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.

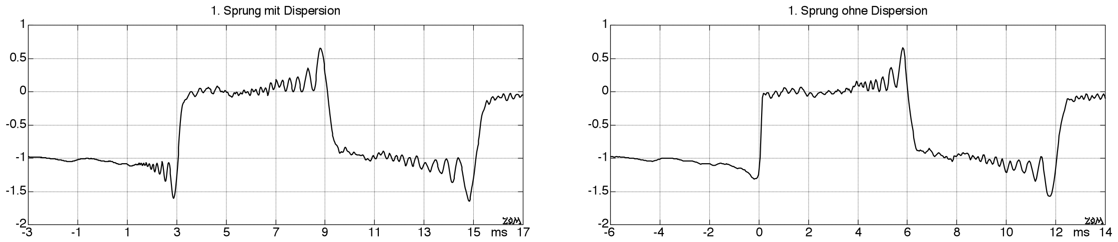

Fig. 1.25: Original piezo-signal (left), de-convolved piezo-signal (right); low E-string plucked in the middle. “1. Sprung mit/ohne Disperion” = 1st step with/without dispersion.

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.

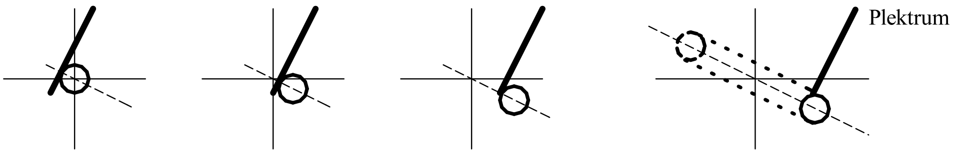

Fig. 1.26: String movement fro friction-free plectrum excitation; guitar top horizontal (sectional image). “Plektrum” = plectrum.

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.