1.5 The plucking (or picking) process

The guitar string is plucked (or picked) with the finger (-nail) or a plectrum (pick, fingerpick). The following calculations and measurements describe the excitation with a pick because this represents the dominating approach for electric guitars.

1.5.1 Dispersion-deconvolution

Compared to the (particle) velocity of the string, the speed of the pick is relatively slow; in fact, the displacing of the string can be regarded as quasi-stationary. For low-frequency movements, the string acts as a spring with a lateral stiffness s_Q (depending on the scale M), the tension force Ψ, and the distance x between location of picking and bridge:

$$s_Q = \frac{\Psi}{M} \cdot \frac{M/x}{1 - x/M}$$ Lateral stiffness

Usually, the location of picking is about 6 – 10 cm from the bridge, with a lateral stiffness of about 1000 – 2000 N/m resulting. Given a typical displacement of 2 mm, the potential **excitation energy** will be around 2 – 4 mWs. No significantly higher energy levels will be obtainable due to the distance of string to fretboard, but lower energy levels may certainly occur with light plucking. Because the lateral stiffness is similar for all 6 strings, the excitation energy of all strings is comparable, as well.

First, the string converts the excitation energy into vibration energy that is on the one hand radiated as airborne sound, and that on the other hand will directly be converted into heat energy. If all of the vibration energy would remain within the string, the latter would heat up by about 1/1000th of a degree – no really much at all. A well-built acoustic guitar will convert a considerable portion of the vibration energy into airborne sound: in an anechoic chamber, peak sound pressure levels of just shy of 90 dB may be reached at 1 m distance. Measurements with a Martin D45V yielded an **airborne sound energy** of about 1 mWs. This, however, represents merely an orientation because beaming and plucking strength were not determined precisely – indeed the investigation of acoustic guitars is not the actual aim here.

When analyzing the string oscillation from an instrumentation-point-of-view, several systems need to be distinguished: generator, string, and pickup. The **generator** describes the string excitation. Idealized, the plucking delivers a force-step, but in reality differences to the ideal step are found depending on the movement of the pick. For the first few milliseconds, the **string** may be described quite well as a loss-free, dispersive, homogeneous transmission line; for more extended observations, damping increasing towards high frequencies needs to be considered. The **pickup** converts mechanical vibrations into electrical signals. Its sensitivity depends on the oscillation plane of the waves, and moreover we encounter strong frequency dependence. The term “pickup” shall here be used rather broadly at first; it includes all frequency dependencies that are not directly due to the plucking process or to the flexural wave. A distinction into further subsystems may be necessary – depending on the circumstances.

The objective of the present investigations was to describe the transmission behavior of the above systems. Since all three subsystems interact (the plucking process cannot be analyzed without the string, the pickup will re-act towards the string), an isolated system analysis was not possible. In some respects, the vibration instrumentation also provided limitations, in particular if measurements up to 10 kHz or even 20 kHz are targeted.

The below measurements were taken with the Ovation Viper already mentioned. The string was plucked with a **plastic plectrum** given realistic conditions (in situ). This provided, as a first approximation, a step-shaped imprinted force; however, more precise investigations show significant deviations from this. The problem is not so much the actual **step** itself (which of course may not be of infinitely fast speed: natura non facit saltus), but much more the way the force develops ahead of the actual step. First, the plectrum relatively slowly presses the string to the side. Just before the step, a relative movement between string and plectrum commences which may in turn include both sliding friction and static friction (slip-stick). In this, the force fluctuates quickly. After the plectrum separates from the string, it moves according to a damped Eigen-oscillation (natural vibration) that may include another short contact to the string. It is almost impossible to directly measure the forces occurring at the tip of the plectrum – especially not up to 20 kHz. However, the piezo-signal allows for conclusions regarding the excitation signal.

To describe it, the overall transmission line is divided into three subsystems: the **plectrum-filter** that forms the real force transmission from the ideal step, the **string-filter** modeling the dispersive flexural-wave propagation, and the **piezo-filter** emulating the transfer characteristic of the pickup (incl. connected resonators). If on top of the step-transmission, the reflections are of interest too, a recursive structure is required (Chapter 2.8).

The individual filters are taken to be linear – this should be a correct assumption at least for light plucking of the string. Moreover, the piezo-filter is of time-invariant character. The string definitely does not have that quality: an old string features a much stronger treble-damping than a new one. Within a single series of experiments, however, the string may be seen as time-invariant as long as no detuning occurs. The plucking process is difficult to repeat the exact same way; it is time-variant, as well. Using suitable mechanical contraptions, an acceptable (albeit not ideal) reproducibility is possible.

The overall system between step-excitation and piezo-signal is described via an overall transfer function and a step response (or impulse response). Without supplementary knowledge, a division into the individual subsystems is not possible. Assuming restricted conditions, it is, however, possible to determine approximated transfer characteristics.

First considerations are directed towards the wave propagation. The frequency dependence of the group delay could already be shown using short-term spectroscopy, with good agreement between physical explanation (cantilever) and measurement. The measurements of the evolution of the levels of the partials during the first milliseconds indicates only very little damping; therefore assuming a loss-free all-pass is justified.

The following considerations relate to the low E-string plucked in its middle with a plectrum. While the step runs from the middle of the string, the levels of the partials do not change, but the phases are shifted such that the step is spread out (Fig. 1.16). If we shift the phases back using an inverse filter, the step reappears. It is changed by the piezo-filter, though, and after a short time, the saddle reflections superimpose themselves (**Fig. 1.25**).

Shifting back the phases corresponds to a de-convolution using the impulse response of the all-pass, or a multiplication with the inverse transfer function of the all-pass. We need to consider here that a de-convolution is only possible for one single line-length (e.g. $L/2$), and for this reason the steps following later on the time-axis in Fig. 1.25 still show all-pass distortion. Due to the de-convolution, the step spread out across the time range from 1 – 3 ms is concentrated to the zero point on the time axis. The signal occurring ahead of that is the excitation by the plectrum, convolved with the impulse response of the piezo-filter. Now, this is where things get complicated: the plectrum-filter and the piezo-filter cannot be separated without any further assumptions. There are an infinite number of possibilities to separate a product into two factors.

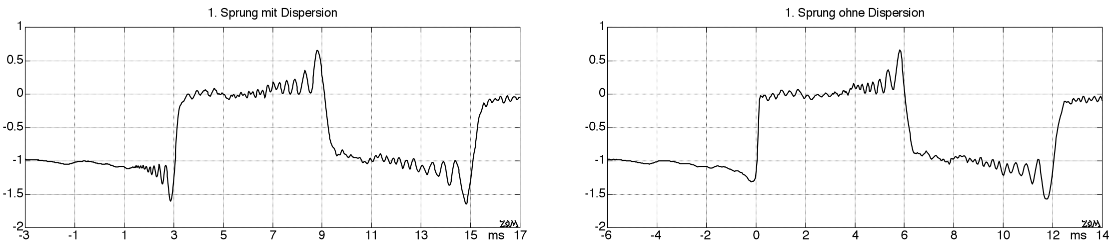


Fig. 1.25: Original piezo-signal (left), de-convolved piezo-signal (right); low E-string plucked in the middle. “1. Sprung mit/ohne Disperion” = 1st step with/without dispersion.

However, in order to fundamentally understand the plucking process, an exact system-separation is not necessary in the first place. We already obtain a good approximation from defining the signal shape ahead of the first step as the plectrum-excitation. For a more exact analysis, measurements with the laser vibrometer are being prepared.

Already a simple evaluation of many plucking processes reveals various mechanisms influencing the vibration:

The distance between plucking location and bridge is responsible for characteristic comb-filters; this will be discussed in-depth later.
Shape and hardness of the plectrum influence the treble response.
The attack angle of the plectrum influences the bass response.
Bouncing and “slip-stick” processes lead to comb-filtering.

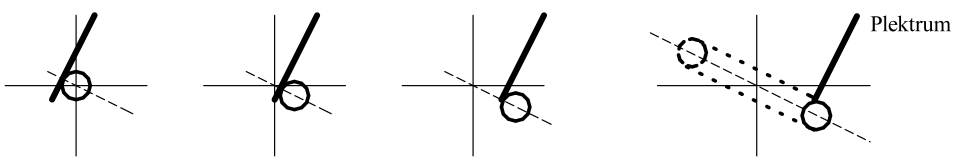


Fig. 1.26: String movement fro friction-free plectrum excitation; guitar top horizontal (sectional image). “Plektrum” = plectrum.

In **Fig. 1.26** we see (from left to right) four consecutive points in time of an excitation process. The guitar top is horizontal and the plectrum is steered in parallel to it. On the left, the plectrum touches the string without transmission of any force. In the second figure, the string is displaced along a line perpendicular to the plectrum and running through the zero position of the string. In the third figure, the displacement progresses, and in the fourth figure the string just starts to leave the plectrum and vibrate along the dashed path. The whole process is taken to be free of friction.

Given constant horizontal plectrum-speed a sawtooth-shaped string displacement results. A piezo-pickup built into the bridge will react mainly to movements normal to the guitar top (as will your usual magnetic pickup with coils), and therefore only the vertical vibration is of any significance. With slow plectrum movement, the string acts as a spring. The vertical force is proportional to the vertical displacement, and both increase time-proportionally up to a maximum value. The excitation force then instantly breaks down to zero.

In reality, the plectrum will not move precisely in horizontal fashion. Rather, contact forces will deflect it upwards. Moreover, its angle of attack will change, and for thin plectra bending will occur in addition. The sliding friction between string and plectrum also allows for small deviations from the dashed line, and there might be stochastic **slip-stick** movements. The latter stem from the difference between sliding friction and static friction: if the plectrum-parallel string force becomes greater than the static friction force, a relative movement between string and plectrum sets in along the plectrum. Since the smaller retention force is now substantially surpassed, the string can slip over a small distance – until it is stopped again via the (higher) static friction force.

For Fig. 1.26, the plectrum is angled at 63° relative to the guitar top, but remains parallel to the longitudinal axis of the string. The smaller this angle of attack becomes, the easier it is for the string to continuously slip towards the bottom. Increasing this angle to 90° (i.e. the plectrum is perpendicular to the guitar top), the string is displaced only horizontally at first – there is no vertical movement. It some point the plectrum has to yield, though – either it boggles towards the top, or it bends or changes its angle such that the string can move downwards. The associated excitation impulse has a shorter duration compared to the angled plectrum: the “boggling” can happen only during the very last millisecond, so to say.

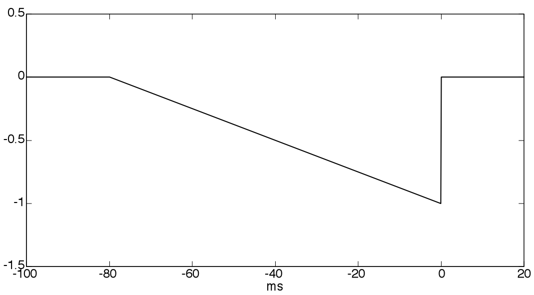
If the plectrum is not held exactly in parallel to the longitudinal axis of the string but at a slight angle, the friction changes. This is because the string does not slide along the surface of the plectrum anymore but skips along the edge of the plectrum. In most cases, the edge is rough – which increases the stochastic component in the excitation. The latter effect is further increased for wound strings.

Therefore, the guitar player has many possibilities to influence the excitation impulse – and thus the sound of the guitar. This begins with the choice of the pick, its free length, and its angle relative to the guitar top and relative to the longitudinal axis of the string. In addition to the plectrum, the fingertip may contact the string during the plucking process (teeth have also been know to get used here …), and on top of it all the location of the plucking may be varied, and the strength of the plucking, of course.

A simple, step-shaped excitation is conducive to the system-theoretical description of the string. Since moreover the evaluation of its reproducibility is done with relative ease, this excitation was the basis for many measurements. However, that does not mean that the ideal step-excitation represents the desirable objective for the guitarist.

1.5.2 Influence of the plectrum

It is most purposeful to discuss the effects of the plucking process on the sound in the frequency domain (**Fig. 1.27**). The force impulse shown in the figure has an arbitrary duration of T = 80 ms; $\hat{F}$ is the maximum value (negative in the present case). F_S describes the spectrum corresponding to this sawtooth impulse, and F_δ pertains to the time-derivative of the sawtooth impulse. Within the frequency range pertinent to the guitar it makes no big difference whether the impulse starts at –80 ms (as it does in the figure) or much earlier … it is only important that the actual step occurs at t = 0. For this reason, we use the term **step excitation** despite the fact that strictly speaking we have an impulse. We obtain the mathematically correct limiting case as T moves towards ∞; the first fraction in the spectral function vanishes in this case and – with $1/j\omega$ – a pure (rectangular) step-function remains. The time-derivative of this ideal step is the **Dirac impulse** that corresponds to a constant (white) spectrum F_δ. In systems theory, (Dirac-) impulse excitation and impulse response are most commonly used; step excitation and step response are somewhat closer to the practical application. Disregarding the frequency f = 0 that does not actually exist, both descriptions are equivalent and may be converted from one to the other.



$$F_S(j\omega) = \hat{F}\left(\frac{1-\exp(j\omega T)}{\omega^2 T} - \frac{1}{j\omega}\right)$$

$$F_\delta(j\omega) = \hat{F}\left(j\frac{1-\exp(j\omega T)}{\omega T} - 1\right)$$

Fig. 1.27: Sawtooth impulse: time- and spectral-function

Because in reality the force process occurring upon plucking does not correspond to the depiction in Fig. 1.27, we define a **plectrum-filter** that shapes the actual force process from the theoretical rectangular step. The magnitude of the frequency response this plectrum-filter has describes the impact of the plucking process onto the sound.

The following figures show the analyses for the already mentioned Ovation guitar. The low E-string was plucked with a thin nylon-pick (Meazzi 19), while the piezo-signal was fed directly into a high-impedance measuring amplifier – and cleared of the dispersion via de-convolution with an inverse all-pass (Chapter 1.3.2) **Fig. 1.28** shows two time functions obtained that way. Compared to Fig. 1.27, there are several striking differences: the force increase (in terms of its amount) is not linear but progressive; during the last few milliseconds several peaks appear (slip-stick); after the step, reflections are visible that presumably are caused by longitudinal resonances.

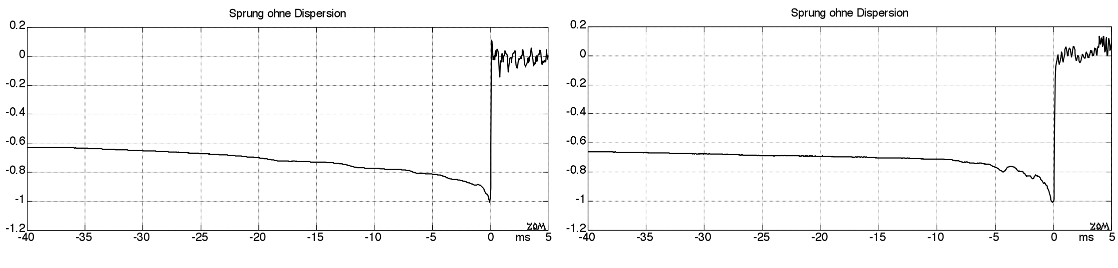


Fig. 1.28: De-convolved piezo-signal; two different plucking processes.
“Sprung ohne Dispersion” = step without dispersion.

 Translation by Tilmann Zwicker

In **Fig. 1.29** we see different plucking processes in comparison. The left-hand column shows the dispersion-free, de-convolved piezo-signal while the right-hand column shows the magnitude spectrum belonging to the differentiated piezo-signal. The derivative makes for an easier evaluation: the ideal rectangular step is linked to a constant (white) spectral function.

The first line a) depicts an almost perfect step. Only from about 3 kHz, a treble loss occurs; it is connected to the rounding off of the step. There may be several reasons for this: the tip of the plectrum is rounded off, and therefore the string is not displaced in an exactly triangular manner. This effect is probably further increased by the bending stiffness of the string. The high frequencies are consequently attenuated already in the excitation signal. In addition, dispersion effects in the string need to be considered that also manifest themselves in the high frequency range.

In the case of b), the force rises to its magnitude maximum only during the very last milliseconds. This will occur if the plectrum has a high angle of attack and moves in parallel to the guitar top. The shape is more impulse-like, and in the spectrum the bass is attenuated.

The analyses c) to e) indicate a progressive treble damping as it is typical for a round, hard plectrum.

For the remaining analyses, the force increases first (in its magnitude) and then moves through a magnitude minimum (the force acts in the negative direction). Presumably, this includes a sliding along the string of the plectrum, the latter getting stuck on the string for a short time and then finally separating from the string.

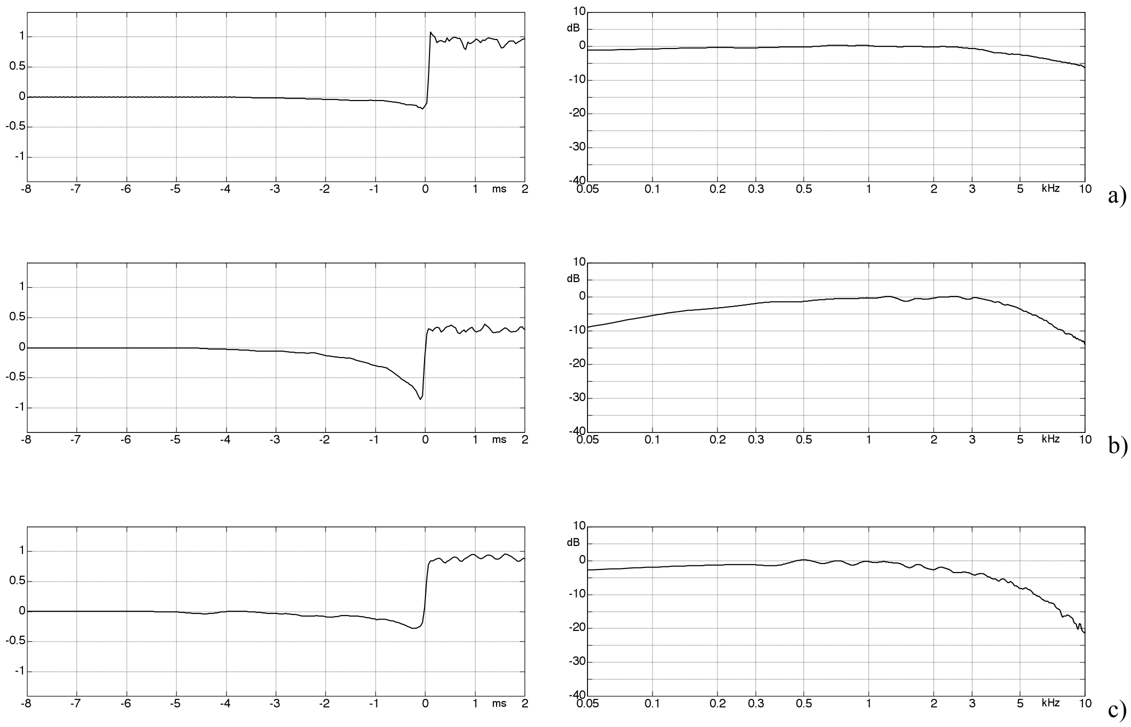


Fig. 1.29: Excitation step, and spectrum of the differentiated step for various plectrum movements.

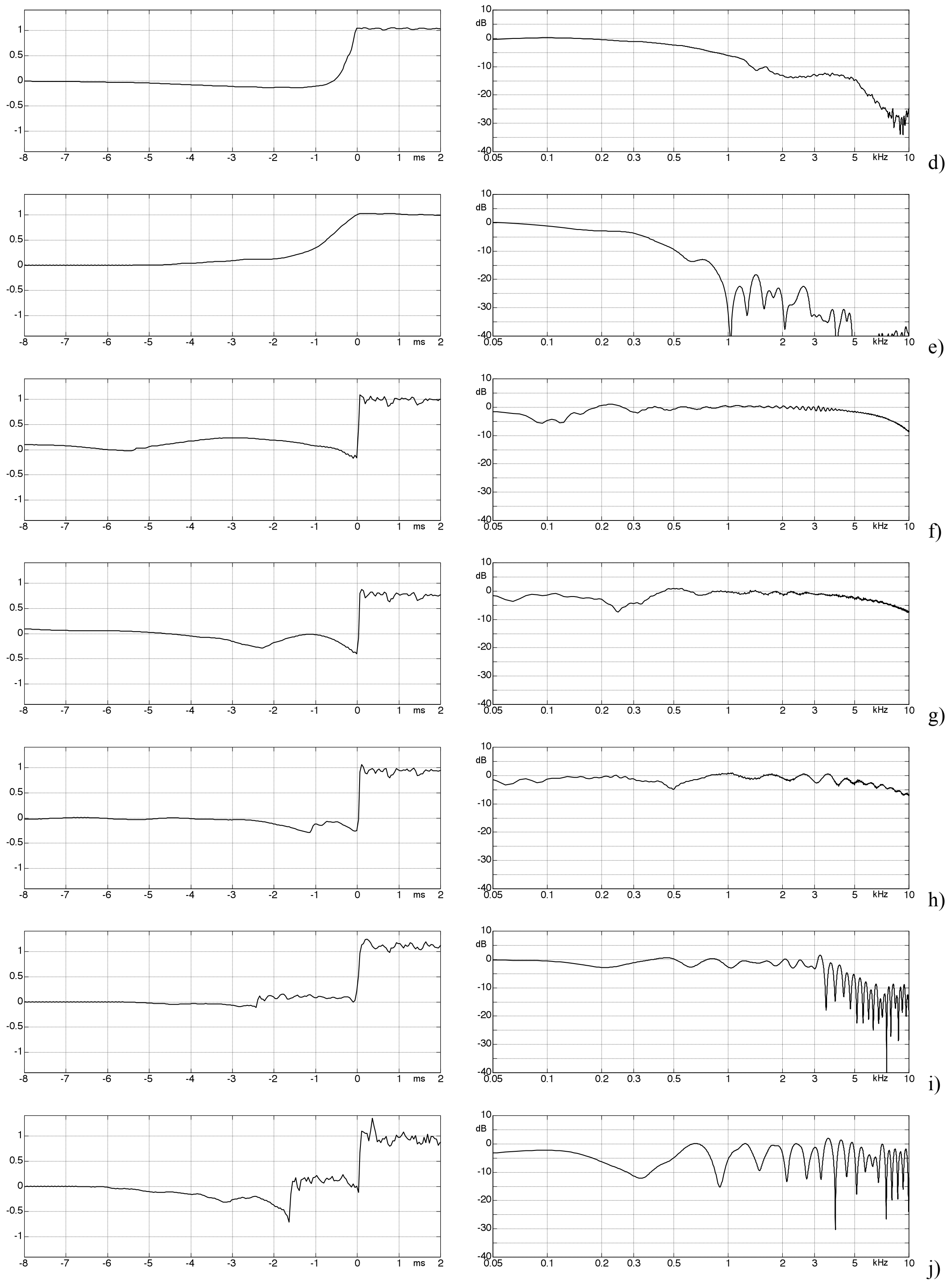


Fig. 1.29: Continuation from the previous page.

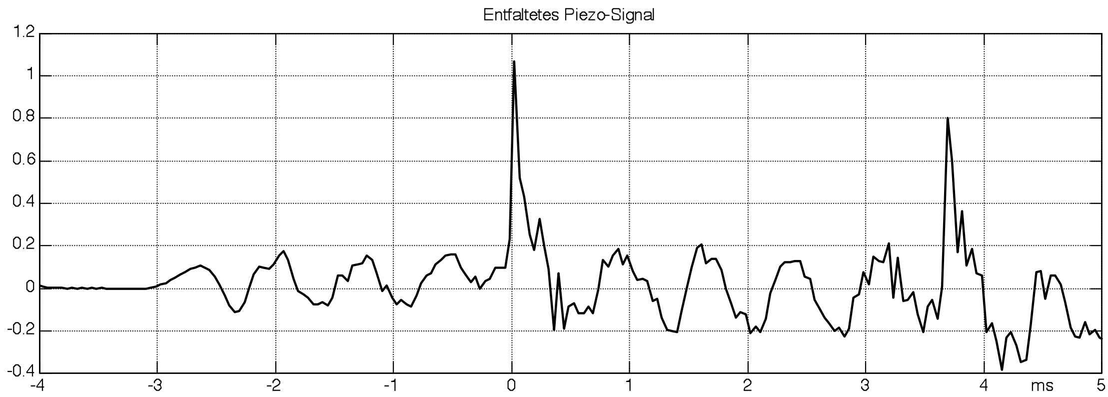


Fig. 1.30: De-convolved piezo-signal for the string excited in its longitudinal direction (scratched string). "Entfaltet" = de-convolved.

Fig. 1.30 documents an interesting detail: here, the low E-string was excited using a sharp-edged metal plectrum at mid-string in the **longitudinal direction**, i.e. the plectrum scratches along the string, jumping from one winding to the next. The signal transmitted by the piezo was again de-convolved i.e. cleared of the dispersion. As the plectrum jumps across the winding, a flexural wave is generated. The first (de-convolved) impulse of this wave is shown at 0 ms (the second impulse appears at 3,7 ms). However, in addition a **dilatational wave** of about 1,4 kHz occurs (Chapter 1.4). This (non-dispersive) dilatational wave propagates with a considerably higher speed than the transversal wave; its start is shifted by 3 ms towards the past due to the de-convolution. In fact, the de-convolution algorithm does separate according to wave-type but it corrects the phase delay of any 1,4-kHz-signal by -3 ms. Further details of the dilatational wave (in particular regarding its coupling to the transversal wave) have already been described in Chapter 1.4.

The plucking processes shown in Figs. 1.29 and 1.30 are typical for guitars but represent merely a relatively arbitrary selection. There is also a multitude of other possibilities to excite the string – and we need to particularly consider that the tip of the thumb or the first finger may also come into contact with the string. It is therefore not necessarily an indication of excessive vanity if the well-known professional guitarist, after an extensive narrative highlighting his wonderful custom-built paraphernalia, concludes the interview about his equipment with a confident: "90% of the sound is in the fingers, though".

1.5.3 String-bouncing

If a string is plucked with little force, it will approximately react as a linear system. This means that doubling the initial displacement will also double the displacement at any instant of the subsequent vibration process. Of course, any displacement is limited – at some point the string will hit the frets on the fretboard. In doing so, it generates a somewhat rattling, buzzing sound. To some degree, this is in fact a means of musical expression and thus not something generally undesired.

In the book "E-Gitarren" by Day/Waldenmaier we find the recommendation: "A slight tilt of the bridge makes it possible to adjust the action of the high E-string a little lower than that of the low E-string. The latter has a more pronounced vibration amplitude and requires more space that the high strings ". However, the transverse stiffness for all customary string sets is higher for the low E-string (E_2) than it is for the high E-string (E_4) – why then would the stiffer string require more space for its vibration? It is o.k. to concede this space to it; that decision is, however, just as individual as the choice of the string diameter and cannot be justified with a generally larger amplitude.

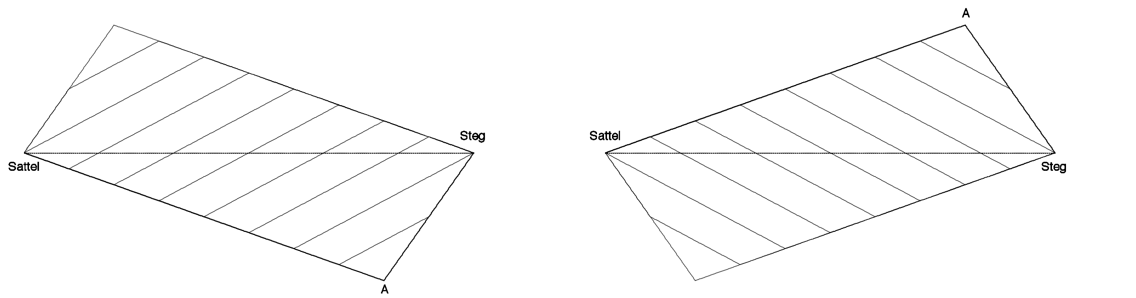


Fig. 1.31: String displaced at A (bold line), intermediate positions of the vibration (thin lines). In the left-hand figure, the string was pressed to the guitar body and then released, on the right it was pulled up and released. "Sattel" = nut; "Steg" = bridge.

The string is displaced in a triangular fashion by the plectrum (or the finger-tip, or –nail, or teeth …). After the plucking process, the string moves in a parallelogram-like fashion – given that we take a dispersion-free model as a basis (**Fig. 1.31**). However, this movement in the shape of a parallelogram can only manifest itself if the string does not encounter any obstacles. Frets are potential obstacles; their immediate vicinity has the effect that the string does not only occasionally establish contact but hits them on a regular basis … with the parallelogram-shaped movement being correspondingly changed. **Fig. 1.32** shows (seen from the side) a neck with the typical concave curvature. The axis-relations of this figure hold for the following figures, as well.

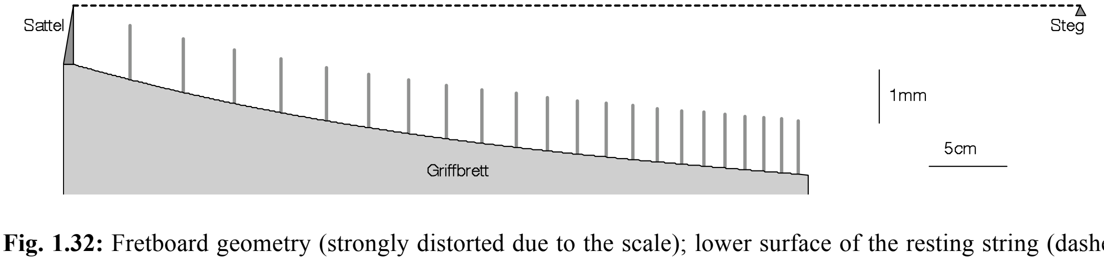


Fig. 1.32: Fretboard geometry (strongly distorted due to the scale); lower surface of the resting string (dashed). The frets are distorted into lines due to the strong magnification of the vertical dimension.
"Sattel" = nut, "Steg" = bridge; "Griffbrett" = fretboard.

If the string pressed down at point A (**Fig. 1.33**) has no contact to the frets, it can freely decay in the dispersion-free model case. The string that has been lifted up, however, hits the 10th fret already after less than half the vibration period – its vibration-shape is completely destroyed.

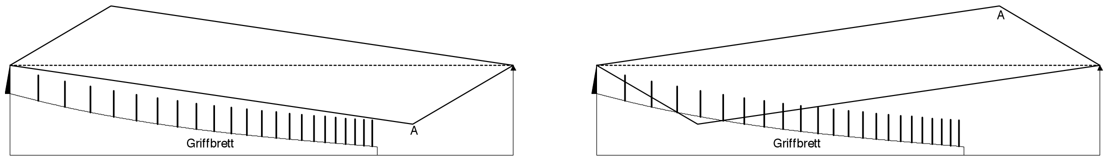


Fig. 1.33: String-parallelogram. On the left, the string was pressed down and then released (uninhibited vibration); on the right it was lifted up and then released (fret-bounce at the 10th fret). “Griffbrett” = fretboard.

The well-versed guitarist will vary his/her “attack” as required and shape the sound of the respective picked note via change of the picking-strength and –direction: both pressing-down and lifting-up of a string happen. However, in particular when using light string sets, a further vibration pattern occurs. It is generated as the string contacts the last fret (towards the bridge) when being pressed down during plucking (**Fig. 1.34**). As soon as the string is released, a transverse wave propagates in both directions and is first reflected at the last fret and then at the bridge. Consequently, a peak running towards the nut is generated – it is reflected there and bounces onto the first fret (right-hand part of the figure).

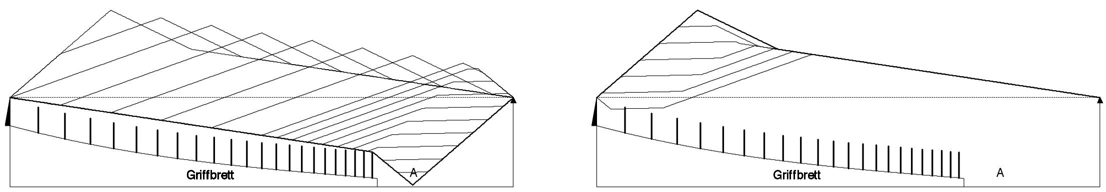


Fig. 1.34: String displacement at different points in time. On the left, the first half-period is shown, on the right we see the subsequent process including bouncing off the first fret. Plucking happens at point A with contact to the fretboard. The time-intervals are chosen such that the resolution is improved at first and after $t = T/2$. Without dispersion. “Griffbrett” = fretboard.

Immediately the question pops up: how often does this case happen? Contact-measurement at the last fret tells us: a lot. For better understanding, **Fig. 1.35** depicts the connection between plucking force (transverse force) and initial string displacement (at A). Since the transverse forces often reach 5 N (or even 10 N occasionally), contact to the last fret often occurs.

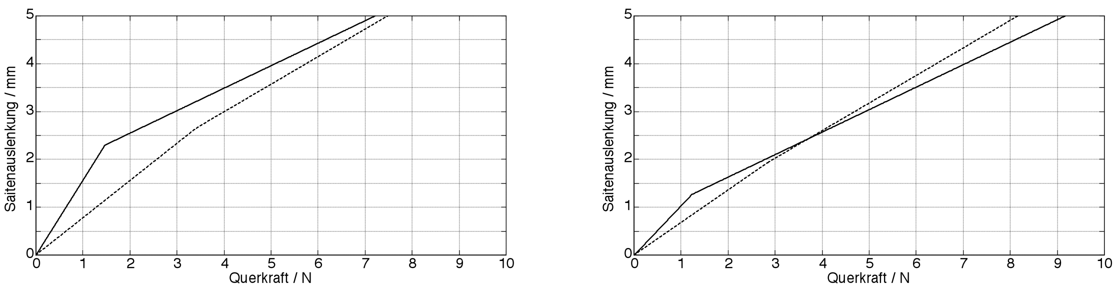


Fig. 1.35: Connection between transverse force and string displacement, open string (left), string fretted at the 14th fret (right), plucking point 14 cm (—–) and 6 cm (---) from the bridge. 2,1 mm clearance between the string and the last fret (= 22nd fret). B-string, 13 mil, calculations.
“Saitenauslenkung” = string displacement; “Querkraft” = transverse force.

We can see from Fig. 1.35 that the string operates as a linear system only for soft plucking. As soon as the string gets into contact with the last fret, the force/displacement characteristic experiences a knee – a jump in the stiffness of the string occurs. This degressive characteristic tends to correspond to the **behavior of a compressor**: despite stronger plucking force, the string-displacement grows only moderately. However, here we also find a source of potential misunderstanding, for displacement does not equal loudness! With the string establishing contact to the last fret, the shape of the vibration deviates from the mentioned parallelogram, and changes result in the spectrum, and thus in the sound.

For the following graphs, the E_4-string of an **Ovation** guitar (EA-68) was plucked using a plectrum; the electrical voltage of the piezo pickup built into the bridge was analyzed (i.e. the force at the bridge). The location of plucking was at a distance of 125 mm from the bridge, and the plectrum was pressed towards the guitar body such that a fretboard-normal vibration was generated. **Fig. 1.36** shows time function and spectrum for the linear case (no contract between string and last fret). The voltage of the piezo jumps back and forth between 0 V and 0,4 V, with a duty cycle resulting from the division of the string (517:125, scale = 642 mm). Given the transfer coefficient of 0,2 V/N (Chapter 6), the corresponding force at the bridge calculates as 2 N, this representing good correspondence to Fig. 1.35. In this example, 2 N forms the limit of linear operation – using a larger force makes the string bounce off the frets.

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Fig. 1.36: Time-function and spectrum of the piezo-signal. The upper half of the left-hand graph shows the measured time function, below is the result of the calculation. On the right is the measured spectrum and the (idealized) envelope. Open E_4-string, fretboard-normal vibration. “Frequenz” = frequency.

The analyses shown in the following graphs (**Fig. 1.37**) correspond to Fig. 1.36 but are based on (fretboard-normal) string excitations of different strengths. For the upper two pairs of graphs we can see proportionality in the time domain and in the spectral domain: the level spectrum is simply shifted upwards for stronger plucking. As soon as the plucking force exceeds 2 N (in the lower two pairs of graphs), the string touches the last fret and bounces off it. Time function and spectrum become irregular. The strong peak in the time function finds its counterpart in the location function (Fig. 1.34); it may be interpreted as the interaction between two excitations:

a) string displacement, force step at $t = 0$ (idealized), and

b) opposite-phase force step at the last fret; occurring at the instant as the string leaves the last fret ($t \approx 0{,}2$ ms).

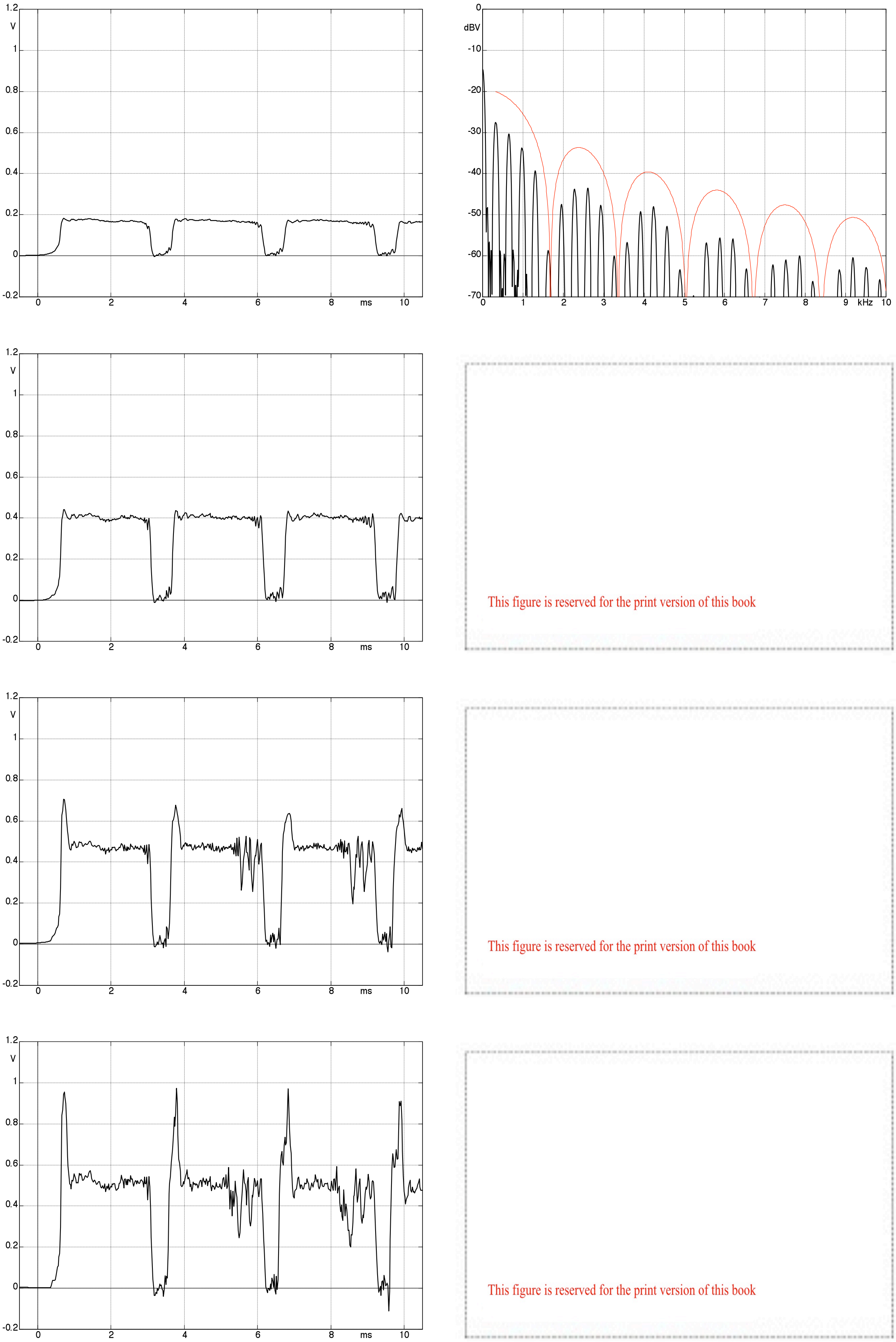

Fig. 1.37: Time-function and spectrum of the piezo-voltage. String plucked with different force. See text.

A spectral analysis encompassing the whole of the auditory range is conducive for the acoustic guitar, and the same holds for a piezo-pickup (Chapter 6). In **Fig. 1.38**, three of the sounds from Fig. 1.37 are shown as third-octave spectra. On the left, we see the spectra of strings plucked lightly and with medium strength, respectively – the system is still linear and the spectra merely experience a parallel shift. Strong plucking (right figure) leads to a level-increase merely in the middle and upper frequency range; below 1 kHz, there is even a decrease in level. As other strings are played, or as the E_4-string is fretted at other frets, this effect tends to remain, but the spectral differences are specific to the individual case.

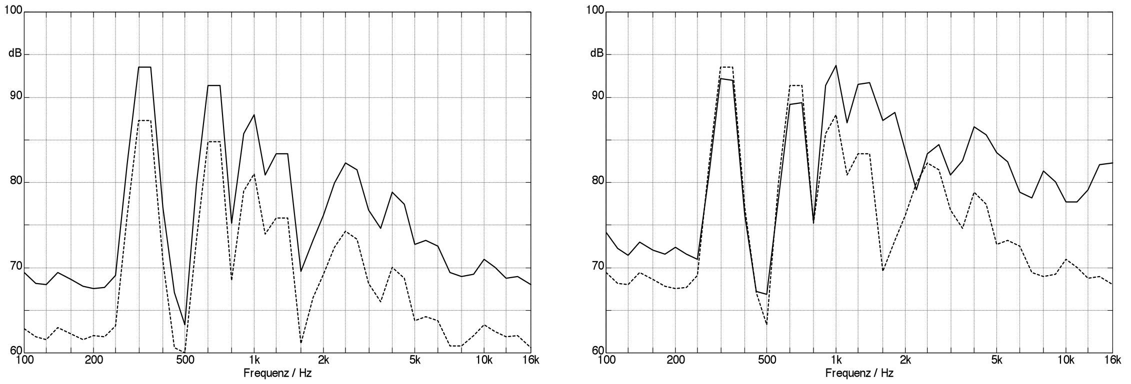

Fig. 1.38: Third-octave spectra, open E_4-string, overlapping analysis of main- and auxiliary third-octave. On the left, and for the dashed curve on the right, there is not yet any bouncing off the frets. Strong plucking (solid line of the right) causes the string to touch the last fret and bounce off it. 1st and 2nd harmonic actually decrease in this process, while there is a strong increase in level at middle and high frequencies.

From this, we can deduce a **compressor-like behavior** in any guitar: for light plucking, the string operates as a linear system, and slight changes in the picking strength lead (with good approximation) to similar level changes in the whole frequency range. However, already at medium picking strength, the string bounces off the frets – the lower the action and the lighter the strings, the lower is the threshold to this occurring. Now, if filtering (due to magnetic pickups) accentuates a specific frequency range, this compression is perceived with different strength. Fender-typical single-coil pickups emphasize the range around 3 – 5 kHz. This will lead to less perception of compression compared to humbuckers sporting resonance frequencies around 2,5 kHz. This may not happen for all played notes, but it does happen in the example shown in Fig. 1.38. So does a humbucker compress more strongly than a single-coil? “Somehow”, yes – but not causally. The source of the compression is the string (in conjunction wit the frets) that compresses in different ways in various frequency ranges. Pickups and amplifiers make this different compression audible in different ways.

Here’s an opinion voiced in the Gitarre & Bass magazine (02/2000): "What happens when I, for example, pick the low E-string first softly and then more and more strongly via a slightly distorted amp? The Strat behaves much more dynamically and you can open the throttle ever more until, purely theoretically, the string throws in the towel and breaks. The Les Paul shows an entirely different character: first, the increasingly harder picking also generates more loudness, but then the whole thing topples over: the notes don’t get louder anymore but more dense – almost as if there were a compressor/limiter switched in. Say what?! Indeed, the information of the string vibrations resulting from the behavior of the wood determines the tonal characteristic of the Les Paul, but not the fatter sounding humbuckers.”

The G&B-author was careful (?) enough not to throw in something like “and that shows that mahogany compresses more strongly than alder”. Still, he infers: “*now we understand, why a Strat even with Humbuckers can never turn into a Les Paul. You can at most make the tone warmer and fatter, but the typical compression is out of reach.*” Unfortunately, the author does not report which experiments or models were the basis for his last conjecture.

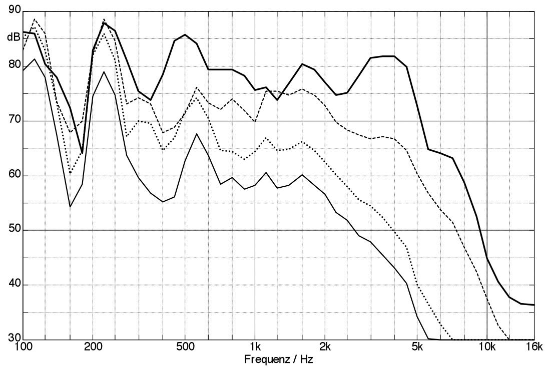

Fig. 1.39: Third-octave spectrum, Stratocaster, neck-pickup, E_2-string (42mil) fretted at the 5th fret. Plucked from lightly to strongly. Distance between plectrum and bridge: 13 cm. Clearance of the open E_2-string to the last fret: 2,3 mm.

As we can see from **Fig. 1.39**, a **Stratocaster**, too, compresses in the range of the low partials. While the level-difference between light and very strong plucking is no less than 39 dB at 4 kHz, the fundamental changes only by 7 dB. Your typical Gibson Humbucker will only transmit the spectrum of the low E-string up to about 2 kHz and therefore misses the dynamic happening in the 4-kHz-range that a Fender pickup will still capture. However, in the experiment reported in G&B, it is likely that behavior of the amplifiers was almost more important: *“via a slightly distorted amp”*. There you go! The Gibson Humbucker will have generated approximately double the voltage of the Fender single-coil. That makes the **amplifier** participate in the signal compression: it will compress (or limit) the louder signal (that of the Les Paul).

However, that does not mean that the compression is determined merely by the action on the guitar, and by the amplifier. As the string bounces off the fret, a metal hits metal (at least on the electric guitar). The result is a broad-band bouncing noise that extends to the upper limit of the audible frequency range. String- and fret-materials are of particular significance in this bouncing noise: pure-steel wound strings generate a more aggressive, treble-laden noise compared to pure-nickel wound strings. Old string with their winding filled up by rust, grease, etc, will sound duller than fresh strings. And the **fret-wire** that the string hits (that may in fact be any fret in the course of the vibration) contributes, with its mechanical impedance, to the bouncing noise, as well. A detailed analysis of the mechanical neck- and body- impedances follows in Chapter 7; string/fret-contacts are analyzed in detail in Chapter 7.12.2.

1.5.4 String-buzz

If the string is plucked with little force, it reacts approximately as a linear system. This implies that double the initial displacement also leads to double the displacement at every moment during the subsequent vibration process. Of course, the displacement cannot become indefinitely large – at some point the string will hit the frets on the neck (Chapter 1.5.3, Chapter 7.12.2). If this contact to the fretboard happens right after the plucking itself, it becomes part of the attack process of the respective tone. Later occurring contacts to the frets (with the limit at later than about 50 ms) will become audible as single events – given they are strong enough. Weak or short string/fret contacts are, to some degree, a means of expression and therefore not generally undesirable.

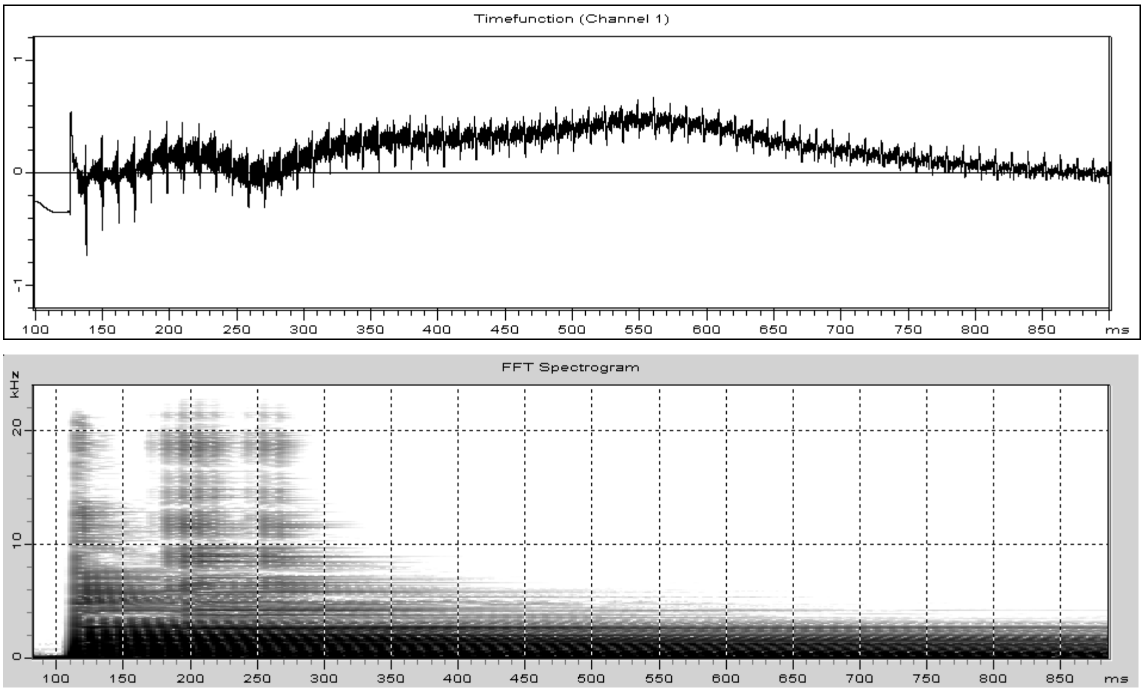

Fig. 1.40: Time-function and spectrogram of the piezo voltage resulting from a strongly plucked low E-string (E_2).

In **Fig. 1.40** we see the piezo voltage taken from an OVATION Adamas SMT (open E_2-string), with the string so strongly plucked with a plectrum that a clear buzz became audible. The spectrogram reveals – after the broadband first plucking impulse has passed – further string-to-fret hits around 200 and 350 ms; these act like high-frequency echoes. The string hits the frets repeatedly and strongly, and generates a clearly audible buzz.

Besides the impulses occurring with a separation of 12 ms, very low-frequency vibrations are visible in the time-function. These point to the reason why the string bounces off the fret not only at the very beginning of the vibration. However, an exact analysis of the low-frequency vibration cannot be derived from the time-function. This is because the cutoff-frequencies found in the piezo pickup, the amplifier and the analyzer at around 2 Hz result in strong phase shifts. The cause of the low-frequency signal components is a rotation of the plane of vibration (Chapter 7.7.4, Chapter 7.12.1).