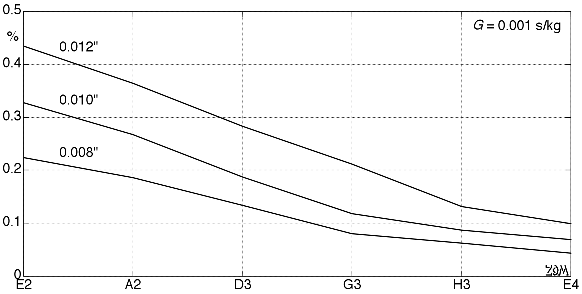
7.7.4.4 Bearing conductance

All damping mechanisms considered so far had their origins in the string or in the surrounding air – the guitar and especially its noble tone-wood were not investigated as being involved in the sound shaping. However, they of course also affect the string oscillation, and therefore now a more detailed analysis of the mechanical properties of both string bearings will follow. Consideration of the string as a waveguide (Chapter 2) shows reflection processes that can approximately be described by the wave impedance of the string, and by the bearing impedance. The **wave impedance** is a string-specific quantity (Chapter A.5), the bearing impedance is formed by the nut and the bridge saddle. However, not only these play a role but also their substructures, i.e. bridge base, and neck and body of the guitar. The **bearing impedance** is the mechanical impedance $\underline{Z} = \underline{F}/\underline{v}$ found at the bearing by a wave running along the string. An immobile, rigid bearing features a velocity of $\underline{v} = 0$, and therefore the bearing impedance of an ideal bearing is infinite. Such a perfectly loss-free bearing would show perfect (i.e. loss-free, total) reflection – but this only occurs in the ideal model. Every real bearing absorbs a small part of the incoming wave energy (e.g. 1%) so that e.g. only 99% will be reflected. The more often per second this absorption occurs, the faster the string oscillation decays. Assuming 1% of energy loss at each bearing for a string oscillating with 100 Hz, a wave reflected 200 times per second at each bearing will have only $0.99^{200} = 13\%$ of its initial energy after 1 s. The corresponding level-decrease would be 8.7 dB; for a string oscillating at 200 Hz, the energy would have decreased to 1.8% after 1 s (i.e. by 17.4 dB).

The bearing absorption may be described by the **bearing conductance** G. This is the real part of the **bearing admittance** (admittance = 1 / impedance, for more detail see Chapter 7.5.3). The higher the conductance, the more the bearing absorbs, and the shorter the “sustain”. On the one hand, the power absorption factor of a bearing is proportional to the wave impedance of the string, and on the other hand it is proportional to the bearing conductance. With the wave impedance of each string being proportional to its diameter squared, we get: the heavier the string, the more the bearing damping affects the string oscillation. In **Fig. 7.73**, the **power absorption factor** is given percentage-wise for three string sets, with $G = 0.001$ s/kg.



$$W = D^2 \cdot \rho \cdot M \cdot f_1 \cdot \pi / 2$$

$$a^2 \approx 4 \cdot W \cdot G$$

W = wave impedance
D = diameter of the string
ρ = density of steel
f_1 = fundamental frequency of the string
a^2 = degree of power absorption

Fig. 7.73: Degree of power absorption a^2 for three different string sets.

A transversal wave running along the E_2-string will, depending on the string thickness, lose 0.22% – 0.44% of its power at a bearing which has a conductance of 0.001 s/kg. For the E_4-string this would only amount to 0.04% – 0.1%. For comparison: given these conditions, a power loss of about 1% would result for the E_1-string on an electric bass! It must be borne in mind, though, that the wave propagation speed decreases with decreasing frequency, as well – on the E_1-string of an electric bass, the transversal wave arrives at the absorbing bearing significantly less frequently (sic!) than on an E_4 string of an electric guitar. Therefore, two processes working in opposite directions dominate the frequency-dependency of the decay time: the process of decreasing absorption from the bass strings to the treble strings, and the increasing frequency that the absorption happens with.

The bearing absorption caused by constant conductance (e.g. $G = 0.001$ s/kg) is, in a simple model, of the same value for all partials of a string: here, both the wave impedance and the conductance are constant. And because in the simple model (i.e. leaving aside dispersion) all partials of a string propagate with the same wave velocity, the decay time correspondingly caused does not show any frequency dependency, either. Thus, given an overall consideration of various absorption mechanisms, the frequency-independent bearing absorption defined for a constant G will mainly have an effect in frequency ranges where other absorption mechanisms are weak, i.e. in the low-frequency range, and for the bass strings. For real string bearings the conductance is not constant, though, but rather frequency dependent. **Fig. 7.74** shows related measurement values gathered within the nut groove of the E_4 string of a **Les Paul Historic** (with the string taken off). Eigen-oscillations of the open string are possible only at positions marked by dots, and only here the measured conductance values have any impact on for the decaying oscillation of the E_4-string.

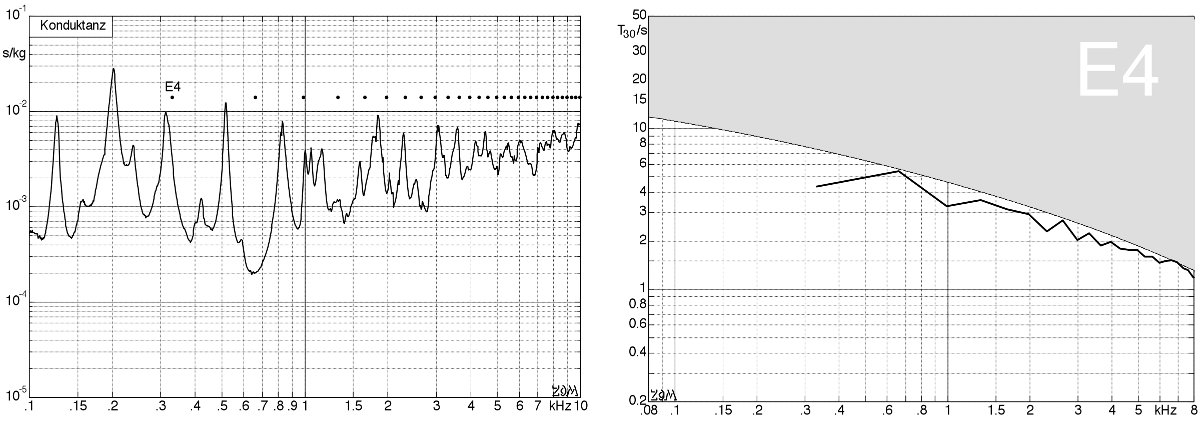


Fig. 7.74: Les Paul, E4-string: conductance (“Konduktanz”) at the nut (left), calculated decay times (right).

The right-hand diagram shows calculated decay times for the partials of the E_4-string considering the attenuation by radiation, the internal dissipation, and the bearing absorption. *One* bearing absorption only - because the bridge saddle had not been considered yet. In general, this calculated curve stands up nicely to measurement curves. Not that this is all that surprising – T_{30} is, in the end, predominantly determined by the attenuation by radiation and the internal dissipation. The bearing absorption dominates only if a conductance maximum happens to be near the frequency of a partial frequency, and in that case a selective absorption maximum results (i.e. a selective minimum in T_{30}). For the fundamental of the E_4-string (at 330 Hz) this is nearly the case: if one would merely tune the E_4-string down by approximately a semitone, the decay time of the fundamental would be reduced to half (2.2 s). On the other hand, the decay time of that fundamental may also be extended up to more than 7 s, for example if the guitar is laid in a different way onto the measuring table for the conductance measurement (Fig. 7.75). However, only the damping of the fundamental will change in this case, all other T_{30} minima remain practically unchanged.

Fleischer [8] has published a variety of different impedance plots for various guitars, measuring not only at the nut or bridge saddle, but at each fret, as well. These and further investigations [Fleischer 2001, 2006] indicate bending and torsional vibrations of the guitar neck – causing low-frequency bearing absorptions. If the string bearing happens to be at a node of the neck oscillation (in consideration of the frequency relations), small conductance and thus long sustain result, bearing at an anti-node position yields high conductance and "dead spots". Once again, it is shown that a noticeably resonating guitar neck may delight the sense of touch – but it is likely to be detrimental long sustain in one way or another.

Fig. 7.75 shows how the conductance at the nut can be changed without permanently damaging the guitar. For both measurements shown in the left-hand image, the guitar (again the Les Paul Historic) was placed on a **stone table**, supported underneath the neck/body-interface by a soft **mouse pad**. The other bearing – the edge of the body near the rear belt pin – was placed directly onto the stone table for one of the measurements. For the other measurement, a second mouse pad served as a cushion (and as damper). As a result, we see pronounced resonance shifts below 400 Hz, but there is practically no change in the frequency range above. On the one hand, this indicates a good reproducibility; on the other hand it shows that low-frequency modes of the neck vibration depend on the bearing of the guitar – to the vibration engineer, that's not actually a highly unexpected behavior.

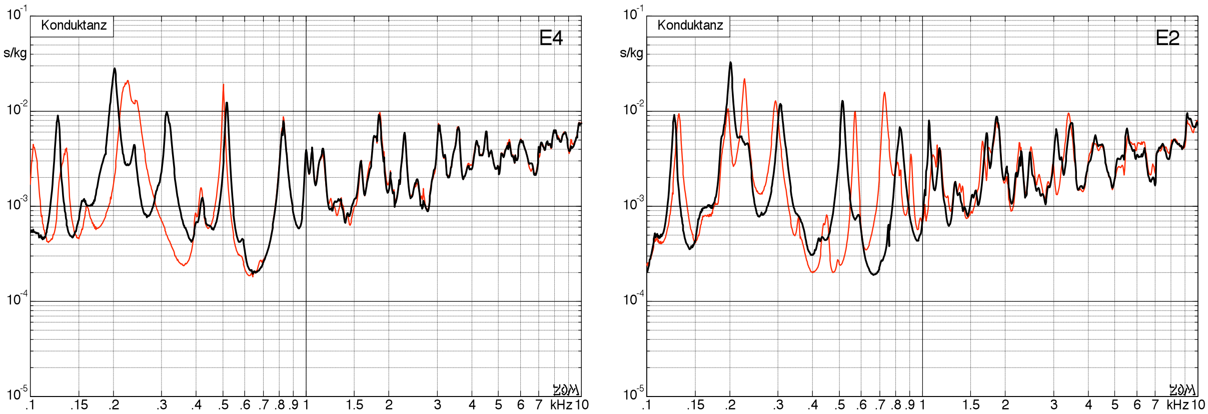


Fig. 7.75: Les Paul, conductance ("Konduktanz") at the nut: E4 (left), E2 (right). Mechanical modifications.

In the right-hand diagram, the differences are caused by a vise mounted to the headstock. This now is an approach that tackles the situation in close proximity of the string bearing – the effects therefore are bigger than those in the left-hand diagram. Neither result can be interpreted as improvement, or as deterioration: both have an impact on all strings. Even though the decay time of one partial may be extended according to Fig. 7.75, it is to be feared that, at the same time, the decay time of another partial is reduced.

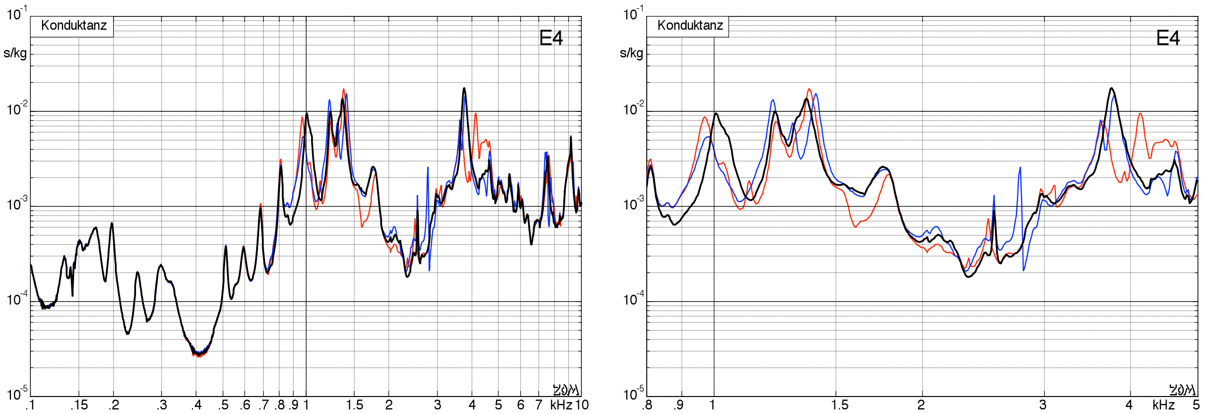


Fig. 7.76: Les Paul, bridge saddle conductance ("Konduktanz"), E4. Modifications = clamp mounted to the bridge.

The **bridge saddle** conductance of the Les Paul Historic, measured at the E$_4$-bridge-piece, is shown in **Fig. 7.76**. From his oscillation measurements, Fleischer concludes that the neck of a solid-body guitar is relatively flexible whereas the bridge remains relatively immobile.

Our own measurements confirm this for the frequency range up to 700 Hz (the range investigated by Fleischer). However, for higher frequencies, and depending on its design, the bridge absolutely may show some veritable Eigen-oscillations, and thus may become an efficient absorber. In **Fig. 7.76** three measurement curves are shown in either diagram: one for the guitar in its original condition, and two more for the bridge modified via fixing a clamp on it. In particular the conductance maxima – important for the string damping – react to these modifications, leading us to the assumption that these maxima are **bridge resonances**. This hypothesis found support via measurements using a laser vibrometer: significant bridge oscillations showed up in critical frequency ranges. At low frequencies, the bridge is nearly immobile, and thus an attached **additional mass** attached will not bother it. However, there are strong bridge resonances between 1 and 1.5 kHz, as well at around 4 kHz, and those will change when attaching an additional mass.

Supplementary findings regarding the effect of the bridge design on the decay of partials of the string-vibration were provided by measurements with a **non-trem Strat**. Two variants are common as bridge saddle: on earlier Strats, the string was fed through an S-shaped sheet metal – the **vintage bridge saddle** – that could be adjusted with three adjusting screws. In late 1971, the design was changed to the solid die-cast (injection-molded) bridge saddles still customary today [Duchossoir]. For both bridge-piece designs, the decay of the partials of a 0.013" B-string was analyzed. **Fig. 7.77** (left-hand image) shows corresponding decay times. Disregarding – for the moment – the smaller variations in the curve, we find the following: the string supported by the injection-molded bridge saddle (continuous line) shows a behavior nicely approaching the orientation line given by radiation attenuation and internal damping. Conversely, the decay time of the string supported by the vintage bridge saddle is only about half as long at high frequencies. The explanation is simple: The sheet-metal bridge saddles bend easily, and thus absorb more than the solid design. So: do upload the graph to the Internet – and we have one more ineradicable rumor.

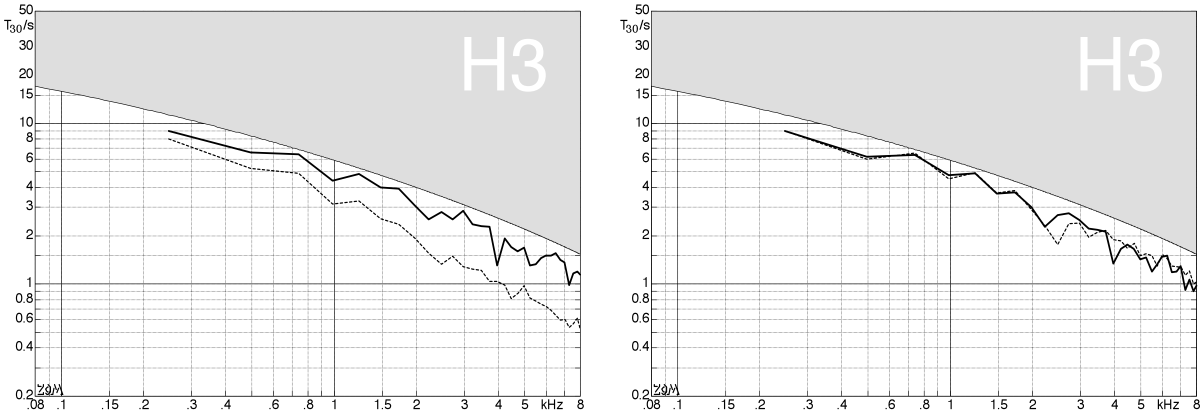


Fig. 7.77: Decay times of the B3-string (= "H3") of a non-trem Stratocaster. Left: solid (——) or vintage (---) bridge saddle. Right: solid bridge saddle (——), other specimen of vintage bridge saddle (---).

To re-check, the solid bridge saddle was mounted to the guitar again: the measured curve (right-hand graph) is quite comparable. Then it was sheet-metal saddle's turn again; however, a different specimen was used: different results show. Fig. 7.77 unambiguously indicates that the bridge saddle affects the decaying oscillation of the string to a not inconsiderable extent. It therefore participates essentially in the shaping the sound. Obviously, there are non-negligible **manufacturing tolerances** in the bridge saddles – not surprising when taking a closer look at the particular construction. As Kollmann [1993] notes very persuasively: *the gap absorption is the most important damping mechanism in machine acoustics.*

There is a generous helping of gaps within the construction of the Stratocaster bridge, e.g. between the saddle and its three screws, between the screws and the support plate, and of course between the string and the saddle. The whole contraption does not seem to be expert-optimized in terms of its damping properties; therefore it may actually be even expected that each bridge develops an individual life of its own, and its individual damping character.

To clarify this once again: given such pronounced inter-individual scatter we cannot maintain that the vintage saddle will absorb significantly differently compared to the solid saddle. Instead, we only may conclude that even identically constructed saddles may differ in their damping properties.

The damping processes presented so far shall in the following be summarized in an example. The measurements were carried out on a **Gibson ES-335** equipped with new strings (9/46). The A_2-string was plucked fretboard-normally near the nut; its oscillations were detected two-dimensionally with two laser vibrometers. The left-hand section of **Fig. 7.78** shows the evaluation of the decay times of the partials. Up to about 1 kHz, the minima can be attributed to neck resonances, the two dips between 1.5 – 2 kHz are related to dilatational wave resonances and to bridge resonances, respectively.

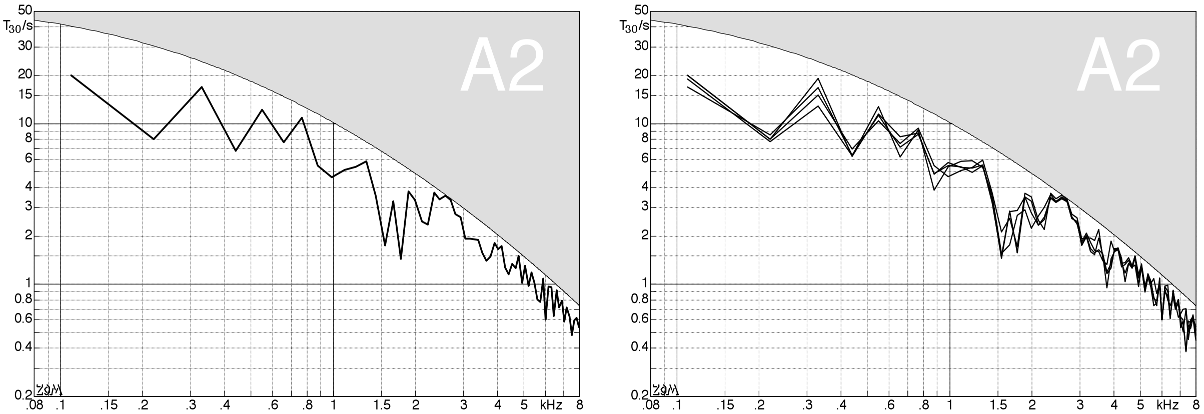


Fig. 7.78: Decay times of partials of the open A2-string of a Gibson ES-335; different bridge positions.

The **bridge of the ES-335** is of the famous "Tune-O-Matic" type. As it often happens with celebrities, there is an obvious tendency towards lability. In particular, the bridge is given height-adjustment – and it can move laterally because some excessive clearance has been built into it. The right-hand section in Fig 7.78 shows a family of curves that results from the bridge being moved laterally. The overall trend remains while differences appear in the details. For a Les Paul (Fig. 7.76), it already has been demonstrated how the string damping caused by the bridge can be modified by mounting a small clamp. **Fig. 7.79** now gives additional proof. In the left-hand section of the figure, the decay times for the A_2-string are shown: once for the guitar in its original condition, and once more for a modification (a clamp on the residual string at the bridge). Especially around 1 kHz the decay of the partials changes – suggesting the combination bridge/residual-string to be a possible source of attenuation. The right-hand section of Fig. 7.79 shows a velocity spectrum. It is gathered with a laser vibrometer, the beam of which was focused directly beside the A_2-saddle onto the bridge below it. To measure, the A_2-string was plucked fretboard-normally near the nut. An oscillation maximum can be seen between 1.5 and 2 kHz – obviously there must be a bridge resonance here. And once again we get confirmation on what guitar magazines have a hard time to grasp: bridge oscillation = string damping.

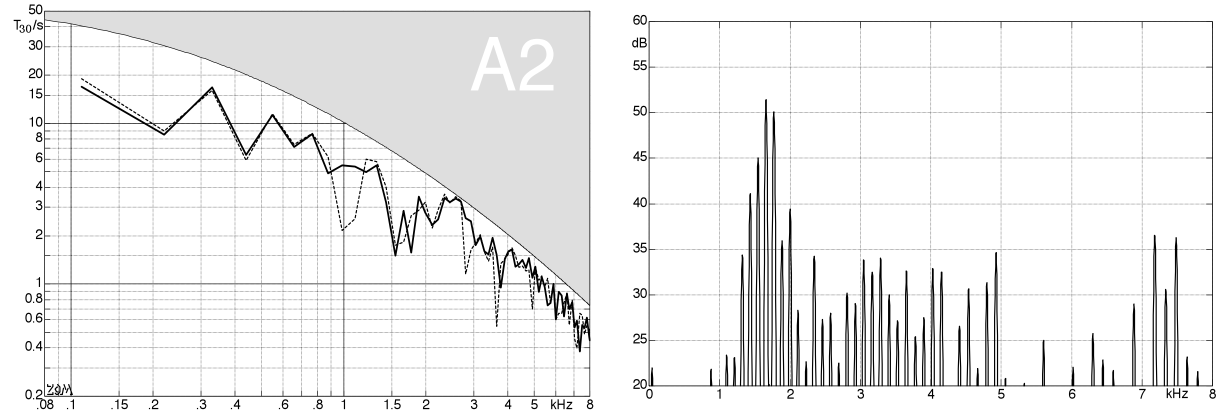


Fig. 7.79: Decay times of the partials of the empty A2-string on a Gibson ES-335. Left: original condition (**---**), small clamp on residual string at the bridge (---). Right: velocity spectrum of the bridge, next to the A2-saddle.

The fundamental frequency of the resonances of the A_2-dilatational-wave is at 1.8 kHz – these resonances can contribute to the attenuation, as well (3.6 kHz). Compared to the area offset in grey and marking the global shape of the string-damping curve, the decay time of the ES-335 shows characteristic deviations. These are even more striking if we do not evaluate the string vibration two-dimensionally, but analyze only the fingerboard-normal string vibration (just as the pickup would). The corresponding decay times are shown in **Fig. 7.80**. Differences between the two types of analysis can be attributed to non-exponential decay (Chapter 7.6.3); beats or salient curves lead to ambiguities. Differences between the results for the ES-335 and the Stratocaster analyzed in Fig. 7.80 need to be discussed with regard to two focal points: Up to approximately 1 kHz, neck resonances determine the string damping, and in the frequency range above there are mainly bridge- and string-specific processes. The drop of the ES-335 between 1.5 and 2 kHz clearly has its cause in a bridge resonance, possibly amplified by a dilatational-wave resonance. The latter are also highly likely to be the cause for the minima at 3.7 and 5.4 kHz. Not looking at these specifics, only small differences remain in the range above 1 kHz. These small differences moreover change in many details as minor shifts are made to the respective bridge saddle. Therefore: although the two guitars differ considerably in construction (Strat = solid-body, ES-335 = thinline), the treble range of the string vibrations is determined by the string and its bearings only. There is practically no influence by the wood. Below about 1 kHz, neck resonances (very selectively) determine the string damping, and only here does the wood have an impact. **The wood of the neck, that is**! Although the body as a bearing for the neck is also involved, the bending- and torsion-resonances of the neck are the decisive factor.

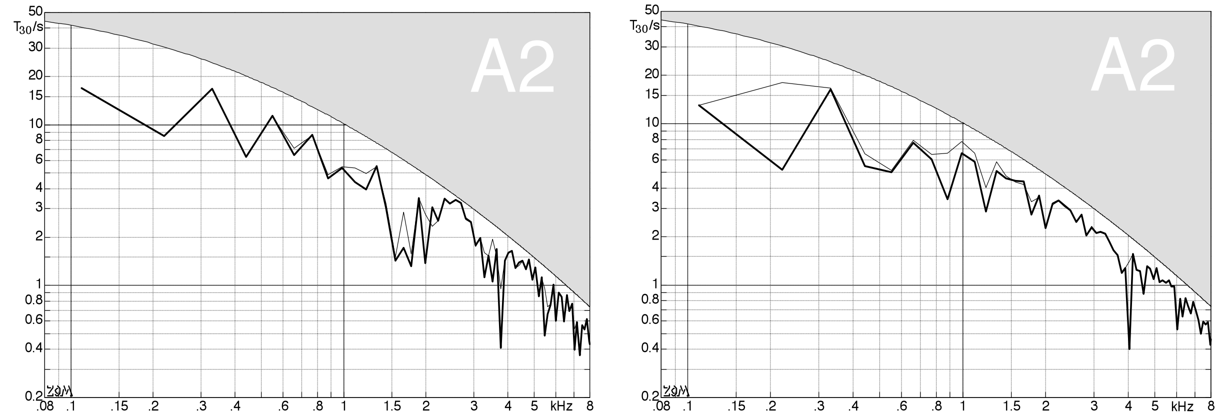


Fig. 7.80: Decay times of partials in a Gibson ES-335 (left), and a Fender Stratocaster (right). The thick line refers to the fingerboard-normal string vibration; the thin line refers to the two-dimensional analysis.

Fig. 7.81 shows a similar comparison, but now for the E_4-string. In the 2D-analysis, there are only small differences; these may in part be due to the fact that the string diameters were different. In the Stratocaster, some partials decay with a beat, this leads to the already discussed discrepancies. In direct comparison they are just about audible, but do not have their cause in either the pickup magnets (completely lowered for this measurement), nor in the body wood, but exclusively in the string bearings. The guitar body certainly has considerable impact on the radiated **airborne sound**, but for the voltage generated by the pickups, it is insignificant as long as typical design rules are not grossly violated.

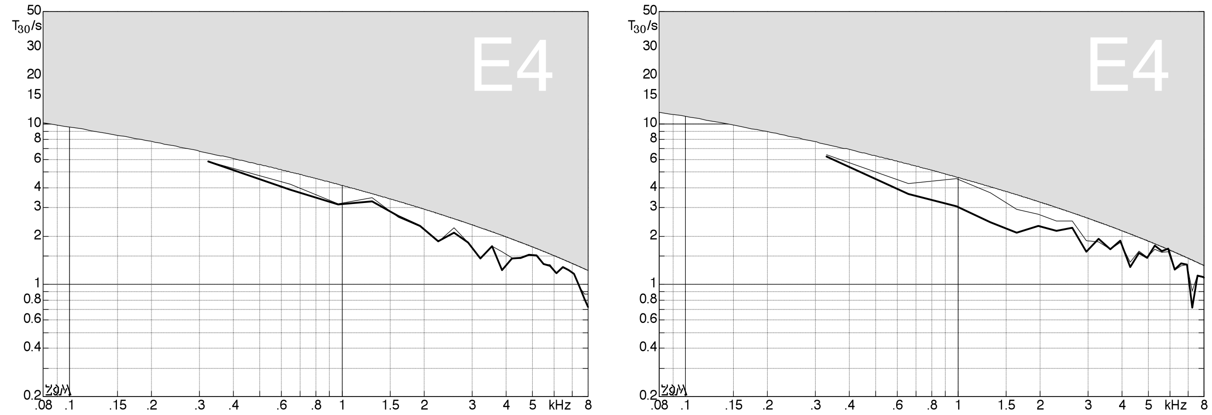


Fig. 7.81: Decay times of the partials of an ES-335 (E4, 0.009", left), and a Stratocaster (E4, 0.010", right). The bold line refers to fingerboard-normal string vibration; the thin line refers to the two-dimensional analysis.

The T_{30}-differences found so far shall be discussed again with consideration of musical requirements. How relevant is the difference between, e.g., T_{30} = 3.0 s and 2.5 s? For a tone duration of 0.5 s (a quarter note at 120 bpm), a level drop of 5.0 dB occurs at T_{30} = 3.0 s, and 6.0 dB at T_{30} = 2.5 s. By contrast, the level of a partial may change by 10 dB (or much more) when the string is plucked an inch or so closer to the bridge! This is not to say that a short decay time can generally be compensated with a higher level. These are entirely independent quantities to start with – they do now receive a special joint assessment by the **hearing system**. Defining "**Attack**" as the first section of approximately 100 ms of the guitar tone, we can choose a time span that corresponds to the integration time of the ear [12]. During this time-span, psychoacoustic “trading” between initial level and decay time is actually possible. However, the change in the location where the string is plucked has a much greater effect on the sound than e.g. the differences shown in Fig. 7.81. Listening tests confirm this: you can almost always hear differences, but in most cases these are due to slight differences in the picking location or in the way the plectrum is held. There is no denying that substantial physical differences exist between T_{30} = 1.5 s and T_{30} = 0.4 s (Fig. 7.80) – however, if these differences occur at 4 kHz, their auditory relevance is very low. In fact, the ear combines into a joint processing about 7 partials in the corresponding critical band (the hearing-related frequency-range division); thus the level of one single partial does not play a significant role. Also, we must not forget that the decay times shown so far have all been measured with brand-new strings - just a few minutes of (more or less) virtuoso playing will deposit skin, oil, and fat particles on the wound strings – significantly reducing the decay time, and thus even more significantly reducing the influence of any parameters of the guitar body *(translator’s note: if there are is such an influence at all)*. So again: **it's in the fingers**, in every respect …