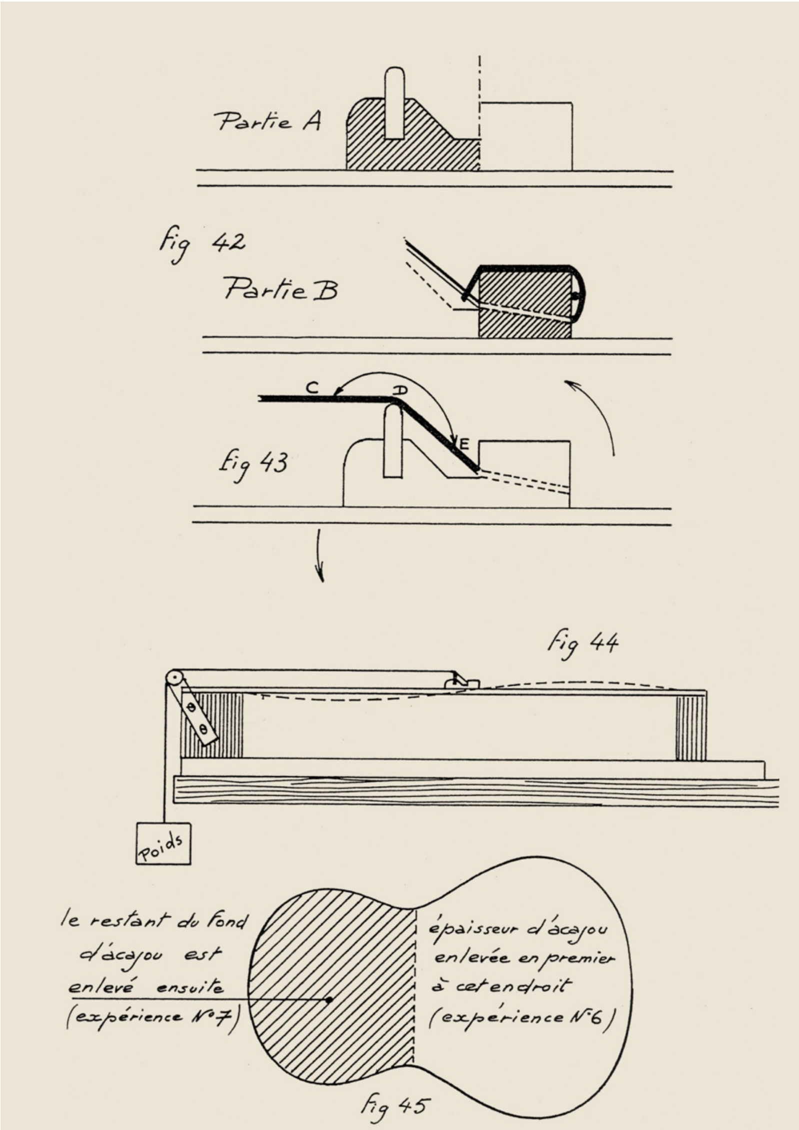
Historical bridges from the 16^{th}, 17^{th} and 18^{th} centuries were similar to those of the lute – a simple piece of wood, a small glued-down bar the strings were attached to, which should properly have been called 'tie block', as the strings did not pass over a bridge, as was the case in the 13^{th} century.

The modern bridge was developed following numerous experiments throughout Europe. A few sketches will provide an idea of the main stages in its evolution (fig. 41).

French luthier La Prévotte appears well-placed in this creative process, as he was using a bridge featuring modern characteristics before 1856, namely the implementation of two distinct parts for its structure (fig 42)

Part A: a new addition, called the 'bridge' with its saddle

Part B: which can be called the 'tie block' to make things easy, which is the traditional simple bar common to both lutes and guitars.



Part A will precisely define the end of the vibrating string length, and the height of the saddle will insert itself under the string, raising it upwards, letting the string tension apply pressure and torsion when combining parts A and B.

One has only to combine the two parts on a single base to understand the practical reality of their function.

One element becomes immediately apparent. The more closed angle CDE (fig. 43) is, the greater the torsion and the more vigorous the string pressure is on D. This will generate strong bass notes with large amplitude, deep tone and good timbre if the soundboard is not too rigid. This was one of the characteristics of guitars built in the 1850's; with their larger bodies, they had the novel ability to deliver truly deep, robust bass notes.

The luthier can adjust this angle if he decides to use a 'thick' soundboard, which requires a brute force approach to work.

The modern bridge is made of rosewood, and weights about 18 grams. Being a transverse brace located more or less in the middle of the soundboard, if it is too rigid and too heavy – for example if made of ebony – a poor sound result. The inertia and rigidity combined suppress a certain independence between the bass and treble sides of the instrument, cancelling out certain possible vibrational modes, thereby cutting a series of frequencies and impoverishing the instrument's timbre and evenness of sound.

In order to objectively determine the effects of a specific type of bridge, the apparatus depicted in fig. 44 must be built. Using 10 kg of traction acting on the string via a weight, the deformation of the board can be measured in front of and behind the bridge.

The modern classical bridge leads to greater distortion towards the back of the soundboard than towards the front. In reality, this action may be more strongly emphasized if a transverse brace is glued to the soundboard close to the front edge of the bridge.

In this case, the back of the soundboard is subjected to movements of a greater amplitude and works harder than the front, because the bridge rests on the stiffer front part of the soundboard in order to gently oscillate and pivot.

When the guitar is completed, this can be verified using two dial gauges placed to either side of the bridge. With the strings tensioned, the part of the soundboard doing the most work can be identified, providing additional information about function (differences can vary with a factor of up to three or more).

Using the same device described in fig. 44, it is possible to measure and plot the deformation caused by a narrower bridge (17 millimetres) with the same angle C-D-E and the same total saddle height (in fact the current bridge without its tailpiece). Though the local effect is stronger, the overall effect is the same, or slightly greater, as the force necessary to achieve similar deformation in a rigid plank is greater for a smaller lever than for a normal bridge 30 mm wide. One aspect compensates the other.

The only negative aspect of the narrow bridge is that it is at risk of delaminating if used. On the other hand, its light weight may be interesting for the instrument's response, and the establishment of the higher frequencies generated by the string.

The modern bridge has certainly not reached the pinnacle of its evolution. Asymmetrical bridges can be made, with a larger gluing area for the bass side, making it heavier and wider at the bass side, theoretically allowing more solid basses, with a narrower, thinner part at the treble side favouring the latter. Guitarists still need to be convinced to allow this modification.

In the United States, Kasha conceived of the use of separate bridges for bass and treble strings, and is building his guitars this way. This raises the question – with some reservations – of whether this attenuates sympathetic frequencies, leading to difficulties in the midrange frequencies.

The evolution continues...

The back and sides
General considerations
The overall weight of an instrument can be said to influence its sound. If the guitar is heavy, the sound of string attack (cause by finger action) is less easily perceived than on a guitar that is extremely light; the sound is born differently, with a matte, extremely attenuated sound that seems more crystalline. The guitarist's phrasing becomes more precise in rapid runs.

The heavier instrument has a longer sustain and generally has a better response in the upper register – the overall effect is more brilliant. In order to achieve this end, modern luthiers have used heavy woods, or thicker component parts for their instruments.

Where Jean Voboam was already using extremely exotic woods in 1706 – 'Violet wood' (Kingwood) – very thin and very dense, we interpret this as being for decorative effect. However, when Pages in Andalusia used rosewood for his backs in the late 18th century, one has to consider he may have made certain observations concerning its tonal effects.

Over time, this wood would come to be recognised as delivering the best results, and it is worth noting that all attempts to use other woods were invariably abandoned. Antonio de Torres frequently tried Maple in the last century, Francisco Simplicio loved Cuban Mahogany in the first third of this century and more recently, Ignacio Fleta created a Flamed Maple guitar around 1958. Woods we have personally tried include Purpleheart, Ceylon Satinwood Cypress and Cuban Mahogany.

Whether Indian, Madagascar or Brazilian, rosewood confers a noble voice on the guitar, with a pleasing, robust, full timbre that defines its quality, its personality as a classical guitar.

These guitars are significantly heavier now than they were 15 years ago, weighing between 1650 and 1850 grams. Guitarists heavily influenced by the lightweight creations of Antonio de Torres, Manuel Ramírez and Francisco Simplicio found it difficult to recognise the qualities of a heavier instrument. It was rejected, often compared to the 'old guitar' without which it never could have succeeded.

This mindset has completely disappeared, and concert guitarists playing guitars more than 10 years old are currently extremely rare.

In terms of construction, two extremes may be identified:

1) Build with thin, lightly braced back and sides which will deliver a strong bass response, mellowness, extremely audible attack, a short sound that is slightly dull and possibly a little thick.
2) Build with a thicker back (heavier than 300 grams), braced more heavily, using heavy, thick sides which will provide brilliance, a metallic timbre, with longer sustain and a more moderate bass response.

The sides
The role of the sides is not negligible, as their vibrating surface is approximately equal to that of the back. Additionally, their height defines the volume of the resonant air cavity of the guitar's sound box, potentially lending a certain 'boxiness' to the guitar. The fundamental frequency of the sides is raised due to their curvature.

The back
Three well-defined functions can be attributed to the back:

1) The back and its bracing more or less vigorously stabilise the guitar's heel, preventing it from tilting under string tension (40 to 50 kg).
2) The back braced with three or four transverse wood braces is also a multiple resonator for numerous frequencies.
3) The back is also a sound reflector within the acoustic enclosure that is the instrument's sound box.

The thicker the back, the higher its fundamental frequencies and vibrational modes are. It will then naturally favour trebles.

The greater the number and height of the braces which divided it into sectors, the higher frequencies will be able to resonate.

Resonator
This is easily verified using a hollow glass tube roughly 25 cm long and 5 to 7 mm in diameter to acts a frequency generator. Simply place the tube (fitted with a wooden shim) perpendicularly onto the back of the guitar, gently holding the top of the tube between thumb and two fingers, like a pencil. After first moistening those three fingers with a bit of vinegar and water, slide them along the tube in a single, swift motion. Varying the amount of finger pressure will excite the 'vibrating plate' of a defined sector of the back, emitting a tone specific to this sector. By changing the point of contact with the back,

numerous frequencies will appear.

If this experiment is repeated on a strung guitar, each sound, each frequency emitted by the tube will elicit sympathetic resonances, high frequency harmonics from the strings, which might lead one to deduce that the phenomenon could be reversed – if a string is excited by a finger, the produced signal and its harmonic content will find the amplification and resonant potential of various sectors of the back, confirming its second role as a multipurpose resonator.

It is easy to measure the vibrations of a back at a given point when excited by one of the open strings. A dial gauge capable of measuring up to one hundredth of a millimetre will yield variations that can be significant: 2 to 3 hundredths of a millimetre for low E and 4 to 5 hundredths for the open D, displaying the back's preferences for certain frequencies.

Reflector

The back is also a reflector, or as some builders say, a 'pusher' of sound. In effect, the interior sound wave generated by the soundboard upon release of the string (a compression series) will encounter a more or less rigid, more or less polished or varnished surface when it reaches the inside of the back. This series of waves will be reflected back – slightly damped or not – through the soundhole, which acts like a speaker placed at the centre of the soundboard, contributing to the overall sound produced by the instrument – all surfaces of which are actually vibrating (1).

(l) These waves emitted from the soundhole can be visualised by placing a piece of light paper on the soundboard, almost entirely covering the soundhole opening. Plucking a low note will cause the paper tremble.

A number of luthiers active in the first third of the 20^{th} century even thought of placing an 'acoustic cone' facing inwards, embedded around the rosette and under the soundboard. This device ('tornavoz') was supposed to 'collect' all of the waves reflecting off the back, and direct them towards the exit with greater ease.
This system has not withstood the test of time, so the experiment must not have been conclusive.

Comments

All of the guitar's parts components vibrate, but it is largely a directional instrument. A listener facing the instrument will hear a louder sound than the listener seated at the side. We have already seen that the back and its first brace hold the neck heel in position. This part of the back vibrates more intensely due to the lever effect produced by the neck pulling back and forth in accordance with the string's vibration (to simplify the concept). This can easily be verified by pressing a hand onto this spot after strumming a chord, and noting the disappearance of one or more harmonics as well as their return if the hand is removed again. This is more apparent the more flexible and lightly braced the back is, and the lower the struck chord is.

These observations led Dionisio Aguado to conceive of a device he named the 'tripodison' in the last century, which allowed him not to squeeze and rest the guitar against the player, allowing it to vibrate freely.

The lever represented by the neck and its heel applies yet another direct force onto the flexible, lightly braced back; it acts on the back in time with the impulse of the vibrating string. Each string excursion corresponds to maximum tension at its extremes, leading to an elongation of the back if it is arched, flattening it out.

For a low E, at about 80 Hz, there will be 160 such movements per second, producing a vibration an octave above the fundamental – a strong second harmonic – which is common in guitars with thin backs.

Theoretically, if the part of the soundboard in front of the bridge (1) is excited by the same antinode and the same tension present in the vibrating string, its inward displacement will create an inverse motion to that in the back, which move outwards. The combination of these two movements will create a train of high amplitude sound waves, creating an even more prominent second harmonic, generating a deep, full bass response with good timbre.
(1) The bridge, according to the internal bracing layout selected for the soundboard, can preferentially excite the area in front of or behind where it is situation.

However, if the part of the soundboard behind the bridge is most active, it's outward motion will be compensated by the back's inward motion, and the two can cancel each other out; this explains the presence of poor bass response in lightweight guitars with thin construction that should not suffer from this lack.

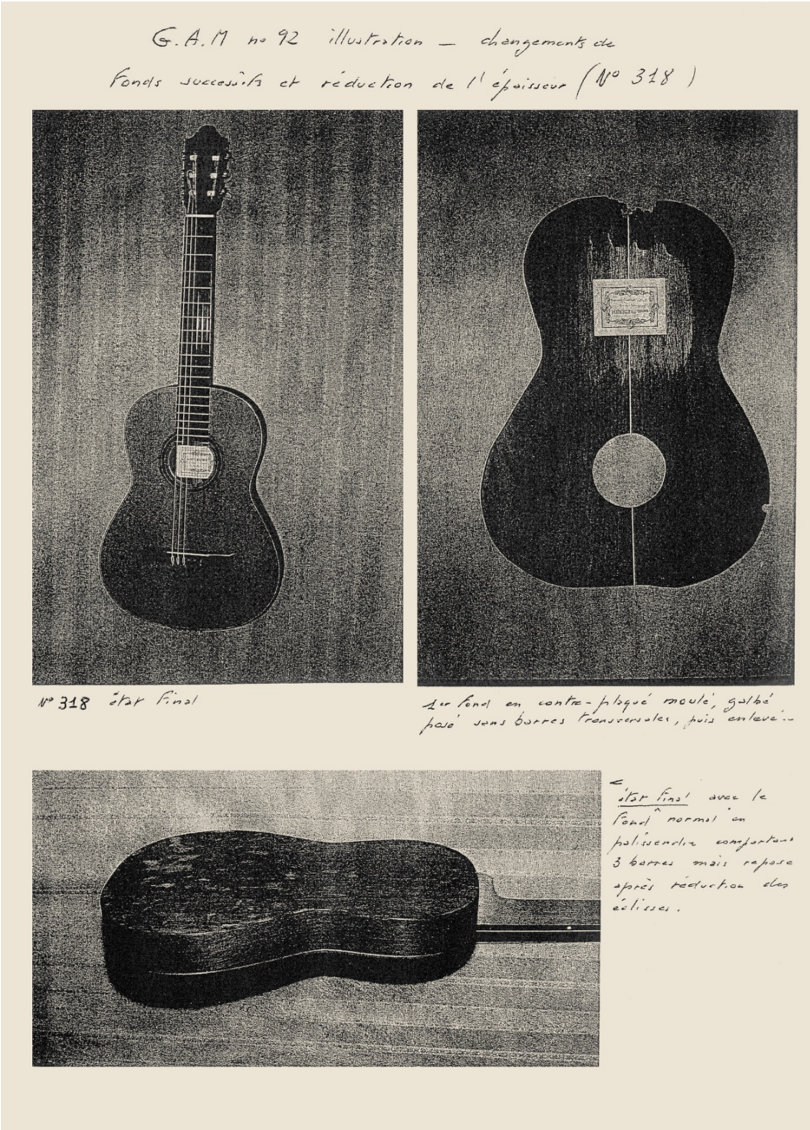
In the real world, every possible vibrational situation is possible, layering onto each other and, depending on the frequency of the note, making better or worse use of their resonators, resulting in a more or less homogenous, satisfyingly even response.

Given the broad array of problems facing the luthier – at the level of the neck, the soundboard, the back, the sides and the harmonious cooperation between all of these coupled parts – numerous years of observation are required. The situations are always complex and often contradictory, but if the answers start forming, the investigator and creator draw satisfaction from them. Albeit limited satisfaction, as the degree of control and advancement opens the door to other problems.

In order to precisely define elements of back and side response, we created and performed a series of experiments.

Description of experiments (and luthier's comments)
To this effect, we made a guitar with a back that was laminated and arched from three pieces (three layers) – two rosewood layers surrounding a 1.8 mm

thick centre layer. The total thickness was 2.8 millimetres. The maximum height of the arch was 19 mm, with a total weight of 272 grams. This back was unbraced, and was experiment N° 1.



Experiment 1
This guitar was easy to play due to the extreme flexibility of the back. It had strong, deep basses due to the back's low fundamental frequency as a resonator, whose movements – initiated by the action of the neck and its heel – also contributed to the bass response. On the other hand, the mids and trebles had poor timbre and were of little interest, with little homogeneity in terms of timbre and sound level. The three highest notes on the fretboard were weak.

Experiment 2
On the same guitar, the soundhole was completely blocked using a foam rubber pad. The instrument emits only part of its normal sound, the soundboard's movement is inhibited due to the air trapped inside, which tends to couple soundboard and back, the sound is short, extremely damped, heavily veiled, with poor bass.

Experiment 3
Having liberated the soundhole, an opening was made in the back comparable to the size of the soundhole (87 millimetres) at the centre of the widest point of the back. The basses lose all of their initial timbre, the sound becomes generally poor. The vibrational mode of the back has changed due to the opening. Part of the sound passes through the back and is dispersed (the instrument is less directional); the air volume in the sound box loses its role, and the soundhole appears to emit very little sound.

Experiment 4
The soundhole is closed again, leaving the hole in the back in place. The guitar works better, the 'speaker' emits the series of compressed waves, the *bass* frequencies from the back of the sound box which now functions better. The trebles seem to suffer less.

Experiment 5
The back glued on initially is removed, and replaced by a very heavy back (braced with three sticks of mahogany), consisting of two layers of different woods glued together. The first is rosewood, weighing 280 grams, the second is mahogany, weighing 155 grams and placed on the outside, yielding a total weight of 435 grams without bracing. The functioning guitar weighs 1,920 grams. The sound is dry but lacking in suppleness, rich but lacking in mellowness, it is difficult to play as the neck is entirely immobilised by the thick, heavily braced back. The direct effect of the heel and neck, which tries to stretch and relax lightly arched back is nullified due to its rigidity. As a resonator, this back favours higher frequencies.

Experiment 6
The superficial layer of mahogany is planed off the lower bout of the back (fig. 45), representing 90 grams less of wood, for a total weight of 1,830 grams for the guitar. The sound is better, the mellowness appears, the touch seems easier. The normal rosewood back, free from an additional layer of mahogany on its lower bout, once again favours lower frequencies and yields a more interesting, warmer timbre. The balance between basses and trebles is satisfying. This is the best of the entire series of experiments, but the three highest notes are still weak and have poor timbre.

Experiment 7
The remaining layer of mahogany is planed off the upper bout (fig. 45). The guitar now weights 1,765 grams with a single layer Indian rosewood back weighing 280 grams (with its three additional mahogany braces). The sound becomes even rounder but also thicker and mushier, less clear, less crystalline. The basses are dark, sound across the fingerboard is uneven, the three highest notes remain dull. The back works even better for the bass frequencies, and the tone is darker by a degree. The neck is freer to move under string action, the thickness of the back being thinner at the heel than it was in the previous experiment.

Experiment 8
The normal rosewood back is removed carefully, and the side depth is halved. The removed back is then reinstalled – it is re-glued, resulting in a very thin guitar, only 6 cm deep. Overall, the sound is fairly thin, clear and biting. Basses are weak, lacking in depth (but the three highest notes on the fretboard are better), with the lack of bass resulting in a feeling of dryness when listened to directly. The volume of the cavity, of the sound box having been halved, the instrument has lost one of the major components and is missing its 'boxiness'. The fundamental frequencies of the sides are significantly higher, naturally vibrating at a higher pitch, reinforcing the extreme trebles. The back is relatively passive in the bass frequencies, the action of the neck and heel is minimal due to its size (the excursion of the 'lever' arm are much reduced).

Daniel Friederich
Paris, 1977