7.12 Vibration – Sound – Tone

Presumably, most guitar players seek to make music rather than solve differential equations for vibrations. That's the right spirit – despite all that physics stuff we should remind ourselves of that main purpose of the electric guitar! Okay, the instrument may also be set on fire (Monterey et al.), but that brings the service life down to inacceptable levels. How marvelous when we use it as tone generator: notes and sounds, rapture and ecstasy, consonance and dissonance, emotion and tinnitus. However, just asking about the tone generation, we're back in physics: vibration generates electricity generates airborne sound generates perceived tone.

The guitar string will carry out vibrations – if you let it. The previous chapters have shown that, for the magnetic pickup, the vibration velocity of the section of string above the magnetic pole is significant. The pickup transforms the vibration velocity (the particle velocity) into an electrical voltage that, if sufficiently amplified, will power the loudspeaker membrane. The latter in turn excites air particles into vibrations, and these propagate as waves in the medium of air, and form the **sound field**. As these sound waves reach the ear, they are converted into membrane- and lever-vibrations, in the end generating impulses on nerve fibers and auditory perceptions: tones, in plain language. The term **tone** is used in a number of ways: in signal theory, it may designate the sum of many individual harmonic partials[♣], while in auditory psychology, it may indicate any perceived sound. Outside of the realm of psychoacoustics, however, the tone simply is what science designates as "tone color" or "sound color": the guitar has a "throaty", "chunky", "singing", or simply a "hot" tone. How does it do that?

7.12.1 Linear string vibrations

The source for the pickup voltage is the section of string vibrating over the magnet. Plucking the string feeds energy to it that then is lost again during the decay process. Friction against the air and internal friction within the string convert part of the energy into heat while the remaining part wanders off: via the string bearing (bridge, and nut or fret) into guitar body and neck. And no, despite what many guitar and bass magazines' continuously circulate: the vibration energy should not as much as possible transferred to the guitar body, it should nicely stay within the string. It has proven to be conducive to expand the string vibration into a harmonic series (Chapter 8.2.4) i.e. to interpret it as the sum of individual partial sine-tones. The previous chapters have shown that these **partials** decay quickly or slowly, depending on the partial-specific damping mechanism. The tone results from frequency, level and decay behavior of all partials – that's easily said but much harder exactly described, because e.g. for the E_2-string, we would need to analyze more than 60 partials that do not simply decay exponentially. Due to this vast variety of parameters, one may arrive at very different strategies: we could mistrust "any theory whatsoever", and plug different guitars into various amps to conduct listening tests, or we could extract typical parameters from vibration measurements to synthesize artificial tones. Both approaches have their merits as long as the experimentation methodology does not contain any grave errors. Unfortunately, many of those seeking a "practical" approach are of the opinion that one cannot go wrong with performing listening tests. Rest assured, you can …

♣ The sum of sine-tones of only whole-number frequency relationships may also be termed *complex tone*.

Here's a typical "listening experiment": at a concert, you get to hear Draco Deathbringer playing his black Gothic Special (the one with the real-blood position markers). The next day, you visit your large local store down by the river – they advertise just that model (along with 1400 others). You check out the guitar on display and are disappointed beyond measure. The sales guy has an insiders' tip: the production model sports only dabs of red varnish, it doesn't have the real thing … ah, in that case …! Exaggerated? How about this: you grab a Strat with an alder body, and one with an ash body, play both extensively, hear differences – you have discovered the influence of the wood on the tone! That cannot be an exaggeration because something like it happens daily in editorial offices around the globe. Please listen up, dear specialist editors: if you want to fathom *one single* factor of influence, you may only change *one single* influencing factor. The same type of string needs to be installed on both guitars to be compared, yep - brand new ones. Action and pickup-positions need to be identical, and of course you need to mount one and the same pickup (have fun repeatedly de-installing and re-mounting it). Because: if you do not use the same (specimen of) pickup, you risk evaluating differences in the pickups and not in the bodies. And while we are at it: the guitar body normally ends where the neck starts. So: go ahead and swap the necks, as well, otherwise you will assess the neck differences. That doesn't work when comparing the LP Standard to the LP Studio? Don't loose heart – let's consult that compendium about glues over there in the corner. Seriously, though, it is here where the limits of this experimental methodology become visible, long before we arrive at the recommendation that the strings need to be picked to the millimeter at the same position, and that we need to carry out blind tests, of course, and … and … and …

Such "listening experiments" often degenerate into euphoric racketing (you don't get to play a '58 Strat very often, do you!), followed by the insight that the '58 sounds more authentic than the relic'd copy. This may happily be corroborated with the rationale that the old woods are just so much more inclined to vibrate along, and most of all, they have been "played-in" for decades. However, maybe it's only that nut, rock-solidly glued-in by some previous owner so that it cannot be changed anymore without damage? Or it's that loose vibrato fit? Or the worn-down frets on the '58 that must not be changed? Or the metal pickguard; you would never imagine it to throw in a damping by eddy-currents, maybe because you have never heard of them? Or the cables of different lengths that are being used to plug the two guitars into that home-made switch box? Or the coat of varnish that hampers the guitar body to "vibrate freely"? That lost pickguard-screw? The Leonids? For real, the latter actually exist, turning up each November – probably to help prepare Fender products for the Winter-NAMM (what "The Emissary" and "The Orbs" are for the people of Bajor, the **Leonids** are for the Fenderides). The multitude of possibilities that may influence the sound of a guitar is staggering, and herein lies the problem of such listening experiments: it is simply impossible to separate the manifold causes, or to attribute exactly *one single* cause to *one single* effect. It is here where the opportunity of artificial sounds lies: because we know exactly how they are generated, we can change every signal parameter arbitrarily, and check for its audibility or relevance. Nothing is perfect, though, and we run into other difficulties: how authentic is the artificial sound – have we considered all significant parameters – doesn't this all sound very technical, still? Most of all: what does the (in-) audibility of the 15th partial tell us about the ash/alder-issue? It all remains difficult … many paths lead up the mountain; not in the otherwise customary disjunction, though, but rather in a unifying conjunction. Investigations into materials are more the domain of the manufacturer because other folks can hardly screw, one after the other, 10 necks to a body just like that. These would be necks for which it is certain that really only the fretboard differs, and not the bearing of the truss-rod. Investigations into parameters, however, may well be carried out in a university lab, and the following pages will be dedicated to them.

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It is conducive to divide the string vibration, with regard to time, into a "forced" part and a "free" part. **Plucking** is the forced movement (it is not really a forced *vibration* in the strict sense), because the string is forced to follow the pick (or fingernail, or such). After the string and the pick have lost contact, the string may still come into (possibly frequent multiple) contact with the frets – this will be elaborated on extensively in the following chapter. If the string has no further contact to the frets (except the one against which it may be pressed), the "free" vibration (also called the **decay process**) sets in.

The quantity relevant to the hearing system is the short-term spectrum of the velocity of the string; specifically of the part of the string located above the pickup magnet (aperture, see Chapter 5.4.4). The pickup maps the velocity to an electrical voltage that – after amplification – is converted into a sound wave by the loudspeaker. Given the usual parameter setting♣, the short-term spectrum (also called **spectrogram**) shows the level of the partials over time; the parameters are fundamental frequency, inharmonicity, attack- and decay-spectrum, T_{30}-spectrum.

- **Fundamental frequency** (e.g. $E_2 \rightarrow$ 82.4 Hz) and **inharmonicity** (e.g. b = 1/8000) were explained extensively in Chapters 1 and 2.
- The **attack-spectrum** is the magnitude- or level-spectrum of the plucking/picking process.
- The **decay-spectrum** is the magnitude- or level-spectrum at the start of the regular decay process.
- The $\boldsymbol{T_{30}}$**-spectrum** indicates the decay time of the partial as a function of frequency.

All magnitudes mentioned above are simplifications: in particular for light strings and strong picking attack, the fundamental frequency is time-dependent. The inharmonicity does not describe the irregularities caused by all-passes (Chapter 2.5.2), and the attack may not be describable with a single spectrum. Moreover, the T_{30}-spectrum may consider beat-effects too little or too much. Still, it is appropriate to start with a simplified consideration that may be extended in special cases to a more complicated model. Especially for weakly plucked strings, the pickup voltage can be described adequately well with the above model parameters; non-linear behavior will be examined in Chapter 7.12.2.

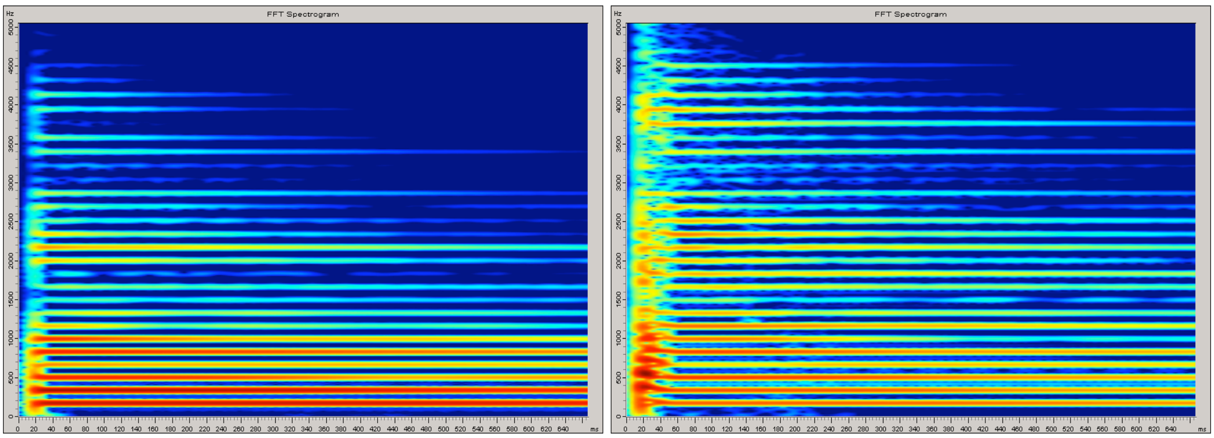

Fig. 7.126: Spectrograms (0 – 650 ms, 0 – 5 kHz). E_3 plucked weakly (left) and strongly (right) on the A-string. Color dynamic (blue ... red) = 60 dB. Fender Telecaster, fresh strings, bridge pickup.

♣ Window length 20 – 40 ms, Chapter 7.6.2, Chapter 8.6.

Fig. 7.126 shows two spectrograms of the output voltage of a Telecaster. The A-string was fretted at the 7th fret and plucked at a distance of 12 cm from the bridge; the guitar was connected to a high-impedance instrumentation amplifier input via a regular cable (580 pF). A suitable normalization compensates for the lower voltage generated by the less strong plucking; there are, however, still differences in **the attack** which forms the very short signal portion immediately following the plucking. During the attack, the spectral lines form; the duration of this onset of the tone can only be approximately determined: in the picture on the left, it is about 20 ms, while in the picture on the right, it is about 60 ms long. If the strings buzz audibly, the attack phase may take even longer – this will be discussed in Chapter 7.12.2. For the lightly picked A-string (picture on the left), the **decay spectrum** establishes itself after about 20 ms; the levels of its partials decay approximately linearly during the period following the attack. We shall investigate later why some partials contravene this approximation, decaying with a beating effect. As a first-order approximation, it is assumed that the decay process is comprehensively described by the decay- and the $\boldsymbol{T_{30}}$**-spectrum** (Chapter 7.6.3).

In Chapter 1, the plucking of the string was interpreted as a step-excitation of a linear system, supplemented by recognizing that the step is not ideal but "rounded-off". From the positions of the plucking point and of the pickup, two interference filters result (Chapter 2.8), and the pickup acts as a treble-attenuating low-pass filter (Chapter 5.9.3). In the transmission model, the excitation step passes through the mentioned filters; the latter map the step onto the voltage. So, we now have: step, pick-filter (for the "rounding off"), plucking-interference-filter, pickup-interference-filter, pickup low-pass, and output voltage. The two interference filters have a particularly strong influence – their effect is shown in **Fig.7.127**. Just shifting the plucking position by as little as 5 mm already substantially changes the interference filter (and thus the spectrum; upper right and lower left). The same happens as the pickup is moved by 3 mm (lower right). Those who see the pickup as immovable may consider that it is the distance between pickup magnet and bridge saddle that counts: the latter certainly can (and may need to) be shifted. N.B.: it's mere millimeters that are crucial here!

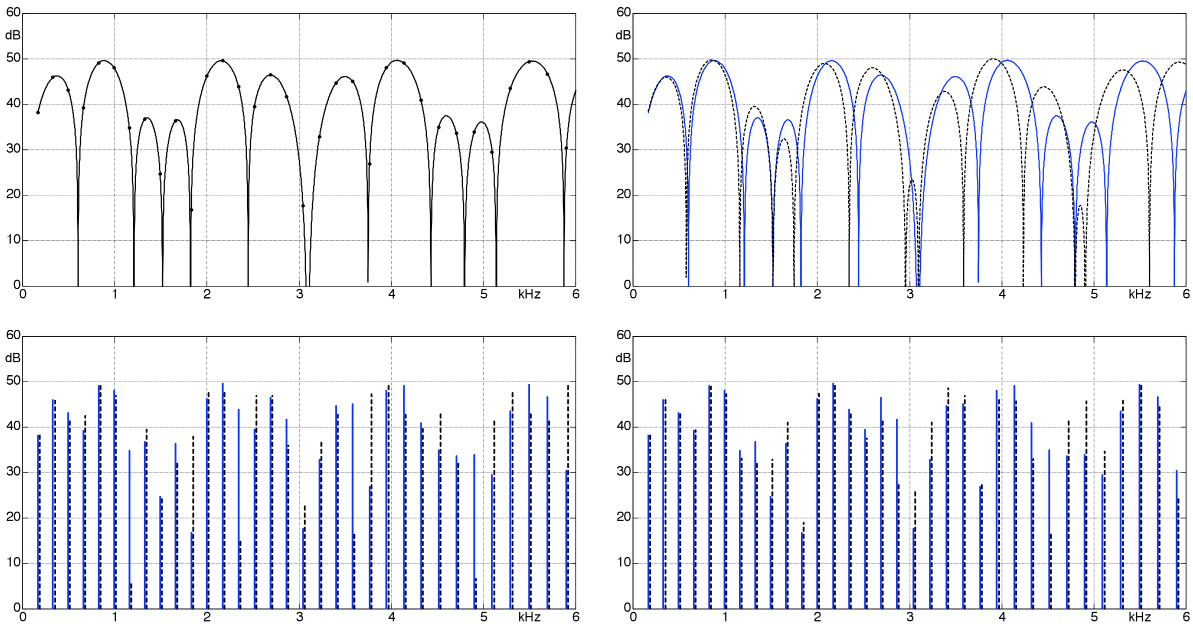

Fig. 7.127: Interference filters for the Telecaster. Upper left: A-string plucked at the 7th fret, bridge pickup. Upper right: plucking position changed by 5 mm (added to upper left graph). Lower left: line spectrum for the upper right picture. Lower right: as lower left but with the pickup position changed by 3 mm.

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Fig. 7.128 shows to which extent model and reality agree. On the left, the decay-spectrum♣ is depicted; it was on the one hand derived from a measurement (Fig. 7.126), and from the above filter model on the other hand. In view of the large differences that already show up as the plucking position is changed by a millimeter, the correspondence is to be seen as very good. The T_{30}-spectrum (the decay times of the partials) is shown in the picture on the right, with the grey area indicating an estimate for the upper limit valid for the open A-string (due to radiation and internal damping of the string, see Chapter 7.7.2, "orientation line").

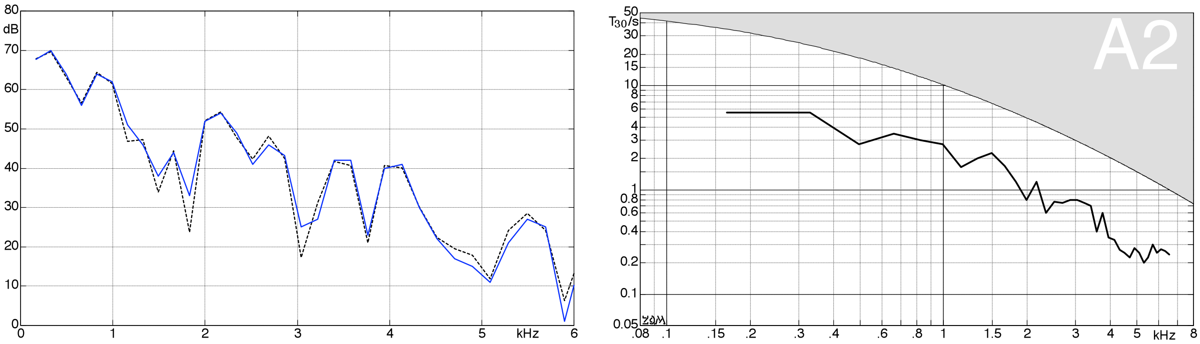

Fig. 7.128: Left: decay-spectrum (measurement ——, model: ----); right T_{30}-spectrum (measurement). The region marked in grey estimates the upper limit of T_{30} due to radiation/internal damping of the string, Chapter 7.2.2).

From the dataset shown in Fig. 7.128, we synthesized an **artificial guitar tone** (f_G = 165 Hz and b = 1/6060). The spectral analysis (**Fig. 7.129**) indicates a good correspondence – merely the beating is (deliberately) not included. In turn played back via a guitar amplifier, both signals sound identical as long as the duration is kept short (about 0.5 s). Only when extending the duration to several seconds, minimal differences in the strength of the beating become apparent. However, since any halfway gifted guitarist would almost always play a note held for 3 s with finger-vibrato, this effect was ignored. If it were considered to be relevant, after all, it would be very simple to add some beating to the artificial signal.

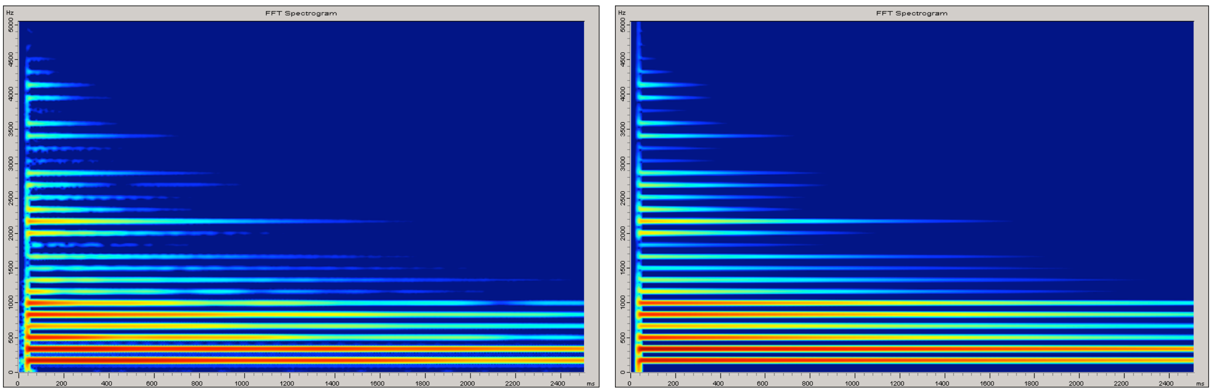

Fig. 7.129: Spectrograms. Left: real Telecaster-signal, right: synthetic signal. 0 – 5 kHz, 0 – 2.5 s.

We now arrive at a first conclusion: the time-variant short-term spectrum is a powerful tool to analyze the voltages generated by weakly plucked strings, and the associated analysis of partials is well suitable to generate artificial guitar tones. The decay spectrum results from the data of pick, string and pickup, and from the plucking- and pickup-position. There is practically no dependence on the remaining guitar parameters (in particular not on the wood). The T_{30}-spectrum, i.e. the speed of the decay of the partials, is defined by the remaining guitar parameters.

♣ Here and in the following the results are not shown anymore as discrete frequency lines but as a polyline.

In Fig. 7.128, the decay time reveals the already known decrease towards high frequencies, as well as smaller frequency-selective variations. In the following we shall investigate how far these small T_{30}-peaks (e.g. around 2 kHz) have an effect on the audible sound. In the following listening experiments, the tone synthesized according to Fig. 7.128 was the standard sound. Starting from it, the decay times of individual partials were changed as modifications. In these experiments, we could confirm very quickly the masking models [12], according to which partials with small levels contribute practically nothing to the perceived sound. It consequently is not important for the auditory impression how fast the 11th partial (1.8 kHz) decays, as long as the modifications stay within the regular range. Even reducing the decay time of the 1.8-kHz-partial to 0.5 s, or extending it to 2.5 s (**Fig. 7.130**) does not change the aural impression. For the same reason, the particularly clear level difference between model and measurement (Fig. 7.128, decay spectrum) for specifically this partial at 1.8 kHz is insignificant: the partials with low levels are masked and do not contribute anything to the aural impression.

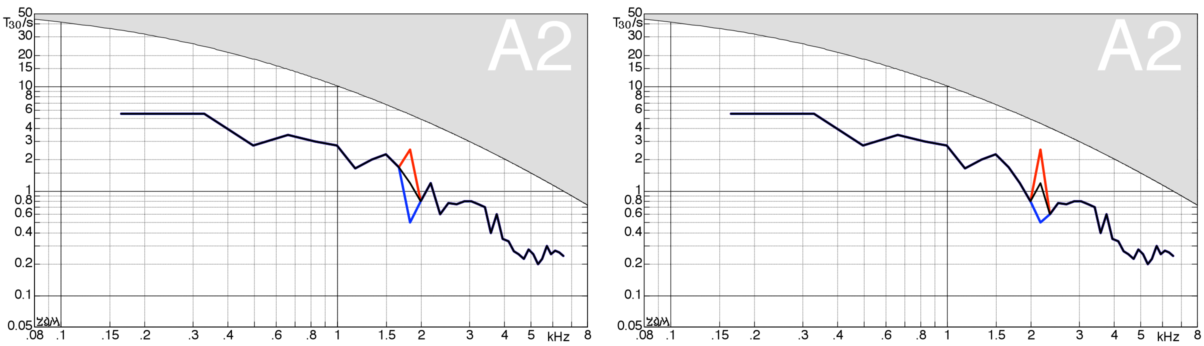

Fig. 7.130: Modification of the decay times of individual partials. The changes affected in the left-hand graph remain inaudible; the extension (red) in the right hand graph is audible, the shortening (blue) remains inaudible. The region marked in grey estimates the upper limit of T_{30} due to radiation/internal damping of the string).

A different situation is found for the 13th partial (2170 Hz): extending its decay time to 2.5 s is audible, while the shortening to 0.5 s remains inaudible. However, small changes in the decay time are caused already by minor shifts in the position of the fretting hand (**Fig. 7.131** left) – again, this has very little bearing on the sound. Only when playing the notes for several seconds and when directing ones concentration specifically to the fundamental, miniscule sound differences become apparent – but these have practically no importance. Yet another situation emerges at the 2nd fret of the D-string: although the same note (E_3) is being played, both decay- and T_{30}-spectrum are different. Despite the same plucking- and pickup-positions, the two interference filters change their frequency response – due to the changed *relation*: the A-string is plucked at the relative position 12/44, the D-string at 12/58.

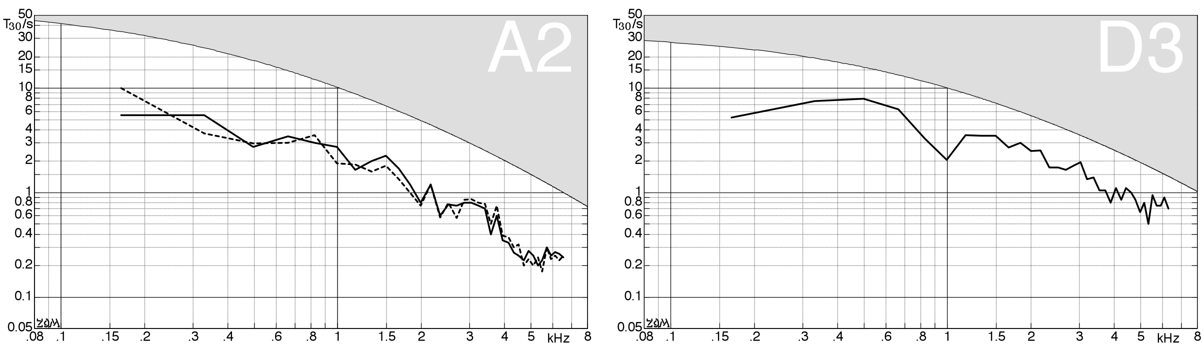

Fig. 7.131: T_{30}-spectrum. Left: E3 played at the 7th fret the A-string, left hand held in different positions. Right: E3 played at the 2nd fret of the D-string. Fender Telecaster, fresh strings (009 to 046). The region marked in grey estimates the upper limit of T_{30} due to radiation/internal damping of the string).

The changes in the decay time (**Fig.7.131 right)** are due to a strong location dependency of the **neck-conductance** on one hand, and on the other hand due to the length-dependency of the internal string damping. For the synthesized tone it is now very simple to keep the decay spectrum (as shown in Fig. 7.128), and to change at the same time the T_{30}-spectrum according to the right-hand graph in Fig. 131. Does the sound change audibly due to this? It's the same fundamental frequency, almost the same inharmonicity, the same spectrum at the beginning, but a different decay of the partials – indeed, that sounds different. Not yet for very short durations (250 ms = 1/8th-note at 120 BPM), but already from a duration of 500 ms. The longer the tones last, the more muffled the A-string note sounds compared to the D-string note. This difference cannot be compensated for by the tone control – cranking up the treble-knob does not change the decay speed of the partials!

These audible differences between E_3's played on the A-string and on the D string can hardly be attributed to the body wood, because that is the same for both notes. To once more summarize the causes for the differences: even when keeping the location of plucking the string and the location of the pickup constant, the *relative* distances still change, and so do the two interference filters. This is, for "normal guitar-playing" the main difference between the A-string E_3 and the D-string E_3. If both notes are given the same decay spectrum (which is only possible for synthetic notes), we notice a progressive treble-loss for the A-string E_3: the string sounds increasingly duller. The D-string sounds progressively brighter in comparison.

Now on to the **Gretsch Tennessean**, a true semi-acoustic guitar. Its hollow body promises peculiarities in the decay behavior – but the listening tests do not show this. Of course, the Tennessean sounds different – but that is mainly due to the different pickups and their different position (compared to a Telecaster). The scale is different, as well – and therefore Telecaster and Tennessean form different interference filters, even if the same note is played on the same string. However, if – for the same decay spectrum – we change only the T_{30}-spectrum (i.e. the spectrum of the partials), we cannot hear any difference between Telecaster and Tennessean for short notes. Only as the duration of a note increases to about 500 ms, differences start to become noticeable – and these are minute differences!

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Fig. 7.132: Gretsch Tennessean, E3 played on the A-string (left) and on the D-string (right). The solid lines are the result of fresh strings (009 – 046), the dashed lines are the result of "broken in" strings (009 – 046).

The differences caused by the aging of strings are much larger (**Fig. 7.132**). Only for completely fresh strings, any frequency-selective peculiarities can be detected at all – for "broken in" strings, string-internal loss mechanisms dominate. Still, there is no generally applicable rule about the loss of brilliance as a function of time, because the individual parameters (dust, skin-fat/oil and -abrasions, bending-grooves, rust, fret- and string-material) are too diverse.

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Fig. 7.133: Decay time of partials. Comparison Fender Telecaster (----) vs. Gretsch Tennessean (——). Fresh strings (009 - 046), E3 on A-string (left) and on D-string (right), plucked with a pick. The region marked in grey estimates the upper limit of T_{30} due to radiation/internal damping of the string).

The direct comparison between Tennessean and Telecaster is shown in **Fig. 7.133**. In some ranges, shorter decay times can be seen for the Tennessean – an effect of the hollow, flexible (and thus absorbing) body. For shorter notes, however, these differences are certainly put into perspective: a T_{30}-difference of 1.9 s relative to 3.0 s translates into a level difference of 1.5 dB for a note of 0.25 s duration (an 8th-note at 120 BPM). Such a difference may just be noticeable under conducive laboratory conditions, but it is of not much significance in everyday life on stage or in the studio. We cannot often enough remind ourselves of this: it's in the fingers. And also in the pickup, and in its position. How the spectrum is shaped by the plucking- and pickup-positions, that is subject of the following investigations.

As with every **spectral analysis**, we need to find a compromise between high spectral and high time-related resolution (compare to Chapter 8.6). In order to keep leakage-effects at a bearable level, the time-function needs to be subjected to a "window". In **Fig. 7.134**, the left hand part depicts the pickup voltage of a plucked E_3, starting with a positive peak. Multiplication with a window-function yields the right-hand graph – and it is here where the multitude of parameters catches up with us, because duration as well as type and parameters of the chosen window define the spectrum.

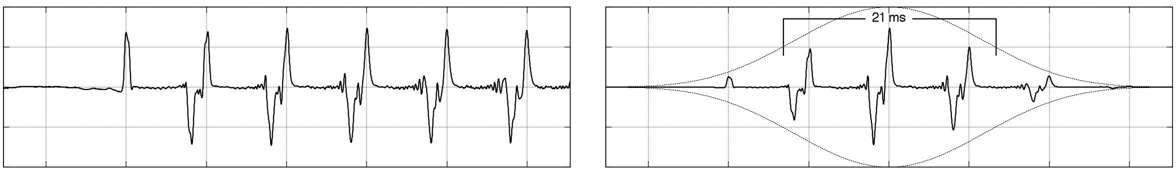

Fig. 7.134: Weighing over time of the pickup voltage (E3) by a Kaiser-Bessel-window (N = 2048).

To spectra for the above depictions are shown in **Fig. 7.135**: on the left using a 2048-point window, on the right with a 1024-point window. We could live with both representations, but due to the clearer line-structure the following analyses use the **2048-point window**.

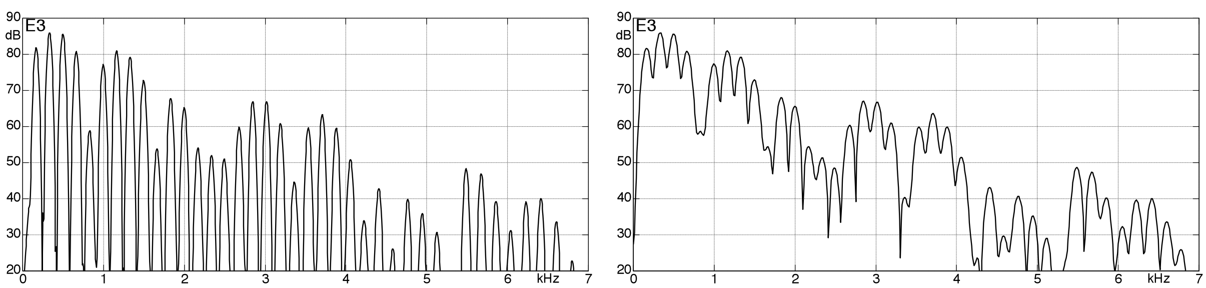

Fig. 7.135: DFT-spectrum for Fig. 7.134, Kaiser-Bessel-window, N = 2048 (left), N = 1024 (right).

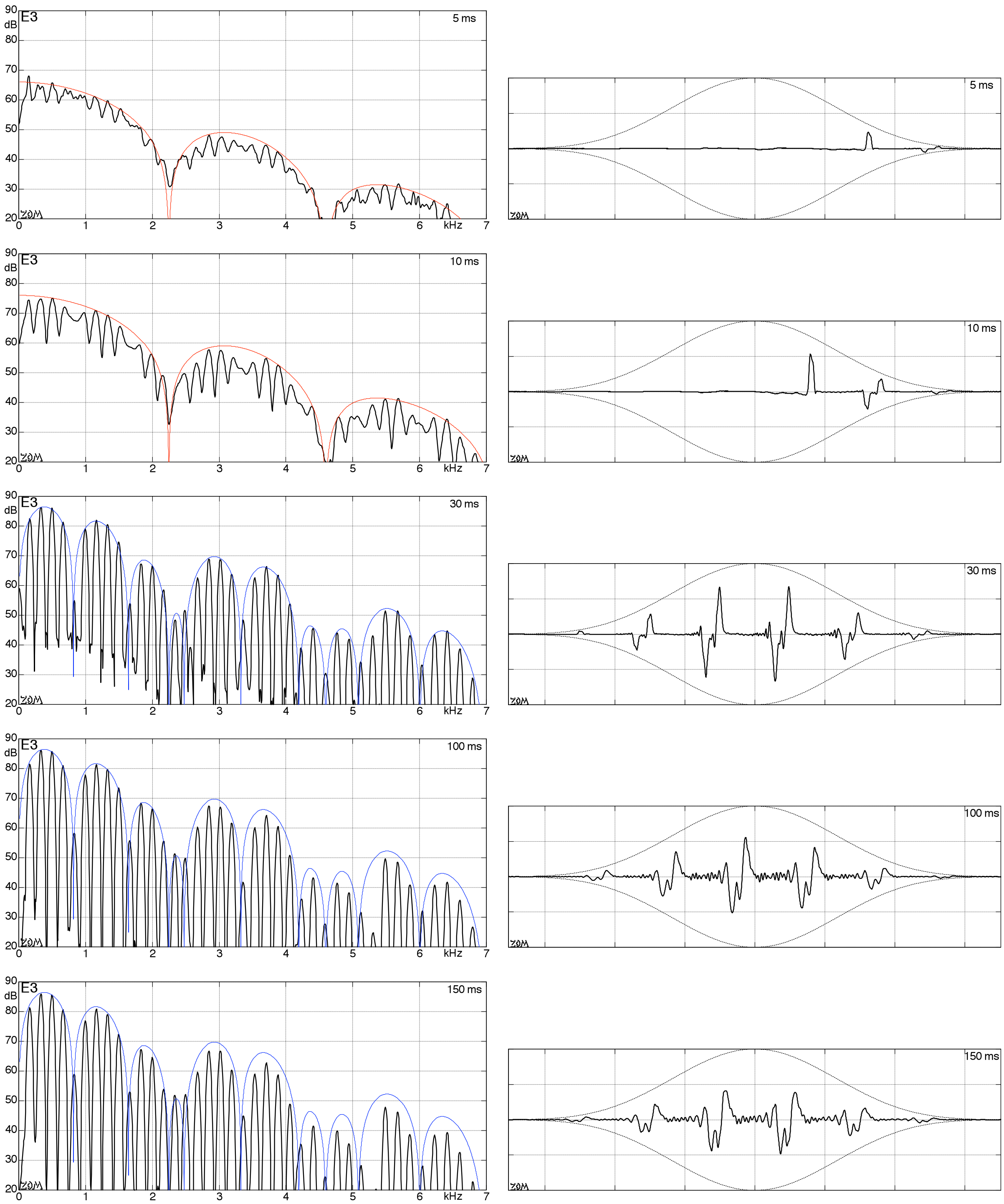

Fig. 7.136: Spectra and time-functions (subjected to the window) of the pickup voltage. E3 on D-string, Telecaster. The calculated model-envelopes (----) fit perfectly to the measured line spectra.

In **Fig. 7.136** we see the spectra corresponding to different time-excerpts. During the first milliseconds, the pickup position, and pick- and pickup-filter determine the shape of the spectral envelope (*dashed in red*). As the pick leaves the string, two step-response waves run off in two directions. The wave running towards the bridge crosses the bridge pickup first and is compensated shortly afterwards by the opposite-phase bridge-reflections – this results in a short positive impulse. The other step-response wave is reflected by the 2nd fret and reaches the pickup somewhat later – only now the picking-interference filter (on top of the pickup interference filter) takes an effect (*dashed in blue*).

The impact of these two interference filters depends on the string length, and on the picking- and pickup-positions. In this example, the pickup itself approximately acts as a 2nd-order low-pass (f_x = 4 kHz, Chapter 5). As shown by the example, the aperture of the magnet and the rounding-off of the excitation step may very nicely be modeled by a further 4.3-kHz low-pass. The **body wood**? That can exert any influence on the spectrum and the sound of the guitar only via the damping of the reflections, and here the following holds: the shorter the observation period, the fewer reflections we get, and the more insignificant the body! Even at 150 ms (lowermost graph), we still recognize the dominance of the two interference filters in the decaying spectrum. Only the 5.3-kHz-partial behaves differently: it decays significantly faster than its colleagues. Still, as already elaborated extensively in Chapter 7.7: first we need to consider the damping characteristics due to strings and bearings. The influence of the body wood comes last.

Fig. 7.136 justifies a distinction into an **attack**- and a **decay**-spectrum. During the first milliseconds, the spectral envelope (dashed in red) depends only on the pickup-interference filter (besides the pick- and pickup-low-pass). Only from about 10 ms, the picking-interference filter gains in significance. For the auditory perception, the decay spectrum formed by all filters is decisive; its envelope is included dashed in blue in Fig. 7.136 for the 30-ms-spectrum.

A different situation only appears as we move to the non-linear system, but before we concern ourselves with its idiosyncrasies in the next chapter, let's first look at some **fringe-effects**. Besides the guitar, also amplifier, loudspeaker, and listening room will of course influence the sound arriving at the ear. Boosting a partial originally weak in level by a frequency selective filter (EQ), this partial may increase in significance and become audible. A similar development may occur if the decay time of a partial is changed to the extreme (e.g. from 1 s to 5 s). Any statement regarding the audibility (or non-audibility) is therefore never of general validity but should be taken in the framework of normal stage- and studio-technology. Moreover, the results found for one note cannot be directly carried over to all other tones – a guitar has more than one string, more than one fret, and more than one partial. Only the transmission-filter of the pickup (Chapter 5.9.3) may be seen as reasonably string-unspecific. Pick- and aperture-filter are string-specific, and on top the two interference filters are also strongly position-specific.

Last, it should be mentioned that we were not out to obtain the absolute threshold of perceived differences. In basic research it may be justified to exactly determine the difference between a real guitar note and a correspondingly synthesized note using a representative group of subjects. Or to e.g. find out that beat-differences were recognizable from a note-duration of about 0.23 s. However, if the fretting hand grabs the neck a bit more strongly for the repeat measurements, this duration would change, and the same would happen if the angle of attack of the pick would change minimally, of if the guitar is pressed a bit more tightly to the belly. This threshold of perceived differences is not unimportant – but it is connected to an overwhelming variety of parameters. The functional model including pick filter, picking-interference filter, pickup-interference, and pickup-transmission filter explains the spectrogram in a simple manner; the data-sets of **decay-spectrum** and **T_{30}-spectrum** are the most important ones for this spectrogram. If we additionally supplement fundamental frequency and inharmonicity, weakly plucked notes of an electric guitar may be synthesized with good quality, as long as their duration is not too long. Based on this model, parameter variations may be checked, with the result being the assessment of the relevance of individual components. Indeed, this is much better than the pure hunch that alder would give a shorter sustain due to its higher elasticity [G&B and others, see Chapter 7.8].

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7.12.2 Non-linear string oscillations

Now, we will have to dive into the thicket of complicated matter. That's because communication engineering teaches us that for non-linear systems there is neither superposition nor proportionality, and neither transfer function nor step response. Of course, we may drive also a non-linear system with a step excitation, but the response (reaction) is not a signal-independent system function, but it depends on the excitation signal – and as a result there is not "the one" step response but there is an infinite number of such step responses.

Strictly speaking, every technical system is non-linear, but often this is to such a small degree that the transmission characteristics may be simplified towards linearity. Chapter 5.8 had dealt with the non-linearities occurring in pickups – the effects are far from insignificant yet they are far outweighed by the non-linearities possible in the string vibrations. The latter become non-linear if, after being plucked, the string hits the frets. In this case, the step-waves generated by the plucking are not only reflected by the bridge and the nut (or the fretted fret) but also at the (other) frets. This process is dependent on the plucking-strength and therefore it is non-linear.

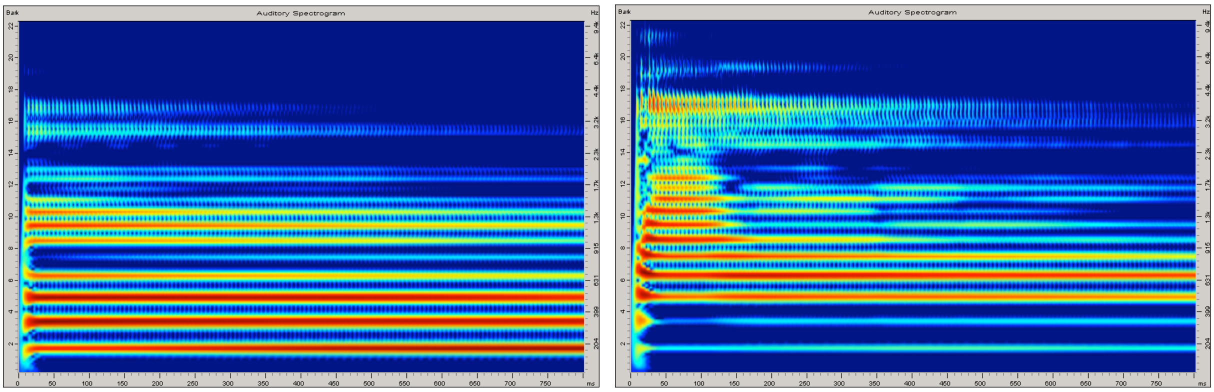

Fig. 7.137: Spectrogram of a plucked D-string (E3, 0 – 800 ms, 0 – 10 kHz, dynamic in the graph = 30dB). Left = lightly plucked, right = strongly plucked. Fender Telecaster, strings 009 - 046, bridge pickup. The analyses were scaled to the same maximum drive level.

Fig. 7.137 shows spectrograms of a D-string plucked with different strengths. Depicted are **auditory spectrograms** (Cortex VIPER) the analysis-parameters of which are adapted to the characteristics of our hearing system. It is hard to believe that both analyses were obtained with the same guitar, the same string and identical plucking positions – only the plucking strength varied. The lightly plucked string clearly reveals the interference filter, with the spectral emphasis being formed by the first three partials. The outcome for the strongly plucked string is very different: the first two partials (fundamental and second harmonic) have only a weak level – their vibrations cannot unfold due to the amplitude limitation. Even if a simple model would attribute the same displacement-amplitude to each partial, the pickup voltage – corresponding to the velocity – would increase with increasing order of the partial in this model. In a real plucked string, the partials do not have the same displacement amplitude: the plucking-interference-filter causes gaps (e.g. for the 5^{th} and the 10^{th} partial). However, already the first string/fret-contact starts to fill in these gaps. If we interpret the plucking of the string as a **step-excitation**, the string hitting the fret could be seen as a kind of **impulse-excitation**, albeit quite a special one. This is because while the plucking action feeds vibration energy to the string, hitting the frets can only cause an energy loss. How big this loss is depends on the surface qualities (among other factors): little loss for a fresh string and a clean fret but more loss, if an in-between layer of dust/grease/talc acts as an absorber.

The (normalized) time function shown in **Fig. 7.138** underlines the differences between the lightly and the strongly plucked string: during the first few periods, only the dispersion has an impulse-changing effect in the left-hand graph, while for the strongly plucked string, reflections are clearly visible already within the first period. These are reflections that can only stem from the obstacle located closest – and that is the last (22^{nd}) fret. There is a significant chance that a strongly plucked (thin) string comes in contact with the last fret already in the plucking process (compare to Chapter 1.5.3), but the exact evolution over time of this and other fret-contacts are dependent on the individual plucking – this is in fact why the system behavior is non-linear. A model can therefore emulate the fret-bounce either only for the individual case, or simulate – as a stochastic model – a generic average event. Which is the problem: we will not get far with one model alone, because the well-versed guitarist is able to generate a *multitude* of fret-bouncing "snap-sounds".

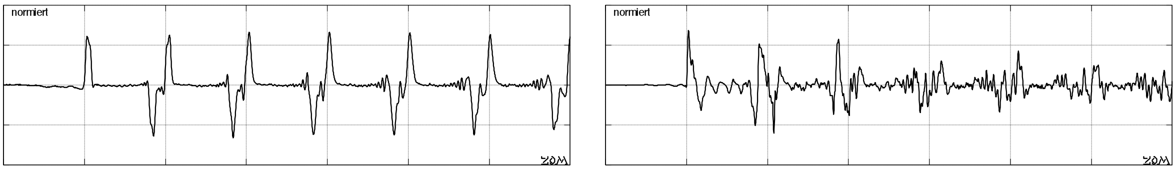

Fig. 7.138: Time function of the pickup voltage; left = lightly plucked string, right = strongly plucked string.

Fig. 7.139 depicts in which unexpected variants the decay of a strongly plucked string can occur. Again, the D-string of a Telecaster fretted at the 2^{nd} fret is shown, strongly plucked at 12 cm distance from the bridge (as in Fig. 7.137). As opposed to the above analysis, the string was not pushed downward at a slant, but lifted up and then let go. At 0.6 s, the spectrum (and the sound) change unexpectedly: the 5^{th} partial literally cuts out, while other partials only come to life at that point in time. These changes are not connected to the fretting hand but are the work of the string alone – in cooperation with the frets.

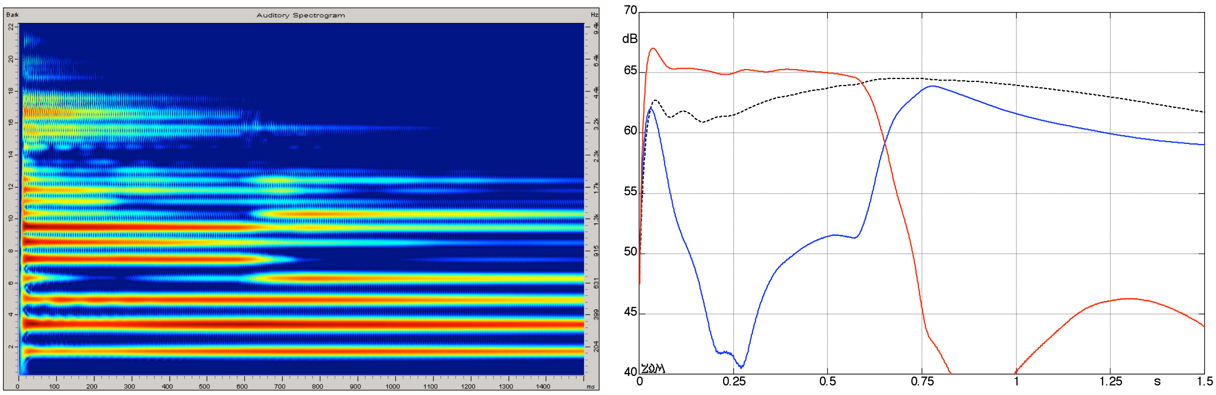

Fig. 7.139: Spectrogram of a plucked D-string (E3, 0 – 1500 ms, 0 – 10 kHz, dynamic = 30dB).
Right: red = 5^{th} partial, blue = 4^{th} partial, black = level of fundamental; all as a function of time.

The string, with a vibration that is at first almost perpendicular to the fret-board, hits the frets which transfers part of the vibration energy into a mode parallel to the fret-board. Over time, however, the plane of vibration changes back again, as easily visible from the level of the fundamental (----). Around 0.6 s, the increasingly fret-board-normal vibrating string approaches the frets again such that a further crash occurs. This crash considerably disrupts the 5^{th}-order vibration, but at the same time retriggers and amplifies the 4^{th}-order vibration. A model describing vibrations in only a *single* plane would not succeed for such a behavior, even if that model would allow for non-linear amplitude limiting.

Fig. 7.140 shows further spectrograms; again only the strength of the plucking was varied. It is characteristic that the partials decay neither exponentially nor according to a simple beating-model, but suddenly change their decay behavior. Even an increase in level is possible (albeit one only for a limited time) – this can be attributed to a slowly rotating polarization plane. Contact between string and fret may be limited to the first 0.1 s, but may also still occur after 1 s. The evolution of the level and the sound color over time is correspondingly rich in variation. These figures highlight that the neck (or rather the frets) enjoy an elementary significance: a fret minimally projecting over the other frets will generate other bounce-contacts than one that is worn down.

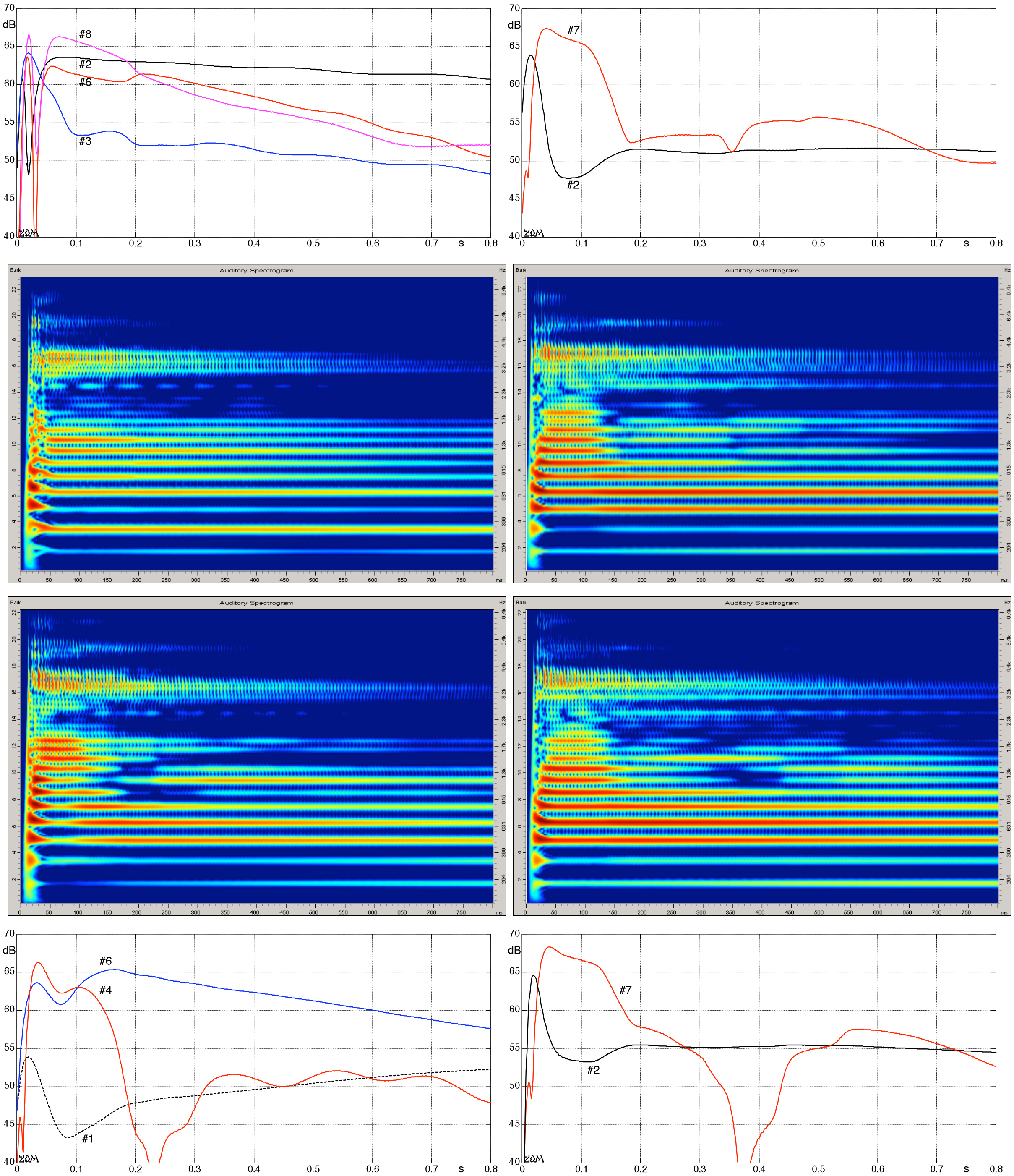

Fig. 7.140: Auditory spectrograms and levels of partials of a plucked D-string (compare to Fig 7.139). Level-normalized scaling; dynamic in the graph = 30 dB. Telecaster, bridge pickup, fresh strings (009 – 046).

It is not difficult to corroborate speculations about string/fret-contacts by measurements: for this, all 22 frets of a **Telecaster** were electrically connected to a 22-channel analyzer, and all contacts occurring during the decay were stored. The representation in a **tactigram** (bounce chart) shows characteristic patterns that agree well with a line model (**Fig. 7.141**). The D-string of the Telecaster is pushed down such that it comes into contact with the last (22^{nd}) fret – this happens often when light strings are used. As the string looses the contact to the pick, waves propagate in both directions and are reflected at the last fret and at the bridge, and lift the string off the fretboard, as shown in **Fig. 7.142**.

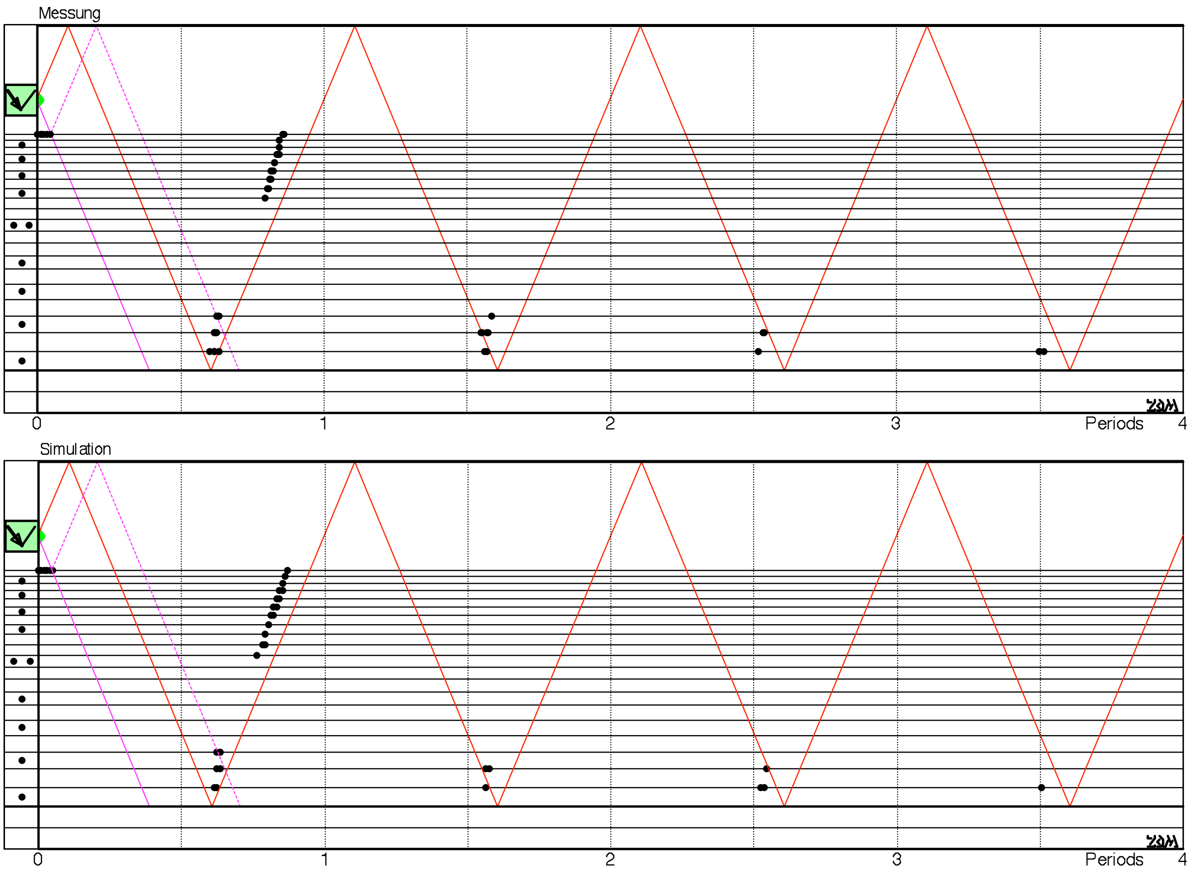

Fig. 7.141: Bounce chart. Telecaster, D-string fretted at the 2^{nd} fret, pressed down strongly 12 cm away from the bridge and then released. Top: measurement; bottom; model-calculation. Dots = string/fret contacts.

After half a vibration period, a maximum in the displacement has formed above the 6^{th} fret (**Graph #8** in Fig. 7.142); it breaks down again during the further continuation of the vibration. Immediately afterwards, the string hits the fretboard, with curvature of the neck and condition of the frets deciding where exactly the string/fret contact happens. The angle with which the string is pressed down also plays a role: it makes for a difference whether the string is pushed down exactly perpendicular to the fretboard or with a slant relative to the fretboard. This is because the orientation of the string excitation determines the share of the fretboard-parallel vibration. During the decay process, the plane of vibration rotates (even specifically to each partial), and it is in particular the fretboard-normal share of the vibration that is clipped by bounce-processes. The fretboard-parallel vibration-mode is a kind of energy-storage that only slowly feeds its vibration energy to the fretboard-normal vibration. The latter (being important for the pickup signal) can therefore repeatedly generate further string/fret contacts. Note that in the model calculation shown in Fig. 7.142 only one plane of vibration was considered.

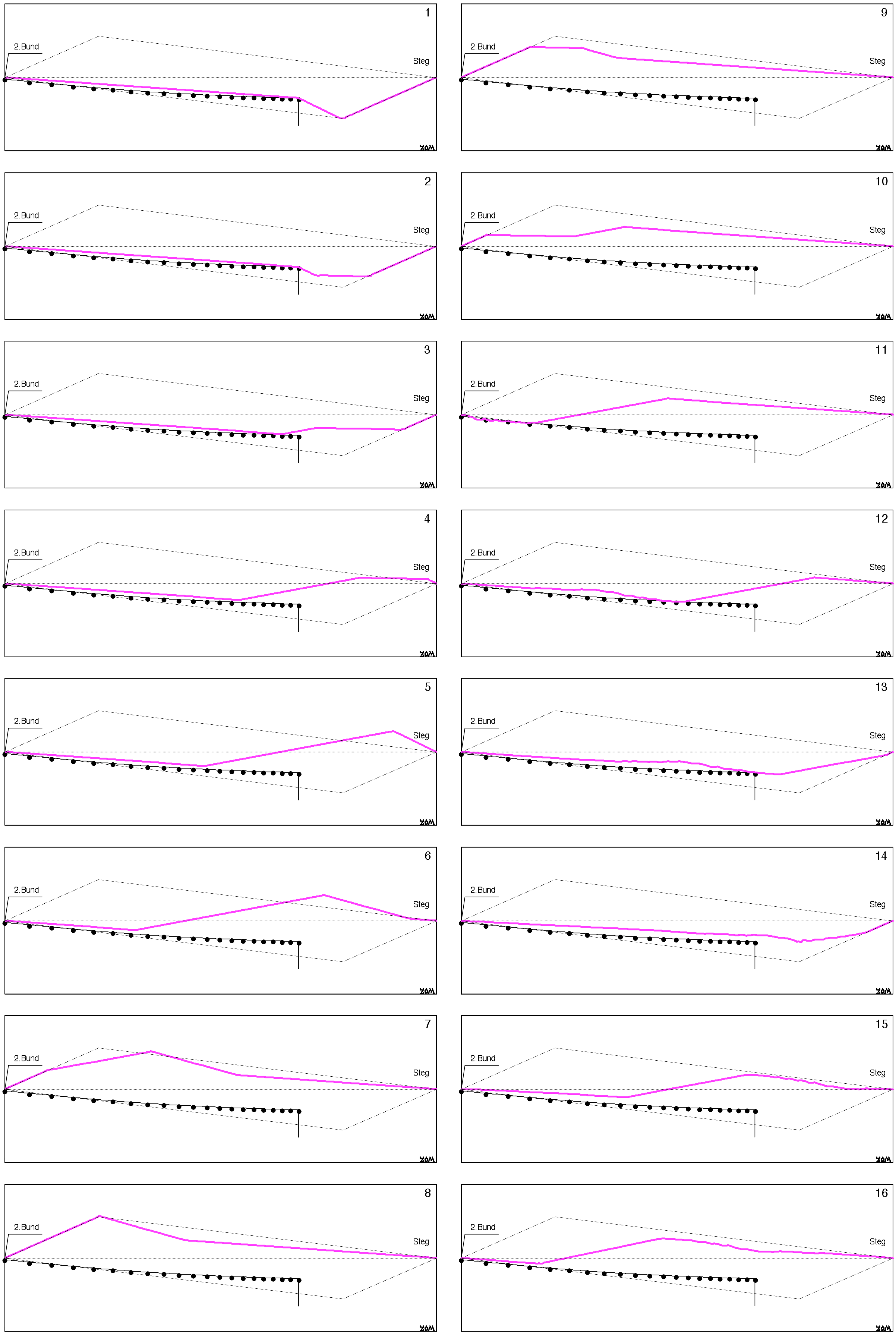

Fig. 7.142: String displacement at various points in time. Parameters as in Fig. 7.141.

Fig. 7.143 shows how big the spectral differences between strongly and lightly plucked strings can be: in the left column we see, during the first milliseconds, the **attack-spectrum** already known from Fig. 7.136 (red envelope, interference gaps dependent on the pickup position); it transitions into the **decay spectrum** (blue envelope). In the column on the right, a sinc-shaped envelope cannot form at the beginning due to the string/fret contact supplying additional impulses. Only later, an influence of the pickup position establishes itself as an outline, while the plucking-position is not evident anymore at all as interference filter.

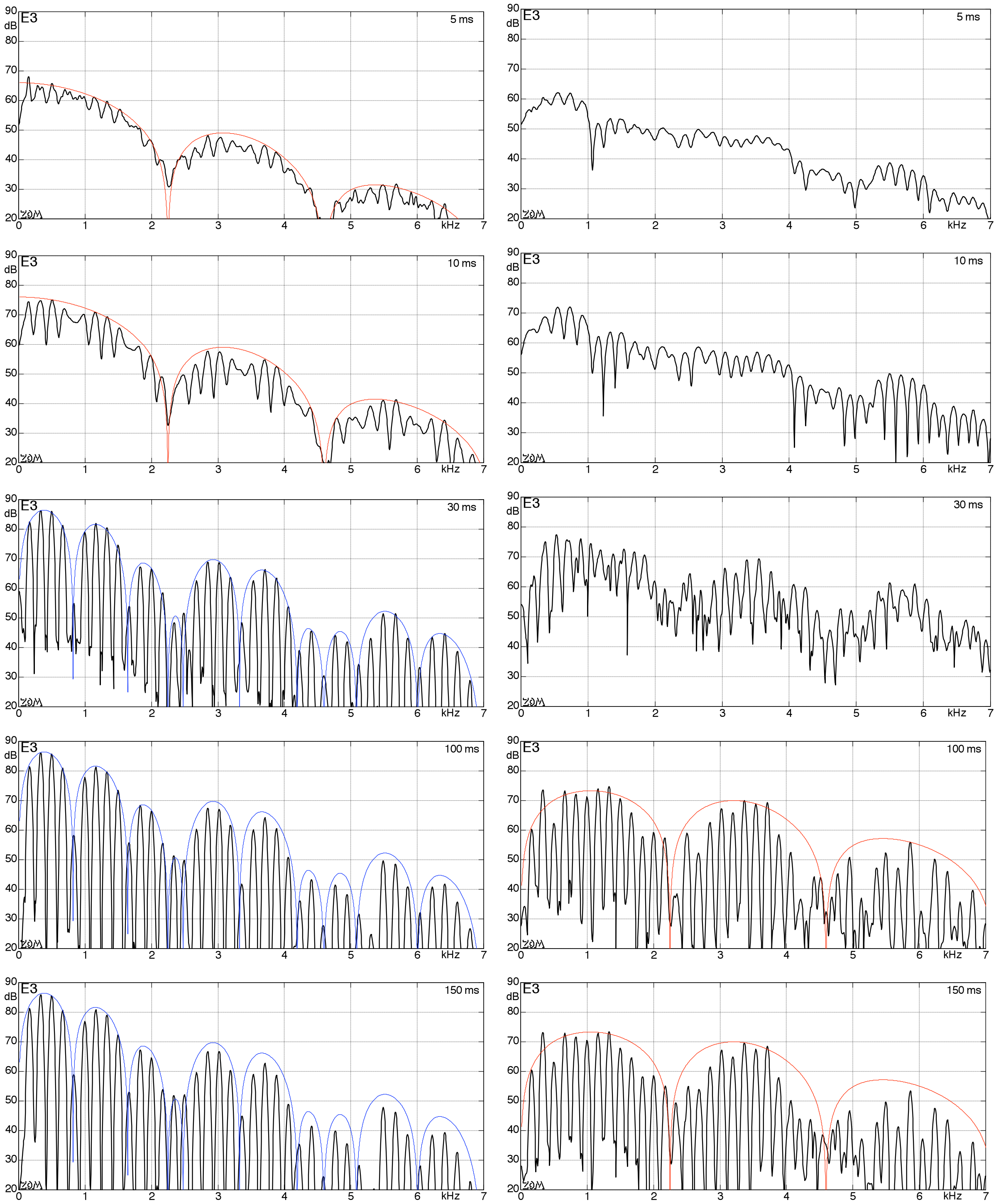

Fig. 7.143: Spectra of the pickup voltage (subjected to a window). E3 on D-string, Telecaster (cf. Fig. 7.136). Left = lightly plucked string, right = strongly plucked string. Level-normalized representation.

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An entirely different vibration happens if the string is not plucked pressing down, but is lifted and then released. This plucking technique is found especially with guitarists playing finger-style (i.e. without a pick) – but even with a pick, an at least similar behavior can be achieved. **Fig. 7.145** shows snapshots for a string pulled up far enough so that it bounces on the frets after its release. In this example, first contact happens at the last (highest) fret, followed by a series of contacts running along the fretboard towards the lower frets. Then (**Graph #7**), the string looses contact only to touch all frets in quick succession (**Graphs #13 – 14**). Or at least almost all frets – in details this of course again depends on minute differences in the heights of the frets.

Fig. 7.146 once more compares contact-measurements with model calculations. Considering the complexity of the matter, the correspondence is very good at the start – as they progress along the time-axis, the two representations differ more considerably. This is because dispersion was not modeled, because the polarization was only calculated for one plane (and not circularly), and because the fret-heights were idealized in the model (in the investigated Telecaster specimen, the fret were already slightly worn).

Fig. 7.147 indicates that string/fret contact is not necessarily limited to the attack-phase. In this example, the string repeatedly bounces off the 3rd fret – however this happens so lightly that no annoying buzz but merely slight brightening of the sound (a mixing-in of treble) occurs.

We see from **Fig. 7.144** how strongly even tiny differences in the height of the frets can make themselves heard. Here, we first calculated the string velocity over the pickups using the non-linear string model, and then derived the spectrum from it. This was done for two different fret-boards on which the 18th fret differed in height by 0.2 mm.

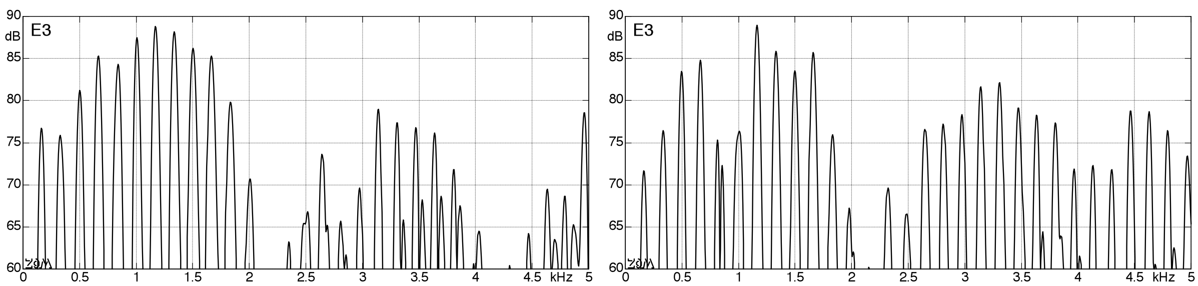

Fig. 7.144: Calculated spectra of the D-string bouncing off the frets. The only difference between the two graphs is that the height of the 18th fret differs by 0.2 mm.

These results give an indication of what can happen when comparison tests are run by a magazine checking out the "holy grail" – i.e. if, for example, a original 1950's Les Paul is compared to a more recent reproduction. Of course, the frets of the priceless♣ vintage guitar are worn, maybe so strongly that it causes the celebrating tester to grimace a lot, and of course the trained ear will hear all kinds of differences. Too bad: as soon as this "grail" is put in a playable condition, its $-value takes a nosedive. Thus do note: on every grail rests a curse of some kind.

♣ Not to be taken all that literally: that's from about € 200.000; quite nicely done fakes may be acquired.

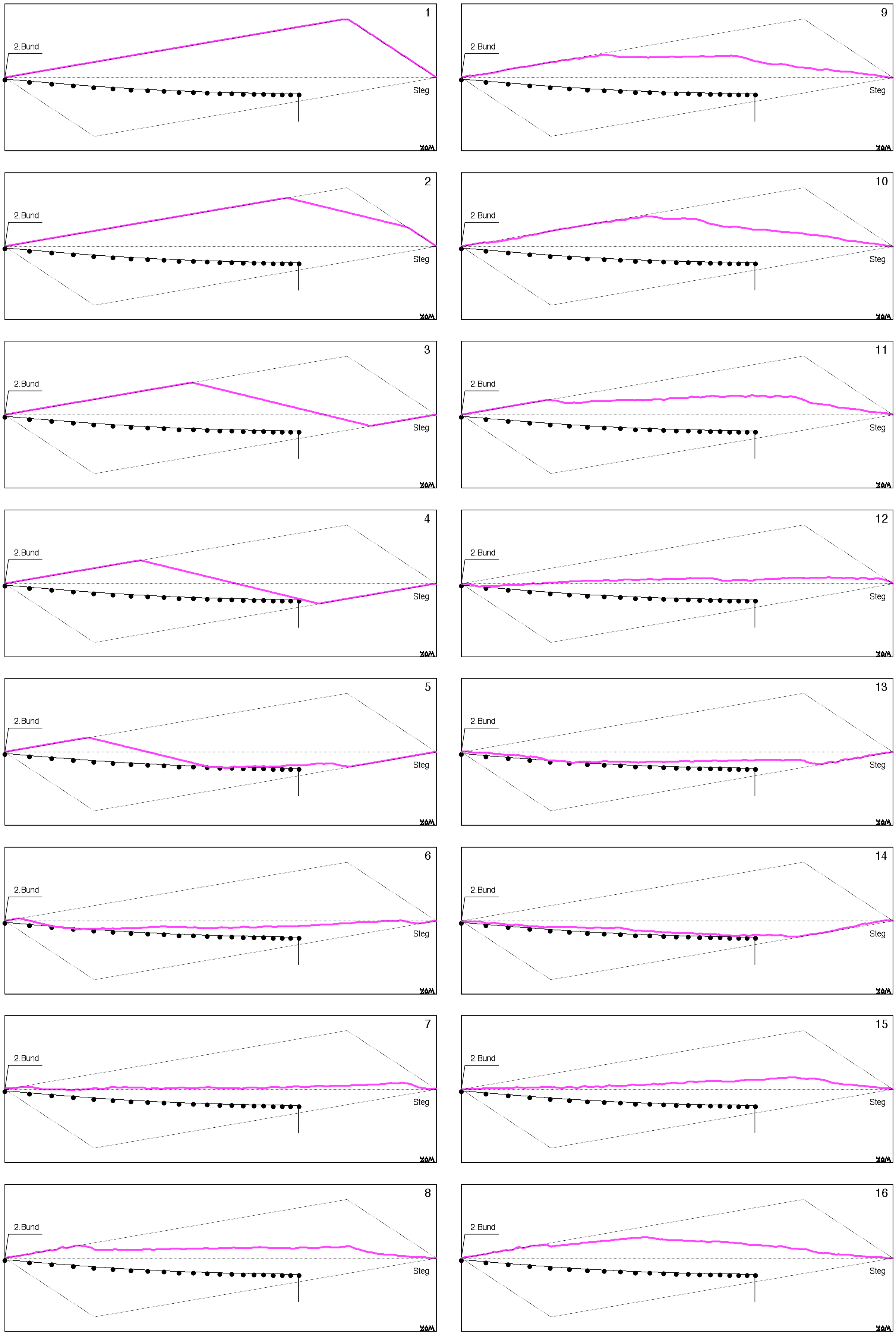

Fig. 7.145: String displacement at various points in time. Parameters as in Fig. 7.141.

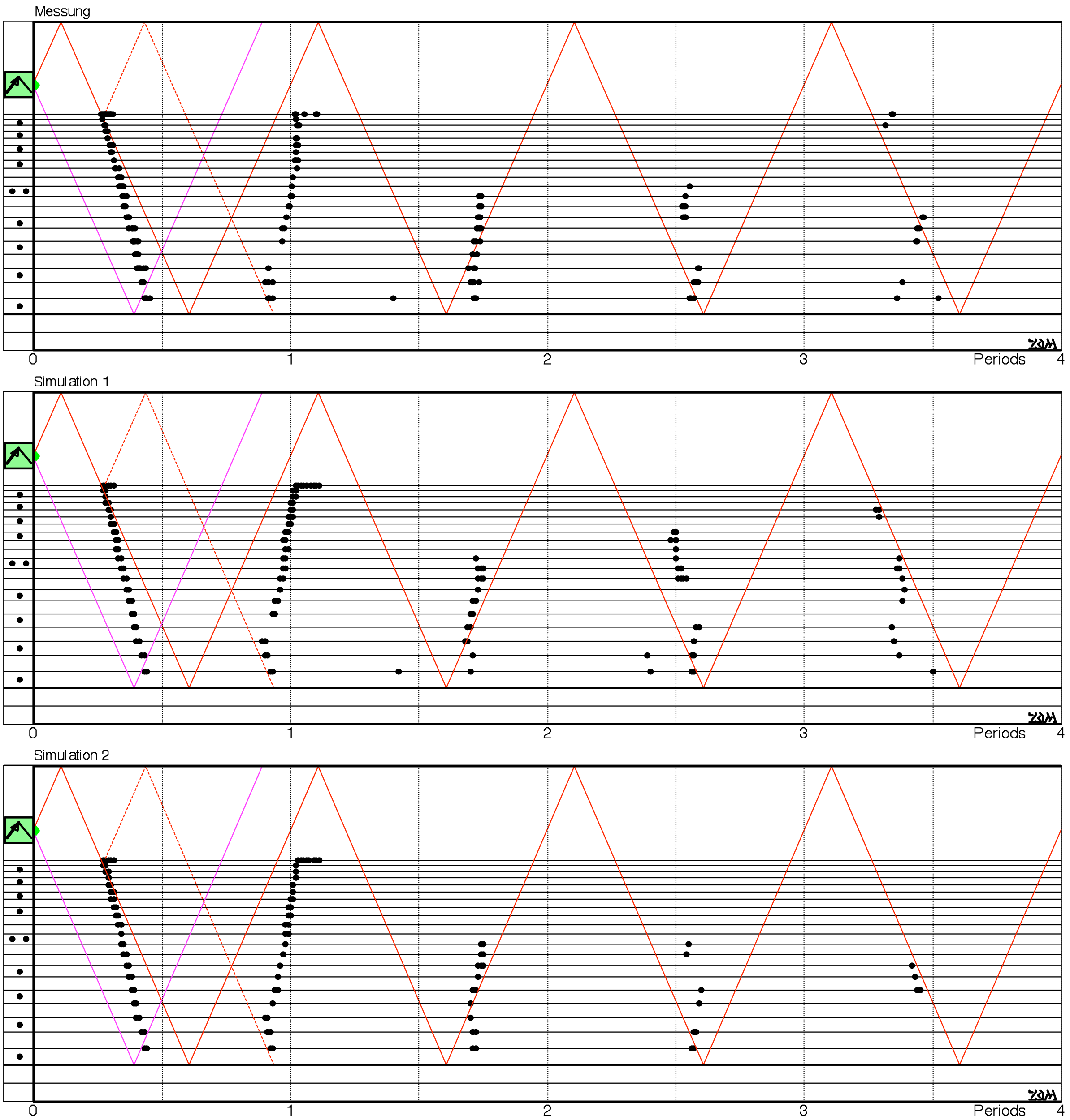

Fig. 7.146: Bounce chart. Telecaster, D-string fretted at the 2nd fret, pulled up at 12 cm from the bridge and released. Top: measurement, middle and bottom: model calculations. Dots = string/fret contacts.
For simulation 2 (bottom), the bridge was raised by 0,3 mm relative to the setting for simulation 1.

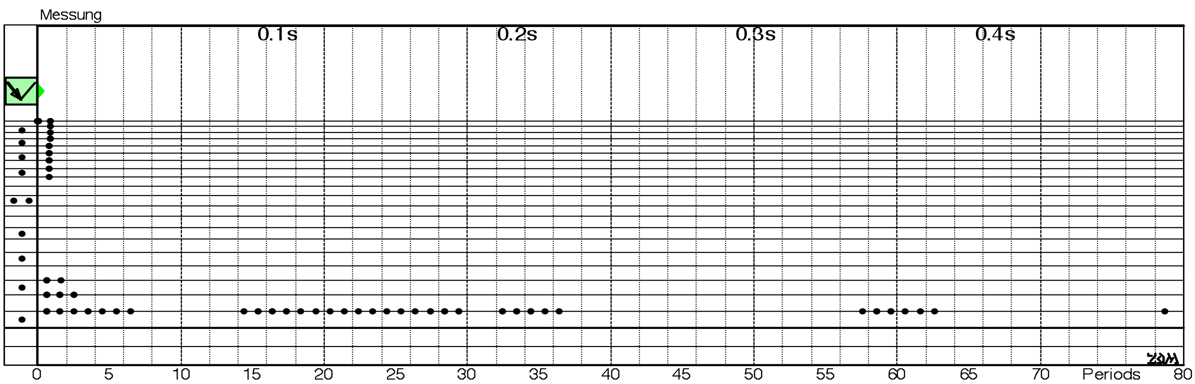

Fig. 7.147: D-string fretted at the 2nd fret: even after 0.5 s there are string/fret-contacts

In a nutshell, we have the following situation (for further elaborations see Chapter 7.12.3): In electric guitars with heavy strings and a high action, string/fret contacts (other than the actual fretting action) are rather rare, the low partials can develop nicely, and the electric sound is quite full. The string vibration can approximately be modeled in a linear fashion. Given light strings and the correspondingly connected light playing forces (Chapter 7.4.1) each individual note may be accompanied by string/fret contacts (especially for strong plucking), resulting in a more percussive sound with more treble. The low-frequent partials are less distinct because they lack the required amplitude. Of course, the individual plucking process always is essential: with brute force, it is possible to make a heavy string bounce onto the frets, as well, and a light string may be plucked so gently that it does not come into contact with the frets. That's what this statement is based on: **it's all in the fingers, man!**

For short notes, the **guitar body** has next to no influence on the electric sound, and for solid body guitars no influence is felt for longer sustained notes, either. With hollow-body instruments, in particular two effects are found: since especially the low-frequency notes are (acoustically) radiated better, the corresponding decay times are shorter, and for the same reason these instrument tend to feed back more quickly.

In terms of influencing the sound, the way/style of playing comes first, and strings and pickups are next (in high quality guitars). We then get to the mechanical characteristics of the bridge, and then to the frets (even the higher-most, possibly "never used" ones). That the acoustical sound radiated by an electric guitar would give "complete" testimony about the electric sound is a fairytale – albeit one that apparently cannot be silenced. Already Leo Fender and Les Paul fully understood that the vibration-energy needs to remain in the string as long as at all possible – as little as possible should be transferred into the body. Any acoustic sound needs to be channeled through the body (to use layman's terms) – so the material it is made of is relevant, but – alas! – only for the acoustic sound. The guitar body can influence the electric sound, but only in terms of absorption. Since it seems that every guitar player demands a sustain as long as possible, the absorption needs to be as low as possible. In that case, however, the influence of the body wood on the electric sound has to be as small as possible, too. Knowing that, it is not surprising that an electric guitar build from undefined, knotty platform-wood can fill the guitar player with enthusiasm due of its sound (G&B 7/10) … because of its electric sound, that is, of course.

7.12.3 The roots of the electric sound

Of course, the pickup voltage does not yet yield a "sound" – for that, amp and speaker are required, and – diving into philosophy – a listener, as well. Wouldn't it make for a great debate to ask whether airborne vibrations that are not heard by anybody merit the term "sound"? But that would be the realm of those physicists who – good heavens! – seek to become a DPhil rather than a DSc, i.e. move into a world completely foreign to the Doctor of Engineering. In short: without amplification, the electric guitar generates an acoustic sound, amplified it generates the electric sound. Only the latter is addressed in the following, as is the analysis and description of its origin.

Step-excitation and pick-filter

From a systems-theory point-of-view, plucking a string represents an impressed force-step – however not one in the form of an ideal step-function but modified by the pick-filter (Chapter 1.5.2). Due to mode-coupling in the bearings (bridge, frets) and magnetic pull-forces, the string vibration does not remain in one plane but starts a wobbling motion in space (circular polarization, Chapter 7.7.4). Using angle of pick-attack, plucking-strength and -direction, and via further finger/string contacts, the guitarist shapes the electric sound to a significant degree.

String vibration

Starting from the plucking location, transversal waves and dilatational waves run in both directions. They are reflected at the bearings and (approximately) result in standing waves. Dilatational waves that propagate dispersion-free are of lesser significance but they may lead to frequency-selective absorption losses (Chapter 7.7.4.2). Transversal waves (the important wave-type) propagate with dispersion; their propagation velocity increases towards higher frequencies, leading to an inharmonic spreading of the line spectrum (Chapter 1.3). This inharmonicity (dependent on the string diameter) is quite desirable: it livens up the tone, especially in case of non-linear distortion in the amplification chain (difference tones, see Chapter 10.8.5).

String material

The (manufacturer-specific) relation of core- and winding-thread (Chapter 1.2) is – right behind the overall diameter – the other important parameter influencing the inharmonicity of the partials. A further influential factor could be how tightly the outer thread is wound onto the core; but compared to ageing processes (skin oils, corrosion), it takes a backseat.

Plucking (picking) position

The plucking-position separates the string into two sections, the length-ratio of which determines the zeros of the plucking-interference-filter. The closer the plucking happens to the bridge, the further apart the filter-zeros are, and the harder and more trebly the sound gets (Chapter 2.8). The plucking-interference-filter operates with an individual characteristic for each string and cannot be simulated with a simple effects device.

Pickup position

Just like the plucking-interference-filter, the pickup-interference-filter is a comb-filter; its zeros are, however, determined by the pickup position and not by the plucking position (Chapter 2.8). For the single-coil pickup, one comb-filter is active, for a humbucker there are two. If there is a difference between the two humbucker-circuits, further degrees of freedom in the signal filtering result. Again, the pickup-interference-filter acts string-specific, and its effect is dependent on the fretted pitch.

Magnetic aperture, non-linearity

The aperture-filter is a string-specific low-pass (Chapter 5.4.4) that is defined by the width of the magnetic window. Decreasing the distance between magnet and string, and increasing the magnetic strength increases the cutoff frequency. The filter is string-specific. For strong picking attack, the magneto-electric transfer (Chapter 5.8) based on the law of induction shows a non-linearity that should not be neglected. This non-linearity is string-specific and therefore must not be mixed up with amplifier distortion.

Pickup directionality

If a pole-piece of a pickup is positioned exactly underneath the string, the pickup will sample almost exclusively the fretboard-normal string-vibration (Chapter 5.11). This implies that pickups offset to the side will to some extent tap into the fretboard-parallel vibration, as well – this may be of significance for fret-bounce processes (Chapter 7.12.2)

String damping

The string vibration is dampened by several mechanisms (Chapter 7.7); it is in particular the internal damping, and the damping at the bearings, that stand in the way of "endless sustain". The internal damping is generated by micro-friction as the string is deformed; for wound strings, the damping occurring between core-wire and winding may be included here, too. Also, already minor residue from skin or talcum in the winding leads to dramatic reduction of the decay time (Chapter 7.7.6). The damping due to bearings happens at the bridge and at the frets (or at the nut) because a small part of the vibration energy is not reflected but drains into the bearings. This is the only mechanism with which the **guitar body** can have any influence on the electric sound at all♣, but because this damping effect is supposed to be as small as possible in order to support long sustain, the influence of the body is very small. In particular in solid-body guitars, the body inflicts little absorption. The bridge – located between string and guitar body – may exert a comparably larger influence on the string vibration.

Neck, action, frets

Forceful picking and/or low action will have the effect that the string often bounces off the frets (Chapter 7.12.2). The percussive sound caused by this depends largely on the height of the individual fret – and the "never touched" uppermost frets are relevant here, as well. Therefore, if a musician notices the sound of a guitar changing over time, this is not because – as Neil Young opines in G&B 12/05 – every played note somehow stays in the guitar ☹, but very probably because of fret-wear ☺. Which would also explain why that vintage guitar acquired for a 5-number sum does suddenly not sound "vintage" anymore at all after the urgently required re-fretting job has been performed.

Finger- and hand-damping

As soon as the fretting hand touches the guitar neck, it acts as an absorber and potentially reduces sustain, and a similar effect is caused by the finger pressing the string against the fret. We may find pertinent frequency-dependencies with open-played, brand-new strings – however, these dependencies quickly loose their significance after having played for half an hour, and when analyzing not only open strings.

Pickup transmission

The transfer-function of a magnetic pickup is predominantly determined by the inductance of the winding, and the capacitance of the cable (Chapter 5). Together, the two form a low-pass the cutoff frequency of which may lie below 2 kHz, or above 5 kHz – thus, the pickup plays a decisive role for the electric sound. The transmission coefficient that may easily vary by +300% contributes significantly to the sound in case the input stage of the amplifier is overdriven. Consequently, there can be no serious statement along the lines that the pickup would just add a few "nuances" to the "sound of the wood". Apart from the LC-lowpass, the pickup may contain further frequency-determining components, such as metal sheets causing dampening of eddy-currents, or guides for the magnetic field that result in a spatially more spread-out sampling of the string vibration. In humbuckers, inductive and capacitive coupling processes may cause complex filtering. The parameters of pickups of seemingly the same build can have considerable scatter: in particular in old pickups, the number of turns in the winding, the thickness of wire and varnish, the magnet material, and the fittings can vary strongly, and even magnets mounted the wrong way 'round may occur. Moreover, old pickups may have shorts in the winding, and therefore there is not "the" Strat-pickup, nor is there "the" 1958-Strat-pickup.

♣ Regarding body- and neck-resonances, see Chapter 7.7.4.4.

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Electrical circuit in the guitar

The electrical components (potentiometers, capacitors, possibly also coils) included in the guitar form an electrical network the filtering effect of which may be described without much effort. The "holy aura" attributed to old components can scientifically not be substantiated, and in particular horrendous markups are not justifiable, even if corresponding myths are eagerly celebrated by some failed HiFi-authors. On the other hand, the coaxial cable connected to the pickup may spring a surprise due to a possible peculiar, humidity-dependent capacitance. Also: amplifier, loudspeaker and room must not be forgotten (Chapter 10 & 11).

The insignificant

Of course, given the right equipment and putting in many hours of effort, even minute changes in the decay behavior can be measured, e.g. when machine heads (tuners) are exchanged. The same may be possible if varnish is stripped off the guitar body, or if it is replaced by another type of varnish. However, all these changes are so tiny compared to the variations effected by the fretting hand that they simply bear no significance whatsoever.

Kaput: the broken, busted, worn out and dead

And then there are of course all those more or less broken, in fact unplayable guitars that "feature" unacceptably uneven frets, loose necks, rattling truss rods, pickups with shorts in the winding, scratching pots, bridges that shift from one rest-position to another at the slightest touch, or a "custom job" done by Mr. Knowitall. May the Eternal Shredder graciously accept their souls ….

You others, though, who in your hands an unbroken guitar you hold:
Do search not for new gimmicks, but to play learn – everything else come to you it will.

7.12.4 There's nothing there, or is there??

That we tried, in this chapter, to trace the tiniest measurement artifact, and to capture conductances with, if possible, no less than 80 dB dynamic range – that does not imply that all the little peaks we could eventually measure are at all audible. Just as the executive authority needs to be separated from the judiciary authority, we need to distinguish psychoacoustics from instrumentation when doing an analysis of sound. The better the analytics, the safer it is to attribute a measured effect to the object to be measured, rather than running the danger that the measurement device fooled us. Indeed, it is a great result, as well, if a bridge conductance measured with much effort proves to be so small that its irrelevance is now safely established. And even if an audible effect shows up: not every difference in sound points to the source of the purportedly never-again-reproducible vintage-tone (whatever that may be) … not every fart renders the planet inhospitable.

