Kungl Tekniska Högskolan

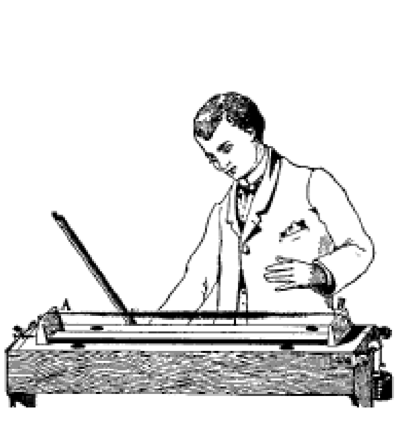
Dept of Speech, Music and Hearing

ACOUSTICS FOR VIOLIN AND GUITAR MAKERS

Erik Jansson

Chapter VI: The Function, Tone, and Tonal Quality of the Guitar

Fourth edition 2002
http://www.speech.kth.se/music/acviguit4/part6.pdf



Index of chapters

Webpage: http://www.speech.kth.se/music/acviguit4/index.html

ACOUSTICS FOR VIOLIN AND GUITAR MAKERS

Chapter 6 – Applied Instrument Acoustics
THE FUNCTION, TONE AND TONAL QUALITY OF THE GUITAR

First part: THE FUNCTION OF THE GUITAR

Second part: THE TONE AND TONAL QUALITY OF THE GUITAR

Chapter 6.
THE FUNCTION, TONE AND TONAL QUALITY OF THE GUITAR
First part: THE FUNCTION OF THE GUITAR

INTRODUCTION

As a guide for this chapter on the acoustics of the guitar six questions have been set up:

1. What is a guitar?
2. What properties are built into the guitar?
3. How does the guitar work?
4. What is quality?
5. How do the different construction details influence the acoustical properties?
6. How to make the best guitar?

The questions are answered as well as possible in the following. But let us first look a little on the acoustical fundamentals for the function of the guitar. And as the guitar string cannot be separated from the guitar, this introduction contains a short repetition on the acoustics of the guitar string.

A guitar tone contains a spectrum of partials. One effect of the number of partials is the timbre effect of smoothness versus roughness. For a spectrum of one to four partials all played tones sound smooth. If the number of partials are increased to six the played tone attains some roughness. The perceived difference smooth to rough can be explained by properties of our hearing. This is an example of how we can predict perceived qualities from acoustic measurements.

But let us look further into the tone of the guitar. Three diagrams, the snapshots of spectra of a note of the sixth string (an octave above the open string fundamental 165 Hz) are shown in Fig. 6.1. The three diagrams show the spectrum just after plucking, 0.2 and 0.4 sec later. We see here that the uppermost "snapshot" contains 14 visible partials of different levels. The second spectrum contains 9 partials and the third 7 partials. If we look a little closer, we can see that the level for the different partials decrease at different speed, the lower five partials decrease approximately 3 dB in 0.2 sec, the following 5 partials 10 dB and the higher four 15 dB.

A guitar sound can be synthesised, but not by only synthesising the partial spectrum (of the string) in Fig. 6.1. Care must also be taken of the partials of the guitar body. Let me point out another detail. If we look a little closer we can see that the sixth and eleventh partials have very low levels - two obvious minima are to be found here. I shall later return to these minima and explain what they derive from.

The player can select point of plucking along the string, direction of plucking and way of plucking. But each selection will give a different spectrum and a different character of the played tone.

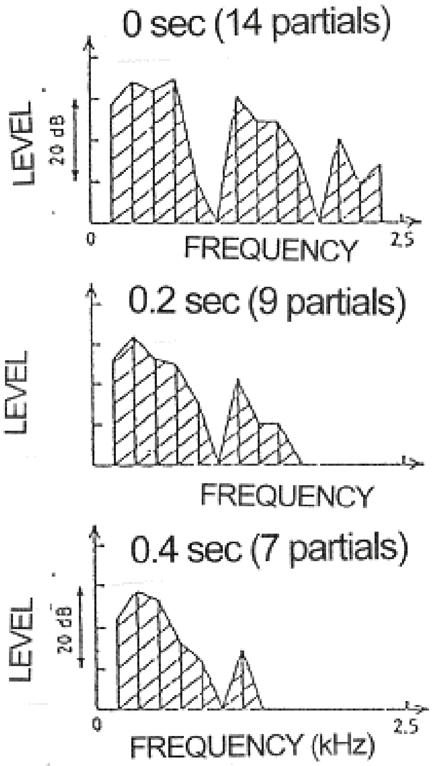


Figure 6.1 Analysis of a real guitar tone

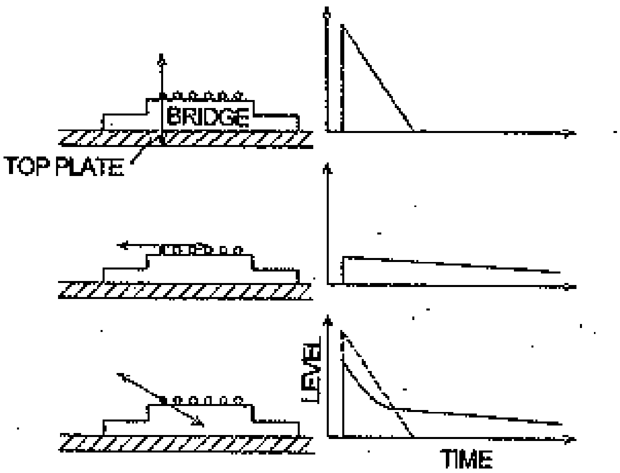


Figure 6.2. Effects of different plucking directions.

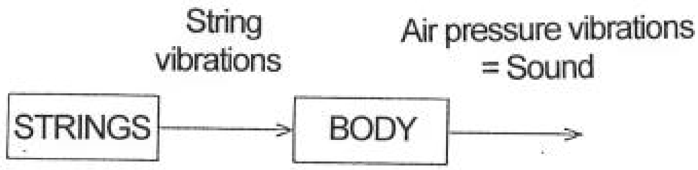


Figure 6.3. The production of the guitar tone (in principle)

We have seen that a musical tone consists not only of one single frequency component but a number of frequency components, partials. Every partial corresponds to a specific mode of the string vibration, a string resonance. The lowest partial, the fundamental corresponds to a resonance with nodes at the ends and an antinode in the middle. In the second partial the string vibrates with nodes in the ends and in the middle. Halfway between the nodes there are antinodes. The two vibrations can be demonstrated by looking at the guitar string. To enhance the second resonance the octave flageolet is played.

The following fundamental relation is valid: A partial can not be excited at the positions of its nodes. The minima in Fig. 6.1 correspond to plucking close to the nodes of the sixth and 11th partials.

Another plucking effect can be used, see Fig. 6.2. If the string is plucked perpendicular to the top plate a strong but short tone is obtained, in principle as in the uppermost frame. If the string is plucked parallel with the plate a long but weak tone is obtained. A more normal plucking at an angle directed towards or away from the top results in a guitar tone as sketched in the lowest frame and is best described as consisting of two parts. In the first part the vibrations perpendicular to the top dominate and in the later part the vibrations parallel with the plate. In an intermediate phase both parts contribute which result in a soft transfer from initial to the later part.

6.1 CONSTRUCTION OF THE GUITAR

The guitar consists of six strings stretched over a wooden box (the corpus) elongated with a neck. When a string is plucked the string starts to vibrate. The vibrations are coupled to the body via the bridge and the vibrations of the body set the surrounding air into vibration, which gives the guitar tone we hear, c.f. Fig. 6.3.

Let us look a little closer at the construction of the guitar, see Fig. 6.4. The back plate, has strong cross bars. There are also such strong cross bars underneath the top plate under the fingerboard and just on the opposite sides of the sound hole. This favours the top plate vibrations in the lower part of the top plate, below the sound hole. Therefore we somewhat arbitrarily call this part the "the free top plate part".

Two examples of the construction of two guitar top plates are shown somewhat more in detail in Fig. 6.5. Again we see the strong cross bars under the fingerboard and one strong cross bar on the other side of the sound hole. The "free" part is made stiffer by the transverse bridge, sometimes combined with extra stiffening underneath the top, and mainly lengthways by thin braces. Often slightly slanted, an extra crossbar can be found at the sound hole, see Fig. 6.5b.

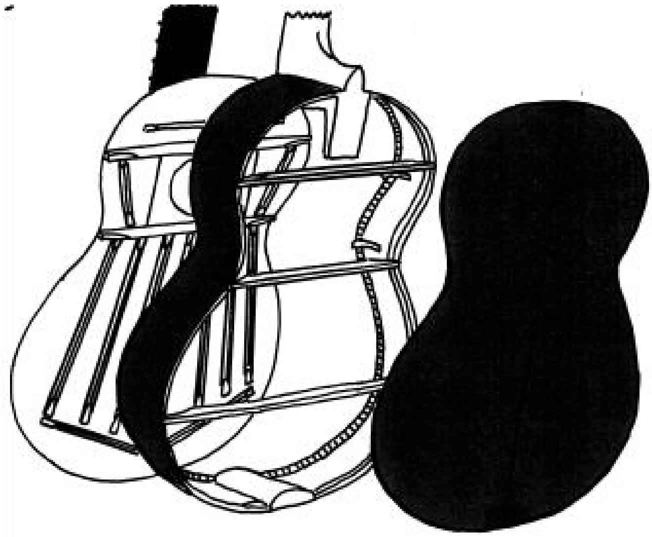


Figure 6.4. The construction of the guitar - an example (after Sloane)

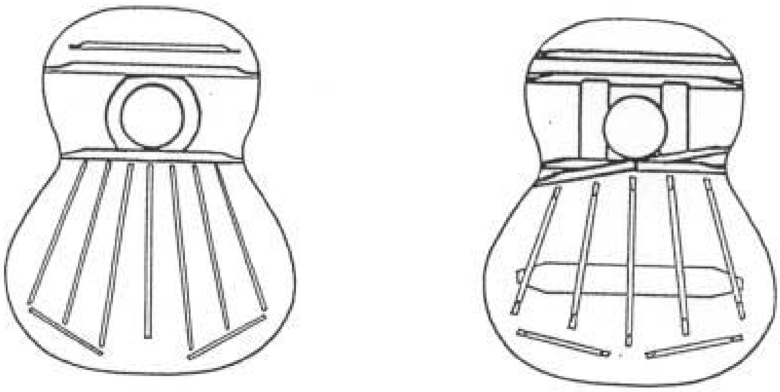


Figure 6.5. Examples of different constructions of the guitar top plate: common simple construction (left) and typical handmade Spanish construction (right).

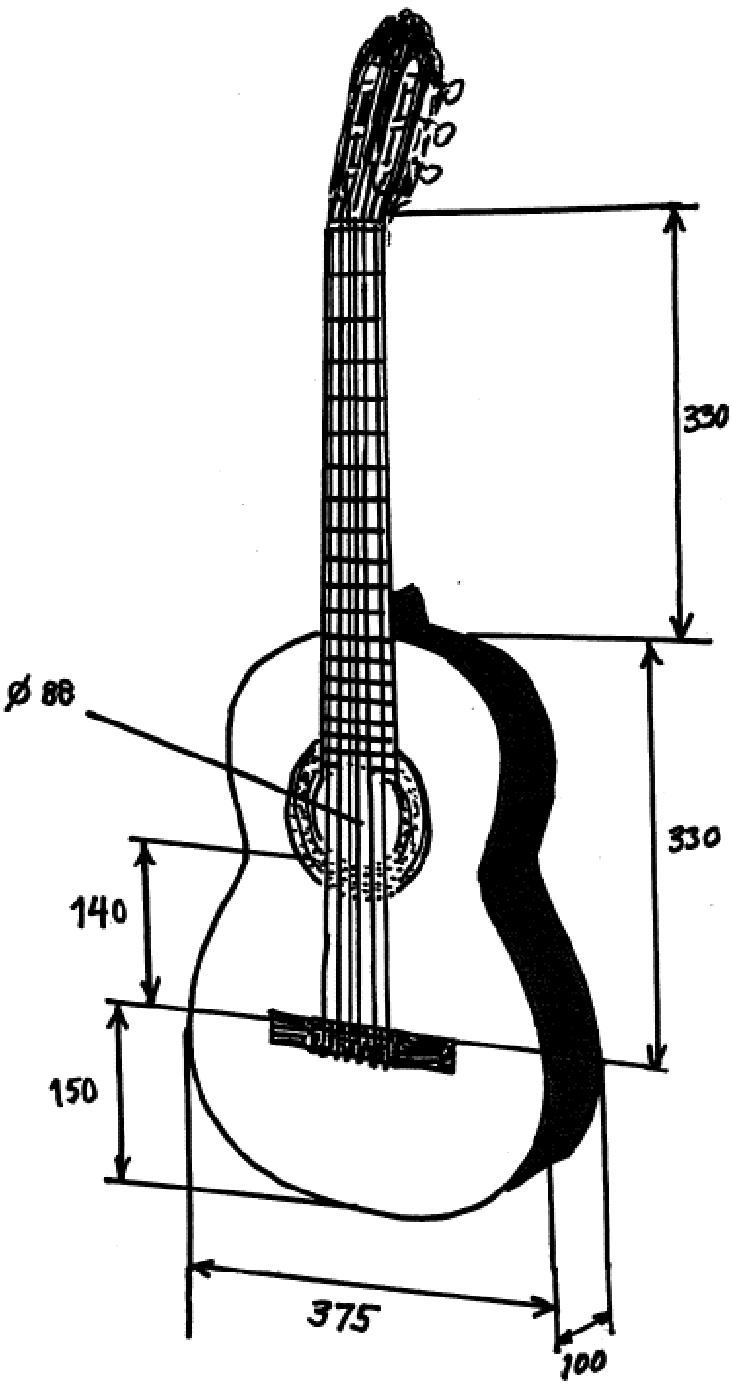


Figure 6.6. Typical measures for the classical guitar.

The measurements of a guitar vary moderately, see Fig. 6.6. The neck length equals half the string length. Guitars may look different but still the external measures are rather similar. Note that the bridge is positioned approximately halfway between the sound hole and the lower end, i.e. approximately in the middle of the "free top plate part". The width and length of the "free part" are approximately the same. The bracing system may vary considerably, positions, number and dimensions. A most interesting question is: What do these differences do to the tone?

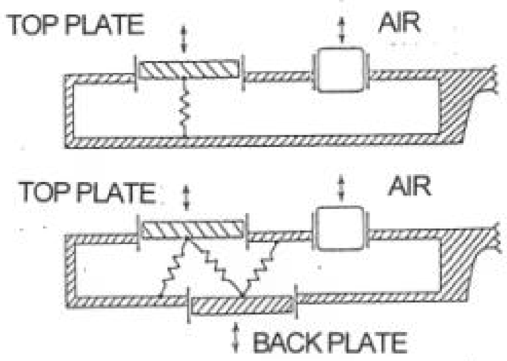


Figure 6.7. Function of the guitar, in principle (after Christensen)

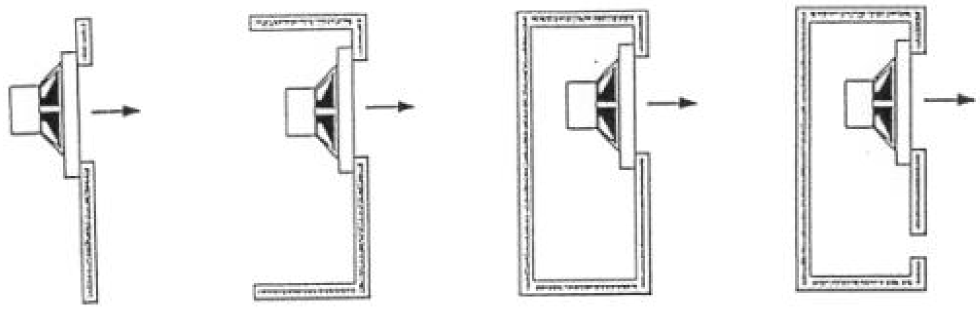


Figure 6.8. For comparison with different loudspeaker enclosures a) open baffle, b) open back baffle, c) closed baffle, and d) bass reflex baffle (after Cohen).

6.2 RESONANCES OF THE GUITAR

The fundamental construction of the guitar is thus an air volume enclosed by walls, see fig 6.7 top. The top has a part , the "free part" which is more easily set into vibration than the other parts. In the top plate there is also a large hole, the sound hole. The construction is basically the same as a rather advanced loudspeaker construction, the bass reflex enclosure, c.f. Fig. 6.8. The properties of the guitar, this several hundred years old bass reflex enclosure, are mainly determined by the top plate and the air volume resonances.

But the guitar has a back plate too, which can vibrate, i.e. we have the much more complicated system, top plus volume plus back resonances to take care of. Experiments on this complex system have shown (c.f. Fig. 6.7 bottom) that the back can supply prominent resonances to the guitar body.

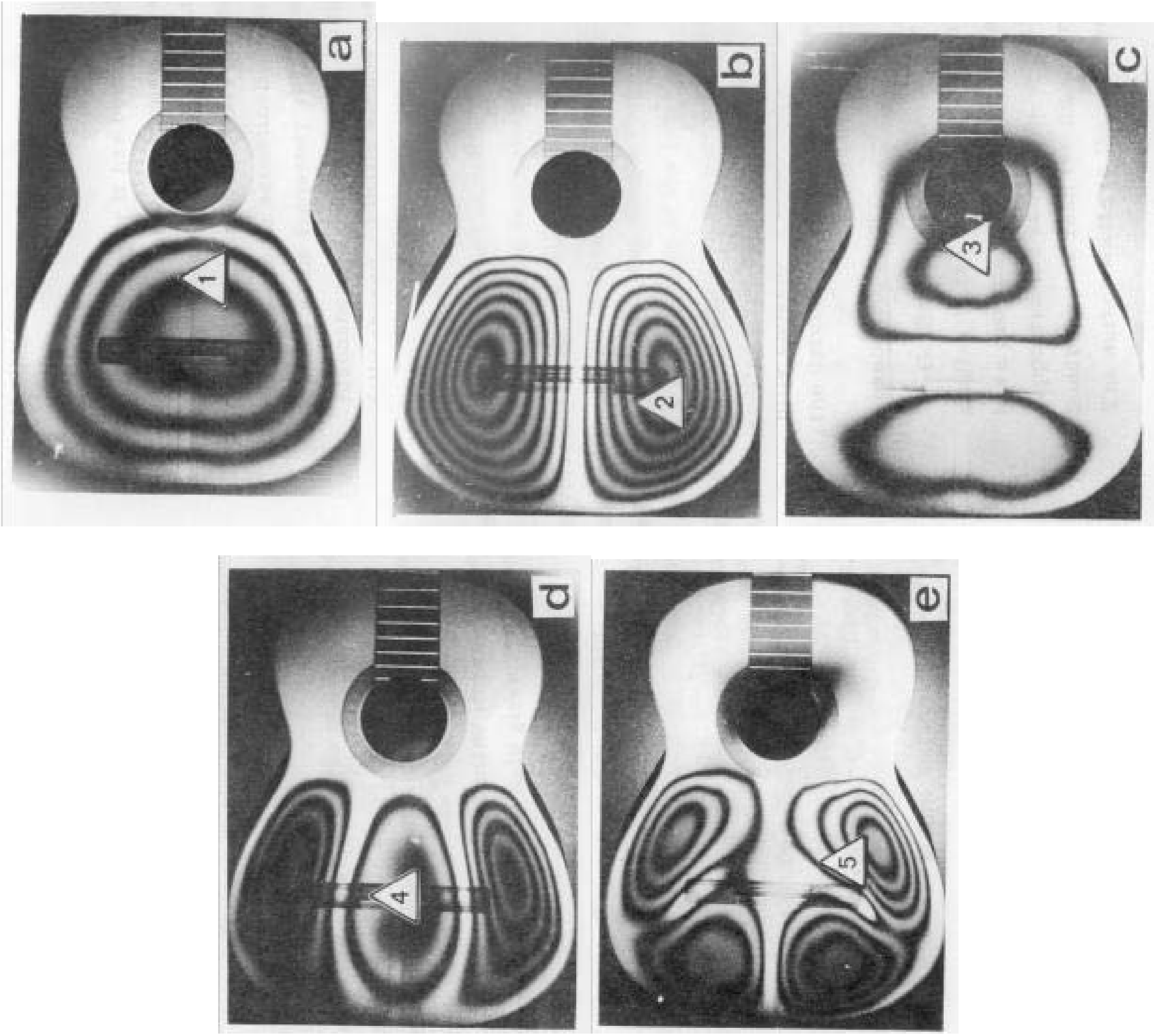


Figure 6.9. Top plate resonances recorded with hologram interferometry. The closed rings (fringes) connects lines of equal vibration in the same way as lines of equal altitude are connected in a topographical map. Resonant frequencies at a) 185 Hz, b) 285 Hz, c) 460 Hz, and d) 510 Hz, and e) 645 Hz. (guitar top made by G. Bolin, interferograms by Molin and Stetson).

It has been shown that the two resonances are present by vibrating the guitar with a small vibrator or a loud speaker. As the frequency of the vibrations are slowly increased, similar to glissando, one can clearly hear the so called Helmholtz resonance or A0 and thereafter the first top plate resonance. If the glissando is continued to higher frequencies higher resonances will be heard. The vibration patterns of the higher resonances can be demonstrated with a rubber membrane stretched over a set of sides for the guitar. Small pieces of cork are spread over the membrane. The membrane is set into vibration by a small vibrator. For a glissando the "first top" resonance will first be seen thereafter the second, the third etc. All show up at a specific frequency, their resonant frequency and they all show different patterns. The nodal patterns remind us of the patterns found for a real guitar top (measured with hologram interferometry, see Fig.. 6.9)

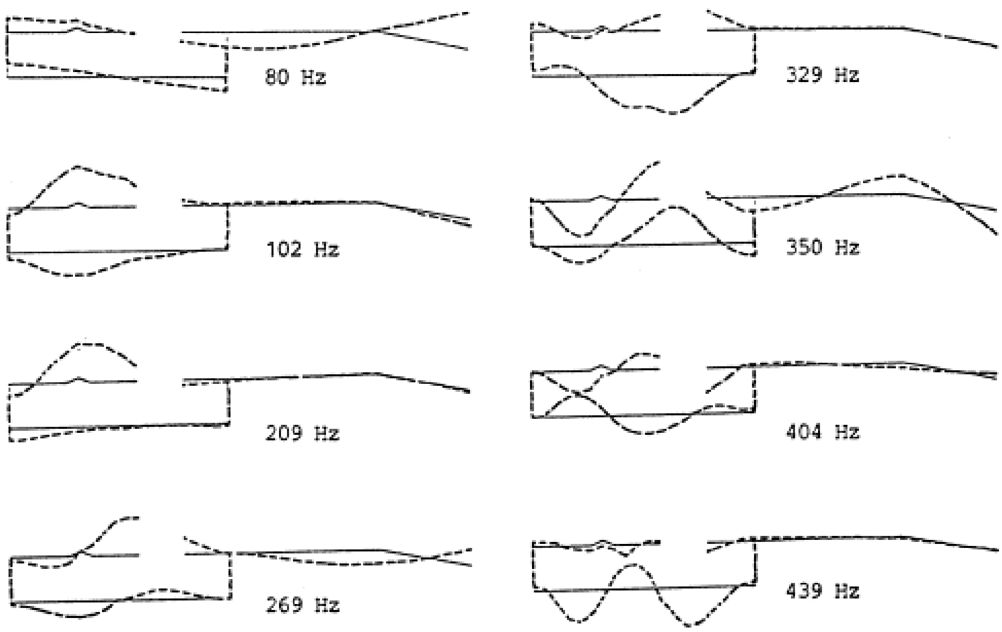


Figure 6.10. Vibrations of a guitar body with neck (by E Meinel)

The guitar neck may also vibrate. The neck vibrations can cooperate with the body vibrations, c.f. Fig.. 6.10.

In Fig. 6.9 it is shown that the lowest resonance of a guitar top plate has one vibration antinode (a "hill"). The following resonance has two antinodes and a vertical nodal line in between. The third resonance has two antinodes with a horizontal nodal line at the bridge, the fourth has three vibration antinodes with two vertical nodal lines, and the fifth has four antinodes with two nodal lines in a cross through the bridge. We have thus shown that there are many resonances in the free part of the top plate. These resonances are important for the tonal quality. It can be seen that except for the first top plate resonance, the vibrations tend to be small at the bridge and large outside the bridge. In addition we have earlier shown that the guitar tone consists of several partials, which are important for the tonal quality.

If the plate resonances are compared to the string resonances, similarities are to be found regarding the position of antinodes and position of antinodes, see Fig. 6.11. The top plate vibrations can be said to be a combination of string vibrations along and across the top plate.

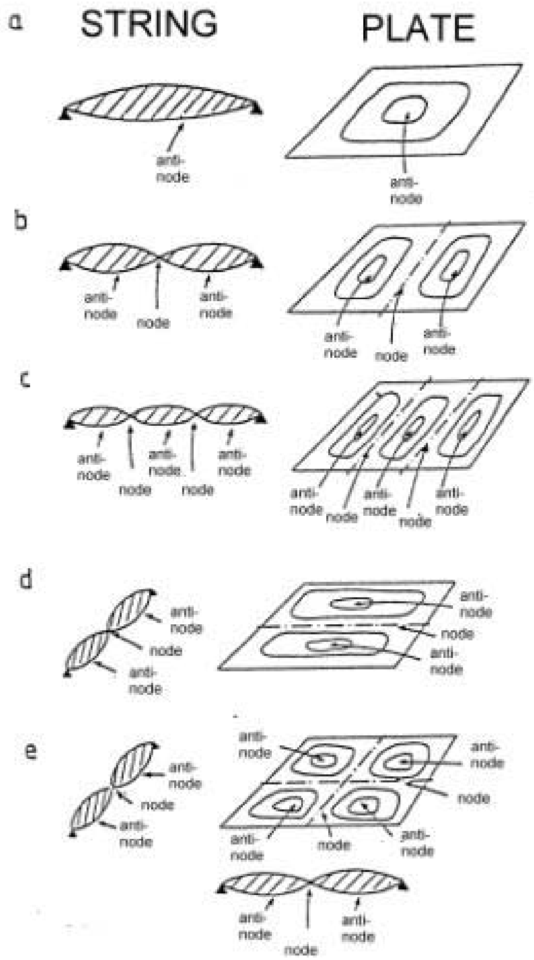


Figure 6.11. String and plate resonances.

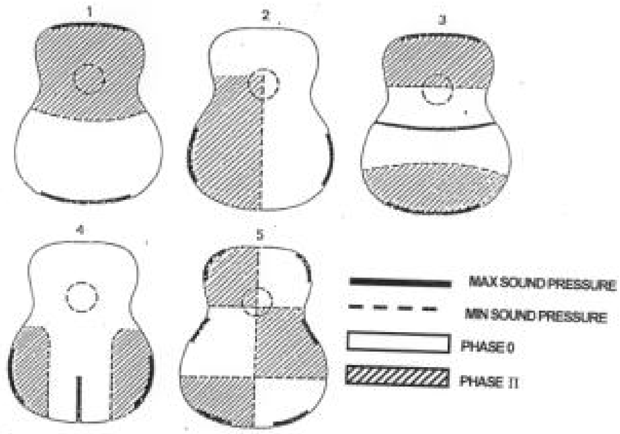


Figure 6.12. Air resonances at 370 , 540, 760, 980 and 1000 Hz - positions of pressure antinodes (thick lines), pressure nodes (dashed lines), white and shadowed areas mark phase of motion - the same marking for in phase and different marking for antiphase.

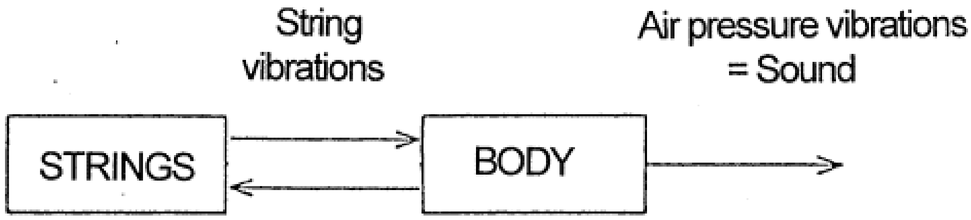


Figure 6.13. The production of the guitar tone including the feedback (in principle)

An air volume like the one of the guitar has many resonances too, see Fig. 6.12. These air resonances can play an important role and co-operate with plate modes. To be able to use the construction of a guitar to an optimum a monitoring of the co-operation between resonances is important. The lowest resonance is especially important. The lowest air resonance can be demonstrated with a small loudspeaker inside the guitar. With a glissando tone a strong maximum is heard at the frequency of the air resonance, but also higher air modes may be heard.

6.3 THE FUNCTION OF THE GUITAR

Let us look more in detail at the co-operation between the strings and the guitar body, see Fig. 6.13 marked by the arrows pointing to the right. On plucking, the string is set into vibration and thereby the top plate too. But the top-plate vibrations can also react to the string vibrations. This reaction (feedback) has been marked with an arrow pointing to the left. The main road is though from left to right. Too much reaction gives a wolf note - too little means a weak tone (the electric guitar without amplifier).

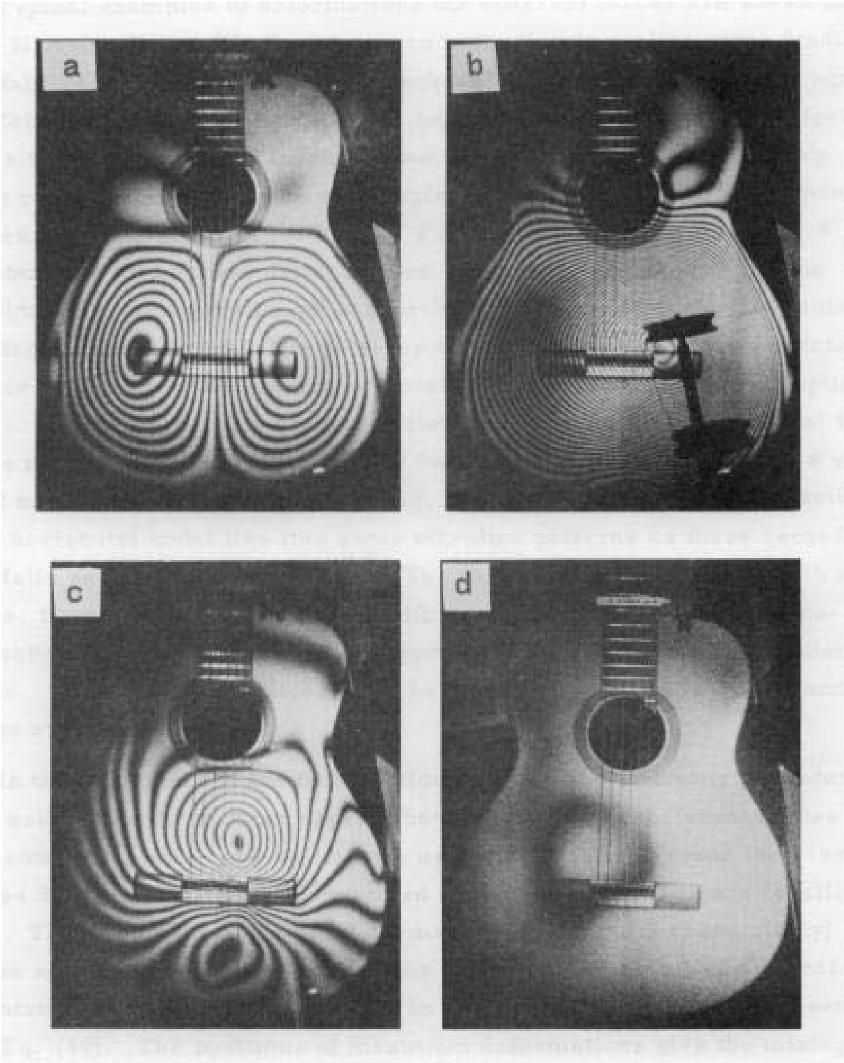


Figure 6.14. Deformations of the guitar top plate Measured (with hologram interferometry, double exposure) for different string forces: parallel with the top plate along the bridge (force 1 N, upper left), perpendicular to the top plate (force 0.5 N, upper right), along a string (force 2 N, lower left) and torsion of a string (one revolution in the middle of the third string, lower right).

Let us continue a little theoretically, to show how one can use the resonances to explain what happens in the guitar body. We have earlier (in chapter 2 on resonances), explained the relations between resonance vibrations, normal modes, frequencies and bandwidths. For resonances of the top plate the same relations are valid. The resonances can be heard by tapping the top plate with damped strings.

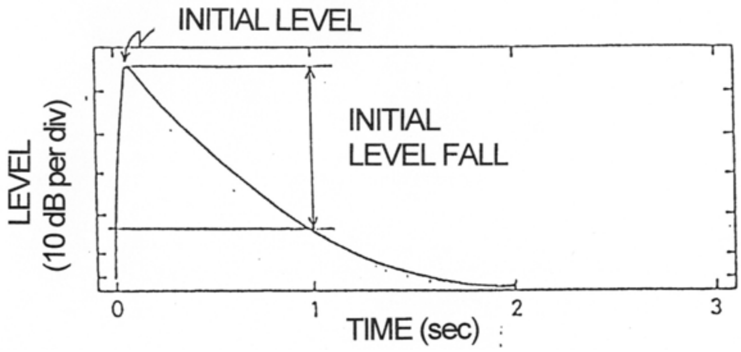


Figure 6.15. Definition of initial level and initial level fall.

The string and the guitar's top plate co-operate in the following way, c.f. Fig. 6.14. The string is pulled from equilibrium in different ways and gives rise to three partial forces. The partial force parallel with the plate gives a deformation reminding us of resonance no 2, c.f. Fig. 6.9. The partial force perpendicular to the top plate gives a deformation corresponding to resonance no 1. The increased tension of the string at the plucking gives a deformation corresponding to resonance no 3. It can be seen that the top plate is most sensitive to the forces directed perpendicular to the top plate and the least sensitive to the forces directed along the string. This indicates that the string vibrations perpendicular to the top plate are the most important for setting the plate into vibration.

An experiment to find how the guitar influences the tone was conducted by Graham Caldersmith and the author. For the experiment two measures were defined: initial level, i.e. the level just after plucking, and initial level fall, i.e. the decay of the level during the first second, c.f. Fig. 6.15. Three chromatic scales on each string were recorded.

Let us see how the initial level varies with different pitches, frequencies for single partials (acoustically the analysis must divided into single partials as partials of different frequencies are treated differently). We can see that the initial levels marked with the different bars mark a softly bending line, see Fig. 6.16a, with maxima and minima.

We continue by looking at the initial level fall at different frequencies for the single partials (here also the analysis must be made of single partials for the same reason as given above), see Fig. 6.16b. We can here see that the initial level fall marked with the different bars again mark a softly bending line with minima and maxima.

In Fig. 6.16c a recording is shown of the sound resulting from driving the bridge with a small vibrator and a "glissando tone" (the frequency response), which should predict the level of partials at different frequencies (pitches). We can see that the level of radiation as a rule varies greatly from one frequency to another - we can see marked peaks with valleys in between. What does this mean? Let us try to find some relations!

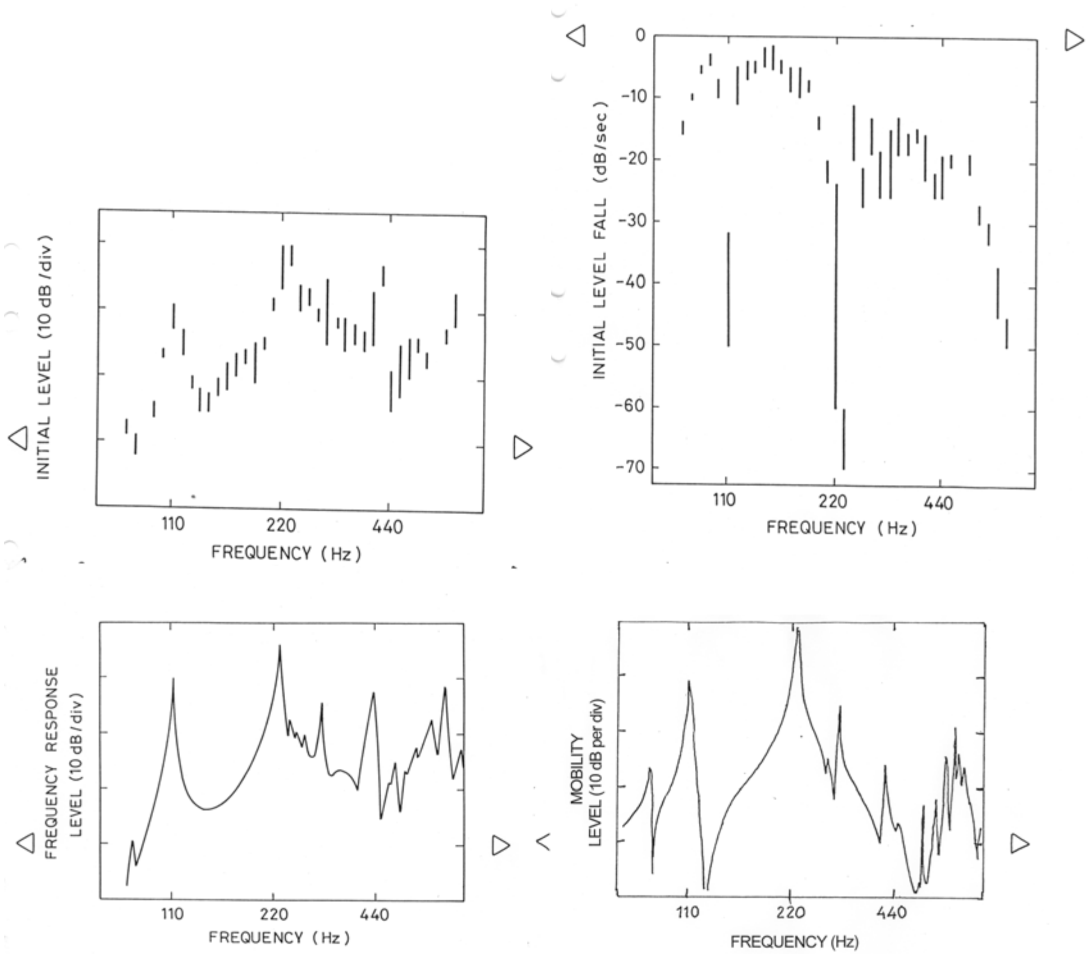


Figure 6.16. From measurements on a guitar a) initial levels, b) initial level falls, c) sound radiation (in one direction), and d) vibration sensitivity.

First trial: If we place Fig. 6.16a on top of Fig. 6.16b no relations are found (the two softly bending curves indicated by the two set of bars do not follow each others).

Second Trial: If we place Fig. 6.16b up-side-down on top of Fig. 6.16a, we can see that the two sets of bars indicate a similar curve. This implies that the initial level and the inverse of the initial level fall tend to follow the same curve. We have found a relation between initial level and initial level fall.

Third trial: Place now Fig. 6.16c on top of the Fig. 6.16a and the up-side-down Fig. 6.16b. Again we see something. The sound radiation response predicts fairly well the initial level and the up-side-down initial level fall. This means that the properties of the guitar tone can be tied to the properties of the guitar body. This is nice but not as surprising as it may look. The sound radiation peaks overestimates the initial levels but underestimates the initial level falls, though.

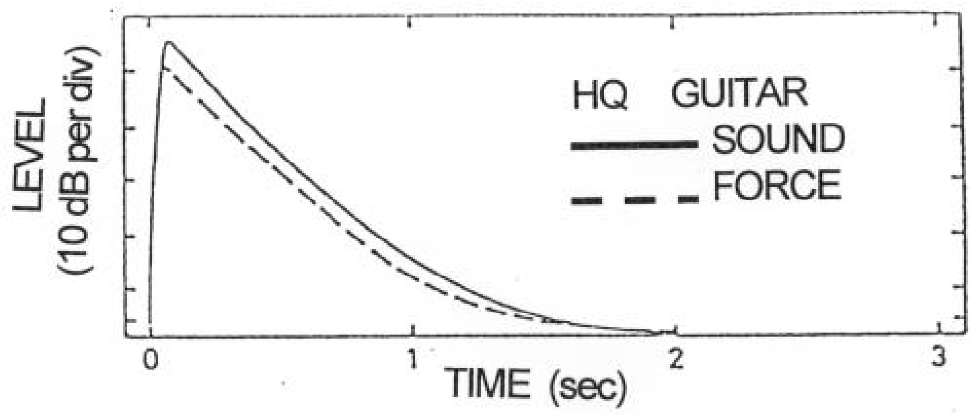


Figure 6.17. Force from string vibrations and sound.

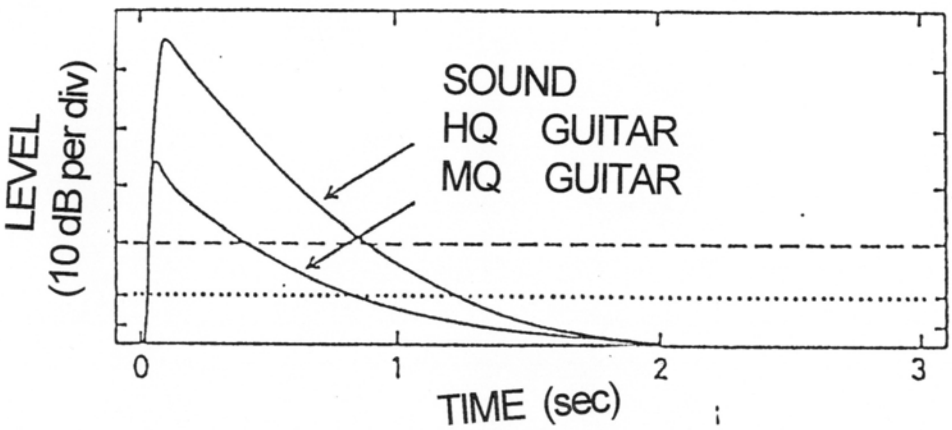


Figure 6.18. Time history of sound levels for the same tone of a high quality guitar (HQ) and a medium quality guitar (MQ).

It is very difficult to measure the sound radiation like that shown in Fig. 6.16c and it demands an anechoic chamber. The same information is obtained by measuring the vibration sensitivity, see Fig. 6.16d. To measure the vibration sensitivity has the great advantage that it could be made in an ordinary room.

Thus the string vibrations predict the properties of a guitar, see Fig. 6.17. This is demonstrated with the analysis of the tone of a high quality guitar. We see that the sound level curve and the force level curve follow the same course. Further it can be seen that the start levels are the same for the string forces but that the quickly decaying tone gives a higher initial sound level. I believe much of the secret with the quality of a guitar is shown with the presented material.

In Fig. 6.18 we can see that a tone with high initial level may in spite of faster decay give a tone of longer duration also for a fairly low level of the reverberant sound in the room. This indicates that one guitar can be good for fast loud music but less good for slow soft music.

6.4 SUMMARY - THE FUNCTION OF THE GUITAR

In this part the construction of the guitar has been described, its function and its built-in properties. Properties of played tones have been related to properties of the guitar.

6.5 KEY WORDS:

Resonances, frequency responses and vibration sensitivity, initial level and initial level fall.

Chapter 6.
Second part: THE TONE AND TONAL QUALITY OF THE GUITAR

6.6 QUALITY DETERMINING PROPERTIES

The results from three large investigations, one by Jürgen Meyer, one by Bernard Richardson and one by the author form the sources of information to the second part of this chapter. The author, in his investigation on guitars and their quality, asked: what is the most important properties of a concert guitar. The answers showed that the "tonal strength" of the guitar should be the most important. When asked, all guitar players answered that volume, carrying power, strength etc. are desirable. Tone length and timbre should be the second most important, as six gave answers relating to these properties. Further results are presented in table 6.1.

Table 6.1. The most important properties of the guitar (3 of 9 means that three of nine guitar players gave this property as important)

1. Attack	3 of 9
2. Carrying	9 of 9
3 Dynamic range	3 of 9
4. Eveness	5 of 9
5. Timbre	6 of 9
6. Timbre plasticity	4 of 9
7. Length of tone	6 of 9.

Further an informal listening test (with trained listeners) with five guitars was conducted, which gave the results presented in table 6.2. The three handmade Spanish guitars (no 1 to 3) were perceived as better than the factory made Swedish ones (no 4 and 5) both in music performed live and recorded. The order was slightly changed between the Spanish ones though.

Table 6.2. Quality order of five guitars (how well do the guitars sound, thirteen and nine guitar students SMH)?

rank	music recorded	music live
1	guitar no 2	guitar no 3
2	1	1
3	3	2
4	4	4
5	5	5

RESULT: TRAINED LISTENERS ARE LIKELY TO JUDGE THE QUALITY OF A GUITAR WELL AT A LISTENING TEST.

Tones from the open strings and their octaves were recorded on tape for guitar 1 and 4 for listening tests. The tones were presented in pairs for the subjects and the subjects were asked to judge which tone was the strongest, sounded the best and was the longest. The results are summarised in Fig. 6.18. The tests showed that it was rather simple to make the judgements and that non-trained listeners gave judgements with good agreements. The results for the tone lengths are somewhat unpredicted as the tones were physically of identical length by "electronic cutting".

RESULT: AT COMPARISONS OF TWO TONES DIRECTLY AFTER EACH OTHER, ALSO NON-TRAINED LISTENERS CAN EASILY JUDGE DIFFERENCES.

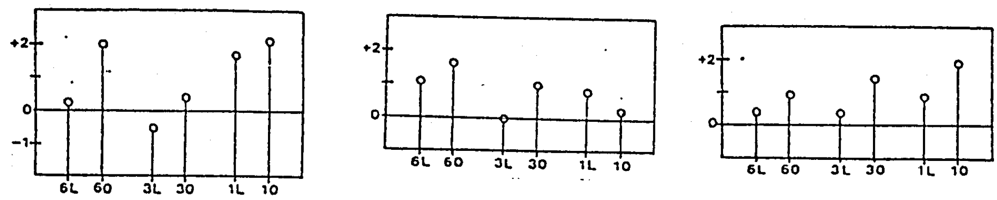


Figure 6.18. Results from three simple listening tests with tones of two guitars: How much stronger is (18 guitar students), how much better timbre has (5 members of Dept Speech Communication and Music Acoustics), and how much longer tone has (7 department members) guitar 1 than guitar 4?

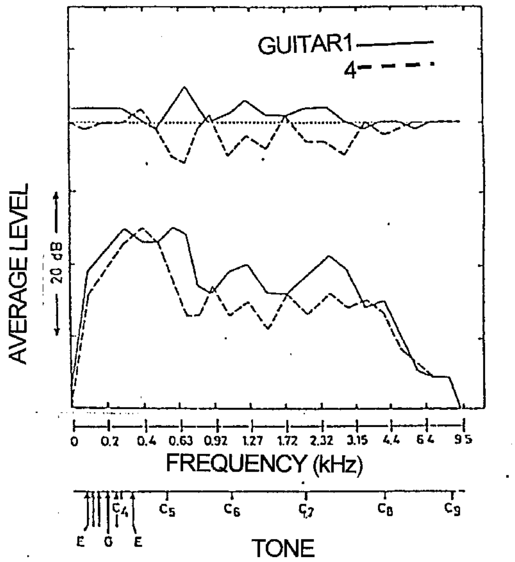


Figure 6.19. Long time average spectra for a high quality (1) and a medium quality (4) guitar.

Tones from recorded music was analysed in form of average spectra over a long time, see Fig. 6.19. Thereby it was found that the better guitar had a higher level up to 3 000 Hz. Within this frequency range the less good guitar had a noticeably lower level below 200 Hz and above 400 Hz.

Meyer has conducted listening tests and measured properties for 15 guitars. The listening test with recorded music showed that the quality order between the guitar depends somewhat on the played music. The variations are moderate though. The guitars seem to group into three quality classes, see Fig. 6.20.

For the 15 guitars also the sound radiation was measured. Three resonances (corresponding to our A0, T1 and T3) were analysed in detail. Thereby it was found

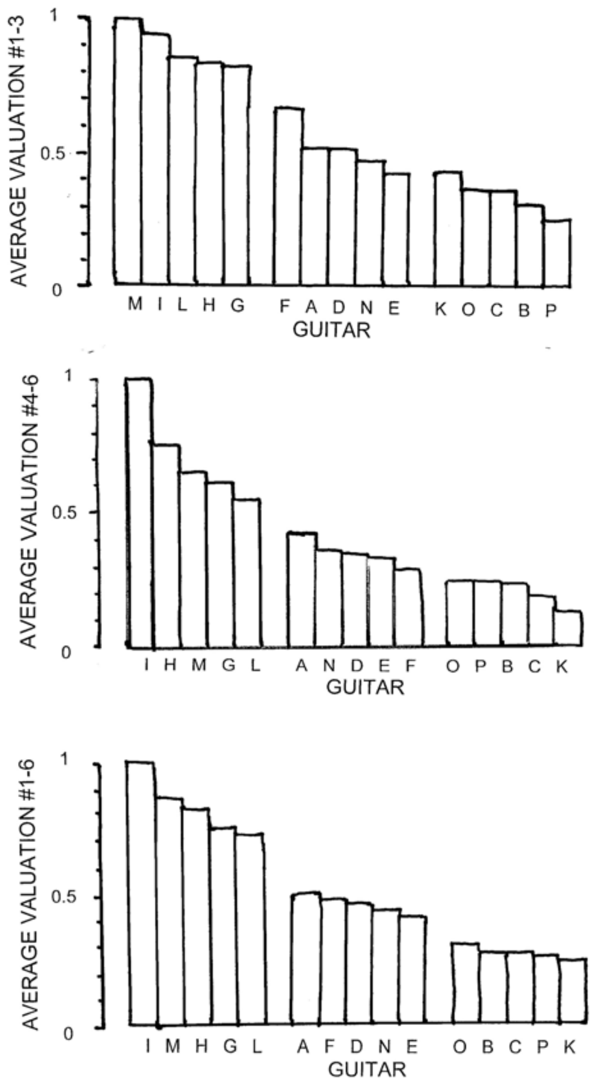


Figure 6.20. Quality ordering of guitars A through P (1 is the highest and 0 the lowest quality) for different pieces of music no 1-4, no 4-6 and all 1-6 (from Meyer).

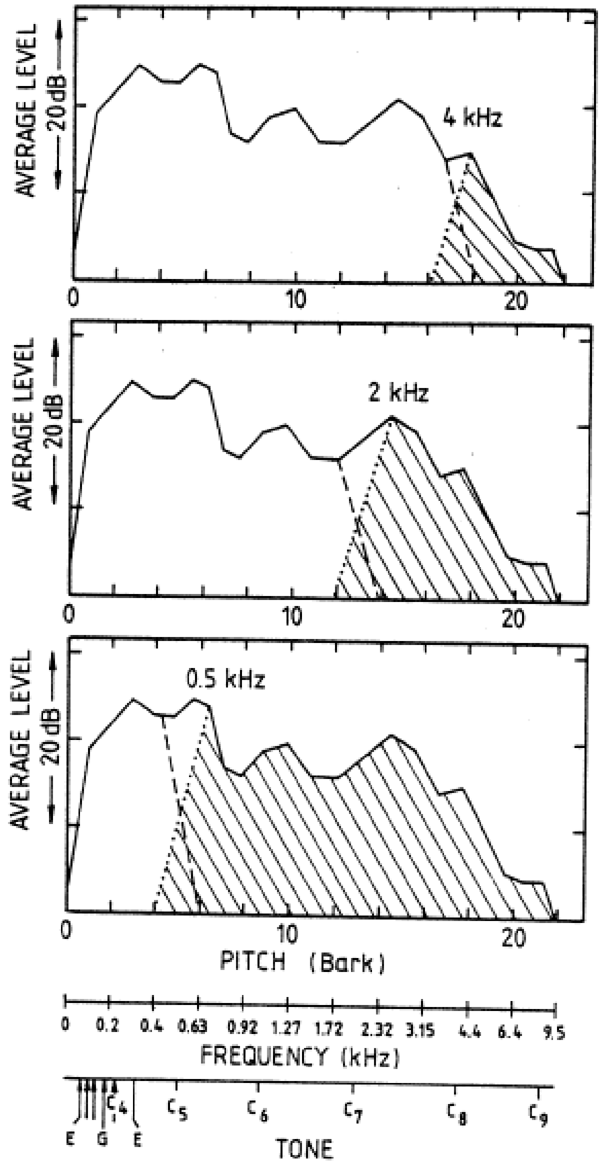


Figure 6.21. Average spectra at filtering experiment. The total areas below the curves show non filtered, the shadowed area the high pass filtered and the white area the low pass filtered average spectrum.

that the third resonance (our T3) was the most important: it should have a high level and a narrow bandwidth. Further it was found that the second resonance (T1) should have a high level. The first resonance (A0) should have a high level too. In addition A0 should have a large bandwidth.

Meyer also analysed the levels averaged over wide frequency bands. He found that the level should be high between 80 and 1000 Hz to give a full sound, the level should be high between 1 000 and 3 000 Hz to give brilliance and clarity (a level that is too high gives a harsh tone though). For the playing of chords a high level above 3 000 Hz is good. This high level affects the tone just after plucking. A suitably high level in this range gives a clear and incisive tone but a level that is too high gives a too harsh tone.

The importance of different frequency regions can be studied with filtering and listening experiments, see Fig. 6.21. The filtering to give only components above 4 kHz demonstrate that there is only plucking sounds here. The sound filtered to give components only below 2 kHz sounds dull and hollow. With the sound filtered to below 500 Hz dull and "revelling" tones with indistinct attacks are heard. The sound filtered to above 500 Hz sounds clear but very thin.

RESULT: TOO STRONG PARTIALS AT LOW FREQUENCIES GIVE DULL, HOLLOW TONES WITH INDISTINCT ATTACKS. THE HIGH PARTIALS GIVE THE TONE CLARITY, ESPECIALLY AT THE ATTACKS, BUT GIVES A THIN TONE IF THE LOWEST PARTIALS ARE TOO WEAK. THUS A BALANCE OF SEVERAL FACTORS SHOULD GIVE THE BEST INSTRUMENT.

6.7 CONSTRUCTION AND ACOUSTICAL PROPERTIES

For the guitar maker it is valuable to know how different construction details influence different properties of the guitar. Therefore the vibration sensitivity was measured for a guitar top plate after several steps of construction, see Fig. 6.22. The figure shows that the vibration sensitivity is little changed, possibly it is increased somewhat at high frequencies by the braces and increased somewhat at low frequencies after the top is glued to the sides.

The bridge influences the vibration sensitivity strongly. The vibration sensitivity decreases much when the bridge is glued on. From this fact we can draw the conclusion that the bridge should be one of the most important construction elements of the top plate. In a following step, a thinning of the top plate edge gave a pronounced influence but the width of the glue joint gave little. The experiments show that the bridge make the vibration sensitivity decrease the most; approximately 5 dB at 200 Hz, 10 dB at 500 Hz and more than 20 dB above 1 000 Hz. Meyer has experimented with different shapes of the bridge and found that a bridge without "wings" gave the best result.

The resonance frequencies for the top plate at different steps of assembly with sides and back, see Fig. 6.23. Again it is to be found that the large changes occur when the bridge is glued to the top (only in this step are most connecting lines sloping, not vertical).

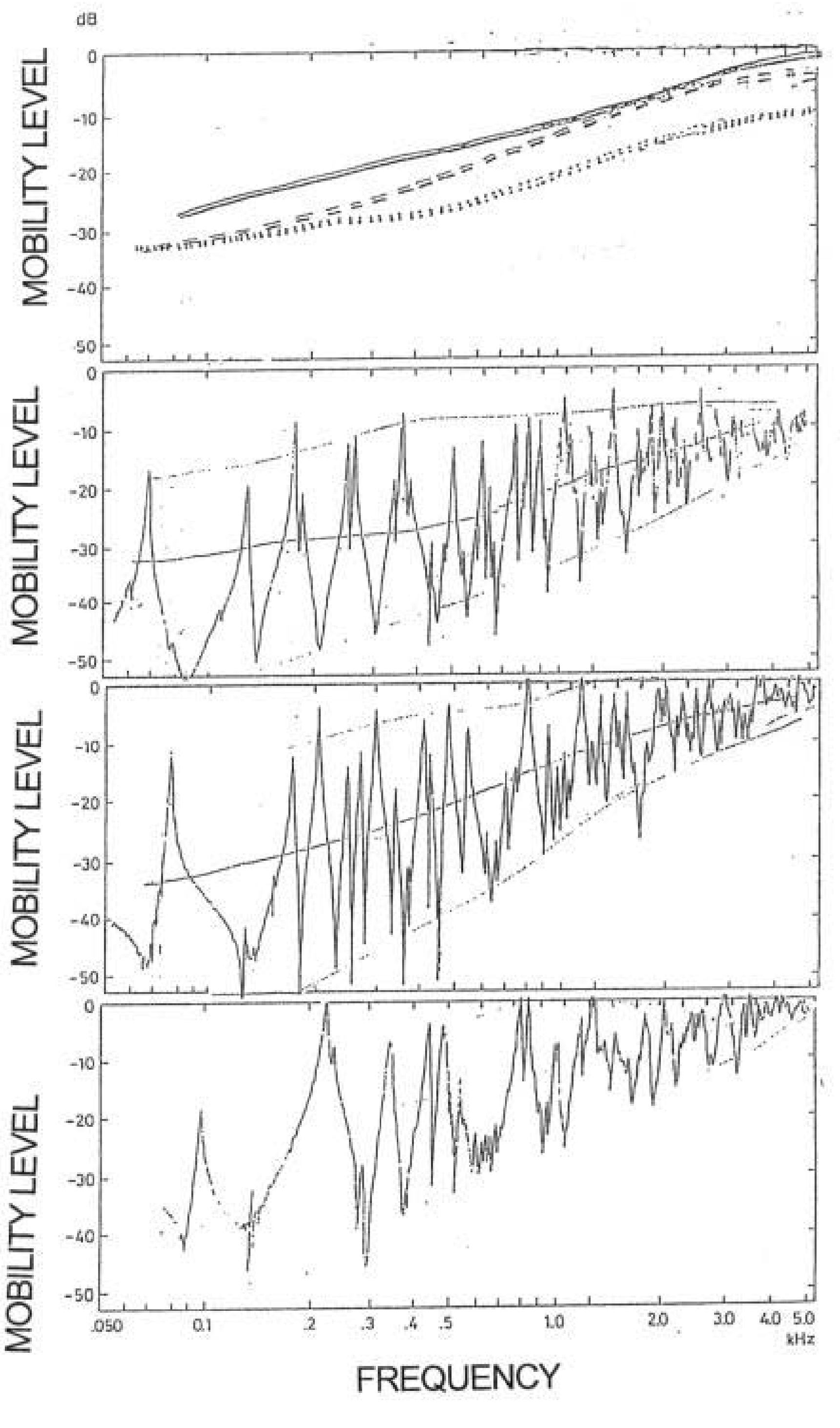


Figure 6.22a. Vibration sensitivity for a top plate in different steps of production: uppermost frame) vibration sensitivity averaged for free top without bracing (dotted lines), for free top plates with bracing (dashed lines), and top plates with bracing and sides (full lines); (second frame) vibration sensitivity for free top without bracing, (third frame) for free top plates with bracing , and (lowest frame) top plates with bracing and sides lines.

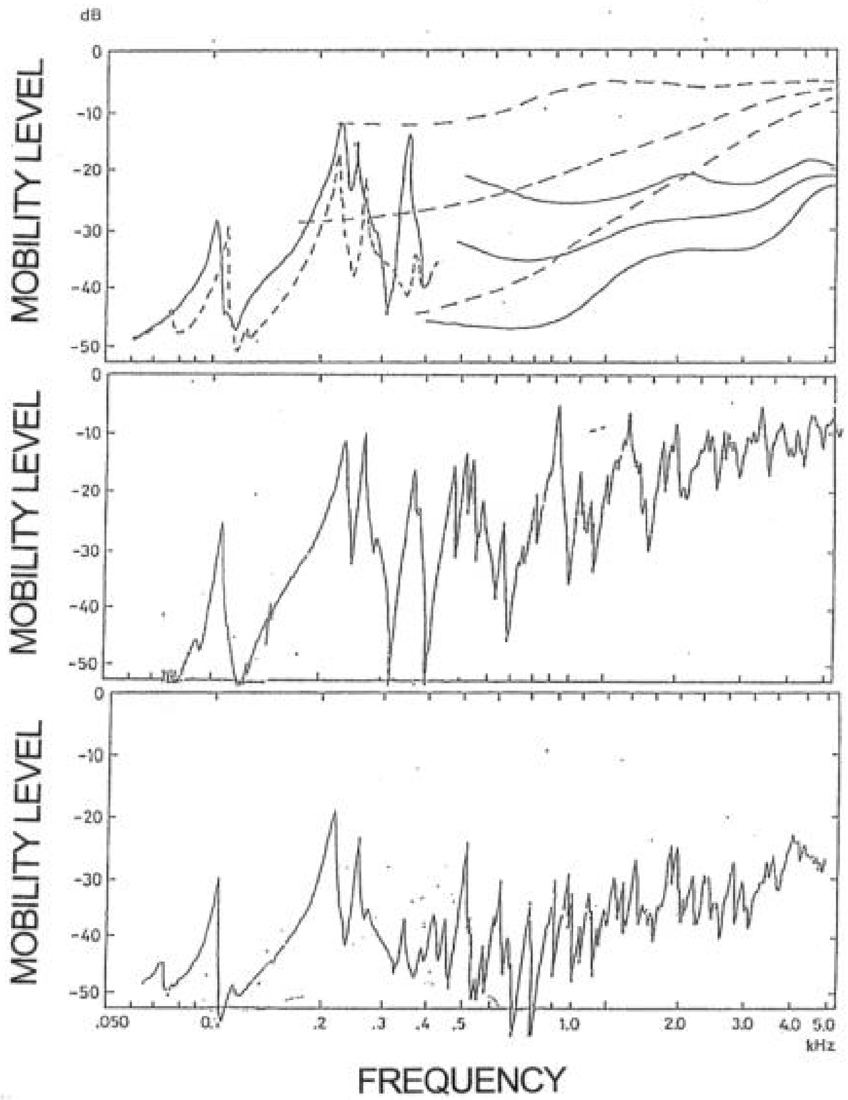


Figure 6.22b. Vibration sensitivity for a top plate in a guitar body in different steps of production: summary (uppermost frame) of top without bridge (dashed lines) and with bridge (full lines), (second frame) vibration sensitivity without plates with bracing and sides but without bridge, and (lowest frame) as above but now for top plate with bridge (c.f. Fig. 6.22a).

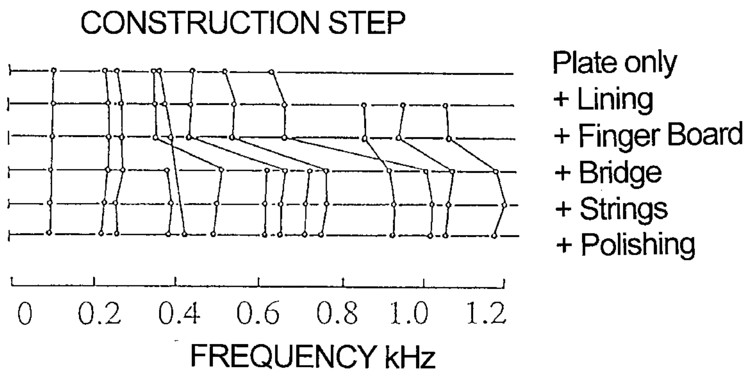


Figure 6.23 The shift of resonant frequencies at different construction steps for a guitar body, from the top glued to the ribs (the uppermost line) to the completed guitar (the lowest line). Circles mark resonant frequencies and the vertical lines (mainly) connect the same modes in the different steps (after Richardson and Roberts).

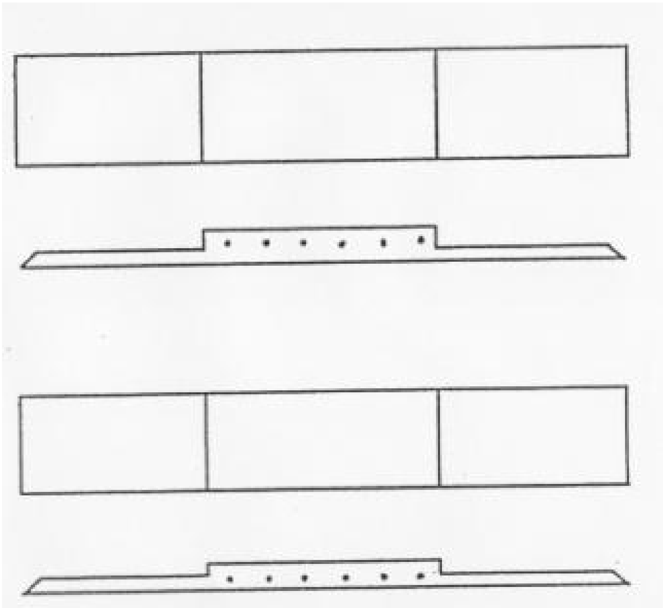


Figure 6.24. The bridge of typical factory made guitar and of handmade Spanish guitar.

RESULT: According to the measurements presented the most important part of the guitar body is the bridge.

As the bridge is likely to be one of the most important parts of the guitar let us look a little more in detail at the bridge. A guitar bridge looks as shown in Fig. 6.24, i.e. a high middle part to which the strings are fastened and over which the strings are stretched. The bridge has two lower "wings" on the sides. Factory made bridges seem to be considerably higher and more rigid than handmade Spanish bridges.

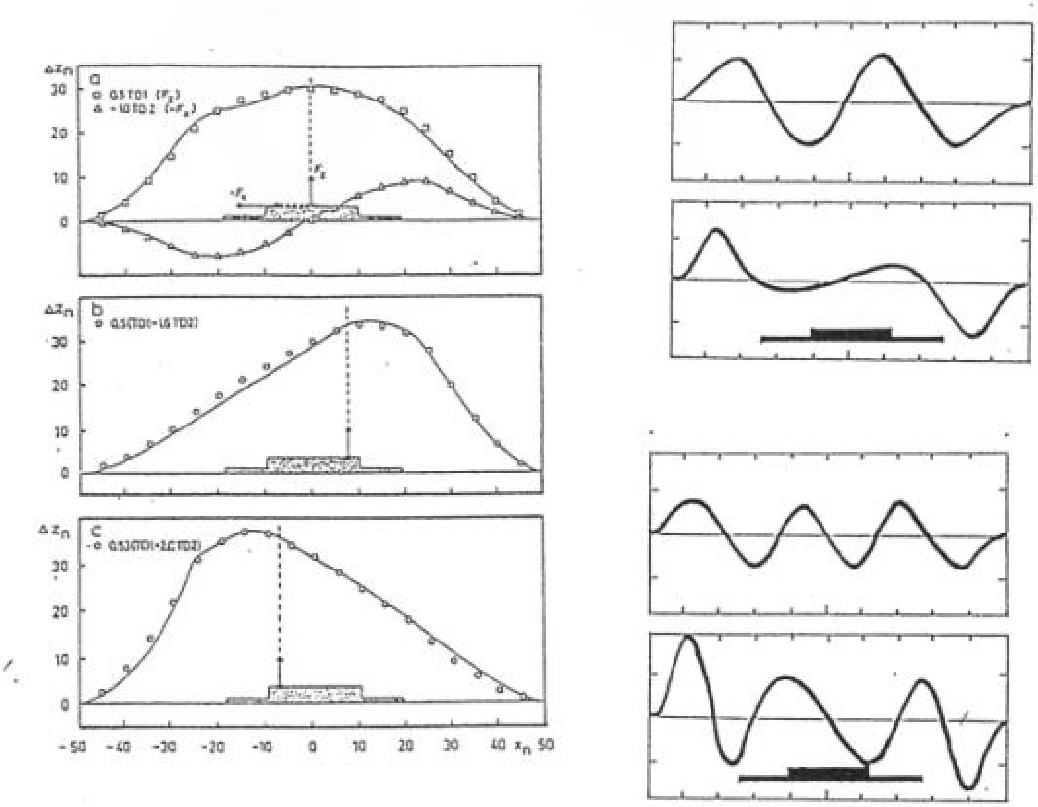


Figure 6.25. The bending of the top plate along the bridge line for different forces: for forces parallel (1 N) with the bridge and perpendicular (0.5 N) to the top (uppermost left frame - triangles and squares respectively), perpendicular (0.5 N) to the top plate on treble side (second left frame), and perpendicular to the top plate on the bass side (lowest left frame), c.f. Fig. 6.13.
The bending of the top plate with and without the bridge for the mode with four antinodes in the bridge line, and for the mode with six antinodes (right frames after Richardson and Roberts).

When the guitar string is plucked, it is pulled aside and thereafter left to vibrate freely. When the string is pulled aside it will exert forces on the bridge and on the top plate. Thereby the top plate is deformed as is shown in the left side of Fig. 6.25. Only when a middle string is plucked perpendicular to the top plate, the top plate is deformed symmetrically. When plucked perpendicularly to the top plate besides the central line, the top plate tends to flip up at the nearby bridge "wing". This is one demonstration of the cross-stiffening effect by the bridge.

The bridge has a marked stiffening effect on the top plate and thus affects the vibrations greatly, see Fig. 6.25 right part. For the two resonances with deflections as shown in the figure their resonant frequencies increase from 439 Hz to 622 Hz, and from 666 Hz to 1029 Hz, which corresponds an increase in plate thickness from 3 to 4.5 mm. For a heavy bridge the frequency of the first top plate resonance may decrease - the weight can give a larger contribution than the stiffness increase.

RESULT: THE BRIDGE GIVES A WEIGHT INCREASE BUT ABOVE ALL A STIFFNESS INCREASE OF THE TOP PLATE. FOR LOW FREQUENCIES THE WEIGHT EFFECT MAY DOMINATE (A0 AND T1). FOR HIGHER FREQUENCIES THE STIFFENING EFFECT DOMINATES AND IS VERY LARGE.

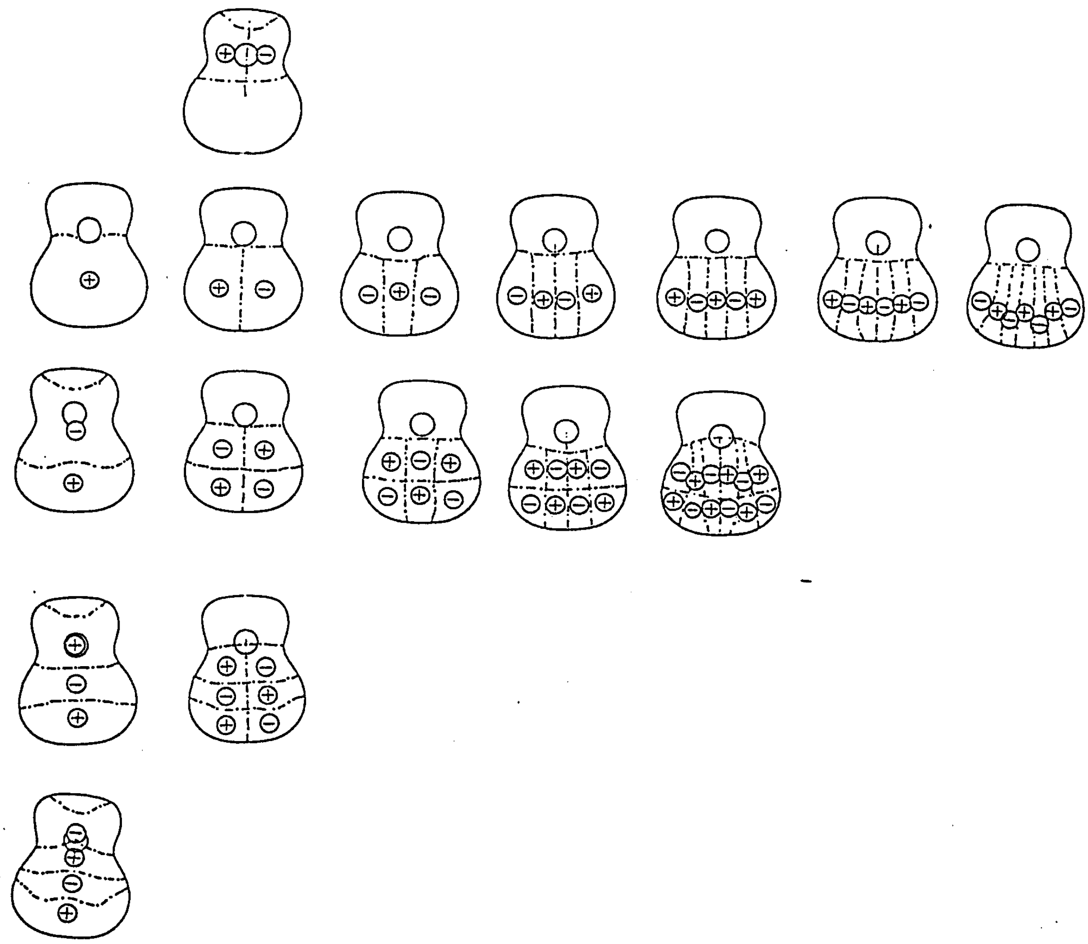


Figure 6.26. Calculated modes for a guitar top plate ordered after the number of antinodes (marked with plus and minus signs for phases of vibration and nodal lines as point dashed lines (after Richardson and Roberts).

A better knowledge of how other construction details influence the properties of the bridge is necessary. Richardson and Roberts have therefore conducted a large series of computer calculations (with finite element modelling) for a guitar top plate fastened at its edge. The top plate for which the calculations were made is sketched in Fig. 6.5a. As a start the plate thickness was set to 2.9 mm, the cross bars were 14 mm high and 5 mm wide, and the braces were 4 or 5 mm high and 5 mm wide. There was no bridge on the top. Calculated vibration modes are presented in Fig. 6.26. The modes are ordered as sketched in Fig. 2.13, i.e. after the number of antinodes horizontally and vertically.

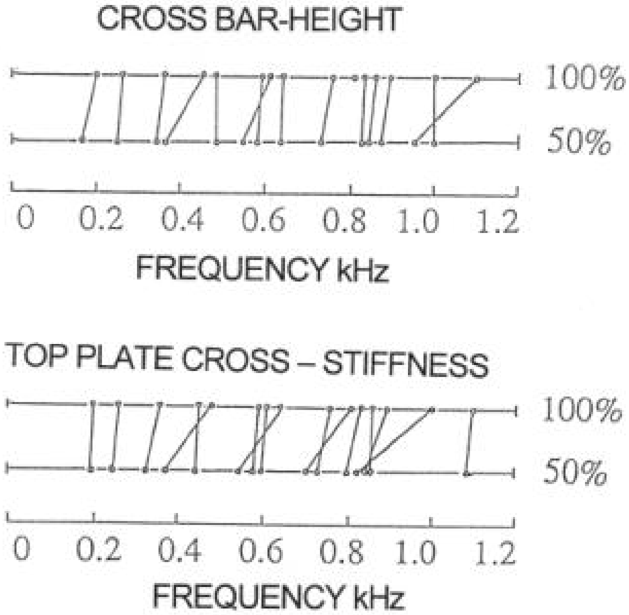
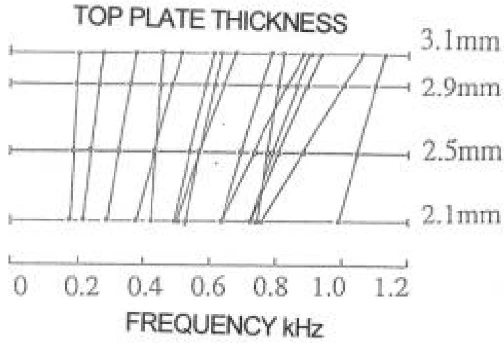


Figure 6.27. The effect of the crossbars and top plate stiffness on the resonant frequencies (from Richardson and Roberts).

Richardson and Roberts say that the wood stiffness varies the most across the grains and therefore the effect of a 50 % reduction in this stiffness was calculated, see Fig. 6.27. The calculations predicts a dominating frequency shift of up to half this value (25 %) for the resonances mainly oriented across the grains (modes with antinodes horizontally), which is in agreement with theoretical prediction. In a second step the influence of the cross bar height was calculated. The calculations show that the crossbars should give a large influence at least for the low resonances which are oriented mainly longitudinally (modes with few antinodes in the vertical direction).

Similar computer calculations were made for different thickness and brace heights, see Fig. 6.28. The figure shows that a thickness reduction from 3.1 to 2.1 mm results in a large influence on the resonance frequencies. The measurements by the author shows that a reduction of plate thickness influences the level of the vibration sensitivity rather little and that the thinning along the edge does the most.

In guitar making the braces (the fan bars) are usually considered to play a major role and a large amount of different arrangements can be found.. It is therefore of great interest to calculate the influence of the braces as Richardson and Roberts have done. Their calculations show, however, that the braces influence the resonant frequencies of the top plate little, not as much as changes in the top plate thickness. Possibly the braces give a slightly higher vibration sensitivity level than without braces for frequencies above 500 Hz (from the authors experiments).



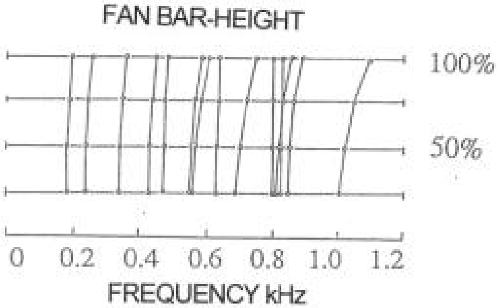


Figure 6.28. Influence of top plate thickness and height of braces on the resonant frequencies - vertical lines indicate no change, leaning lines a change (from Richardson and Roberts).

Meyer has found in his extensive investigations using mirror symmetrical and fan shaped bracings that a maximum of seven braces should be used, they should be positioned far away from the centre line except for one brace along the centre. Increased number of braces improves the evenness of the response at the price of a weaker tone.

RESULT: A THINNER TOP PLATE GIVES NOTICEABLY LOWER RESONANT FREQUENCIES BUT THE LEVEL IS LITTLE INFLUENCED. THE THICKNESS ALONG THE EDGE SEEMS TO BE THE MOST IMPORTANT. THE BRACES (THE FAN BRACING) SEEMS RATHER TO BE A FINE ADJUSTMENT.

6.8 HOW TO MAKE THE BEST GUITAR?

What answer can we find to this most important question? A recipe can unfortunately not be given, the question is much too difficult. The information presented gives, however, some clues to what is likely to be the best choice for experimenting in optimising a construction or a design.

In answer to our question of desirable properties for a concert guitar, we found that a strong, long tone with colour were the most wanted properties. Analysis of played guitar tones showed that a higher level was also perceived as advantageous. A balance between different frequency ranges does seem to be needed: sufficient level between 80 and 1 000 Hz for a full tone, a high level between 1 000 - 3 000 Hz for brilliance, the right level in the initial part for frequencies above 3 000 Hz for an incisive tone. Too high a level in the low frequency range gives a dull tone and too high a level in the high frequency range gives a clear but thin tone. Listening tests have shown that a stronger tone sounds longer without necessarily being so.

The guitar is not only top, sides, back and a volume. For an optimal design co-operation between these and other parts are demanded. Antoine Chaigne has shown with synthesized guitar tones that the dominating resonances in the vibration sensitivity curve can influence the perceived quality, i.e. more than 15 resonances below 1 000 Hz. This means that the maker cannot hope to be able to tune all noticeable resonances separately.

The experiments and calculations presented have shown that the bridge has the largest influence on resonant frequencies and vibration sensitivity levels. The thickness of the top plate seems to be the second most important, especially along the edges, and the width of the fastening is less important than the thickness. The number of braces should be few and they should be fairly strong. Many braces give eveness but at the price of a weaker tone. Small internal friction in sides, back and neck seems also to be desirable. For low frequencies single resonances play a major role and the maker must at least intuitively be able to tune some resonances relative to others (but not to the same frequency). The resonance T1 should be tuned in relation to the resonance A0, and the resonance T3 in relation to the resonance A1. Good properties at high frequencies should be determined rather by the general construction than the tuning of single resonances.

MAIN RESULT: THE EXPERIMENTS SUGGEST THE FOLLOWING ORDER OF IMPORTANCE FOR DIFFERENT PARTS - BRIDGE, TOP PLATE THICKNESS AND CROSS BARS.

The conclusion from the (experimental) experience of the author is thus to start with a fairly rigid but light construction (back, sides, neck and cross bars), a fairly thin top plate the properties of which primarily are adjusted by means of the bridge and thereafter edge thickness and braces. A good knowledge of the possibilities of bridge adjustments should be most valuable. In the opinion of the author a high handicraft skill and a good feeling for the material must be developed before experimenting after the sketched lines.

6.9 SUMMARY - THE TONE AND TONAL QUALITY OF THE GUITAR

In this part we have tried to relate tonal properties to resonance properties. Further the effect of different construction details on the resonant properties have been described. Finally the information have been summarised in suggestions for profitable areas of experimenting in new constructions.

6.10 KEY WORDS

Carrying power, timbre, duration, resonant frequencies, resonance levels, bridge, top plate thickness, cross bars and braces.