7.5.4 Measurement results

Measuring the mechanical parameters of a string saddle is complicated because on the one hand mode-coupling and dispersion lead to a large variety of parameters, and on the other hand very high measurement accuracy is required. It does make a difference whether 99.8% or 99.9% of the incoming energy is reflected. Given as little as 0.5% measurement error, a degree of reflection of in excess of 100% could result – which of course is nonsense. The analysis of the decay (of string vibration) would seem to offer a welcome alternative – however, this allows only for statements relating to *both* string-bearings such that a differentiation of nut/fret and bridge is not possible. Moreover, measuring the mechanical impedance or admittance of the saddle shows only part of the picture since it captures neither bending coupling (Chapter 2.7) nor the excitation of dilatational waves. The measurement results given in the following therefore are a first step towards an analytical description of the reflection process.

The measurement results for a Les Paul Standard are shown in **Fig. 7.40**. All 6 strings were in place; the guitar rested on a stone table (with a mouse pad serving as a cushion). The impedance measurement was done using a B&K-4810 shaker and a B&K-8001 impedance head. The tracer pin of the impedance head was placed onto the bridge saddle of the A-string in such a way that the impedance perpendicular to the fretboard could be measured. Representation on paper with logarithmic scaling on both axes shows many resonance maxima that are not all of interest in detail. The degree of absorption therefore is depicted with *linear* ordinate scaling – to guide the focus to the essential.

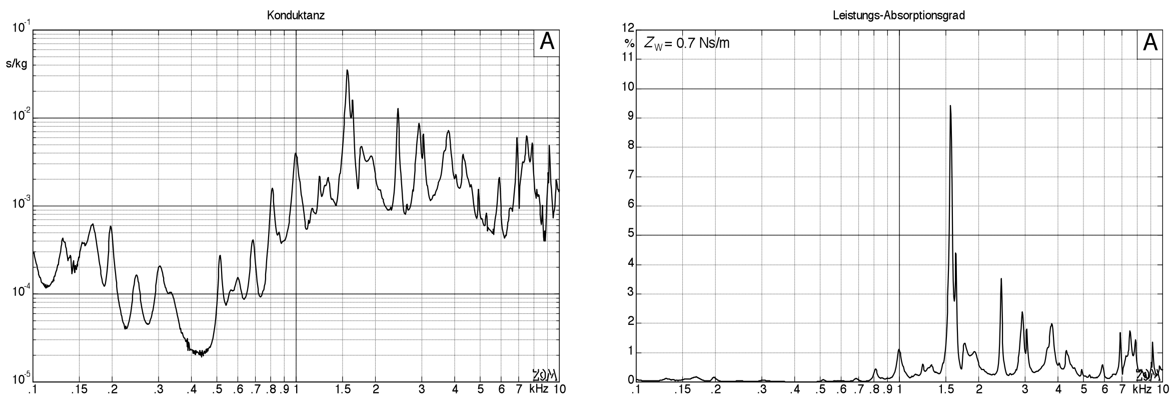

Fig. 7.40: Conductance G and degree of absorptions a^2, measured at the A-bridge-saddle of a Gibson Les Paul Standard. "Konduktanz" = conductance; "Leistungs-Absorptionsgrad" = degree of power absorption.

Essential is: below about 1 kHz, the absorption is very small, above 1 kHz several selective maxima of the absorption show up. The degree of absorption is calculated for a wave impedance of 0,7 Ns/m, approximately corresponding to that of an A-string. If we assume that the nut has a similar absorption behavior as the bridge♣, there would be twice the absorption loss per period of the fundamental (i.e. per 9 ms); with a^2 = 9.5% this would give us an increase in damping of 95 dB/s. On the other hand, e.g. a^2 = 0,1% would yield as little as 1 dB/s. This example indicates the range of the absorption: 1 dB/s would for normal guitar playing have the effect of almost non-existent damping ("endless sustain"), while 95 dB/s would mean immediate complete loss of the tone. In reality, however, we cannot assume the same absorption at nut and bridge, and therefore additional measurements are necessary at the nut (see Fig. 7.41).

♣ This assumption does not correspond to reality, though – see below.

Showing results for the nut of the Les Paul, **Fig. 7.41** supplements the measurements of the absorption behavior. Here, the highest absorption shows up in the low-frequency range – of course we always need to consider how the selective absorption maxima correspond to the frequencies of the partial of the strings [compare to Fleischer 2001].

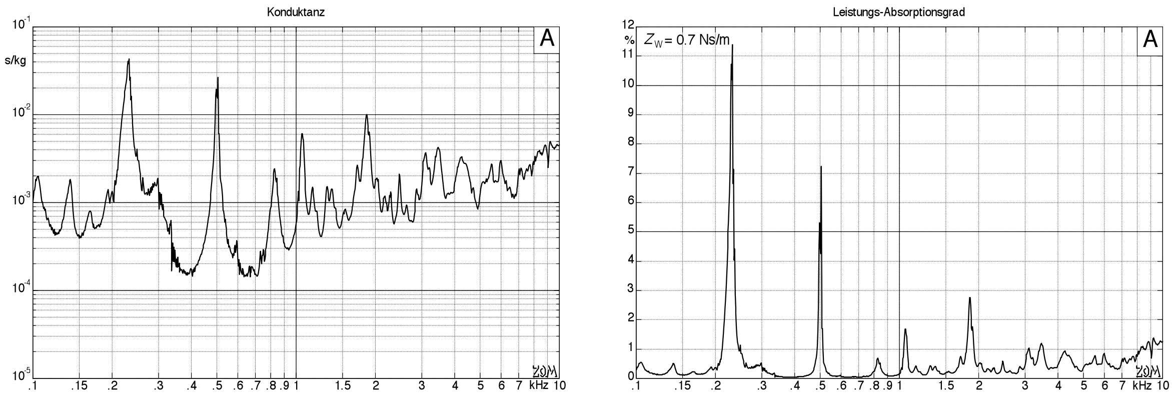

Abb. 7.41: Conductance *G* and degree of absorption a^2, measured at the nut (A-string) of a Gibson Les Paul Standard. “Konduktanz” = conductance; “Leistungs-Absorptionsgrad” = degree of power absorption.

Consolidating the degrees of absorption at both nut and bridge via computation, we get the graphs depicted on **Fig. 7.42**. What causes these extreme maxima in the absorption? Summarizing/simplifying a bit: **the low-frequency absorptions result from resonances of the neck, the high-frequency absorptions stem for bridge resonances**. Fleischer has clearly shown in several of his publications that it is not possible to manufacture a resonance-free guitar neck. At first glace, it may be surprising that even Gibson’s much-lauded Tune-O-Matic bridge successfully operates as a vibration-killer at some frequencies – but in the end that is a concession to the adjustability: many parts – many resonances.

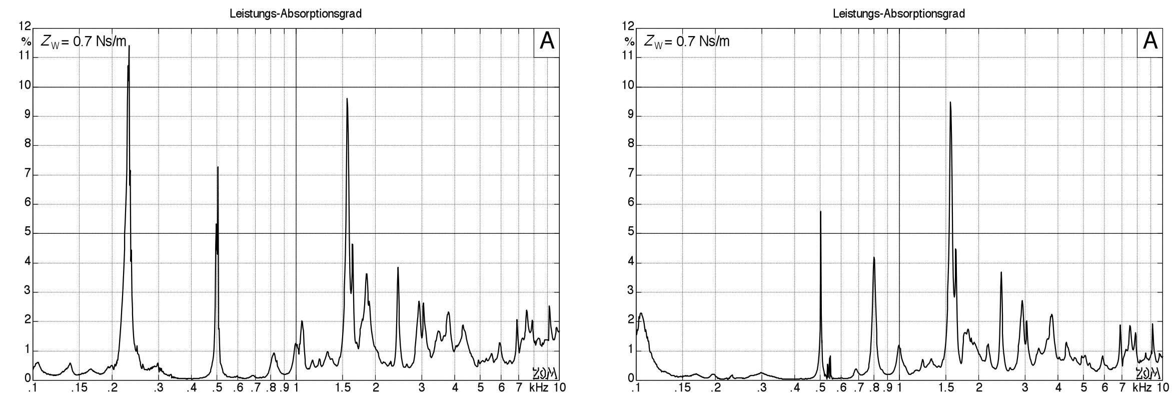

Abb. 7.42: Overall degree of absorption for one period of the fundamental (A-string). Left: string supported by nut and bridge. Right: string supported by 12^{th} fret and bridge. Gibson Les Paul Standard. “Leistungs-Absorptionsgrad” = degree of power absorption.

In his analyses of a Les Paul, Fleischer observed bending Eigen-shapes of the neck at 208 Hz and 445 Hz – this is a good match to the absorption spectra shown above. For 208 Hz, a node exists at the bridge and at the 10^{th} fret. For 445 Hz, 3 nodes show: one at the bridge, one at the 12^{th} fret and one at the 2^{nd} fret. That there is no exact match between the measurement results is not a surprise: first, it was not the same specimen of guitar, and second, the bearing of the guitar was different. There is, however, a simple procedure to unambiguously identify the guitar neck as reason for the absorptions: detuning its resonances by an additional mass.

To accomplish this, a 250-g-vise was clamped to the headstock of the Les Paul – which indeed re-tuned the low-frequency resonances (**Fig. 7.43**). There was, however, little influence of this additional mass on the higher-frequency absorption maxima – the latter are not caused by neck resonances but by resonances in the bridge. This was clarified via measurements for which a metal clamp was mounted to the bridge (Fig. 7.43, right-hand part). What was said above is again supported here: below 1 kHz neck resonances form selective vibration absorbers, above 1 kHz the corresponding effect is the result of bridge resonances.

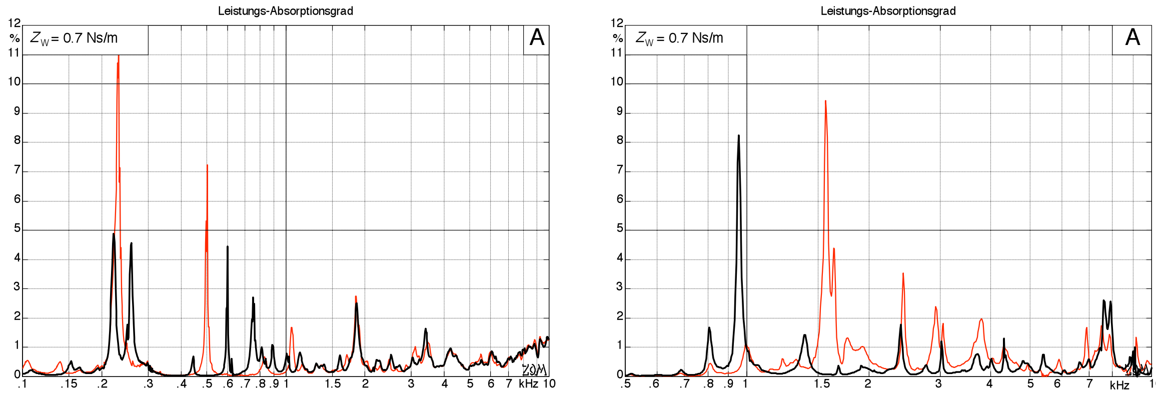

Fig. 7.43: Gibson Les Paul Standard, A-string. Degree of absorption calculated from the conductance measurement. Left: degree of absorption at the nut, without (red ——) and with (black ——) vise clamped to the headstock. Right: degree of absorption at the bridge, without (red ——) and with (black ——) a small clamp mounted to the bridge. "Leistungs-Absorptionsgrad" = degree of power absorption.

At this point we do not seek to carry out any detailed modal analysis, but rather to outline the principle of the absorption behavior at nut and bridge. The exact shape of the absorption spectra depends on all involved masses, springs and dampers – it is specific to the individual guitar, and string and fretting. We may assume the same mass for each of the bridge saddles on the Gibson Tune-O-Matic bridge, but already their position on the adjustment screw, and the area and condition of their seating (surface area!) is specific for each string. The bridge itself, i.e. the part in which the bridge saddles are held, vibrates in the higher-frequency range according to Eigen-modes, but these cannot be excited to the same degree from every point: given a node, the admittance is small, and only little excitation happens. The conductance of the A-bridge-piece will thus in detail be different from the conductance of the D-bridge-piece.

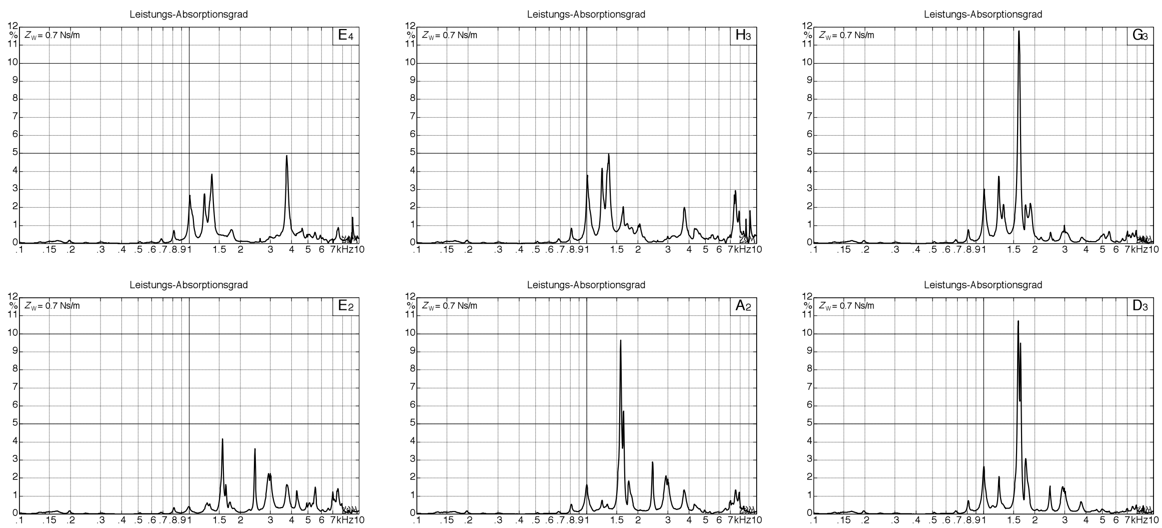

Fig. 7.44: Gibson Les Paul Standard: spectra of the degree of absorption for the individual bridge saddles. "Leistungs-Absorptionsgrad" = degree of power absorption.

 Translated by Tilmann Zwicker

As common ground of all 6 measurements in **Fig. 7.44**, we recognize merely minute absorption at low frequencies – only above about 1 kHz, individual maxima in the absorption show. The height of these maxima depends on the measured conductance and the **wave impedance**, for which in all graphs 0.7 Ns/m was taken as a basis. This is typical for the A-string – for all other strings, a different wave impedance should in fact have been used. However, the decay behavior of the string depends not only on the degree of absorption but also on the fundamental frequency. Since fundamental frequency of the string and wave impedance are approximately reciprocal to each other, a string-specific consideration is not imperative in this first step.

In view of an individual fit and position of every bridge saddle of the Tune-O-Matic bridge it is, however, easily comprehensible that the absorption spectrum looks different for every bridge saddle. On the other hand, we would not expect such differences for the nut, because all 6 strings run over the same strip of plastic. Still, **Fig. 7.45** shows that there are differences here, was well: in the middle of the neck (for the D- and G-strings), the absorption is smaller in the higher frequency range when compared to the edges of the neck (E_2- and E_4-strings). Presumably, the distal strings (in contrast to the mesial♣ strings) can more efficiently excite torsion-vibrations of the neck [Fleischer 2001].

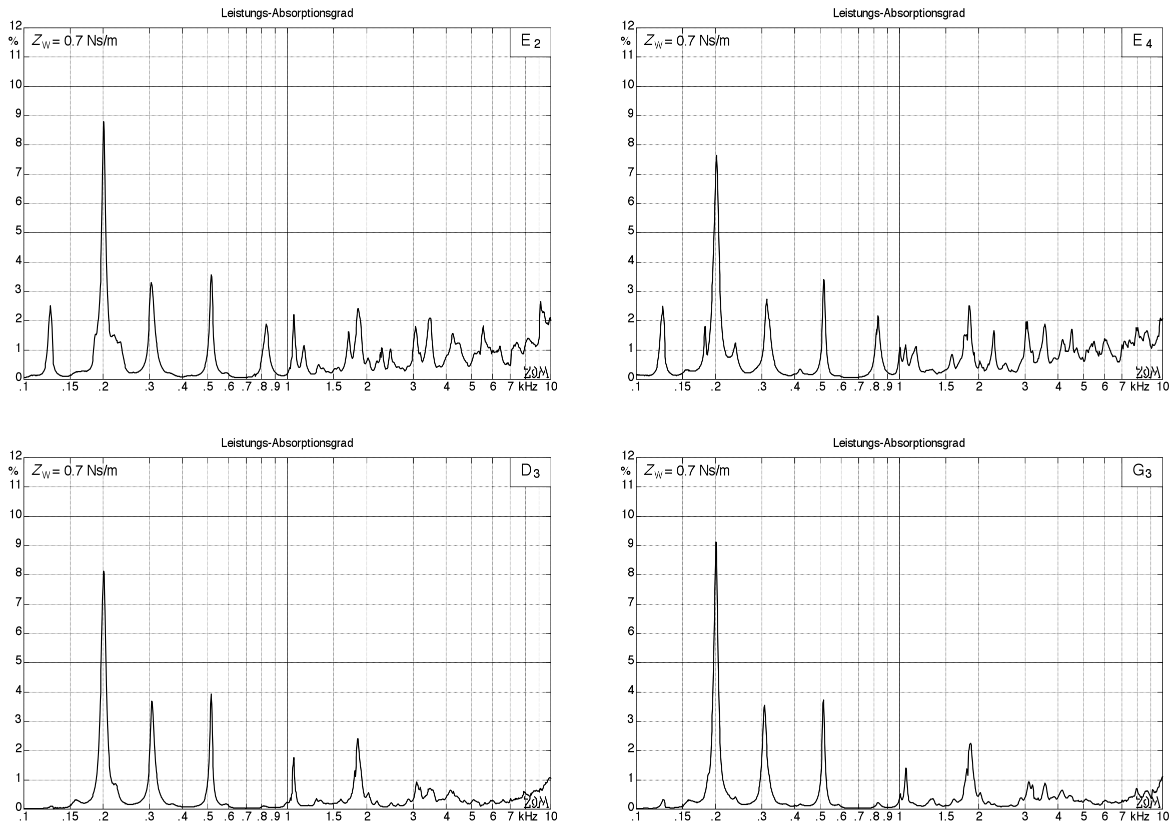

Fig. 7.45: Gibson Les Paul Standard: spectra for the degree of absorption measured for the nut. "Leistungs-Absorptionsgrad" = degree of power absorption.

When analyzing the saddle-absorptions, we must not forget one significant absorber: **the guitarist**. To determine the above absorption spectra, the guitar was laid on a stone table aiming for a low-attenuation fashion; in the following, external absorbers will also be considered.

♣ Mesial: located towards the middle; distal: located towards the edge.

There are mainly two **external absorbers** that act on a guitar: part of the back of the guitar body is in contact with the body of the guitarist, and moreover the fretting hand dampens the back of the neck. To approximately model these absorbers, the guitar was laid on the stone table such that a large area of the cranial half of its the rear body rested on a soft mouse-pad, and moreover a hand clasped the rear of the guitar neck at the 5th fret (without touching a string). The effects of this additional damping are shown in **Fig. 7.46**.

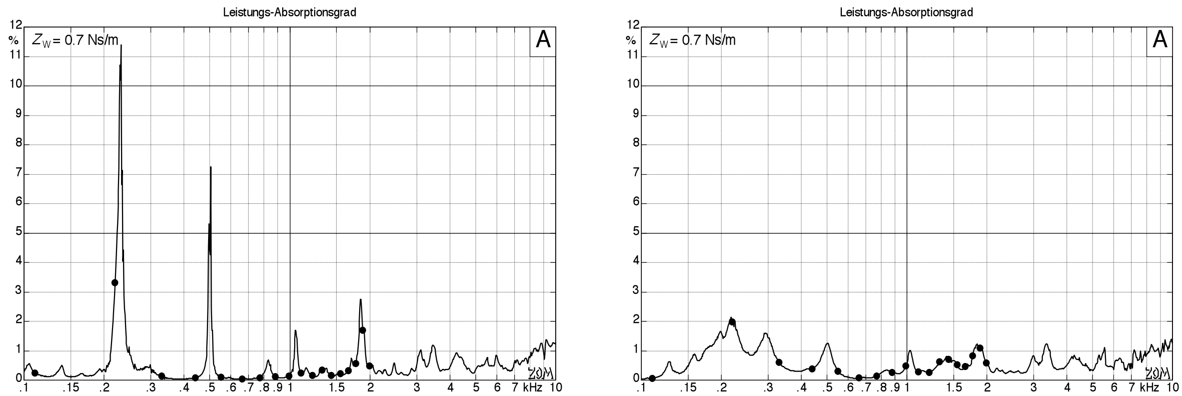

Fig. 7.46: Gibson Les Paul Standard: spectra of degree of absorption measured at the nut (A2-slot).
Left: low-damping guitar bearing. Right: including typical external absorbers. Some frequencies of partials are marked with dots (f_G = 110Hz). "Leistungs-Absorptionsgrad" = degree of power absorption.

The additional absorbers reduce the height of the maxima in the spectrum of the degree of absorption, and the peaks get broader. We may, however, not derive from these absorption-maxima how these absorbers influence the decay of the string vibration – rather, the crucial value is the degree of absorption at the frequencies of the partials (marked by the dots). It is easy to see in particular for the guitar positioned on the low-attenuation support, that already a minor de-tuning of the string may result in a considerable change in the degree of absorption. Of course, the same holds for modification of body- and neck-parameters.

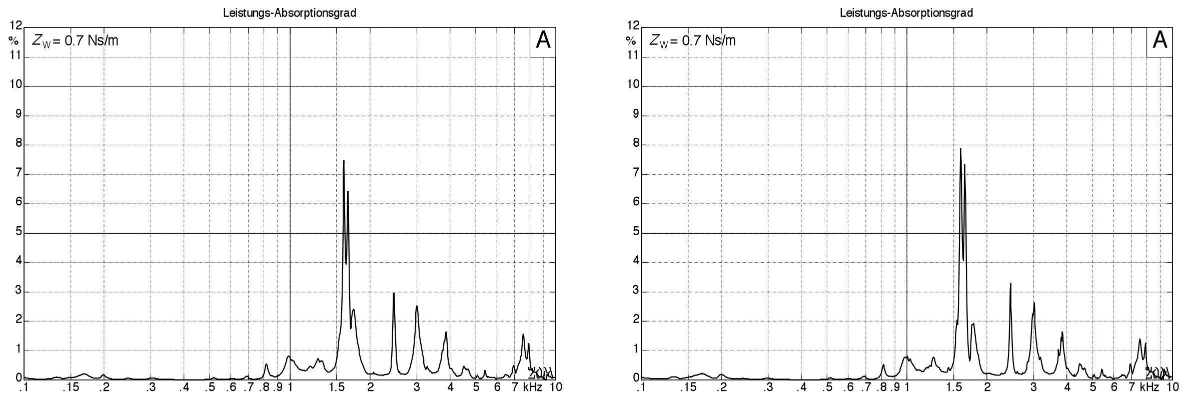

Abb. 7.47: Les Paul Std.: spectra of the degree of absorption measured for the bridge (A2-bridge-saddle).
Left: guitar on a low-attenuation support. Right: with typical external absorbers.
"Leistungs-Absorptionsgrad" = degree of power absorption.

However, it is almost impossible for the guitarist to influence the absorption behavior of the bridge (**Fig. 7.47**) because the bridge is rarely touched when playing the guitar *(translator's remark: in fact, this usually happens only when strong string damping is sought, anyway).* In contrast, some absorption maxima change if the bridge is shifted back and forth within the slack resulting from manufacturing tolerances (compare to Fig. 7.40).

Via combining the nut- and bridge-absorption, we arrive at the overall degree of absorption of a string, i.e. at the magnitude that represents the energy loss per period of the fundamental oscillation (Fig. 7.48).

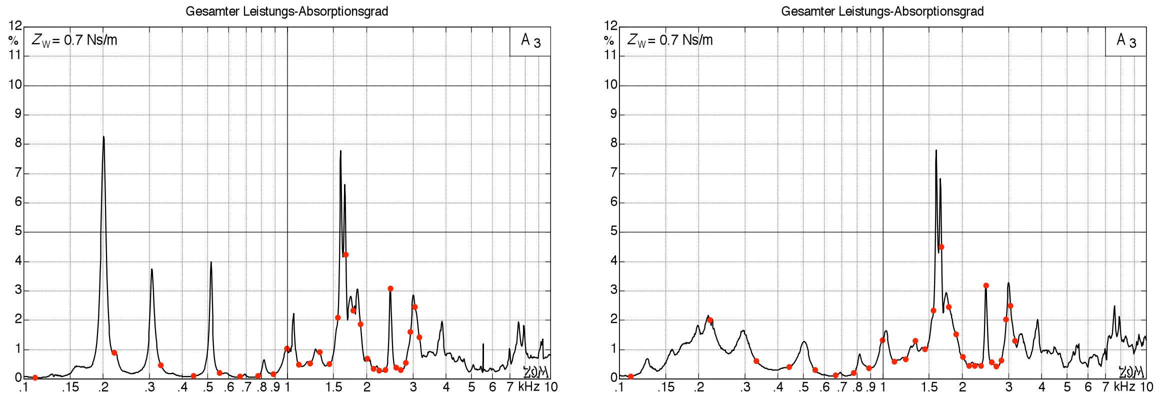

Abb. 7.48: Gibson Les Paul Standard: overall degree of absorption of the A-string, without (left) and with (right) damping by the fretting hand. Frequency dependence calculated from conductance measurements.
"Gesamter Leistungs-Absorptionsgrad" = overall degree of power absorption.

Fig. 7.48 shows the overall degree of absorption for two cases: for the freely vibrating guitar neck, and for the neck damped by the fretting hand. The A-string has a fundamental frequency of 110 Hz, i.e. a basic period of 9.1 ms. If the string were to lose 8% of its vibration energy per basic period, its oscillation level would drop by 40 dB per second – that would be a strong damping. For 1% loss we would get a 4.8-dB-drop per second, and for 0.1%, 0.5 dB/s loss would remain. Two other processes need to be considered here, though: the degree of absorption is only of significance at frequencies where the string offers Eigen-oscillations (partials), and there are other absorption-mechanisms besides the absorption at the bearings (Chapter 7.7).

The un-damped neck of the guitar investigated here shows a pronounced maximum of the conductance (or the damping) at 200 Hz – this is close to the 2^{nd} partial (220 Hz) of the A-string. If this resonance frequency (or the frequency of the partial – e.g. when tuning down) is detuned by as little as a few percent, the absorption for this partial changes significantly. All maxima seen in the figure are of a relatively narrow-band characteristic, and therefore the damping of the partial that occurs in the end depends strongly on minute de-tuning effects. As the fretting hand touches the backside of the guitar neck (not something entirely unheard of when playing a guitar), the low-frequency peaks become wider and the extreme frequency-dependency decreases somewhat. The damping of the first 5 partials is, however, increased.

Last, it should be mentioned that for wound strings, the exact frequencies of the partials of the strings depend on both the string-diameter and the ratio of core-diameter to overall-diameter. The inharmonicity-parameter (*b* in Fig. 1.7) determines the spreading of the spectrum, and thus the exact position of the individual partials. **The damping of a certain partial therefore is a highly fragile quantity that depends on many parameters and may not be seen as a guitar-specific constant.**

Chapters 7.7 and 7.12 will investigate the individual damping mechanisms in detail.