Investigating dead spots of electric guitars
(Improved Version)

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Summary

A long decay of the string vibrations of an electric guitar ("sustain") is considered as a quality attribute. In practice, there are particular locations on the fretboard where for one of the strings the sustain is shorter than at adjacent frets. The player calls this irregularity a "dead spot". It originates from the fact that the string causes the neck of the guitar to vibrate. As a consequence, energy flows from the string to the neck which results in a faster decay.

Three structurally different electric guitars (symmetric and asymmetric heads; neck screwed and glued to the body, respectively) served as measuring objects. In a first step, the decay times of the string signals were measured. In a second step, a technique was applied which allowed for in-situ measurements of the mechanical point conductance on the neck of guitars [7]. The experiments revealed a clear inverse relation between the decay time of the string vibrations and the magnitude of the neck conductance. A local high neck conductance indicates a dead spot. In conclusion, the driving-point conductance, measured on the neck perpendicular to the fretboard, promises to be a key parameter for the diagnosis of dead spots.

1. Introduction

The body of an electric guitar is normally manufactured from solid material in such a way that the bridge is as rigid as possible. As a rule, no considerable energy is transferred from the string to the body, and therefore the string signal of a solid-body electric guitar does not decay as rapidly as the signal of an acoustic instrument. In general, the "sustain" (long decay) of the electric guitar exceeds that of the acoustic guitar.

The sustain depends on several factors, e.g. the quality and the state of the string. For a given string, a uniform decrease in the sustain with increasing pitch can be observed. However, there are exceptions to this rule. At particular locations on the fretboard of an electric guitar the sustain is shorter than at adjacent frets. Players call this a "dead spot".

Theoretical considerations suggest that interactions the string and the instrument body have to be taken into account in order to explain the dead spots (cf. Fletcher and Rossing [1], Gough [2]). Heise [3], Wogram [4] and Fleischer and Zwicker [5] have measured the vibrations of the bodies of electric basses. Ziegenhals [6] dealt with the vibrations of electric guitars at the bridge. In a recent study, Fleischer and Zwicker [7] concentrated on the necks of electric guitars. They found that the mechanical point conductance proved to be a promising parameter for characterizing the energy-absorbing behaviour of the string supports.

In this study, three solid-body electric guitars are investigated with respect to dead spots and the relation to the conductance at the string terminations.

2. The guitars

The three guitars included in the study were made by well-known American manufacturers. All have six steel strings, about 62 to 65 cm in length, and 18 to 22 frets. The string vibrations are picked up by electromagnetic transducers. During the measurements the strings were normally tuned (E_2, A_2, D_3, G_3, B_3, and E_4, bottom to top open strings), and to concert pitch (A_2 = 110 Hz). The bodies and necks are all of wooden construction. The instruments can be characterized as follows:

* Stratocaster SRV Signature. Body made from ash wood and the neck from maple with a glued-on fretboard of rosewood. The headstock is asymmetrically shaped. The neck is bolted to the body by four screws. A typical Stratocaster-type vibrato unit is included.
* Les Paul K.M. A version of the well-known Les Paul Standard. Mahogany is used for the body and the neck, rosewood for the fretboard and maple for the top of the body. The neck is glued to the body. The headstock is symmetric.
* Explorer. This instrument originates from the same manufacturer as the Les Paul. Mahogany and rosewood are used for the same parts as above, and the neck is glued to the body. There is no maple top. The headstock is highly asymmetric. A Bigsby-style vibrato unit is added.

3. Decay of the string signals

In a first step, the sustain was investigated. Some typical experimental results will be presented for the three guitars.

3.1. Measuring procedure

The string signals of an electric guitar are easily accessed via the electric output socket of the built-in pick-ups. For the measurements, the tone and volume knobs were turned to their maximum positions. The pick-up closest to the neck was selected, located at approximately 1/4 of the string length from the bridge. No check of the amplitude linearity (mV/mm string amplitude) of the pick-ups was made. The measured decay processes represent, however, the actual conditions in playing.

The single strings (denoted E for E_2, A for A_2, D for D_3, G for G_3, B for B_3 and e for E_4) were plucked manually by means of a plectrum. The output signal was fed to an FFT analyzer (Ono Sokki CF 350) and analyzed. The time window had a length of 0.4 s corresponding to a bandwidth of 1 kHz.

As an example, the decay of the open strings of the Explorer guitar is shown in Figure 1. The level is plotted in a 3D-representation as a function of frequency and time. Since the neck pick-up was used, the level of the fundamental is relatively high. As a rule, the fundamental decays more slowly than the higher partials. This means that under normal conditions, the decay of the total signal will be dominated by the fundamental. As can be seen from a comparison of the six diagrams, the high-pitched strings will normally decay faster than the lower. A similar relation can be expected for the fingered notes, so that the higher the number of the fret at which the string is stopped, the shorter the decay will be.

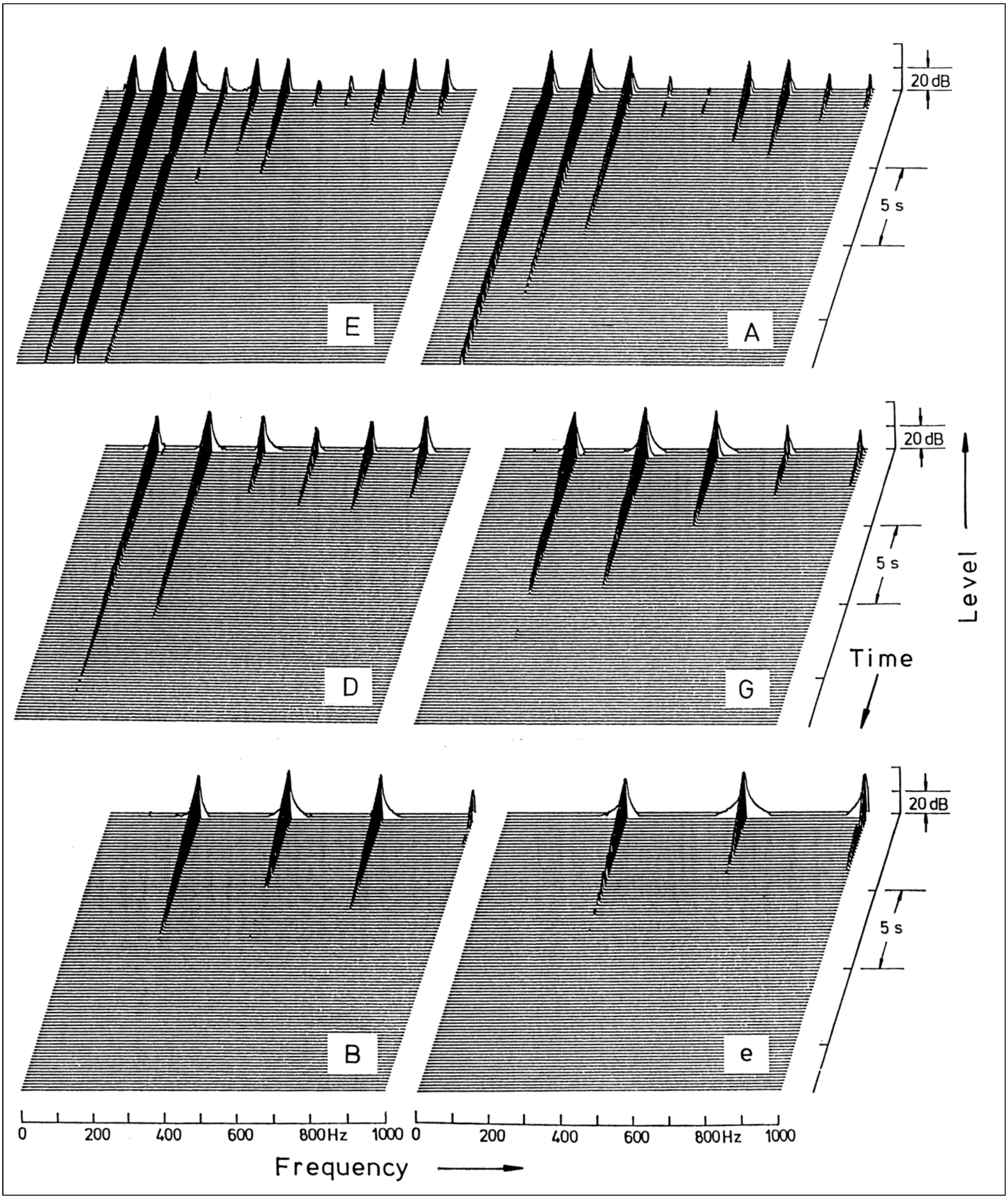


Figure 1. 3D-diagrams (level versus frequency versus time) showing the decay of the open strings of the Explorer electric guitar.

In order to quantify the sustain, the level of the total string signal was evaluated. The guitar under measurement was held by author T.Z. – an experienced amateur musician – in playing position. The player plucked the string by means of a plectrum in such an angle that the string vibration contained components both parallel and perpendicular to the fretboard. The output signal of the neck pick-up was fed to a level recorder (BK 2305).

Three characteristic variants of the decay behaviour of the string signals were observed (see Figure 2). In Figure 2(a) the level decreases linearly versus time, and in Figure 2(c) approximately linearly. This represents the normal case indicating that one partial – normally the fundamental – dominates the decay of the string signal. In some cases, a non-monotonic decay as shown in Figure 2(b) was observed. Such a decay is characteristic of two tones beating against each other. Most probably it is caused by two partials with similar amplitudes and decay rates but with their frequencies not exactly in harmonic relation (cf. the first two partials in the G-string diagram of Figure 1).

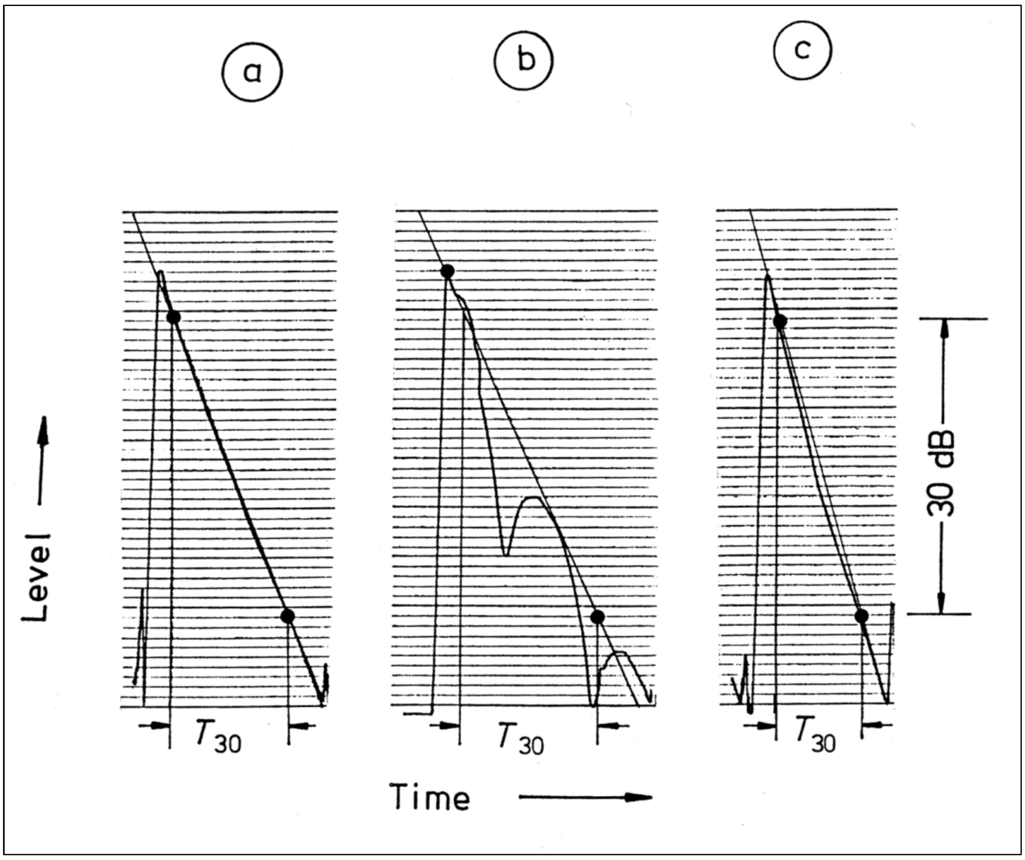


Figure 2. Typical decay curves at different locations on the G string of the Explorer electric guitar: (a) 6th fret, (b) nut (open string), and (c) 11th fret. Sloping lines are inserted lines for determination of the decay time T_{30}.

The decay curves were approximated with straight lines in order to calculate the average decay (see Figure 2). These lines were manually fitted to the curves. A decay time T_{30} was determined, during which the total level of the string signal decreased by 30 dB. According to Zwicker and Fastl [8] this level difference corresponds roughly to a decrease of the loudness sensation by a factor of eight. In the following, the sustain will be characterized by the decay time T_{30}. A "dead spot" on the fretboard is indicated by an abnormally short T_{30} for the respective note. Correspondingly, a position on the neck where the decay time is longer than at adjacent frets is called a "live spot"

3.2. Experimental results

Decay times T_{30} for the Stratocaster guitar are presented in Figure 3. They were measured for the open strings, as well as for each fret position of all strings. Results of two subsequent measuring series by the same player are given by open circles. The filled circles represent the linear averages of the two plucks. Normally, the decay times obtained in repeated measurements agreed closely, indicating satisfactory reproducibility. Discrepancies between repeats as observed in some cases (cf. the lower frets of the A string) never exceeded 20%. Such discrepancies may be caused by slightly differing angles of the plectrum when plucking the string (cf. Jansson [9]).

As can be seen, it takes between 2 to 20 s approximately for the string signal to decay by 30 dB. An approximately steady decrease of the decay time with increasing fret number (pitch) is observed, most pronounced for the lower strings (E and A). Uncommonly short decay times which indicate dead spots are observed, for instance, at the 10th fret of the A string, at the 4th and 9th fret of the D string, as well as at the first and 5th fret of the G string. Examples of relatively long decay times suggesting live spots are found at the 8th and 11th fret of the D string, and at the 9th fret of the G string.

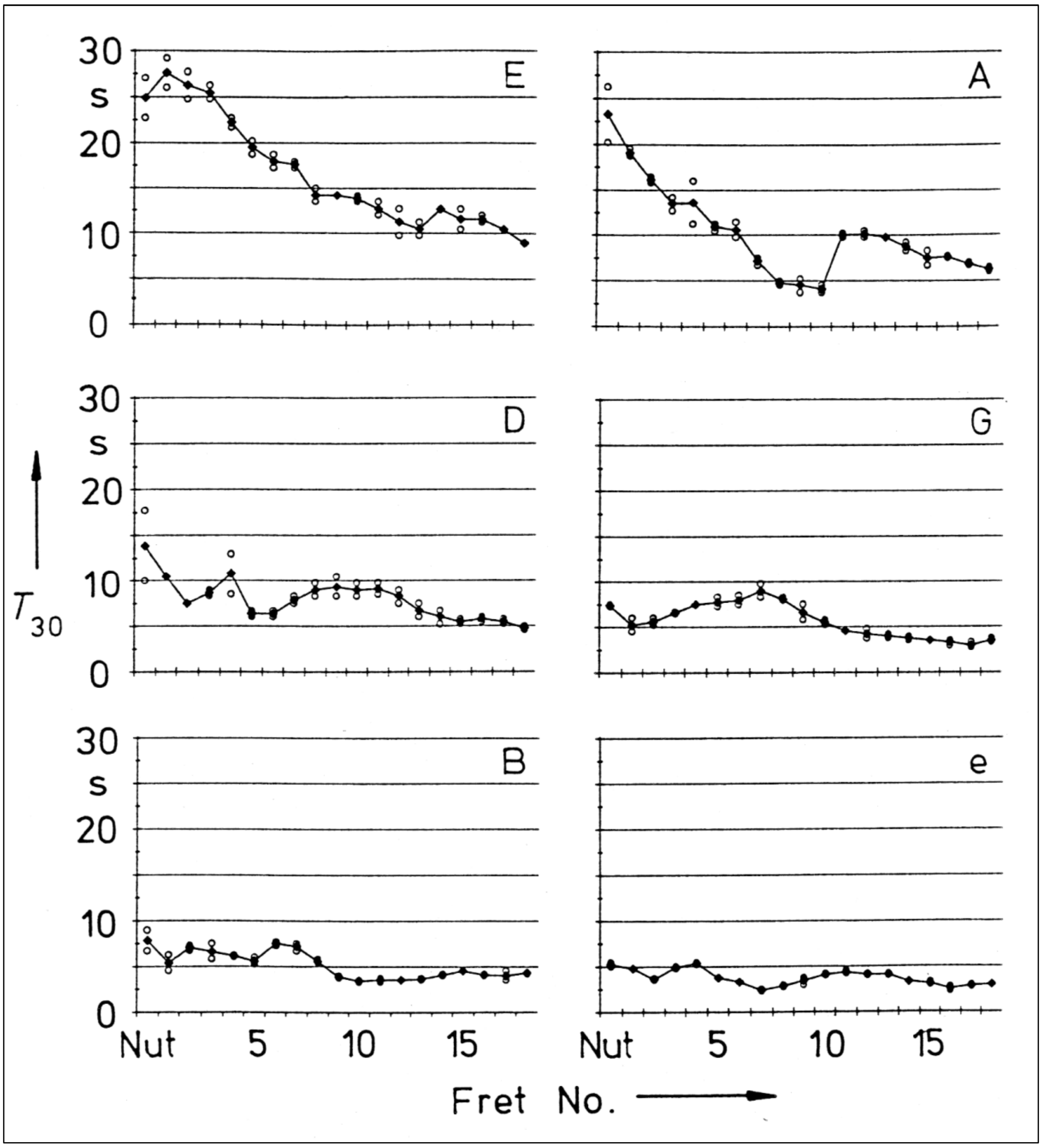


Figure 3. Decay times T_{30} of the signals of the six strings (open and fingered) of the Stratocaster electric guitar. Open circles indicate single plucks and filled circles the linear average of two measurements.

4. Conductance measurements

The second step aimed at characterizing the mechanical behaviour of the end supports of the strings. A parameter suited for this purpose is the driving point admittance [5, 7, 10 - 15] The real part of mechanical admittance, the conductance, characterizes to which extent a structure is capable of accepting active power.

For the guitar, the driving force is the force which the string exerts on the end supports. Depending on the plucking conditions, the transverse vibrations of the string are polarized resulting in two components of the force, one parallel and one perpendicular to the body-fretboard plane (cf. Jansson [9]). The corresponding conductances differ. Experiments by Fleischer and Zwicker [7] indicate that, in general, the neck conductance tends to be smaller in the fretboard plane than out of the plane. In order to focus on the most prominent effect, all conductance measurements in the present study were restricted to the direction perpendicular to the fretboard-body-plane. The out-of-plane conductance at the contact point between the string and the fretboard (nut) was taken as a measure of the parasitic energy flow which primarily determines the dead spots.

4.1. Measuring set-up

A method for measuring the neck conductance of guitars has been reported recently [7, 13 - 15]. Pink noise from a noise generator (BK 1405) is fed via an amplifier (BK 2706) to an electrodynamic vibration exciter (BK 4810). Force and acceleration at the measuring point are picked up simultaneously by an impedance head (BK 8001). After conditioning, both signals are fed to a dual-channel FFT analyzer (Ono Sokki CF 350) where the mechanical conductance is computed.

Measuring the driving force directly at the contact point and using it as a reference ensures that the dynamic mass and stiffness of the shaker do not influence the vibrational properties of the neck. This was checked by measurements using several vibration exciters with differing mass of the driving system. The only additional loading of the guitar neck is caused by the dynamic mass below the force gauge of the impedance head. This mass of about 1 g was compensated electrically by means of a mass compensation unit (BK 5565). In the figures which follow the conductance is normalized to a reference value of 0.016 s/kg.

All measurements were performed *in situ*. The player was sitting on a chair with the guitar resting on his thigh. His left hand held the neck near the location where the conductance was determined. The shaker was fixed in such a way that the player could press the instrument lightly against the tip of the impedance head. In this way, the conditions of normal playing could be closely simulated. The reproducibility between repeated measurements was good [7].

Previous experiments have revealed that the conductance of the neck may depend on the lateral measuring position on the fretboard (bottom string - centre - top string; cf. [7]). This applies in particular to instruments with strongly asymmetric headstocks such as the Stratocaster or Explorer guitars. In contrast, the conductance is largely independent of the lateral location for essentially symmetric instruments such as the Les Paul guitar. For the sake of simplicity, only results which refer to measurements at the mid-points of the nut and the bridge, and along the centre line of the fretboard will be presented in the following. Consequently, only dead spots on the mid-strings D and G will be discussed.

4.2. Nut and bridge conductances

In Figure 4 typical conductances are presented as measured at the mid-points of the nut and the bridge, respectively (the end supports of the open D and G strings) of the Explorer guitar. The lower diagram shows that the conductance at the bridge is low over the entire measured frequency range with a minor increase towards higher frequencies. This means that at the bridge termination the string "sees" a support with no considerable energy loss, despite the fact that this guitar features a vibrato mechanism.

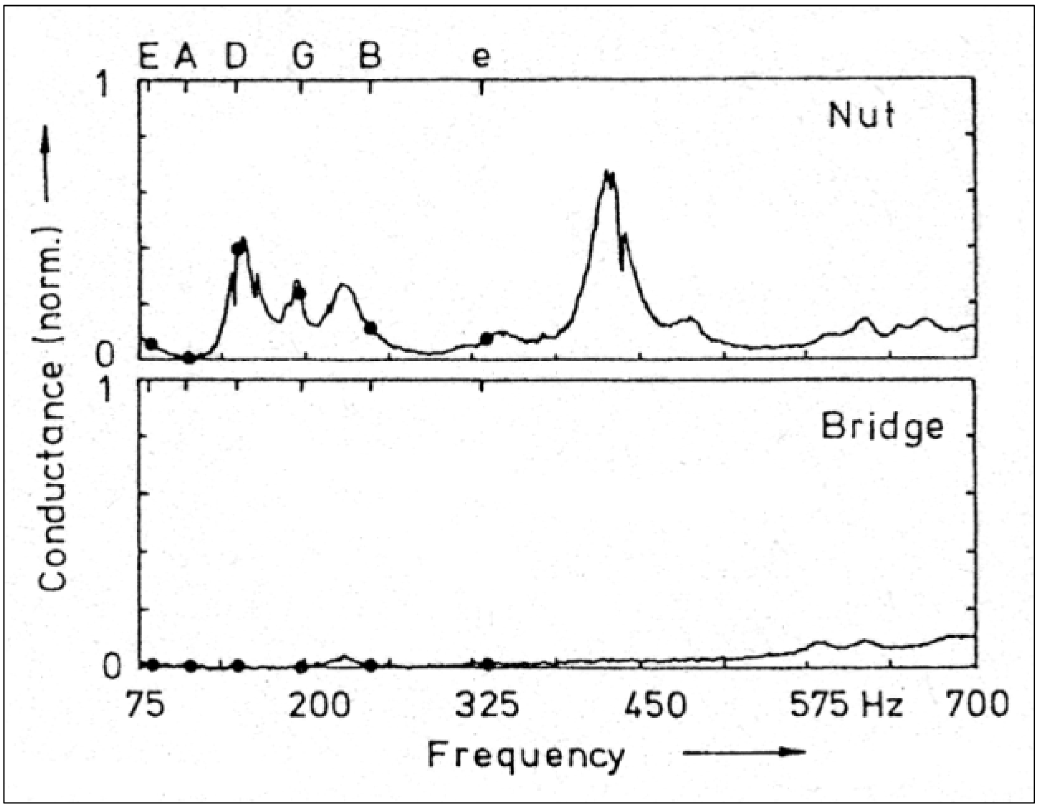


Figure 4. Conductance of the Explorer electric guitar, normalized to 0.016 s/kg, as a function of frequency measured at the nut (top), and at the bridge (bottom). The dots indicate the fundamental frequencies of the open strings. The measurements were taken at the centre of the nut and bridge, respectively, between the D and G strings. The conductance curves may differ for the outer strings.

For the open string, the other termination is defined by the nut. The upper diagram in Figure 4 shows sharply pronounced peaks in the conductance at the nut in the low and mid frequency range. In certain frequency bands the conductance at the nut exceeds that at the bridge considerably. Obviously, the strings of the electric guitar tend to lose less energy via the bridge termination than via the nut.

In order to interpret the measured conductances at the frets in view of the practical significance, the combination of the fret position and the frequency of the string has to be taken into account. Since in the normal case (no dead spot), the decay of the string vibrations is dominated by the fundamental (see e.g. Figure 1), the following discussion will be restricted to the fundamental frequencies. If necessary, it could be expanded to any other partial frequency.

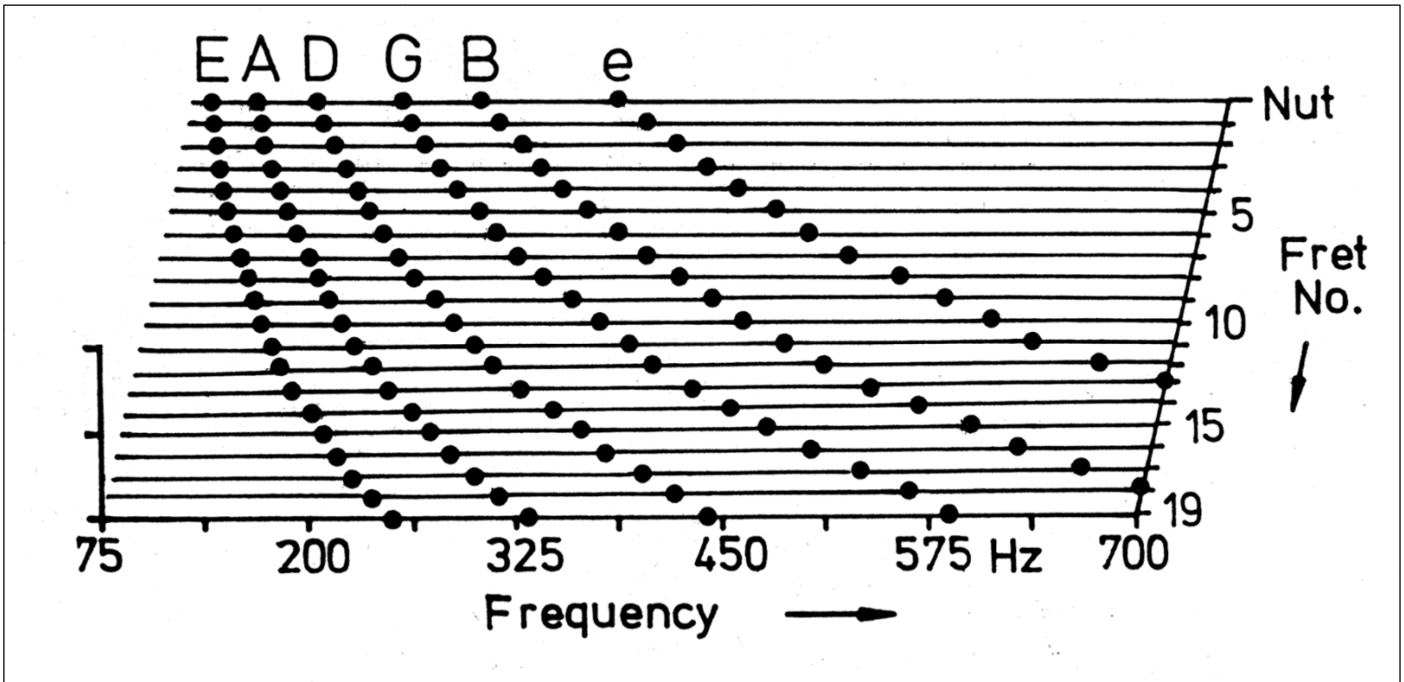


Figure 5. "Overlay chart" for the evaluation of the neck conductance diagrams. The dots indicate the fundamental frequencies of all string-fret combinations.

At the bridge the frequency of the driving force can take any value in the whole set of fundamental frequencies which can be played on the strings. At the nut, the relevant frequencies are the fundamental of the open strings. At each fret only one specific frequency value will be relevant for each string (the corresponding fundamental frequency). The higher the conductance is at a certain fundamental frequency, the faster this fundamental will decay.

In Figure 4 the nut and bridge conductances at the fundamental frequencies of the open strings are indicated by dots. In this example, no considerable effects on the decay are indicated for the fundamental of the open E and A strings as well as of the top e string. In contrast, a more rapid decay is to be expected for the open G and B strings, and, in particular, for the D string. As illustrated by this example, the decay of the string signal of a well-made electric guitar will be determined mainly by the termination at the neck rather than by the bridge.

4.3. Neck conductance

When a string is fingered, the neck-end termination is defined by the conductance at the fret against which the player presses the string. Hence, the discussion above which referred to the open string termination at the nut must be repeated for each single fret. Examples are given in Figures 6 through 8. In all cases, the conductances were measured along the centre line of the fretboard between the D and G strings.

A 3-D representation (cf. Fleischer and Zwicker [7] and Fleischer [13, 15]) is used in order to condense the measuring data. In one diagram, the conductances at the nut and at the first nineteen frets of all six strings are plotted as a function of frequency. Each curve refers to a specific fret as indicated by the corresponding number (right abscissa). A mountainous "conductance landscape" is created in which the mountain crests reflect vibrational patterns ("modes") of the guitar body and neck. Some of them exhibit a multiple-peak structure which is discussed by Fleischer and Zwicker [7]. Since a high conductance corresponds to high losses of energy at the corresponding frequency, the peaks serve as indicators of dead spots, while valleys correspond to live spots.

An overlay chart (see Figure 5) may facilitate the interpretation of the conductance landscapes in Figures 6 through 8. This chart shows the fundamental frequencies versus fret position of all six strings, open and fingered. The conductance magnitude has to be checked for each string-fret combination. Coincidence with a mountain in the conductance landscape or a local high peak suggests a dead spot at that particular string-fret combination. Correspondingly, a deep valley indicates a live spot.

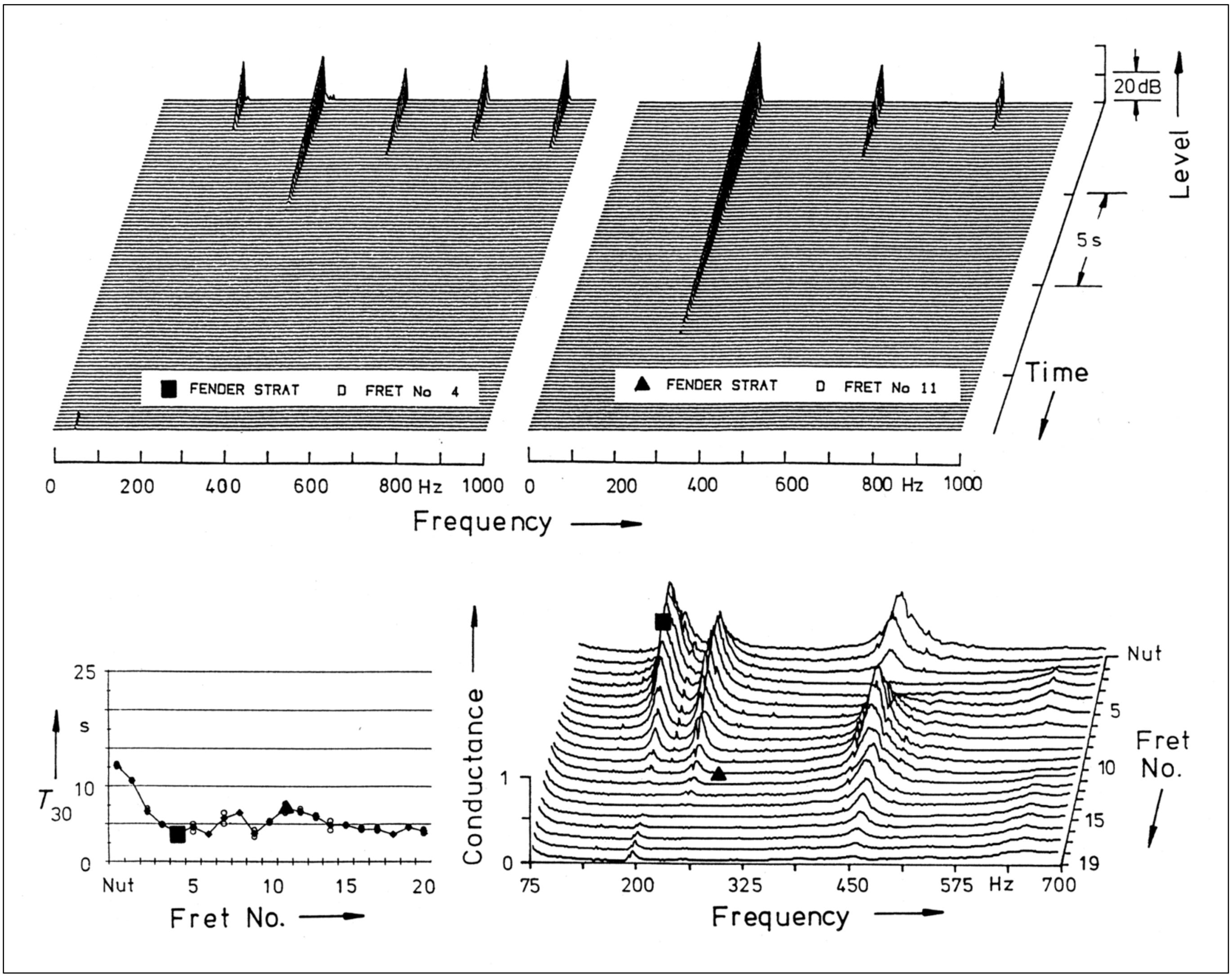
5. Comparison between decay times and neck conductance

In order to illustrate the relationship between the neck conductance and the decay time, the experimental data for all three guitars including string decay versus time, decay times, and neck conductances were compiled (Figures 6 through 8). Two contrasting cases (irregularities) on one and the same string, representing a dead spot (square) and a live spot (triangle), respectively, are indicated in each conductance plot. The live spot is always found at a higher fret than the dead spot. Since the conductances were measured along the centre line, and there may be a lateral variance, only the D or G strings are considered in the following discussion.

5.1. Stratocaster guitar

The Stratocaster exhibits a dead spot (square) at the 4th fret and a live spot (triangle) at the 11th fret of the D string (see Figure 6). The corresponding decay times differ by a factor of almost two. The upper two diagrams show a drastic difference in the decay of the fundamental. While at the 11th fret (right) the fundamental component decays very slowly and therefore dominates the decay of the total signal, the situation is reversed at the 4th fret (left) where the decay is determined by higher components.

The fundamental frequencies of the D string played at the 4th and 11th fret are 185 Hz and 278 Hz. As seen in the conductance plot, the conductance is dramatically different for the two fret positions. At the 11th fret (triangle) the conductance is very low for the fundamental frequency and there is no essential damping due to the neck-end support. At the 4th fret (square) the conductance reaches a maximum and the fundamental is extremely damped as seen in the upper left decay diagram.



3D-diagrams at the top: Signals of the D string at the 4th fret (dead spot, left) and at the 11th fret (live spot; right).
Bottom: Decay time T_{30} of the D string (left) and normalized neck conductance (right).
The square indicates a dead spot and the triangle a live spot.

5.2. Les Paul guitar

According to Figure 7 a dead spot is found at the 3rd fret and a live spot at the 6th fret of the G string of the Les Paul guitar. At the live spot, the decay time is more than twice as long as at the dead spot. The decay diagrams reveal that the cause is the difference in the decay of the fundamentals at 233 Hz and 278 Hz, respectively.

The square in the conductance diagram at the 3rd fret indicates a very high conductance value, which promotes the decay of the fundamental.

The second partial at 466 Hz also decays relatively fast. This is caused by a peak of the second mountain at approximately the corresponding frequency. In contrast, the triangle attests a very low conductance at the 6th fret of the G string, indicating a live spot.

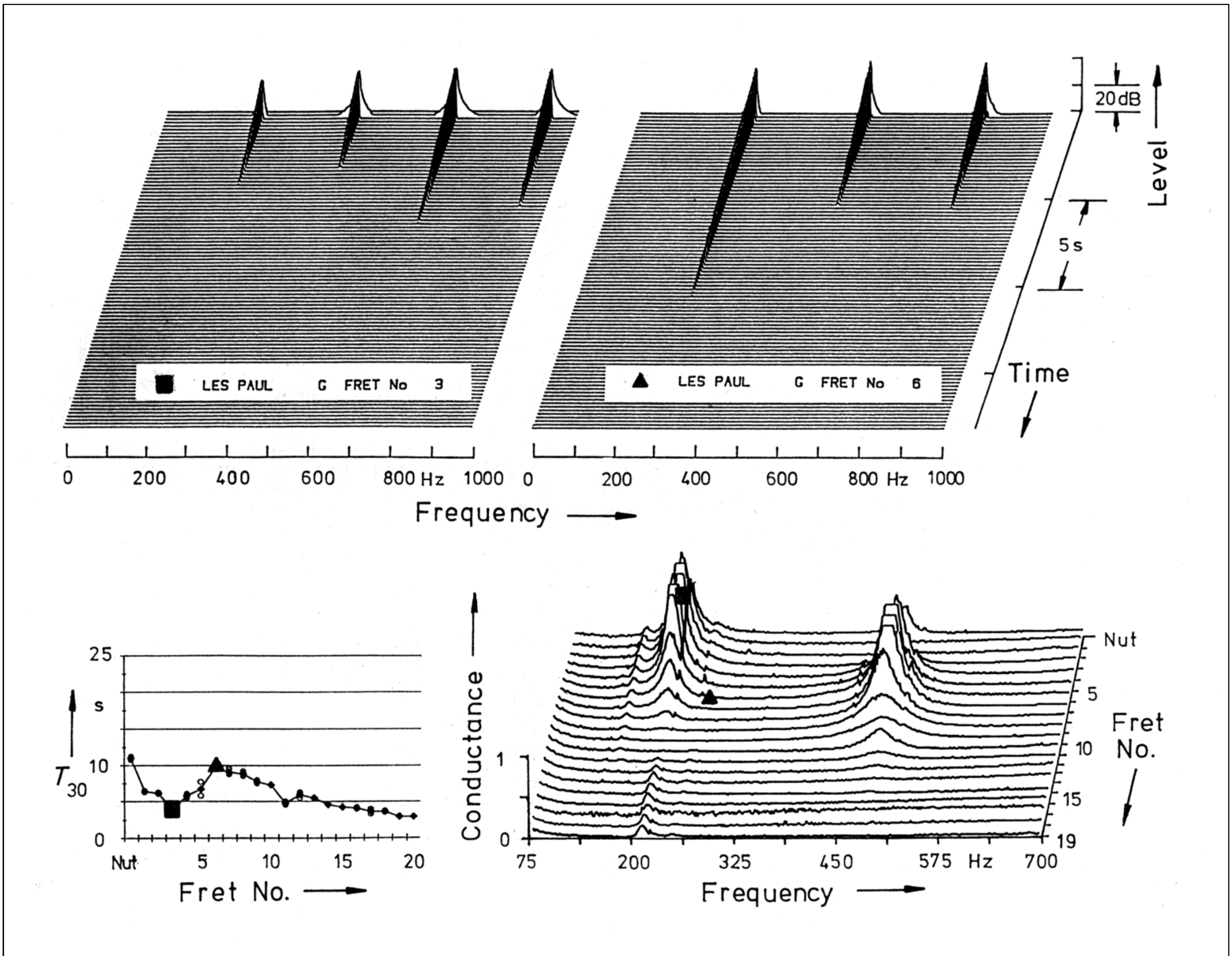


Figure 7. Les Paul electric guitar.
3D-diagrams at the top: Signals of the G string at the 3rd fret (dead spot, left) and at the 6th fret (live spot; right).
Bottom: Decay rate T_{30} of the G string (left) and normalized neck conductance (right).

5.3. Explorer guitar

On the D string of the Explorer guitar (Figure 8) a dead spot occurs at the 8th fret. Only two frets up from this position (at the 10th fret, corresponding to two half tone steps) a live spot is observed. Normally a faster decay would be expected at a higher fret, but in this case the string signal lasts almost three times longer at the 10th fret compared to the 8th fret. Again, the upper diagrams reveal the fundamental to be the cause of the difference.

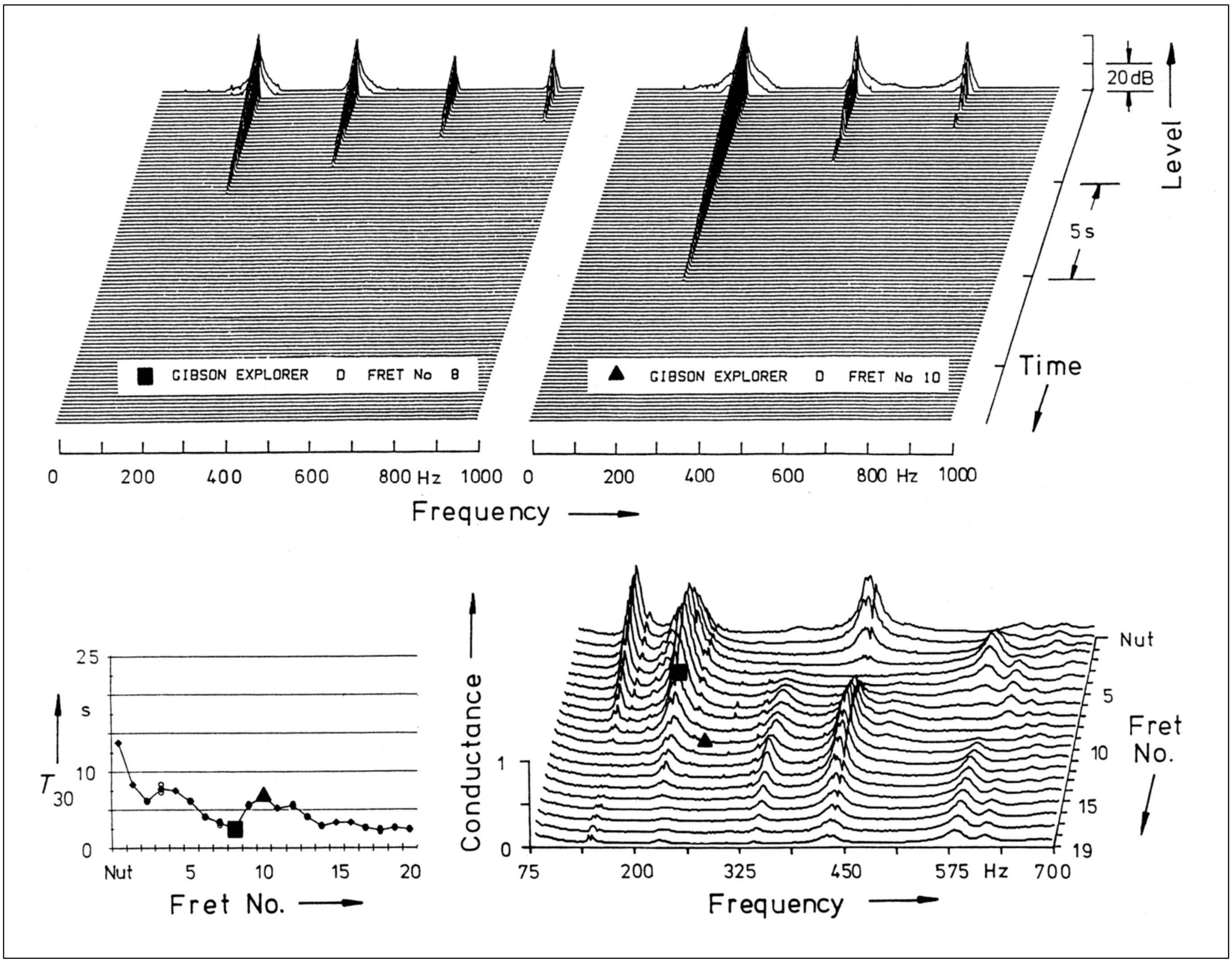


Figure 8. Explorer electric guitar.
3D-diagrams at the top: Signals of the D string at the 8th fret (dead spot, left) and at the 10th fret (live spot; right).
Bottom: Decay rate T_{30} of the D string (left)
and normalized neck conductance (right).

The conductance is high for the fundamental at the 8th fret (233 Hz, square) and considerably lower at the 10th fret (262 Hz, triangle). A dead spot at the third fret (fundamental frequency 175 Hz), visible in decay time diagram, is caused by a high conductance in the region of the first mountain at about 160 Hz.

6. Conclusions

The aims of the present study were to find the origin of dead spots, to develop a diagnostic tool, and to investigate its applicability. Dead spots are caused by the fact that the instrument body is flexible and may be excited to considerable vibrations with the consequence that the string vibration is additionally damped. The real part of the mechanical admittance, the conductance, determines the rate at which energy flows irreversibly from the string into the neck and body via the string supports. For this reason the conductance is a suitable indicator of the frequency-selective damping behaviour of the end supports.

In contrast to the acoustic guitar, the conductance at the bridge is very low for a well-made electric guitar, and the decay of the string vibrations is determined mainly by the neck-end support. The conductance should therefore be measured at the nut and at the frets. Earlier investigations [7] have suggested that the neck of the electric guitar is more mobile out of the fretboard-body plane than in the plane. Consequently, to describe the main effect, the conductance was measured perpendicular to the fretboard.

An *in-situ* measuring set-up was used which allowed for positioning the guitar in contact with the body and the hand of the player. In this way, "natural" boundary conditions were achieved, comparable to those in actual playing.

The conductance was measured at the centre line of the fretboard and is therefore relevant for the D and G strings. As the conductance may depend on the lateral measuring position [7], it may be necessary to make several conductance measurements at each fret position, in the extreme case as many as one at each string position, in order to characterize a guitar completely.

Measurements of the decay time ("sustain") were made, using the output of the neck pick-up. As the fundamental normally dominates the decay of the signal, when using this pick-up, a dead spot can be identified as an abnormally fast decay of the fundamental. For all three guitars investigated, a close inverse relation between the decay time T_{30} and the height in the "conductance landscape" at the corresponding string-fret combination was evident.

The higher the neck conductance at the frequency of the fundamental, the more probable it is to find a dead spot at the corresponding fret. This conclusion is verified for the example of the G string of the Explorer electric guitar. At the bottom of Figure 9 the decay times are plotted for the nut and the first 15 frets. The top shows the corresponding neck conductance as taken from the 3D-diagram of Figure 8 using the overlay chart of Figure 5. A comparison reveals that at the locations on the fretboard where the conductance is very high (e.g. at the second, 10^{th} and 14^{th} fret) the signal decays faster that at adjacent frets. The strong inverse coincidence of neck conductance and decay times is obvious and suggests that conductance maxima are useful as indicators of dead spots, but additional research is necessary.

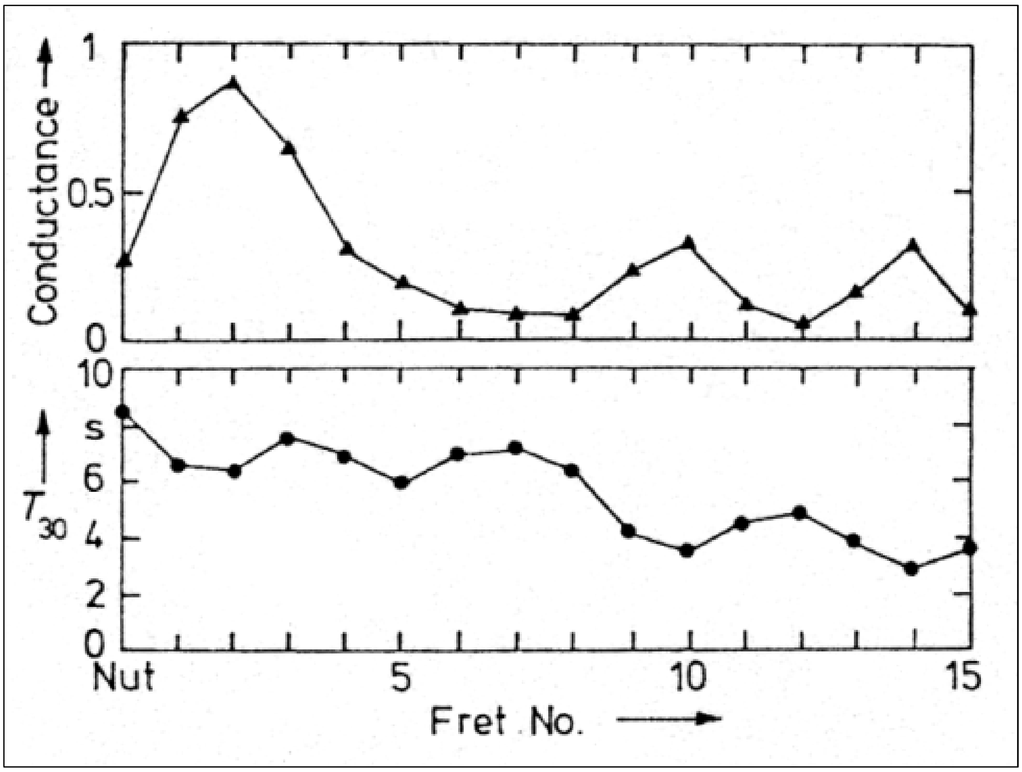


Figure 9. Decay times T_{30} of the G string of the Explorer electric guitar (bottom) and corresponding normalized conductance (top).

No clear indications were found that the different fixture of the neck to the body (screwed and glued, respectively) is reflected in the conductance. However, as a clear connection between the design of the guitar and the conductance landscape it was observed that the symmetric headstock of the Les Paul guitar results in only one mountain in the 200 Hz region while the asymmetric headstock of the Stratocaster and Explorer guitars result in two. As shown in [7], the asymmetry causes splitting of the corresponding bending vibrational shape due to superimposed torsional motion as well as shifting of the frequencies. The conductance mountain of the Les Paul guitar influences primarily the lower frets of the G string (cf. Figure 7). The additional low-frequency mountain of the Explorer guitar indicates further dead spots at the low frets of the D string are (cf. Figure 8).

The results suggest that it is not necessary to suppress the vibrations of the neck *per se* in order to avoid dead spots. Rather, the neck vibrations need to be tuned in such a way that the conductance does not exceed a certain level at the fundamental frequencies of the scale tones which correspond to the fret positions. Using the landscape representation, this means that conductance mountains may exist as long as the fundamental frequencies do not coincide with high peaks, but stay in valleys or plains of the conductance relief.

In conclusion, the out-of-plane conductance as measured in situ at the neck of an electric guitar can be simply determined. Such a measurement yields condensed information about the amount of damping at the neck-end support where the main part of the losses occur. The neck conductance promises to be a key parameter for assessing the quality of electric plucked instruments since it can be used as a tool for predicting (and avoiding) dead spots.

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