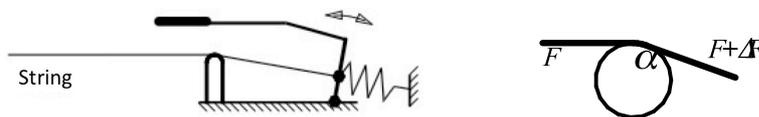


### 7.10.3 Bridges with vibrato

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”<sup>\*</sup>.

To change the string pitch in a continuous manner, the tension force  $\Psi$  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  $\mu$ , 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.

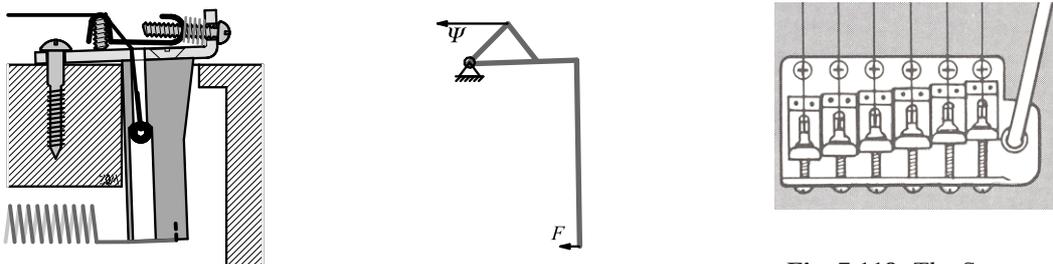
If the string runs around a fixed cylinder with an encirclement-angle  $\alpha$ , the two tensile forces differ by  $\Delta F = F(\exp(\mu\alpha) - 1)$ . Pulling to the right (in the figure), the right-hand force is (at the max) larger by this value; pulling to the left, the left-hand force is. In conjunction 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  $\Psi$  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.

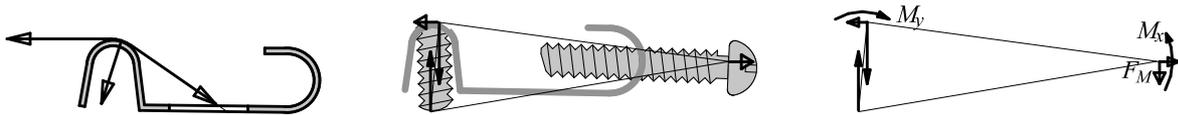


Fig. 7.119: Flux of force in the Stratocaster bridge.

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<sup>1</sup>, 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.

<sup>1</sup> Friction forces are disregarded for his simplified consideration.

6 steel strings are positioned above the bridge pickup of the Stratocaster, and 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	<b>9</b>	<b>11</b>	<b>16</b>	<b>24</b>	<b>32</b>	<b>42</b>	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	<b>12</b>	<b>16</b>	<b>24</b>	<b>32</b>	<b>42</b>	<b>53</b>	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  $\pm 1$  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!

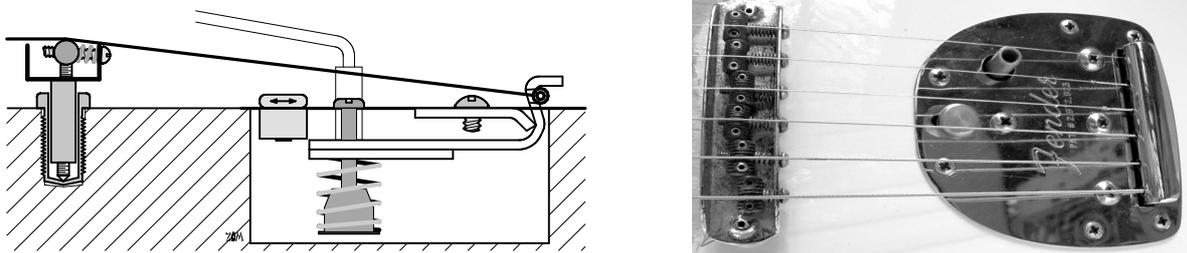


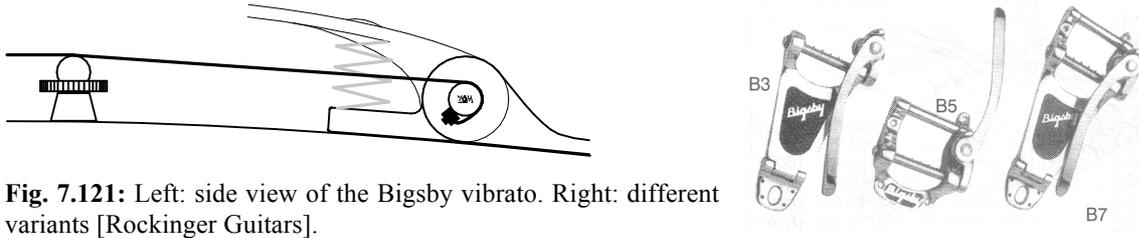
Fig. 7.120: Vibrato system of the Jazzmaster.

The main issue with the Jazzmaster vibrato system is that the strings bend across the bridge saddles with a very shallow angle ( $6 - 7^\circ$ ). 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 gauge 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 from 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].

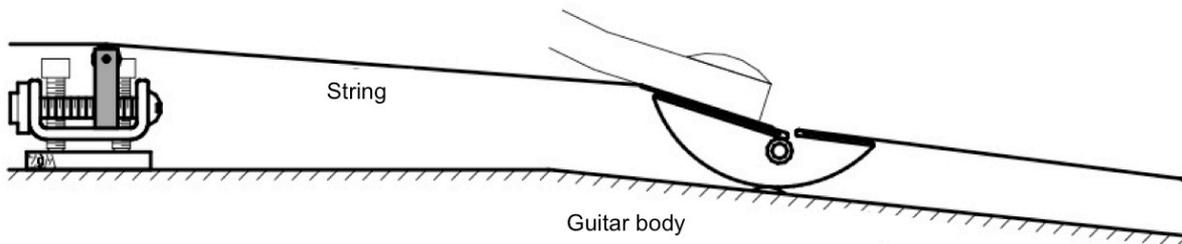
The Gretsch Tennessean is a hollow guitar without any sustain block; its thin top cannot take any large forces. Maybe the bend angle of the strings must in fact not be more than  $4^\circ$  (as it showed up on the investigated guitar), maybe more could be allowed ... we cannot find out using a non-destructive 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.