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.

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 ***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.

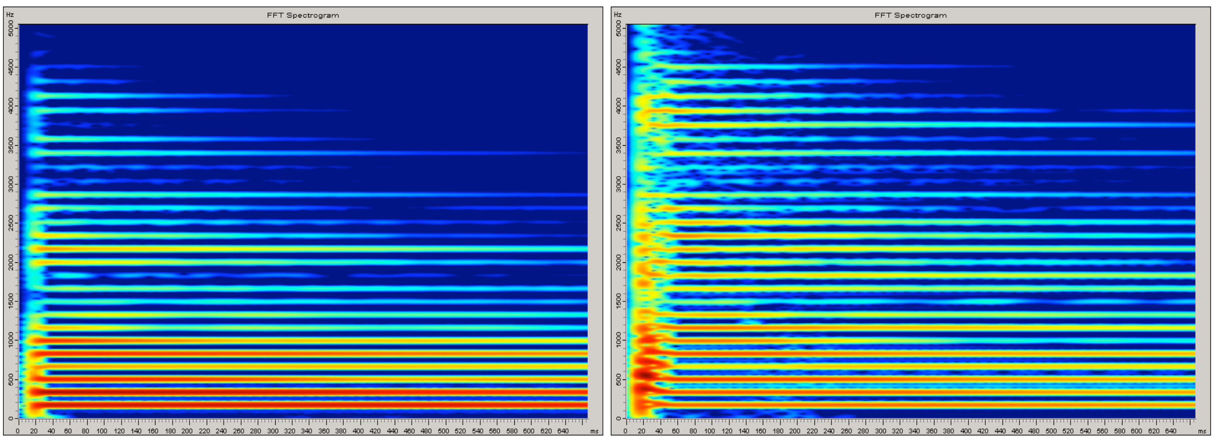

Fig. 7.126: Spectrograms (0 – 650 ms, 0 – 5 kHz). E_3 plucked weakly (left) and strongly (right) on the A-string. Color dynamic (blue ... red) = 60 dB. Fender Telecaster, fresh strings, bridge pickup.

♣ 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 **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!

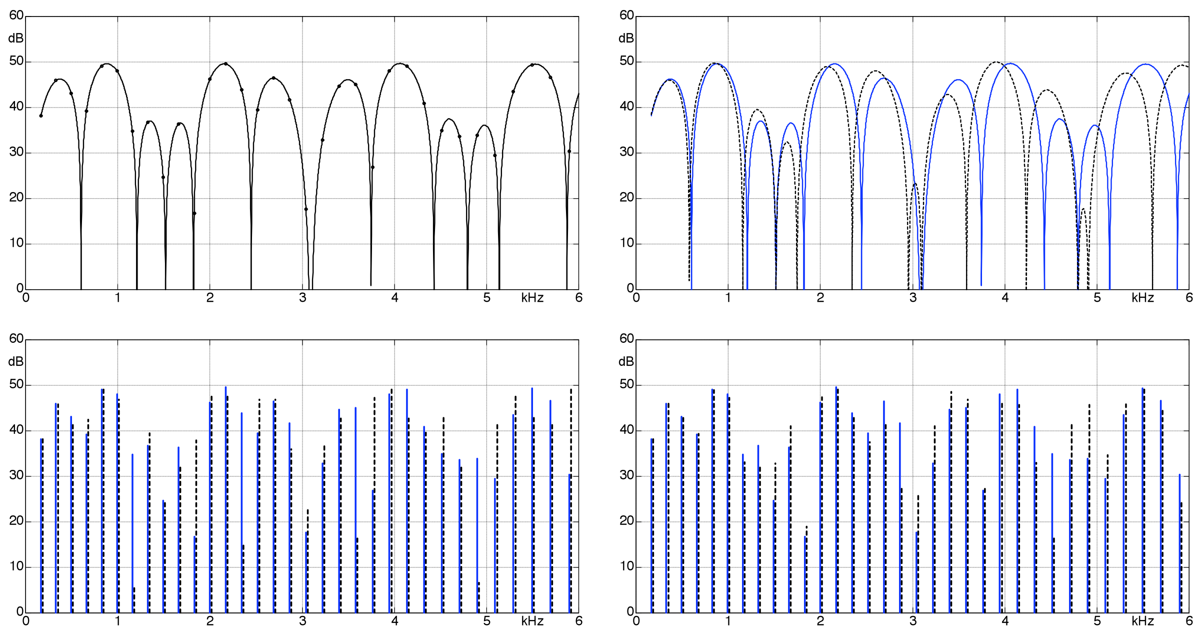

Fig. 7.127: Interference filters for the Telecaster. Upper left: A-string plucked at the 7th fret, bridge pickup. Upper right: plucking position changed by 5 mm (added to upper left graph). Lower left: line spectrum for the upper right picture. Lower right: as lower left but with the pickup position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

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”).

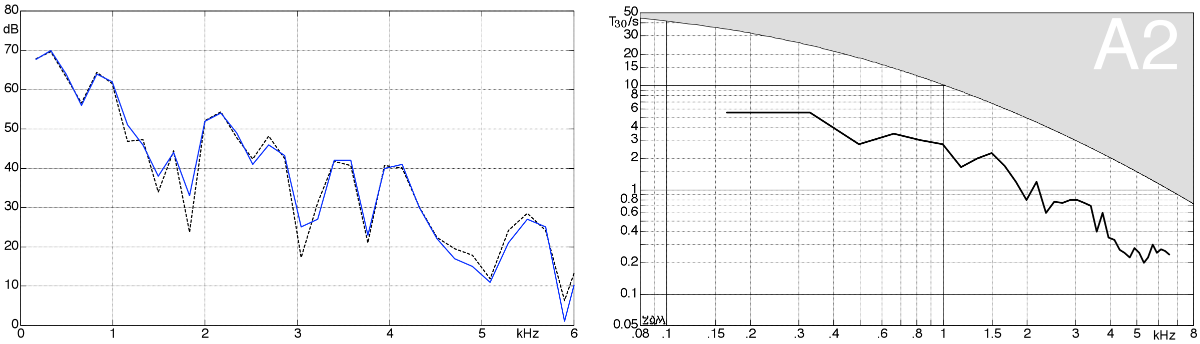

Fig. 7.128: Left: decay-spectrum (measurement ——, model: ----); right T_{30}-spectrum (measurement). The region marked in grey estimates the upper limit of T_{30} due to radiation/internal damping of the string, Chapter 7.2.2).

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.

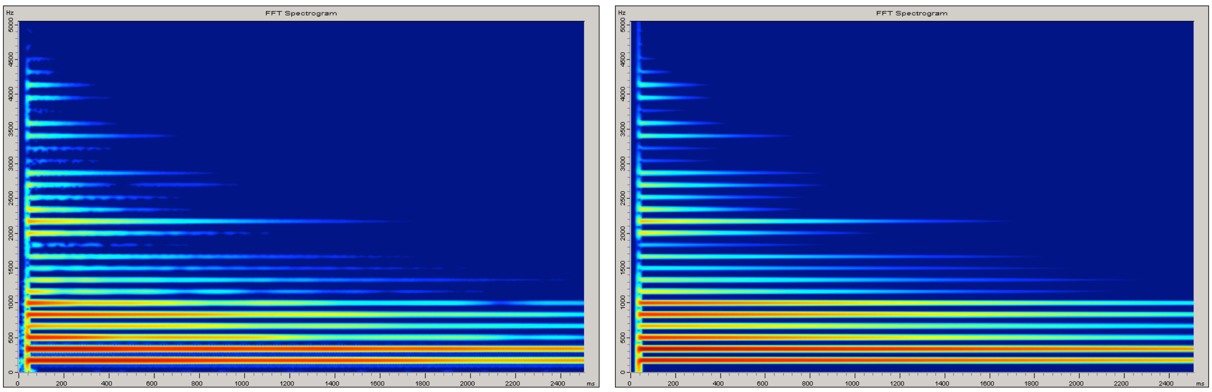

Fig. 7.129: Spectrograms. Left: real Telecaster-signal, right: synthetic signal. 0 – 5 kHz, 0 – 2.5 s.

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.

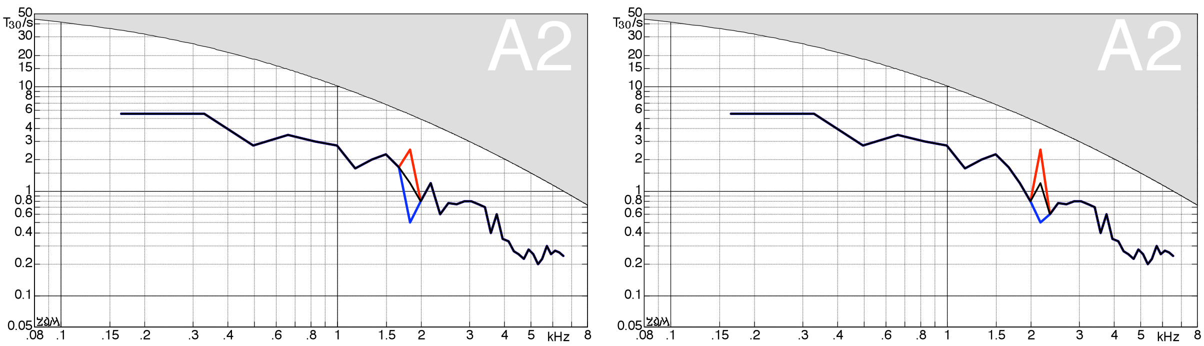

Fig. 7.130: Modification of the decay times of individual partials. The changes affected in the left-hand graph remain inaudible; the extension (red) in the right hand graph is audible, the shortening (blue) remains inaudible. The region marked in grey estimates the upper limit of T_{30} due to radiation/internal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

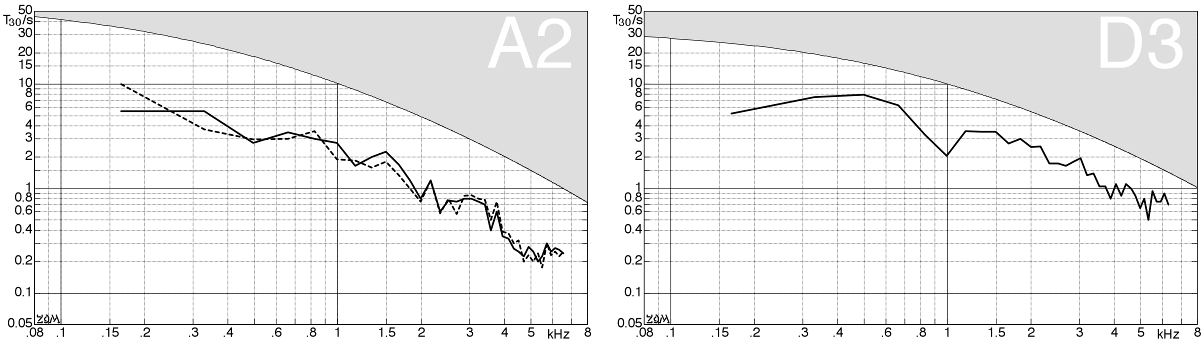

Fig. 7.131: T_{30}-spectrum. Left: E3 played at the 7th fret the A-string, left hand held in different positions. Right: E3 played at the 2nd fret of the D-string. Fender Telecaster, fresh strings (009 to 046). The region marked in grey estimates the upper limit of T_{30} due to radiation/internal damping 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 8^{th}-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.

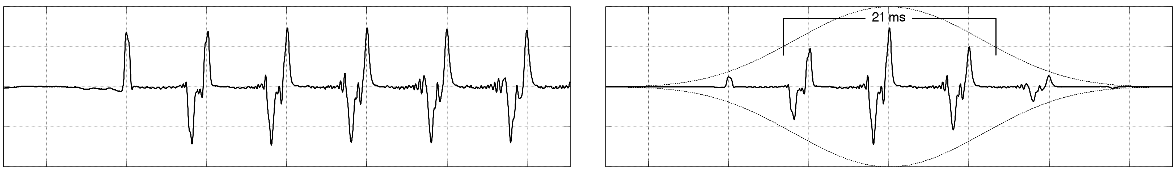

Fig. 7.134: Weighing over time of the pickup voltage (E3) by a Kaiser-Bessel-window (N = 2048).

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**.

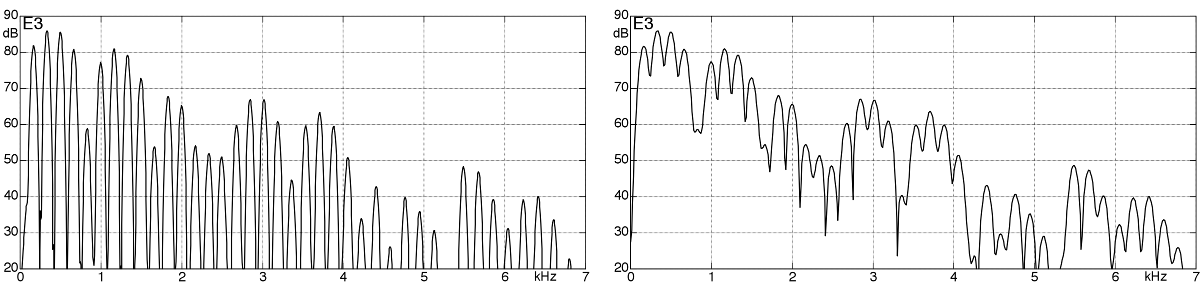

Fig. 7.135: DFT-spectrum for Fig. 7.134, Kaiser-Bessel-window, N = 2048 (left), N = 1024 (right).

 Translated by Tilmann Zwicker

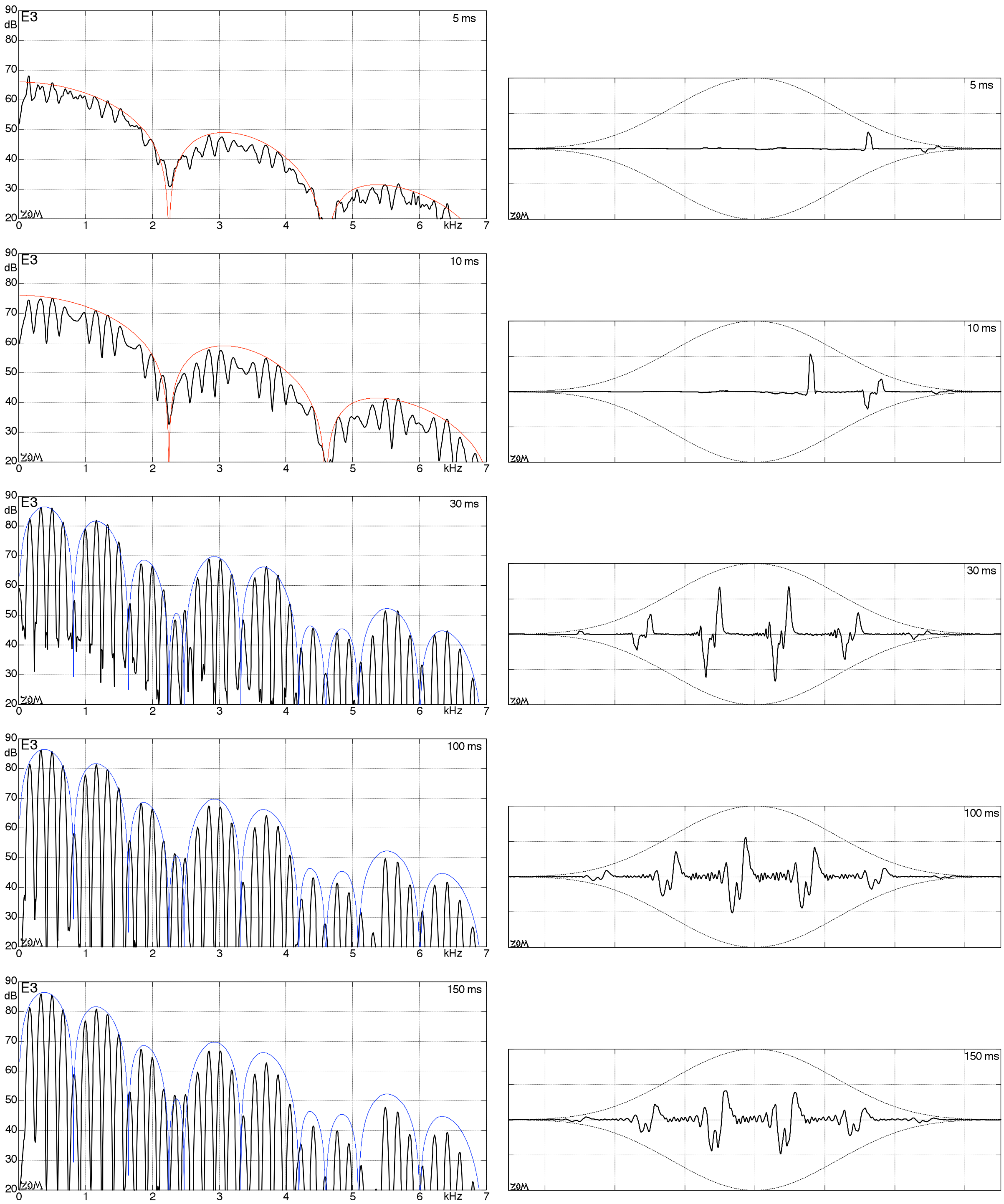

Fig. 7.136: Spectra and time-functions (subjected to the window) of the pickup voltage. E3 on D-string, Telecaster. The calculated model-envelopes (----) fit perfectly to the measured line spectra.

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].