7.7.4 Bearing absorption

In Chapter 2, the discussion has focused in detail on describing the string as a mechanical line along which waves are running. The reflection process occurring at both bearings (bridge, and nut or fret) is defined by the **characteristic wave impedance** of the string, and by the respective particular **bearing impedance** (or admittance). Typically, the bearings are rigid - thus having a very high mechanical impedance – so that nearly the whole wave energy will be reflected. However, a small percentage will be absorbed at the bearing, and this is where the designs of bridge and nut/fret come in, as well as the materials used for these components. The guitar neck and its resonances [Fleischer] need to be looked into at some point, and subsequently, at the very last, one may also wonder about the wood of the guitar body. First, however, term "bearing absorption" must be clarified – because a simple punctiform impedance is not good enough. Instead, we can isolate several absorption processes, each of them to be discussed in their own subchapters.

7.7.4.1 Coupling of transversal waves

The magnetic pickup customarily deployed on electric guitars transforms into an electrical voltage predominantly those string oscillations that occur perpendicular to the fretboard (Chapter 5). Therefore, it is obvious when performing measurements to pluck the string normal to the fretboard, and to measure the fretboard-perpendicular string-oscillation component e.g. using a laser vibrometer. In the simple model, an exponential decay of the velocity of the partial is assumed:

$$v(t) = v_i \cdot \exp(-t/\tau) \qquad \tau = \text{amplitude-time-constant}$$

Because the instantaneous power is proportional to the square of the velocity, its decay needs to be described by a power-time-constant – that is half as big as the amplitude-time-constant. Thus, if we talk merely about a "time constant", there is a risk of confusion. However, the specification of the **decay time T_{30}** (during which the level is reduced by 30 dB) is clear; it will be applied in the following. The decay time T_{30} is 3.45 times the amplitude-time-constant or 6.9 times the power-time-constant. However, not all analyses of partials show a purely exponential decay. In **Fig. 7.67**, the measured decay of the 4th partial of a B-string of a Stratocaster is shown. An analysis encompassing 2 s shows a progressively decreasing curve to which a single gradient can only hardly be related – both inserted approximation lines mightily reek of being arbitrary. Enlightenment in the truest sense of the word is provided by a second laser-vibrometer that upgraded our lab-setup to a **2D-measuring-station**. The fretboard-normal and the fretboard-parallel string oscillations perfectly complemented each other to sum up (in terms of the energy) to an exponential decay that would do justice to any textbook, and featuring a decay time (5.7 s) significant longer than the one initially expected.

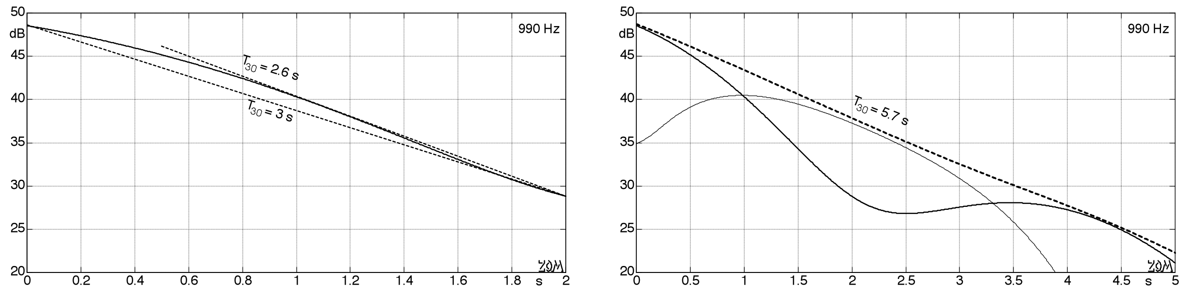

Fig. 7.67: Decay of the 4th partial of the B-string (Stratocaster). On the right, the level of the fretboard-parallel oscillation is plotted in addition, and also the level of the sum (----).

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The interpretation of these measuring results may vary depending on the question. The fretboard-normal oscillation the pickup senses – only this being relevant to the sound – reaches a minimum after 2.5 s. The related loss in level of 22 dB must not be considered as an energy drop of 99.4%, because a part of the energy is not yet “lost” but stored temporarily in the orthogonal oscillation mode. After another 2.5 s, the level therefore has not decreased by 44 dB in total but only by 26 dB. However, this does not at all help the guitar player who wants to play a tone that lasts 2.5 s – he simply feels the **sustain** of this particular partial as being all too short. Let’s assume that in particular this partial is of eminent importance, and let us hold fast onto this: the decay time measured in one oscillation plane must not just blindly be converted into dissipation parameters.

Conspicuously, the decay analyses of the investigated American Standard **Stratocaster** showed that in particular the B-string featured strong beats of partials. Now, of course every ‘in-the-know’ guitar player is aware that these beats, this ‘chorus-like warble’, belongs to the specific charm of the Strat, and – being privy to it all – our man knows the (supposed) cause: it’s the magnets! These conniving guys sneakily exert a vicious pull on the strings and ‘hinder them to decay freely’. We do not know the originator of the moderately intelligent term '**Stratitis**' for this ‘illness’ of the Strat … but that’s probably for the best. In Chapter 4.11, we had already explained that pickup magnets in fact may change the decay characteristic of individual partials – however, this mainly affects the fundamental. To be on the safe side, the pickups had been lowered as much as possible before the measurement specified in Fig. 7.67 was taken – in other words: it’s not **the magnets**, they are not responsible for this beating. **Fig. 7.68** shows further levels of partials of this B-string – all fraught with various beats. If one does not have unlimited possibilities for modal analysis (one does not: the Free State of B. in the south of the country G. needs cut back and saving money after the latest banking disaster), only simple approaches remain for such studies. In the present case: we lift the B-string out of its groove in the nut, move it sideways by a millimeter, re-tune, and repeat the measurements. And behold: the beats were yesterday. If only all analyses were that easy.

In its original state (**Fig. 7.68**, left-hand section), the B-string of the investigated Stratocaster generates audible beats that one may love or hate. Still: this characteristic definitively must not be attributed to the specially selected and long stored wood of this American dream – the mundane source is in the **nut**. No, don’t even go there and say that this nut has been filed down with love and given brilliant workmanship exactly in such way that these beats result, because only they would generate that authentic ´Strat-sound´. Once the measurements had been carried out, the B-string was allowed back into its original groove and was re-tuned … and there they were back again: the beats. However, they were not the same anymore – a closer look showed deviations in frequency and amplitude of the beating. Thus, this sound characteristic has to be seen as accidental and fragile – a result of a naturally always tolerance-affected manufacturing. In the case of the investigated Stratocaster, only the B-string showed such strong beats, all other strings behaved completely inconspicuously. It is, however, to be expected that among the many Strats manufactured to this day today there are more than a few that feature more than one string generating stronger beats, and perhaps these are in fact exactly those holy cows a lot of money is shelled out for. The top nut, stupid ...

No, of course the nut is not the only reason for certain sound characteristics, it is essentially involved in sound shaping, though. At the beginning of the 21st century, aficionados still commemorate those fair maidens (or ladies) who – by hand! – wound Fenders' first pickups (hail oh Mary, Gloria, Abigail!); however, that kind of honor and appreciation is denied to that master nut-slotter *(translator’ question: would that be a nutter, then?)*. By Leo, he would have deserved it, too.

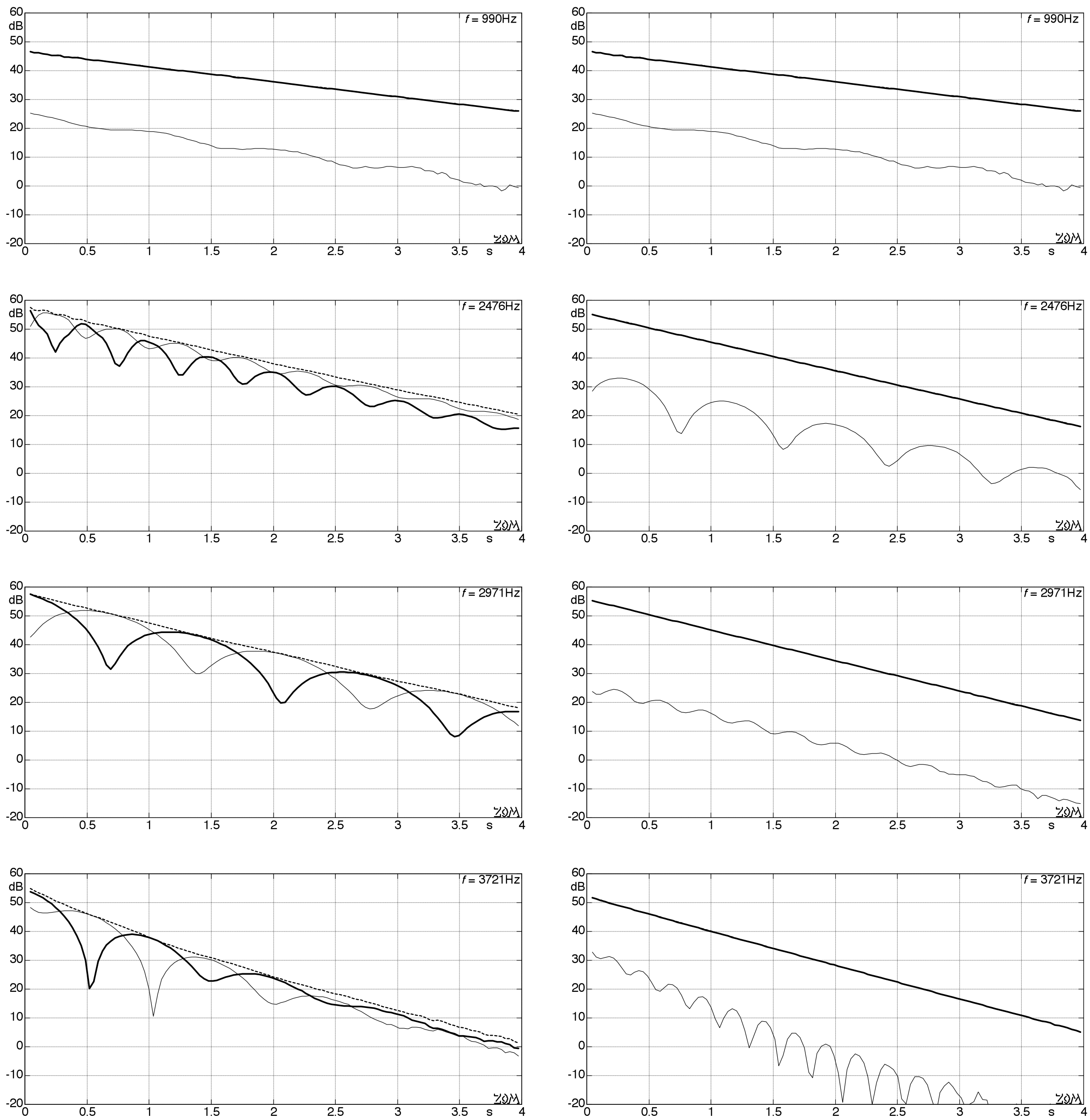

Fig. 7.68: Level of partials, B-string, Stratocaster. Left: string in the saddle groove. Right: string beside the groove. Bold line: fretboard-normal string oscillation. Thin line: fretboard-parallel string oscillation. ---- = Sum.

Before thinking about how the wood of the guitar body could affect the string oscillation, we should first consider those components that are in direct contact with the strings. These are in fact the nut (or fret) and the bridge saddles – but not any pieces of ash or alder. If the string does not rest on a line that is perpendicular to its longitudinal axis, a coupling of the oscillation planes may result. The same might happen if the compliance of the support is direction-dependent. The coupling of the transversal oscillations as it is caused at the string bearing is shown in **Fig. 7.69** as an **orbit-diagram** (abscissa = fretboard-parallel oscillation, ordinate = fretboard-normal oscillation). In the upper-left diagram we can see how the string first begins to oscillate vertically, but then subsequently shifts the oscillation plane first to the left, and then to the right. After about 370 ms, the vertical oscillation has nearly decayed to zero, and the oscillation energy has mainly been transferred to the orthogonal component. This is completely different for the B-string when positioned *beside* the groove of the headstock saddle: it substantially keeps its oscillation plane, because the coupling between both oscillation modes is much smaller (bottom images).

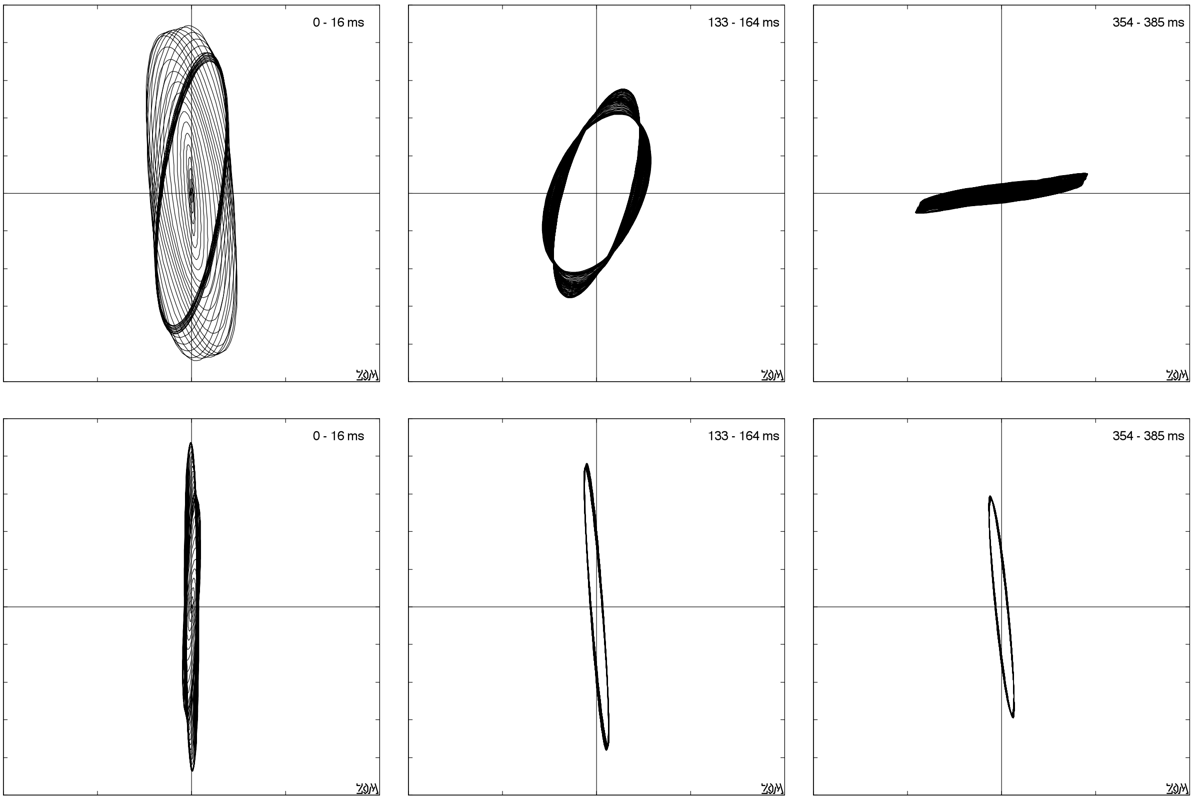

Fig. 7.69: Orbit-diagrams (vertical vs. horizontal movement). B-string, Top: bearing in the nut-groove, bottom: bearing beside the nut-groove. Stratocaster, 10th partial of the B-string (2476 Hz). The analysis had been run with signals that were similar but not identical to those used for Fig. 7.68.

When investigating damping (dissipation processes), we need to analyze both oscillation planes. If merely the voltage generated by the pickup is of interest, only the fretboard-normal oscillation-component is essential. That common magnetic pickups can pick up not only transversal oscillations but also longitudinal oscillations is explained in Chapter 2.9, while the directional characteristic of these pickups is looked into in Chapter 5.11.

The mode coupling at the *headstock saddle* (nut) of the B-string found in the above example is, of course, only relevant as long as the open B-string is plucked. As soon as the string is pressed down on the fretboard by a finger, the fret that is next to it takes over the bearing function. Furthermore, corresponding coupling may just as well occur at the *bridge saddle* - and this will have effects also when the string is fretted. The **bridge construction** of most electric guitars encourages the assumption that the designers did not worry about mode coupling, but predominantly considered as their task the adjustability of the action, and lowest possible production costs. On the Jazzmaster (planned to be Fender’s top model), Leo Fender guided the strings at the bridge by means of screw threads. However, he did not use screws with six different threads – no, three different threads had to be enough. As generally known, the strings have six different diameters, and therefore the fit for the strings will turn out to be very different from string to string … What? Fit?? On the Tune-O-Matic bridge, Gibson guides the strings by means of bridge saddles looking fishily similar – all six of them! The guys at Rickenbacker lay the strings into small rollers, probably hoping that the gap damping won’t become all that pronounced. And surely: there are six identical rollers! Obviously, not all builders of electric guitars were aware to the same degree of the function of the guitar bridge in terms of vibration technology.

More details regarding bridge constructions are compiled in Chapter 7.10.

7.7.4.2 Damping of longitudinal waves

Chapter 7.7.4.1 had shown that a coupling of transversal string-vibrations occurs at the bridge and at the nut (or fret). In addition, transversal and longitudinal oscillations exchange part of their oscillation energy, as well (Chapters 1.4 and 7.5.2). The dilatational waves induced that way showed high loss factors in the decay measurements: individual partials decay rapidly, i.e. they exhibit short decay times. For the following vibration measurements, a **Fender US-Standard Stratocaster** was used with its tremolo (aka vibrato) genre-typically adjusted to be *floating*. The investigated string was plucked fretboard-normally close to the nut; an oscillation analysis was made close to the bridge using a laser vibrometer.

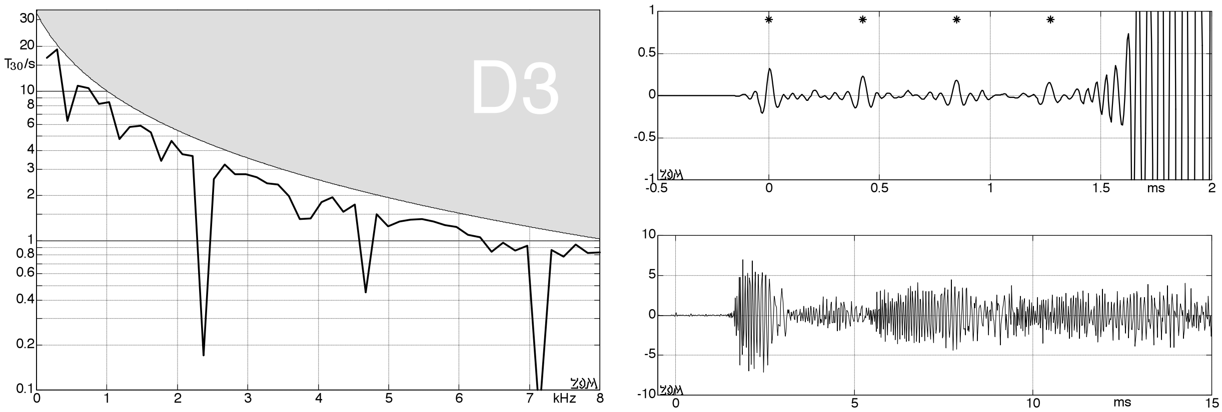

Fig. 7.70: Decay (left) and time function of the fretboard-normal velocity. Dilatational wave period = 0.42 ms.

For the fretboard normal velocity, the left-hand image in **Fig. 7.70** shows the decay time of the D_3-partials. Damping maxima – i.e. T_{30} minima – can be identified at 2.36, at 4.7 and at 7.1 kHz; r**esonances of dilatational waves** can be assumed to be the cause. In the time function we can see that - even before the transversal wave arrives at the measurement point – small impulses with a periodicity of 0.42 ms occur. Although the laser vibrometer (which is sensitive to lateral string oscillations) cannot itself detect the dilatational waves, it does capture their secondary waves (Chapter 1.4). Apparently, dilatational waves are absorbed efficiently in the wound D-string, and a selective damping arises at a frequency of 2.36 kHz (and its multiples).

Depending on how well the resonance frequency of the dilatational wave matches the frequency of the partials, this dilatational-wave damping can be more or less pronounced. The measurements done until now let us assume that especially the fretboard-normal oscillation can transfer its energy to the dilatational wave; the cause could be the curvature of the string at the bearing (Chapter 7.5.2). In **Fig. 7.71**, the level drops of the partials of the D-string are represented: the fretboard-normal oscillation decays very fast at 2364 Hz, while the fretboard-parallel oscillation exhibits a decay time as it is found with the adjacent tones.

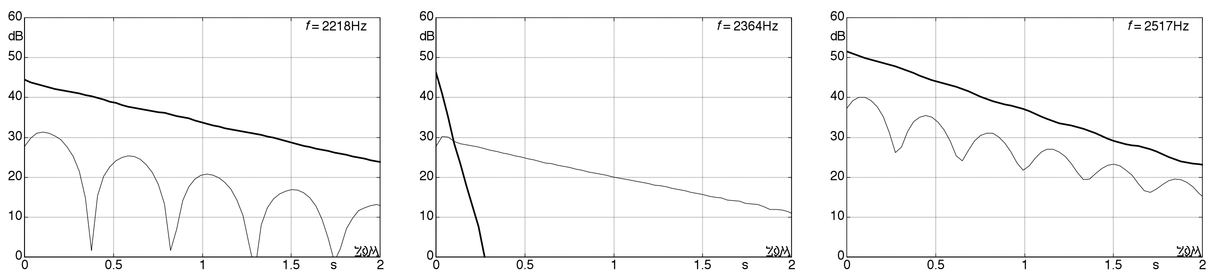

Fig. 7.71: Level drop of partials; bold = fretboard-normal oscillation, thin = fretboard-parallel oscillation

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7.7.4.3 Residual damping

Generally, the string does not end at the bridge or the nut but passes over it to its actual mounting point. In certain circumstances, these **remaining sections of the strings** (residual strings) located beyond the main section of the string may form an effective absorber that can deprive the main section of the string of oscillation energy. This is termed residual damping.

If the string would exhibit a pure transversal movement, it could not transfer energy to the residual string across the fixed support bearing. However, as was already explained in Chapter 2.7, the string is also subject to a **bending stress**, and the related bending moment acts across the bearing and excites the residual string. Also, the longitudinal forces occurring within the string (→ dilatational wave) may at least partially act across the bearing – especially for small bend angles, the string may relatively easily slide across the contact area.

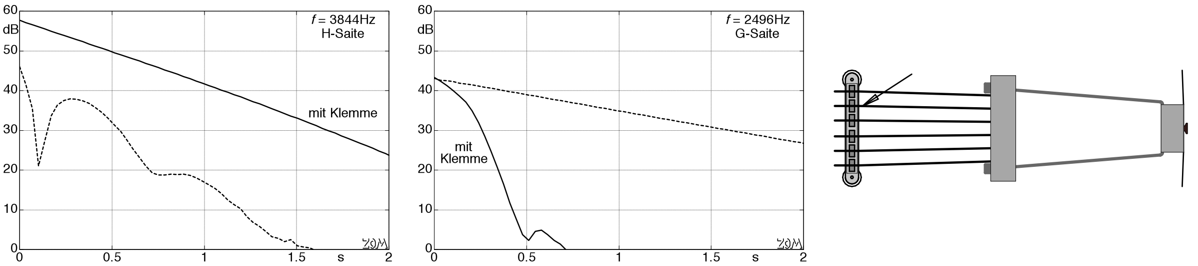


Fig. 7.72: Modification of the decay of partials (at the specified frequ.) due to mass loading by the residual string at the bridge; Gibson ES-335 TD; “H-Saite” = B-string, “G-Saite” = G-string, “mit Klemme” = with clamp.

To quantify the effects of this residual damping via two examples, a string of an ES-335 was plucked fretboard-normally near the nut; measurement of the fretboard-normal velocity was done near the bridge saddle using a laser vibrometer. As a modification, a small clamp was attached to the residual string near the bridge (**Fig. 7.72**, arrow). The measurements were carried out for the B- and G-string, with always the plucked string being measured and modified. For many partials, no considerable effect resulted – but in some cases the decay was indeed influenced. This happened in different ways: for the partial of the B-string shown in the left picture, the additional mass improves sustain and level, while in the other example, the additional mass chokes off the oscillation rather rapidly♣.

It is difficult to formulate these damping mechanisms analytically because two transversal modes and one dilatational wave occur in combination – in fact on both sides of the bridge! Therefore, these examples only serve to show that the effect of the residual strings must not be generally neglected. However, because the decay of only a few partials will vary, the sonic impacts remain fairly low. With the investigated ES-335, no audible difference in the "electrical sound" could be found when damping the residual strings during playing with the heel of the hand.

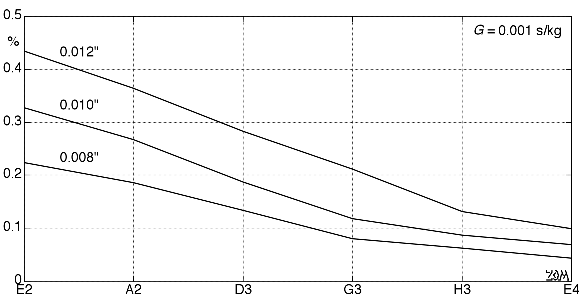
It is obvious that such a damping mechanism cannot be found with measurements at an empty bridge (bridge without string). On the other hand, the saddle conductance (Chapter 7.7.4.4) can only be determined without the string because the location of the string bearing can only be allotted once to one single taker. Already the ancient philosophers knew: where there already is something, nothing else may be.

♣ For the sake of completeness it is noted that even between the individual strings und their partials, vibration coupling and thus damping may occur – this effect will not be further investigated here, though.

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.

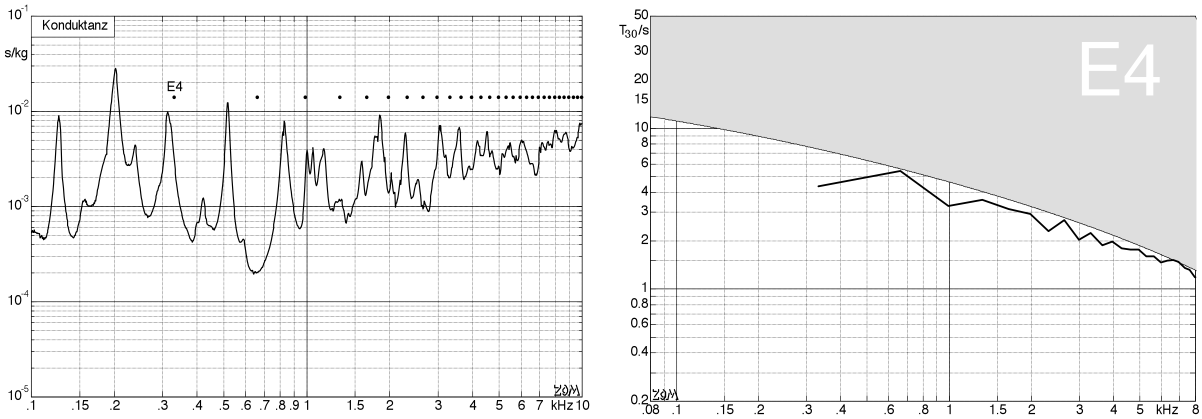


Fig. 7.74: Les Paul, E4-string: conductance (“Konduktanz”) at the nut (left), calculated decay times (right).

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.

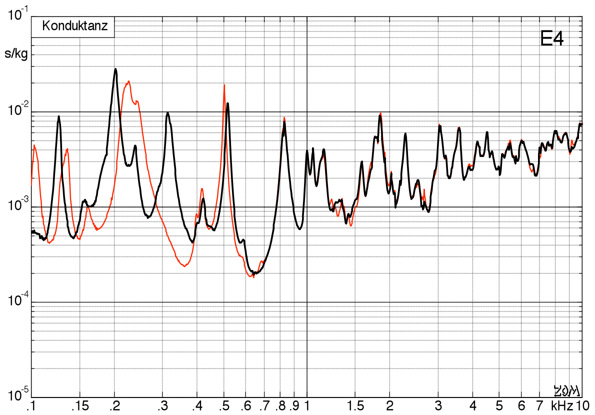


Fig. 7.75: Les Paul, conductance ("Konduktanz") at the nut: E4 (left), E2 (right). Mechanical modifications.

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.

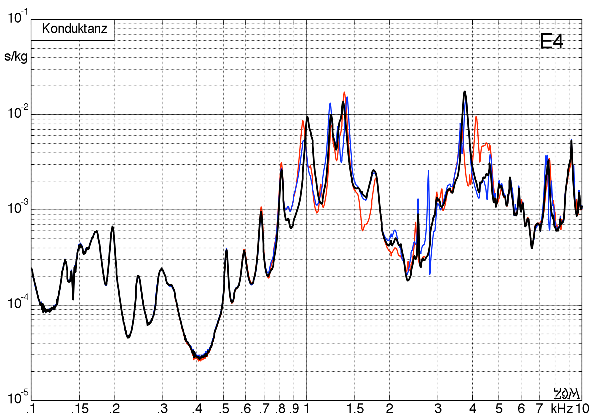


Fig. 7.76: Les Paul, bridge saddle conductance ("Konduktanz"), E4. Modifications = clamp mounted to the bridge.

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.

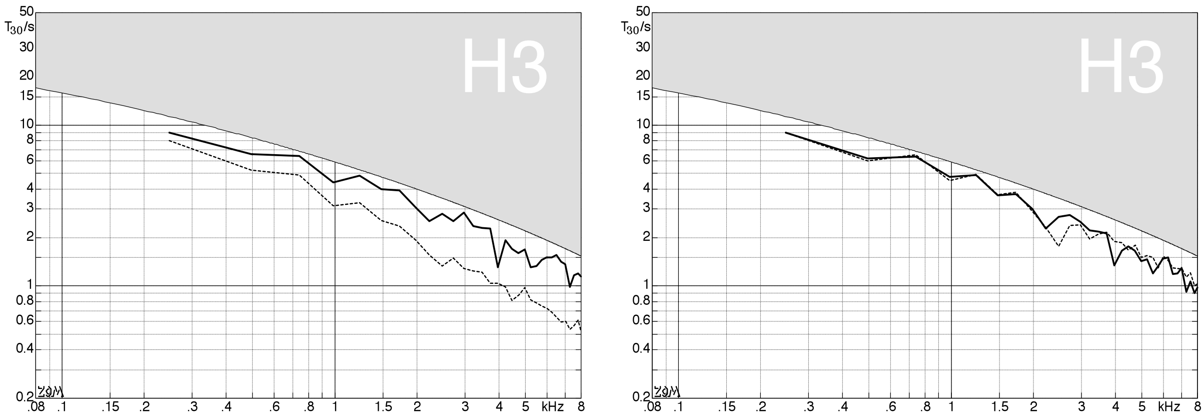


Fig. 7.77: Decay times of the B3-string (= "H3") of a non-trem Stratocaster. Left: solid (——) or vintage (---) bridge saddle. Right: solid bridge saddle (——), other specimen of vintage bridge saddle (---).

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.

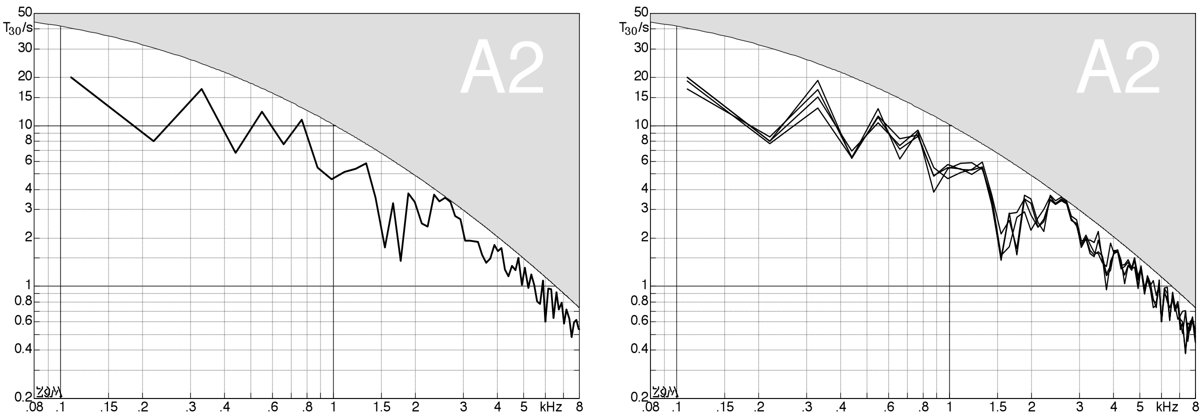


Fig. 7.78: Decay times of partials of the open A2-string of a Gibson ES-335; different bridge positions.

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.

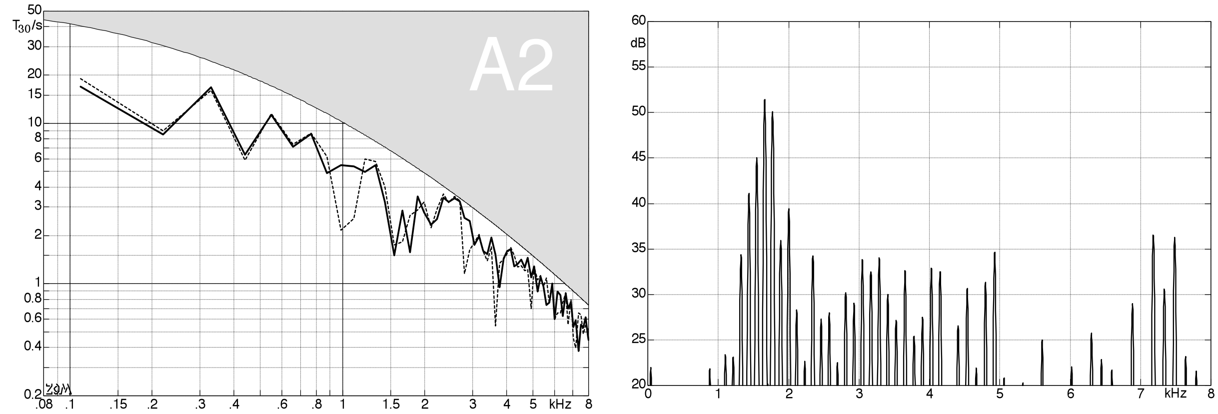


Fig. 7.79: Decay times of the partials of the empty A2-string on a Gibson ES-335. Left: original condition (**---**), small clamp on residual string at the bridge (---). Right: velocity spectrum of the bridge, next to the A2-saddle.

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.

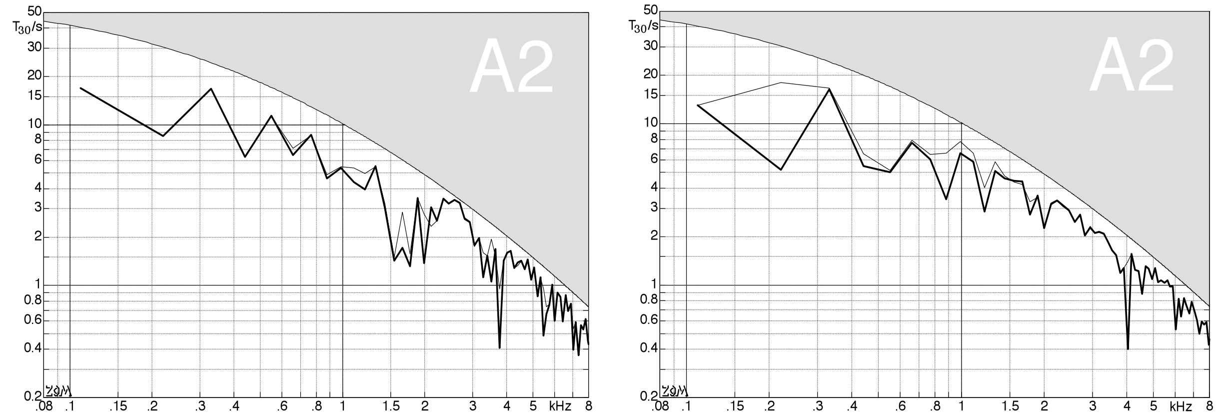


Fig. 7.80: Decay times of partials in a Gibson ES-335 (left), and a Fender Stratocaster (right). The thick line refers to the fingerboard-normal string vibration; the thin line refers to the two-dimensional analysis.

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.

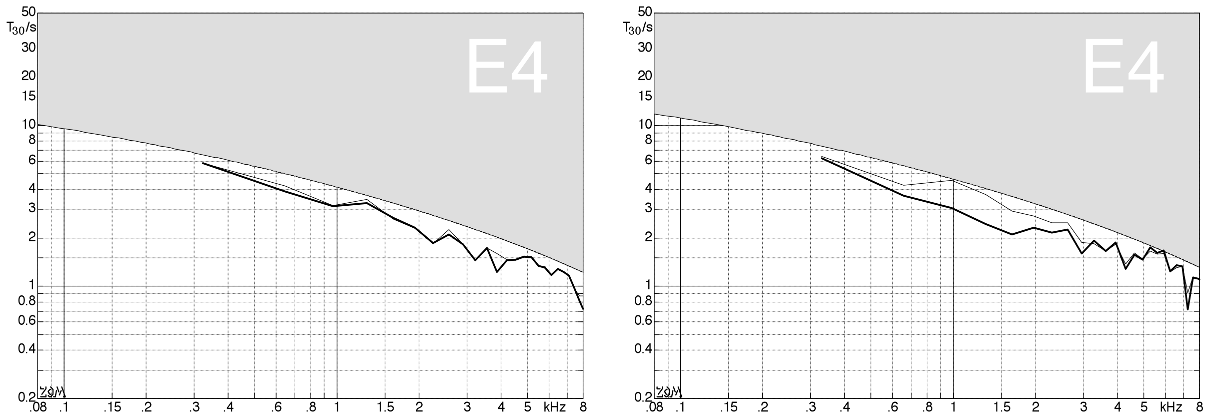


Fig. 7.81: Decay times of the partials of an ES-335 (E4, 0.009", left), and a Stratocaster (E4, 0.010", right). The bold line refers to fingerboard-normal string vibration; the thin line refers to the two-dimensional analysis.

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 …