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Mechanical Vibrations of Electric Guitars

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Summary

The vibrations of strings are influenced by their end supports. As a result of non-rigid supports, energy can flow from the strings to the body of an instrument causing the string signal to decay faster than in the case of rigid supports. In electric stringed instruments featuring a neck and a fretboard such as guitars or basses, this mechanism can evoke effects of practical relevance at particular locations on the fretboard which players denote "dead spots". For a precise understanding of the causes of this phenomenon the vibrations of the bodies of electric guitars were measured. In addition, the energy transfer via the end supports of the strings was assessed using a straightforward experimental procedure. Emphasis was put on the measurement of the mechanical conductance under realistic playing conditions in situ. Experiments on electric guitars revealed that the conductance at the bridge is generally smaller than at the neck. As a rule, the neck conductance proves to be smaller in the fretboard plane than perpendicular to the fretboard. The out-of-plane neck conductance is suggested as a relevant measure for characterizing the end supports of the strings in evaluations of electric guitars and basses, in particular the phenomenon of dead spots.

PACS no. 43.75.Gh, 43.75.Tv, 43.40.Yq

1. Introduction

The electric guitar belongs both to the chordophone and electrophone instrument families [1]. Without doubt, electric guitars are the most widely used musical instruments in modern popular music. Nevertheless, little scientific work on the subject has been published until now. Extensive literature exists for acoustic guitars; see for example [2, 3, 4, 5, 6, 7, 8]. It is, however, hard to find corresponding papers on the electric sister of the acoustic guitar. A thesis [9] deals with the rôle of electric stringed instruments in modern popular music. Besides books mainly addressing guitar players [10, 11] there are some few recent works [12, 13, 14] studying the vibrational behaviour of electric guitars or basses.

In guitars the original signal is produced by the strings. Since a string is not able to radiate sound to a practically sufficient extent, vibrational energy has to be transferred from the string to the instrument body in an acoustic guitar. For this reason the bridge must be mobile. The body as well as the air enclosed within and surrounding the body are forced to vibrate with the result that a useable sound signal is produced [3, 4, 5, 6, 15]. As a consequence of the energy transfer, the decay of the string vibrations is relatively fast.

In contrast to the acoustic guitar, the electric guitar does not radiate the sound itself and consequently there is no intrinsic need for energy transfer from the strings to the instrument body. Therefore, the string vibrations of a solid-body electric guitar do not decay as rapidly as for the acoustic guitar. In the words of guitar players: The "sustain" is better for an electric guitar than for an acoustic one.

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This is true for a majority of the fret positions at which the musician fingers the strings. However, there are exceptions to the rule. At particular fret positions on a given string, the sustain can be much shorter than for adjacent frets. The player calls this irregularity a "dead spot". Investigations on bass guitars have revealed some evidence of the origin: Under certain circumstances the strings can cause the body and the neck to vibrate [12, 13, 16] with the result that the string vibrations decay exceptionally fast. The aim of the present investigation was to find a simple measuring technique, suitable for diagnosing the causes of dead spots. As typical objects two instruments were chosen which represent two basic types of electric guitars: A Les Paul and a Stratocaster guitar, both made by well-known American manufacturers. Both instruments had an adjustable bridge without vibrato mechanism ("wiggle bar").

2. In-situ measurements of instrument vibrations

2.1. Previous experiments

In texts on a basic level, a string is normally considered as rigidly fixed on both sides. This means that any interaction between instrument and string is excluded. However, the body of a real instrument does vibrate and influences the vibrations of the string via the end supports.

Several experiments on vibrations in guitars are reported in the literature. They refer in particular to the top plate (e.g. [17, 15]), the plate and neck [7] and in some cases to the whole body (e.g. [18, 8]) of acoustic guitars. When dealing with acoustic guitars, a complex coupled system has to be considered including both structural and acoustical components. Electric guitars represent, in comparison, a delightfully simple problem where only structural vibrations of the body, neck, and head have to be considered.

Since an electric solid-body guitar is much thinner than it is wide, the vibrations can be expected to be more pronounced in the out-of-plane direction than in-plane. A basic measurement can thus be restricted to just one direction, the out-of-plane motion.

An important issue in all experiments with guitars is the support of the instrument. Fleischer and Zwicker [14, 16] made use of a laser technique to acquire vibration data of electric bass guitars. On the basis of these data, modal analysis was performed. In later experiments, decay rates of the string vibrations were measured. However, the instruments were supported in different ways in the experiments: When the string decay was investigated, the bass guitar was held by a player in normal playing position. For the acquisition of the vibration data, the instrument was fixed in an experimental set-up. Consequently, the boundary conditions of the vibrating system were not the same for the two measurements and the analysis of the data showed that the results were not comparable to a satisfactory extent.

These two experiments verified the well-known fact that eigenfrequencies and eigenmodes are highly sensitive to the boundary conditions. In order to make the results comparable, the boundary conditions should be kept as similar as possible between measurements. Further, the boundary conditions should be as "natural" as possible in order to yield realistic results.

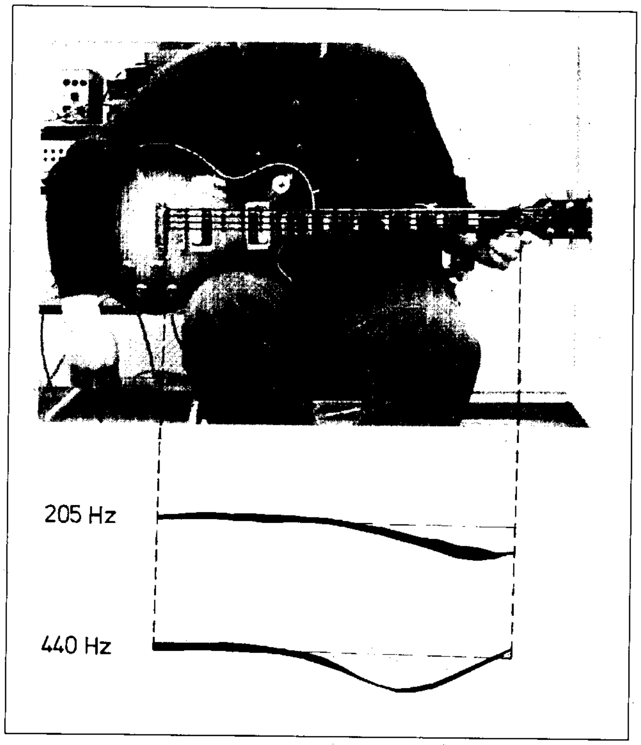

Figure 1. In-situ measurement of the out-of-plane vibration (velocity) of the Les Paul electric guitar. Top: Guitar held by a subject for measurement. The measurement region is delimited by dashed lines and the mesh points are indicated by black dots. Bottom: Vibration patterns of the two main out-of-plane resonances; zero-lines are indicated.

2.2. Measuring procedure

The advantage of in-situ measurements, taking into account the influence of the body of the player, is obvious. A measuring technique was thus tried which allowed for normal playing conditions. The surface velocity of the guitar was determined by means of a laser vibrometer. The scanning procedure lasted only a few minutes and allowed the instrument to be supported in playing position. The subject was sitting in a chair and held the guitar resting on his right thigh. The left hand grasped the neck at one of the lower frets (cf. Figure 1). In this way, the boundary conditions of normal playing could be reproduced to a high degree.

For exciting vibrations in the instrument an electrodynamic mini-shaker (BK 4810) was used. It was fed with pink noise from a noise generator (BK 1405) via an amplifier (BK 2706). As a reference signal, the force transferred to the guitar was measured by a piezoelectric force transducer (BK 8200) in combination with a conditioning amplifier (BK 2635). Since it is known from former investigations [14] that body vibrations are easily excited at the neck-end of the instrument, the shaker was positioned at the rear side of the neck near the 7th fret perpendicular to the fretboard, thus mainly driving out-of-plane motion of the instrument body.

For the vibration measurements a Polytec Scanning Vibrometer was used. This system contains a laser Doppler vibrometer which allows for non-contact measurements of the velocity of a surface in the direction of the laser beam. Only the region from the bridge to the nut is relevant with respect to the influence of the body motion on the string vibrations and the measurements were limited to this part of the guitar (cf. Figure 1). The velocity of the instrument surface was measured at 80 mesh points. The frequency range covered in the measurements was 500 Hz, and the resolution 2.5 Hz. The following data processing gave access to vibration patterns (operating deflection shapes) at any desired frequency.

2.3. Results

In Figure 1 the Les Paul guitar is held by author T.Z. In the lower panel vibration patterns of the main out-of-plane resonances are presented. For better visualization, the deflections are exaggerated. Only vibrations in the range between the fundamental frequency of the lowest tone (E_2 = 82 Hz) and 500 Hz (top string 7th fret) were considered. Within this range, two resonances are observed. In both cases the left end of the strings – the bridge – proves to be practically at rest. The lower resonance occurs at about 200 Hz. It exhibits a second node near the centre of the measuring area, and an anti-node close to the nut (at the 2nd fret, approximately). A higher resonance is found at 440 Hz at which the neck vibrates with an anti-node at the 5th fret and a node near the nut.

Figure 2 refers to the Stratocaster guitar held by author H.F. For this instrument, three pronounced resonances were found. At 425 Hz the vibration shape compares to the resonance at 440 Hz in Figure 1. In contrast, the resonance at

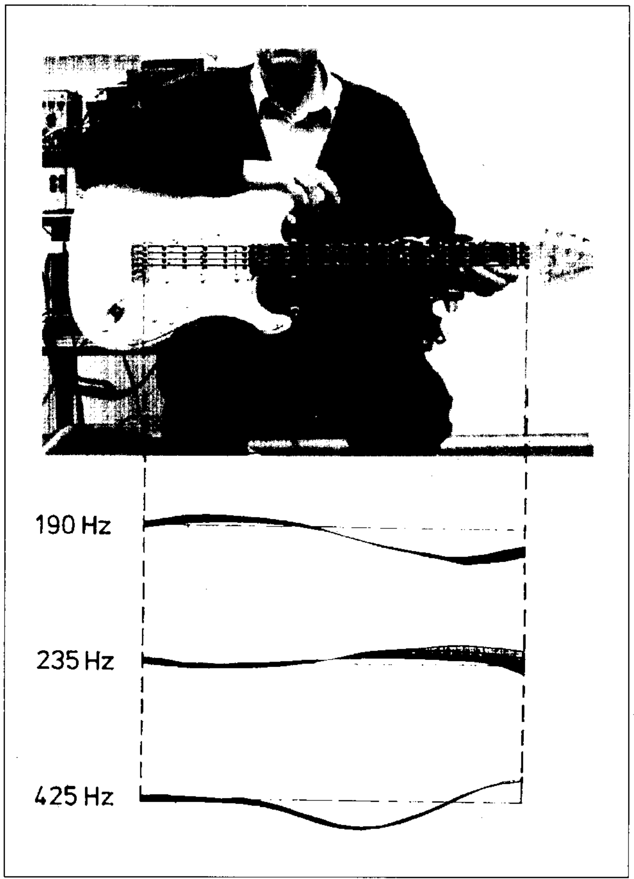

Figure 2. In-situ measurement of the out-of-plane vibration of the Stratocaster electric guitar. Top: Guitar held by a subject for measurement. Bottom: Vibration patterns of the three main out-of- plane resonances; zero-lines are indicated.

about 200 Hz in Figure 1 is split into two at 190 Hz and 235 Hz, respectively, with similar vibration shapes. Both resonances seem to be closely related with regard to the bending motion, and they both include a pronounced torsional motion of the neck as well. The main difference can be explained by differences in the phase relations between the superimposed torsional component and the bending component. Most probably, this effect is related to the asymmetry of the headstock of the Stratocaster guitar.

The results reveal that the neck of an electric guitar is not at all rigid. At particular frequencies it exhibits a pronounced motion. It can happen that one of these resonance frequencies coincides with the frequency of one of the strings and an interaction is then possible. In order to evoke a vibration of the neck by an excitation from the string, two requirements have to be fulfilled simultaneously: (1) The frequency of the string has to be close to the frequency of one of the neck resonances, and (2) the location of the point excitation on the neck (the string termination at the fret where the string is depressed) must be reasonably close to an anti-node of this resonance. For these reasons, the vibration patterns in Figures 1 and 2 are not easily interpreted in terms of influence of neck vibrations on the string motion. A more direct measuring approach is needed.

3. In-situ measurements of the admittance at the bridge

3.1. Mechanical admittance

The main topic of the present work is related to the energy transfer from the string to the body of the instrument. The response of a particular point of a structure to an excitation can be expressed by the mechanical point impedance (see e.g. [6]) or its reciprocal, the mechanical point admittance. The admittance, which sometimes is referred to as the "vibration willingness" [3], is used in the following in order to characterize the ability of the instrument to accept vibrational energy from the string.

The admittance is defined as the ratio of the complex amplitudes of the velocity and the force at the same point in the same direction. According to the German standard DIN 1320 [19] its real part is denoted conductance, and its imaginary part susceptance. The susceptance characterizes the spring- or mass-type behaviour of the structure at the driving point. The conductance determines how much of the active power available from the driving system, in this case the string, can be transferred to the structure.

3.2. Measuring procedure

The following set-up was used. A noise generator (BK 1405) fed pink noise via an amplifier (BK 2706) to a mini-shaker (BK 4810). At the tip of the shaker an impedance head (BK 8001) was fixed for simultaneous acquisition of force and acceleration. The influence of the transducer's mass was minimized by a mass compensation unit (BK 5565). The force and acceleration signals were processed by two conditioning amplifiers (BK 2626). After having reversed the polarity of the acceleration by a differential amplifier (Tektronix AM 502), FFT was performed and the complex mechanical admittance was calculated using a dual channel FFT analyzer (Ono Sokki CF 350).

The fundamental frequency of the lowest open string on the guitar is E_2 = 82 Hz, while the fundamental frequency of the top E_4 string at the 12th fret is 659 Hz. In order to cover this region a frequency range between 75 Hz and 700 Hz was chosen. In all figures which follow, the admittance is normalized to a reference value of 0.05 s/kg.

The measurements were performed in situ in a similar situation as shown in Figures 1 and 2. The shaker with the impedance head was fixed horizontally to a support in such a way that the guitar could be lightly pressed against the tip of the impedance head. Thus, in-situ measurements of the admittance at the bridge, nut, or frets, were possible. In order to simulate normal playing conditions, the experimenter's left hand grasped the neck close to the nut, or at the fret at which the admittance was measured. The output plug of the guitar pick-ups was left open-circuited. The strings were under normal tension and left undamped. All measurements were made by the same person. A comparison of data obtained in repeated experiments revealed that the reproducibility was satisfactory (see section 4.1).

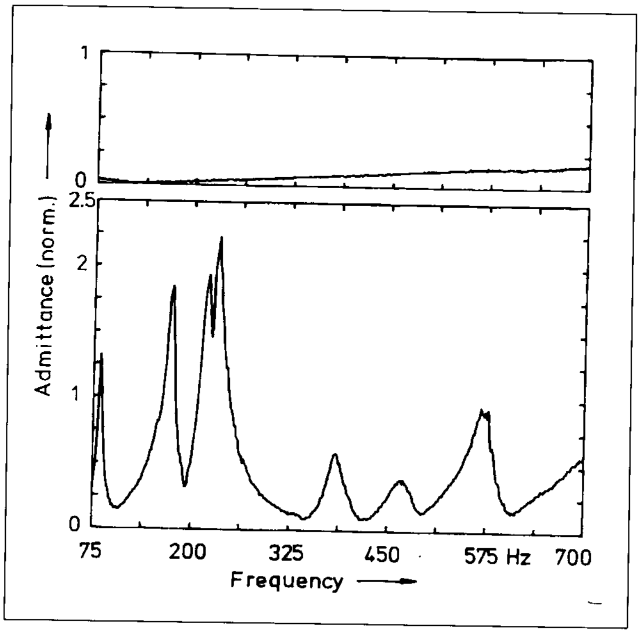

Figure 3. Magnitude of the mechanical driving-point admittance (normalized to 0.05 s/kg) measured at the bridge as a function of frequency; electric guitar Stratocaster (top), and acoustic guitar of the Spanish type (bottom).

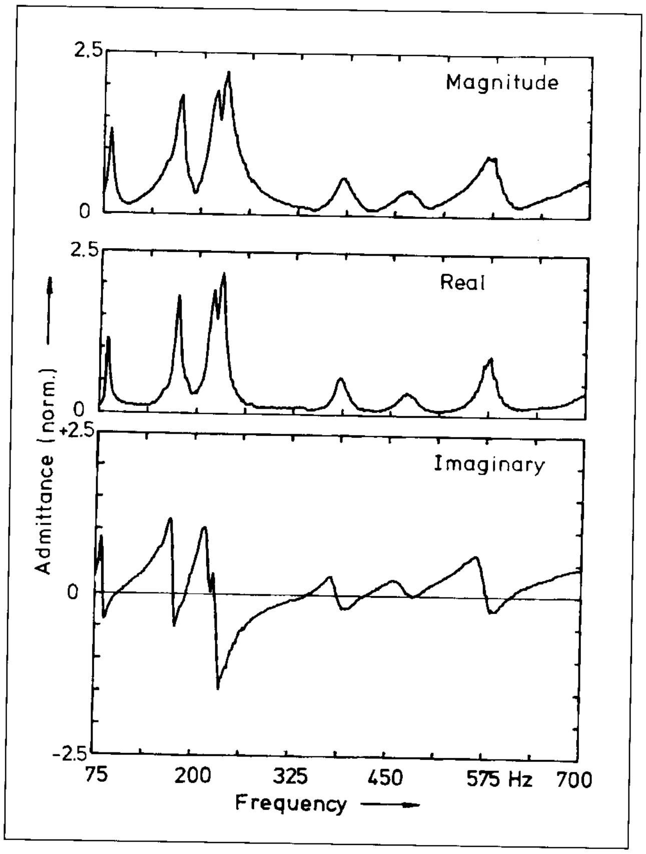

Figure 4. Normalized bridge admittance of a Spanish guitar as a function of frequency. Top: magnitude (admittance), middle: real part (conductance), and bottom: imaginary part(susceptance).

3.3. Results: Comparison between electric and acoustic guitars

In a first step, the orders of magnitude of the admittance at the bridge of an electric and an acoustic guitar, respectively, were compared. The measurements were taken on the bridge at the location of the G_3 string (close to the centre of the bridge) perpendicular to the top of the guitar. In the lower panel of Figure 3 the magnitude of the bridge impedance of a Spanish guitar is plotted versus frequency. Sharply pronounced peaks appear which reflect the well-known resonances of the body-air system of an acoustic guitar (see e.g. [3, 4]).

The upper panel in Figure 3 shows the measurement for the Stratocaster guitar. The bridge admittance is low and essentially constant over the measured frequency range. Only a minor increase in admittance with frequency is observed indicating that the bridge behaves like a stiff spring. It is to be noted that none of the two electric guitars included in the investigation had a bridge with a vibrato mechanism. As expected, the bridge admittance is much smaller for the Stratocaster than for the Spanish guitar. In conclusion, the support at the lower end of the string (bridge) proves to be very rigid for the electric guitar, and to be very flexible at distinct frequencies for the acoustic guitar.

In Figure 4 the mobility of the bridge of the Spanish guitar is described by the complex admittance. The magnitude of admittance as well as the real part (conductance) and imaginary part (susceptance) are given as a function of frequency. The susceptance shows the well-known fact that, depending on frequency, the bridge can behave like a spring or like a mass. This is one of the causes of inharmonicity of the partial frequencies of stringed instruments.

The transfer of (active) energy from string to bridge is related to the real part, the conductance, which is the ratio of the in-phase components of velocity and force. The conductance gives a direct measure of the damping of the string motion due to the mobility of the end supports. For the Spanish guitar in Figure 4 an efficient energy transfer can take place in narrow frequency regions at about 100 Hz, just below 200 Hz and, in particular, between 210 Hz and 230 Hz.

In these regions, the conductance at the bridge of the Spanish guitar reaches about 0.1 s/kg. The characteristic admittance of the string can be calculated from the tension and the linear density. The tension of a guitar steel string is between 100 and 180 N [6]. The density of steel is 7850 kg/m^3. Assuming a diameter of 1.2 mm for the lowest string and 0.3 mm for the top string, the characteristic admittance can be estimated to 1 s/kg for the E_2 string and 5 s/kg for the E_4 string. Thus, the maximum conductance at the bridge of the Spanish guitar is about 2 to 10 percent of the characteristic string admittance.

Figures 3 and 4 show that for an acoustic guitar the bridge is relatively mobile. Mobility is of course an intrinsic need for the transfer of energy from the string to the radiating part of the body in this type of instrument. However, this is not true for an electric guitar, in particular not for the solid-body type. Loss of energy via the instrument body is regarded as parasitic and undesired. Since the energy transfer

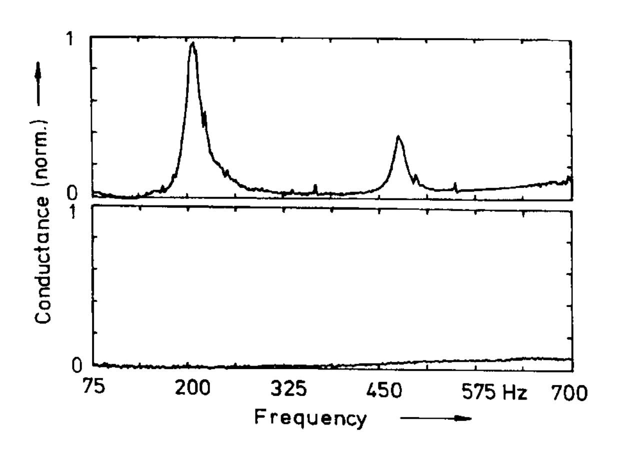

Figure 5. Normalized conductance of the Les Paul electric guitar as a function of frequency measured at the nut (top), and at the bridge (bottom).

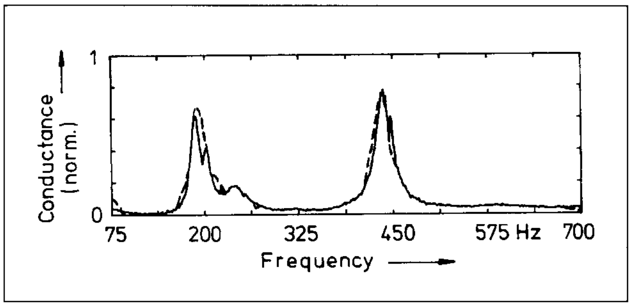

Figure 6. Repeated conductance measurements taken at the nut of the Stratocaster electric guitar by the same person with an interval of seven months.

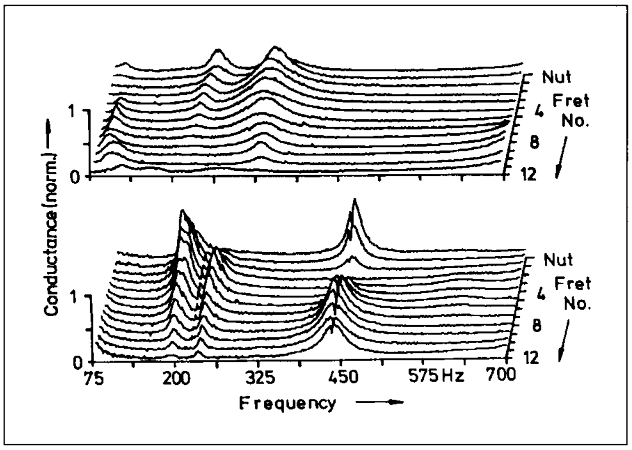

Figure 7. Normalized neck conductance of the Stratocaster electric guitar as a function of frequency measured at thirteen positions along the fretboard from the nut to the 12th fret. Measuring directions; in the fretboard plane (top), and perpendicular to the fretboard at the centre line between the D_3 and G_3 strings (bottom).

is determined by the conductance, only this part of the complex admittance will be discussed in the following sections dealing with electric guitars.

4. In-situ measurements of the mechanical conductance of electric guitars

4.1. Conductance at the bridge and nut

The normalized conductance at the nut and bridge for the Les Paul electric guitar is shown in Figure 5. As for the Spanish guitar the measurements were taken close to the centre line of the fretboard, at the position of the G_3 string.

The conductance at the bridge turns out to be relatively small for this well-made solid-body guitar. Only a slight uniform increase with frequency is observed. This result holds also for other measuring positions on the bridge which implies that all strings "see" an almost rigid support at their bridge-side termination. Since the conductance is small, only a minor energy loss via this end of the string is to be expected.

As Figure 5 also shows, the contrary is true for the upper termination of the open G string. The conductance at the nut exhibits pronounced peaks at about 200 Hz and 450 Hz, corresponding to the resonance frequencies indicated in Figure 1. In the vicinity of these frequencies the conductance at the nut is high. Energy flows from the string to the body via the upper termination which behaves like a damper. For an open string with a frequency close to one of these two frequencies, such as the G string (G_3 = 196 Hz), a considerable loss of energy from the string via its nut-side termination will occur.

This is the point to illustrate the reproducibility in the experiments. Two conductance measurements on the Stratocaster guitar taken seven months apart are shown in Figure 6. As can be seen the differences are small, less than 6 percent in peak amplitudes. Also the shifts in resonance frequencies are marginal, about 5 Hz corresponding to 1 percent. These comparisons of data obtained in repeated measurements with a considerable time in between indicate that the reproducibility was satisfactory.

4.2. In-plane and out-of-plane conductances at the neck

A guitar player shortens the strings by pressing them against the frets on the neck. In order to study this case, conductance measurements were made at the positions of the frets. Figure 7 shows the neck conductance up to the 12th fret for the Stratocaster guitar. The measurements were taken along the side of the neck (in the fretboard plane) and along the centre line of the fretboard (perpendicular to the fretboard plane), respectively. In order to simulate the influence of the hand and arm of the player when fingering the string, the experimenter held the neck close to the measuring position with his left hand.

The reason for measuring in two perpendicular directions is due to the plucking process. Normally, a plectrum is used for plucking the strings of an electric guitar. To a certain extent, the player is able to vary the plucking angle by changing the direction of motion of the tip of the plectrum. Consequently, the player can alter the plane in which the string initially vibrates within certain limits. There will always be components of vibration parallel (in-plane) and perpendicular (out-of-plane) to the fretboard. In order to account for both components of the string motion, the conductance was measured in both directions (see Figure 7).

The 3D-representation of the neck conductance for the Stratocaster guitar in Figure 7 creates "mountains" which indicate increased damping in certain frequency bands for certain measuring positions. In the fretboard plane, the peaks are relatively flat and not very high. When measuring out-of-plane along the centre of the fretboard (between the D_3 and G_3 strings), three pronounced "mountain chains" appear. They reflect the three body-neck resonances in Figure 2.

A comparison reveals that the conductance perpendicular to the fretboard plane reaches much higher values than in the plane. Obviously, the out-of-plane conductance dominates the damping effects (cf. [3, 6]). For this reason, only out-of-plane conductance measurements will be reported in the following.

4.3. Influence of the lateral position on the fretboard

The vibration patterns in Figures 1 and 2 indicate that a torsional motion may be superimposed on the bending motion of the neck. The influence of the torsional component was checked by comparing the point conductance at the centre of the fretboard with the conductances at the edges. These outer measuring positions were located between the two bottom and the two top strings, respectively.

The results for the Les Paul guitar are shown in Figure 8. The conductance is plotted for the nut and the first nineteen frets in a 3D-representation as a function of frequency. Separate diagrams are compiled for the three lateral measuring positions. The two main peaks at about 200 Hz and 450 Hz reflect the neck resonances displayed in Figure 1. Small discrepancies in the frequencies compared to the vibration measurements are presumably a consequence of variations in the support by the left hand (cf. Figures 1 and 8). While the player held the neck near the nut in Figure 1, the hand was positioned at the corresponding fret in the conductance measurement (Figure 8). The results for all three lateral positions are very similar. The small variance indicates that, for this guitar, the influence of the lateral measuring position on the conductance is negligible.

The headstock of the Les Paul guitar is symmetric, but the head of the Stratocaster guitar is asymmetric. The vibration measurements in Figure 2 have already shown that a pronounced torsional motion occurs with mode-splitting as a result. The consequences for the conductance can be seen in Figure 9, which shows the influence of the lateral measuring position for the Stratocaster guitar. Although all three diagrams (bottom strings, centre, and top strings) show the same basic characteristics, they differ in detail to a certain extent. The discrepancies are most evident for the double peak in the vicinity of 200 Hz. For the measuring position at the low string side the conductance is particularly high at about 190 Hz for the lower frets. The conductance at the high string side at the same frets is only about half this value,

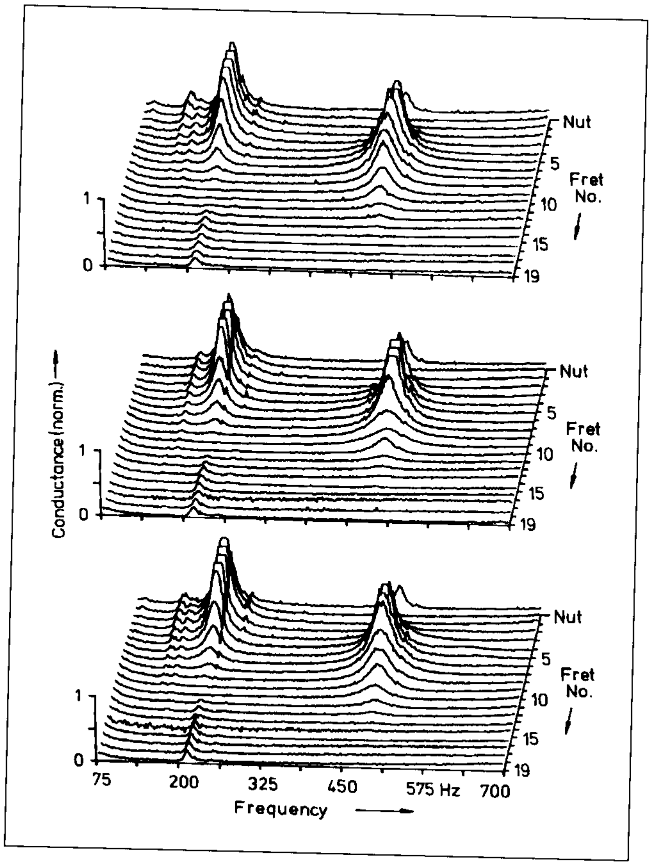

Figure 8. Normalized neck conductance of the Les Paul electric guitar measured along the fretboard from the nut to the 19th fret. Measuring positions: between the two lowest strings E_2 and A_2 (top), between the two middle strings D_3 and G_3 (middle), and between the two highest strings B_3 and E_4 (bottom). For comparability with the other figures the common normalization of 0.05 s/kg is used. For this reason, high peaks are clipped.

but an additional peak appears at a frequency about 40 Hz higher. Obviously, the conductance at one and the same fret can differ considerably between strings. The measurement at the centre position represents some kind of a mean value of the conductances at the outer positions.

These results reveal that, for detailed investigations, it is advisable to distinguish between guitars with symmetric and asymmetric heads, respectively. For instruments with strongly asymmetric headstocks such as the Stratocaster guitar, the conductance at the low-string side, the centre, and the high- string side of the fretboard can be quite different. In contrast, for instruments with symmetric headstocks such as the Les Paul guitar the conductance can be expected to depend only weakly on the lateral position. In this case, the centre-string conductance can be regarded as representative for all strings.

5. Conclusions

In the electric guitar the string signal is picked up and amplified electrically. In contrast to the acoustic guitar, signal

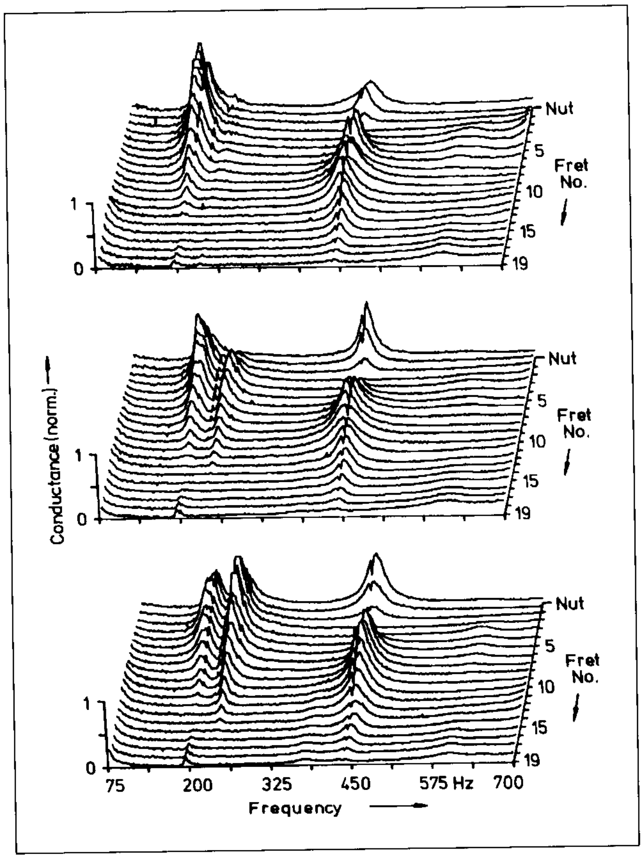

Figure 9. Normalized neck conductance of the Stratocaster electric guitar measured along the fretboard from the nut to the 19th fret. Measuring positions: between the two lowest strings E_2 and A_2 (top), between the two middle strings D_3 and G_3 (middle), and between the two highest strings B_3 and E_4 (bottom).

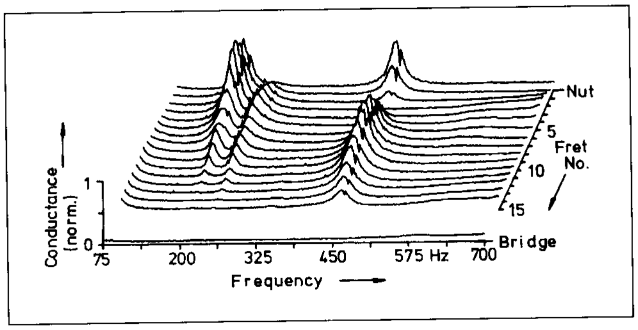

Figure 10. Normalized conductance at the nut, the first fifteen frets, and at the bridge of the Stratocaster electric guitar as a function of frequency measured along the centre line of the fretboard (between the D_3 and G_3 strings).

generation and sound radiation are distinctly separated. Consequently, there is no intrinsic need for energy transfer from the string to the body of the electric guitar. Our experiments show that the mechanical bridge conductance is very small for solid-body guitars compared to that of acoustic guitars. The result is in general a better "sustain", which electric guitar players mostly appreciate as a quality attribute.

Energy can be transferred from the string to the instrument body not only via the bridge but also via the neck. A complete characterization of a guitar requires knowledge of the energy loss at both end supports of the strings. The neck-end string termination is defined by the nut or by the fret against which the finger presses the string. In Figure 10 the conductance at the bridge and at the neck (measured at each fret from the nut up to the 15th fret) are summarized for the Stratocaster guitar in one diagram. As can be seen, the neck proves to be much more flexible than the bridge for a solid-body electric guitar of good quality.

There are particular positions on the fretboard called "dead spots" where, for one of the strings, the decay is extremely fast. This phenomenon has already been studied for electric basses by comparing string decay rates with body vibration measurements [12]. These experiments have suggested that the non-rigid behaviour of the instrument is the cause of dead spots. Previous studies [14, 16] indicate further that, compared to a description of the vibrations of the instrument body by modal parameters, the mechanical point admittance measured at the string terminations is easier to measure and interpret. The transfer of energy, which is the focus of interest for explaining the dead spots, is determined by the real part, the conductance. It is a measure of the damping at the end supports of the strings and therefore directly related to the decay rate of the string vibrations. Thus, the conductance can be regarded as a key parameter in studies of dead spots and associated phenomena on guitars.

Indications of dead spots can be found in Figure 10. If a conductance peak occurs at a certain fret position and at a frequency which happens to be close to a frequency of one of the strings when pressed down at that fret, a considerable energy loss can be expected via the neck-end termination of the string. The most prominent effect is to be expected for the fundamental frequency of the string. An example would be G_3 (fundamental frequency 196 Hz) played at the 5th fret of the D_3 string. Extensive experiments on the relations between neck conductance and dead spots will be reported in a following companion paper.

Special care was taken during the experiments to ensure realistic and reproducible boundary conditions. When a guitar is played it is in contact with the player's body. Up to now, guitars have had to be positioned in some experimental set-up for vibrational measurements, thus giving a basically different support of the instrument. This fundamental shortcoming has been overcome by the experimental technique used in this study. In order to keep the boundary conditions as natural as possible, normal sitting playing position was chosen with the experimenter's left hand grasping the neck of the instrument. This in-situ measuring approach has given the possibility of measuring the vibration patterns of the instrument body and the point conductances at the bridge and neck under the same boundary conditions. The method yields reproducible results and can be used in a number of studies of guitars from various aspects, such as the relation between design principles and the sound properties of electric guitars.

In conclusion, measurements of the neck conductance in situ have shown to be a powerful tool for studying the properties of the string terminations in guitars. Future work will extend the measurements to comparisons between the neck conductance of electric guitars and the decay rates of the string vibrations.

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[19] DIN 1320: Acoustics; Fundamental terms and definitions.