FUNCTION, CONSTRUCTION AND QUALITY OF THE GUITAR

Papers given at a seminar organized by the Committee for the Acoustics of Music

Edited by Erik V. Jansson

Publications issued by the Royal Swedish Academy of Music No. 38
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PREFACE

On November 14, 1981, the Committee for Music Acoustics of the Royal Swedish Academy of Music arranged a full-day seminar on the acoustics of the guitar. The seminar was held at the Royal Institute of Technology (KTH) in cooperation with the Department of Speech Communication and Music Acoustics. The purpose of the seminar was to present the latest findings of research and to combine these findings with an education in fundamental acoustics and the experience of players and makers. Thus Professor Jürgen Meyer was invited to present the results of his extensive investigations in which perceived tonal qualities were linked to the function and the construction of the guitar. Results of the investigations at KTH were presented, combined with an introduction in fundamental acoustics. During one of the lectures, Dr. Leif Ek, at the Institute of Optical Research, displayed the fundamental vibration patterns of a guitar top plate with his optical interferometer, Vibravision. Finally two panel discussions were held as a direct exchange of information between the researcher, players and makers. The papers have been edited and are hereby presented together with the panel discussions summarized by the editor.

In breaks between lectures, music was performed. Svenska Gitarrtrion - Jörgen Rörby, Erik Möllerström and Göran Wiström - demonstrated the potential of the guitar trio and Torbjörn Bergstam played contemporary music on the baroque lute and an early 19th century guitar (Staufer).

Si Felicetti has typed Prof. Meyer's papers, and Karin Holmgren has read and improved all the manuscripts in point of language. Bertil Alving has attended to the production of the gramophone record.

KTH, May 1983

Erik Jansson, editor
Committee for Music Acoustics

ACOUSTICS FOR THE GUITAR PLAYER

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Introduction

In two papers I shall present basic acoustics for the guitar player and maker respectively. Therefore in this first paper I shall talk mainly about the guitar tone and in the second mainly about the guitar body. I shall try to convey an understanding of fundamental properties of the guitar tone by answering three questions:

1) What is a guitar tone?
2) What can the player do to the tone?
3) What does the guitar do to the tone?

In seeking the answers we have to stand with one leg in each of two worlds - one leg in the world of music and the other in the world of acoustics. In the music world, i.e. a world of experience, man is the recording instrument. Only man can record and create an experience. In the other world, the world of acoustics, physical properties are recorded with technical measuring equipment. The relation between the human experience of a specific sound and its acoustic description is often very complicated. Such relations are in fact often so complicated, that still today we only can give clearcut answers to how a specific sound is experienced in simple cases. In this paper recorded acoustical properties are presented. The reader is invited to use his own "built-in experience" meter to relate his experience to measured acoustical properties, by means of the included sound examples.

What is a guitar tone?

Let us start with a comparison of how the tone is described in the world of music and the world of acoustics.

In music we use a staff consisting of five parallel lines, c.f. Fig. 1a. Extra lines can be added above and below to extend the staff. The tone to be played is marked by its position in the staff, on a line or between two lines. In the acoustical description, a diagram is generally used. In this diagram the frequency of the tone is marked by its position along a horisontal scale, the horisontal axis, c.f. Fig. 1b. The strength of the tone, its sound level, is marked along a vertical scale, the vertical axis.

Let us study a few examples. In Fig. 1c the tone position of A, two lines below the staff has been marked. This tone position corresponds to the frequency 220 Hz, the position of the bar on the horisontal scale in Fig. 1d. The musical tone position corresponds to the acoustical frequency.

In the musical description, the strength of the tone is marked with additional signs such as ff for strong and pp for weak, Figs. 1e and 1g. This is marked in the acoustical description as high level, i.e. a high bar in Fig. 1f, and a low level, a low bar in Fig. 1h, respectively. The dynamical level in music correponds to acoustical sound level. The acoustical sound level is measured in dB.

But the acoustical description of a musical tone generally contains several bars as shown in the example of Fig. 1j. This musical tone consists of five bars at equal frequency distances from its neighbours. Thus the musical tone consists not of one tone but a series of five acoustical tones, five partials. The five partials constitute a harmonic spectrum. If the partials are plotted in the staff, we obtain the marked chord.

The effect of the partials in Fig. 1i and 1j on musical tones is demonstrated by sound example 1, which is arranged according to Fig. 2. First we hear each individual tone, partial, according to the four

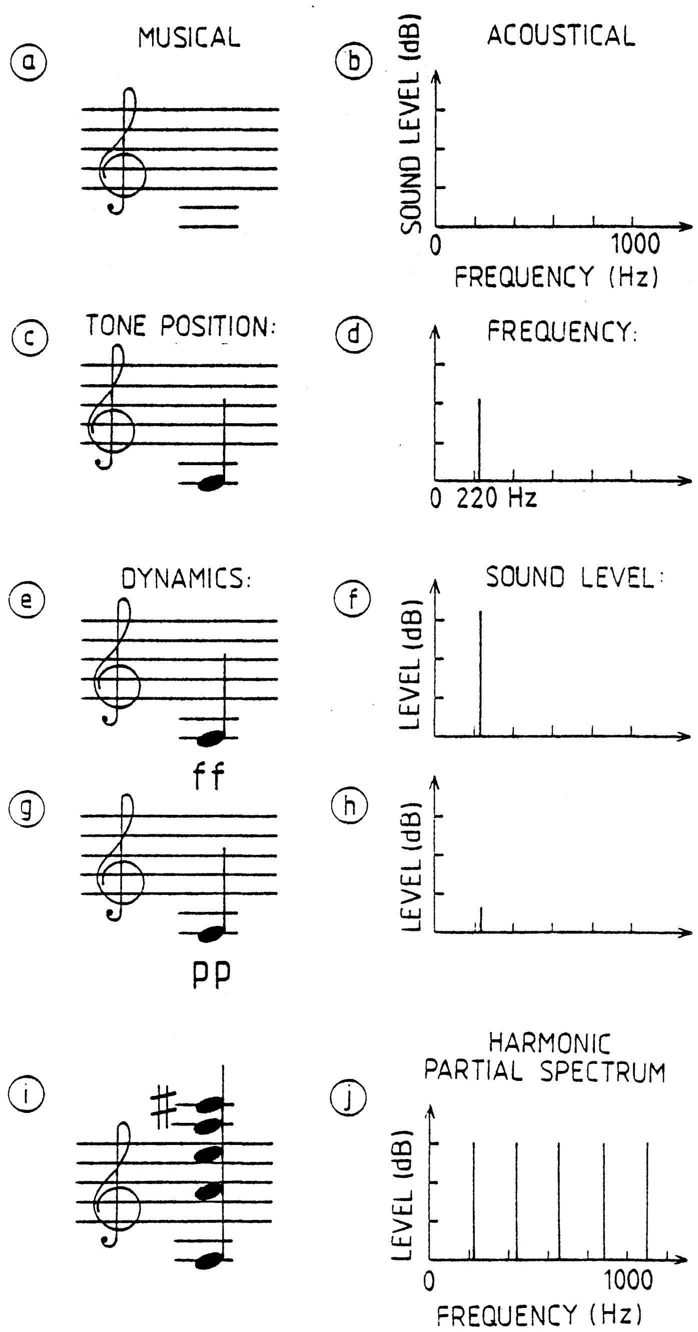


Fig. 1. Musical representation and acoustical representation.

diagrams in the left column of Fig. 2, repeated twice, thereafter the successive additions of the tones, the partials, in the sound examples corresponding to the right column of Fig. 2, repeated twice: first the lowest tone, the first partial, thereafter the first and the second

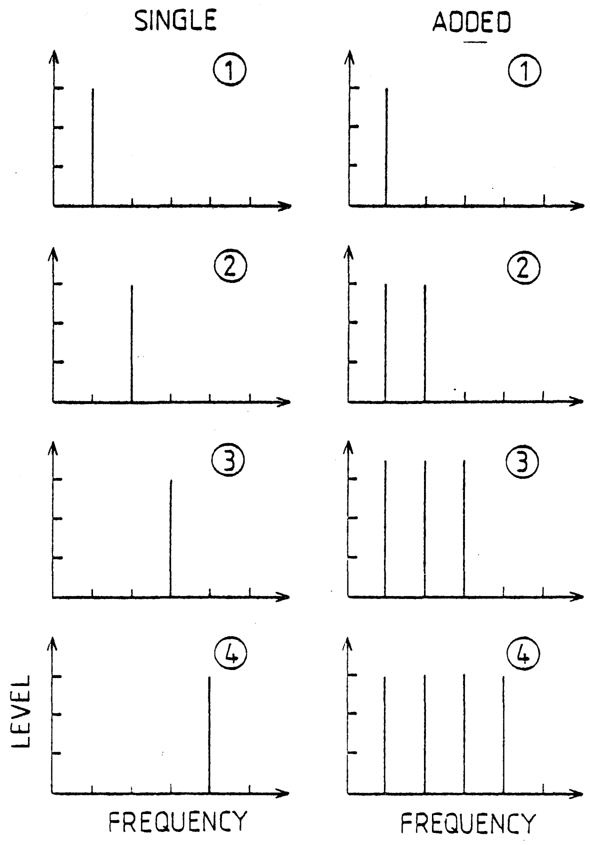


Fig. 2. Single tones and spectral components, i.e. partials, c.f. sound example 1.

partials together, then the first, second and third partials together, and finally the first, second, third and fourth partials together. We can clearly hear that the timbre impression of the musical tone changes with the increasing number of partials. This demonstrates the correspondens between the musical timbre and the (acoustical) partial structure, the tone spectrum.

A timbre effect, "roughness" contra "smoothness" can be explained by means of the number of partials. A musical tone with one to four partials, c.f. Fig. 3, sounds smooth. But if the number of partials is increased to six, then a timbre of "roughness" is developed (sound example 2). This experience of "roughness" contra "smoothness" depends on properties of the human hearing (Terhardt 1974). A musical tone consisting of five or more partials will contain at least two partials within a so called critical band of hearing, which creates an experience

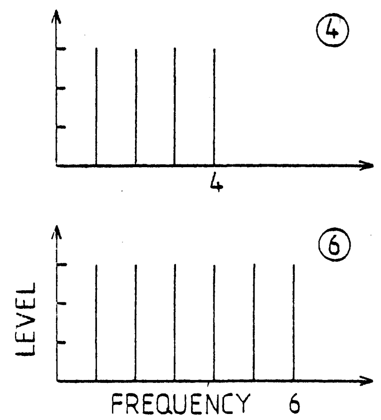


Fig. 3. Spectra producing sensations of smoothness (four partials) and roughness (six partials), c.f. sound example 2.

of roughness. Thus we have here an example of acoustical measures predicting an "experience".

Let us look in some detail at a typical guitar tone. In Fig. 4, three diagrams, three acoustical "snapshots" of a guitar tone E (165 Hz, the sixth string stopped at the 12th fret) are shown. The three diagrams show the partial tone structure shortly after the plucking, and at 0.2 and 0.4 sec later. The the upper diagram shows 14 partials of varying strengths. The 0.2 sec one, the middle one, shows 9 partials and the 0.4 sec one, the lower one, 7 partials. A closer look reveals that the levels of the different partials decay with different rates approx 3 dB

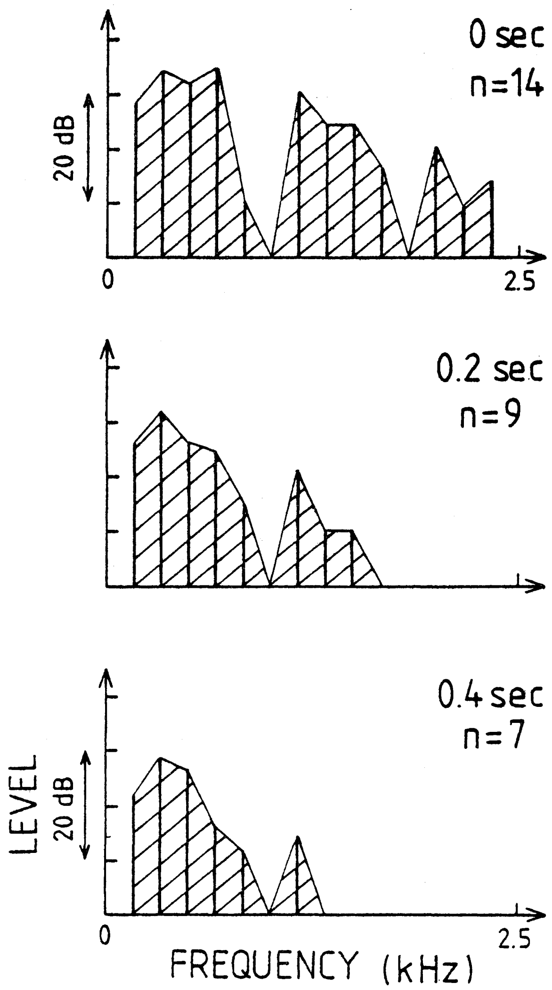


Fig. 4. Instant spectra of a guitar tone at 0, 0.2 and 0.4 sec after plucking.

in 0.2 sec for the first three partials, approx 10 dB for the next higher ones, and 15 dB for the four highest ones.

By means of this analysis a guitar tone can be electronically reconstructed, synthesized. If the reconstruction produces the same listening experience as the "natural" guitar tone, then the important acoustical elements of the tone have been captured. Let me demonstrate the power of this method of investigation, with sound example 3.

In sound example 3 we hear three typical and completely synthesized guitar tones, followed by three repetitions of a synthezised partial spectrum similar to that of Fig. 5. The partial spectrum sounds fairly "natural" but there is something missing in the attack. The missing components is a weak body sound, which is presented first separately then added to the above partial spectrum. The result is the typical guitar tone again.

We now have a sufficient understanding of the main acoustical elements to create a characteristic guitar tone. The characteristics of the guitar tone are set by the partial structure with a weak body sound added initially. Before leaving the "snapshots" of the guitar tone, another detail should be pointed out. The sixth and the eleventh partials have very low levels, i.e. the partial spectra each have two clear minima. We shall explain these minima later.

What can the player do to the tone?

The player can vary the position, the direction and the way of plucking. All three factors influence the character of the played tone. But to be able to understand how this is possible, we must first learn some basic string acoustics. First let us study how a string may vibrate, see Fig. 5 the upper half. Previously we have seen and heard that a musical tone is not a single tone, but a series of tones, so called partials. Every such partial corresponds to a special kind of string vibration, a so called standing wave. In the first partial, the fundamental, the vibrating string describes a smooth line with one maximum in the middle. In the second partial the string describes a smooth line but now with two vibration maxima and a minimum in the middle. The vibration minima are called nodes and the maxima antinodes. The two vibration patterns can be seen, if one looks along the sixth guitar string immediately after plucking. The vibration pattern of the fundamental, the first partial, is obtained by plucking the open string in the position of the twelfth fret. The vibration pattern of the second partial is obtained by plucking at the sound hole and by fingering simultaneously the octave flageolet.

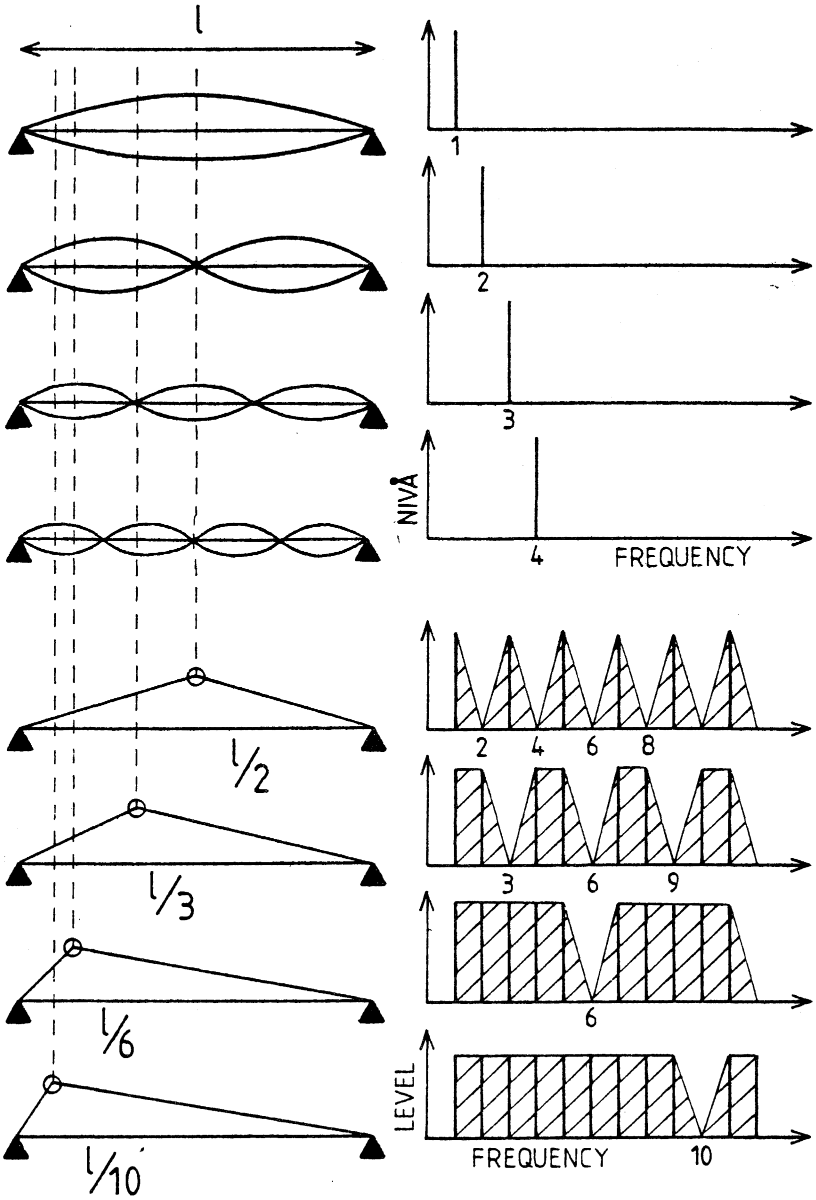


Fig. 5. Demonstration of the influence of plucking position. Upper left: the four lowest string partials (vibration modes), upper right: corresponding tone partials (spectral components), lower left: four different plucking modes (different plucking positions), and lower right: sketch of the spectra resulting from the different plucking positions, c.f. sound example 4.

The third partial has three antinodes and two nodes as shown in Fig. 5. The fourth partial has four antinodes and three nodes. Note that these partials correspond to specific flageolet tones. Analogous relationships hold for higher partials and flageolet tones.

Now let us examine how the plucking position affects the played tone. Below the vibration patterns of Fig. 5, the initial deformations for four different plucking positions are sketched, i.e. plucking at the middle, at a third, at a sixth and at a tenth of the string length from the bridge. The following fundamental relation is valid: a partial can not be initiated at the nodal position of the corresponding standing wave, and a partial is initiated maximum at its antinodal position(s).

The consequence of this is that when the string is plucked in the middle position, then we initiate the standing wave of the first partial and thus the first partial. The standing wave of the second partial has a minimum, a node at the middle and thus the second partial is not initiated. The standing wave of the third partial has maximum in the middle, the fourth a minimum etc. Thus the third partial is initiated, the fourth not etc. The resulting partial structure of plucking in the middle is sketched to the left of the corresponding initial plucking deformation of Fig. 5. When the string is plucked at a third of a string length from the bridge, then the first, the second, and the fourth standing waves are intiated, but not the third. Thus this plucking will not give a third partial nor a sixth, ninth etc. When plucking at a sixth of the string length, the sixth, (the twelfth etc) partials are not initiated, and when plucking at a tenth of a string length, the tenth (and twentieth etc) partials are not initiated. Normal plucking position is somewhere between a third and a tenth of the string length.

In sound example 4 we can listen to the different spectra of Fig. 5. First one hears first a gong-like sound, followed by three somewhat guitar-like sounds, which vary quite noticeably in quality. In reality the result of different plucking positions are somewhat more complex. The presented principle applies but a more detailed analysis shows that the levels of the partials decrease after every minimum, thus enhancing the effect of playing close to the bridge.

The string may be plucked in different ways for instance by the fingernail or by the fingertip. I am not aware of any acoustical investigations of this topic, but I find a theoretical prediction to be in place, see Fig. 6. If the string is plucked with the fingertip it will be bent smoothly, but if it is played with the fingernail it will make

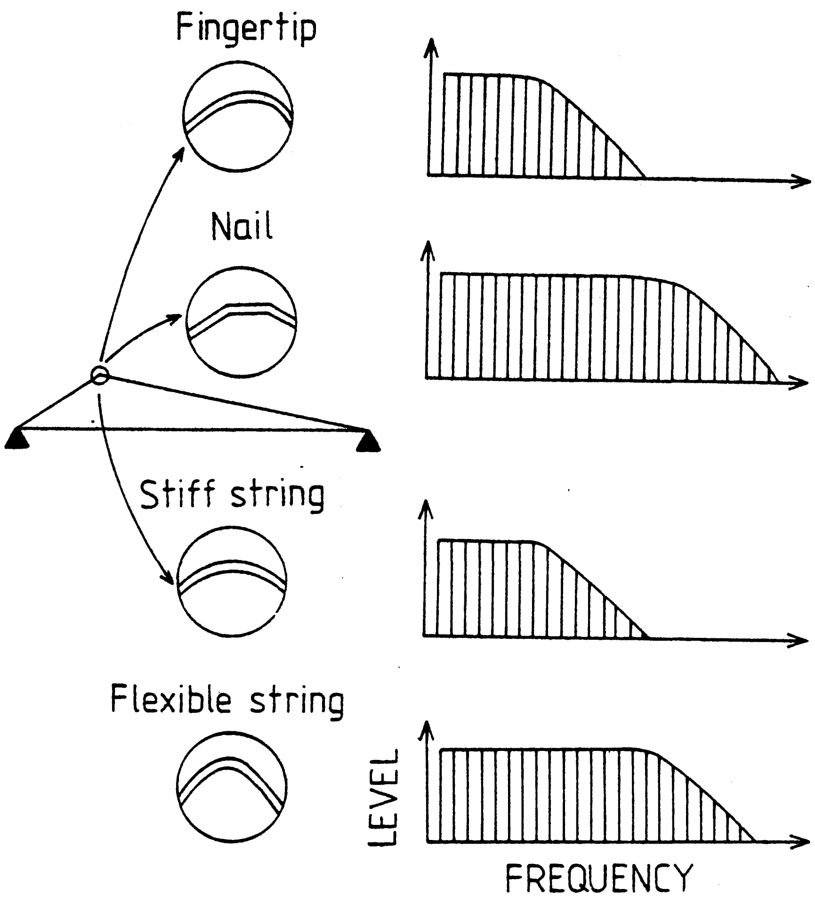


Fig. 6. Sketch of the influence of different ways of plucking and of stiffness of the strings on the resulting partial spectrum.

sharpe bends. A smooth bend will give a guitar tone with fewer partials than the sharp bend, that is a qualitative difference as sketched in the Fig. 6 to the right. The difference should be still more pronounced by the slow release of the string from the fingertip and the fast release from the fingernail. A somewhat similar effect should be expected between a "flexible" and a "stiff" string.

Another fact available for use in practical playing is the direction of the plucking, see Fig. 7. Let me start by showing two extreme cases. When the string is plucked perpendicular to the top plate a strong but short tone is obtained. If the string is plucked parallel with the plate a weak but long tone is obtained. Normally the string is plucked at an angle slightly towards or away from the plate. Therefore the guitar tone can be regarded as consisting of two parts, one part resulting from the

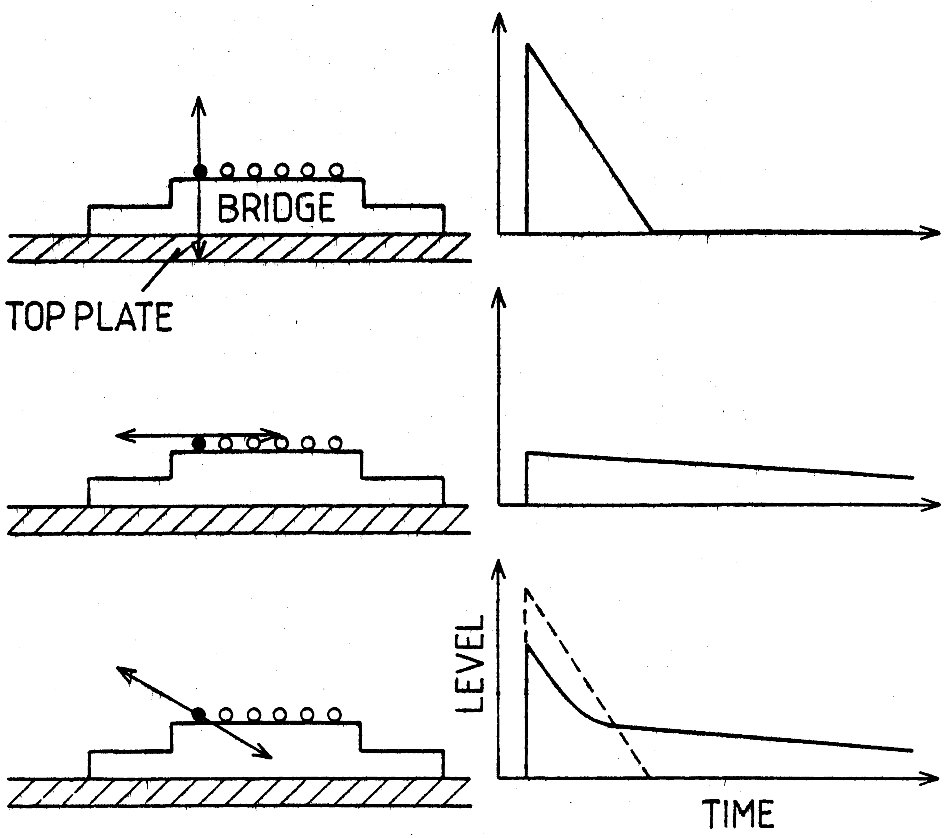


Fig. 7. Sketch of the influence of different plucking directions.

plucking perpendicular to and a second part from the plucking in parallel with the top plate. During the beginning of the tone, i.e., the initial part, vibrations from the plucking perpendicular to the plate dominates. After a while, in the late part, the vibrations in parallel take over and dominate. During the intervening time the two parts contribute equally, which results in a smooth transition from the the initial part to the late part.

What does the guitar do to the tone?

As mentioned previously the guitar tone is composed of string partials. These partials start out strong and decrease at different rates. In an investigation together with Graham Caldersmith the relations between tonal properties and body properties were studied (Caldersmith and Jansson 1980). Chromatic scales covering a one-octave range were played twice on each string in an anechoic chamber. The tones were recorded on tape. In the laboratory the tape was replayed and the level of the partials were plotted as a function of time.

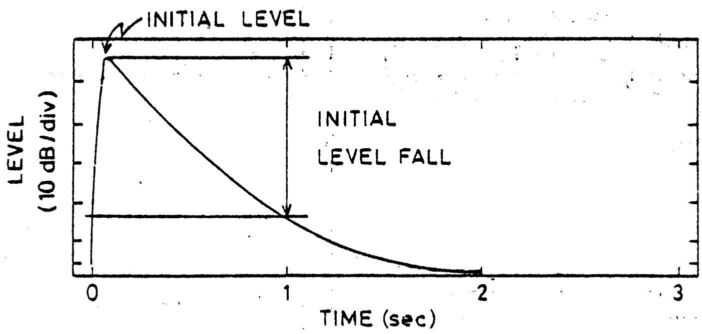
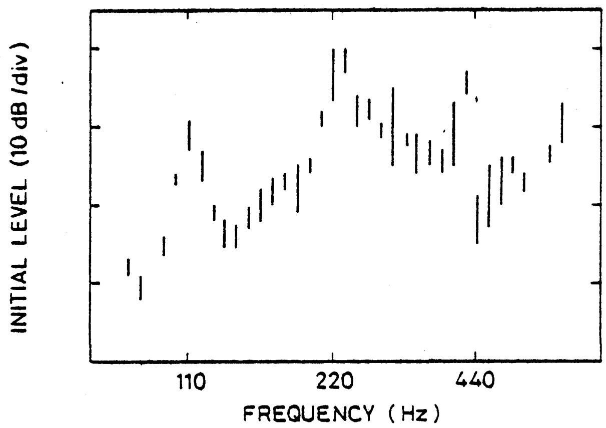


Fig. 8. Sketch of the partial level as a function of time, and definition of initial level and initial level fall.

Two measures: (1) initial level and (2) initial level fall, i.e. the level fall during the first second were defined according to Fig. 8. These two measures were extracted from all played tones. In Fig. 9 the results are plotted. The variations in initial levels of partials of the same frequency are marked with the vertical bars. The lengths of the bars are in most cases within 5 dB, but there is a difference of 30 dB between the maximum and the minimum of the different bars. This means that the variations in playing are considerably smaller than those caused by the instrument.

The variations of the initial level falls for partials of the same frequency are plotted in Fig. 10. They are marked by vertical bars. The variations, the lengths of the bars, are somewhat larger than those in Fig. 9, but still within 10 dB with few exceptions. The variations



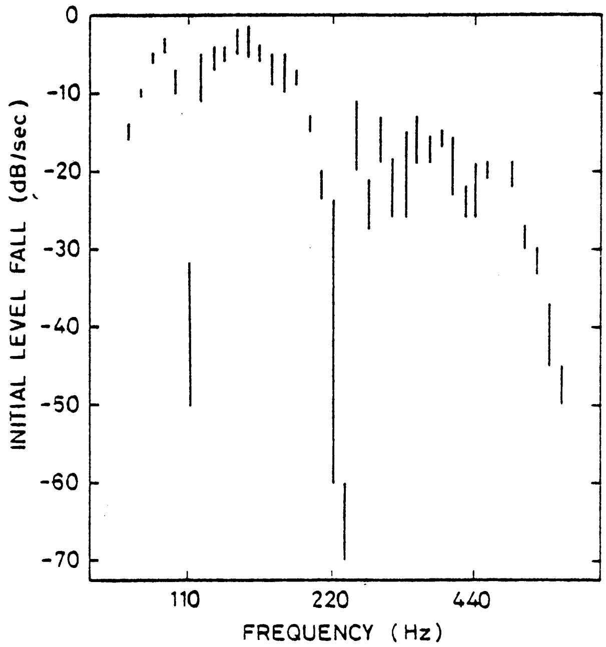


Fig. 9 (upper diagram). Initial levels of partials as a function of frequency.

Fig. 10 (upper diagram). Initial level falls of partials as a function of frequency.

between the initial level falls at different frequencies are considerably larger - a maximum of 50 dB.

A comparison of Figures 9 and 10 shows that the initial levels have maxima where the initial level fall have minima, i.e. there is an (inverse) relationship between the initial levels and the initial level falls. Thus an initially strong partial decreases quicker than an initially weak one.

The strings and the way of playing are important for the guitar tone. Therefore in a second experiment the playing was kept "constant" and the strings were switched between two guitars. Thus we could achieve a measure of the importance of the strings and the guitar body with no disturbances from differences in playing. The experiments were limited to two tones, the octave tones on the first and the sixth strings.

First, the guitars were tested with the original and fairly old strings. Secondly, the guitars were tested with the strings of the high quality guitar shifted to the medium quality guitar and new "medium quality" strings put on the high quality guitar. Thirdly, the guitars were tested with the original strings on the high quality guitar and the new medium quality strings on the medium quality guitar. Five to six tones were played for each combination during one and the same afternoon in the anechoic chamber.

A direct comparison of the high tones (E 660 Hz) from the two guitars shows quite a startling fact although not unpredictable, see Fig. 11. The initial level fall is approximately 15 dB/sec faster for the high quality guitar compared to the medium quality guitar. In spite of the faster decay, the high quality guitar most of the time gives a higher level for the sounding tone, approximately 10 dB higher after one second, for instance.

Let us assume that the tones were played in a situation where they could be heard to a level 50 dB below the upper frameline of the diagram, i.e. to the level of the dotted line. If so, the fundamentals of the two guitars will be heard for 0.8 and 1.2 sec, respectively, i.e. a 50% difference in tone duration. Assuming that the tones could be heard to only 40 dB below, the broken line, a still larger difference is obtained.

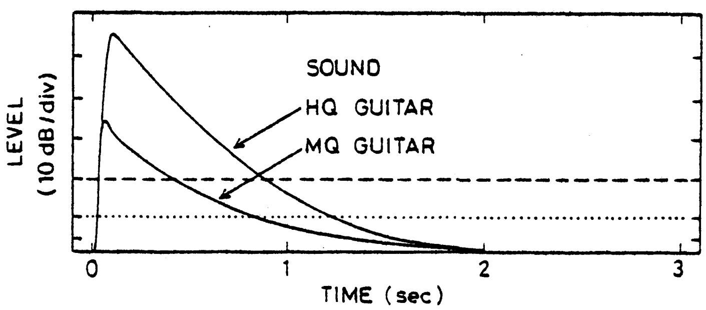


Fig. 11. Level of the fundamental as a function of time for the octave tone (E 660 Hz) played on the first string of a high quality (HQ) and a medium quality guitar (MQ).

Thus summarizing the second experiment and the parameters investigated we found:

1. The differences between strings are generally small. An old spun string may, however, produce a considerably lower level.

2. The differences between guitars are greater than the differences between strings - especially for the tones of the first string.

3. A higher initial level may, in spite of a more rapid decay, result in a tone of longer duration.

The presented physical relations between initial levels, initial level falls, perception threshold level, and duration are likely to set the limits of use, and thus the quality of a guitar. Quiet music in a quiet room should best be played on a guitar with slowly decaying tones in spite of the low level. Quick and "noisy" music should, however, best be played on a guitar with high initial levels, where, in addition, the fast decay should be advantageous.

The music room may be regarded either as a part of or an extension of the guitar, which makes it natural to include some basic room acoustics. When a guitar is played outdoors, the listener will hear the sound coming directly from the played instrument. If the listener is close enough with no disturbing objects between himself and the player, then the listener gets a clear and distinct impression of the played tones and the direction of the player. This clear and distinct impression is given by the sound radiated directly from the played guitar to the listener. With objects positioned in between or almost in between the player and the listener, the impression is less distinct. The high frequency components are affected most.

The same conditions apply to music in a room, but with one most important addition. The sound that impinges on the walls, the ceiling and the floor, is reflected. If much of the sound is reflected and little absorbed, the "reflected" sound dies out slowly, and results in a long reverberation time. The "reflected" sound amplifies the direct sound and more "volume" is obtained at the price of loss in clarity.

The listening conditions can be summarized in measures of relations between useful and harmful sounds. One measure, the reverberation radius is the distance from the player to the listener where the direct sound and the reflected, reverberated, sound are equally strong. A reverberation radius of 5 m is typical for a large concert hall. The distance from player to listener in relation to the reverberation radius presents one way of predicting distinctness - blurring for a listening position. The second measure, early-to-late sound, represents a measure more closely related to the human hearing. This measure says that the direct sound, and the reflected sound arriving shortly afterwards (within say 50 msec) are advantageous, while late and strong reflections are disturbing (Jordan 1977 and Schroeder 1979). Early side reflections are especially advantageous. To get sufficient direct sound it is advantageous to see the player well, i.e. have ones head well above the listeners in front.

For the player the position in relation to nearby reflecting surfaces are important, especially when playing in groups. Investigations of such relationships imply, that the players should try to sit at a distance of

3 to 6 m away from a strongly reflecting stage wall (reflections within 17 to 35 msec being useful, Marshall et al 1978).

Let us end this paper with a demonstration of the importance of different frequency regions, sound example 5. We hear a part of Lagrima by Tarrega, according to Fig. 12. First we hear the full frequency range - the first two bars; then the low frequency range below 4 kHz - the following two bars; the full frequency range in the following bar; the high frequency range above 4 kHz - one and a half bars; and finally the full frequency range - the last one and a half bar. The corresponding

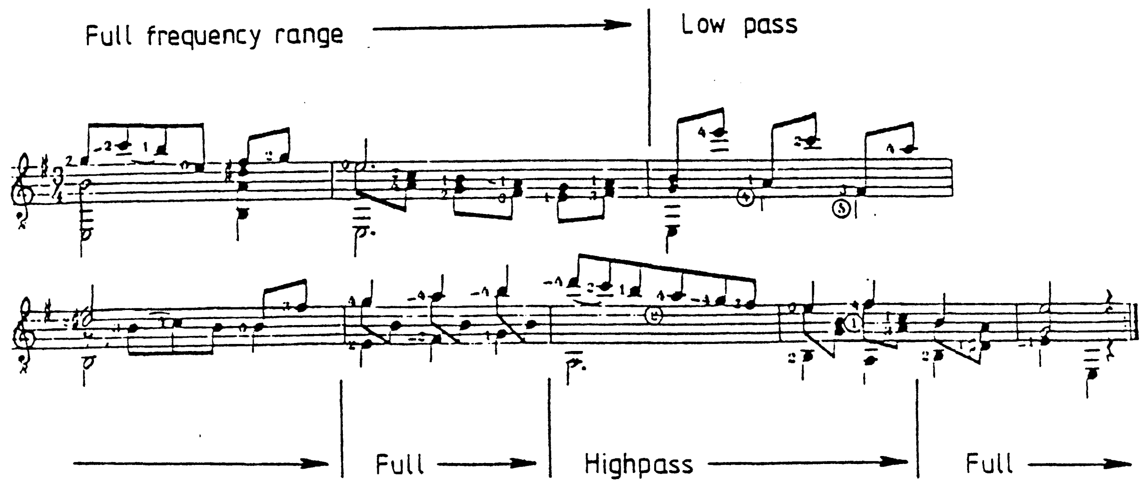


Fig. 12. Demonstration of the importance of different frequency regions by filtering, sound example 5 (Lagrima played by P. Riis): the different parts are replayed with the full frequency range, a low frequency range, and a high frequency range as marked. Frequency limits used 4, 2 and 0.5 kHz respectively, cf Fig. 13.

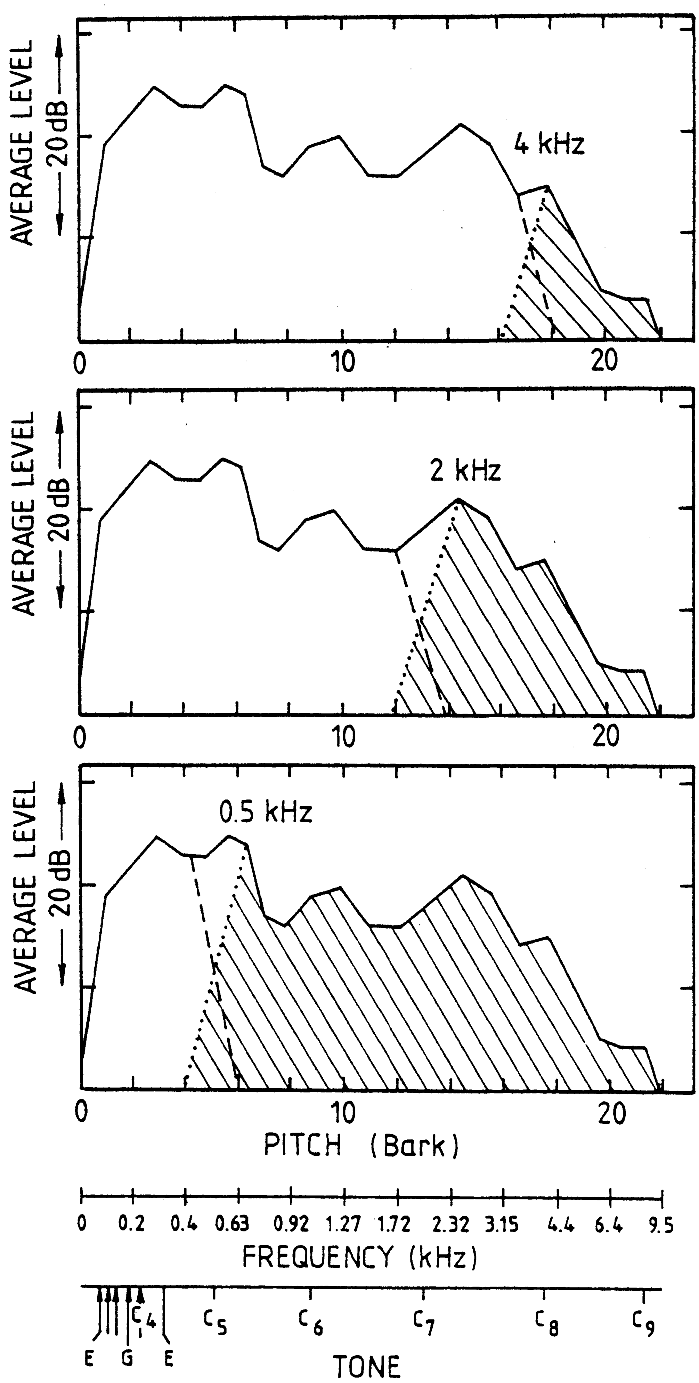


Fig. 13. Resulting spectra from the different frequency ranges, the full frequency range enclosed by the full line, the broken line shows the upper frequency limit of the low frequency range (the non-shaded area), and the dotted line marks the lower frequency limit of the high frequency range (the shadowed area), cf Fig. 12.

frequency regions are marked in Fig. 13. The sound example is repeated with the frequency limits set at 2 and 0.5 kHz. By listening to the music one finds that about 4 kHz one only hears sounds of the attack, the low frequency range below 2 kHz gives a somewhat hollow sound, while the high frequency range gives a tone of guitar character. The low frequency range below 0.5 kHz, including the main resonances, gives a very hollow sound with indistinct tone attacks. The corresponding high frequency range creates the impression of a "very cheap guitar", a guitar with a very thin tone. Analyses of guitars of different qualities indicated that high sound pressure levels including high levels at 500 - 800 Hz and at 1500 - 4000 Hz are favorable.

Conclusion

The tone of the guitar has two components - the partials of the strings and the body sound. The body sound dies out quickly after the attack, but plays an important role in the tone attack.

The player can vary the partial spectrum of the tone in a physically predictable way, by choice of plucking position, way and direction of plucking. Closer to the bridge, playing with nails and a "flexible" string give the strongest high frequency components. Plucking in parallel with the top plate gives a weak but long tone.

Fundamental properties of the guitar tone such as initial levels and initial level falls are set by the properties of the guitar body. A high initial level means a rapid initial level fall, i.e. the initial level is proportional to the initial level fall. The duration of a more rapidly decaying tone may, however, be considerably longer than that of a slowly decaying tone - the higher initial level may "overcompensate" for the more rapid decay.

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ACOUSTICS FOR THE GUITAR MAKER

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Introduction

The guitar is an intricate physical system. In principle it contains an unlimited number of properties which influence the quality of the played tone to varying degrees. Some of these properties are important, others not. Therefore, to give a feeling for the important ones and their role for the played tone, I shall in this my second paper give a description of the fundamental acoustics for the guitar body by answering the following questions:

1) What is a guitar?
2) What properties are built into the guitar?
3) How does the guitar function?

The answers to these questions are sought in the world of acoustics, i.e. the world of physics. Therefore some fundamental physics must be introduced to make the answers meaningful. The third question of this paper and that of my previous paper overlap, which is natural as the interests of maker and player overlap.

What is a guitar?

The main parts of a guitar are the six strings, the body and the neck. The strings are attached to the bridge, which is glued onto the top plate of the body. They are stretched over the top plate and across the nut to the tuning mechanism. The guitar is played by pulling the strings to one side and releasing them, "plucking". After a string is released it starts vibrating. The vibrations are large but because of the small area of the string, the vibrations give almost no sound. As the top plate is not rigid it is set into vibration via the bridge. Thereby a small amount of the vibrational energy of the string - large vibrations of a small area - are transformed into vibrations of the top plate - small vibrations of a large area. The large vibration area of the top plate makes it an efficient sound radiator and the plate radiates the guitar tone that we hear. The body works as an amplifier of the weak string sound. A schematic diagram of this tone production chain is given in Fig. 1.

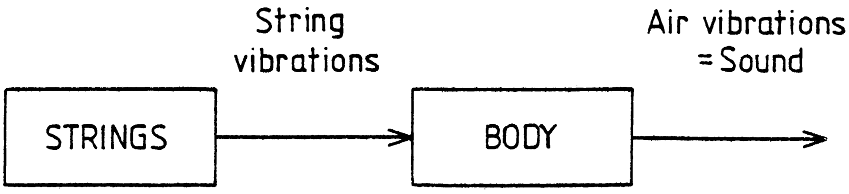

Fig. 1. The tone production chain in its simplest form.

The guitar body, a wooden box, is a rather complex structure. It consists of a top plate (sound board) sides and a back plate, see Fig. 2. The neck with the fret board is attached to the top plate and to the sides. The back plate is stiffened by thick cross struts. In the upper part of the top plate there is a large hole, the sound hole. Above and below the sound hole the top plate is stiffened by thick cross struts which support the neck and the fret board. The cross struts and the fret board make the upper part of the top plate fairly rigid. It is mainly the top plate area below the sound hole that is free to vibrate. We shall therefore call this the "free part" of the top plate.

The "free part" of the top plate has an additional stiffening structure. First the bridge on the outer side, which gives a marked cross-stiffening. Secondly, there is the bracing system of the inner side, see Fig. 3, which should provide the final adjustments of the top plate thus

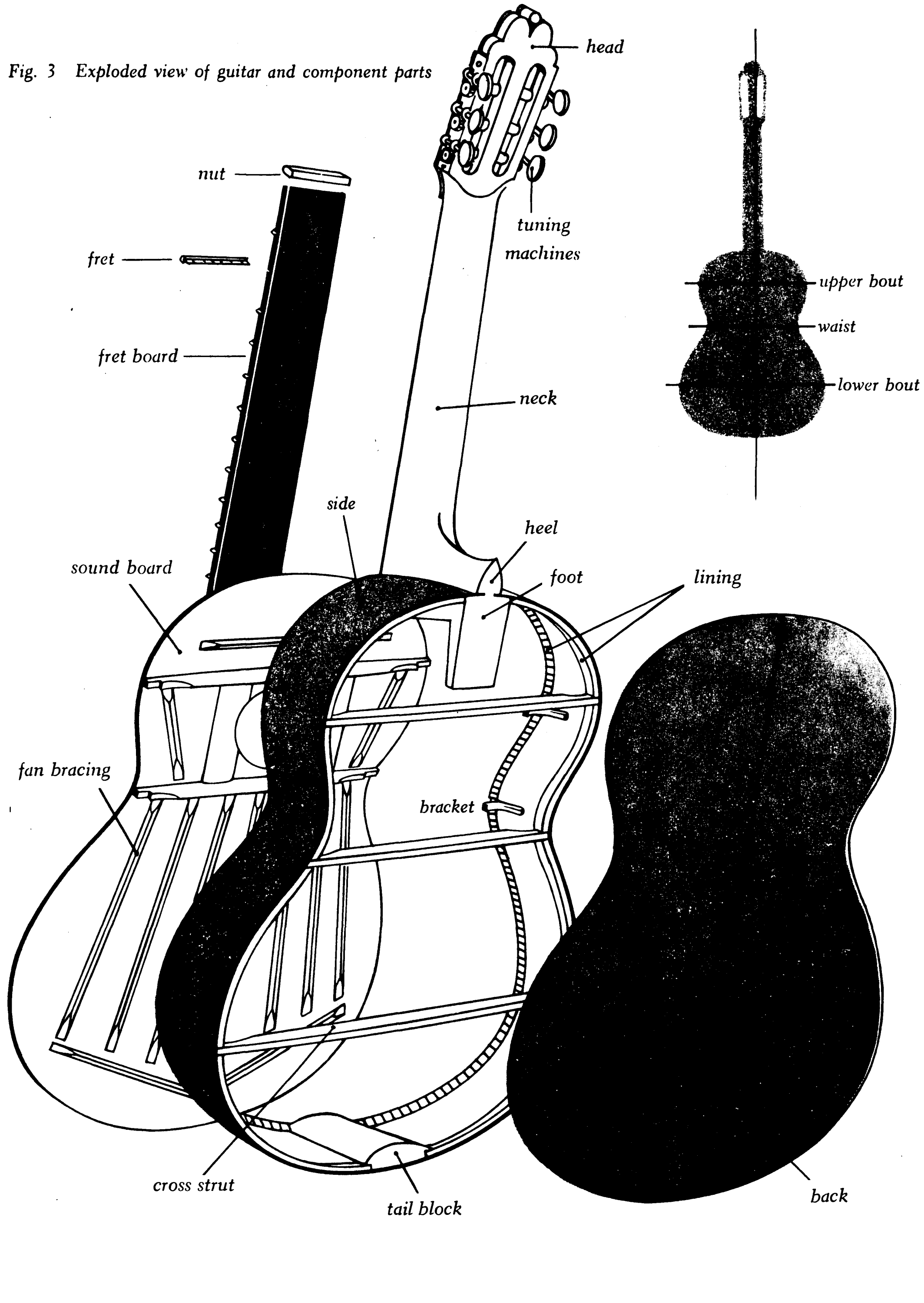

Fig. 2. The basic guitar construction (from Sloane 1976).

producing the desired properties. Traditionally a fan bracing system is used which first was developed by Torres, see Fig. 3a. This system contains a number of thin braces diverging towards the lower part but mainly in parallel with the wood fibres of the top plate. Some makers use an extra cross-stiffening under the bridge, Fig. 3b, some use an extra cross bar below the sound hole, Fig. 3c.

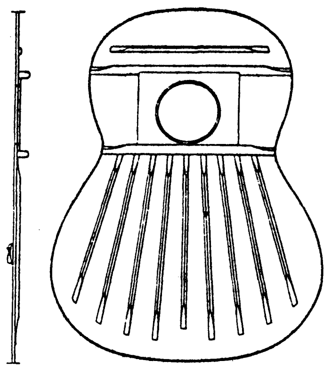

Fig. 4 Traditional fan bracing

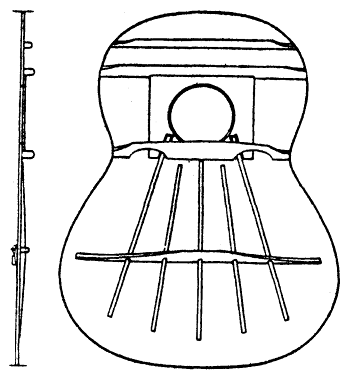

Fig. 5 Bouchet system

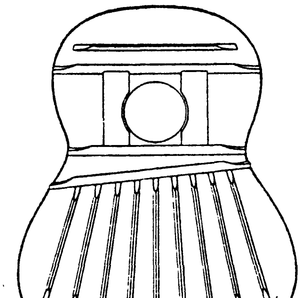

Fig. 6 Transverse bar

Fig. 3. Examples of different top plate constructions as seen from the back side (from Sloane 1976).

Typical geometrical measures of the guitar are given in Fig. 4. The length of the neck (from body to nut) is half of the open string length. The bridge is positioned halfway down the "free part", but still a little above the middle. Guitars may look rather different but the main measures vary little. Note thus that the bridge is approximately in the middle of

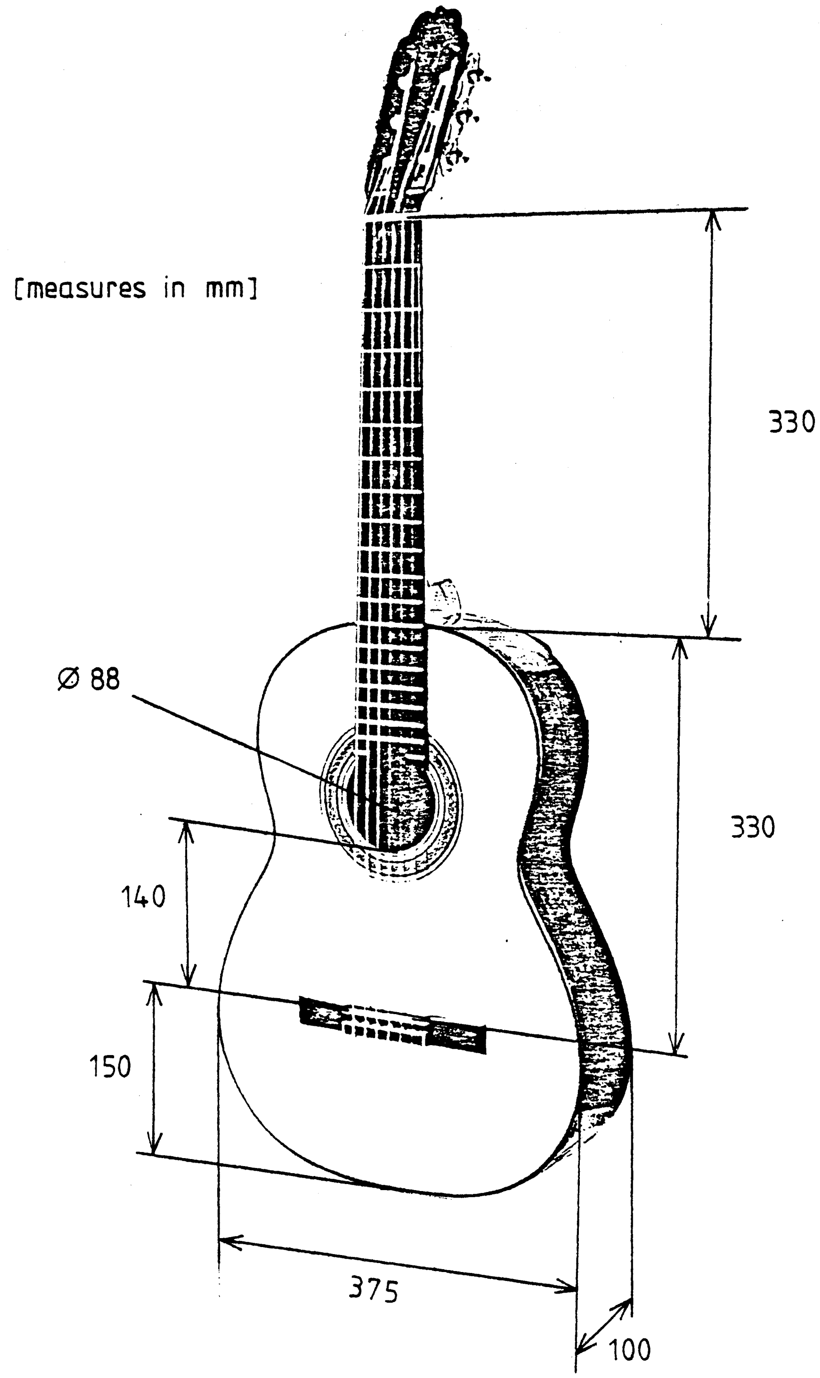

Fig. 4. Typical measures for the classical guitar (photo from Sloane 1976).

the free part and that the width of the free part is approximately the same as its length. The thin bracing on the inside can vary quite a lot - positions, number, dimensions and shape of the braces. A very interesting question is: How important are these variations for the tone? This question is discussed in detail in the following second paper by prof. Meyer.

What properties are built into the guitar?

The gross acoustical features of the guitar are the following. They mainly describe the low frequency properties.

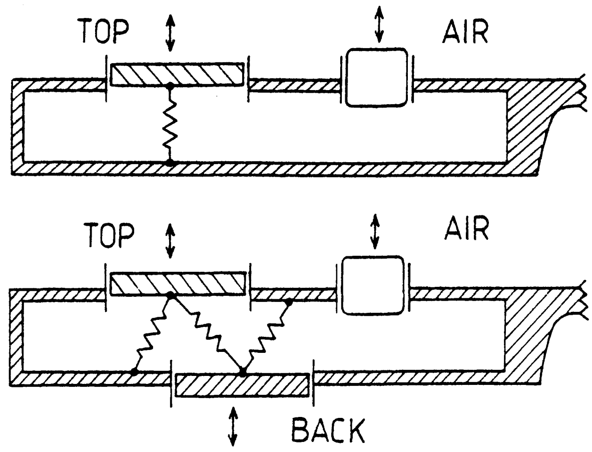

Fig. 5. Cooperation between different resonances a) the first top plate resonance and the air volume resonance (after Christensen and Vistisen 1980), and b) as in case a) but with a back plate resonance added.

The guitar body is acoustically an air volume enclosed by vibrating walls. The free part of the top plate is the easiest part to set into vibration. The air volume can breathe through the sound hole. This acoustical construction resembles closely an advanced loudspeaker construction, i.e., the bass reflex box. The principal function of the guitar bass-reflex-box is sketched in Fig. 5a. The free part of the top plate, a piston, is working against a spring, the suspension of the top plate and the compression of the air volume. A plug of air in the sound hole works as a second piston, which can also compress the air in the cavity. The two pistons are coupled via the air vibrations of the cavity, i.e., the compressions and rarefactions of the enclosed air volume. The relation between the two resonances, the top plate resonance and the air volume resonance, and the properties of the total system are well known. They have proved to describe the guitar properties accurately (Christensen and Vistisen 1980).

In addition the guitar has a back plate, thus producing a piston-spring system as sketched in Fig. 5b. This means that the guitar is a considerably more complex system than sketched in Fig. 5a. Recent work has proved that the back plate can influence guitar properties (Caldersmith 1981).

The model of the guitar, which has been presented above, predicts the low frequency properties. The air volume together with the sound hole gives a resonance at approx 100 Hz and the top plate a resonance at approx 200 Hz. The two resonances cooperate. A removal of the back plate thus removing the air volume resonance lowers the top plate resonance approx 50 Hz. This is also predicted by the model.

The air volume resonance fills out the bass range of the guitar and the top plate resonance the next higher frequency range. The air volume resonance is most easily changed in frequency. A larger air volume, a smaller sound hole, or a sound hole with a "chimney" lowers the frequency, while a smaller air volume or a larger sound hole increases the frequency. The top plate resonance is moved to higher frequencies by stiffening the top plate and lowered by adding a weight (a mass) on the bridge. However, the cooperation between the two resonances means, that when the frequency of one resonance is shifted, then the other resonance is perturbed in the same direction. Thus the maker must include this dependence between the resonances in his adjustments of properties.

The guitar has not only the two (three) discussed resonances. It contains a large number of resonances, which will be discussed in the following.

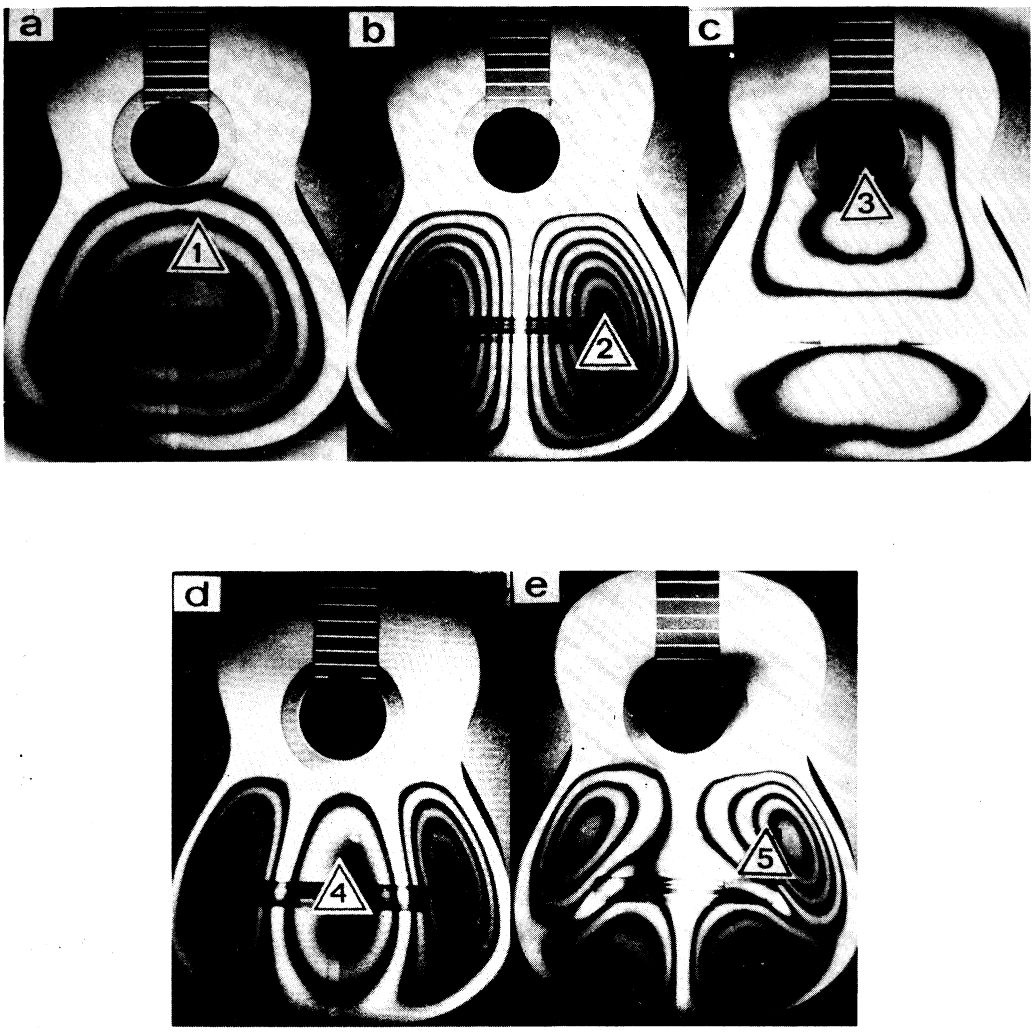

Fig. 6. Time-average interferograms (made by N.-E. Molin and K. Stetson) of a guitar top plate (G. Bolin, Stockholm) at resonance. The black lines mark positions of equal amplitude and the triangles mark the driving points, at a) 185 Hz, b) 287 Hz, c) 460 Hz, d) 508 Hz and e) 645 Hz (Jansson 1971).

In my first paper I introduced the fundamental and the higher partials of a vibrating string. The guitar top plate also has a fundamental tone and higher partials, i.e. the plate has not one but several resonances. By means of an optical technique, hologram interferometry, small vibrations can be made visible and be photographed, see Fig. 6. In Fig. 6 the first five resonances of a guitar top plate have been photographed. These resonances are mainly in the free part of the top plate. The pictures are read as a typographical map, not showing altitude of a landscape but vibration amplitude. The first resonance, Fig. 6a consists of one vibratory hill, the second, Fig. 6b, two vibratory hills with a line of no motion in between, a so called nodal line (In prof. Meyer's investigations the second resonance showed to be of less importance and was thus excluded in his numbering of resonances). In Fig. 6c we have again two vibratory hills but now a nodal line along the bridge. In the following two pictures, we have two still more complicated vibration patterns. The different resonances are important to the acoustical properties of the guitar body in the same way as the different partials of the string tone. Note that the vibrations are mainly in the free part and tend to be small in the bridge region except for the first resonance.

The air volume in itself contains resonances, see Fig. 7. These resonances do not "breathe" through the sound hole, i.e. they do not radiate sound. They can, however, be important in cooperation with higher top plate resonances. The first air resonance at 370 Hz cooperates, for instance, with the third top plate resonance. Thus to be able to make the optimal guitar construction the maker has to control at least some of the air resonances.

Thus we are now in a position to specify the acoustical properties of the guitar body:

Given the resonances of a guitar we have a complete description of its acoustical properties. The description may be simplified by using the fact that the strong resonances dominate the properties. Thus we can say that the main vibrations of a guitar are in the top plate below the sound hole. The upper part of the top plate, the back plate and the sides give weaker resonances and are less important. The vibrations of the lower part of the top plate typically contains five resonances at approximately 200, 300, 400, 500 and 600 Hz. These resonances form one set of partials of the guitar body. In addition there is the air volume resonance at approximately 100 Hz, in which the airvolume radiates through the sound hole. Note that the resonances form at least approximately a harmonic series with the air resonance as the fundamental.

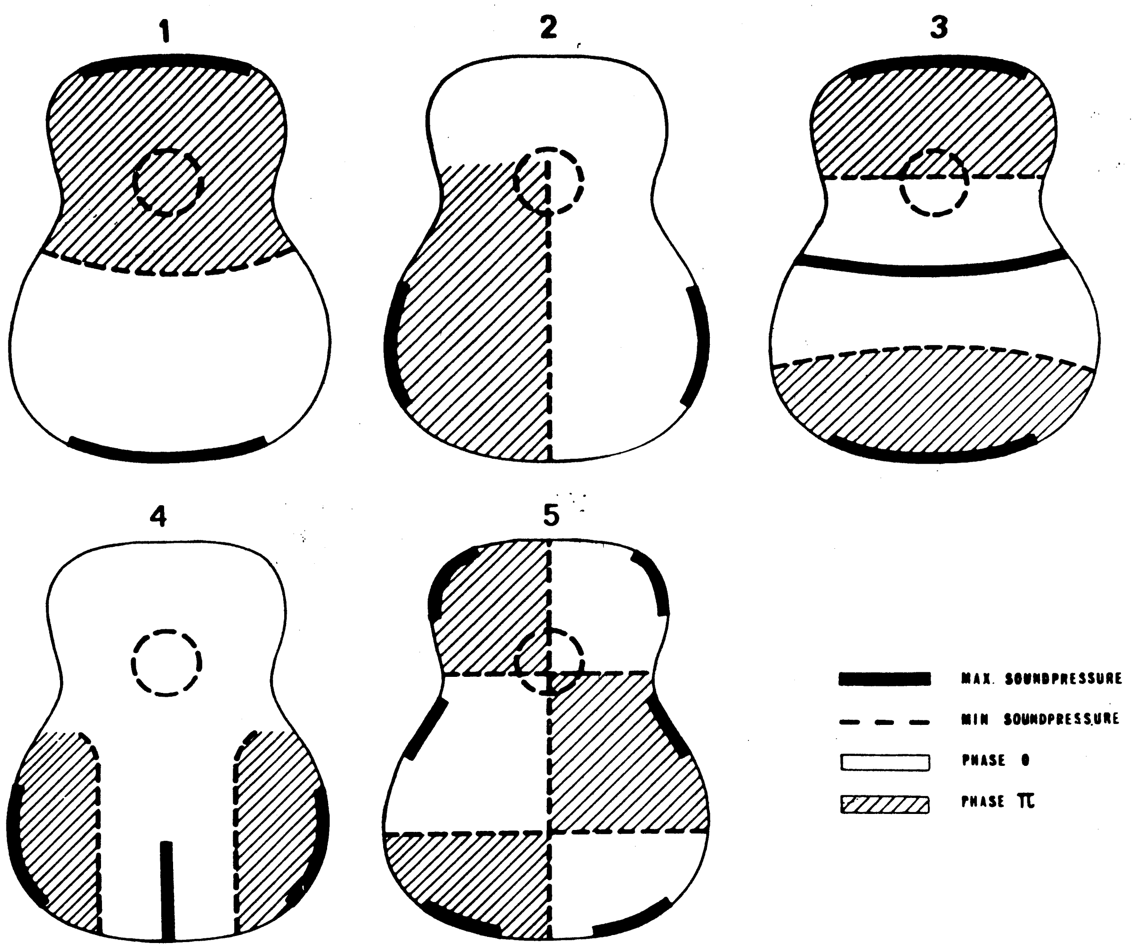

Fig. 7. Vibration patterns of the five lowest resonances of a guitar-shaped cavity at 1) 370 Hz, 2) 540 Hz, 3) 760 Hz, 4) 980 Hz and 5) 1000 Hz (Jansson 1977).

At the frequency of a resonance there is amplification depending on the quality factor, the Q-factor of that resonance. The Q-factor is typically of magnitude 40 for the first resonance and increases to 80 for the fourth.

The vibration patterns at a resonance give two more pieces of information. If the vibration amplitude around the bridge is large at a specific resonance, then this resonance is efficiently driven. The sound radiation can also be calculated from the vibration patterns.

For high frequencies, the single resonances starts to overlap, i.e. the frequency separation between the resonances is smaller than their bandwidths (resonance frequency divided by the Q-factor). In this case one finds, by comparisons with formulas developed for room acoustics, that the amplification properties are determined by the frequency density of resonances (Kuttruff 1979).

How does the guitar function?

A. Cooperation between strings and resonances.

Let us study how the strings and the guitar body cooperate. When a string is plucked it starts to vibrate and thus sets the top plate into vibration. But the vibrations of the top plate and of the the bridge gives a reaction on the string vibrations. The string action on the body and the body reaction on the strings are fundamental for the tone produc-

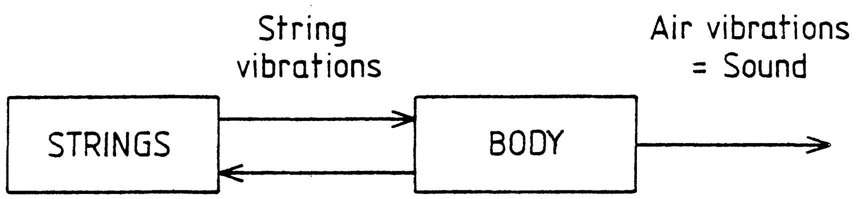

Fig. 8. The tone production chain in a more complete form.

tion, cf Fig. 8. The "main road" for the vibrations are from left to right, cf Fig. 1. However, without including the reaction, i.e., the arrow pointing from right to the left, basic properies of the guitar can not be explained. To much reaction can give a so called wolftone - to little indicates that that the top plate is too stiff. The "electric guitar" can not be "transformed" to give a sound like an acoustical guitar, because there is almost no interreaction between the body and the strings.

B. Top Plate Resonances.

Let us take a closer look how the resonances, the action of the strings and the body reaction can explain the function of the guitar. Typical vibration patterns of the five lowest resonances of a guitar are shown in Fig. 6. The patterns are principally the same as those of a vibrating rectangular plate. The vibration patterns can be explained by the vibrating string, see Fig. 9. In its first resonance the string has a vibration maximum in the middle. The rectangular plate also has a maximum in the middle, and so does the guitar top plate c.f. Fig. 6a. In the second resonance, the string has two vibratory maxima separated by a minimum, a so called nodal point. The second plate resonance also has two maxima separated by a minimum, a nodal so called line (cf Fig. 6b for the guitar top plate resonance). The third string resonance has three maxima and two minima as does the plate resonance to the right (corresponds to the fourth resonance of the guitar top Fig. 6d).

The string has only one direction, while the plate extends in two directions. Therefore the plate vibrations can be regarded as being in two perpendicular directions and the string vibrations in one direction only. The string resonance with two maxima and one minimum, can in the plate thus be found in two directions, the second of which is sketched in Fig. 9d (corresponds to the third top plate mode Fig. 6c, labelled second resonance in prof. Meyer's second paper). The two directions can be combined to give for instance four maxima (two times two) separated by two minima (cf. Fig. 6e). Thus the string partials have a similar but more complex counterpart in the top plate partials.

The frequency of a string partial is determined by 1) the weight (mass per unit length), 2) the tension, and 3) the length of the string. The same applies to the plate after exchanging stiffnes for tension. Thus the weight (the mass) of the plate, its stiffness, its width and length determine the resonance frequencies of a guitar plate. The plate resonances are, however, considerably more complex. In the string we have only one direction. In the plate there is always a combination of two directions. Furthermore the properties of the two directions are not the same, the wood is much stiffer to bend across than along its grains. In addition the width and the length vary continously. Finally the bridge and the bracing makes the effective stiffness vary from point to point. In my

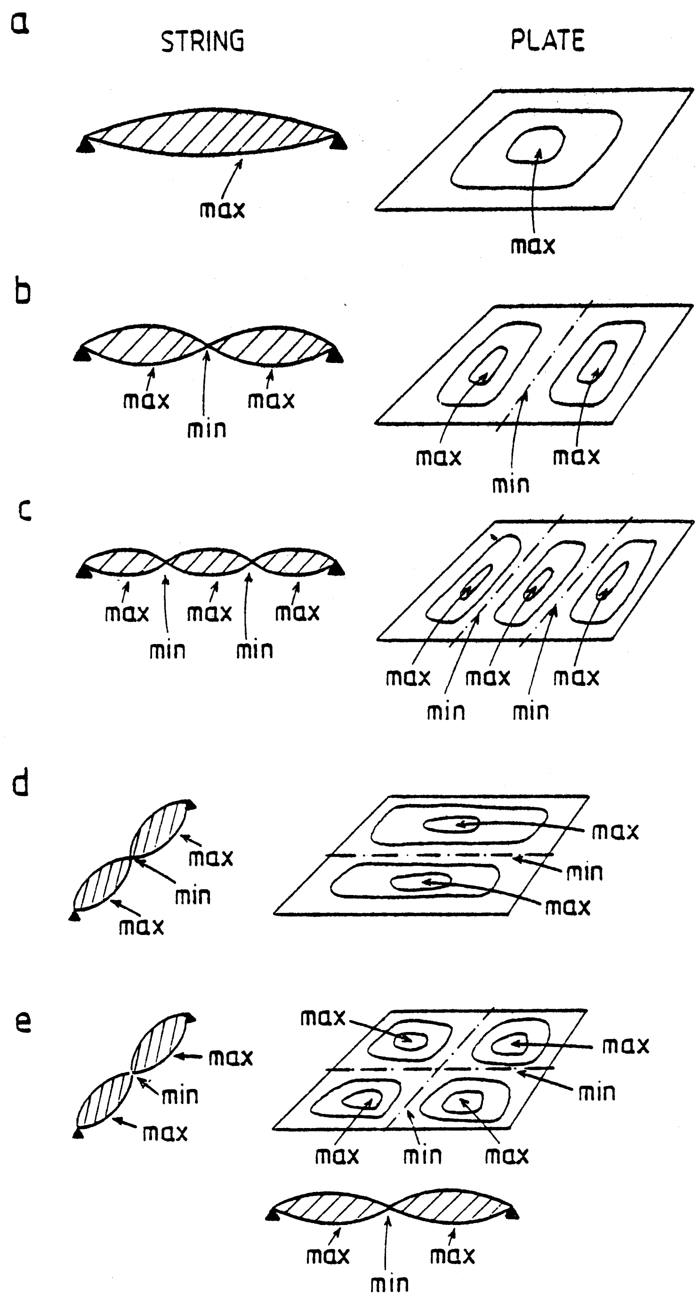

Fig. 9. A comparison of string resonances and resonances of a rectangular plate: a) the first plate resonance, b) the second plate resonance, c) the third plate resonance, d) the fourth plate resonance, and e) the fifth plate resonance.

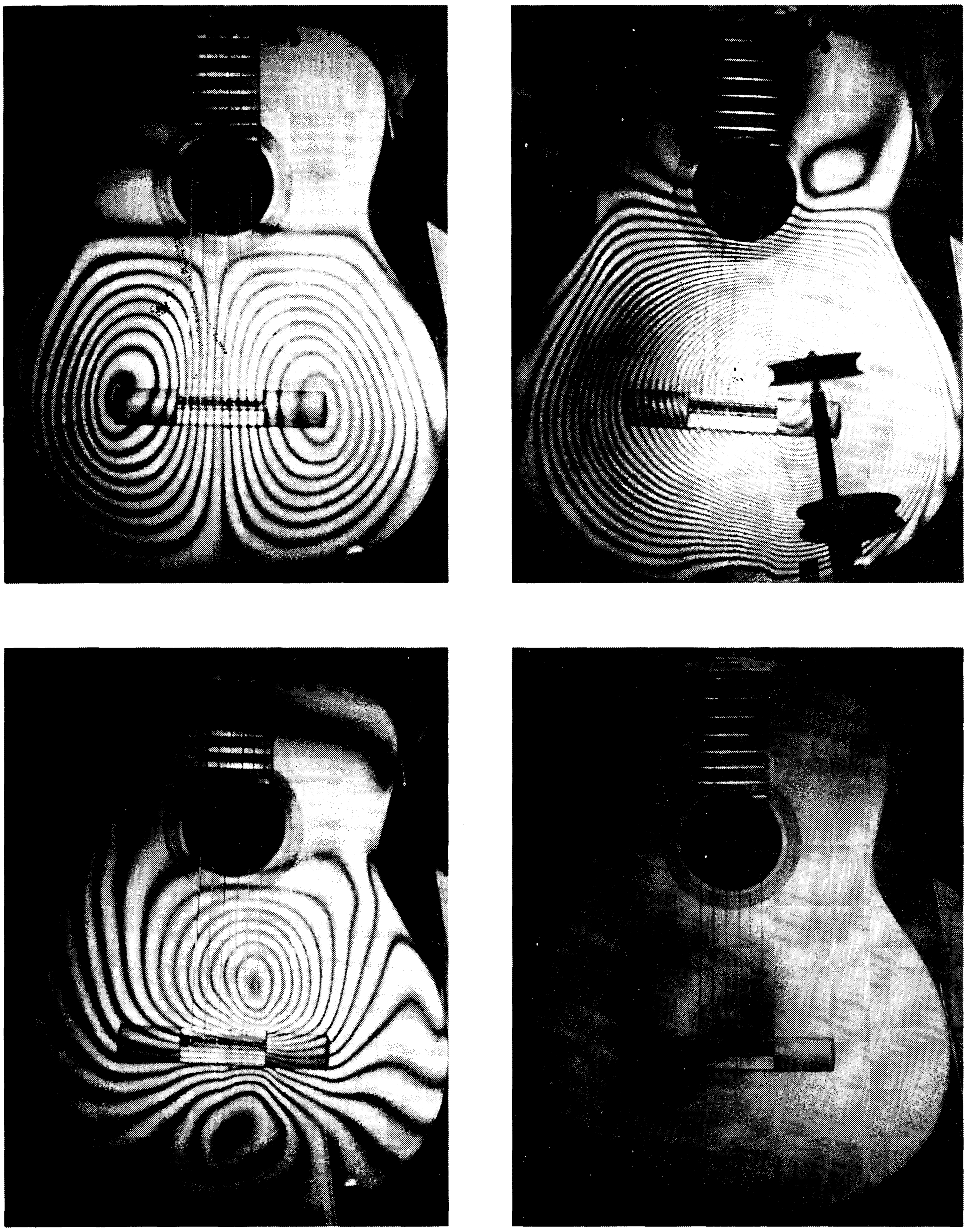

Fig. 10. Examples of initial displacements of a guitar top plate, for a) a force of .98 N applied to the sixth string at the bridge in parallel with the bridge, b) .49 N to the first string perpendicular to the plate, c) 1.96 N applied to the first string in the direction of and to the first string, and d) a torsion moment from a one revolution at the middle of the third open string (Jansson 1973).

experience moderate changes of the bracing system give smaller changes in the vibration pattern than in the resonance frequencies. Fairly substantial changes are necessary to change the vibration patterns.

C. Plate Partials and Plucking Forces

The similarities between string and plate partials can be used to explain fundamentals of the string action on the guitar body. When a string is plucked, it is initially pulled out of equilibrium. The pulling gives rise to three pulling forces, one in parallel with the bridge, one perpendicular to the top plate, and one in parallel with (along with) the string.

The force perpendicular to the top plate pulls out (or pushes in) the middle of the top plate, cf Fig. 10b. In accordance with the string plucking this "plate plucking" gives much of the resonances with large vibrations at the position of the applied string force, i.e. at the bridge. The first top plate mode, Fig. 6a, has maximum vibration in the bridge region. A comparison between Fig. 6a and Fig. 10b shows that the two vibration patterns are very similar, i.e. plucking a string towards or away from the plate gives much of the fundamental plate mode. A more careful analysis shows that the second top plate resonance is also initiated. This is in agreement with the discussion of string plucking, c.f. Fig. 5 of my previous paper. The plucking force from the string is applied at the maximum of the first resonance and somewhat beside the nodal line of the second resonance.

The string force pulling in parallel with the bridge pulls one half of the plate outwards and pushes the other one inwards, see Fig. 10a. This deformation of the top plate is enforced by a rotation along the the nodal line of the second resonance. The height of the bridge acts as a lever. The (increased) pulling force along the string gives the deformation of Fig. 10 c, i.e. only a minor one and mainly the resonance of Fig. 6c.

At the release of the plucking force, the resonances, i.e. the top-plate-partials, are set into vibration as the plate returns to its resting postion. The relation between the plucking force components and the resulting top-plate-partials, we have already estimated from Fig. 10. The force component perpendicular to the top plate produces the dominating deformations. Furthermore we can see that the first top plate resonance, partial, is strongly excited. This means that the "Helmholtz' air mode" also is strongly driven. Higher plate partials are excited too. The duration of the plate partials is short compared to the duration of the string partials. However, they play an important role in the attack portion, i.e. the very initial portion of the tone, as demonstrated in my previous paper, sound example 3.

Summarizing we have shown the following. The plucking of the string gives an initial deformation of the top plate. This deformation corresponds to a combination of the resonances of the top plate. The restoring of the intial deformation gives the weak but important initial body sound of the guitar tone.

D. Top Plate Resonances and String Vibration Forces

The string vibrations succeeding the initial pluck drives the top plate in the same way as the initial plucking force. The string vibrations perpendicular to the top plate drive most efficiently, and as the vibration pattern of the first resonance has its vibration maximum at the bridge, this resonance is most efficiently driven. Thereby the Helmholtz' air resonance is also driven. The vibration patterns of the higher resonances are driven via small vibrations at the bridge or with the height of the bridge acting as a lever. The vibration patterns of Fig. 6 give a measure of the willingness of the plate to take up string vibrations.

The willingness of the body to take up the vibrations can be measured in another way. A vibrator is attached to the bridge and the resulting vibrations of the bridge are measured. Thereby the willingness to take up vibrations can be measured for all frequencies. The result of such measurements are shown in Fig. 11, where the level of "vibration willingness" is read along the vertical axis.

The driving efficiency for each resonance, as discussed in connection with Fig. 10, does not vary with frequency, which may seem contradictory

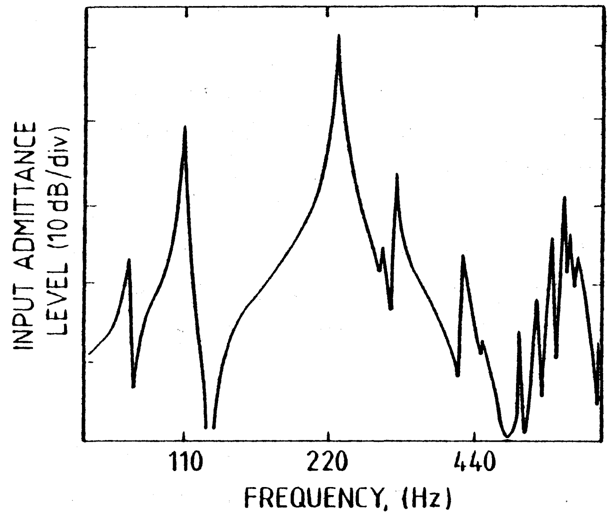

Fig. 11. Frequency response in form of input admittance of the high quality guitar (vibration willingness, i.e the velocity of the bridge between the 5th and 6th strings perpendicular to the top plate resulting from a driving force of constant magnitude in the same position and direction).

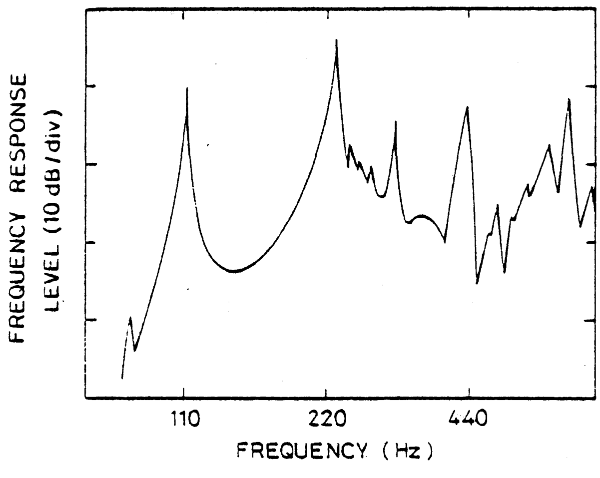

Fig. 12. Frequency response (sound pressure from one a location in an anechoic chamber resulting from a driving force of constant magnitude) of a high quality guitar (Caldersmith and Jansson 1980).

to the widely varying level measured in Fig. 11. However, the vibrations of each resonance vary with frequency even if the size of the driving force is kept constant. Thus the willingness to take up string vibrations change with frequency and results in the jagged curve of Fig. 11.

The peaks in Fig. 11 correspond to resonance frequencies, i.e., the frequency of maximum vibration of that resonance. The lowest peak corresponds to a bending motion of the complete guitar and the 110 Hz peak is the resonance frequency of the Helmholtz' air mode. The peaks at approx. 220, 300 and 440 Hz correspond to the resonances of Fig. 6a, b and c. The maxima, the peak levels of vibration are determined by the internal friction, low friction gives narrow and high peaks, high friction produces low and wide peaks.

Thus we have introduced the two measures, the efficiency of driving as function of position, and the resonance amplification of this driving as function of frequency. Both of these measures are included in the peak levels of Fig. 11. A complete specification of a guitar top plate can be made by Fig. 6, the vibration patterns of each resonance, and Fig. 11, the resonance frequencies and resonance peak widths and levels.

For high frequencies above 2 kHz, the resonances are as mentioned previously so close in frequency that it is no longer the single resonances but the density of the resonances and their internal friction, that determines the properties of the body.

E. Resonances and Radiated Sound

In principle the properties of the guitar can also be measured in another way. Instead of measuring the vibration willingness at the driving point, the radiated sound can be measured by a microphone set at a distance away from the guitar. Results of such measurements for the same guitar is shown in Fig. 12. The data were obtained in an anechoic chamber to avoid the room influence. A comparison between Fig. 11 and Fig. 12 shows that the frequency of the lowest five peaks are the same and that at least similarities can be traced for higher frequencies. Thus the resonances give similar "resonance amplification" in both the "vibration willingness" the the "radiated sound" properties.

Qualitatively we can now state that the guitar body gives much amplification, at some frequencies but little in between. This means that two adjacent tones, for instance tones A and B, would not only have different frequencies (pitches), their spectral properties are also different. The frequencies with much amplification are given by the resonances of the guitar body.

The similar results of Figs 11 and 12 means that the two ways of measuring can be used interchangeably. The first method is, however, by far the most easy to apply and gives meaningful and interpretable results. A method to measure the radiation properties in a way more relevant for the room is presented in the first paper by prof. Meyer.

F. Tonal Properties and the Guitar Body Reactions

As previously stated the guitar tone is composed of string partials. These partials start out strong and decrease at different rates. In presented experiments the relations between tonal properties and body properties were sought (Caldersmith and Jansson 1980). The experiments proved that the influence of the guitar body is by far larger than that of the strings. Furthermore even with "constant" plucking the tonal variations are considerable. It was proved that the reaction of the guitar body on the strings are important.

The frequency response, Fig. 12, was measured with the microphone in approximately same position in relation to the guitar as was used for the tone recordings in our experiments (the driving force was applied perpendicular to the top plate, thus representing the most efficient component of the driving force). Thus we can compare tonal properties with the frequency response. The frequency response, of Fig. 12, with the variations in <u>initial levels</u> of partials added, Fig. 9 of my previous paper are presented in Fig. 13. This shows that the the initial levels follow the frequency response curve except for an over-estimation of the peaks.

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QUALITY ASPECTS OF THE GUITAR TONE

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Introduction

There is always a certain amount of subjective evaluation inherent in the discussions on the quality of musical instruments. To develop objective, measurable criteria for the quality of musical instruments, an attempt must be made to record statistically the subjective judgements of a large number of listeners. Listening tests, with a program doing justice to the different tonal ranges of the guitar as well as making allowance for the fatigue of the listener, are best suited for this purpose.

It is very difficult to convey the same acoustic signal of a solo guitar performance to a large number of listeners in one room. It is also difficult to present several instruments in rapid succession without introducing extra uncertainties such as differences in playing and visual identifications of instruments. Therefore, the use of an electroacoustic transmission system is unquestionably preferable to a live performance. Using a tape recording has the particular advantage that each piece of music needs to be played only once on each instrument, and afterwards, as many copies as are required can be made for purposes of comparison. The player can adjust himself to the instrument before every recording and does not have to change instruments constantly as in a live performance. In addition tape recordings also offer the advantage that exactly the same sound examples can be played repeatedly to several groups of listeners.

Recording method

Among all the recording methods used nowadays, that of head-related stereophonics appears to be best suited to listening tests of this kind. It was originally developed for room-acoustic listening tests, and has proved to be of value for these requirements (1). At present it offers the best possible representation of a natural acoustic perspective. It conveys the impression of spatial development of sound to the listeners, even at a small distance from the sound source.

For reproduction of the guitar sound as objectively as possible, the "artificial head technique" offers a particular advantage. Neither the recording nor the reproduction involves any retouching as a result of the acoustic properties of the room. Thus the spectral characteristics of the sound are replayed unchanged.

Tape recordings made with an dummy head usually have to be played through headphones so that each ear receives only the signal from the corresponding "ear-microphone". Reproduction through headphones has still another advantage in listening tests. Identical signals are presented to all test subjects.

For the guitar recordings, the dummy head was set up in a medium-sized studio at a distance of 2 m from the instrument, its height corresponding to that of a seated listener. Orientation problems arise in recordings with the dummy head if the sound source is directly in the line of vision. Therefore, the head was adjusted so that the guitar was positioned about 30^{o} away from the line of vision. All recordings were made at the same amplification setting. In the reproduction, great care was taken to reproduce the original volume, so that any differences in volume among the individual instruments remained unchanged.

Music for listening tests

For the tonal comparison of the guitars, excerpts were selected from six compositions which clearly differed with regard to tonal range, tempo, and composition technique. The duration of the excerpts was limited to 20-25 seconds each. Experience has shown that this amount of time is sufficient to impress a definite sound pattern upon the memory, but it is not so long that the first item in the comparison of pairs, is forgotten (2).

The six test pieces are shown in Fig. 1. The first piece is a sarabande in a slow tempo; the melodic line is in the upper part, it is accompanied in chords. The overall impression of this piece is chordal. In contrast with this, the character of the second piece is marked by a rapid series of semiquavers with the center of tones at A_3 (220 Hz). The melody lies below the accompanying figures. At the end, there is a danger that the two lower open strings dominate over the high ones too much. In the third piece, with its gentle series of quavers, the tonal range is particularly wide and the highest notes of the melodic line reach a very high pitch. The melody is more strongly pronounced than in the first example and is in some parts accompanied by parallel thirds. This makes great demands upon the tuning of the instrument and, in particular, upon the exact position of the frets.

The test pieces 4 to 6 include monophonic passages. Piece No. 4 moves in the low and middle register with a tonal range of barely two octaves and requires a good timbre balance between these two ranges. Despite the andante tempo, the descent in the 5th and 6th measure requires the notes to be clearly separated.

The fifth piece presents the opportunity to compare similar figures on various strings; it requires, above all, a balanced sound effect in the middle register, since the few deep notes have scarcely any effect on the overall impression. Here, too, the fairly fast tempo demands a clear separation of the notes within the legato figures. The 6th piece consists of calm quaver figures to be played exclusively on the highest string. The carrying of the notes in the upper register is decisive for the impression of this piece.

Test procedure

The test tapes assembled for the performance can be grouped into two parts, the first of which contains polyphonic pieces, and the second

Fig. 1. Polyphonic and monophonic test pieces.

containing monophonic pieces. Each part lasts about twenty minutes, so as not to put too great a strain on the listener's concentration. For the listening comparison, the examples are combined in pairs and separated by a pause of about one second. A pair of such examples for comparison consists basically of two recordings of the same piece played on different instruments. Each pair is separated by an interval of about five seconds. Two or three pairs of one and the same piece are played one after the other, followed by a group of recordings of another piece. When the test tapes are arranged in such a way, the listener is less fatigued than if all possible pairs of a piece of music are played one after the other. In putting the test tapes together, it was avoided playing the same recording (i.e., the same piece and the same instrument) twice in succession.

It is known from room-acoustic listening tests that the additional information gained from particular questions is relatively insignificant compared with that from a simple decision of preference (3, 4). Questions about individual attributes were likewise dispensed with in the judgments of sound quality. Therefore, test subjects were only required to answer the question: "Of the examples of pairs of instruments demonstrated, which instrument do you prefer with regard to tone?"

More than 40 persons took part as subjects in the listening tests. The test material consisted of 15 guitars of various makers and qualities. They are referred to by the letters A to P in the following. The results of the listening tests were evaluated statistically and, to begin with, were calculated separately for each test piece. There were considerable differences in the appraising of one guitar playing different pieces. This will be discussed later. Naturally, the question now arises as to which instrument, all in all, could be called the best. To answer this, we can first take the arithmetical mean of the results for each of the three monophonic pieces and the three polyphonic pieces. The result does not, of course, tell us whether a guitar rates fairly evenly in the individual pieces, or if the mean value in question arises as a result, for example, of the very unfavorable evaluation of one piece being balanced by a considerably higher rating of the other two pieces.

Listening results

A. Polyphonic-monophonic music

Mean values for the evaluation of the polyphonic and monophonic pieces as well as the mean value for all six pieces are shown in Fig. 2. In the three diagrams the guitar judged to be the best is equated with 1. To clarify the differences in rank order of the individual guitars between the three diagrams, the position of each instrument is indicated by arrows. Comparing first the two upper diagrams, it is noticeable that three groups of instruments are formed, each consisting of five guitars. In both diagrams, these groupings in each case occupy the upper, middle, and lower third of the diagrams. For the individual pieces, the rank order for a given guitar differs more than ten positions in some cases. Between the groups of test pieces the rank order differs four points at the most. Interestingly enough, only one instrument (D) occupies the same position for the monophonic pieces as for the polyphonic pieces. In the monophonic pieces, nine guitars are more favorably evaluated (by only one position in the majority of cases), whereas five instruments are less favorably evaluated usually by two or more positions. This difference indicates that the individual registers are indeed sonorous in the first group, but that the balance is not so good, whereas the preference given to the second group is due to the overall sound.

The lower diagram in Fig. 2 shows the final order of preference for all the test pieces. Here, too, classification into an upper, middle, and lower group, each containing five guitars, can be recognized. Remarkably, in seven cases, the positions in the order of preference agree with those of the monophonic pices, and only in two cases does the difference amount to two positions. A direct comparison of the diagrams for the polyphonic pieces together with the overall assessment would, on the other hand, show agreement in the position of only three guitars and differences of up to four positions. From this it follows that the evaluation of monophonic pieces is closer to the overall evaluation and that the tone quality in the individual registers evidently is more highly evaluated than the balance between high-pitched notes and bass notes.

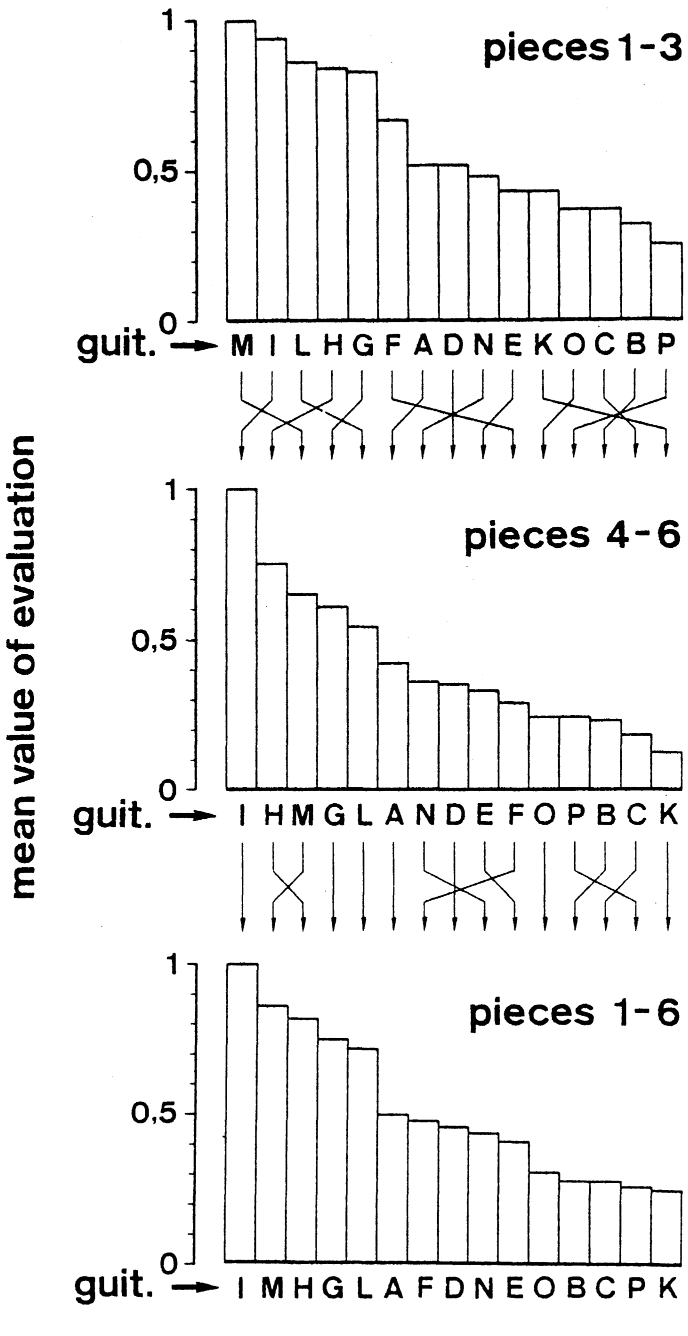

Fig. 2. Averaged evaluation of 15 guitars.

B. Single music pieces

To demonstrate in detail how the overall evaluation is formed from the results for the particular pieces, the evaluation for the individual guitars is shown in Fig. 3. The order of preference of the instruments is according to the overall evaluation. Fig. 3 makes it clear that the order of preference within the leading group apparently is determined by

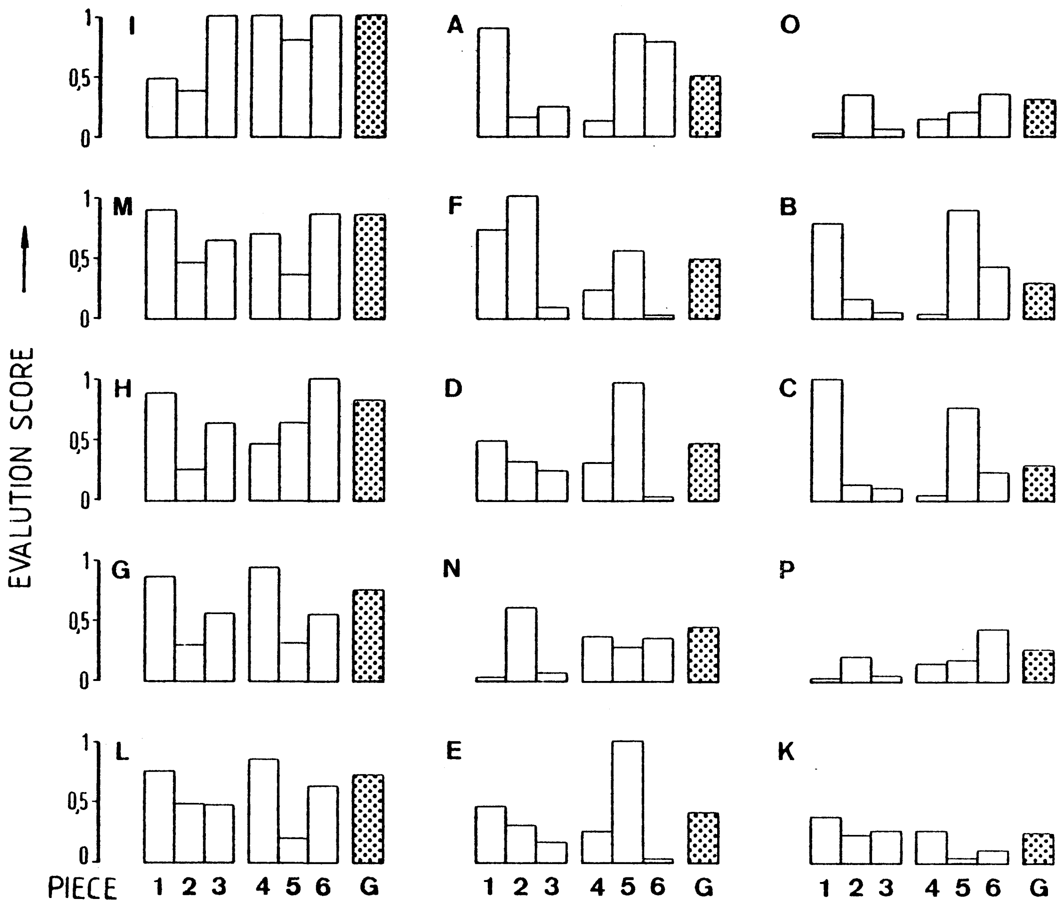

Fig. 3. Evaluation of 15 guitars.

the piece for which the instrument is least suitable. It follows from this, that those instruments for which the variation between different pieces is slight, are the ones judged most favorably. For this reason, these superior guitars should be advantageous in a very comprehensive repertoire.

Yet another conclusion can be drawn from Fig. 3; the evaluation of an instrument varies from piece to piece. Thus, for some guitars, the middle piece of the first three was judged least favorable each time. This is particularly apparent for the five best instruments. The character of the particular pieces, points to that the superiority of these guitars is to be found in the lower and upper pitch ranges, but, that on the other hand, they have certain disadvantages in a rapid succession of notes.

In contrast, there are a number of instruments which were particularly favorably judged in piece number five. Guitar F is conspicuous among these in that piece number two also received excellent evaluation. The other pieces came far behind in comparison. This fact points to a particular sound quality in the middle register and in fast passages; the balance with regard to the low register is good, while there are obvious short-comings in the upper register.

An even stronger preference for piece number 5 with guitars B, C, D, and E is associated with a preference for the polyphonic pieces. The preference is stronger the more sound components in the bass notes. All four instruments are weak in the highest register. The middle register is good, but in the solo playing, the sound in the low register is negatively judged. In the ensemble playing, it suits the overall character more (B, C) or less (D, E), as far as chordal accompaniment is concerned (piece 1); in the low register of the melody of piece number 2, however, it is not satisfactory.

If the individual instruments are summed up according to the characteristics described, a remarkable discovery is made. The groups of guitars correspond at the same time to a classification according to the maker. It can be inferred that a certain quality of tone in various gradations is realizable. Therefore, the possibility exists of basing the total production of a company upon a uniform concept of sound.

Acoustical test method

The next task facing us is to relate the order of preference of the guitars to their resonance characteristics. This must be done in order to clarify which characteristics are decisive for good instruments and which for bad ones. The frequency curves of the guitar form a basis for an objective description of its resonance characteristics. The method, used to measure these curves, to a large extent is the same as for violins (5).

The strings of the guitar were dampened with small pieces of foam rubber so that their quality does not affect the tests and only the resonance characteristics of the body are determined. The guitar was set into vibration by an electrodynamic vibration system (Philips PR 9271), with its vibrating pin on the bridge from above. The vibration direction was oriented perpendicular to the top since preliminary tests had shown that the results obtained from this technically simple form of excitation scarcely differed from those obtained with an excitation parallel to the top.

Six microphones were placed around the instrument in an anechoic chamber, each of them connected to a measurement amplifier. The rectified microphone signals were connected to a network producing a mean value. Thereby, an extensive equalization of the directivity without any disturbing influence on the phase relationships was achieved for the six microphones.

Acoustical quality criteria

An example of frequency curves for two guitars is shown in Fig. 4. The instrument at the top occupied a leading position in the subjective overall evaluation, whereas the instrument in the lower diagram was judged to be relatively poor. The upper curve is characterized in the lower frequency range by three distinct resonance peaks, each slightly above 100, 200, and 400 Hz. Above 1000 Hz a number of single resonances are recognizable which change into a fairly compact resonance range. In the lower curve, the resonance peaks slightly above 100 and 200 Hz are

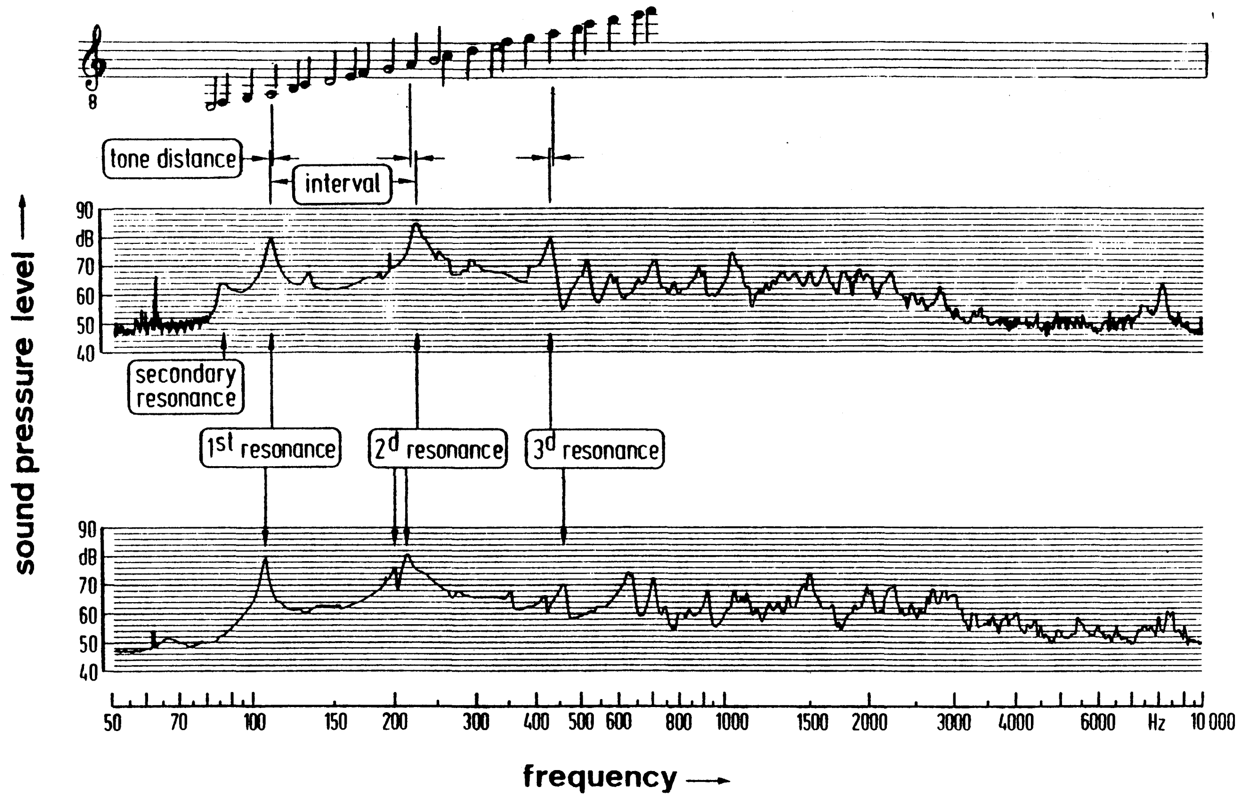

Fig. 4. Response curves of two different guitars.

recognizable too; but for higher frequencies the two curves are quite different.

Characteristics of the frequency curves in the form of numerical values must be determined to enable a correlation between the resonance characteristics and the subjective evaluation. For this purpose, the following characteristics were tested (see Fig. 4):

Frequency, peak level, and the Q-factor of the first three resonances;

the distance between the peak frequencies and the frequency of the nearest note;

the depth of the cleft when the second resonance is split into two peaks;

the presence of a secondary resonance below the 1st resonance;

the interval between the 1st and 2nd resonances (according to the investigations carried out by Letowski and Bartz (6) in 1971, this should be as close to one octave as possible.

Another way of evaluating the frequency curves, which has also proved its value in use with violins, is to subdivide the curve into frequency sections a major third wide and to determine an average value of the amplitude for each section. This results in rectangular curves like the curves traced in Fig. 5, which can easily be combined for wider frequency ranges by averaging. The center frequency of the individual third octaves serves to indicate these ranges. What proved to be interesting here, in particular, were the average values for some of the octave ranges, for the entire range of the fundamental tones, and for the overtones from 80 Hz to 1000 Hz which are decisive for a full sound. Finally, it also proved to be of importance whether the rectangular curve above 1250 Hz assumed a higher value again.

Objective versus subjective

The influence of the various characteristics on the quality of the instrument can be seen when their numerical values from the frequency curve are plotted against the rank order of the preference from the listening tests. Fig. 6 gives three examples. The upper diagram shows that with few exceptions, the higher the average level for the third octaves from 80 to 1000 Hz, the better the evaluation of the instruments. The same applies to the third octave range from 315 to 500 Hz. In the lowest diagram, the best instruments apparently have only a small level difference; a level jump above 1250 Hz is not desirable.

In order to be able to comprise the influence of the large number of criteria, the area of the measuring values was divided into three zones. In these zones the measuring points were coordinated in simplified form; a positive, an average, and a negative evaluation. This point rating, shown at the right edge of Fig. 6, made it possible to sum up all criteria for the overall judgement.

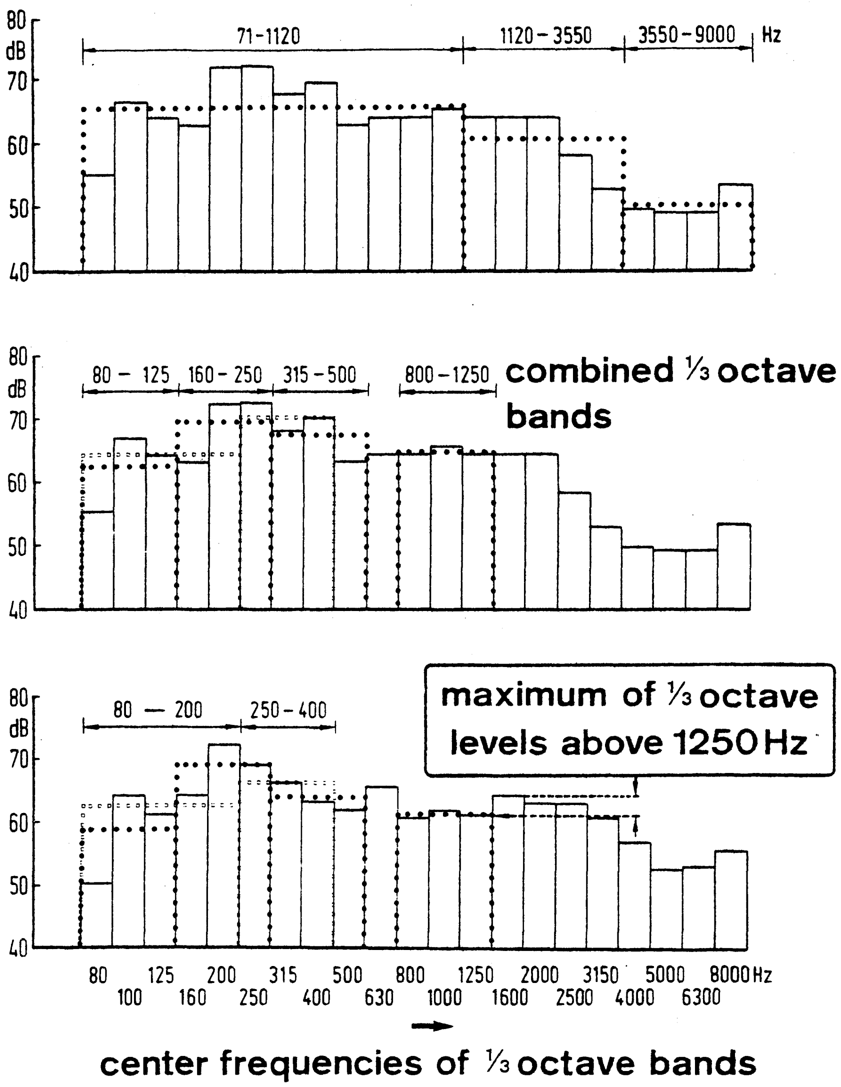

Fig. 5. Averaged response curve of a guitar.

Here, of course, the question of the significance of the specific criteria arises. When a monotone dependence between the rank order and the measured values for a criterion was recognizable, the correlation coefficient was calculated. These coefficients are presented in Table 1 for those criteria which, in the last analysis, turned out to be of importance for the overall evaluation. This table also contains symbols of the specific criteria which are to be used in some of the diagrams. As can be seen, the degree of correlation in the first 13 criteria

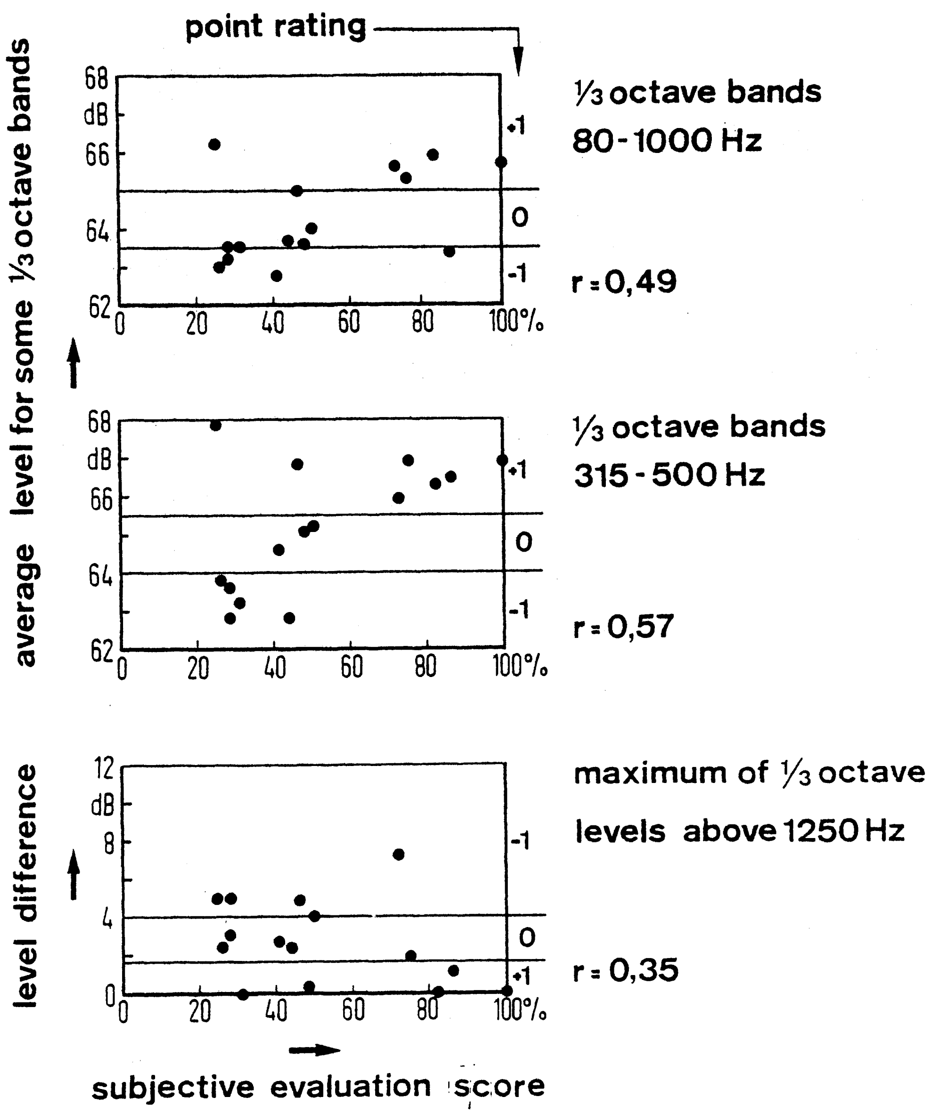

Fig. 6. Correlation between measuring values and subjective evaluations.

steadily decreases. No calculation was possible for the remaining criteria. The relation between the subjective numbers and measured criteria was not monotone. There were values too high <u>and</u> too low that had to be evaluated negatively.

Summing up the rank ordering after the first six criteria results in a very good correlation with the subjective evaluation, as can be seen in

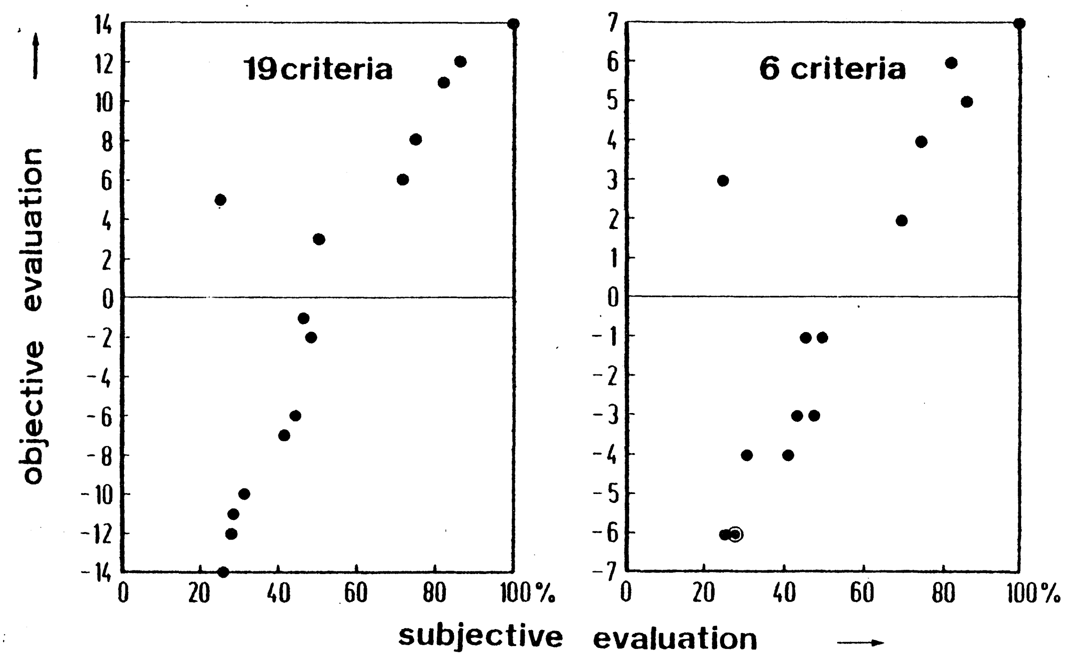

Fig. 7. Correlation between objective and subjective evaluations.

the right-hand diagram in Fig. 7. By adding all the 19 criteria listed in the table, we obtain an even finer quality grading as can be seen in the left-hand diagram of this figure. The degree of correlation between the subjective evaluation (based on six pieces of music) and the objective evaluation carried out on the basis of the frequency curve is 88%. Excluding that instrument which obviously does not fit into the group, the degree of correlation reaches 97%. This exclusion is not completely unjustified, inasmuch as this instrument exhibited fluctuations of frequency which were probably caused by the strings.

Objective criteria and music pieces

It can be concluded from the high values of correlation that the majority of the criteria accountable for the quality is contained in this tabulation. Naturally, it should not be assumed from this that the table contains <u>all</u> factors influencing quality. The basis of this table is the summarized judgement of the instruments on the basis of the six pieces of music. The influence of the individual pieces can, however, be determined by the same method. These results are referred to in the following when the effect of the individual criteria upon the tonal characteristics of the guitars is discussed.

Criteria for very wide frequency ranges

Let us now turn our attention to those criteria which relate to very wide ranges of frequency.

1. The average level of the third octaves from 80 to 1000 Hz: This frequency range provides the overall radiation of the instrument in the region of the fundamental tones, and the overtones decisive for the sonority. The average level should be as high as possible. As in the case of the overall radiation of violins, differences in level of only a few dB play an important part. This criterion is of particular value in pieces requiring a full sound without being fully chordally composed.

2. The average levels of the third octaves from 1250 to 3150 Hz: This frequency range is vital for the brilliance and clarity of the timbre and also for the clear attack of a note. On the basis of the overall judgement the average level should be neither too high nor too low. High levels are an advantage only in strongly chordal pieces and, due to the clearness, in fast, close tonal figures. Generally, they produce an undesirable hardness, which is particularly disturbing in a melodic line in the bass.

3. The difference in level between the average value of the third octaves from 80-1000 Hz and 1250-3150 Hz also reaches an optimum in the average values, according to the argument in 2. This difference is a measure of the balance between sonority and clarity and should not be too great. If it exceeds a value of 6 dB, the sound impression on the whole will be too feeble. Furthermore, the attack of a note

Table 1. The quality criteria of guitars derived from the frequency curves.

No.	Criterion	Symbols	Degree of correlation
1	Peak level of 3rd resonance (at approx. 400 Hz)	L_3	0.73
2	Resonance rise of 3rd resonance	ΔL_3	0.69
3	Quality factor of 3rd resonance	Q_3	0.64
4	Average level of third octaves 80 - 125 Hz	L_{80m125}	0.59
5	Average level of third octaves 250 - 400 Hz	$L_{250m400}$	0.58
6	Average level of third octaves 315 - 500 Hz	$L_{315m500}$	0.57
7	Average level of third octaves 80 - 1000 Hz	$L_{80m1000}$	0.49
8	Peak level of 2nd resonance	L_2	0.46
9	Average level of third octaves 800 - 1250 Hz	$L_{800m1250}$	0.43
10	Quality factor of 1st resonance (at approx. 100 Hz)	Q_1	-0.40
11	Average level of third octaves 160 - 250 Hz	$L_{160m250}$	0.39
12	Maximum of the third octave levels above 1250 Hz	ΔL_{1250}	-0.35
13	Depth of cleft in the 2nd resonance	ΔL_2	-0.21
14	Average level of third octaves 1250 - 3150 Hz	$L_{1250m3150}$	-
15	Difference between average levels of third octaves 80 - 1000 Hz and 1250 - 3150 Hz	ΔL_{1000}	-
16	Average level of third octave 630 Hz	L_{m630}	-
17	Distance of 1st resonance from the closest note	i_1	-
18	Distance of 2nd resonance from the closest note	i_2	-
19	Average level of third	$L_{4000m8000}$	-

is not sufficiently distinct which is all the more noticeable in close tonal figures. Values of the balance which are too low are not felt to be quite so disturbing. The exaggerated clearness is apparently preferable to a very blurred sound.

4. The frequency components from 4000 - 8000 Hz are only excited briefly to vibration in the striking of a note and are radiated from the body comparatively weakly. They add to the incisiveness of the sound production. Large values and a relatively good radiation is in general felt to be an advantage, while too small values are negatively evaluated. This is most apparent in chordal playing. High levels have a more negative influence upon the sound impression only in the case of a melodic line in the bass with overlying accompanying figures. They produce a certain hardness of sound.

Criteria for third octave ranges

Having dealt with these four criteria for the overall radiation of the instrument, we now turn our attention to the energy distribution in narrower frequency ranges.

5. The third octave range from 80-125 Hz comprises the low registers of the tonal range and includes the first main resonance (criterion 4). The upper limit is approximately at C sharp. A glance at Table 1 shows that criterion 4 produces the highest correlation of all the averaged ranges of third octaves, so it is of particular significance. High values in this range were, above all, positively evaluated when a full sound in a slow succession of notes is required. Here it should be mentioned that melodies in upper registers also profit from these low frequency components, as the low resonances are also added in the starting transient. This effect is negative, however, when very fast, close successions of notes are played, because the sound then becomes muffled.

6. The frequency range of the following third octaves from 160-250 Hz comprises the tone region from D3 to C sharp 4, so it also encompasses the second main resonance in this range. The differences in level between the various guitars are smaller than in the third octaves from 80-125 Hz. High values are held to be favorable, and this applies in particular (in contrast to the thirds from 80-125 Hz) to chordal sounds in the middle register, but is noticeable in all other pieces with the exception of the fast, close tonal figures.

7. The third octaves from 250 to 400 Hz comprise the tone region from B3 to A4, thus partly overlapping the region mentioned in 6 and 8.

With regard to the overall judgement, it has proved advantageous to include this region lying above the second main resonance, as an additional criterion. High level values are favorable, remarkably enough, even in piece no. 5 with its close tonal figures. No negative correlation worth mentioning occurs in any piece, in contrast to the previous frequency ranges. This criterion is therefore especially valuable for the versatile application of a guitar.

8. The range of the third octaves from 315 to 500 Hz (D4 to C sharp 5), overlapping the previous ones, shows a similar tendency on the whole, indeed. In the fast pieces nos. 2 and 5, there is no noticeable correlation. High levels give a coloring, which is very favorable in quiet pieces.

9. The 630 Hz third octave comprises the region from D5 to F5 and corresponds approximately to the vowel colour "å". Extreme values are considered disadvantageous: "too low" values lead to an uneven high E-string, and "too high" values give unsatisfactory timbre.

10. The third octaves from 800 to 1250 Hz (F sharp 5 to F6) cover the region of the vowel colour "a" (German "a"), which is generally considered to be of particular importance in judging musical instruments , ref. (8, 9). As shown by the correlation values this frequency range has a considerable influence on the sound quality of guitars too. A high level value is especially desirable in pieces whose tonal range extends to a very high one. Thus, the 1250 Hz third octave is particularly important for the highest registers of the high E-string, as it includes the partials of the octave. On the other hand, in pieces requiring a rather subdued sound, too high a level in this third octave is a disadvantage.

11. A level rise above the 1250 Hz third octave leads to a disturbing effect. It is of no importance for the judgement whether this maximum is in the 1600 Hz or in the 2000 Hz third octave. Only the magnitude of the level rises is of importance, since a level rise of this kind leads to a nasal or a hard, obtrusive timbre. Its effect is disturbing, more so when the higher registers are enhanced over the bass.

Criteria for individual resonances

The rest of the criteria is concerned with the detailed course of the frequency curves and refer to certain characteristics of individual resonances.

12. The tuning of the lowest resonance varied greatly in the guitars tested; the frequencies were between 95 and 112.5 Hz, i.e., the lowest value lay below G and the highest above A. This frequency has no direct influence upon the overall evaluation. However, the frequency distance from the next note of the scale is important. If the resonance coincides with a note, this note drops out of the sound pattern of the adjacent notes because it decays faster. For this reason, the resonance should, if possible, lie at a distance of more than 25 cent from the frequency of the nearest note.

13. The tuning of the second main resonance, which falls between 184 and 242.5 Hz, should also lie at a distance from the nearest note. But as the second resonance generally is more dampened than the first resonance, and as the same cent deviation results in an approximately doubled beat frequency, a detuning to the nearest note by more than 20 cent suffices.

    In this connection, it should be mentioned that the requirement to tune both fundamental resonances precisely to one octave, ref. (5), cannot be deduced from the results under discussion. It should only be noted that the resonances of one of the best-judged guitars were spaced exactly one octave apart; there was no further correlation.

14. The lowest main resonances should be dampened as much as possible, as this improves the balance in the lowest register - as does the tuning. A resonance which has been little damped stresses the next note too much. The peak level of the first resonance scarcely varied in most of the guitars, and thus was not regarded as a special criterion.

15. A stronger correlation was found for the level of the second resonance, although its values for the individual guitars do not fluctuate very much. A high peak level is, however, an advantage here, because the damping of the resonance is generally sufficient.

16. A negative influence must be associated with a splitting of the second resonance into two separate peaks. This is most noticeable in those notes which are encompassed in this resonance range. The negative influence manifests itself particularly in the repetition of notes in the second piece and in the middle part of the third piece. The highest notes of piece no. 4, as well as the octave partials of the low register, fall into this region.

17. The third resonance, which was in the range between 390 and 440 Hz, is obviously of great importance. The position of the peak frequency apparently does not influence the quality, but the peak level is important. This criterion showed the highest correlation of all the individual criteria. A high level is of value, above all, for the

middle register of the high E-string and at the same time leads to a positive judgement of the strengthening of the overtones of the bass region.

18. Contrary to the two lower resonances, the third resonance should be as little damped as possible. This requirement results from the high correlation with the overall evaluation and was found in practically all the pieces. The prolonged reverberation of a resonance which has been only slightly damped is evidently regarded favorable. Only in the fast, close succession of notes of piece no. 5 does the slight damping have a negative effect. The clarity of the individual tone steps is impaired.

19. Finally, it is also important how strongly the third resonance is lifted from its background. In the majority of pieces, a strong resonance rise was judged to be advantageous, the high correlation with the overall evaluation being most evident. Beyond this, it is remarkable that this criterion shows no negative correlation worth mentioning in any of the pieces, i.e., there is no case where a very slight resonance rise is an advantage.

Criteria and industrial mass-production

In closing, let us turn our attention to the criteria and the industrial mass production of guitars. An important aspect is whether a constant quality is achieved with the present technical methods. Frequency curves were recorded for a large number of instruments from one and the same production series, and evaluated with the aid of the criteria introduced above.

The analysis of a production series is summarized in Fig. 8. The quality distribution within the series is in each case numerically expressed as the standard deviation for the levels measured in the individual frequency ranges or resonances. In this figure, one recognizes clearly a tendency of the level variations within the production series. The level variations increase considerably at frequencies above 1000 Hz. The greatest uniformity is achieved for the average levels of the third octaves from 250 to 400 Hz and 315 to 500 Hz. The balance is also relatively good in the region of the lowest frequencies. In the last two cases, the standard deviation is below 0.5 dB. It is striking that the standard deviation for the three third octaves from 160 to 250 Hz and for the 630 Hz third octave is higher than for the neighboring regions.

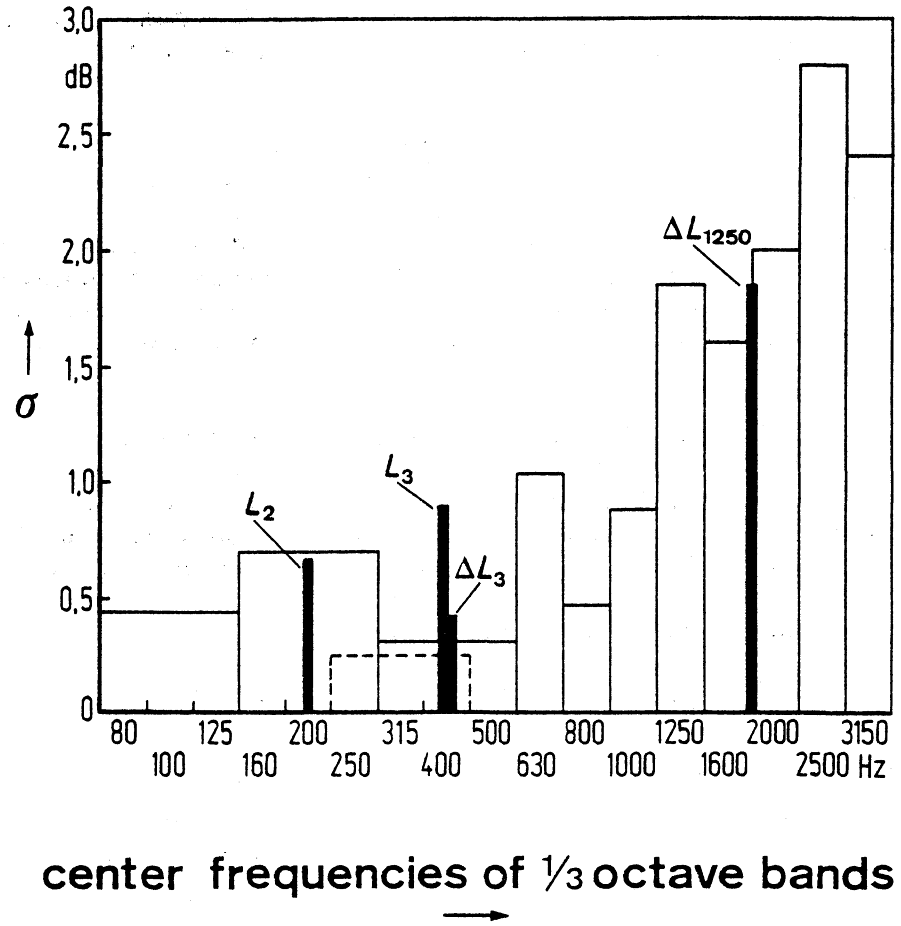

Fig. 8. Quality distribution of serial manufactured guitars.

A disadvantage of this representation is that the quality factor and tuning of the first three resonances cannot be included, as these parameters cannot be expressed in decibels. To find a common measure, the standard deviations in the individual criteria were related to the difference which corresponds to a quality improvement from "-1" to "+1", i.e., two points. Thus, the level variations and the variations in frequency separations, which are logarithmical measures in dB and cent, respectively, can be plotted in the same diagram as the variations in the linear Q-factor. In practice, this means that the standard deviations are transformed into "quality grades". The variation of the acoustical characteristics for the mass produced series of guitars is shown in this form in Fig. 9.

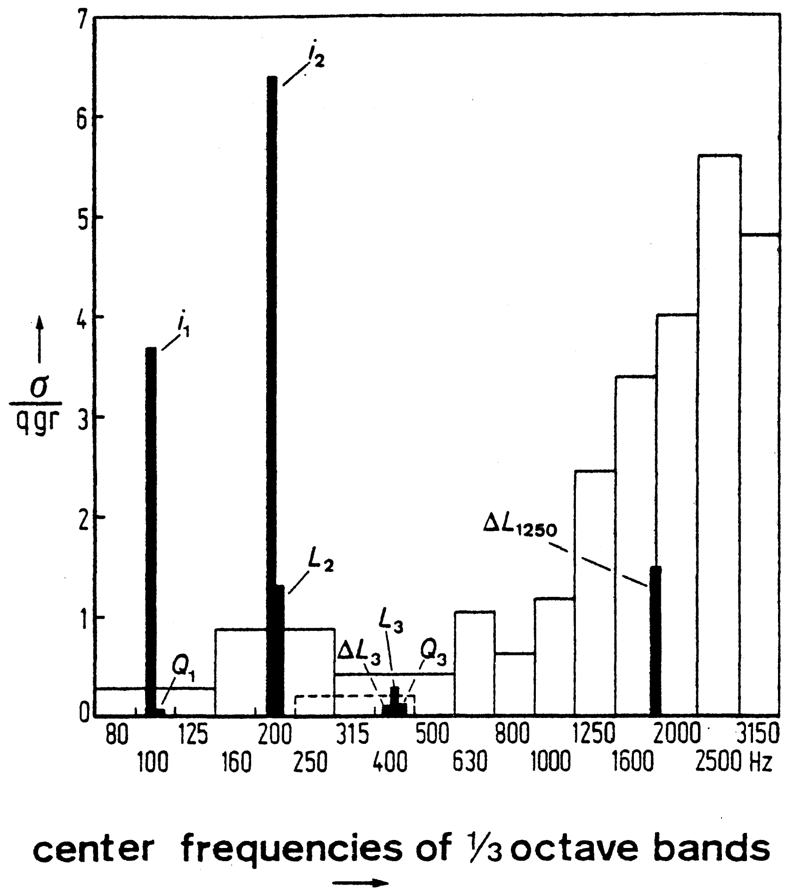

Fig. 9. Quality distribution of serial manufactured guitars.

The diagram shows the same tendency as that seen in Fig. 8 with a clear increase of the variations at higher frequencies. Furthermore, the very large variations with respect to the tuning of both fundamental resonances are remarkable. Although both of these high values partly depend on the narrow quality grades of the criterion, the influence of the raw material is nevertheless demonstrated. This was also the case with the tuning of the fundamental resonances (7).

The quality factor of the first resonance, determined chiefly by the cavity properties, and the average level of the third octaves from 80 to 125 Hz show only very small variations despite the variable tuning. The level variations of the second resonance as well as those of the third octaves from 160 to 250 Hz is noticeably larger, because of the top plate properties. The top plate is the dominant element for this resonance range, it oscillates as a whole and not in parts and is therefore more strongly influenced by the acoustical characteristics of the plate material. Furthermore, the level in the 160 Hz third octave - below the second resonance - decreases noticeably when the resonance is tuned higher. This also affects the average value of the third octaves from 160 to 250 Hz.

All three criteria affecting the third resonance show very slight variations in mass production; there is also only a slight variation of the average levels in the third octaves from 250 to 500 Hz. The top plate oscillates in the third resonance with a nodal line along the bridge and the possibility of exciting this resonance depends much on the kind of stiffening elements under the top plate. This will be discussed in my second paper. It should only be mentioned here that the exact frequency position of the third resonance does not influence the sound quality.

The level variations increase with the rising frequency in the individual ranges of the third octaves. It can be ascribed to a growing influence of the plate material. This becomes more marked the stronger the subdivision of the oscillating plate (8). The limit for the increase of variations is shifted to somewhat higher frequencies when the top is stiffened with a larger number of struts. In the present case there are only three. For more struts the sections in-between are smaller, and the stiffness of the top is more strongly determined by the struts.

The measurement results presented in Fig. 9 can be summarized in three points:

1. The more additional construction elements (struts) of the top plate the greater the uniformity of quality within a production series. The irregularities of the raw material are better compensated for.

2. A reduction of the variations in the upper frequency ranges within the production series can be achieved primarily by the preselection of uniform materials for the top plate, and to a lesser degree by additional construction elements.

3. Constructive measures to improve the quality of a guitar model are most effective for those criteria for which the influence of the material on the variations within the series is small. The lower and middle frequency ranges up to 1000 Hz are the most important.

If one compares the criteria, which from this standpoint should be given priority with the criteria derived from the subjective evaluations, Table 1, there is, fortunately, a large measure of agreement: The third resonance and the ranges of the third octaves from 80 to 125 Hz, 250 to 400 Hz, and 315 to 500 Hz are of the greatest importance, followed by the Q-value of the first resonance and the peak level of the second resonance. In comparison with these, the other criteria are of only secondary importance, and are of interest only when the first mentioned criteria are close to being optimal.

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THE FUNCTION OF THE GUITAR BODY AND ITS DEPENDENCE UPON CONSTRUCTIONAL DETAILS

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Introduction

Acoustic measuring methods are available today, which allow the sound quality of guitars to be defined objectively and to be described in detail. The basis is provided by a frequency curve of the sound radiation. The curve is recorded in an anechoic room with six microphones arranged around the instrument which is excited by an electrodynamical system. To obtain measures of the quality of guitars we carried out large-scale listening tests with guitars of different quality. The subjective evaluation of the instruments is related to the frequency curves. The results allowed a listing of the sound quality criteria used in the evaluation of the frequency curves. The measuring method as well as the relationships between the subjective evaluation and the objective measurements were the subject of my first paper.

My second paper deals with the problem of systematically determining the influence of constructional details on the established quality criteria. Indications are obtained for improvements of the instruments. As expected, certain constructional measures effect improvements with respect to some criteria but may at the same time effect changes for the worse with respect to others. Therefore, the significance of the individual criteria must be balanced to establish priorities for optimal solutions. In serial production the quality variations within a series is an important question. Constructional improvements of a guitar model will influence the quality advantageously if the variations due to manufacturing are not too great.

Quality criteria

We selected eight criteria from the 19 quality criteria derived in my previous paper, and studied their dependence upon constructional details.

Five of these criteria can be obtained directly from the frequency curve:

1. the quality factor of the 1st resonance Q_1,
2. the peak level of the 2nd resonance L_2,
3. the peak level L_3 of the third resonance,
4. the quality-factor Q_3 " " " " , and
5. the resonance rise ΔL_3 " " " " .

The other three criteria refer to the average levels of the frequency curves in third octave bands:

6. the average level of the third octaves from 80 Hz to 125 Hz = L_{80m125},
7. the average level of the third octaves from 250 Hz to 400 Hz = $L_{250m400}$, and
8. the average level of the third octaves from 315 Hz to 500 Hz = $L_{315m500}$.

In some cases it is also worthwhile to extend the investigations to:

9. the total radiation in the range of the third octaves from 80 Hz to 1000 Hz ($L_{80m1000}$), and
10. the average level of the third octaves from 800 Hz to 1250 Hz.

Test method

To determine the influence of individual constructional details on the quality criteria mentioned, model tests were carried out. Only one constructional parameter at a time was changed systematically.

To investigate different constructions of guitar top plates a special "body" was used, which consisted of a rigid frame edge and a rigid bottom. The various test tops were glued to this body. The glueing was done only on a narrow edge. This fastening of the edge corresponded, from the point of view of vibration, to the glueing of a top onto a standard guitar body.

The vibrating elements in the model tests were restricted to the top and to the cavity. Preliminary tests had shown that stringing could be dispensed with without affecting the results. The bridge largely influences the vibration behavior in the main frequency range. Therefore, all top constructions were tested with the bridge glued on.

Vibration modes

To clarify the nature of the change of individual constructional parameters in order to influence the vibration behavior at certain resonances adequately, we first thoroughly investigated the significant modes of vibration of cavity and top. In this paper, a description of the cavity vibrations will be dispensed with, as this subject was discussed with in detail by E.V. Jansson (1). We measured the vibration patterns of the top plates for the individual resonances by means of a probe microphone. The microphone was moved over the top plate at a distance of 1 mm. The top plate was excited via the bridge by the same electrodynamical system as was used for the recording of the frequency curves.

In the low frequency range the top plate vibrates as a whole, i.e., without being subdivided by nodal lines. As long as no bridge has been glued on, the lines of the same vibration amplitude in the case of resonances are more or less circular. The bridge makes the vibration patterns more elliptic and at the top plate resonance, approx. 200 Hz, c.f. lefthand side of Fig. 1. The maximum vibration amplitude is found in the area of the bridge.

In the next higher and important top plate resonance (i.e. the third top plate resonance in Jansson's second paper Fig. 6) the principal part of the top, below the sound hole, is divided by a transverse nodal line into two areas vibrating in opposite phases. This resonance generally falls between 400 and 450 Hz and is the "third resonance" of particular significance for the guitar quality. This resonance is easy to excite for tops without a bridge whereas it is strongly affected by attaching the bridge.

The middle section of Fig. 1 shows the amplitude distribution of the vibrating top for a guitar with this resonance relatively well developed. The two parts are vibrating in opposite phases, the lower part having a smaller area and a lower maximum amplitude. Because of the asymmetrical design of the stiffening elements on the inside of the top, the nodal line is asymmetrical as well.

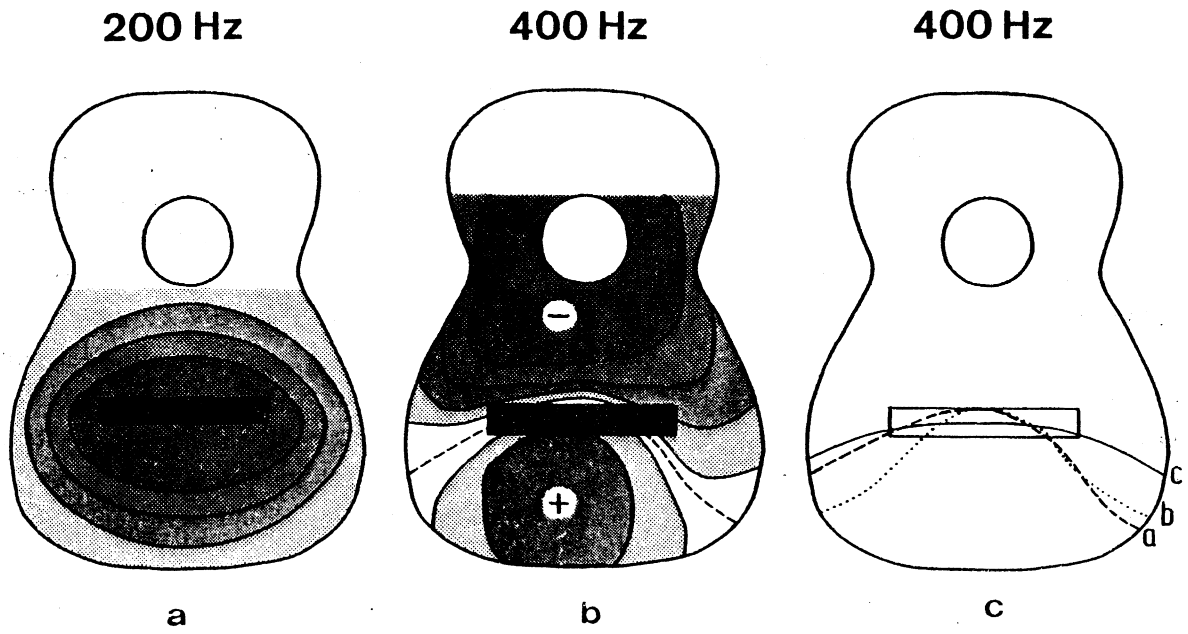


Fig. 1. Vibration modes of guitar tops.

The right hand section of Fig. 1 compares the nodal lines of three different guitars curve (a) having been taken over from the middle section. Curve (b) combines the values for a guitar for which the lower area of vibration is particularly small and for which the third resonance in the sound radiation curve is pronounced. Curve (c) belongs to an instrument for which this resonance is almost suppressed. The lower area of vibration is particularly broad but its maximum amplitude is only somewhat smaller than that of the upper area. It appears, however, that with the nodal line (c) running through the middle of the bridge, the excitation of this resonance is inefficient.

Sound radiation

The sound radiation of a plate divided into two areas vibrating in opposite phases is certainly comparatively poor. Considerable amounts of vibration energy mutually cancel each other as a result of the acoustic short circuit. However, the greater the difference between the two acoustical currents radiated from the two areas the smaller the effect. In order to achieve the most favorable sound radiation, the phase opposed areas should be different in vibration magnitudes (the amplitude or the velocity of the larger area should be greater than that of the smaller area).

The first condition, different sizes of the vibrating areas, can clearly be seen from the shape of the nodal lines in Fig. 1c. A third condition can be seen as well: to facilitate the excitation of the third resonance, the nodal line should not run through the middle of the bridge. To comply with both conditions, one should obviously design the top to make the nodal line originate from the "lower edge" of the top and run as closely as possible into the bridge.

Perturbation theory

When the principal resonances of the top are required to reach as favorable conditions of vibration as possible, it is in fact necessary for the thickness of the top plate to be varied. Some successful experiments with guitar tops with thinner zones in the peripheral area or close to the bridge, have been reported by W. Kruger (2). He has also indicated the basic relationships between the thickness distribution of the plate on the one hand and the quality factors of the resonances on the other. These properties have also been investigated theoretically by M.E. McIntire and J. Woodhouse for rectangular plates (3).

Fig. 2 shows the form of vibration for the two lowest resonances of a square plate and a function $\mathfrak{D}$ determinative for the resonance damping. The form of vibration gives the maximum deviation of the plate from the rest position. Function $\mathfrak{D}$ is a so-called perturbation function, the term "perturbation" referring to the deviation from a uniform plate thickness.

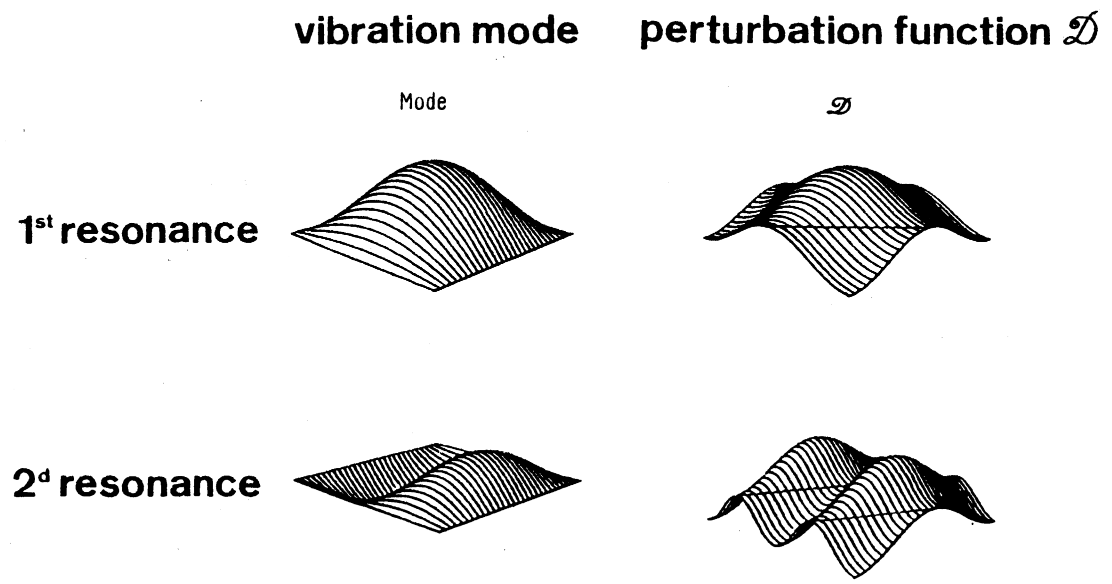
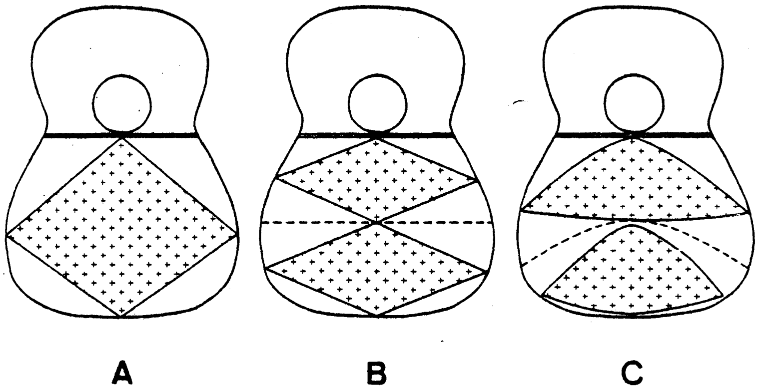


Fig. 2. Vibration modes of rectangular plates (from McIntire & Woodhouse 1978).

As the right-hand sections of Fig. 2 show, function 𝔇 can assume both positive and negative values, the straight lines entered corresponding to the original plane. The relationship between the plate thickness and the quality of the resonance is as follows: In the areas in which 𝔇 shows positive values, an increase of the plate thickness results in an increase of the resonance Q-factor, whereas a reduction of the plate thickness results in a reduction of the Q-factor. The opposite applies to the areas in which 𝔇 is negative. The higher the absolute value of 𝔇, the stronger this effect.

Perturbation applications

When applying these results to guitar tops, the vibration patterns (modes) shown in Fig. 1 must be taken as a basis. The first resonance of the square plate corresponds to the second resonance of the guitar body and the second resonance of the square plate to the third resonance of the guitar (The first guitar resonance is attributed to the cavity). This means that the upper part, the upper two patterns, of Fig. 2 can be transferred to the guitar resonance at 200 Hz (and, to a limited extent, also the resonance at 100 Hz because of the coupling of the two lowest guitar resonances) and the lower part to the guitar resonance at 400 Hz.



+ areas of positive values of $\mathcal{D}$

Fig. 3. Simplified areas of the perturbation function of guitar tops.

This transformation is shown in Fig. 3 but it has to be pointed out that an exact calculation of the function $\mathcal{D}$ for the complicated geometry of the guitar is not easy to make. Fig. 3a shows the distribution of function $\mathcal{D}$ for the fundamental resonances, the area in which the $\mathcal{D}$ -values are positive being marked with small crosses. From this figure it can be seen that the quality-factor of the resonances is increased when a mass is added in the middle of the top. This effect is particularly important in the investigations with different bridges.

In analogy with Fig. 2, the third resonance of the guitar is based on a nodal line which runs in a transverse direction. The nodal line divides the guitar top into two more or less equal areas. As a first approximation of the $\mathcal{D}$ -function, we see two rhombs as shown in Fig. 3b in analogy with the results for the square plate. Fig. 3c shows a nodal line corresponding to the real conditions of a guitar top. The original lines of the $\mathfrak{D}$ -function are distorted, which results in a partial displacement of the areas for positive $\mathfrak{D}$ -values. It can now clearly be seen that additional masses in the bridge area decrease the Q-factor of the third resonance. It would, however, be advantageous to have additional masses in the areas of vibration above and below the bridge.

Construction details and quality

Let us now consider the influence of guitar top details on the instrument quality.

Generally, the top is stiffened with so-called struts, which are glued longitudinally under it. The struts used in our experiments had a cross section of 5 x 5 mm and were 220 mm long.

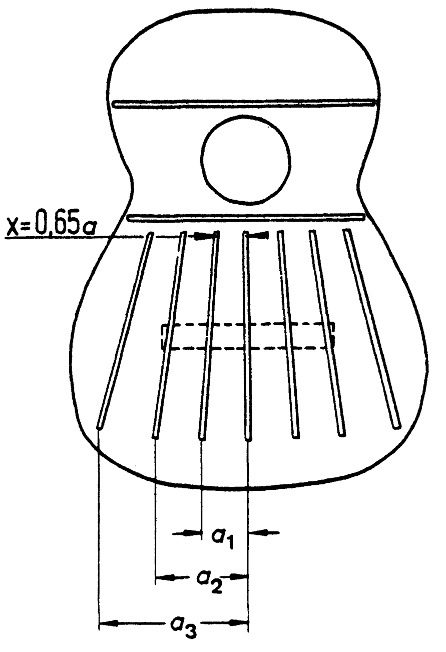
The design of the top with struts can be changed by varying either the number or the position of the struts. There are three basic strut arrangements: they can be arranged in parallel, they can converge from the sound hole towards the bottom, or they can diverge towards the bottom. In all these cases, the struts are almost as long as the lower top plate area and the number of struts can vary between three and nine. It should be mentioned in passing that in a few rare cases, guitars have shorter struts which are arranged vertically to one another.

Basic-strut-configuration

We first studied the question, which of the three basic strut arrangements, is the most advantageous. The investigations showed that, on the whole, the arrangement with diverging struts is the most advantageous from the acoustic point of view. This form also best fits the widening of the top plate towards the bottom. With parallel struts, the sound radiation is somewhat less advantageous in wide frequency ranges; but they do contribute to a good balance in the frequency range above 1250 Hz. In the case of converging struts, the level of the total radiation is also lowered, but the third resonance is somewhat more pronounced.

Even when limiting the top plate constructions to arrangements with struts converging towards the bottom, the constructions depend on several variables: the number and the position of struts (the position of each pair of struts if the arrangement is symmetric). When investigating up to nine struts, five variables should have to be considered as a basis of the individual quality criteria.

The relationships between constructional details and quality criteria are complicated. A six-dimensional representation of the results is not, for instance, sufficient. Summary criteria have to be found to describe the different constructions.



$$S = \sum_i \frac{a_i}{n}$$

Fig. 4. Guitar top with struts.

The evaluations showed that the "center of gravity of the struts in one half of the top plate" plays an important role. The position of the individual struts is defined by their distance a, c.f., Fig. 4, from the center line at the lower edge. Thus, the center of gravity is given by s = Σ a/n, where n is the number of the struts in one half of top plate, including the center strut.

In many cases, the number of the struts and their center of gravity describe the construction of the top quite precisely. More-over, it proved important to investigate whether uniform distances between the struts produce better sound than nonuniform distances and which positions are the most favorable for the arrangement of the struts.

Number of struts

As an example for measurement results of different strut arrangements, Fig. 5, shows that the average level of the third octaves from 80 to

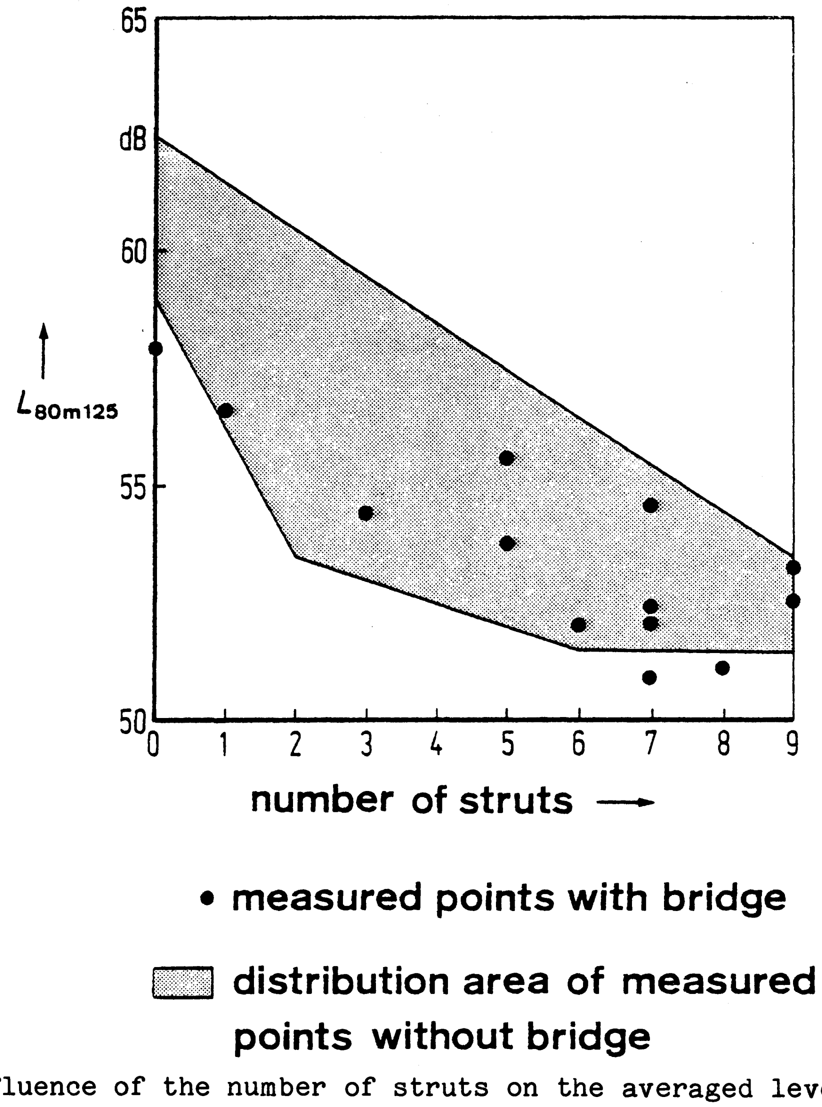


Fig. 5. Influence of the number of struts on the averaged level L_{80m125}.

125 Hz depend upon the number of struts. The results, with the bridge glued onto the top plate, are plotted as single points and the ranges of level variations, without the bridge, are shaded. The position of the points within these variation ranges shows that the attached bridge results in a more or less pronounced reduction of the level - a reduction of 3 dB on the average.

Furthermore, it can be seen that the overall level decreases with an increasing number of struts, about 1 dB for each additional strut. Taking no account of the top plate without or with only one strut, a maximum

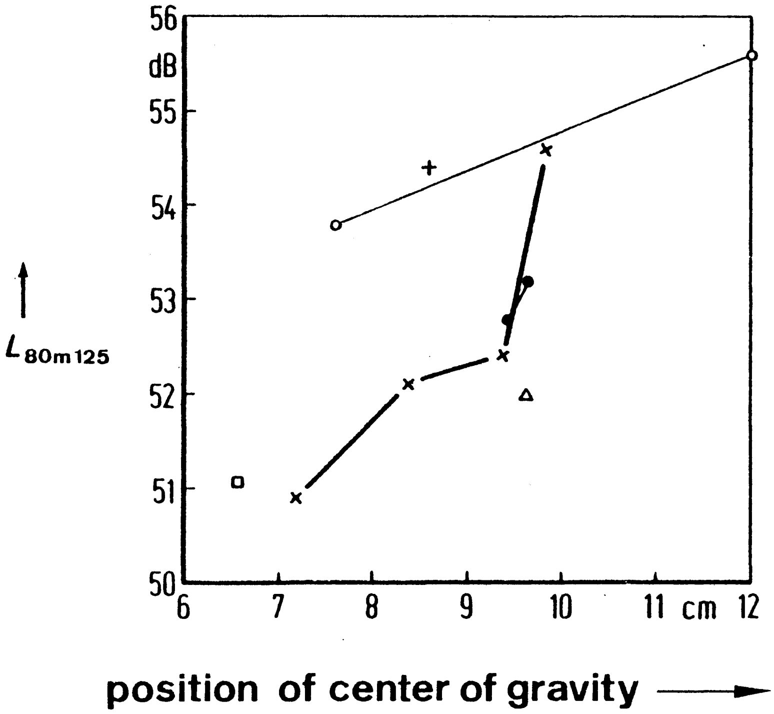


Fig. 6. Influence of the position of struts on L_{80m125}.

level is found for five struts. The values are most unfavorable for six or eight struts, i.e., for arrangements without a center strut.

The different points with the same number are obtained with the struts in different positions. The differences can be interpreted with the aid of Fig. 6. As can readily be seen, the level is higher, the more the center of gravity of the strut arrangement is shifted towards the outside. With seven struts, about 1 dB is gained per centimeter of the shifting of the center of gravity, the influence being somewhat smaller with fewer struts. For a stiffer material the influence of the struts, i.e. their position of the center of gravity, is more notable.

Influence of struts in detail

The evaluation of the frequency curves for the different strut arrangements showed that the effects produced on the individual criteria

struts \ criterion	Q_1	L_{80m125}	L_2	L_3	ΔL_3	Q_3	$L_{250m400}$	$L_{315m500}$	$L_{80m1000}$
increasing number	0	− 1dB/str.	0	0	0	0	0	− 0,7dB/str.	− 0,5dB/str.
optimum number	/	5	/	/	6....7	6....7	/	3....5	(5)
center of gravity outwards	− 20%/cm	+ 1dB/cm	+ 1,2dB/cm	0	− 1,7dB/cm	(+)	+ 0,3dB/cm	+ 0,6dB/cm	+ 0,3dB/cm
unequal distances	0	+	+	0	+	−	0	0	0
central strut	0	+	+	0	0	0	0	+	+
distance of inner struts	>4	<5	<5	<4	/	>4,5	4....6	>6	/
struts at the edge of bridge	0	0	−	+	+	+	0	0	−
struts outside the bridge	0	+	+	0	−	−	+	+	+
struts bar outwards	−	+	+	+	+	+	+	+	+

Fig. 7. Influence of struts on the quality judgements of guitars.

are very different. A general view of these results is provided by Fig. 7, which shows the relationship between the strut arrangement details and the acoustic efficiency in the form of a table. The results are classified simply as positive (+), or negative (-), and the sign (o) indicating no effect or no uniform effect. In detail, the following can be concluded from this figure:

1. An increased number of struts, which is favorable for the uniformity of serial production, on the whole has a rather negative influence upon sound radiation. The optimal solution is never more than seven struts. Six or seven struts are favorable for the development of the third resonance, whereas five struts contribute to an improved overall radiation.

2. A strut arrangement with the center of gravity far towards the outside is more favorable on the whole, but does not give a strong third resonance.

3. A nonuniform spacing of the struts is favorable with respect to some criteria and is never a disadvantage.

4. A strut arrangement with one strut along the center line offers advantage with respect to some criteria and never proves to be basically disadvantageous.

5. The distance between the inner struts should be about 4.5 cm, if possible. For the deep sound components a somewhat closer spacing is favorable, whereas a distance of up to about 6 cm is more advantageous for the middle register.

6. Struts arranged close to the ends of the bridge, i.e., at a distance of 8 - 10 cm from the center line, favor the development of the third resonance, but they also result in a decrease in the level of the second resonance and a slight decrease of the overall radiation.

7. Struts at a distance of between 12 and 14 cm from the center line adversely affect the development of the third resonance but are favorable for the overall radiation as well as for the low register.

8. Struts at a distance of 16 cm and more from the center line are favorable for almost all criteria.

One cross brace

The model tests with different strut arrangements showed that stiffening of the top plate by arranging the struts lengthwise and the bridge crosswise is very unfavorable for the development of the third resonance. Thus, the idea of trying to stiffen the top plate by arranging the elements transversely suggested itself. Cross braces, such as for the guitar back plate, were used. These braces had a section of 8 x 16 mm. In two test series, the main area of the top plate was provided with either one or two of these cross braces.

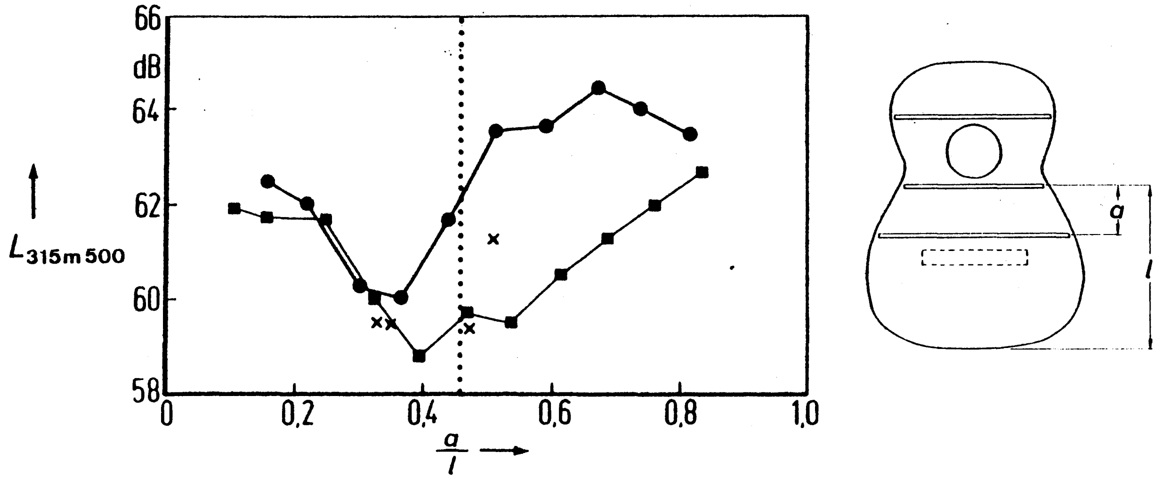


Fig. 8. Influence of the position of one cross brace on $L_{315m500}$.

The basic arrangement of an additional cross brace is shown in Fig. 8. The only variable parameter is the cross brace position, which is the distance from the cross bar below the sound hole, divided by the overall length of the main area. According to this definition, the center line of the bridge is at a/l = 0.46.

As an example, Fig. 8 shows results which were obtained with two plywood tops differing somewhat in the density of the material (weight) and the modulus of elasticity (stiffness). However, it must be remembered here that the density varies as much as 2% in the same top plate and that the elastic modulus may vary even by up to 7%. The latter value also involves directional dependence within the plywood. Compared to the top plate indicated by points, the density of the top indicated by filled squares is 4% less and the elastic modulus is 11% smaller. Basically the two curves have a similar shape with a clear minimum for the cross brace closer above the bridge. The area close to the sound hole is favorable for the cross brace, both top plates giving approximately the same level. Advantageous positions are also found far below the bridge. In this area, the stiffer top plates prove to be considerably better, as the sound levels reached are higher than those with the cross brace close to the sound hole.

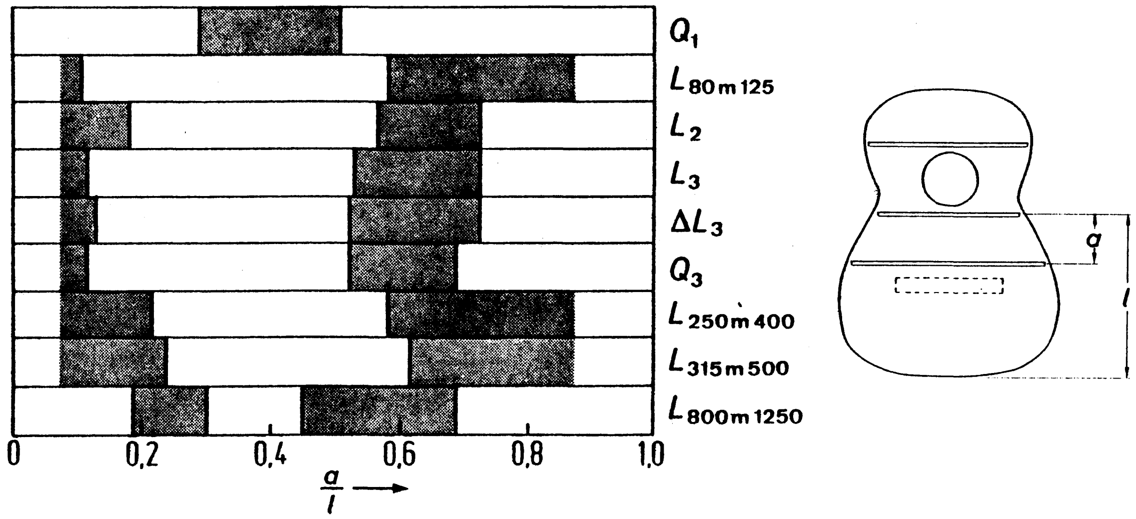


Fig. 9. Influence of the position of one cross brace on the quality judgements of guitars.

The results for the other criteria are shown schematically in Fig. 9. The areas of the cross brace positions, which produce relatively favorable values for the individual criteria, are shaded. It can be seen that the conditions are advantageous for most of the criteria, when the cross brace is either closely below the sound hole (the values for a/l being approx. 0.1, i.e., approx. 3 cm) or when the cross brace is at a certain distance below the bridge (the a/l values being approx. 0.65, i.e., approx. 19 cm). In the latter case, the radiation at the frequencies around 1000 Hz ($L_{800m1250}$) are favorable as well, whereas it is unfavorable with the cross bar placed in the vicinity of the sound hole. At a/l values slightly below 0.6, there is an interesting combination: strong low and high registers, weaker middle register, but with a very distinct third resonance. The area which increases the quality-factor Q_1 does not overlap with the areas favorable for the other criteria.

Two cross braces

The basic arrangement of two additional cross braces to stiffen the top is shown in Fig. 10. Here the variable parameter is the spacing of the two cross braces, a symmetric position in relation to the bridge always being assumed. The bridge position is the same as in the arrangement with one cross brace or with struts.

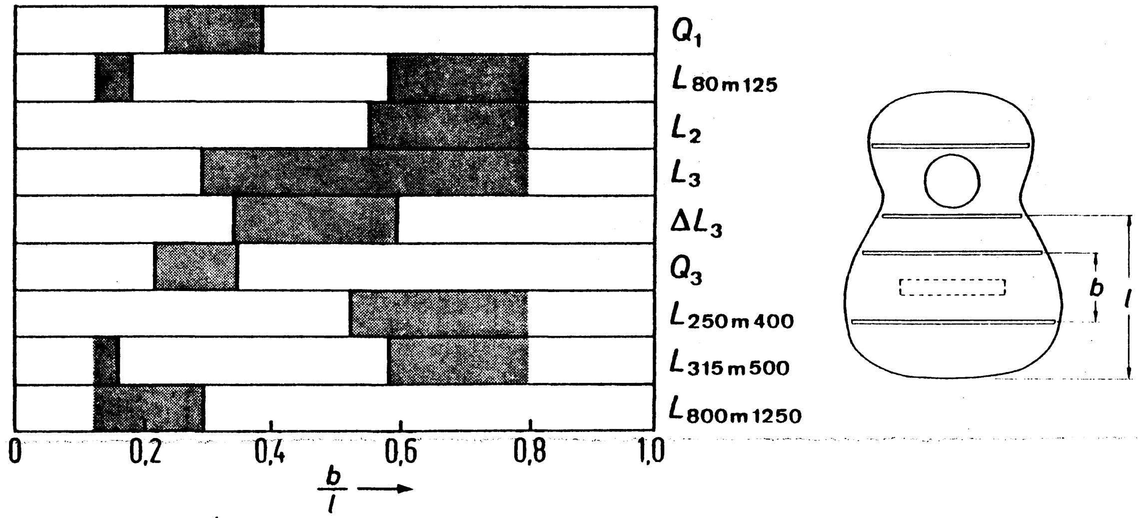


Fig. 10. Influence of the position of two cross braces on the quality judgements of guitars.

The results of these tests carried out with two cross braces are shown schematically in Fig. 10. As can be seen, these top arrangements do not allow such a great number of criteria to be optimized as in the case of tops with only one cross brace. The best combination for a b/l range between 0.58 and 0.60 just covers six criteria, referring both to the low and to the medium frequency range. These b/l values indicate a distance between the two braces of about 16 cm. Values of b/l between 0.6 and 0.87 still cover five criteria, the third resonance, however, not being so distinctly marked. A construction which is also favorable for the frequencies around 1000 Hz is obtained with b/l values below 0.3, i.e., the cross braces would have to be spaced at about 8 cm.

Unconventional stiffening elements

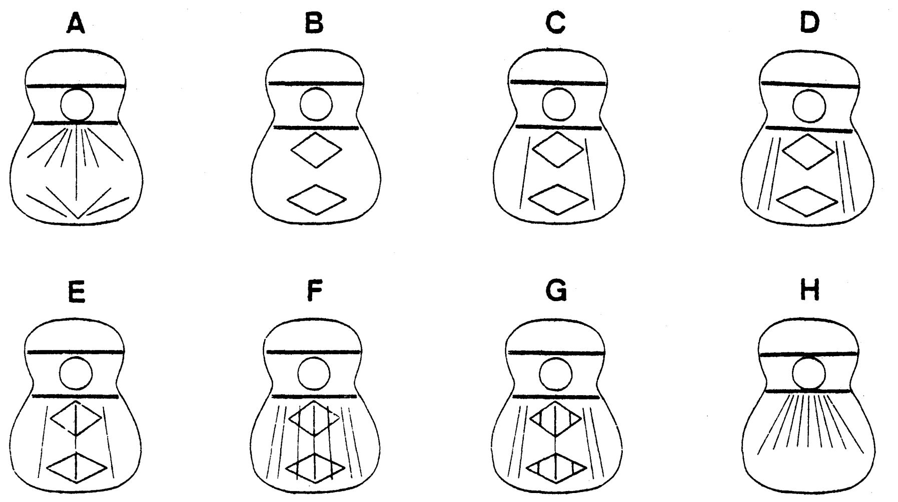
All top constructions described above refer to plates of a constant thickness and to stiffening elements of standard type and arrangement. The initial considerations of the influence of non-uniform mass distribution and non-uniform thickness of the top plate are not accounted for.

It appears, however, quite reasonable to test the potentialities by applying the theoretical considerations on the form of vibration. Plywood tops, i.e. plates with a uniform thickness, again provide a good starting point (such tops are also representative of the inexpensive manufacture of quitars). The tops were furnished with different mass covers and stiffening elements. The constructions are shown in the head column of Fig. 11.

When arranging the struts of top A, we attempted to limit the additional elements to the areas in which function $\mathfrak{D}$ assumes positive values. According to the same principle, two small plywood plates (each 10 g in weight) are glued to top B. However, largely due to the very deep tuning involved in this step, this top is of theoretical significance only as a transition to the following top forms. The forms C and D are not only provided with these small plates but in addition the outer area of their tops is stiffened. In the E and F design, the center field of the top is stiffened, and for G the stiffness of the middle portion is reduced whereas the mass of the small plates is increased again. As an example to demonstrate the opposite, top H with shortened struts leaves the lower range of positive $\mathfrak{D}$ -values free and has a particularly stiff center portion.

As the large number of criteria and constructional details does not allow the detailed results to be given, the table shown in Fig. 11 will be taken as a starting point for explaining the most significant results. In this table, the measurement results are again classified into three groups: favorable (+), tolerable (o), and unfavorable (-) values.

As the first resonance of the guitar body is basically a cavity resonance, the vibrational behavior of which is influenced by the resilience of the wall, the values for the quality-factor of this resonance differ



criterion / top	Q_1	$L_{80\,m\,125}$	L_2	L_3	ΔL_3	Q_3	$L_{250\,m\,400}$	$L_{315\,m\,500}$
A	0	0	+	+	+	0	+	+
B	+	+	-	0	+	-	0	+
C	0	0	-	0	0	-	-	-
D	0	+	+	+	0	-	+	+
E	+	0	0	0	0	0	+	0
F	-	-	0	-	0	+	0	0
G	-	-	0	0	+	+	-	-
H	+	-	-	-	-	+	-	-

Fig. 11. Influence of the top construction on the quality judgements of guitars.

for the various tops within only a relatively narrow range. The lowest and, thus, most favorable value is attained with top B, for which mainly the mass has been increased and the stiffness to a lesser degree. Almost equally good results were obtained for tops E and H which are adequately stiffened in the center but not too strongly on the periphery.

The average level value L_{80m125}, too, is favorably influenced by the mass increase of the additional small plates although they were primarily adapted to the vibrations of the third resonance. The maximum value is obtained with top B, additional stiffening results in a decrease. The qualitative order shows that stiffening on the periphery still gives good values (top D), whereas a stiffening in the center area reduces the level. This phenomenon can be explained by the form of vibrations (the top vibrating as a whole) giving maximum bending in the center area. The small additional masses have a positive influence on top G, whereas top H with the especially stiffened center area and the unstiffened lower edge area is extremely bad.

The development of the second resonance is most favorable with top A, since - as it is shown in Fig. 3a - practically all additional elements were within the range of the positive values of the $\mathfrak{D}$-function. Furthermore, for the most part, they follow lines of equal vibration amplitude so that they are not subjected to bending stress and, thus, act predominantly as masses (weights). Among the combinations of additional mass and stiffening, top D again presents the best values. Thus, it is important to provide a stiffening extending into the border area, which means that the shortened struts of top H are extremely bad.

With respect to the development of the third resonance, the measurements gave the fundamental result, that a high level is not necessarily connected with a high quality-factor. This is usually the case with simple resonance circuits. The maximum quality-factor is obtained with top H which has an extremely low level. As opposed to this, top A, where no additional element overlaps with the nodal line according to Fig. 1, is particularly advantageous with respect both to the level and to the quality-factor. The lateral stiffening (of top D) does not, on the whole, influence the third resonance as favorably as the reinforcement by a center strut (top E), although the stiffening extended into the border area results in a very high peak level. The additional elements of the small-mass plates (top G) must be regarded as quite advantageous; this means that these small plates might even have a somewhat larger mass. Similarly, the top plate with masses without struts (B) proves favorable, as the additional elements are arranged according to the function $\mathfrak{D}$ in Fig. 3.

For the sound radiation in the overlapping frequency ranges of the third octaves from 250 Hz to 400 Hz and 315 Hz to 500 Hz, the results obtained are very similar. Only for top B higher levels result in the higher and for top E in the lower of the two ranges. On the whole, top A again is very favorable but top D still yields a somewhat higher value, which probably is a result of the stiffening of the border area. A stiffening along the center line (top E) and in its vicinity (top F) is still to be regarded as relatively favorable. It is disadvantageous to place the stiffening in the area more or less in the middle between the center line and the border. The shortened struts of top H again give minimal sound radiation.

Different bridge designs

In all the measurements referred to above, the same bridge was used. Technically, the frequent glueing of the bridge to the top plate and its removal were facilitated by a thin sheet of paper in the glue layer, which also was used in fastening the top to the body. To determine the influence of the bridge material and forms, further series of measurements were carried out. First, bridges of the standard form but of different kinds of wood were glued to several tops. Finally, bridges of a modified shape were investigated.

Normally, guitar bridges consist of a higher center section about 75 mm in length and two lower side sections about 50 mm in length, the width of the bridge being constant over the whole length and just under 30 mm. The center section carries the so-called saddle (the bridge insert) which forms the proper end boundary conditions for the vibrating string. The lateral sections probably serve mainly to increase the surface glued onto the top and thus fulfill a predominantly static function. They may also influence the vibrational behavior of the top.

Within the scope of the investigations, the lateral sections were systematically reduced to lessen the bridge mass. The stiffness also varies according to the resulting shape of the bridge.

bridge \ criterion		Q_1	L_{80m125}	L_2	L_3	ΔL_3	Q_3	$L_{250m400}$	$L_{315m500}$	$L_{80m1000}$
increasing weight (normal bridge)	A	–	+	+	0	+	0	0	0	+
	B	0	+	+	0	0	0	+	+	+
	C	0	–	–	–	–	0	–	–	–
	D_1	–	0	+	0	–	0	+	+	+
	D_2	+	0	+	0	–	+	0	+	+
	E	+	–	0	–	–	0	+	+	0
	F	0	+	+	+	+	+	+	0	+
increasing weight	F	0	0	–	0	+	+	0	–	(–)
 G	/A	0	+	+	+	+	+	(+)	0	+
G	/F	–	0	0	0	+	0	–	0	0

Fig. 12. Influence of the bridge on the quality judgements of guitars.

In the left column of Fig. 12, the different forms are shown schematically, A defining the standard bridge form.

In shape B, the bridge was shortened laterally in three steps. The shaded areas correspond to the second and to the third shortening step, the third shortening resulting in shape F. In shape C, the lateral sections were first cut to form a triangle so that more mass was cut off at the end than towards the center section. In form D, too, only a center strip is preserved so that the stiffness is not reduced as much as in the case of the mass reduction in system B. As opposed to this, the height of the lateral sections of shape E is reduced with the surface remaining unaltered, so that the stiffness is reduced to a greater extent than in the case of B and D.

Fig. 12 shows the advantages and disadvantages of the different bridge shapes and weights in the form of a table. When considering first bridges of the customary shape and design, it becomes apparent that with heavier bridges, the radiation can be slightly improved for the low frequencies. At higher frequencies, the positive and the negative influences of the weight practically balance each other. However, it has to be noted that for some top designs lighter bridges are more favorable for the development of the third resonance; this cannot, however, be seen in detail in Fig. 12.

The other lines of Fig. 12 give a simplified classification of the advantages and disadvantages of the modified bridge shapes as compared to the standard shape A. A remarkable aspect of these results is that the bridge of shape F, which is reduced to the center section, results in a considerable improvement of almost all criteria in comparison with the standard shape. This bridge form would have to be given absolute preference over all other modified bridges, if the surface, reduced to less than the half, proves still large enough to be glued to the top. With this bridge form it is favorable, by the way, to have a weight as low as possible.

The results obtained for bridge shapes B to E clearly show, that not every form of shortening or weight reduction of the bridge is an advantage. The most favorable way is to uniformly shorten the lateral sections by about one third of their length, according to shape B. Although this measure does not improve the development of the third resonance, the radiation is clearly increased in the low as well as in the middle register without any negative influence on the other quality criteria.

On the basis of the favorable acoustical results obtained with shape F and remembering that the glueing area of this form is less than half that of shape A, tests were carried out with a bridge of shape G. This bridge is of the same length as shape F or the center section of shape A, i.e., only the length required to accomodate the strings. As compared to the standard bridges, however, it is twice the width in order to increase the glueing area. To save mass, the height of the lower half is only one third of the height of the upper half, i.e., the lower half is as high as the usual lateral sections.

Shape G, which from a mechanical point of view can be regarded as equivalent to the standard form because of the large glueing area, offers clear advantages with respect to the vast majority of the acoustical criteria. When comparing the bridge shape G with the smaller bridge F, the acoustical characteristics of almost all criteria are equally good, the third resonance being even somewhat more pronounced. Because of the higher weight of the bridge of shape G, only the sound radiation in the range of the third octaves from 250 Hz to 400 Hz and the quality-factor of the first resonance are somewhat less favorable.

Other constructional details

As compared with the properties of the top, the influence of other constructional details upon the quality of guitars is of only secondary significance. An increase in the cavity volume can be obtained, for example, by increasing the height of the sides. It results in a slight improvement in the low frequency range but some small deterioration in the medium frequency range.

The size of the sound hole, too, has only a very weak influence upon the quality. The overall radiation of the guitar, i.e., the average level of the third octaves from 80 Hz to 1000 Hz increases with an increase of the sound hole diameter, but for other criteria there seems to be an optimum in the range of the usual dimensions, i.e. a diameter of some 90 mm. This means that the sound hole size should be modified only within very narrow limits. The diameter of the sound hole should be regarded mainly as a detail in the frequency tuning of the cavity resonance.

As compared to this, the quality of the material of the top plate is of greater significance, in particular when plywood is used. Particularly in top constructions with cross braces it is noticeable that the stiffening effect of the additional elements appears only in the cross direction. The stiffness in the longitudinal direction depends only upon the plate material and is, therefore, completely subject to the material variations. The influence is strongest in the medium frequency range where, for example, an elastic modulus higher by 7% results in an increase of the resonance level of up to 3 dB.

The quality variations of top constructions with struts are much less important. The cross stiffening as a result of the bridge is complemented by the longitudinal stiffening produced by the struts. The top plate material alone is not the determining factor for the stiffness of the top in any direction. The focal point of weak influence of the material is found at frequencies lower than the designs with with cross braces.

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PANEL DISCUSSIONS

The musician, the instrument maker, and the scientist may work with the same subject matter, i.e., music and musical instruments but they often use different languages as they have different educations and work with different conceptual frameworks. For this reason it was decided to have two panel discussions to bridge differences in background and ideas, and combine the experience of the player and of the maker, respecitvely, with that of the music acoustics scientist. The two panel discussions "The Guitar and the Player" and "The Guitar and the Maker" following below are summarized by Erik Jansson, the moderator of the panels.

I. THE GUITAR AND THE PLAYER

Four prominent guitar players were invited to the panel: Bo Dahlman, Rolf la Fleur, Peder Riis and Jörgen Rörby. They represent the guitar teacher, the chamber musician and the studio musician as well as the lute player. Three main topics were discussed: the ideal guitar, desired properties of the guitar, the player and music acoustics.

The ideal guitar

All players agreed that there was no ideal all purpose guitar. They also agreed that the first voice in guitar trios and quartets demands a guitar with special properties, notably a more carrying tone of the first string.

Bo Dahlman: As I have not been able to find an ideal guitar, I bring several guitars to my performances. I want to be able to vary timbre and duration more.

Rolf la Fleur: There are different ways to select the ideal guitar. One guitar may work well for some music but not for other music. The guitar may be choosen according to the character of music. In early polyphonical music a guitar with a long and even tone may be suitable. In more romantic or Spanish music a guitar with a fast "attack" is preferable. Another approach is to select a "white", "neutral" instrument and leave the variations to the player. A third way is to play the music on authentic instruments, or replicas, i.e., lute music on the lute, baroque music on the baroque guitar etc. This last alternative would make for very laborious concerts for the player.

Jörgen Rörby: Although "my guitar" is not ideal for all music, I only use this one. In trio playing the three guitars of the trio should sound like three different guitars. The instruments seem to support each other - what is missing in one instrument is supplied by the others.

Rolf la Fleur: In duo playing it is similar. An individual difference is necessary to give the duet character. In music transcribed for the guitar there is often a problem, when the larger range of the original instruments can not be used.

Peder Riis: The performers may produce sufficient difference between voices. Still we use the usual six-stringed guitar supplemented with Georg Bolin's Altgitarr to make it easier to separate the voices in our guitar quartet. For my solo guitar I want an even tone for the whole playing range with no tones of singular defects.

Lute music on the guitar

The players all agreed that the lute and the guitar are two different instruments, but that lute music can be played on the guitar.

Peder Riis: The lute, however, has a different character - "brittle and clear", which makes the individual voices stand out. The strong fundamental of the guitar often makes the bass indistinct in lute music.

Rolf la Fleur: With the right number of strings and the right tuning all early music can be played on modern instruments. But the lute is not only a different instrument, it was also played differently articulating between "heavy" and "light". For the ordinary guitar player it should be much easier to shift between a six-stringed guitar and to Georg Bolin's 11-stringed Altgitarr than to the lute.

Jörgen Rörby: It is most honest to the guitar to play it as a guitar and not to try to imitate the lute. The guitar demands a certain kind of activity to obtain the tone, which is not possible with the playing technique of the lute. I prefer the Altgitarr to unproper luteplaying.

Desirable properties of the guitar

The guitar player generally wants more volume, a stronger tone from his instrument, but not at the price of a loss in tonal quality.

Rolf la Fleur: The guitar has special qualities, which must not be lost. It is an obtrusive instrument with subtle gradations, which should not be overpowered by an increased tone volume. In additon there should be a balance between what you hear and what you see, a large hall should mean a weak sound. The large modern concert hall is a little too large for the guitar.

Peder Riis: The strings are another important factor - with "exhausted" bass strings the guitar does not sound much.

Jörgen Rörby: When Bo Dahlman and I performed in the schools recently, the children prefered our fairly simple acoustical Japanese guitar with a built in microphone connected to a loudspeaker to the exclusive classical guitar. I am afraid that the school children do not pay attention to the delicate gradations of the classical guitar.

Bo Dahlman: I would like to teach children to listen to the different qualities of the guitars, and not only to the electric guitar.

On "Timbre dynamics"

Rolf la Fleur: In my opinion there are sufficient possibilities to vary the timbre. Different positions as ponticello and tastiera give large differences and Ferdinando Sor gives direct rules. However, instruments may be rather different. Some instruments give the desired timbre for large variations in plucking position, others give the desired timbre only for one position. The player all the time works to discover the instrument - to get the most out of it.

The guitar player and music acoustics

Bo Dahlman: I would like to have a system that predicts what happens for different ways of playing, an acoustical procedure for testing the instruments, and an instrument whose tonal character could be changed more.

Rolf la Fleur: I would like to know more about the function of my instrument and to follow how your different acoustical fingerprints develop for the guitar. I would like to know what can be said to be false and what true, i.e. tell which myths and experiences are acoustically founded and which are not. I feel though that the music acoustics can contribute more to the maker than to the player.

Peder Riis: I also think that music acoustics can contribute more to the maker than the player. There are so many subjective factors involved in playing - I can feel that my guitar is poor one day, but still consider it best in the world the next day. The guitar has not changed, but I have.

Jörgen Rörby: The quality of the strings is a serious problem. When I buy strings I may have to buy three or four sets to obtain one complete useful set. If laboratory tests could measure string properties and provide string makers with the information about desired properties of strings much should be accomplished. It is not the same problem for the lute.

Bo Dahlman: I find it very interesting, but still a little frightening, if everything I do when playing is measured - but on the other hand I never play a piece of music exactly the same twice.

Conclusion

Our discussion can be summarized briefly as follows: There is no ideal all purpose guitar. Guitar trios and quartets demand a more carrying first string than does the solo guitar. Generally the player wants more tonal volume from his guitar, but not at the price of a loss of other qualities. We shall remember that the obtrusiveness and subtle gradations are a general quality mark of the guitar. Lute music can be played on the guitar or preferably on G. Bolin's Altgitarr, but will not be the same because of general differences in instrument construction and playing techniques. Music acoustics can help the player by developing procedures to test guitar and string properties, which could specify demands for manufacturers.

II. THE GUITAR AND THE MAKER.

Three highly qualified guitar makers were invited: Georg Bolin, Karl-Erik Gummesson and Lars Jönsson. Two of the makers are since long well established: Georg Bolin has a strong interest in developing new instruments, as for instance the "Altgitarr" and Karl-Erik Gummesson with an equally strong interest in making early instruments such as Baroque guitars and Bandoras. Lars Jönsson represents the young, coming generation of guitar makers. Four topics were discussed: the importance of the material, the maker's way of working and tonal properties, and the maker and music acoustics.

The importance of the material.

All makers agreed that all parts of the guitar are important to the quality of the finished instrument. The top plate is the most important, but the back and the sides also influence the tonal quality. The top plate material and its bracing structure should be matched, i.e., a top plate of a less stiff wood needs a stiffer bracing.

Georg Bolin: The growth of the wood is most important. The wood should have narrow grains but a straight growth is even more important.

Karl-Erik Gummesson: Different materials are used in different types of guitars - Rosewood in Classical guitars and Cypress in Flamenco guitars.

Lars Jönsson: I have made two guitars identical in every respect but with different wood in sides and back: one with Rosewood and the second with African Padouk. The Rosewood guitar produced a tone with more "weight", the Padouk a lighter more transparent tone.

The maker's way of working.

Georg Bolin: The making of guitars is no secret, but every maker has his own method, which influences the quality. I glue back and sides together first and thereafter the top plate and the neck. The glueing method plays an important role. By using "hot glue" and glueing the struts with different time intervals I can give the top built-in strains to obtain a balance between the top and the strings. As I usually do not find the desired balance directly, I tune, adjust, the guitar after it has been assembled.

Karl-Erik Gummesson: I usually build my guitars in the Spanish way. After having thinned down the top plate, I glue the cross bars and the fan struts, tune the plate by cutting down the braces. Finally I glue the sides and the back. Much of the adjustments are made on intuition. The top plate should have a specific stiffness, which sets the frequency of the fundamental guitar resonance. Usually the resonance frequency is adjusted to A 220 Hz. A somewhat lower frequency, G flat, gives a warm and beautiful tone. The A-frequency produces produces a little "sting" in the tone. Increasing the frequency to A sharp, gives a clearer but "sharper" tone, which carries in ensemble playing.

Lars Jönsson: The most important thing for me is that I am satisfied with the instrument I am making. My way of working is that I build "twin" or "triplet" instruments, with only small differences between them. After assembling I play the instruments and note the physical properties as the eigentones, weight and main design parameters, and the musical qualities. The best instrument serves as a guide for the following instruments. It is a slow way of working, so sometimes I have introduced radical changes.

The guitar and the tone quality.

Karl-Erik Gummesson: The earlier instruments were built according to other principles than the instruments of today. During the renaissance the deep full timbre was not desired. Therefore the instruments were constructed to give a weak fundamental and strong higher partials. The bridge was placed differently - close to the lower end of the top plate, thin strings and a thin top plate were used. The renaissance lute had a small crossbar below the bridge to make the treble stronger. With the change of music a stronger fundamental was demanded and the fan bracing system was approached. Both the lute and the guitar tone has been changed from a transparent tone, rich in higher partials to a more "broad" tone with a strong fundamental.

Georg Bolin: My Altgitarr is a a completely new instrument. It was constructed not to replace the lute but to provide the guitar player with a guitar that covers the range of the lute. Such an instrument makes the rich lute music of the baroque and the renaissance possible to play without transcriptions. New music has also been written for the Altgitarr. Recently I constructed a slightly smaller guitar. I have found that the guitar before Torres was smaller. The experimentation has now produced a guitar with only 63 cm string length, without sacrificing tonal quality, on the contrary it has been improved.

Lars Jönsson: The thickness of the top plate is most important. A change of a tenth of a millimeter is noticeable, but the position of a single strut makes little change in tonal quality. However, there seems to excist a lower limit for the thickness though which must not be passed.

Georg Bolin: It is hard for a maker to give simple and clearcut directions on how to work. So much depends on the properties of the wood to which the dimensions of the tops and their bracings must be adjusted. Therefore I believe that it is important to measure, using modern acoustical equipment. We must not be fixed only to old ideas and knowledge.

The maker and music acoustics.

Karl-Erik Gummesson: Makers need information such as presented in the seminar today. We need a better understanding of the functional principles of the guitar and of how to construct guitars with prescribed tonal properties.

Georg Bolin: Tests should be developed for quality judgements of guitars in concert halls. It is necessary to get a better understanding of properties such as clarity and carrying power. The carrying power in the pianissimo playing is especially demanding on the guitar.

Lars Jönsson: I would like to see detailed accounts of the relationships between constructional details and tonal properties. Thus, I would like to have at least a general guide to what happens if I move that strut, or change the air volume for instance. Such a guide would be of great help at least to me.

Conclusion.

The material and the maker's way of working are important for the quality in the experience of makers. The strings should be improved. There has been a change in music which has led to a change in the construction of instruments. From a timbre rich in high partials the sound has changed towards a timbre with a strong fundamental. Newly constructed instruments can be used both for early and contemporary music - although we should not expect the modern instruments to replace the early ones. The music acoustics is interesting for the maker both to supply a fundamental understanding of the function and the tone production of the guitar. Guitarmaking would benefit from general constructional rules founded on acoustical facts.

List of sound examples

Sound example 1. Demonstration of partials in a harmonic spectrum. Four single partials repeated twice, thereafter the partials added one by one into a harmonic spectrum repeated twice c.f. Fig. 2. (33")

Sound example 2. Demonstration of "smoothness" and "roughness" with a spectrum of four and six partials respectively. Spectra of a) four partials, b) six partials, c) four partials, and d) six partials, are presented three times each c.f. Fig. 3. (27'')

Sound example 3. Body sound and partial spectrum sound: three times of a) body and partial spectrum sound, b) partial spectrum without body sound, c) body sound only, and d) body and partial spectrum sound. (40")

Sound example 4. Influence of plucking position assuming the same level of initiated partials. Plucking three times each at a) half the string length, b) one third string length, c) one sixth string length, and d) one tenth string length from the bridge. Each example is presented twice. (1'20'')

Sound example 5. The importance of different frequency regions. A music piece (from Tarrega's Lagrima played by P. Riis) with different frequency ranges filtered out according to Fig. 12:

a)	full range,	below 4 kHz,	full range,	above 4 kHz,	full range
b)	"	" 2 kHz,	"	" 2 kHz,	"
c)	"	" 0.5 kHz,	"	" 0.5 kHz	"

(1'12'')