Preface: Dear reader,
as a long-time and big-time fan of controlling my guitar sound as much as possible directly on the guitar itself (while keeping things simple so that I can concentrate on playing music rather than fiddling with controls), I have modded my guitars a lot with replacement pickups where needed, and by optimizing volume and tone control with suitable potentiometer and capacitor values, and by adding treble-bleed arrangements and switchable capacitors. In fact, I was under the impression that I had completely and utterly sussed the guitar circuits I was using. Translating the present article by Bernd Meiser taught me to be a bit more humble - only after having been intimately confronted with what he relates did I understand that the overall picture still had elude me. The article has provided me with a lot of added value - and I hope that you get as much out of it as I did. Happy reading, and – maybe – happy soldering afterwards!

May 2019, T.Z.

P.S.: Recommended supplementary reading (in the GITEC repository) on some devices shaping the guitar signal and interacting with the guitar circuitry:
- Overdrive, Fuzz & Distortion: investigating Rangemaster, Tube-Screamer et al. ,
- Bernd Meiser's articles on distortion devices, e.g.:
  - British FX-Boxes & Zeitgeist
  - Historical Fuzz-, Distortion- & Overdrive-Devices
  - The MXR Distortion+
  - The Rat
  - Boss DS-1

From the "Effect-ive!" series of articles:

Pickup, Controls, Cable and Beyond: some serious Interaction

By **Bernd C. Meiser**

Introduction

Compared to other musical instruments powered by electricity, the electric guitar is a rather simple contraption. Whether you look at the guitar next to a modern digital synthesizer that contains miles of operating code in its memory, or whether you line it up with an analog Moog with its many circuit boards and modules carrying hundreds (or thousands) of components, or even compared to such dinosaurs as the electro-mechanical old Hammond organ or the tape-gobbling Mellotron, the guitarist's axe seems almost pathetically simple - saved only by its iconic shape and image (but that is in fact another story). However, it would be better to say *deceptively* simple - because already at the very beginning of the signal processing of the electric signal (that is generated by the string), there's much more going on than meets the eye. In most guitars, there are just a few passive electronic components before amplifier or effects pedals start to treat the sound - but even this unspectacular collection of coils, resistors and capacitors result in a kind of tone-shaping that can be of make-or-break significance. Understanding how these components interact between pickup and the first stages of active amplification can assist us in much faster approaching the guitar sound we desire, and to reign in the behavior we want from our instruments.

1. Where it all begins: the Pickup

As one of the foremost exponents of the typical guitar pickup is the one used in the Fender Stratocaster that has been manufactured in almost identical fashion since 1954. Although there are more complicated pickup designs (the Gibson Humbucker comes to mind) and somewhat different approaches (e.g. dummy coils and supplementary magnets), the vast majority of pickups in effect works just like the Strat pickup, and we shall use the latter here to investigate.

Looking at it from a physical point of view (Fig. 1), the Stratocaster pickup consists mainly of a bobbin containing a lot of thin, enameled copper wire (with a diameter of 0.063 mm, AWG42) that is wound around an array of 6 cylinder magnets that are mechanically held in place by fiber sheets. Typically, the resulting coil has about 8000 turns – the exact number will depend on the year of manufacture, and it will vary to some extent especially in the pickups from the early production years.

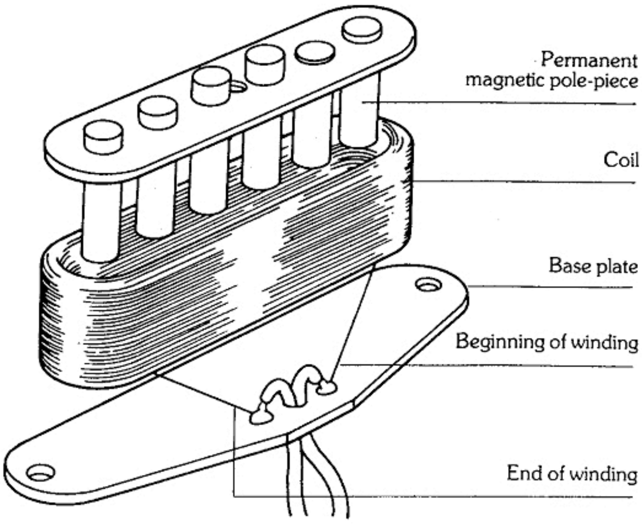

Fig. 1: Fender Stratocaster pickup
(source: https://www.seymourduncan.com/blog/wp-content/uploads/single-coil-diagram.jpg)

We immediately understand that this amount of wire will have a certain ohmic resistance R1 of around 6 kiloOhm (kΩ), and that the arrangement will have the considerable electrical inductance L1 of about 2,5 Henry (H). The individual windings between them act like small capacitances. They all add up to an overall capacitance C1 of the whole coil amounting to about 150 picoFarad (pF), to give a rough guide value. With an inductance and a capacitance, we get an electrical resonance at slightly more than 8 kHz. The Q-factor – the sharpness of the resonance peak, or emphasis – is determined by the ohmic resistance.

The magnets (typically made of an aluminum-nickel-cobalt alloy – AlNiCo!) are metallic and do conduct electrically; they therefore cause eddy-current dampening that reduces the theoretical Q-factor resulting from the individual components L, C, and R quite considerably. In an equivalent circuit diagram of the pickup (Fig. 2), the magnetic dampening can be included as a parallel shunt resistor R2 of about 500 kΩ. The resulting overall Q-factor leads to a resonance emphasis (i.e. a peak) of about 15 dB.

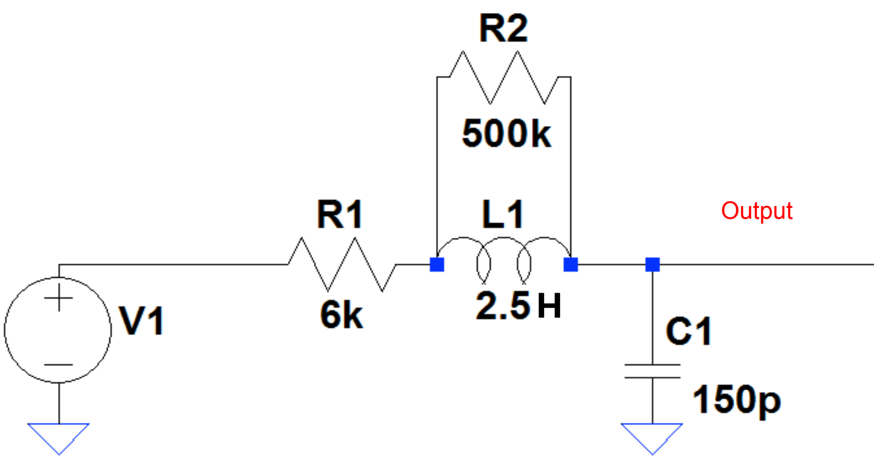

Fig. 2: Electrical equivalent circuit of the Stratocaster pickup; V1 is the electrical voltage induced by the vibrating string.

For those who like math: the overall RLC-resonating-circuit can be represented mathematically by a 2nd-order oscillation-differential-equation that has three characteristic solutions. The solution giving the resonance emphasis (complex conjugate zero) historically is the one that most interests us here in the first place.

If we connect the pickup to a further ohmic load, e.g. in the form of the input impedance of the (pre-) amplifier or any other device down the signal stream, a further reduction of the Q-factor will be the result (Fig. 3).

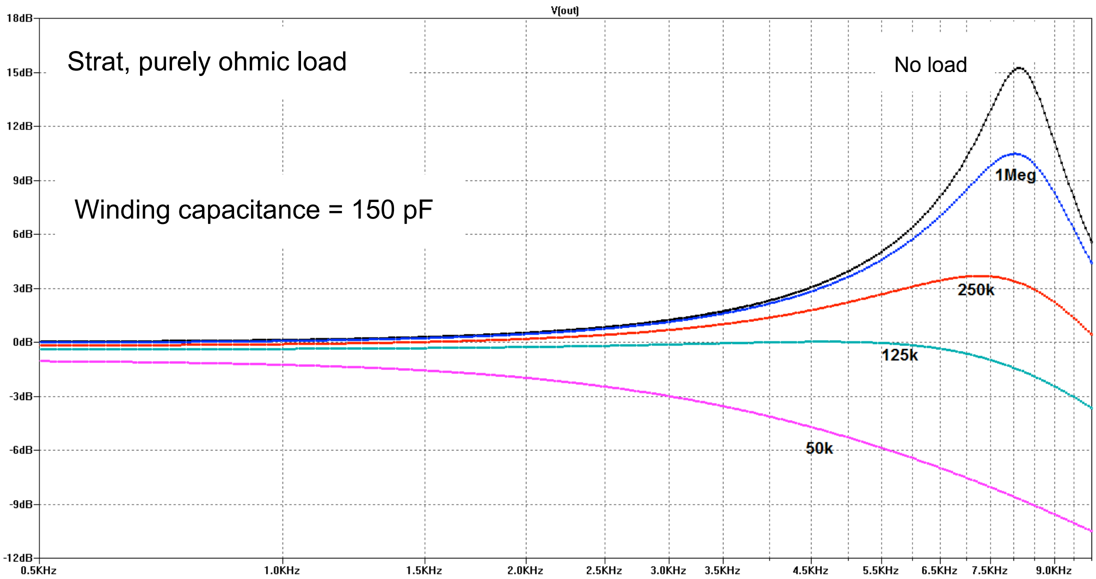

Fig. 3: Resonance behavior of the Stratocaster pickup with purely ohmic load

However, in most cases we work with "passive" electric guitars that have no amplification at all built into the guitar, and therefore this device is connected to the guitar by a cable of non-negligible length. (N.B.: so-called "active" electric guitars do include a – normally battery-driven preamp and therefore face other challenges that we will get to later).

Guitar cables will have a capacitance of 80 - 120 pF per m length so that with a cable of 6 m length we will have an additional capacitance of in the order 600 pF connected in parallel to the pickup output that adds to the overall capacitance. This new larger overall capacitance creates a different, lower resonance frequency that more often than not is considerably below the resonance frequency the "open" circuit (i.e. not connected) will have. This situation is the one occurring in practice, and it formally determines the basic sound of the pickup.

The two determining values here are the resonance frequency and the Q-factor. The former is determined largely by the cable capacitance while the latter is governed mainly by the ohmic load. This ohmic load the guitar is subjected to can take on very different values, depending on the input specifications of the downstream device. From a point of view of metrology and instrumentation, the open-circuit (no-load) condition and the associated Q-factor is highly interesting as a reference value, a sensible high-impedance measurement load should be defined. 10 MΩ would seem appropriate and close enough to the open-circuit condition. Caveat: a system of that high an impedance is very sensitive regarding any connected circuitry!

2. Making it playable: the Guitar ... and the Cable

It is customary to fit an electric guitar with a volume control. This consists of a potentiometer, i.e. a "voltage-divider" resistor-arrangement attenuating the signal according to its setting (in guitars typically of a rotary design). A circular (but not closed) track of resistor-material (with connections to the outside) is tapped by a moveable wiper forming the third (middle) connection of the pot. The potentiometer represents a first load the pickup is subjected to. Historically, many values have found their way to the volume "pot" - mostly we find from 100 kΩ to 1 MΩ, with the Stratocaster used as example above sporting 250 kΩ. Gibson guitars usually had 500 kΩ-pots.

Maybe a word about the control characteristic (also termed "taper") of potentiometers is in order here. In a pot with a *linear* characteristic, the resistance and the voltage-divider effect change the same way the turn angle changes. In other words, at the half-way point the resistance between the wiper connection and the respective end connection of the resistor track is equal on both sides; its value is half the nominal value of the pot. Changing the turn-angle by a given amount leads to equal changes at the beginning and at the end of the turn range. In a potentiometer with a *logarithmic* or *audio* characteristic, the change along the resistor track is very small at the beginning of turn range and increases significantly toward the end of the range. In other words, if the resistance (or the output voltage of the voltage divider) is measured, the same amount of turn-angle rotation has a very small effect at the beginning if the range and a very large effect at the end of the range. For the human hearing system with its non-linear properties, this is a much more suitable control behavior because that way the same amount of turn-angle rotation causes a more similar loudness change across the whole range of the potentiometer. This is why the term "audio" is used in connection to a logarithmic potentiometer.

But back to our guitar control circuit: the second control element we find on most guitars is the tone control. In the vast majority of cases this is a treble-cut arrangement with a series circuit of a capacitor and an adjustable resistor connected in parallel with the pickup. The capacitor value most familiar is 22 nF, although the Stratocaster started out with 100 nF, received towards the end of the 1960's 50 nF and ended up with 22 nF from the End of the 1980's. The tone pot (connected as an adjustable resistor) has the same value as the volume pot: 250 kΩ. Gibson again opted for 500 kΩ. If the tone pot is turned up fully, the capacitor does not contribute much at all anymore to the overall system, and it can be replaced by a shorting bridge in the equivalent circuit. As the "tone is turned down", this changes: approximately below the half-way-point of the maximum resistance value (this would be around position "7" of a potentiometer with logarithmic characteristic), the tone-C may not be neglected anymore - the computer simulation already shows sizeable deviations at that point. Our exemplary Stratocaster features three pickups, a three-way switch to select either pickup, two tone controls for the middle- and neck-pickup, respectively, and a volume control.

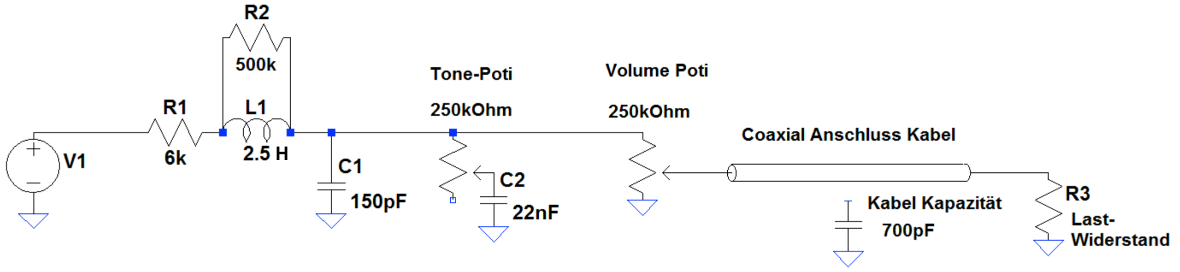

Fig. 4: Complete equivalent circuit for the Stratocaster, neck or middle pickup selected

With the Strat, we get two scenarios in terms of the pickup loading: the bridge pickup being connected only to the 250 kΩ volume pot, and the neck (or the middle) pickup connected to both the 250 kΩ volume and the respective 250 kΩ tone pot (the two pots connected in parallel, with the capacitor acting as a short, as explained above). In "bridge-position", the load acting on the pickup therefore is 250 kΩ, while in the other two positions the load is 125 kΩ. The original resonance emphasis drops to 2,5 dB and 0 dB, respectively.

To generate sound, the Strat now needs a cable; as we have already seen, this will add between 400 and 1000 pF capacitive load. Only now the pickup has received its actual operational environment as we are used to it. The resonance frequency has dropped to roughly 3.4 kHz, and the emphasis is at 8 dB respectively 4 dB, creating that well known and loved bright metallic sound - the Fender Strat sound!

Other resonance frequencies are possible (by switching in capacitors) and may even be musically favorable. This topic is discussed e.g. in the books by Helmuth Lemme (see, for example: "Electric Guitar - Sound Secrets and Technology", Elektor 2012, ISBN 978-1-907920-13-4).

To practically use the guitar, it is plugged into a further device (e.g. the amp) that further processes the guitar's output signal. The input impedance of that device is connected additionally in parallel to the circuitry within the guitar. Let us assume that, for example, that input impedance is 1 MΩ (a typical value for a tube amp input stage). We now have, in "bridge position", 250 kΩ parallel to 1 MΩ resulting in a pickup-load of 200 kΩ (and a resonance emphasis of 7 dB). In the other pickup-positions we get 125 kΩ in parallel with 1 MΩ, resulting in a pickup load of 111 kΩ (and a resonance emphasis of again 4 dB). This is the everyday reality for a Strat plugged into a classic amp made by Fender, Marshall, Vox. or the like -and the situation is similar for many modern stomp boxes that feature the 1-MΩ-input-impedance, as well.

3. A light Load: high Input Impedances in Tube Amplifiers

As has been just mentioned, we find most classic tube amps to have an input impedance of 1 MΩ (at least for their more sensitive inputs, e.g. the input designated with "1" on Fender amps of the "Tweed", "Blackface" and "Silverface" generations). We can see this input impedance as the "normal" load that a tube amp exerts on a guitar, and many amps feature it - not just Fender, Marshall and Vox but Orange and Hiwatt, as well, to mention the historically significant ones. All these amps allow for a decent Q-factor in the guitar circuit, and music history has been written using them.

There are some amplifiers, however, that even go beyond the 1-MΩ-thicket: examples are some Ampeg amps like the old VT-22 or SVT models as they served at one time or another the Rolling Stones, the Faces, or Bad Company, to name a few famous users. Not for the faint hearted, these most serious amps boasted an input resistor (serving as the grid resistor for the input tube) of the rather enormous value of 5.6 MΩ on their "Normal"-channel. This already bears a similarity to tube operation with initial velocity bias (contact bias; the cathode being connected directly to ground). Given that the resonance emphasis is only marginally increased, this circuit has not really proven itself and is all but abandoned.

An interesting situation presents itself in the "Bright"-input of these Ampeg amps: here the input resistor is a mere 47 kΩ in the SVT and 220 kΩ in the VT-22. With the lows being noticeably attenuated via a simple RC-high-pass, the treble content of the signal gets a relative boost. The apparent increase in brilliance of the sound is not due to a pronounced resonance peak – in fact, the low input impedance kills off most of the resonance or even completely prohibits it. We shall get back to this a bit later.

Let's look around some more. The Sound City amps (deployed by the early Pink Floyd, after all, and many others) used to have 470 kΩ at the input and apparently created no cause for concern. The same holds for Peaveys Mace and Deuce amps that use merely 220 kΩ. Lynyrd Skynyrd were highly prominent users of these amps, and they didn't complain. The sounds of their live recording "One more from the road" would appear to be mostly if not exclusively Peavey-generated – it would be difficult to argue that the guitars on that album do not sound great. Also, the Music Man amps preferred back in the day by many Country guitarists (and by Eric Clapton, for that matter) had input resistors of 220 kΩ or 470 kΩ, depending on the model. From these examples, it would appear that the resonance peak as such does not necessarily need to have highest priority.

4. A heavy Load: low Input Impedances in (some) Pedals

In principle, the situation we find with amps is not much different with guitar-pedals. Such stomp boxes include an input-impedance that may strongly differ from one pedal model to the next. Most modern stomp boxes boast high input impedances of 470 kΩ or 1 MΩ, but almost all of the old classical pedals from the 1960's and 1970's are nowhere near that, generally mustering between 10 kΩ and 100 kΩ.

One of the first effects devices (though not a "pedal" as such yet) was the Rangemaster treble booster. Its input impedance at high frequencies was in the range of 10 kΩ - and on top it depended very much on the current gain of the individual input transistor (those were quite different days...). Such low input impedance will dramatically load down the guitar circuitry, and as result the resonance peak struggles to appear at all.

The Rangemaster has not only a small input impedance but also an input capacitor (originally required to separate off any DC components between guitar and device) of a value that aids its function. This input capacitor is small compared to what any HiFi enthusiast would select to achieve a wide bandwidth, but still relatively large compared to the guitar cable capacity (see above). In conjunction with the inductance of the pickup, what little resonance remains is shifted to around 1 kHz. The resulting sound is of a rather nasal character – somewhat like a half-closed wah pedal. While in a "clean" setting, this sound will in fact not create a lot of envy, but things change as the subsequent amp is pushed into overdrive. Now it appears that what counts most is the rising flank of the frequency response that contains the fundamentals of the guitar. The frequencies attenuated in the range beyond 1 kHz are complemented by the harmonics created by the amp distortion (in the preamp or the power amp, or in both). It appears that in this mode of operation, the guitar play s more the role of a dynamic trigger (in the case of Rory Gallagher, Ritchie Blackmore, or the likes), or a pure trigger if the gain is revved up (in the case of e.g. Toni Iommi in early Black Sabbath). Especially if there is much distortion, the high frequencies from the pickup can be detrimental.

We find a similar situation with the FuzzFace that was popularized by Jimi Hendrix. This device features a very small input impedance (in fact current driven with a "zero-Ω-node"), and is even frequency-neutral with its large input capacitor of 2.2 µF (200 to 400 times the input capacitor of a typical treble booster). The resonance peak does not stand a chance here - it disappears. The missing frequency components are balanced out by the (sometimes even overly) rich harmonics generated by the FuzzFace's two-transistor distortion circuit.

While we are in Electric Lady Land, let's remain with Jimi Hendrix a bit. It sees that at the time, the resonance peak was not seen as a staple, and that shows in the design of the devices. Admittedly, in the FuzzFace and the Rangemaster, the input impedances were determined by the circuitry – it would have meant much more effort to increase them. However, the Univox UniVibe (the legendary phaser/chorus used by JH) could have easily been designed with high input impedance. Nevertheless, the latter was set to 70 kΩ.

There are more recent FuzzFace editions that include an impedance converter in order to minimize the perceived disadvantages of the high pickup load due to the low input impedance. These pedals however, do not sound like the old FuzzFaces anymore - they are really a different device.

The Colorsound pedals Overdriver and Power Booster are other vintage pedals with a relatively low input impedance of 150 kΩ. Still, they imprinted themselves in the first class sounds of the likes of Wishbone Ash, Pink Floyd, Jeff Beck and many other early 1970's guitar heroes.

Of interest is also the Roland/Boss CE-1 device - for many THE chorus pedal – with its mild, soft sound. The schematic reveals that the input impedance is merely 220 kΩ - while most other chorus pedals had 500 kΩ. Again, it seems that the subdued or missing resonance peak in not of primary concern - at least for some circles among the musicians.

To conclude this section, let me mention two historic guitar circuits of the active kind. Here, the first amplification stage is integrated into the guitar itself, making the guitar signal independent of the guitar cable. The circuit in Eric Clapton's 1988 Signature Strat had an input resistor of a little less that 270 kΩ, and an input capacitance of 330 pF (the latter "simulating" a very-low-capacitance guitar cable). On the other hand, the Alembic Stratoblaster, a FET (Field-Effect-Transistor) Booster used e.g. by Jerry Garcia of the Grateful Dead) reached a sizeable 5 MΩ or even a little more.

5. The Volume Control: getting in the Way more than suspected ...

Important: the following considerations are based on using potentiometer with a linear taper as volume control - this helps to understand how the position of the volume control gradually influences everything around it. With a logarithmic (or audio) taper, the corresponding effects will happen more abruptly around the upper range of the volume control (i.e. from positions "8" to "10").

5.1 The changing Source Impedance of the Volume Control

Imagine you have your guitar connected to a device with an input impedance of e.g. 1 MΩ and set your rig to a nice crunchy overdrive sound. Needing a cleaner sound for some passages, you will want to turn down the volume to achieve that. As you turn the knob, not only the signal level changes because you effectively adjust the voltage divider - there's more.

Let us check out the equivalent circuit again. Fig. 5 shows parts of the circuit that we seen before - limited to only the volume pot, the cable capacitance, and the input impedance to the downstream device.

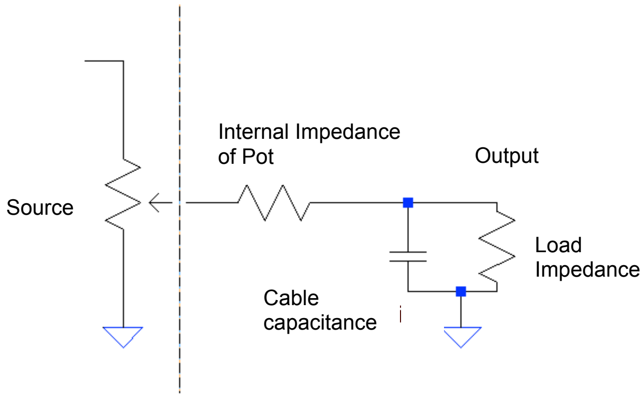

Fig. 5: Equivalent circuit of volume control, cable and input impedance of amplifying device.

As we see, the pot has an internal impedance. From the point of view of the cable capacitance and the load impedance, this would be the "source impedance" of the potentiometer. This internal impedance is dependent on the turn angle where the pot is positioned, and it has a maximum at a certain angle. To calculate that maximum is a nice little problem for your junior math expert that is solved via an extremum-problem approach. For a linear pot, the maximum establishes itself at half the overall turn-angle; for a pot with an audio taper, the maximum occurs much "later" along the turn. In both cases, however, the maximum internal impedance has the same value, namely 1/4th of the nominal value of the pot. The reason is that the two halves of the pot – from an impedance-point-of-view – have the effect of being connected in parallel. For our Stratocaster configuration with the 250 kΩ volume control, the maximum internal impedance of the volume pot would thus be 62,5 kΩ.

5.2 The Interaction of Volume Control and Cable

This impedance behaves like a series resistor, and in combination with the cable capacitance of say, 700 pF, an RC-low-pass with cutoff frequency of 3.6 kHz (at the pot-position yielding the maximum internal impedance) results. The cutoff frequency is dependent on the setting of the turn angle of the pot. **Fig. 6** shows the characteristic of this low pass for various settings of the pot.

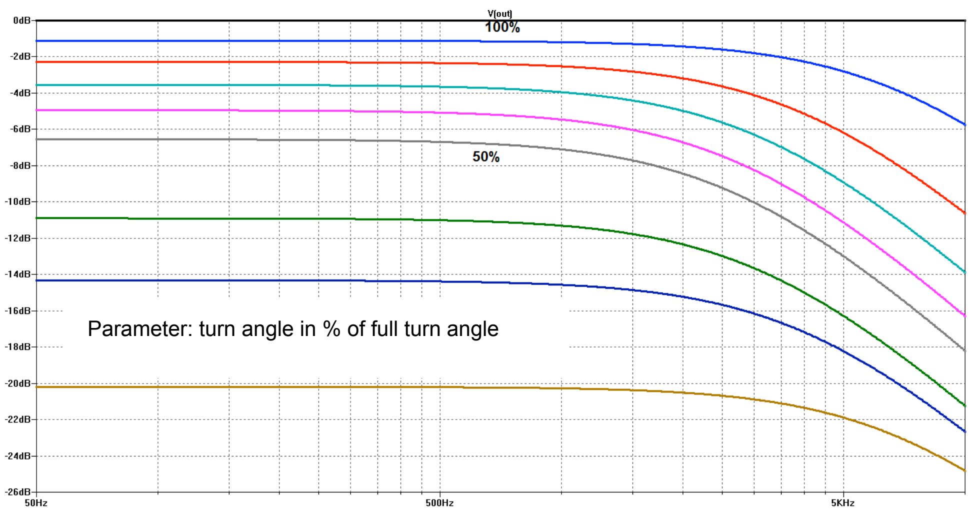

Fig. 6: Frequency response of the low-pass formed by volume control and cable capacitance; for various settings of the turn angle.

We have just seen that, because of the interaction of volume pot and cable capacitance, turning down the volume control has the effect of a low-pass i.e. it cuts the treble. The biggest loss of treble occurs at the mid point of the turn range of a linear pot, but at around 80% or 90% of the overall turn angle for a pot with audio characteristic.

5.3 The Effect of the Volume Control on the Pickup Resonance

However, that's not all: at the same time as we turn down the volume control, the increasing internal impedance of the pot will "separate" the cable from the pickup. This decoupling has a dramatic effect on the resonance frequency of the system. As we have learned in Section 2 above, the cable capacitance will (in interaction with the inductance of the pickup coil) determine the resonance frequency of the pickup – but only if cable and coil are directly connected. With the internal resistance of the volume pot going in between and removing the direct coupling between cable and pickup, the resonance is now determined overwhelmingly by the small winding capacitance (150 pF) of the pickup. It rises up to almost where the no-load resonance of the pickup had been, i.e. to around 8 kHz. However, given the overall load situation with the RC-low-pass formed by pot and cable, the Q-factor of the resonance is strongly reduced such that the pickup as such will have a rather flat frequency response up to just short of 7 kHz. **Fig. 7** shows this (with the potentiometer drawn as two separate resistors (i.e. for a given control position).

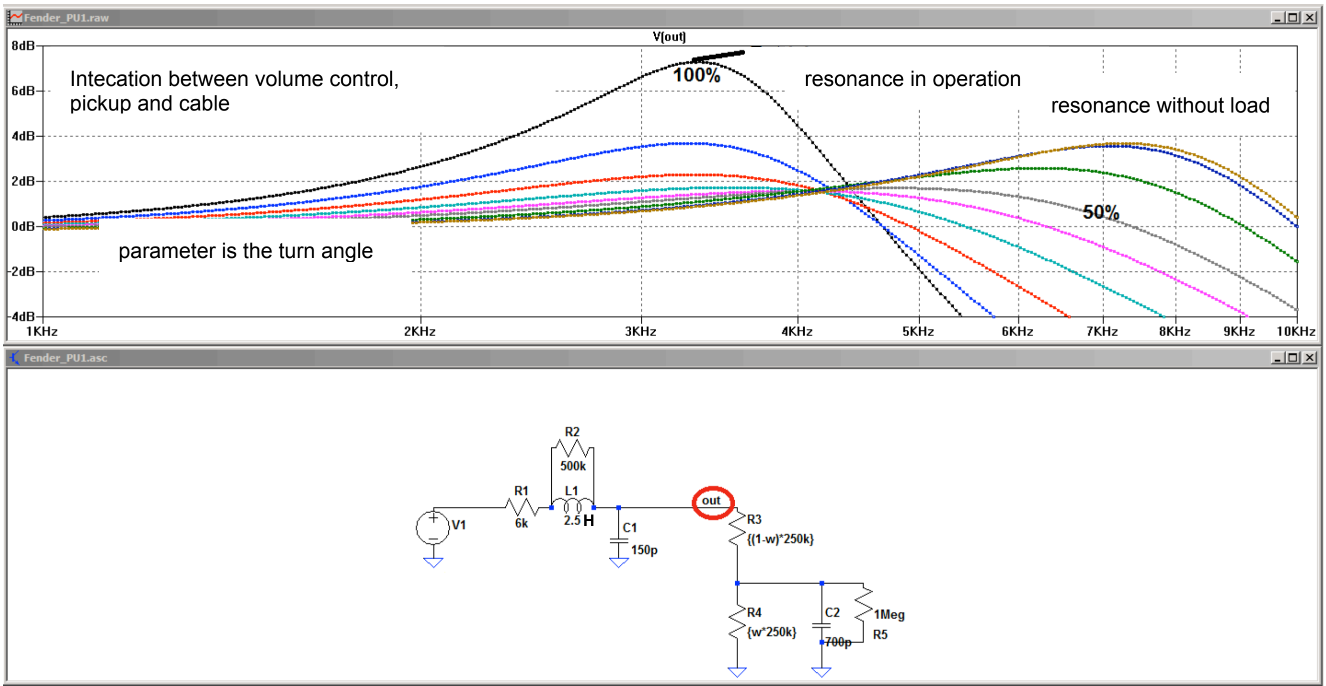

Fig. 7: Interaction between volume control, pickup, and cable. Top: frequency response of the system at the output of the pickup. Parameter is the position of the volume control in % of the full turn angle.

5.4: The overall Interaction: Reality

What is important in the end is not the frequency response at the pickup output, but the one at the output of the guitar as it is fed to the amplifying device. In other words: the overall interaction of all the elements in the guitar and the cable as it influences the signal that arrives at the amplifier (or pedal) is the critical issue.

This is depicted in Fig 8: as we start to turn down the volume control, the frequency response begins to loose the resonance peak (i.e. the sound becomes more "lifeless"). Reducing the volume further leads to an actual attenuation of the treble (i.e. the sound gets duller). The frequency response now is rather flat up to around 1 kHz, tapers off slightly (by 3 dB) up to about 2,5 kHz and drops off more drastically (with a 12 dB/oct slope) above. At very low volume setting, the treble comes back in and even forms a resonance again - albeit at a higher frequency and with less of a peak. Compared to the frequency response with the volume control full "up", most people would call the sound at lower settings of the volume control flat and less expressive – at least for "clean" or "crunch" operation.

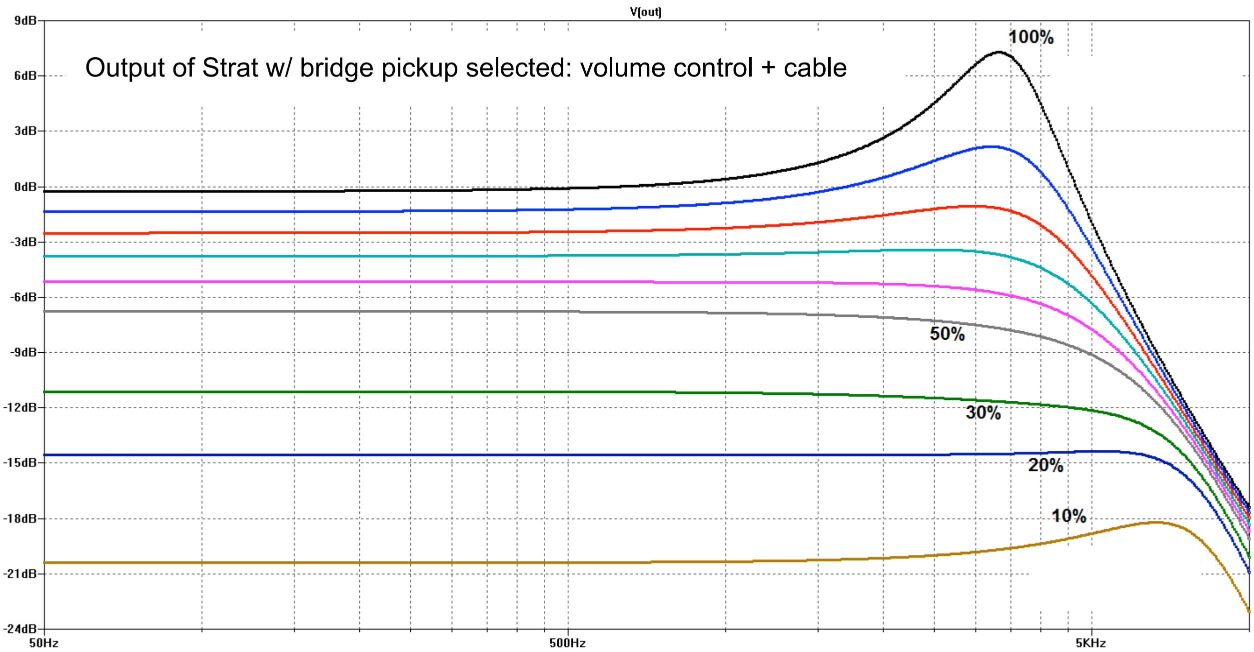

Fig. 8: Overall frequency response at the output of the guitar with cable attached; parameter is the position of the volume control in % of the full turn angle.

So, here is the problem that the traditional (passive) electric guitar with its typical circuitry and layout faces: the sound changes as the volume control is operated. For many players, the best sound is there with the volume control fully "up", and it somehow looses a lot of its desirable quality as the volume is turned down. Of course, this is a matter of taste and required sound, and there may be the situation that a player needs an expressive, treble heavy sound at full volume (e.g. for lead guitar duty), and a duller sound as the volume is turned down (e.g. for rhythm guitar). In fact, this behavior may have been exactly what was in demand back in the day when the electric guitar came emerged. The vocalist in the band appreciated a more subdued, soft sound from the accompanying guitar (with the volume turned down), and the guitarist profited from the brighter sound with the volume turned up fully for his/her (rare?) solos.

Today, the requirements can often be the exact opposite - especially in the context of using overdrive/distortion. As has already been hinted in Section 4 above, an overdriven guitar sound can profit from (or may even depend on) a less treble-heavy, more mid-range-y sound, and therefore that bright sound produced by the Strat may not be what the doctor ordered for that distorted solo.

On the other hand, today often a rather bright and expressive sound is asked for accompaniment, as well (i.e. at lower volume). The "natural" behavior of the traditional electric guitar is the exact opposite of what is frequently desired today - and as a consequence, quite a number of guitarists never touch the controls on their guitar, relying more heavily on foot-switched amplifier channel selection or similar aids from pedals and programmable devices. They do miss out on quite a bit of immediate connection to their instrument: there certainly is something to having volume and tone controls ready at your fingertips ...

Which brings us to the last section in this article - an at least partial remedy for the above problem.

6. Compensation: the "Treble-Bleed"-Approach

6a: Bleedin' Basics

If we have volume control, and if we seek to (relatively) increase treble at low volume settings, we may remember a circuit used in the "Bright"-channels of many Fender amplifiers from the early 1950's, and for the "Bright"-switch arrangement of the Blackface and Silverface Fender amps. These circuits had a small capacitor bridging the inputs and outputs of the volume potentiometers, and in fact such a capacitor is also found in Telecasters (starting in the mid 1960's).

Fig. 9 shows the diagram of the volume control of our Stratocaster complemented by such a bridging capacitor (often termed "treble-bleed" capacitor) that compensates for treble loss.

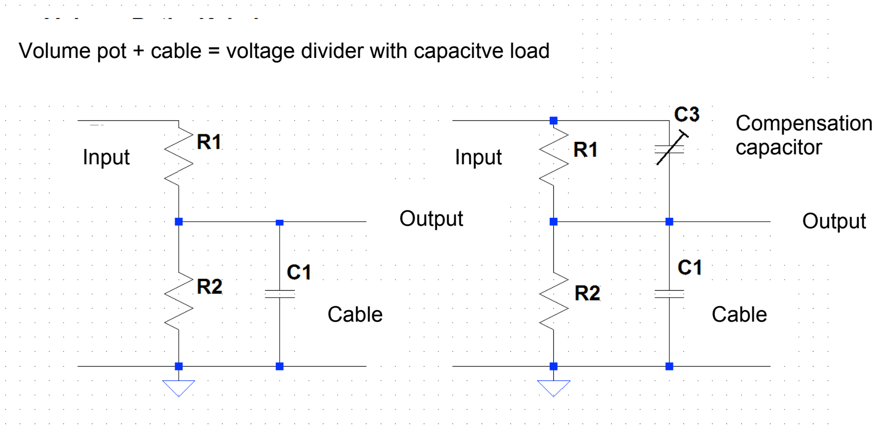

Fig. 9: Equivalent circuits of Strat volume control without (left) and with (right) compensation capacitor – here shown as an adjustable cap.

Electrically, the volume potentiometer of the guitar represents a complex voltage divider with the lower half forming a low-pass and the upper half working independently of the frequency. This diagram will immediately remind the technician familiar with instrumentation technology of a probe as it is used in conjunction with oscilloscopes. To adapt the latter to high voltage sources, or sources with high output impedance, a resistor with a very high value (corresponding to R1 in Fig. 9, e.g. 9 MΩ) is used ahead the scope. Unfortunately, this will form a low-pass filter when connected via a cable to the input of the scope (e.g. with an input impedance of 1 MΩ and an input capacitance of 30 pF plus the cable capacitance, corresp. to R2 and C1, respectively, in Fig. 9) - high frequency measurements become totally unreliable.

What helps here is a small adjustable compensation capacitor that is connected in parallel to the input resistor. It is integrated into the probe and adjusted via a small screw such that – without going into further detail here – the probe/scope arrangement becomes frequency independent.

Knowing about this approach, we can take advantage of it for our guitar volume control. In order to reduce the treble loss at the output of the guitar as we encountered it above, we solder a small capacitor across the "upper" resistor section (the "input") of the volume pot. A perfect compensation of the loss will only be possible for one single specific setting of the pot, but there will be at least improvement for the other position, as well – and we just take what we get! This shows, though, that a mathematically exact rule for calculating the value cannot exist. In internet fora, we frequently find the mention of "the perfect values" - but these do not exist. At most, we can arrive at values that seem to please a number of guitar players.

That small capacitor soldered between input and output of the volume pot (of a capacitance of between 100 pF and 2.2 nF) often (but not always!) is paired with a resistor connected in parallel or (more rarely) in series. The resistor (a value of 150 kΩ or 220 kΩ is often seen for the Strat with the 250 kΩ volume pot) serves to keep the resonance peak at bay for settings where an "over-compensation" would occur. However, for this resistor there is no one "perfect" value, either - again personal tastes and requirements rule.

The parallel (or series) connection of the small capacitor and, if present, the high-value resistor is called "treble-bleed" arrangement, and we will look at it in even more detail below.

Note: as mentioned, many guitar amps (including e.g. Fender's famed tweed Bassman) include a "treble-bleed" around their volume control - especially for their "Bright"-channels/inputs. In this case, however, this not to compensate for attenuation of treble content but to dramatically emphasize the treble. That this emphasis completely depends on the position of the volume control (i.e. it is very strong at low volume settings and tapers off towards high volume settings) seems not an issue for the users - again: beauty is in the eye of the beholder, or rather: great sound is in the ear of the player!

6b: Treble-Bleed scenario 1: your classic amp with high input impedance

As has been already underlined: there is no universally valid and applicable rule how to choose the component value(s) in the treble-bleed arrangement. It will be a trial-and-error process because the result needs to meet the specific individual tastes and requirements of the individual guitarist, and suit the given music style. To repeat: great sound is in the ear of the guitarist!

A treble-bleed arrangement published by Fender some time ago includes a 1000 pF capacitor in parallel with a 150 kΩ resistor. Connecting the parallel-circuit between the input of the potentiometer and the moveable tap creates, for the pot increasingly turned down, a capacitor-bypass that will boost the treble – but more importantly it maintains a capacitive load at the pickup (roughly the treble-bleed cap and the cable cap in series).

Given the dimensioning of the Fender-recommended circuit, the effective capacitance is about 400 pF - with it, the resonance frequency does not climb to 8 kHz but only to about 4 kHz. In order for the Q-factor (resonance emphasis) not to get too high, the parallel resistor provides a dampening effect. Fig. 10 shows the frequency responses of the arrangement at various settings of the volume control.

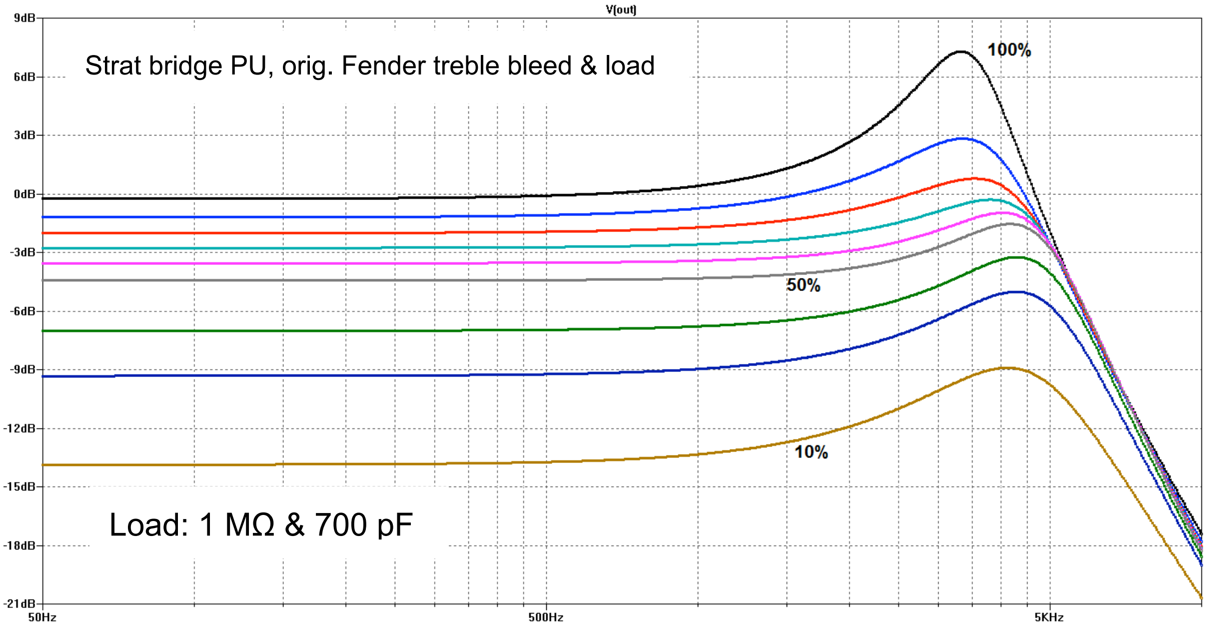

Fig. 10: High-impedance load; frequency responses of the Fender recommended treble-bleed arrangement (1000 pF in parallel with 150 kΩ), at various positions of the volume control in % of the full turn angle.

6c: Treble-Bleed scenario 2: Fuzz et al. ... with low input impedance

Let us now turn back to a scenario mentioned above in Section 4: amplifying devices with low input impedance (such as old-school fuzz boxes). An input impedance of the latter of e.g. 50 KΩ will prohibit any pickup resonance to form itself. At the frequency where it would occur (with a high impedance amplifier input, for example), there is already a 3 dB drop-off of the overall low-pass behavior of pickup and load capacitance (of the cable). For certain classic hard-rock sounds, this is a highly conducive situation with the guitar being more of less just a "dynamic trigger" - the overdriven amp will yield the harmonics.

As the volume control is turned down, the situation is similar to the above scenario 1 but with two distinct differences: the effective internal impedance of the volume pot (at the minimum about 60 kΩ - see above in Section 5.1) is connected in parallel to the low input impedance of the amplifying device, resulting in an effective impedance of slightly below 30 kΩ that pushes the cutoff-frequency of the low-pass constituted by volume control and cable to double that of scenario 1 (i.e. about 7 kHz). The tone becomes fresher. What's more, the treble-bleed arrangement allows for a pronounced resonance peak to form that results in great crunch- and clean-sounds with the volume turned down.

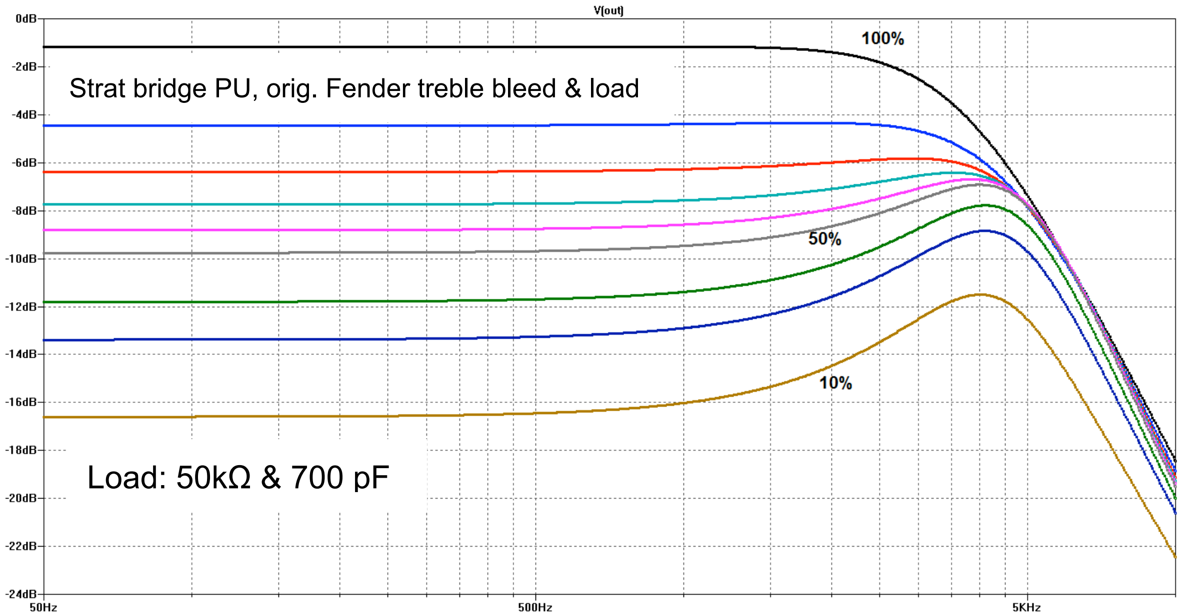

Fig. 11: Low-impedance load; frequency responses of the Fender recommended treble-bleed arrangement (1000 pF in parallel with 150 kΩ), at various positions of the volume control in % of the full turn angle.

For hard-&-heavy applications, the sound given by this scenario gets particularly excellent if the device the guitar is plugged into includes a high-pass characteristic that attenuates the bass relative to the mids and the highs. As the volume of the guitar is turned down, the sound cleans up very nicely, and we get into crunch- and clean-territory very easily.

As a note on the side: most of the devices generating additional harmonics (i.e. overdrives, distortion-, metal- and fuzz-boxes, but also blues-directed drive pedals) do include the high-pass just mentioned - albeit not all have the low-impedance input. The legendary Tube Screamer, for example, has this high-pass set to the quite considerable cutoff-frequency of 720 Hz.

6d: Treble-Bleed scenario 3: the other way round ... RC-series connection

Some sources in Internet fora propagate not only the frequently seen parallel connection of treble-bleed-cap and -resistor but rather a series connection of the two components in fact recently (as of 2019) Fender recommends this solution (designated as "Fender Tone Saver", with 1 nF + 130kΩ). It can easily be seen that the results are different compared to the solutions above (in Sections 6b and 6c) because there is no more direct connection of PU to cable purely via a capacitor. The frequency response of the "Tone Saver" is shown in Fig. 12. As the volume is turned down, the resonance peak becomes much broader but a considerable treble boost effect (relative to the low frequencies) remains. It is interesting that the area where the boost occurs remains where the original resonance was. This is contrary to what occurred with the above discussed parallel RC-connection for the treble-bleed-arrangement – and it may sound more balanced to some (or even many) ears. From the graphs, a global assessment of the sound quality is not possible. The "parallel" solution would seem to provide a more distinct, focused sound as the volume is turned down, while the "series"-solution has an overall bigger effect.

However, the following holds in any case: with the impact of either treble-bleed arrangement being very dependent on the chosen component values on the one hand, and success of the circuit completely dependent on individual taste, preferences and musical style of the respective guitarist, particular emphasis again lies on the assessment: great sound is in the ear of the guitarist!

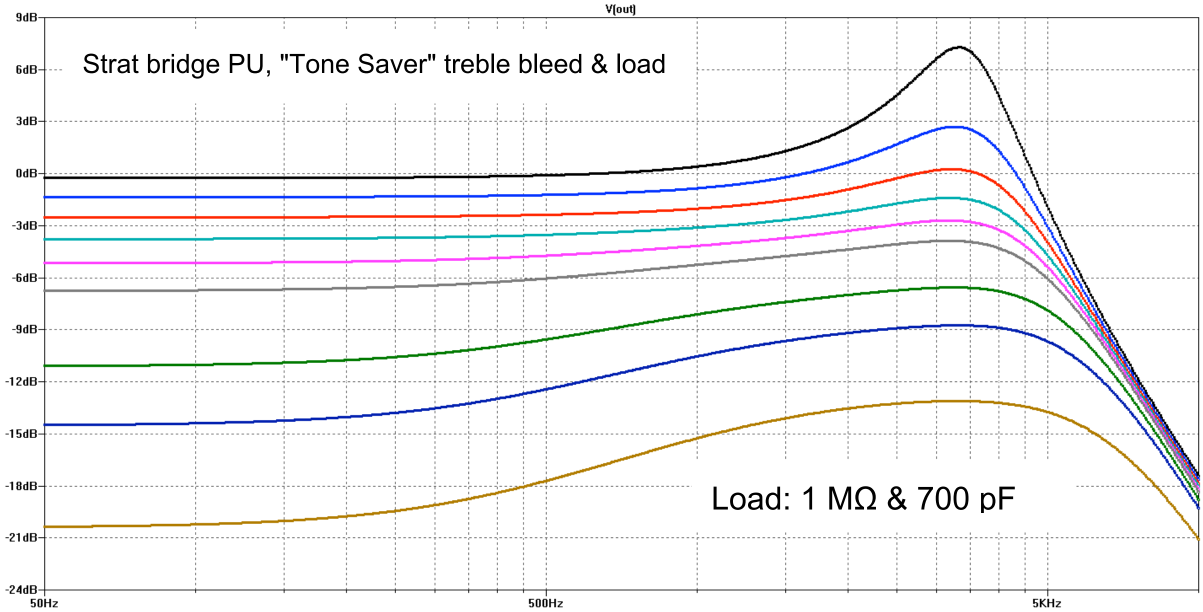

Fig. 12: Frequency responses of the second Fender recommended treble-bleed arrangement ("Fender Tone Saver"; 1000 pF in series with 130 kΩ), at various positions of the volume control in % of the full turn angle.

6. A Summary and some conclusions

1. Looking at the classic rock sounds of the 1970's, it becomes clear again that the cooperation of a whole set number of sound-influencing factors led to those "historically perfect" sound. Attributing, in terms of the guitar itself, all significance to the presence of a pronounced pickup resonance would be too narrow a consideration. Again, it is the sum of all parts that is crucial!

2. The interaction between guitar circuit and the next downstream amplifying device (whether actual amplifier or fuzz/distortion/overdrive pedal) requires much consideration. In some cases (in particular when much distortion is called for), the low input impedance of an old-school fuzz box or (treble) booster can be highly beneficial to the sound. However, if you do not want to be stuck with that influence even when the particular pedal is turned off, you better make sure it has a so-called "true bypass" that isolates the input of the electronics from the guitar when the device is not in use.

3. The cable has a substantial influence on the sound of the traditional (passive) electric guitar - but it is the value of the overall capacitance of the cable that counts and, cooperating with the pickup inductance, makes for the sound. Other aspects (such as insulation materials per se, or which plug goes into the amp and which into the guitar) have no effect at all other than purely psychological/placebo - irrespective of what the ads try to tell us.

4. The simple old volume control will influence the sound - depending on the setting the sound will be different. Guitarists have lived with the specific effect for decades: as the volume is turned down, the sound looses character (brilliance/treble), only to regain some of that in a different (not necessarily very desirable) color as the volume goes to very low values. This influence is not necessarily bad: if a more subdued sound is desired at mid and low volume settings, the traditional volume control will provide just that – but only that.

5. Of course, it may be called for to maintain a similar sound across the full control range of the volume pot, or to even to obtain a (relatively) brighter sound as the volume set low. In this case, one or two cheap, simple components (a capacitor in particular, and possibly an additional resistor) can help to keep or create a more desirable sound with low volume settings: this is the "treble-bleed" arrangement. It allows many possibilities to shape the treble content of the guitar signal across the turn range of the volume control. However, since the success of the circuit very much depends on the taste and requirements of the respective guitarist, and on the given pickup and potentiometer data, it is difficult to present a specific recommendation about which values to choose for the treble-bleed cap and the associated resistor (if present). It would appear that capacitances between 220 pF and 1000 pF, and resistor values between 150 kΩ and 500 kΩ work well. The larger capacitance values having a more dramatic effect in that they influence not only the very top end of the sound but also the upper midrange.

6. It should be noted that it is possible to quite dramatically reshape the guitar sound by adding on or more additional capacitors that can be switched into or out of the guitar circuit. In principle, these capacitors act just like the cable capacitance and in fact can be seen as simulating a longer cable (if such a simulation is desirable). In essence, such capacitors shift the pickup resonance to lower frequencies i.e. they provide a kind of "passive mid-range boost". Values from 1 nF to 47 nF work well – the rule would be: the larger the capacitor, the more mid-rangey (or even darker) the sound will be. If a number of such capacitors are added to the guitar circuit and switched into the circuit with a rotary switch, a corresponding number of shades of mid-range become available (see e.g. Helmuth Lemme's book: "Electric Guitar - Sound Secrets and Technology", Elektor 2012, ISBN 978-1-907920-13-4). These sounds may be particularly attractive as a pre-equalization for distortion/overdrive sounds.