7.10 Special Bridge Designs

The guitar string is supported by two bearings: at the nut (or the fret) and at the bridge. The nuts of acoustic and electric guitars may show variations, but normally they are of similar build. The bridge, however, will be different for these two categories of guitars (save for some exceptions). In acoustic guitars, the bridge often consists of a light (!) saddle made of bone or plastic while the strings of an electric guitar will rest on a solid, massive, adjustable contraption made of steel. Electric guitars often feature individual bridge saddles shaped cylindrically or like a mono-pitched roof, and adjustably resting on the bridge base.

The bridge of an acoustic guitar needs to be light so that any vibration energy worth mentioning can be transmitted to the top of the guitar. In contrast, the bridge of an electric guitar (where the body is not supposed to vibrate) may be of a very solid build. A few adjustment screws will obviously not get in the way here, because otherwise they would not have been included with much enthusiasm. This adjustment possibility is not entirely useless, either (as was elaborated in Chapters 1 and 2), because: in order to achieve correct tuning, the steel strings require corrections in length that may amount to up to 5 mm. We therefore have adjustable bridge saddles und adjustment screws. Leo Fender had still been mightily thrifty when designing his first electric, the “Broadcaster”; he positioned two strings each on a steel cylinder (later a brass cylinder). Apparently, it was attractive to make each string individually adjustable because the successor, the “Stratocaster”, featured string-individual bridge saddles made out of pressed steel, and adjustable both in length and height. Although no classical guitarist will ever demand this from his Ramirez, it seems almost indispensable for the electric guitar to have the action fully adjustable – best in three dimensions: height, length, and distance between the individual strings.

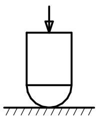
Inevitable, this **possibility of adjustment** entailed a diversification in the components: what had successfully been achieved with just a board and some strips of bone, suddenly required screws, springs, straps, wires, curled nuts, rollers … a hodgepodge of 18 parts or more. Do these vibrate, then? Hold on – these are the ‘50s, and this question was not on the table, yet. Sets of 012 strings were standard; these could not easily be pushed out of the groove in the bridge saddle – something that would become a potential problem with the later 009, or even 008 string sets. *"The 'Floating Bridge' consists of a master bridge adjustable to varying heights. On it rest the six individual bridges each adjustable for string length and height, making possible extremely accurate adjustments for perfect intonation and custom playing action [Fender Jazzmaster, 1968]."* This is the way a faulty design was advertised back then, and room was created for "retrofitters" who could earn their money with accessories for correcting the mistakes. Chief issue: to be adjustable.

Admittedly, it was not easy to design a bridge that was solid and at the same time adjustable. In particular, many a guitar was now treated to a **vibrato-system**: a spring-mounted string-retainer that offered variation of string length – and thus pitch – via a lever (whammy-bar). However, with varying length, the strings needed to slide across the bridge somehow – or the bridge could be made movable in the direction of the string, and move with it. The latter approach resulted in the 'floating bridge' of the Jazzmaster (and other guitars). That bridge could develop, with thin strings, an undreamt-of potential to float around. Under these circumstances, Leo Fender’s unceremonious renaming of the vibrato-effect into **tremolo** was no help, either: this wobbly-jelly did irritate more than just a few guitarists. Everybody else was of course highly enthusiastic: *"Careful design and outstanding playing characteristics of the Jazzmaster have made it one of the favorites of guitarists around the world [Fender 1968]."* Cheers, then!

7.10.1 Simple equivalent systems

The guitar bridge mechanically interconnects string and guitar body. As a system of mechanical vibration, it is an object of mechanical systems theory, the latter analytically representing movements and forces. The small masses, stiffnesses and resistances differentially distributed over a continuum can, however, not be described with complete accuracy – only given the limitation to a finite effort the simplified representation via an equivalent system is possible. In contrast to the continuum, the **equivalent system** consists of a few, discrete elements that vibrate in one dimension only (a further simplification).

Mass (Newton), stiffness (Hooke), and frictional resistance (Stokes) are the fundamental elements of mechanical systems. While a mass can relatively easily be specified as a multiplication of density and volume, the analytical description of stiffness, and in particular of resistance, is difficult. As an example, **Fig. 7.89** shown a cylindrical pin made of metal, the rounded lower side of which sits on a flat surface. The mass of the pin is easily calculated, as is the stiffness of an axially loaded cylinder ($s_Z = ES/l$).



$$s_K = 0.82 \cdot \sqrt[3]{F \cdot R \cdot E^2}$$

Fig. 7.98: contact stiffness
F = axial force, E = E-modulus,
R = radius of round

Given an elasticity modulus $E = 2.1 \cdot 10^{11}$ Pa, the **axial stiffness** of a steel cylinder of 4 mm length and a diameter of 2 mm is calculated, resulting in s_Z = 165 MN/m. However, the largest deformation does not happen in the cylindrical part of the pin but at the contact point. Assuming a spherical round, the axial contact pressure force leads to a circular **contact surface**. The radius r of the latter depends on the contact pressure. The stiffness occurring at the contact point is force-dependent, as well: with increasing force, the stiffness increases, too. With the keywords *contact problem* and *Hertzian stress*, specialist literature [z.B. Szabó] offers approximations for the deformation from which the contact stiffness s_K can be calculated. There are several contact points in a guitar bridge, and therefore several stiffnesses. The magnitude of the latter depends on two variables: on the radius R of the round, and on the force. Both the pressure force perpendicular to the guitar top, and the traction force in parallel to the top depend on the force of the string tension that amounts to between 47 and 135 N (for a set of 010 strings, the benchmark is 80 N). In the Fender bridge, the axial force acting on the height-adjustment screws moreover depends on the bend angle of the strings as they run across the bridge; for e.g. the Jazzmaster this would be only about 6°. Given a string tension of 80 N, a pressure force of 8.4 N results, and since two screws support each string, the force is 4.2 N per screw. The calculation results in a contact stiffness of just under 5 MN/m, with a radius R = 1 mm. For bridges with a higher bend angle (e.g. the Stratocaster) the contact stiffness mounts and can reach, for thick strings, up to 15 MN/m. This is still much smaller than the axial stiffness estimated above, so that the conclusion for the aforementioned cylindrical pin is**: in terms of its effect, the contact stiffness is the dominant one of the two stiffnesses**.

Besides the contact pressure force, the **radius of the round** R is also found under the square-root in the above formula – and here things become complicated: this radius may vary depending on the deployed screw and the manufacturing quality, and therefore the resonance frequencies dependent on R may vary, as well! Similar issues appear for all other joints where two components lie on top of each other: depending on the surface roughness, and on the more or less protruding drilling burrs, an undefined bearing results that may undergo further variations when the strings are changed.

The **first joint** occurs between string and bridge saddle. The approximation using a spherical surface certainly is inappropriate here; due to the string flexion, a roller-shaped interface surface (like in a roller bearing) does not correspond to reality, either. The geometry of the string is predetermined, and cannot really be changed due to its high hardness and stiffness. Unknown, however, is the geometry of the bearing surface (the bridge saddle). The high E-string (E4, ∅ = e.g. 0.25 mm) rests on a probably 10-µm-wide strip; in this scenario, a production tolerance of 1 µm would be advisable – not something that "every manufacturer is likely to achieve". Thus, the mechanical data of this joint can be estimated only very roughly.

The **second joint** is located between bridge saddle and adjustment screw (there may be up to three of the latter per bridge saddle). Where the contact surfaces actually occur, and what the corresponding stiffness is, remains completely undefined, just as the resulting friction. In case of higher age, the degree of rust and corresponding mechanical parameters are also undefined.

The **third joint** occurs between screw and bridge base (or directly between bridge saddle and bridge base). Adjustment screws (so-called setscrews or headless screws) come with 4 different end-surfaces: level, spherical (convex), tapered, or concave (**Fig. 7.99**). These screws are mass-produced and not optimized with regard to any requirement of vibration mechanics, and therefore the contact stiffness varies from one screw to the next. The contact stiffness also changes as the screw is turned (an action that must be considered a regular fate of any screw).

The **fourth joint** is found between bridge and guitar body, and again, what has been stated above holds (as it is the case for any further joints): the stiffness and the resistance of/at the joint are largely undefined, as are their effects on the resonances of the bridge.

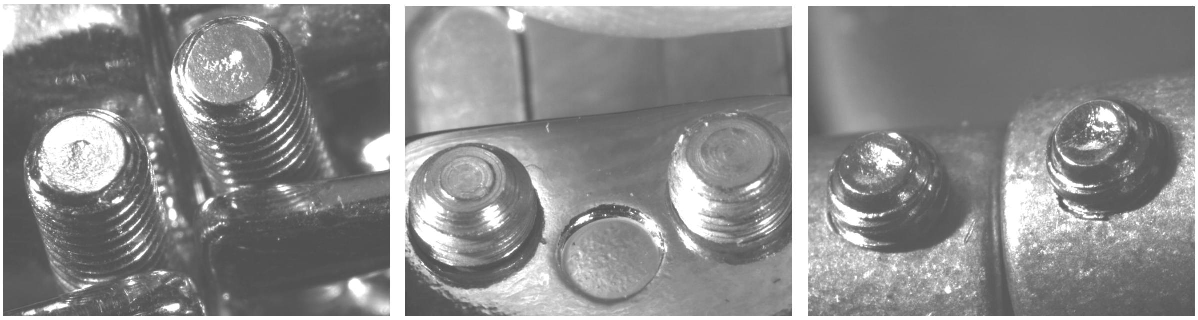
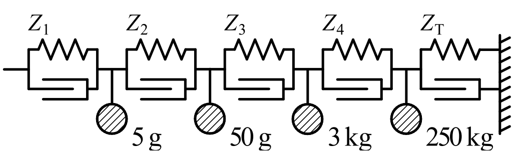


Fig. 7.99: Typical setscrews of a guitar bridge.

Can the guitar then function at all? Sure it can – some kind of stiffness and resistance will always develop; the term "undefined" used above merely means that the corresponding values may vary from one guitar to the next. Some of the involved variations may be without any big effect on the sound, but some will lead to audible inter-individual differences. Because it is very difficult to determine the joint-parameters of a given guitar, a different approach shall be applied now: in a model, we will assemble some basic elements (**Fig. 7.100**), and for these – and some modifications – the frequency responses of the conductances will be determined.



$$s_1 = 20\ \text{MN/m},\quad W_1 = 10\ \text{Ns/m}$$
$$s_2 = 20\ \text{MN/m},\quad W_2 = 50\ \text{Ns/m}$$
$$s_3 = 7\ \text{MN/m},\quad W_3 = 40\ \text{Ns/m}$$
$$s_4 = 1\ \text{MN/m},\quad W_4 = 2000\ \text{Ns/m}$$

Fig. 7.100: Simple equivalent system for a guitar placed on a stone table.

Fig. 7.101 shows the results of the calculations corresponding to Fig. 7.100. Between string and bridge saddle, the very simple Kelvin-Voigt model consisting of a lossy spring was used. Even though the values of the latter are unknown and can only hypothetically be assumed: it only has an effect in the highest frequency range that is relatively unimportant when magnetic pickups are used. This finding holds even if the actual stiffness were only 1/10th of the assumed value. As an orientation, the conductance calculated for the E_2-string is shown in grey in the figure (correspondingly see also Chapter 7.7.2. & 7.7.3); the more the bridge conductance is below this grey line, the less it bears any importance to the overall damping.

Somewhat more important is the (lossy) spring (s_2, W_2) located between bridge saddle and bridge base. It influences the high-frequency resonance that is found at 7.5 kHz for the above values. Again, we need to bear in mind that there are no measurements as basis for these values, and thus it is possible that the grey curve is crossed (e.g. for a smaller resistance W_2).

In this model, particularly important is the bridge-base resonance formed (in approximation) by the mass of the bridge (50 g) and the spring stiffness (s_3 = 4 MN/m). Measurements with Gibson bridges show similar resonance behavior and high string damping (Chapter 7.10.2).

The next spring in this model is found between guitar body and stone table (s_4, W_4) – it influences mainly low-frequency resonances. The stone table with a mass of 250 kg vibrating aperiodically damped with 2 Hz forms the conclusion: it is insignificant for the current measurements.

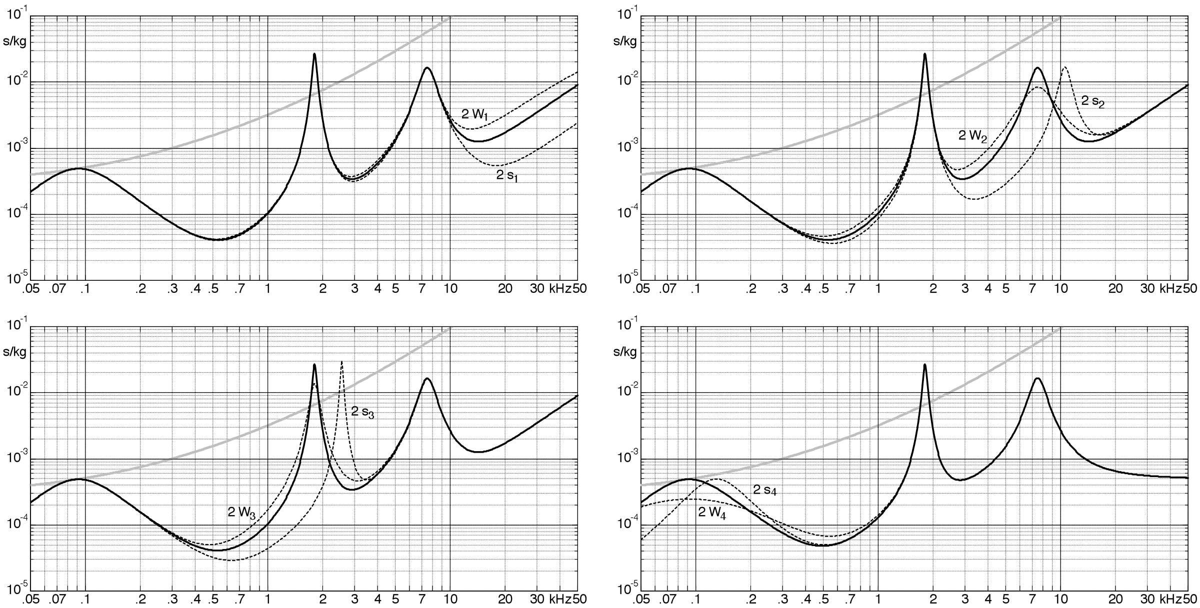


Fig. 7.101: Input conductance of the system according to Fig. 7.100; variation of the system parameters. The grey line is the “orientation curve” recalculated from Fig. 7.66 (E2; esp. radiation damping and inner damping).

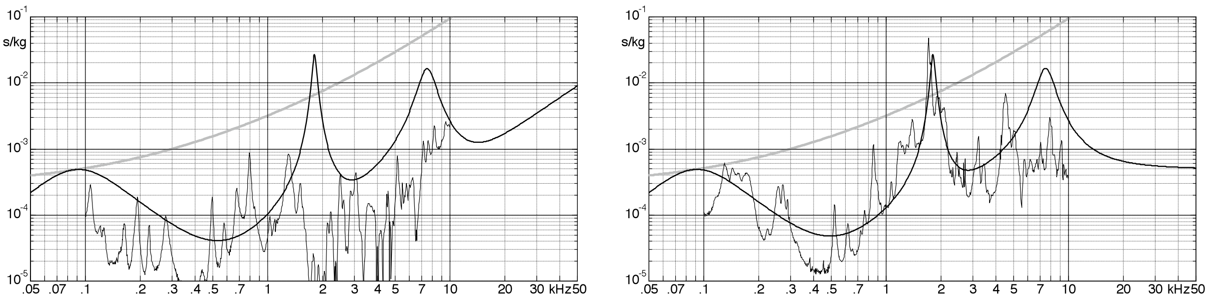


Fig. 7.102: Conductance measurements (thin line); left: Les Paul body, right: Les Paul bridge.

For comparison, **Fig. 7.102** shows the related measurements. While the multitude of highly different resonances can of course not be modeled with such a simple equivalent-circuit approach, the order of magnitude fits well. It is in any case conceivable how the addition of further resonators enables the model to also represent narrow peaks in the frequency response of the conductance (**Fig. 7.103**).

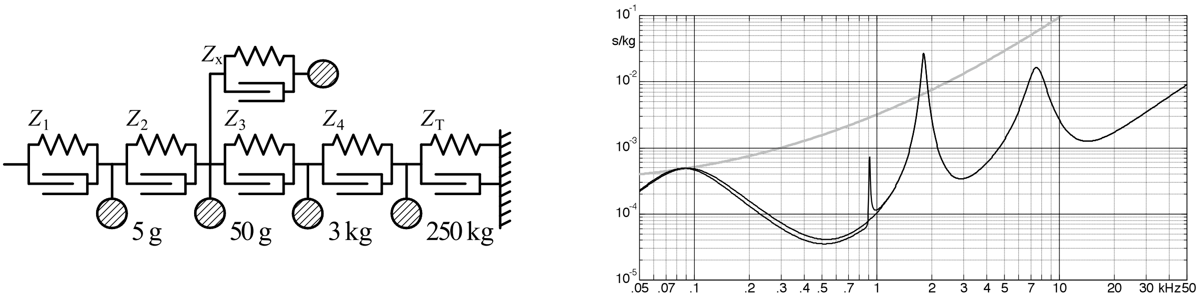


Fig. 7.103: Additional resonance circuit (Z_X), effect on the frequency response of the conductance.

The equivalent circuit shown in Fig. 7.100 is no complete model of a guitar – it does not even begin to represent the multitude of body- and bridge-resonances. These resonances may not only occur as one-dimensional vibrations (as contained in the model), but can take on the shape of three-dimensional flexural vibrations, in combination with torsion-vibrations. Still, the model allows for estimating the approximate orders of magnitude of the stiffnesses and frictional resistances, and of the approximate effect the latter two have on the bridge resonance. It is obvious that this resonance can influence the decay of all partials und thus the **sustain**. However, if the bridge conductance is small (e.g. 10^{-4} s/kg), then the bridge and everything that is mounted to it (including the guitar body) has practically no effect on the sustain! The measurement curve shown in the right section of Fig. 7.102 crosses the grey line only twice: between 100 Hz and 200 Hz, and at 1.8 kHz. If a partial falls into one of these ranges, then the absorption at the bridge does influence the decay process. The other resonance peaks may be attributed a theoretical influence ("everything depends on everything"), but they have no practical relevance.

The considerations related to the contact problem have shown that stiffness and resistance strongly depend on the contact pressure force and the contact surface. Both change if the guitar bridge is shifted within the clearances given by manufacturing tolerances. The bridge saddles of a Stratocaster may have contact to each other – or not. The bridge saddles of an ABR-1 may have a burr on their lower surface, they may have contact on one side or on both sides, or they may be clamped down by the set-screw with a force fit. The distribution of forces (and therefore the stiffness) between the 6 screws holding the old Stratocaster bridge is undefined and depends on the smallest of manufacturing tolerances – or on the tear and wear, which does not make things any simpler. Changes in the contact parameters do not necessarily lead to changes in the sound but they are potential sources of damping that need consideration due to their closeness to the string.

The varnish of a solid body guitar, on the other hand, is far removed from the string, and its mass is small. Still, for completeness sake a few citations: *However, practical use has taught us in the past that very sparingly varnished instruments have generated a rounder, more succinct tone [G&B 7/05]. Hairline cracks (in the varnish) lead to an un-damping of the resonating body [G&B 1/06]. The varnish can constrict an instrument and thus dampen it, or it can adapt itself to the natural resonance characteristics and co-resonate [G&B 1/07].* Actually, any beer-belly will do the same ...

7.10.2 Bridges without Vibrato

7.10.2.1 Gibson's ABR-1-Bridge

Orville Gibson was a guitarist and a luthier – characteristics that were not originally natural to Leo Fender, who of course was a builder of guitars, too – but not in the traditional sense. As Tom Mulhern notes in his book on Gibson guitars [Rittor 1996], Orville's ideas often originated from violin making, and it is therefore not surprising that the famous Style O guitar features an arched top that carries merely the bridge but no tailpiece. The strings are anchored in a trapeze tailpiece that is mounted to the end-side of the guitar body. This separation of bridge and tailpiece resurfaces half a century later in the ES-335, although that guitar is based on a very different principle of construction. The top of Orville's acoustic guitars needed to be thin in order to radiate sound. While it was still possible to anchor gut strings in a combined bridge/tailpiece that was glued to the guitar top, this approach became a problem with the steel strings increasingly demanded by musicians: their higher pull (parallel to the top) could warp the top, or rip off the glued-on bridge and destroy the thin top. Conversely, with a tailpiece mounted to the side at the end of the guitar, the top was subjected merely to a perpendicular force it was able to withstand due to its curvature similar to the arch of a bridge.

The bridge of the Gibson Style O is of a single piece and not adjustable – again similar to that of a violin. However, 2-piece bridges soon found their way to the Gibson acoustics, presumably so that the action that increased with age could be compensated for. The 2-piece bridge includes a base and an upper part both made from wood; the 2 sections can be spread apart via screw and curled nut. Starting out from this construction, it is not all that far to Gibson's patented Tune-O-Matic bridge (US patent 2,740,313, filed in 1952), the top part of which carries six individually adjustable bridge saddles. 6 bridge saddles, 6 adjustment screws, one bridge base, 2 post screws, 2 curled nuts, and the fastening wire that arrived later: all in all that's 18 individual pieces. With this bulwark between the string and the guitar body, it is no wonder then that the latter has so little influence on the string vibration. Worse, though: the **joints** occurring between string and guitar body are undefined to a high degree! The T-shaped bridge saddles are positioned within a groove to which they have contact in some kind of way. The contact between bridge and the curled nuts is not defined, either, and consequently it is no surprise that the mechanical characteristics change as we lightly press against the bridge. Still, the contraption does work – in fact some masterful guitar playing happens using it. A word, however, to all you Gibsophiles ecstatically dancing around every golden calf-o'-1956: before pondering about the woods, you should target the bridge, beginning with the question which way round the bridge should be mounted. On most of the guitars shown in the Gibson book, the heads of the setscrews point to the pickups, but for quite a few, they point to the tailpiece. Indeed, the screwdriver access is easier in the latter case, but now the strings run across the screw heads! These are the residual strings between bridge and tailpiece; they may contribute to the vibration absorption, as shown in Chapter 7.7.4. Thus: it may not be the hairline cracks in the varnish that *"are of highest significance to the resulting sound [G&B 2/07]"* – rather, the bridge may contribute much more.

The strings excite the bridge saddles (T-shaped when seen from the tailpiece, and of monopitch-roof shape seen from the side) to vibrate – the saddles should resist this excitation so as to keep the vibration energy within the string as much as possible. The force fed from string to bridge saddle splits up into an inertia force (to accelerate the mass), and a remaining force that is conducted on to the bridge base. Between bridge base and bridge saddle there are several joints the mechanical impedance of which is of significance to the string vibration. Therefore, requirements regarding the manufacturing tolerances of these components would be very high. That formulation should be agreeable even to laywers, shouldn't it?

If there were any burrs on the Gibson bridge (with "were" expressing purely hypothetically a possibility), the setscrew in its end position would lever the bridge saddle halfway out of its embedment, and the bridge-base/bridge-piece impedance would drastically change. Where in fact does the line of force-flux between string and guitar body run for this bridge? **Fig. 7.104** shows several views of the Gibson ABR-1. A bridge saddle (T-shaped or of the shape of a monopitch roof depending on the view angle) is movable within a groove via a setscrew, with the string (secured in a small groove) resting on the saddle. On what does the latter rest?

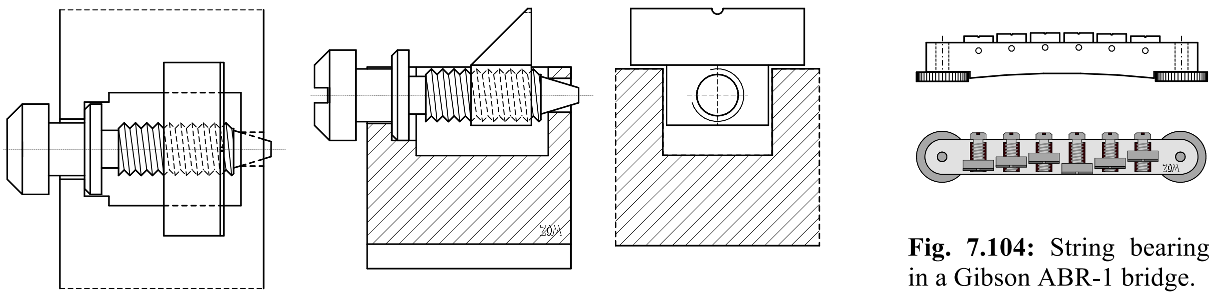


Fig. 7.104: String bearing in a Gibson ABR-1 bridge.

Since the middle section of the "T" does not reach to the bottom of the groove, we could surmise that the bridge saddle rests directly on the sidewalls of the bridge. That, however, is not the case – not for the Historic Les Paul under scrutiny, anyway, nor for the ES-335 from the 1960's. Every introductory course for mechanical engineering includes the lesson that objects not supposed to move need to be fixated with regard to three translational and three rotational movements. **Translational movements** are longitudinal movements (in the direction of the string-axis z), lateral shifts (x) and changes in height (y). In the z-direction, only the setscrew can absorb any forces – but it does so with some slack. Pressing the bridge saddle to the right (in the figure), the conical screw-termination has contact, pressing it to the left, it is the chamfered collar that stops the movement. Possibly, the whole setup was at some point meant to remain under tension and therefore be without slack – the implementation ain't, though. For the y-direction, it is immediately clear that either the screw, or the lower side of the T-piece can transfer any pressure force from the strings, but not both (dividing the force would be at random and fragile). If the bridge saddle rests on the bridge, the setscrew has slack, and if the setscrew absorbs the force, the bridge saddle has slack. Purely theoretically, we could consider of shift-fitting or pressure-fitting – but only those without any experience in production of mechanical elements will go there. No, that T-shaped saddle has slack, resting somewhere on something, depending on production tolerances (**Fig. 7.105**).

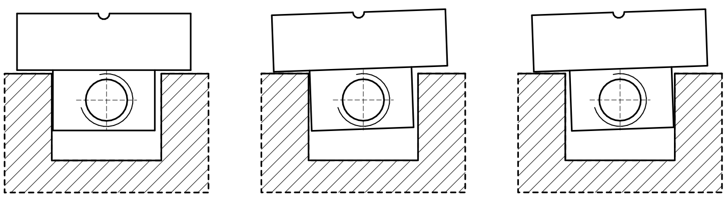


Fig. 7.105: Changes in position.

Trying to push a piece of paper in between the T-shaped bridge saddle and the bridge base is met with success, and proves that the two do not rest slack-free on each other. This test does not work everywhere, but at several places. In the worst case, this instability leads to torsion movements – then the string vibration is completely done for. Dear Mr. McCarty (rip), how was that supposed to work? String movements in parallel to the fretboard imply torsion excitation – anyone disagreeing? The sales speak for themselves? Ah – sorry, that explains everything. We can hope that the whole contraption somehow gets wedged or rusts shut (and for many guitars that will in fact happen) – a planned force-fit looks different, though.

For Fig. 7-100, the interface between bridge saddle and bridge base had been modeled with $\underline{Z}_2$, and Fig. 7.101 shows the effects of variations. That changes in stiffness and damping occur only in the high-frequency range might explain why this bridge in not entirely impractical. As long as the bridge-piece-T rests (or is in firm contact) somewhere, and as long as it is not subject to any torsion movement, any audible effects keep within reasonable limits. However, if any gaps resulting from manufacturing tolerances allow for a twisting motion, the bridge-T will wipe out string vibrations. This *"epoch-making bridge" "was not designed for solid body guitars like the Les Paul models [Berger / Perrius]"*, but for acoustic (!) arch-top guitars – which renders the whole thing even more problematic, because these guitars should be able to reproduce high-frequency partials as well, shouldn't they? Anyway, around 1954, this contraption-of-the-century found its way onto the Les Paul Custom, and from then on there was no holding back any more – in the true sense of the term.

The force introduced by the string to the bridge saddle (as far as it does not serve to move mass) is handed over via undefined paths to the bridge base that, true to its name, crosses the distance from one "shore" to the other. To the mechanical engineer, the arrangement is a **cantilever** supported on both ends. The lowest Eigen-frequency of this cantilever can be calculated using area moment of inertia, geometry of the cantilever, E-modulus and density; it turns out to be 1.6 kHz. Although the bridge has immobile support at both its ends (bearings), it can still vibrate in between; and if it receives excitation to do that, it will dampen the string vibration. Unfortunately, it does receive this excitation, and it is just that string delivering it that should be given an immobile bearing by the bridge. In order to not just theoretically calculate this friendliness towards vibration, measurements were taken with an ABR-1 bridge positioned on a stone table (**Fig. 7.106**). At 1.6 kHz, the conductance rises to almost 0.2 s/kg, reducing the degree of reflection for the E_2-string to below 60%. This means that more than 40% of the vibration energy is absorbed for each reflection! We should not universally condemn such a behavior because only the effect of absorption will enable the luthier to individually influence the string vibration; however, if this was supposed to emerge as McCarty-specific, then this absorption would have to be of a fixed value for all guitars of the same build. That, however, is not the case, since already a slight shift of the bridge (which on top of everything is adjustable in height, as well) changes its damping parameters.

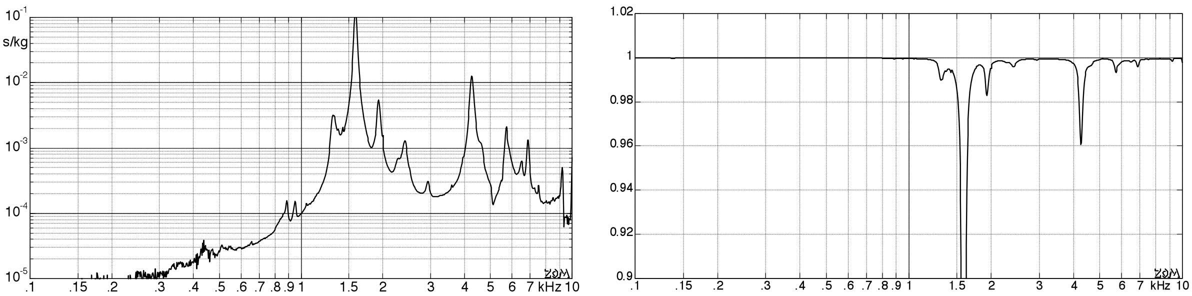


Fig. 7.106: Conductance (left) and reflection coefficient (power) of the ABR-1 positioned on the stone table.

The measurements related to Fig. 7.106 were done with an ABR-1 bridge that was positioned via two knurled nuts directly on a stone table. On the Les Paul, the two disc-shaped knurled nuts conduct the bridge-force to two threaded posts that protrude perpendicularly out of the guitar body. The mechanical input impedance ($\underline{Z}_3$ in Fig. 7.100♣) between bridge and knurled nut depends on the surface quality (burrs!), and on the angle between bridge and post; when adjusting the bridge height, the contact surface changes, and with it stiffness and damping, and thus also frequency and Q-factor of the resonance.

♣ Fig. 7.100 models the bridge as a discrete mass and does not (yet) consider any Eigen-modes.

As an example for differences related to manufacturing tolerances, the decay times for partials were analyzed for a Gibson ES-335 (new strings, **Fig. 7.107**). This semi-hollowbody guitar dating from 1968 sports the bridge shown in Fig. 7.104, across which the strings run to a trapeze tailpiece. The guitar must not be blamed for showing a few minima in the decay times – a bit of individuality certainly is okay. That the decay times change as **the bridge** is **shifted** by one or two 10th's of a millimeter – that's owed to the adjustability. The decay curves will again change somewhat as one seeks to correct a slightly-off intonation with the **bridge-piece screws**. Guitar gurus, near and far, you who claim to hear with your golden ears the smallest detail in the wood-composition, you who even put your guitars in the freezer to get a few more cracks in the varnish so that the guitar body at last is "freed to vibrate" and the sound "blossoms", do see the signs: the one who, in "specialist" magazines, every month propagates bullshit, may finally drown in the same.

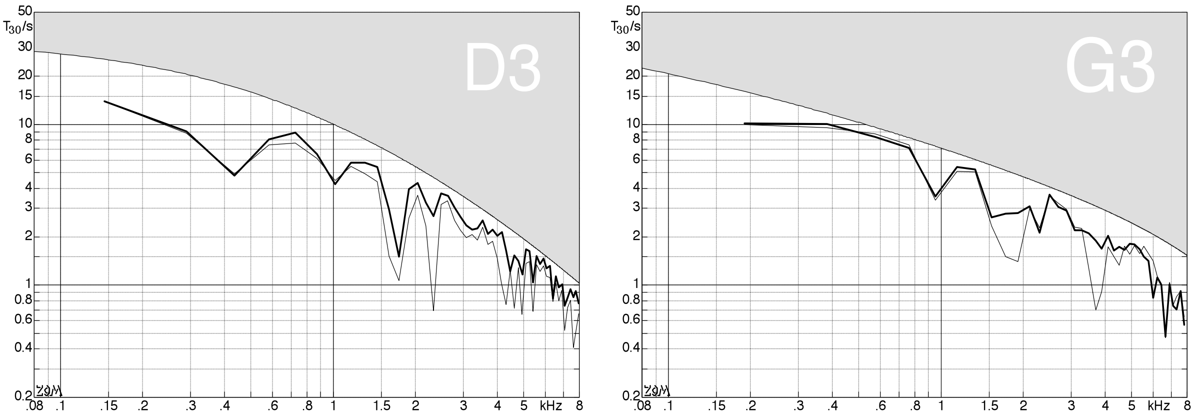


Fig. 7.107: Decay times of partials, ES-335; bridge shifted within the scope of manufacturing clearances. The grey area indicates the theoretical maximum T_{30}-decay due to internal & radiation damping (Chapter 7.7.2).

Since Gibson's ABR-1 bridge is height adjustable, it has some horizontal clearance, as well. Shifting the bridge within the scope of this bearing clearance changes bearing and damping parameters. Still, there was not much attention paid to this sensitive contact surface: in the Gibson bridge shown in **Fig. 7.108**, two burrs influence the surface between bridge and the knurled nut below it; these burrs co-determine the contact stiffness. To vindicate Gibson, it may be noted that not all bridges show such a dismal production quality. However, even a specimen bought for much money in 2010 had not ever come into any contact with a deburrer. That can only lead to the assumption that Gibson does not attribute much significance to this contact point. That, however, makes the little damping peaks that the guitar body itself generates finally loose all relevance. The holy wood, with all the entwined myths – can it be nothing but hype? Yes, it may and must be seen that way, because why would Gibson manufacture the most important link between string and the "holy grail" so sloppily, so wobbly, so unreliably, if the guitar body were important at all? What remains is the insight that while all those little peaks can be measured, they barely have any influence on the sound. That's irrespective of whether they result from the sloppily manufactured burr, or from the wood seasoned for decades. Goof rules.

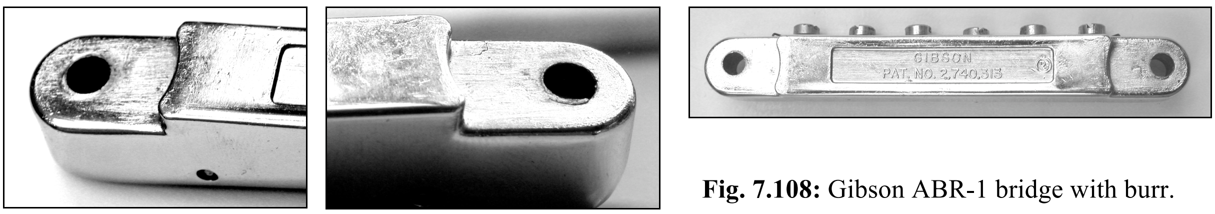


Fig. 7.108: Gibson ABR-1 bridge with burr.

The belief in the Holy Grail is deep-seated – deep enough that instructions for a conversion are found in G&B 6/2010 that are supposed to turn a "halfway" Holy Grail into a "real" one: a '**52 Goldtop** into a '**59 Les Paul**. Too bad, though, that due the rather special neck angle, the ABR-1 bridge does not fit. Therefore a band sander (**Fig. 7.109**) is called into action … which is a physically correct step if the focus is merely on the playability.

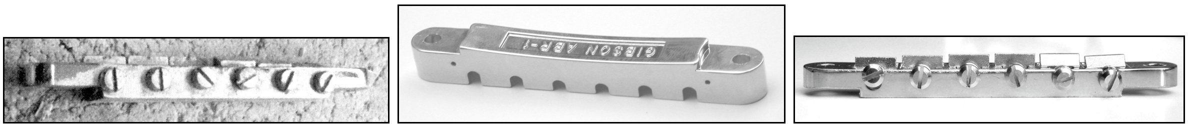


Fig. 7.109: ABR-1. Left the model from G&B 6/2010, center/right the copy pre/post milling.

Playability, however, is not the only aim of the conversion: *in the end the golden one is supposed to sound like a 1959 Les Paul*. The same sound – although its sanctum, the link between strings and wood, has been brutally abused with a belt sander? Let us take a look at the conductance of an original ABR-1 bridge (**Fig. 7.110**) – not the specimen analyzed in Fig. 7.110 but the one bought in 2010. Since professional tooling was available, the bridge was not "minimized" with a belt-sander, but via a high-tech milling machine. The rigorous thinning-out reduces the mass and in particular the stiffness such that the main resonance finally comes down from 1400 to 850 Hz. This gives rise to the question whether a guitar fitted with this bridge can ever sound like one fitted with a bridge developing its maximum genuine absorption at about 1500 Hz?

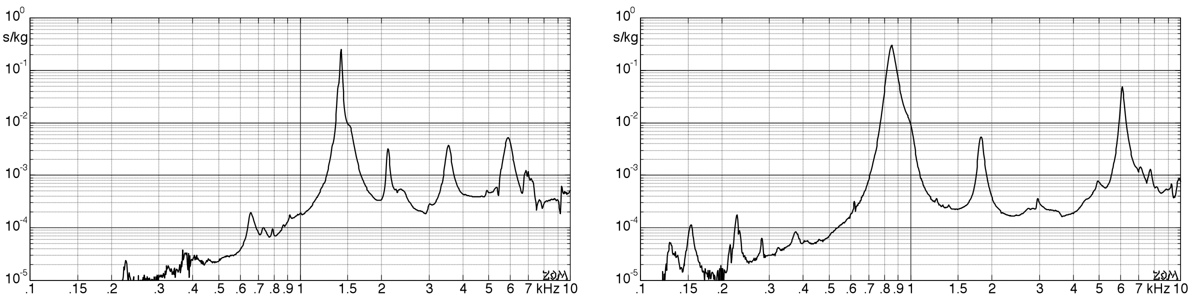


Fig. 7.110: conductance of the ABR-1 bridge; original condition (left), after milling (right). Stone table; knurled screws; bridge without bridge saddles; measuring point between the D- and G-guide-slots.

The alterations described in G&B were performed by a well-known and well-respected luthier having many years of experience under his belt, and therefore we are not willing to simply discard his evaluation ("*same sound*") as unqualified – there must be something to it. And so the only conclusion can be: if such big differences in the absorption have next to no effect on the subjectively perceived sound, then the body wood (with much lower conductance values) has even much less influence. It may be emphasized again and again by some that this Holy Grail *cannot be topped in view of the length of time it has had for being played-in (56 or 57 years)*, but the reasons for that must reside rather more in the metaphysical realm. Which is where a grail is best kept, anyway.

Fig. 7.110 documents the changes in conductance caused by the milling. It is obvious that the decay times of the partials will be influenced, as well, but proper proof is still required. Both variants of the bridge were therefore tested on a **Les Paul** (R9), with the decay times of the partials of the D- and G-string being analyzed for the original bridge and the milled bridge.

Fig. 7.111 shows the corresponding results. Since the bridges are not positioned on a stone table anymore but reside, as intended, on a guitar, the resonance peaks measured in Fig. 7.110 shift a bit. Moreover, the manufacturing tolerances of the bridge saddles come into play now, and these are (benevolently speaking) of an abysmal quality. Three of the bridge saddles fall off if the retaining wire is removed while the other three are so stuck that they can hardly be moved at all via the adjustment screws. This was not an effect of the milling process but the original condition of the bridge. Whatever, after the measurements are concluded, this piece of junk will be discarded anyway. What remains as a result: the main resonance – having shifted to 850 Hz – will clearly cause shorter decay times of the partials in that frequency range for both strings … which apparently does not harm the rating "*same sound"*, though. This implies that the instructions to modify the guitar hold a contradiction: if the minimal influence that the "holy" wood has on the string vibrations is taken to be crucial, then the differences caused by the modifications in the bridge needs to be held as existential feat, and there should be no talk at all that here the '59-sound has been created (*simply put, this is the Holy Grail, G&B 8/2010*). If, on the other hand, the bridge resonances are taken to be of insignificant effect, then the microscopic effect of the wood should be assumed to be irrelevant. In that case, however, any plank from the DIY-store would have sufficed, too ...

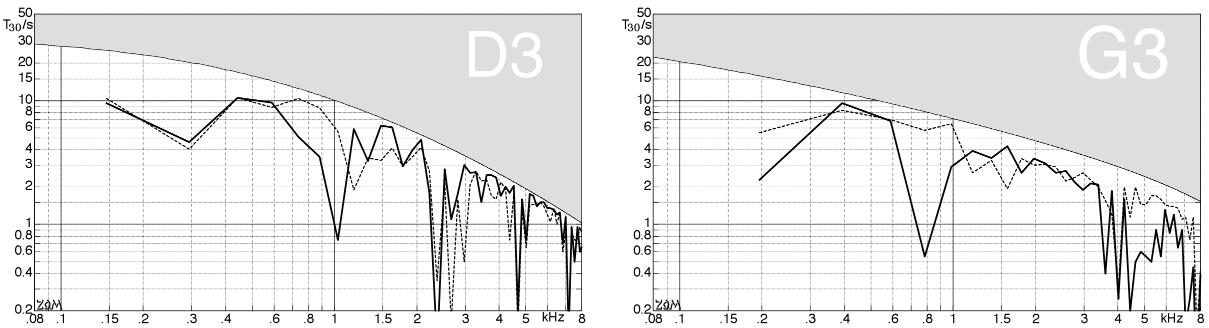


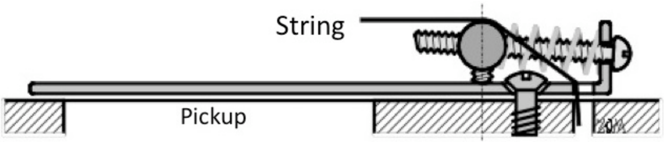
Fig. 7.111: Les Paul R9, decay times of the partials. Original bridge (---), milled bridge (——).
The grey area indicates the theoretical maximum T_{30}-decay due to internal & radiation damping (Chapter 7.7.2).

Of course, a recurring thought has been "it's all in the fingers", and so we can indeed just use the guitar according to its purpose: to be played. Yes, that is possible on most guitars, irrespective of where exactly the bridge is positioned.

After so much theory, how about a bit of some more "specialist press"? Here we go (all statements made by one and the same author): *Kluson machine heads are also very lightweight. The small mass can be easily excited to vibrate but it decays all the more quickly. Theoretically, that would mean that Kluson machine heads give less sustain [G&B 8/05]. Small changes in the height of the stop-tailpiece in part drastically change the sound (of the Les Paul) [G&B 7/05]. Machine heads (about $ 1200) and stop-tailpiece (about $ 2000) had only very little influence on the sound (of the Les Paul)[G&B 2/07]. Of course, build and material (of the stop-tailpiece) have an important influence on the vibration transmission to the body [G&B 7/05]. Hard to believe that simply swapping the machine heads (on the Les Paul) could lead to such (sound-) changes. [G&B 8/05]. Sometimes, I find it inappropriate how self-proclaimed equipment-missionaries roam about seeking to convert everyone to the true belief [G&B 8/07].*

7.10.2.2 Leo Fender's Telecaster

The Telecaster was Leo Fender's first "true" electric guitar. To start with, it was designated Esquire, then Broadcaster, and finally Telecaster [Duchossoir]. According to Fender's patent application US 2,573,254, the string length was to be individually adjustable – but that is only possible in pairs of two: two strings have to share a cylindrical bridge saddle (**Fig. 7.112**). Compared to the non-adjustable bridges customary until then, that definitely represented an improvement although it still was a compromise. Fender however already points to a further development: the bridge saddles are drilled through at an angle. Each of the three bridge saddles may be adjusted in height using two setscrews, and a long tensioning screw takes care of the intonation adjustment. A thick steel plate anchored with 4 large bolts in the guitar body serves as a base for the setscrews and the tensioning screws. The strings run across the bridge saddles through the guitar body to fastening bushings mounted from the rear of the body.



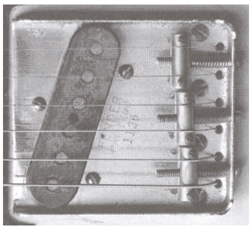


Fig. 7.112: The Telecaster bridge. [Duchossoir]

What has been said in Chapter 7.10.1 holds for the setscrews and tensioning screws – their transmission stiffness depends on contact surfaces and forces. In principle, this bridge does work. It may, however, develop an idiosyncrasy that helps this guitar to achieve a special status: the steel plate rests in an undefined manner on the guitar body, and its resonances (Eigen-modes) may re-act on the strings – not necessarily, but possibly. Using a hard nonmagnetic item to knock on the upward-bent flanks of the plate, we hear a clicking noise coming out of the amp/speaker. The **sheet metal** is not comprehensively damped by the body wood below it, but can resonate with its **natural frequencies** at a high Q-factor. Mechanical reactions from sheet metal to bridge saddles are possible, and – given steel as material – also inductive coupling to the bridge pickup. Generally, the sheet metal is electrically conductive and thus a place where **eddy currents** circling the pickup may roam (Chapter 9.5).

The necessity to make the string action **adjustable** was not only connected to the drive of all guitar players to make each new guitar "playable" according to one's own ideas. It was also unavoidable in view of the separation of guitar body and (bolt-on) neck into two individual production entities each subject to manufacturing tolerances. From Duchossior's close-up pictures it can be seen that these adjustment possibilities were indeed put to use, and that the bend-angles that the strings form as they run across the bridge saddles are specific for each individual guitar (they are string-specific in any case). However, this means that the vibration characteristics of the bridge are specific to each individual guitar, too.

Fig. 7.113 shows the decomposition of forces at the bridge saddle. The string-tension force Ψ is almost the same on both sides of the bearing cylinder (bridge saddle), and the frictional force may be neglected in a first approximation. The force F acting towards the lower left has two components. The setscrew just resting on the surface below can only take on the vertical component F_y; the horizontal component F_x is taken care of by the tension screw. Nevertheless, Fender's patent application shows a set screw mounted at an angle (Fig. 7.113)

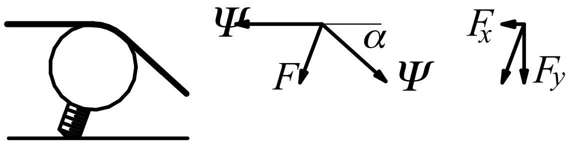


Fig. 7.113: String with bearing cylinder (left), force resulting from the string forces (center), decomposition of the resulting force in horizontal and vertical component (right).

We shouldn't expect too much here: *"Leo Fender was an ingenious, resourceful technician, but – as it is frequently reported – he had not even had formal training as an engineer, and he certainly was not a guitarist – couldn't even tune the instrument" [G&B Fender special edition]*. Duchossoir's citation is even more merciless: *"Leo had a knack of thinking slowly and consecutively – no flashes of genius – a merciless unstoppable slow degree of thinking [Tavares]."* At some point, the angled screws raised some eyebrows, and one day they stood upright (Fig. 7.112). More specifically: in the patent application [USPTO.gov], the angle between setscrew and tension screw amounts to 70°, in later bridges it is 90°. What is better?

The mechanical engineer would probably prefer the setscrew perpendicularly positioned on the base plate, because it can transmit only vertical forces in any case (horizontally, only small frictional forces remain). With the screw positioned at an angle, a bending moment results that loads cylinder and tension screw flexurally, while with a perpendicular setscrew there is merely a tensile force acting on the tension screw. What in fact prohibits sideways motion of the latter? This would be a motion within a borehole in which – according to the patent publication – the screw should be borne *"sufficiently loosely"*! An additional brace could make for more stability but the effect would probably not be very dramatic. Also, an axial force applied to a setscrew could possibly readjust the screw over time – therefore the perpendicularly oriented screw may offer slight advantages. These are, however, untried speculations for which no additional experiments were done. With

$$F = 2\Psi \cdot \sin(\alpha/2), \qquad F_x = \Psi \cdot (1-\cos\alpha), \qquad F_y = \Psi \cdot \sin\alpha,$$

we can see the angle dependency of the forces; the bend-angle of the strings α amounts to about 25° to 50°. The tension screw has the sizeable length of 32 mm – apparently indeed necessary to allow for a sufficient adjustment range. With Ψ = 50 N (certainly possible for thin strings), F_x amounts to a minimum of 4.7 N, and F_y amounts to a minimum of 21 N♣. For heavy strings, F_x = 50 N and F_y = 100 N are possible, as well. That is quite a respectable degree of variability in the compression force, and correspondingly large will be the **differences** in the contact-stiffnesses and –impedances. Which tilting, rotating or wobbling motions the bridge saddle will be subjected to under real deployment conditions cannot be anticipated with a general consideration – the conditions vary too much. The offset-force acting on the setscrew presumably is so strong that this screw can a priori not be suspected as a "vibration killer". A longitudinal force of merely 4.7 N is scant, but then there are 2 strings pulling at one screw. Within the string, however, also longitudinal vibrations appear (dilatational waves) that could excite the bridge saddle to rotational vibrations. In that case, too, much slack between the screw and the bridge saddle would be counterproductive.

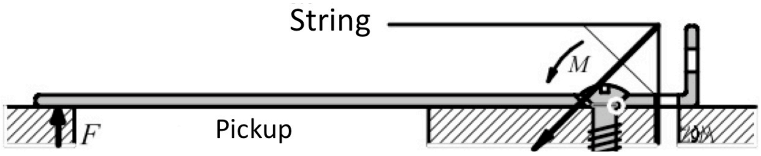


Fig. 7.114: Forces on the guitar body

The interface from the base plate to the guitar body is shown in **Fig. 7.114**. The sum of the two string forces generates a resulting force pointing towards the lower left, just missing the wood screw and thus resulting in a torque around the bearing point (circle). The main share of the retention force occurs at the screw; in order to compensate for the torque, a supplementary force F is necessary (here sketched in arbitrarily).

♣ A mass of 1 kg generates a weight force of 9.8 N (1 N = 1 Newton → 102 Gramm).

Where exactly which forces act cannot be specified, because how the bridge rests on the body wood remains undefined: this depends i.a. on the curvature of both components and materials. The torque designated with *M* rises with increasing string diameter and increasing string height (distance between string and base plate). If there is (at *F* in Fig. 7.114) a tiny gap left of the pickup, half of the base plate is suspended in mid-air … opening un-dreamt of possibilities of vibration.

Also undefined is which of the four wood screws bears the main load – they just somehow share the retention forces. If the guitar body as a vibrating system were to be coupled in a defined manner to the bridge (or the bridge to the body), a completely different design would be required. No, this ain't no sound-design – it was simply a matter of bolting a base plate to a wooden board – over and done! As **Fig. 7.115** shows, the arrangement can in fact work pretty decently: here we see the decay times of the partials compared to the situation with a Stratocaster. Both guitars were measured with brand-new strings, although the diameters were not completely the same (Tele: 009 – 046, Strat 010 – 046). For the Tele, the decay is slightly faster, and it depends a bit more on the frequency. Before anyone starts to derive the general verdict that a Tele would have a shorter sustain than a Strat, let's be reminded that what we have here are individual results, measured merely with one single representative of its species♣.

Note: in Fig. 7.116, the grey area indicates the theoretical maximum T_{30}-decay due to internal & radiation damping (Chapter 7.7.2).

If we would want to extract **Telecaster-typical characteristics**, we would first have to define what a typical Telecaster in fact is: over the decades, Fender changed the headstock, the neck, the body, the pickups, the bridge – it was only the body shape that approximately remained the same: consequently, there is not "the" Telecaster. For most variants, the bridge does have the base plate of about 85x74 mm^2, but differences start already with the bearing-cylinders: thick, thin, made from brass, or from steel, with/without groove, with/without thread. From the 1970s on there is also a version with small or large Strat-like individual bridge saddles, or even a pure-bred Stratocaster bridge. Telecaster-typical remains apparently merely the body shape but that has next to no influence on the sound. Even if we limit ourselves to the single-coil-fitted original type, we find a multitude of different variants: 250-kΩ- or 1-MΩ-pot, bridge pickup impedances between 5.5 – 11 kΩ, (complete) solid body or (half the weight) Thinline body, bolt-on neck, tilt-neck, set neck [more info in Duchossoir]. If the pickup cover is the secret of the neck pickup, why then does Fender include a different pickup in the Thinline-Telecaster (2nd version), the Tele Plus, the Elite Telecaster, the Telecaster Deluxe and the Custom-II? Why are there also Lace and Seymour Duncan variants on top of the Fender version? Presumably, that is so that each guitarist can realize his/her personal idea of the Telecaster sound.

In http://www.tdpri.com/forum/telecaster-discussion-forum/77808-new-body-material-build-w-sound-clip.html, Terry Downs presents his new guitar, and lets the congregations of fans guess which material the body is made from. Everybody enthuses about the sound, and conjecture includes: oak, masonite, teak, cork, semi-hollow-body, synthetic counter top material, soy, hedge apple tree, and others – most guesses meant seriously. In fact, it was three medium density fiberboards that were bolted on top of each other – that's it. Result: *Sounds like a Tele* – what else.

♣ The multitude of limitations in the framework of university operations unfortunately does not make more comprehensive investigations possible.

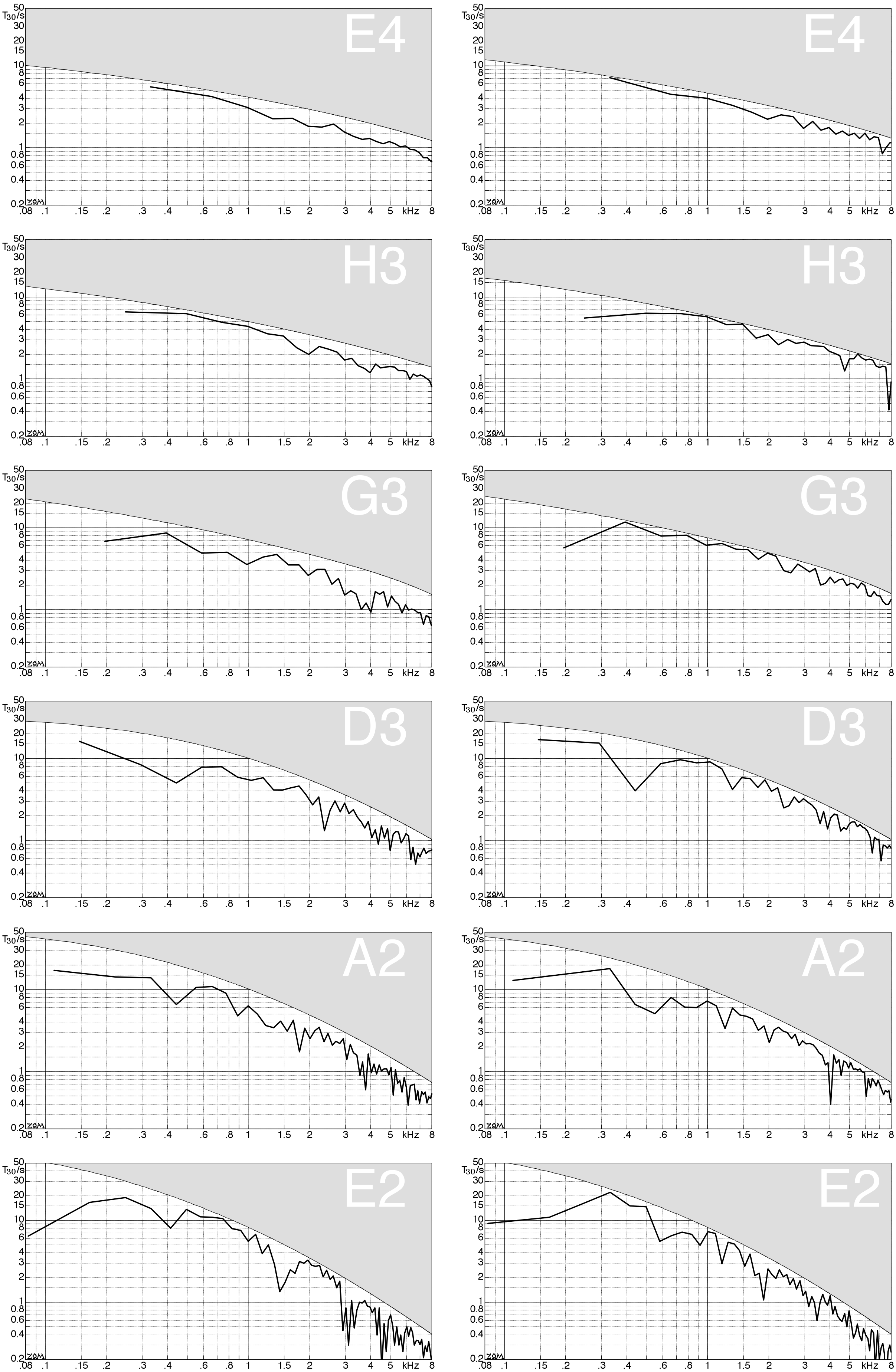
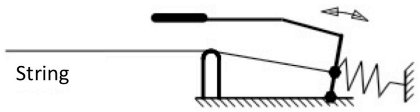


Fig. 7.115: Decay times of partials, Tele (009/046 set, left), Strat (010/046 set, right). “H3” = B(-string).

7.10.3 Bridges with vibrato

A precursor to the electric (spanish) guitar was the steel guitar (lap steel). Its notes can be generated at any arbitrary pitch without the discretization forced due to frets. This feature was attractive to the country musicians (and/or their audience), and it was offered by Bigsby, Kaufmann, Fender, and Co., by mounting vibrato- (or tremolo-) systems on their first electric guitars. These gentlemen could not have had any inkling that years later someone would use the device to interpret the "Star Spangled Banner" in quite a peculiar way, and even less of a foreboding that somebody else would at some point measure bridge conductances – they were fully absorbed in inventing a bridge that at the same time was steadfast and moveable … steadfast regarding the string vibrations, and moveable to achieve the "tremolo♣".

To change the string pitch in a continuous manner, the tension force Ψ of the string needs to be changed; this is done via changing the strain (i.e. the length). Accordingly, the tailpiece has a moveable, resilient bearing: pressing (or raising) the vibrato lever changes the string bearing and thus the strain (**Fig. 7.117**.



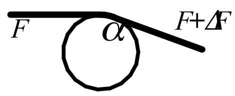


Fig. 7.117: Vibrato-system

The basic problem of all vibrato systems is the tuning instability caused by inevitable frictional forces. Pulling the vibrato level upwards and releasing it leads to a different tuning compared to pushing it down and releasing it. The friction forces are not particularly strong, but to achieve a pitch error of less than 5 cents, the frequency would have to be correct by 0.3%. In vibration engineering, we like to work with friction forces that are proportional to the particle velocity, because they allow for setting up linear systems. However, reality has in store also the Coulomb friction, and that is of non-linear character. For the **Coulomb friction**, the friction force depends solely on the normal force and the friction coefficient μ, but not on the particle velocity. There is, however, a distinction in the friction coefficient between static friction and dynamic friction; as such the coefficient is movement-dependent, after all – but rather in a non-linear fashion.

If the string runs around a fixed cylinder with an encirclement-angle α, the two tensile forces differ by $\Delta F = F\left(\exp(\mu\alpha) - 1\right)$. Pulling to the right (in the figure), the right-hand force is (at the max) larger by this value; pulling to the left, the left-hand force is. In conjunction with the radius of the cylinder, this force difference generates the friction torque $M = \Delta F \cdot R$, which is absorbed by the bridge. The friction is only small if the cylinder can rotate – but easily rotatable, loose rollers do not make for an ideal guitar bridge. As an alternative, bridges with a knife-edge or point bearing have been invented, but these can also only work properly if all strings have the same distance to the axis. That, however, is not the case if the bridge is set on top of the guitar body. It is the case approximately, if the pivot is moved into the guitar body. If the residual string (from bridge to the tailpiece) is long, and if the bend-angle is small (such as it is on the Jazzmaster), again other problems result – it's simply not an easy job. In the end, some creative thinking indeed led to usable results, as long as the involved guitarist limited him/herself to moderate pitch changes. For those operating with brute force, further developments came later, such as the clamped-string approach.

♣ Kauffman and Fender designated the frequency vibrato with the (not really correct) term "Tremolo"

7.10.3.1 Fender's Stratocaster vibrato (aka tremolo)

On August 19, 1929 – when few people were thinking about electric guitars – Clayton Kauffman filed for a patent under the title *"apparatus for producing tremolo effects"* (US 1,839,395). According to it, a spring-loaded, movable tailpiece enabled the change in pitch, *"so as to produce a tremolo effect"*. Indeed, it was this "Doc" Kauffman who later was Leo Fender's business partner for a short time in the jointly operated K&F company, before Fender started his "Fender Electric Instrument Company" in 1946 [Duchossoir]. The latter's first electric guitar, the Esquire, successfully entered the market around 1952, and then had weathered the metamorphosis into the Telecaster. Time was right for the release of a further guitar: *"We didn't invent the tremolo thing. It had been used on many other instruments, but we wanted it because it seemed to be very saleable [Tavares]"*. On August 30, 1954, Leo Fender filed for a patent for the **Stratocaster** (US 2,741,146), an electric guitar with a *"synchronized tremolo"*. Duchossoir describes the first experiments: *"the first vibrato designed by Leo Fender was, by all accounts, fairly similar to the unit later installed on the Jazzmaster guitar released in June 1958. It allowed some string length between the bridge and the tailpiece, were the strings were anchored. This early version was fitted with individual roller bearings, meant to facilitate return to pitch, but in fact they were damping the string sustain because of too much lateral vibration. It would also appear that the steel rod used as a tailpiece did not anchor the strings firmly enough and their energy was dissipating to the detriment of tone and sustain."* Leo Fender comments: *"We had to chunk the whole thing and completely retool"*. And: *"With a string, you can't have vibration in any direction at the bridge, it's got to be as solid as the Rock of Gibraltar"*. This is stated by Leo Fender (bookkeeper by education), and darn is he on target. It's a different story that as late as 2005, the "experts" at Gitarre & Bass opine that *the largest part of the string vibration should be fed to the body.*

In order to keep bridge and tailpiece from developing too much of a life of their own, Fender combines both into a single unit supported on knife edges – that was the groundbreaking idea. Why he deviates again from it in the Jazzmaster remains Fender's secret. **Fig. 7.118** shows a cross-section through the Stratocaster vibrato. The strings run across adjustable bridge saddles to a so-called "sustain block" fitted with tension springs at its lower side that provide the counter-traction. The L-shaped base plate is held in place by 6 wood screws that are not fully bolted down such that the base plate can easily be tilted upwards. The rotational axis is located between wood screw and slightly countersunk hole in the base plate. The traction force Ψ generated by the strings (at the time about 730 N) causes a torque at the short lever (about 9 mm) that is compensated by 5 tension springs at the long lever (about 42 mm). Today, lighter strings are customary and often only 3 springs are used. Their exact traction force may be adjusted via two tension screws (not shown in the figure). The pronounced bend angle with which the strings run across the bridge saddles causes relatively high contact pressure forces, and any residual damping due to the short residual string section (Chapter 7.7.4.3) is weak. Nothing is perfect, now even this design, but it works well enough that to date Fender has only introduced small changes.

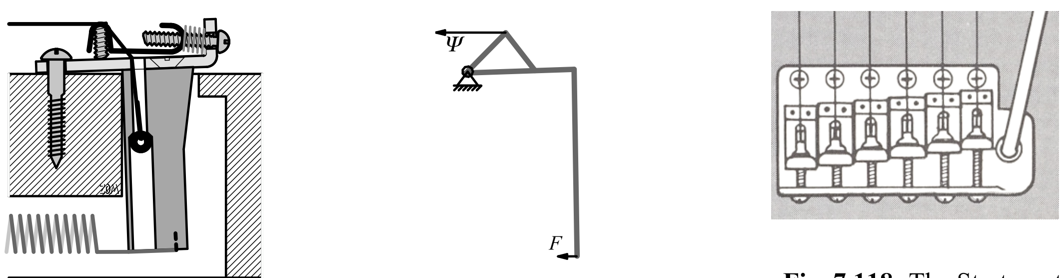


Fig. 7.118: The Stratocaster vibrato.

One of these changes concerned the mounting screws: how does a force distribute itself across 6 screws? In an undefined manner! And so the 6 mounting screws were reduced to two in 1987 for the American Standard Stratocaster, which resulted in a reasonably unambiguous knife-edge bearing, at last. The second change concerned the bridge saddles: originally shaped from sheet metal, they became die-cast cuboids in the 1970's. Not on all models, though: some were still produced with **sheet-metal bridge saddles**. Both versions do work – however, they have their special manufacturing tolerances. Depending on circumstances, every bridge saddle is one of a kind with the 3 screws at each end giving it highly individual contact-stiffnesses and -damping.

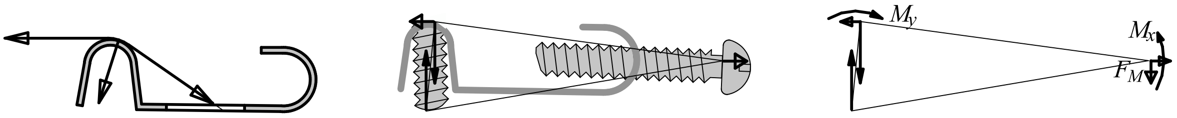


Fig. 7.119: Flux of force in the Stratocaster bridge.

The flux of force in a bridge saddle is shown in **Fig. 7.119**: the bent string exerts a force pointing downward to the left at an angle onto the bridge saddle (compare to Fig. 7.113). Since string diameter, and position and angle of the bridge saddle vary, the amount and the direction of this force vary, as well: its x-component can range from 5 to 35 N, its y-component from 21 to 73 N. The y-component is absorbed by the lower side of the vertical adjustment screw[1], and the x-component is absorbed by the horizontal tension screw. Since, however, the correspondingly parallel forces do not run through the same point, two torques will result – designated M_x and M_y here. As a rule, these torques will not be of the same magnitude which is why the small vertical force F_M needs to additionally act on the tension screws. Given the usual geometry, this force will be directed downward (in the figure) and finds its counterforce (not indicated) at the vertical adjustment screw. The larger F_M is, the more the horizontal tension screw braces itself into the thread of the bridge saddle, and the more this connection becomes solid. Thus: the smaller F_M is, more wobbly the arrangement. F_M becomes small if the string runs across the bridge saddle at a small bend angle. This is, at the same time, the scenario in which the other forces become small and in which only small relative movements – which would remove vibration energy from the string – are possible.

Now, the users of Strats are not exactly know for constantly complaining about un-playability and lack of sustain – for the majority of these guitars, the adjustability of the bridge saddles does not need to be exploited to the limit, and most bridge saddles offer a secure footing to the string. If the bridge saddle is moved back so far that the string experiences another bend at the oblong hole, adequate retention forces can be expected also for light strings. Problems can result only for guitars with such an unfavorable neck fitting that the bridge saddle needs to be positioned at the furthest front end (i.e. the beginning) of the tension screw. Still, when comparing this to the jiggle existing on the Jazzdesaster (Chapter 7.10.3.2), even F_x = 21 N could still be called rock-steady.

When dealing with a vibrato system, the main questions always are: how stable is the tuning, and how large is the possible detuning? In this respect, the Stratocaster vibrato offers an acceptable performance, with some potential for improvement. The effect of the vibrato is, however, not limited to the above main functions, and therefore we will in passing look at some **side-effects**: the tension spring located within the guitar body vibrate close to the bridge pickup and induce electrical voltages, and moreover the sustain block with all the springs constitutes a resonance system.

[1] Friction forces are disregarded for his simplified consideration.

6 steel strings are positioned above the bridge pickup of the Stratocaster, und 5 **steel springs** below it (today, often there may be merely 3 of them). Normally, the steel springs are concealed but that does not keep them from having an inductive effect – and one that is only bearable because they are further away from the pickup than the strings. Each of the springs can adopt longitudinal, transverse, and rotational vibrations, and will do so, too, as soon as strings and/or guitar body are set in motion. Apparently, this latent life of its own is not entirely undesirable but is seen as a kind of Strat-typical **reverb system** (although there are also guitars with the vibrato springs wrapped in a soft cloth to reduce just that effect). A reverb in the usual sense must, however, not be expected because this system features merely a few pronounced resonances. The investigated Strat-specimen (010-gage string set, 3 springs) showed a **47-Hz-resonance** that also prominently manifested itself as a line in the pickup spectrum. This is the Eigen-frequency (natural frequency) of the vibrato arrangement, composed of the stiffness of strings and springs, and (mainly) the mass of the steel block. Eigen-vibrations of the springs appear around **140 Hz**, and at harmonics thereof. The resilient string bearing makes itself felt as selective absorption in the bridge conductance at a frequency range around 500 Hz – however, this effect is not very pronounced.

The following **table** shows orientation values for string tension, string strain, and longitudinal string stiffness, for a 009-set, and for a 010-set of strings. As the vibrato lever is operated, it needs to act against the sum of all string stiffnesses plus the spring stiffnesses.

Diameter	**9**	**11**	**16**	**24**	**32**	**42**	mil
Tension force	59	50	66	75	75	72	N
Strain	4.8	2.7	1.7	3.8	2.4	1.6	mm
Stiffness	12.3	18.5	39	20	31	45	N/mm

Diameter	**12**	**16**	**24**	**32**	**42**	**53**	mil
Tension force	105	105	133	133	130	116	N
Strain	4.8	2.7	1.7	3.8	2.4	1.6	mm
Stiffness	22	39	78	35	54	73	N/mm

Table: String diameter, string tension force, string strain, and longitudinal stiffness of string.

7.10.3.2 Fender's Jazzmaster vibrato (aka. tremolo)

He did give it another try … according to Duchossoir, Leo Fender had already sought the separation of bridge and tailpiece in the Stratocaster, but it did not work out in that first attempt. Once more into the breach, then: in 1958, the Jazzmaster was presented, offering a *"floating tremolo with a floating bridge"* based on a tailpiece-bearing on a knife edge, and a bridge set onto two pins (**Fig. 7.120**). The 6 bridge saddles (short, threaded rods) sat in a u-shaped rail that itself was positioned on two pointed posts. As we operate the vibrato lever (we do call it that, dear Leo, because it is – after all – not a tremolo that we achieve) the strings do not need to slide (with much friction) across bridge saddles, but rather the whole bridge tilts back and forth on the very-low-friction steel points. The inner diameter of the bushing is slightly larger than the diameter of the posts and allows for a shift of the bridge of about ±1 mm. That is enough for moderate pitch changes – they do primarily not depend on the length variation of the string but on the strain variation!

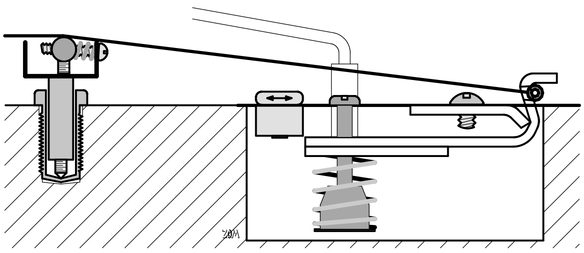


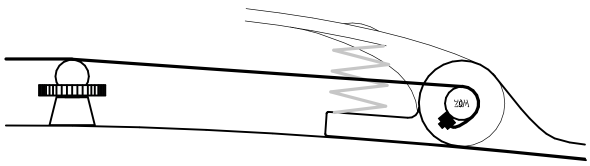
Fig. 7.120: Vibrato system of the Jazzmaster.

The main issue with the Jazzmaster vibrato system is that the strings bend across the bridge saddles with a very the shallow angle (6 – 7°). As late as 1968, 10 years after the introduction of the Jazzmaster, the Fender catalog specifies 012-strings as factory fit; and it was presumably this string gage with which Leo Fender optimized his guitars. For a set of 012-strings, the tension force of the E_4-string amounts to 105 N, for a 009-set it is 59 N, and for a 008-set it is a mere 47 N. This results in a string pressure at the bridge of F_y = 5.2 – 12 N, and a force at each of the two vertical adjustment screws of 2.6 – 6 N (the thinner the string, the smaller the forces become). The longitudinal force resulting from the bend amounts to only F_x = 0.3 – 0.7 N i.e. it is barely existent at all. This force should not be pronounced, too, because it can only be absorbed via the string friction as the bridge "floats". To keep the bridge saddles from longitudinally resting on the bridge in a totally undefined manner, Leo Fender fitted them each with a coil spring – but this generated only a weak tension in the case of the treble strings. For the bass strings, the coil springs got in the way of perfect intonation plus they had to be shortened, presumably killing off many a precision wire cutter.

Maybe this guitar (just like the Jaguar fitted with the same bridge) was reasonably playable with 012-strings, but with the increasingly popular light gauge strings, problems mounted, and the success on the market failed to materialize. Jazz players did not want to change, and all others already had the Stratocaster and the Telecaster if they opted for buying a Fender. Dutifully, the promo-department had exaggerated: *Fender's famous Jaguar guitar is the standard of solid body excellence on today's musical market. This exceptional instrument incorporates Fender features offering playing versatility unmatched by any other.* Well… Hendrix did not burn his Strat at Monterey out of frustration, only to change over to the mentioned "standard" with flying colors, did he? Some sources say that he was seen with a Jazzmaster initially … but only for a short time, and from 1966, the Strat was it for him.

7.10.3.3 Paul Bigsby's vibrato

As some kind of Renaissance man about town, Paul Bigsby repaired and invented devices of all kinds. Around 1947, he also built a few electric guitars (e.g. for Merle Travis). His real claim to fame, however, was his vibrato system that was deployed on many early guitars. The strings were hooked into a rotatable shaft, with the counter-torque being delivered by a spring-loaded lever. Allegedly, it was a spring taken form a Harley – an obvious choice for motorcycle mechanic Bigsby. The vibrato system shown left in **Fig. 7.121** is one from a Gretsch Tennessean built around 1960. Here, the bridge merely consists of a solid metal cylinder that can be adjusted in height via screw and threaded nut – there were however also other bridge designs (aluminum wedge, roller-bridge).



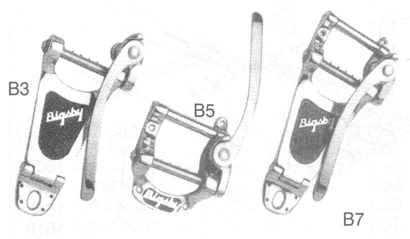


Fig. 7.121: Left: side view of the Bigsby vibrato. Right: different variants [Rockinger Guitars].

The Gretsch Tennessean is a hollow guitar without any sustain block; its thin top cannot take any large forces. Maybe the bend angle of the strings must in fact not be more than 4° (as it showed up on the investigated guitar), maybe more could be allowed … we cannot find out using a non-destructive approach. At least the strings do rest on a solid steel cylinder and not on jittery bridge saddles. For those who like to use thin strings and can do without the rather instable vibrato system: replace the vibrato shaft by a cylinder, drill 6 holes through it and insert the string through the holes. This increases the bend angle, and the bearing forces reach about the value they had with the factory-supplied strings. All that is at your own risk, of course.

For guitars that are able to withstand larger forces on their tops, the Bigsby was (or is) also available with an additional pinch roller increasing the bearing forces but also the disruptive frictional forces (shown on the right of the figure).

The bridge in the form of a cylinder (of a diameter of originally 13 mm, later 9.5 mm) acts as non-linear bearing because the string experiences a shortening as it vibrates *towards* the guitar body. This effect is, however, not strong; compared to a sitar, the cylinder radius is small [Burridge et al. 1982: The sitar string, SIAM J. Appl. Math. 42, 1231 – 1251].

7.10.3.4 The Rickenbacker vibrato

According to GRUHN'S GUIDE TO VINTAGE GUITARS, as early as 1932 an electric Rickenbacker guitar was built with a Kauffmann vibrato – that's 20 years ahead of the Stratocaster, after all. The version described here is, however, not this archetypical guitar but a later variant from the golden 1960's, when the Byrds, the Beatles and the Who helped to create a short period of blossoming of the Rickenbacker tulips. To be specific: it's a model Nr. 335 from 1966. The bridge consists of a u-shaped rail open to the top in which standing "forks" can be shifted back and forth via adjustment screws. In a recess, the forks carry a small roller on which the string rests. The whole thing is tightened up in such a remarkably rigid fashion (at least it is on the investigated guitar) that even the rollers cannot be moved (anymore?). So, is this the perfect bridge? Well, there are 4 screws inserted through the U-shaped rail; they rest on a metal plate (**Fig. 7.122**). With 3 screws, we would achieve a defined bearing but with 4 screws the situation remains undefined. The height of the bridge needs to be very carefully adjusted so that all 4 screws transmit approximately the same force – and then we need to hope that this adjustment never changes again. If we moreover mount heavy strings and take the vibrato arm off …

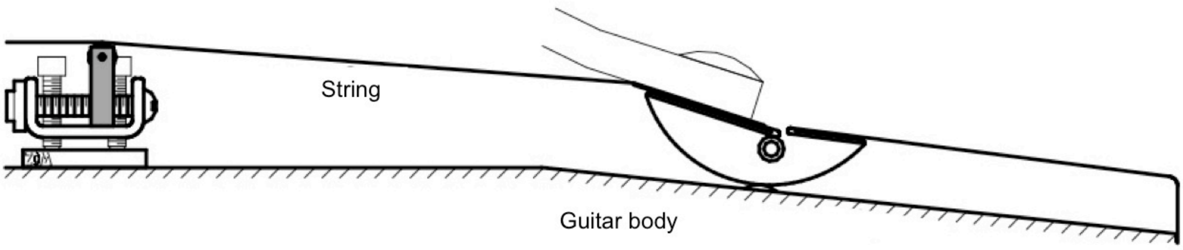


Fig. 7.122: Side view of the Rickenbacker vibrato (1960's vintage).

The spring-loaded tailpiece rivals Fender's ideas when it comes to ingenious simplicity: a u-shaped sheet metal into which 2 further sheets are hooked – done. The vibrato lever serves to bend the u more closed or more open, and changes the string tension that way. Once the strings have been inserted into the tailpiece, the latter for starters won't cause any problems. The latter may, however, occur at the bridge: first because the bearing there is undefined, and second because the bend angle of the string is, at 5°, even smaller than that on the Jazzmaster. It should be noted when considering these numbers that they are measurements on individual guitars; any production tolerances from the 1960's were not looked into.

The Rickenbacker 335 is not a solid body guitar but has a hollow body with a 4 mm strong, vibration-happy top. Compared to a Les Paul, this "semi-acoustic" build leads to higher conductance values and thus to a stronger damping of partials (Chapter 7.11). However, much faith in a well thought out vibration design is not coming our way: the top is stabilized on its lower side with a rather archaic cross-bracing, but then a ½"-cutter was used to mill slots into the top for the pickups – with the cutter taking no prisoners and clearing its way through part of the bracing, as well. Of course: pickups have first priority in the electric 6-string. What's in the way gets removed.