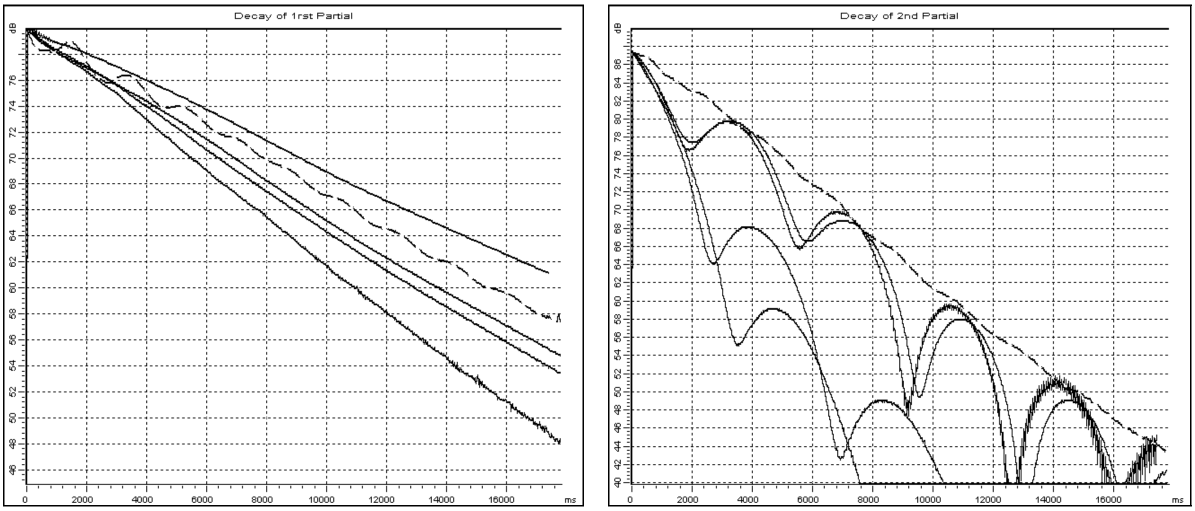

Fig. 4.53: Decay of the first two partial tone levels after fretboard-normal excitation pulse for an E_2-string, with an Ovation EA-68 piezo-pickup. Continuous lines: without magnet, dashed lines: Alnico-5-magnet in neck pickup position for a 2.5 mm distance between the string and magnet. Left: first partial, right: second partial.

Figure 4.53 shows the decay of the first two partial tones. The continuous lines were taken without a magnetic field. The upper curve, with the slowest decrease, shows the level decay of the undamped neck whereas the lower three continuous curves belong to measurements that were made with the fret-hand holding the neck in different ways without touching the strings. The dashed line was taken without neck-damping but with a magnetic field (Alnico-5-magnet placed 16 cm from the bridge). A strong influence of the fret-hand on the decay-characteristic (sustain) is observed in both measurements. The hand primarily acts as a damping resistance removing vibration energy. The level decays linearly with time for the first partial tone (left picture) without a magnetic field (exponential tension envelope curve), whereas a slight level oscillation occurs with a magnetic field. The second partial tone is completely different: There are intense level oscillations without a magnetic field, whereas there is a nearly oscillation-free decay with a magnetic field. **Fig. 4.54** shows similar results for fretboard-parallel excitations (both with magnetic field).

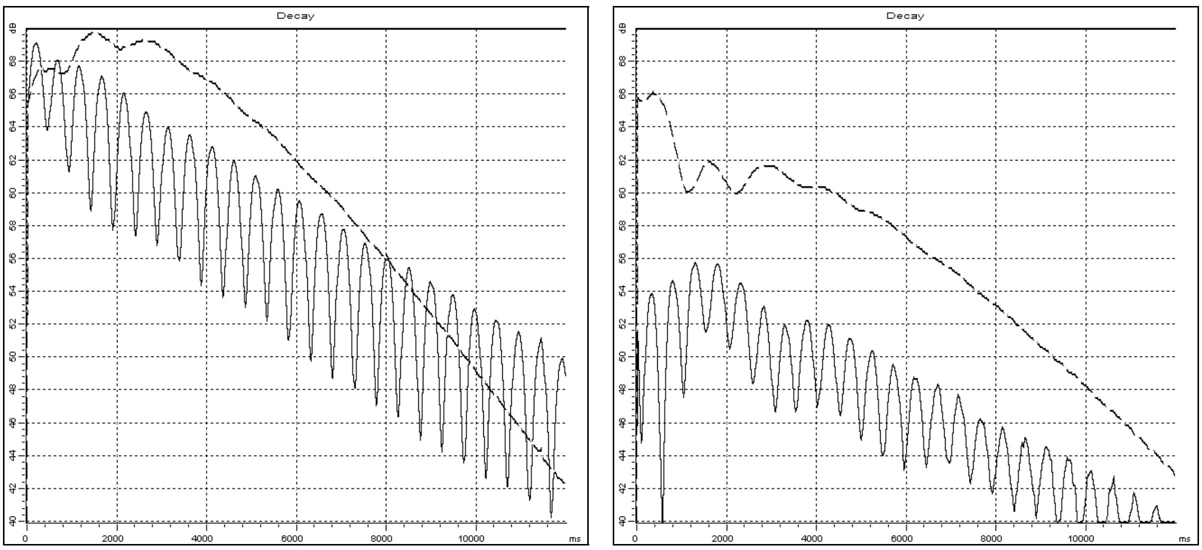

Fig. 4.54: Decay of the first (continuous) and third (dashed) partial tone after fretboard-parallel excitation using an Alnico-5-magnet in the neck pickup position. The only difference between both pictures is a slightly different plucking direction.

4.11.4 Field-Induced Damping

Pickup magnets are rumored to disturb the decay and to deteriorate the sustain of the string. Indeed, as shown in chapter 4.11.3, the magnetic stiffness can induce changes in the vibrational parameters; at small magnet distances these changes are also audible. However, an (ideal) spring is not able to extract energy from an oscillating system. If one pushes an ideal spring (with positive stiffness) it will store energy. However, after expansion this energy is returned entirely and without loss. In information technology one speaks of **reactive energy** in contrast to **active energy**, which is "lost" in a frictional resistance. The term "energy loss" can, of course, not just be viewed globally: in reality energy cannot be lost; however, it will be transformed irreversibly into thermal energy due to the frictional resistance and is no longer available for the oscillating system.

However, energetic considerations at a pickup are dangerous and may lead to the wrong conclusions: a pickup does not transform the vibration energy of a spring into electrical energy; rather it partakes from one component of the oscillation. Customary pickups mainly react to fretboard-normal vibrations. If a magnet would rotate the vibration plane of the string from fretboard-normal to fretboard-parallel this would not affect the vibration energy – nevertheless the pickup output voltage would decrease. Fortunately, this rotation occurs rather in the opposite direction (from fretboard-parallel to fretboard-normal); in this case the magnet will indeed increase the pickup output voltage, however, without increasing the vibrational energy.

At one place, however, real power is necessary: the voltage delivered by the pickup heats the ohmic resistors of the electrical circuit, and this real power has to be drawn from the vibration of the string, because the magnetic pickup is a passive transducer [3]. In addition, the so-called active pickups are passive with respect to their transformation process; in this case only the first amplification stage is located at a different place. The **ohmic resistors** in the electrical pickup load circuit are the volume potentiometer, the tone potentiometer, the amplifier input resistance and the coil resistance. The cut-off frequency of the 250 kΩ and 50 nF series connection (tone-pot) is 13 Hz, for higher frequencies the capacitor is approximately a short circuit. Both potentiometer resistances and the amplifier input resistance are in parallel for the standard circuit and, therefore, the result for the total resistance is 100 – 200 kΩ. Further, one has to add the coil resistance (4-15 kΩ). For the pickup/cable resonance one would have to consider a load transformation for the exact calculation, the following orienting calculation assumes 100 kΩ for simplicity. According to this calculation a pickup, that generates 100mV produces a real power of $P = U^2/R = 0.1\ \mu\text{W}$. This is very small but must be viewed relative to the string energy.

The kinetic energy of a mass differential dm is $dmv^2/2$. Here, v is the velocity of the differential mass. The **kinetic energy of the string** will be highest at the transit through the rest position. Integration over the total length of the string (with sinusoidal length-dependent velocity) yields $W = mv^2/4$, with m = mass of the entire string and v = velocity at rest position.

A typical Stratocaster pickup will generate an effective voltage of U = v·0.186 V for a 0.66 mm solid string at a magnet-distance of 2 mm; the velocity v has to be inserted as an effective value in m/s. However, the velocity is not the one stemming from the energy-formula, rather is it the velocity of the string *above* the pickup. For an oscillation of the first partial the maximum of the velocity is located in the middle of the string (12[th] fret); above the neck-pickup v is only 0.69 times as big. In addition, one has to bear in mind that in the energy formula the amplitude of the velocity is depicted, whereas for the computation of the voltage the effective value of the velocity is necessary. This will yield for the mechanical energy W and for the electrical power P:

$$W_{mech} = \frac{1}{4} m \hat{v}^2 \qquad P_{el} = \frac{U^2}{R} = \frac{(0.186 \cdot 0.69 \cdot \tilde{v})^2}{100\,\mathrm{k\Omega}} \qquad \frac{P_{el}}{W_{mech}} = \frac{3.3 \cdot 10^{-7}}{m} \cdot \frac{\mathrm{kg}}{\mathrm{s}}$$

The power P is the quotient out of the energy loss dW and the duration dt (power is energy over time), the relative energy loss is thus $dW/W = Pdt/W$. Using 1.78 g for the mass of the string, the relative energy loss per second is 0.019 %. The time dependent damping value, the **decay-rate** D thus will be:

$$D = 10 \lg \frac{W}{W - \Delta W} \frac{\mathrm{dB}}{\mathrm{s}} = -10 \lg\left(1 - \Delta W / W\right) \frac{\mathrm{dB}}{\mathrm{s}} \approx \frac{10}{\ln 10} \cdot \frac{\Delta W}{W} \frac{\mathrm{dB}}{\mathrm{s}} = 4.34 \frac{\Delta W}{W} \frac{\mathrm{dB}}{\mathrm{s}} \quad ♣$$

Here, ΔW is the energy-loss over 1 s, which will be computed as $P \cdot 1$ s. With the above string one will get a decay rate of 0.0008 dB/s. This is the level decrease resulting from the electrical damping. Even if one assumes much more efficient pickups with e.g. ten times larger transformation coefficient, this effect is still minimal and can surely be neglected compared to other damping mechanisms.

This seems to result in very simple conditions: the magnetic field acts as a spring mainly on the lower partials and the electrical losses are negligible. However, it is not quite that simple. The problems are already present in the **measurement of the decay curves**. It is relatively simple to choose the appropriate DFT-windows that enable a sufficiently fast and selective measurement of single partials. For most of the measurements with the CORTEX-software *Viper* the 50-dB-Kaiser-Bessel-window with N = 4096 and zero padding = 2 turned out to be well suited. The decay lines of the partial tones, however, are often curved and, thus, hamper the modeling. In **Fig 4.55** the level trends for the E_2 string are depicted, taken without and with magnetic field. How can the decay (the sustain) be defined with one number? As a level change within the first second? Every time interval chosen appears to be arbitrary. The guitarist will not be fussed about the functional decay of the vibrational level, however, for basic research it will rather play an important role whether the level decay will be caused by dissipation or by exchange of vibrational energy. For the case of rapid beat frequencies (right picture) it seems to be relatively simple to derive a time-dependent envelope function from of the maxima. But if the beat frequency period lasts for ten seconds or longer, the measurement can become impossible: Until the next beat frequency maximum the oscillation may possibly have become too small due to other damping mechanisms. It is also not particularly practical to extract average values from a 30 second level decay because in music tones are seldom kept over this time period. OK, *A Day In The Life.* But that was one day. And not guitar but a piano!

♣ Approximation for ΔW <<«W

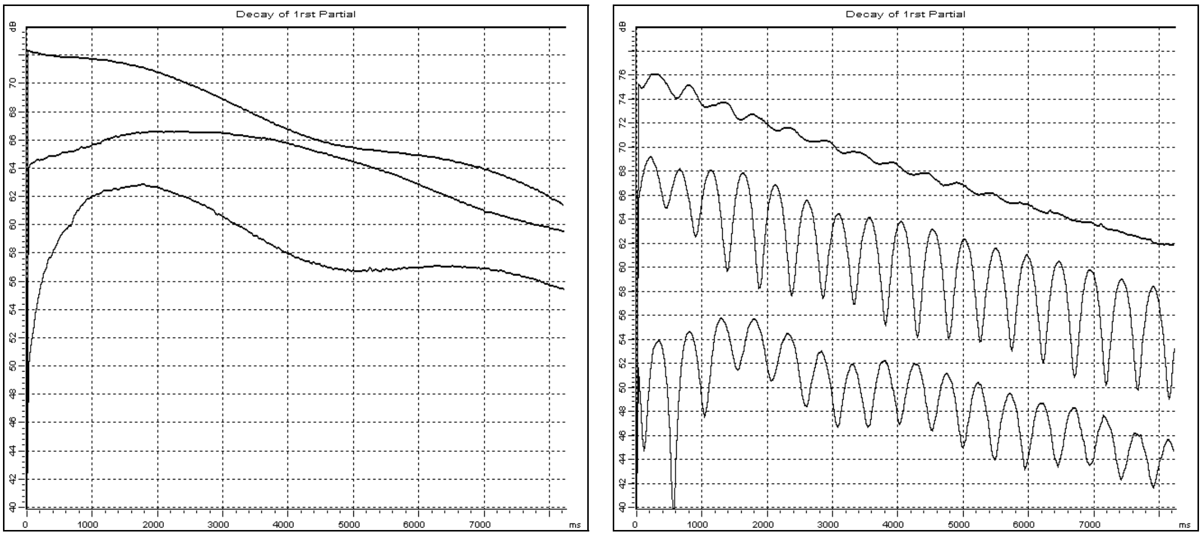

Fig. 4.55: Decay of the first partial of the E_2-string after different excitations; without magnetic field (left), with magnetic field (right).

Since it is discussed over and over again in guitarist circles, if and how the pickup-magnet may dampen the string vibration (and shorten the sustain), we will finally make an attempt at clarification. For this a guitar (Ovation EA-68) was suspended at the strap-button and the E2-string (Fender 3150) was reproducibly hit with a pendulum. An Alnico-5 magnet was attached at a variable distance to the string using a bridge placed over the last fret. The measured signal was generated by the piezo-pickup (**Fig 4.56**). Placing the magnet at 2.5 mm distance causes only a minor level reduction in the 1st harmonic, which hardly stands out. For lower magnet distances the level loss is considerable. At the 2nd harmonic there is an intense beat frequency without the magnetic field; a weak magnetic field (b) will increase the level, a strong magnetic field (c, d) will lead to a substantial level loss. Almost contrary is the 3rd harmonic: here a weak magnetic field (b) will yield intense beat frequencies. The differences in the higher harmonics are so small that they are of the same order as the reproducibility.

From these measurements it can be concluded that the magnetic field *changes* the decay of the partials; the term *dissipation* is conditionally justified only for the first two harmonics – the magnetic field is indeed extracting energy from them in a considerable amount. However, one has to take into account that, in practice, the neck-pickup-magnet is never brought as close as to a distance of 1 mm to the string: the string would otherwise impinge on the magnet. The **small distances** were chosen for the measurements in order to generate a distinct effect. Dissipation effects are only clearly visible for this atypical situation (Fig. 4.56 upper left, curve c and d). During the first seconds the level of the first partial decays much faster than later on. The cause for the higher fluctuation frequency of 4 Hz, as compared to curve b, is the higher negative field stiffness, which will lead to larger detuning. The time-dependent slope of the envelope curve has to be attributed to a non-linear dissipation effect or an amplitude-dependent damping. This is probably due to **hysteresis losses** in the string. As the magnetic field strength in front of the magnetic pole is very inhomogeneous (location-dependent), the field strength and flux density will change within the string during decay. The respective reorientation events within the microstructure are partially irreversible.

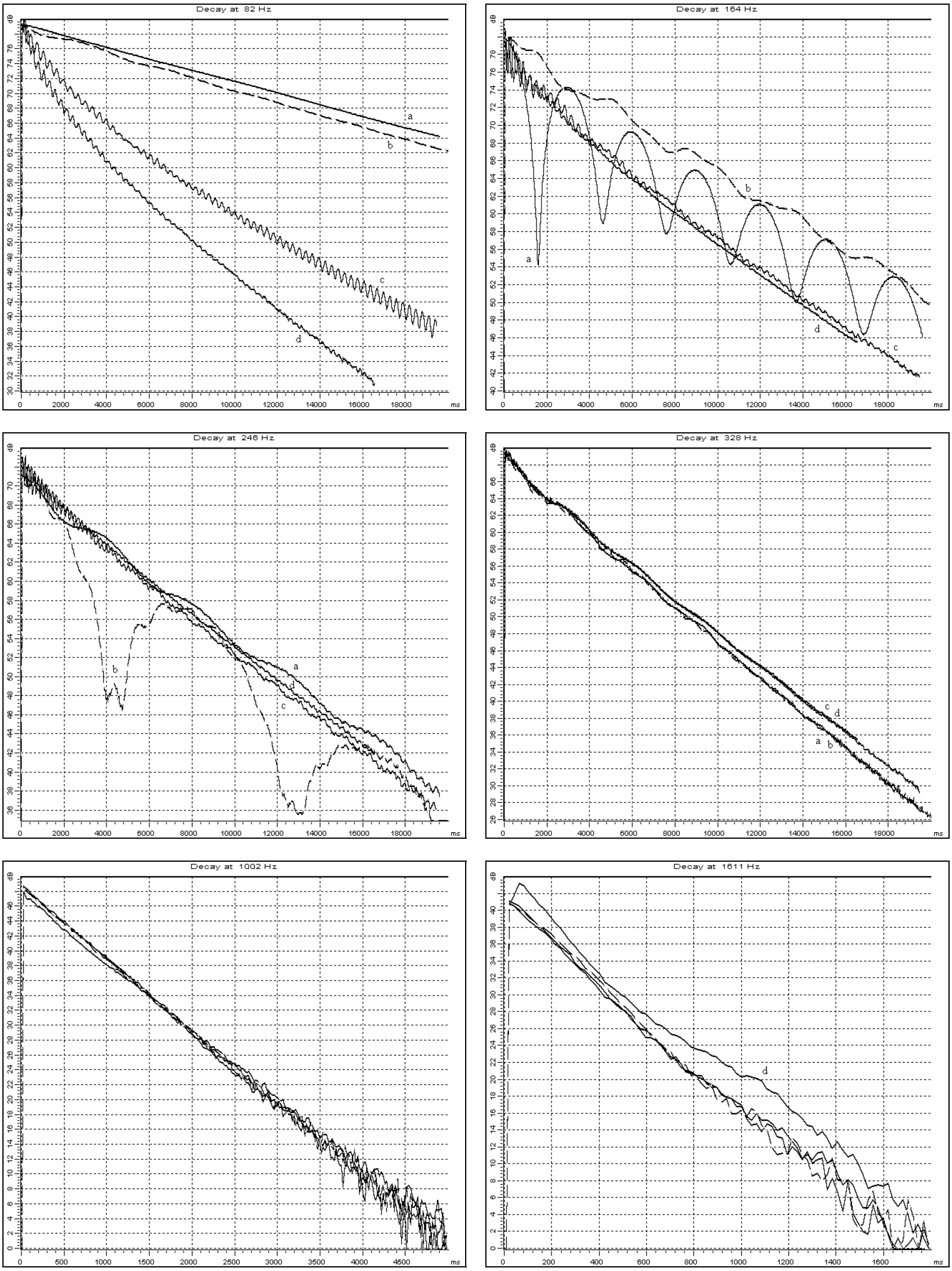

Fig. 4.56: Decay of the partial tone levels of the E_2-string after consistently comparable fretboard-normal excitations: Without a magnetic field (a), a magnet distance of 2.5 mm (b, dashed), a magnet distance of 1 mm (c) and a magnet distance of 0.8 mm (d). The higher d-level trend at 1611 Hz has to be attributed to a slightly different excitation, which shows up only at high frequencies. The results are typical for the guitar under investigation, its specific mounting and excitation; they should not be generalized for other guitars.

The hysteresis losses are proportional to the frequency, in the first approximation. With every cycle of the *BH*-hysteresis loop the magnetic field will lose an amount of energy ΔW; the higher the frequency the higher the number of cycles per second and the higher the dissipation losses. For the string, however, one has to consider that higher frequency partial tones are damped more strongly by other mechanisms and that the strength of the magnetic flux change depends on the displacement. However, the displacement decreases for higher frequencies. The lower pictures in Fig. 4.56 clearly show that the magnetic field does not have any effect in the high frequency range. In addition, for low frequency partials, one should not overestimate the field-induced dissipations. Finally, for comparison, the influence of the **fretting hand** on the decay of the partials is shown (**Fig. 4.57**, left picture). The upper curve shows a measurement in which the guitar was suspended from a steel wire at the strap button, whereas for both of the lower curves the guitar was clamped at the strap button. For the remaining measurements the fret hand surrounded the neck with different tightness but without touching the strings. All measurements were done without magnetic fields. One recognizes that even without magnetic field a variable dissipation is generated – the **heel of the hand** touching the neck has to be interpreted as damping resistance. Its energetic (!) influence on the sustain is considerably larger than that of a common pickup-magnetic-field (right picture).

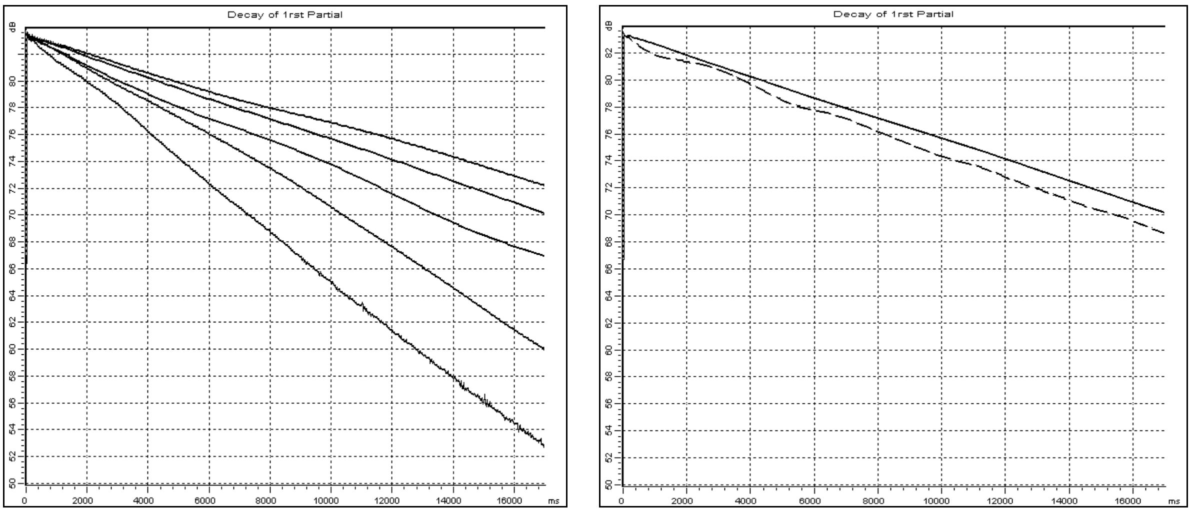

Fig. 4.57: Decay of the first partial tone for different manners of hand-damping (left). On the right, with identical scaling, the influence of an Alnico-5-magnet attached at a distance of 2.5 mm is depicted (neck-position).

4.11.5 Indirect Effects on Sound

In professional music magazines magnet-characteristics are often published without physical rationale. It is to be feared that the following citations are pure speculations resulting from findings after the replacement of an *entire* pickup. In addition, one can only hope that the author also did not replace the strings (… the new pickup delivers much more treble …). For an old Stratocaster pickup, for example, it is impossible to *solely* change the magnets; the coil rests directly on the magnets and as soon as one pulls them out one destroys the flimsy coil-wire. If, however, the whole pickup is replaced by another, the number of turns may change – and, consequently, it would be incorrect to attribute changes in sound only to the magnet.