9. Guitar circuitry

In its original form, the electric guitar was equipped with one, two or three pickups. The voltages of these could be selected or combined with switches. Guitars fitted with four pickups did surface occasionally but proved to be of little interest – apparently switching between the pickups gave too little the sonic difference. With the standard circuitry normally in use, the switch on the guitar allows for the selection of a pickup or the parallel-connected combination of two pickups. Later variations on this arrangement additionally offered series connections and phase reversal. Controlling volume and tone was usually achieved via the installation of simple RC-networks. For manipulating tone, one occasionally one finds more complex filter networks (e.g. in the Gibson ES-345) or battery-powered amplifier and filter circuits. The following descriptions relate to simple passive circuits – more extensive information can e.g. be found in the book "Electric Guitar – Sound Secrets and Technology" by Helmuth Lemme.

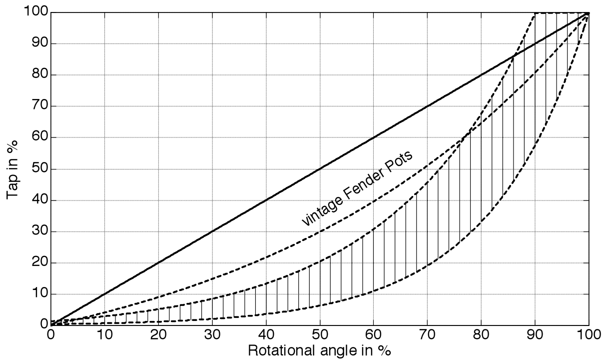
9.1. Potentiometers

In the guitar, potentiometers (i.e. adjustable resistors) are connected to the pickups to control volume and tone. The respective values are in most cases ca. 250 or 500 kΩ, less frequently used are 100 kΩ or 1 MΩ. The tone potentiometer allows for shunting a capacitor (typically in the order of 20 - 50 nF) in parallel to the pickup. As one turns the tone knob counter-clockwise to the end position, the potentiometer reaches 0 Ω, and the now directly connected capacitor further reduces the resonant frequency of the pickup and cable in combination to values below 1 kHz. Turning the knob to the other extreme position leaves the full resistance of the potentiometer connected to the circuit. This results in a minor dampening of the resonance with the capacitor acting like a short circuit (i.e. having no audible effect in itself). Some guitars sport a special potentiometer which completely switches the resistance out of the circuit in the clockwise end position – in this case the resonance is fully retained without any dampening. Normally, however, it is safe to assume that the volume and tone controls do have a load-effect on the pickup. To be certain, one would have to make a measurement or have access to the schematics. The latter are also advantageous if the guitar holds a battery and an amplifier the input impedance of which would be the effective load to the pickup.

Fig. 9.1: Schematics for an electric guitar
T = pickup, P = volume control, R = tone control, C = capacitor.
The figure on the right shows the effective electrical situation for clockwise position of the controls ("full up"). The clockwise end-position of the potentiometer taps in the figure on the left is at the upper end of the resistor for the volume control and on the lower end for the tone control

Translation into English by Tilmann Zwicker

Fig. 9.1 shows a typical guitar circuit. By twisting the knob, the potentiometer tap (the arrow in the figure) can be moved continuously between the end points. The rotational angle usually extends over about 270°. For **linear** potentiometers, the tapped resistance is proportional to the rotational angle while for **logarithmic** potentiometers, the resistance change rises progressively (see **Fig. 9.2**). Theoretically, the potentiometer characteristic can be shown as exponential function. The *logarithm* of the exponentially growing resistance is proportional to the rotational angle: thus the designation *logarithmic potentiometer*. In practice, substantial deviations from the exponential function are likely because for cost reasons this desirable characteristic is only approximated.



Theoretical dependency on angle of rotation:

$R/R_{max} = k^{x-1}$ $x = 0 \ldots 1$ $k = 50 \ldots 300$

Fig. 9.2: Resistance characteristic for a linear potentiometer (straight line) and logarithmic potentiometers (hatched area).
The dashed line shows a typical characteristic of potentiometers used in vintage Fender guitars

Potentiometers of recent production typically have **tolerances** of about +/-20%, i.e. the actual value of a 250-kΩ-Potentiometer lies between 200 and 300 kΩ. Even 150 to 350 kΩ values can occur as outliers – especially with older guitars which appear not to have been subject to any excessive quality control. If a tone pot has a value of 350 kΩ rather than 250 kΩ the guitar sounds more brilliant. If this is not desired, turning down the pot slightly (for the purist: twist the knob counterclockwise) will compensate. Connecting a 0.9 MΩ resistor in parallel to the pot will do the same job. On the other hand, a pot having merely 150 kΩ will make the guitar sound duller. In this case the only remedy will be exchanging the pot. Still really dramatic differences are not to be expected (see **Fig. 9.3**). The most important parameter for a potentiometer are resistance and angle-over-resistance characteristic. The power rating (usually 0,1 - 0,5 Watt) is unimportant since the pickups will generate merely a few micro-Watts. All other parasitic electrical effects (capacity, inductivity) can be neglected in the audio range. Good contacts (i.e. no drop-outs across the turning range) go without saying when using brand potentiometers. The latter will cost in the order of $ 2.- to 4.-. Prices of more than $ 100.- for "vintage parts" are not justifiable from an engineering point of view.

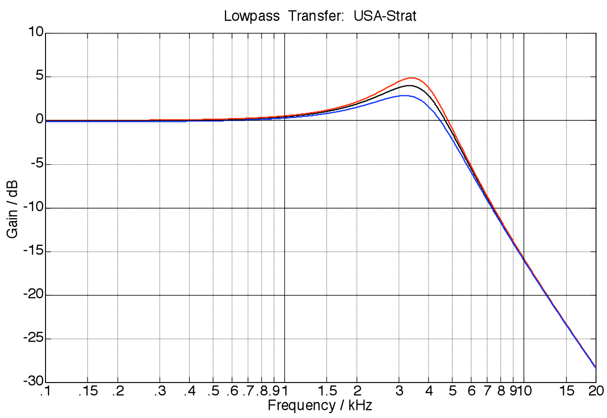


Fig. 9.3: Influence of different potentiometer values for a Fender Stratocaster. Tone and volume pots were (both!) assumed to be having a value of 300, 250 and 200 kΩ.

In **Fig. 9.4**, the effect of tone and volume control is shown for a Stratocaster. Merely turning down the **volume** slightly will already make the resonance peak disappear. The sound becomes duller. The reason for this is that a part of the resistance of the volume control is now connected between the pickup's coil inductance and the capacitance of the cable to the amplifier. This series resistance dampens the resonance. When turning down the volume further, a further resonance at a higher frequency appears but this is not really usable since the signal level is very small. Turning down the **tone** control first also reduces the resonance peak but – at fully CCW-position – then leads to a resonance at a lower frequency (typically around 350 Hz).

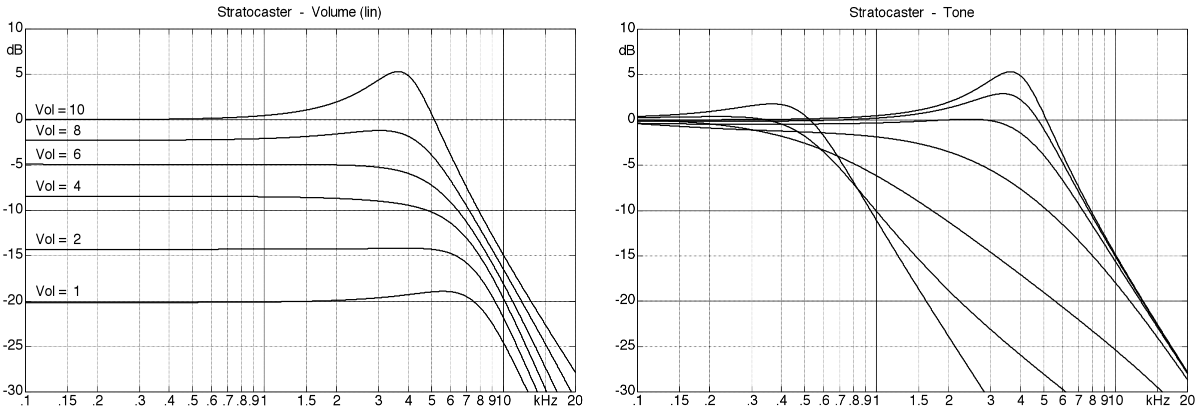


Fig. 9.4: Stratocaster: Volume control (left), tone control (right); 600-pF-cable; 1-MΩ-amplifer-input

Even more extreme is the situation with the Fender Jazzmaster (**Fig. 9.5**). Here, the high-impedance volume pot (1 MΩ) kills the treble radically already when turning down the volume just a bit. Of course, the resistance changes only have the shown effect if a high-input-impedance amp is connected to the guitar. A typical input impedance for tube amplifiers is 1 MΩ (this is indeed considered "high"). Smaller input impedances of the amp will reduce the Q-factor of the resonance circuit and therefore the resonance peak.

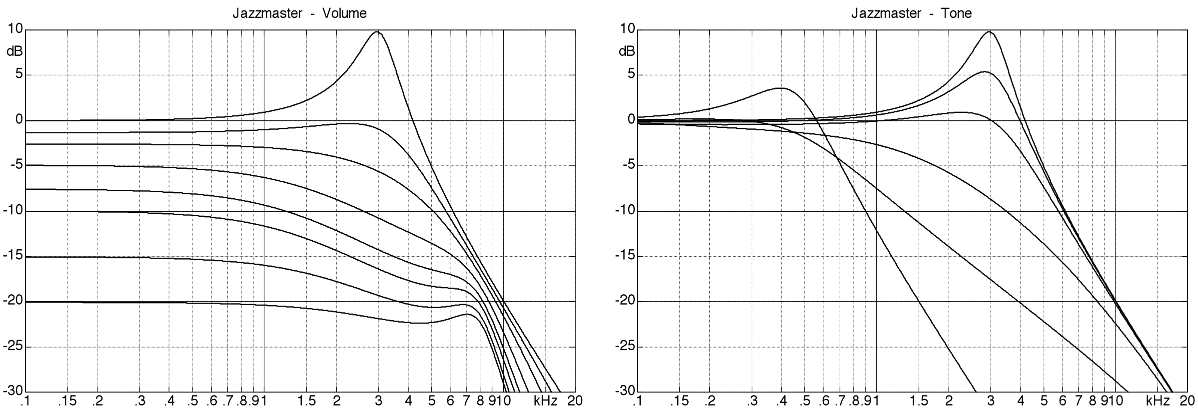


Fig. 9.5: Jazzmaster: Volume control (left), tone control (right); 600-pF-cable; 1-MΩ-amplifer-input

As a potentiometer is turned fully CW or CCW, a **resistance remains** between the tap of a potentiometer and the connection close to it. This might also deserve some consideration. High quality pots have a very small remaining resistance (< 50 Ω). Audible effects can be expected if the remaining resistance is more than ca. 500 Ω – however potentiometers showing this are very low grade and should be discarded.

The treble loss perceived with turning down the volume pot can be reduced by soldering a **bridging capacitor** between the tap and the CW end connection of the pot (**Fig. 9.6**). For low volumes (i.e. a turned-down volume pot) a stronger treble boost can be achieved. When in 1967 the Telecaster was fitted with a 1-MΩ-volume-pot, Fender evidently discovered the strong tone change this pot can result in: the guitar received a bridging capacitor (1 nF).

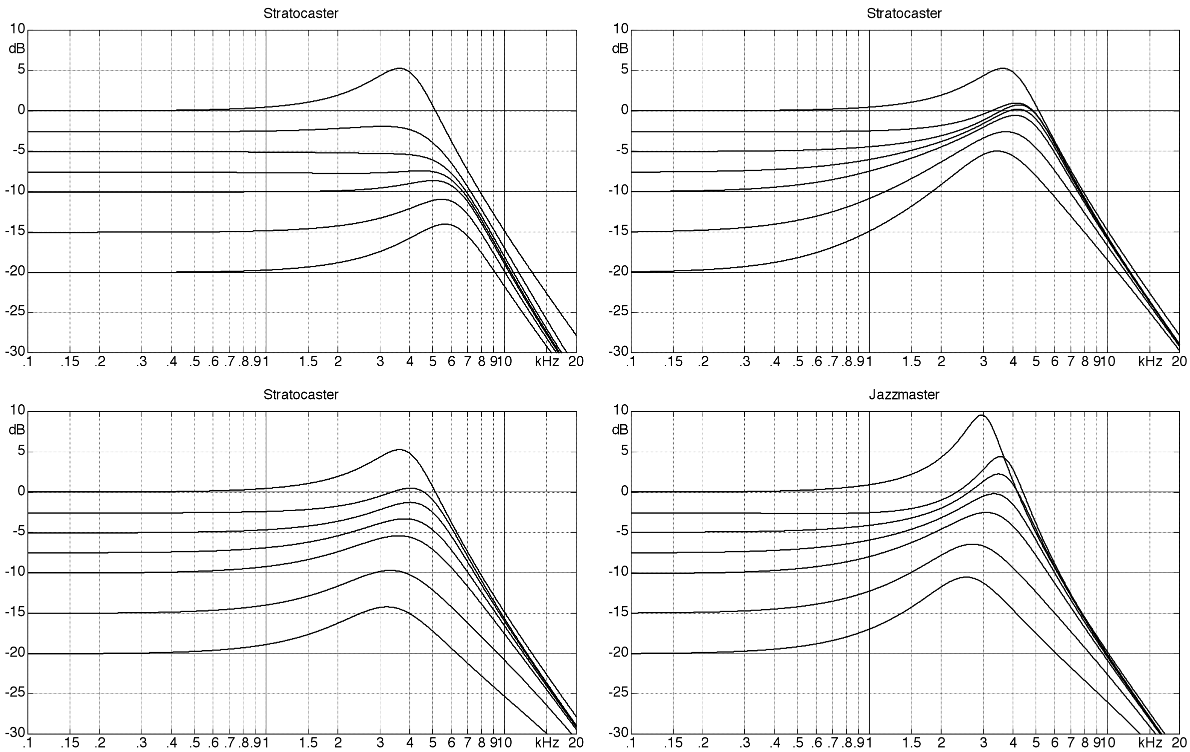


Fig. 9.6: Stratocaster: volume pot with bridging cap; 150pF (upper left), 1nF (u. r.), 1nF//100kΩ (l.l.); Jazzmaster: 1nF//150kΩ (lower right); all diagrams with 600pF-cable and 1MΩ amp input impedance

Selective tone changes are possible with **LC-filter-networks** installed in the guitar. One example is shown in **Fig. 9.7**: for some Gibson guitars a 8-H-coil is fitted. A rotary switch connects various capacitors in series with this coil creating a resonant shunt connected in parallel to the pickup. The result is an attenuation of a narrow band of frequencies. It appears that the tonal control achieved this way did not enthuse many guitar players since the demand remained rather low.

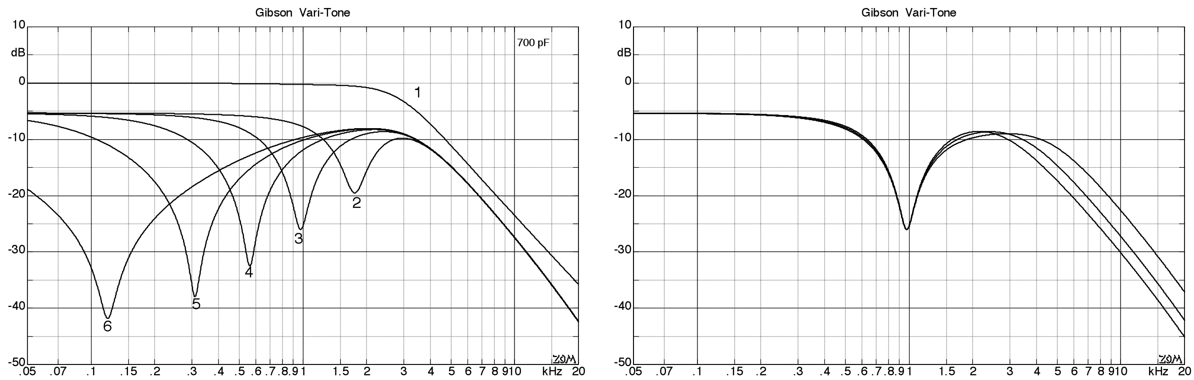


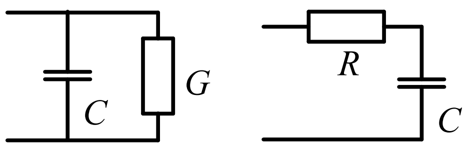
Fig. 9.7: Vari-Tone-Filter of the Gibson Lucille: 6 frequency responses selected via a rotary switch (left, cable capacity 700 pF). Right: the cable capacity is varied (330 pF, 680 pF, 1000 pF) for Vari-Tone position no. 3

9.2. Tone capacitor

The tone capacitor is in a series connection with the tone pot and allows for an attenuation of the treble frequencies. Values of 20 - 50 nF are often used, more rarely one finds 100 nF (in old Fender guitars). Capacitors can be characterized by their capacity value (measured in units of Farad) as a first order approximation. Additional parameters may be important – this depends on how exact the description needs to be.

A capacitor **stores** separated (positive and negative) charges. At the same time it converts a small amount of the electrical energy into **heat** and thus has the effect of a loss resistance. In the overall balance energy cannot be "lost", however the generated tiny thermal energy is not available anymore as *electrical* energy – thus the use of the term "loss". There are several **reasons** for capacitor losses: insulation resistance in the dielectric, connection-wire- and electrode-resistances, polarization losses (the oscillation of the dipoles in the dielectric re. their rest position causes a warming, see 10.9.3)

Simple models for a capacitor extend the capacitor schematic by a resistor (**Fig. 9.8**). A characterizing value is the **dissipation factor** *d*. The arctangent of d results in the **dissipation angle** ∂ which describes the phase shift due to the loss.



$d = G/\omega C; \quad d = R \cdot \omega C$
$d = tan\partial$ = dissipation factor

Fig. 9.8: Simple capacitor equivalent circuits: NEB (left), HEB (right)

In literature, the GC-parallel circuit is designated as the low-frequency equivalent circuit (in German Niederfrequenz-Ersatzschaltbild: NEB) while the RC-series circuit is designated as the high frequency equivalent circuit (in German Hochfrequenz-Ersatzschaltbild: HEB). For the NEB, *d* has a reciprocal dependency on frequency, while for the HEB this is proportional. Measurements show that the NEB is not suitable at all for the audio range because the dissipation angle increases with frequency and does not diminish (**Fig. 9.9**). On the other hand, the HEB reproduces the frequency dependency only very roughly – the quantitative correspondence is unsatisfactory.

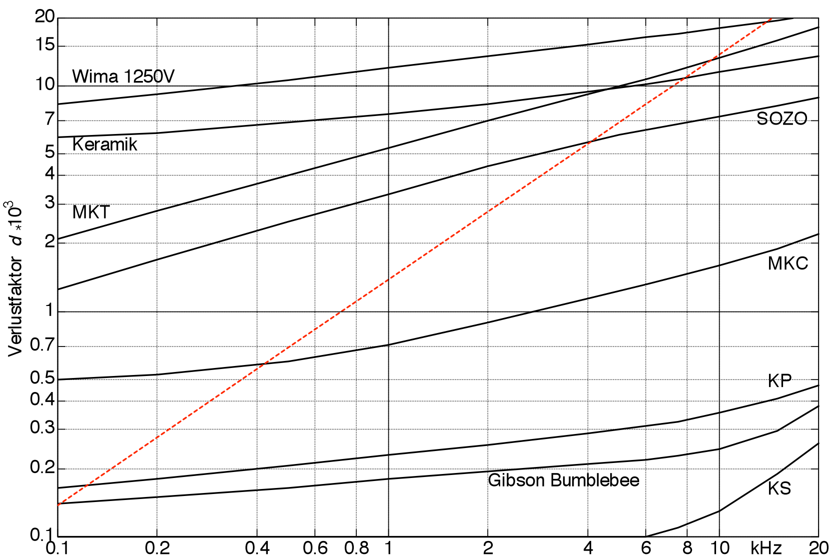


Fig. 9.9: Dissipation factor *d(f)*. Measurements of various 22-nF-capacitors. The high-frequency equivalent circuit results in the dashed straight line (10Ω in series with 22 nF).
MKC = Polycarbonate
MKT = Polyester
KP = Polypropylene
KS = Polystyrene = Styroflex

Fig. 9.9 shows that capacitors can have rather different electrical characteristics - even if their capacitance values are the same. However, it would be wrong to reason based on this fact that the sound of an electrically amplified guitar would vary correspondingly. Components other than the capacitor determine the overall losses in the electrical circuit. With the tone control "fully up" (i.e. the tone pot has its maximum value) there are typically 250 or 500 kΩ in series with the tone cap. Compared to this it is insignificant whether the capacitor losses are 500 Ω or merely 10 Ω. Even if one would radically replace the tone cap by a short, the transmission factor changes les than 0,01 dB in the relevant frequency range. This does not mean, however, that the tone cap has no effect at all if **the tone pot is "fully up"**. It does: relative to the tone pot it works – as a very good approximation –– as a short. It makes no difference whether its value is 20 or 60 nF, and it makes no difference whether the dissipation angle is 0,1% or 5%.

With **the tone control "fully closed"** (i.e. the tone pot has its minimum value), losses are dominated by the pickup and the volume potentiometer connected in parallel. For the Stratocaster the pickup inductance works with the tone cap towards a slight resonance peak around 350 Hz (**Fig. 9.10**). Only here the capacitor losses have any effect. In Fig. 9.10 the corresponding transmission factors for both an ideal, lossless capacitor, and an extremely lossy capacitor are shown. Lossless implies a $d = 0$ while for this example $d = 60\%$ is taken for the lossy component. Such a "bad" capacitor is not normally soldered into any guitar. If one would opt for one of the "bad" capacitors from Fig. 9.9 (e.g. choose a $d = 0{,}1\%$), the level differences in comparison to the lossless capacitor would amount to $\Delta L < 0{,}1$ dB i.e. they would be inaudible. Therefore, for the tone control fully closed it is still true that the dissipation factors of customary available capacitors have **no audible consequences on the sound whatsoever**. This does not only hold for the Stratocaster but for other guitars. Indeed, even the tone caps in a Les Paul are subject to the same laws of physics – irrespective of the price they command on the vintage market. To take a quick look at the remaining resistance of the tone pot: a fully closed potentiometer will of course not result in an ideal short-circuit, however even the remaining resistances (< 100 Ω) of low-cost pots will easily suffice and do not lead to audible differences.

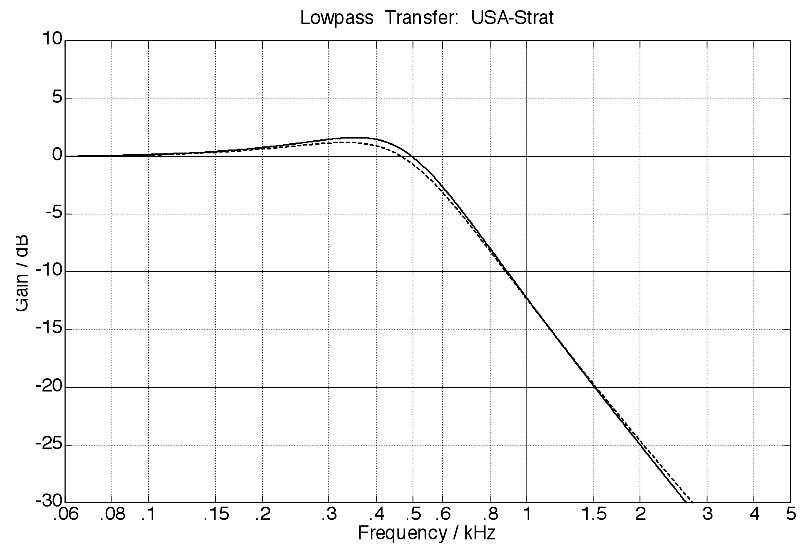


Fig. 9.10: transmission factor of the Stratocaster, tone control full down two different capacitors (solid line = lossless)

If capacitor losses have no audible effects on the sound – how come there are som many reports from guitar players who state that their instrument sounds "totally different" after changing the capacitors? Discarding those cases where the guitarist (or sound guru) also changed the strings as well (since everything was taken apart anyway), enough cases remain which merit consideration. Could there be – other than the dissipation factor – other (possibly undiscovered) parameters to describe the electric effect of a capacitor? Is this question already to restrictive again? Could a capacitor generate non-electric effects? In principle yes: from a mechanical point-of-view it is a mass suspended from springs (the connecting wires). Thus it could co-vibrate. This observation encourages to go further: Does the John-Lennon-Casino sound authentically only when the knob has been lost? Is the original E.C. sound only generated if a cigarette is clamped between strings and headstock? Does then the sound change because the mass of the co-vibrating cigarette goes up in smoke over time? There would also be microphonics and tribo-electricity (Ch. 9.4) ... this will not be considered here.

But back to the electrical parameters: the modeling of a capacitor via an RC-network is only admissible if insinuate linear behavior. However, the moment a voltage is applied to the capacitor's electrodes, attraction forces appear which reduce the electrode distance - and an increase of the capacity follows suit. The systemic quantity "capacitance" becomes dependent on the signal fed through the capacitor, and this situation points to a nonlinear system behavior. **Distortion factor measurements** show, however, that such non-linear processes are insignificant: at 2 V_{pp} the measured distortion amounted to less than 0,01% for film capacitors and 0,1% for ceramic caps. Consequently, this aspect can be excluded as a reason for audible differences between capacitors in electric guitars.

So, what remains? The **capacity** itself, of course! With all the considerations regarding capacitor characteristics we must not forget that the capacity is subject to production tolerances. A new capacitor of nominally 50 nF may well have a real capacitance of only 40 nF. In the mid-20th century, tolerances of +/- 20% were not uncommon, and even today tolerances of 1% are commercially available but certainly not the standard. **Fig. 9.11** depicts the effects of a capacity tolerance of 20% for a Stratocaster – and such level differences are without a doubt audible. Therefore it is conceivable that a guitarist who changes the el-cheapo capacitor fitted into his guitar for a $50 "replica cap" indeed notices a change in sound. This change would have been achievable with a regular MKP capacitor costing a full 18 Cents as well .... but of course an "original bumblebee" exudes are radically different aura (i.e. "mojo"), and everybody should reach happiness after their own fashion. The after-market industry as well lives off those who furnish their $100 guitar with four Centralab pots ($100 each) and two replica caps ($50 each) – which helps to distinguish oneself from the many unenlightened.

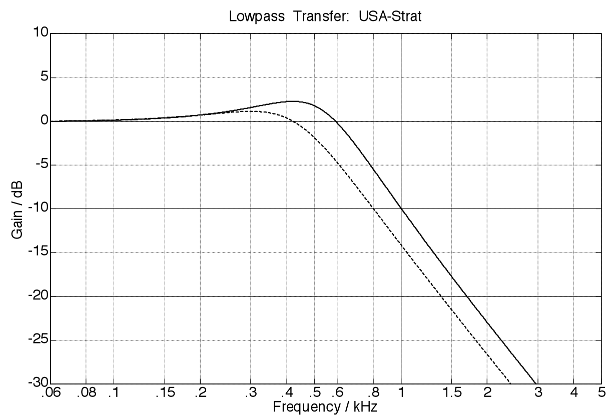


Fig. 9.11: transmission characteristic for a Stratocaster, tone control turned down, two different capacitors: 60 nF and 40 nF. When the Strat was released originally, Fender fitted 100 nF capacitors, from 1970 50 nF were used, followed by 22 nF from 1983. The smaller the capacitance, the higher the resonance is in frequency and the stronger it is pronounced.

The decision for or against a certain tone cap will always depend on subjective preferences. Rumor has it that there are those Jazz guitarists who continue to ask themselves in puzzlement what might have caused Gibson to include a bridge pickup on an ES-335 might be. Why then shouldn't there be a Stratocaster owner who exchanges the 22nF tone cap for one with 100 nF? The guitar could be closer to what Leo Fender devised originally, or it could sound less shrill .... the larger the capacitor, the darker the sound with the tone control turned fully CCW (**Fig. 9.12**). On the other hand, rotary switches are available which allow for selective connection of smaller capacitors (e.g. 1 - 10 nF. To each his/her own – motivated by no-physical thinking (*same as Jeff Beck has*), paraphysics (□□□□□□□), pragmatism (*was already installed, is ok*), or devotion (*was recommended in the March issue of "Guitar Picks & Licks"*). Those who require the exact nominal value but have no capacitance meter at their disposal could buy a 1%-tolerance-MKP-capacitor for 60 Cents. Those who are happy taking a risk buy a handful of 5%-tolerance-MKP-caps (20 cents each) and check whether they can already hear differences between the capacitors. From the dielectrics listed in the following table, polypropylene and polycarbonate are particularly suitable, but MP, KT, MKT or NDK may be used without audible deterioration. Of course, the capacitor needs to be undamaged. A styroflex cap which got too close the soldering iron may well be much worse than an unscathed MKT-capacitor.

Designation	**Abbreviation**	**d in %**	**comment**
Glimmer	Mica	>0,1	difficult to obtain, large, unpractical for guitar
Polystyrene = Styroflex	KS, MKS		0,1 very high-grade
Polypropylene	KP, MKP	0,3	highly suitable
Polycarbonate	KC, MKC	1	highly suitable, very good temperature coefficient
Paper	MP	4 - 8	well suited
Polyester	KT, MKT	5 - 10	well suited
Ceramic class 1	NDK	< 1,5	well suited
Ceramic class 2	HDK	< 30	unpractical for guitar
Ceramic class 1	-	< 60	unpractical for guitar

Table: Dissipation factors of commonly used dielectrics

Fig. 9.12 shows the effects of the tone cap with the tone control all the way "down". Cable capacity is 500 pF; input impedance of the connected amplifier is 1 MΩ. With the tone control all the way up one gets the dashed line.

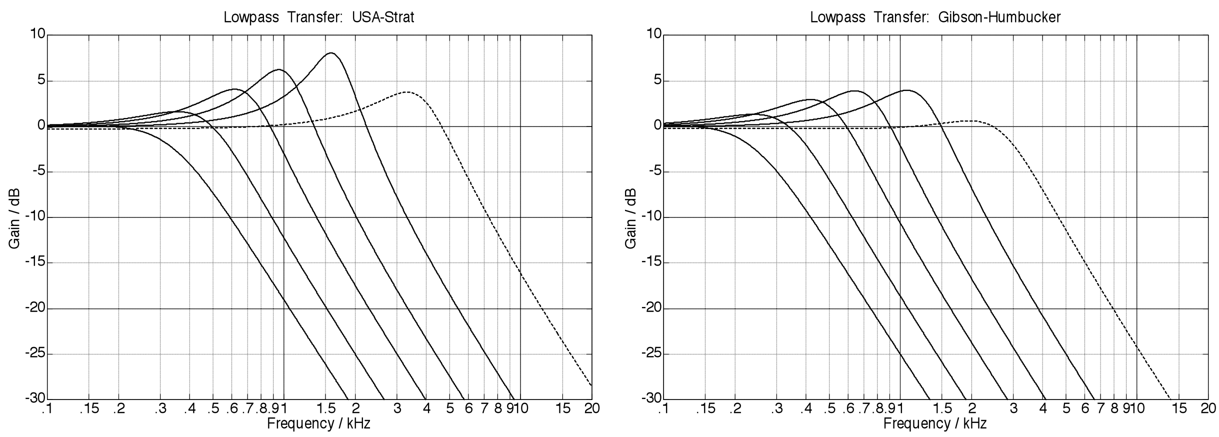


Fig. 9.12: effect of different tone caps: 100 nF, 50 nF, 22 nF, 10 nF, 3,3 nF; dashed line: tone control fully CW

9.3 Pickup Connecting Wires

One would think that the wire connecting the pickups with the switches and controls do not have any significant influence on the electric parameters of a guitar. In most cases this assumption would indeed be correct – however there are exceptions.

In Fender guitars, the internal wiring is often done via **single stranded wires** which are paired and soldered to the pickups as a so-called two-wire line. Such a connection can - for the audio range - described with very good approximation as a pure capacity having about 50 pF/m. A length of 20 cm (as it would typically occur inside a guitar) would thus yield a capacitance of 10 pF which is a value that is clearly negligible relative to the capacity of the guitar cable. Losses, as well, do not play any role: even if one would assume d = 0,01, the loss resistance in the equivalent circuit would be more than 100 MΩ.

As an alternative to the two-wire line, **coaxial wiring** may be used. An insulated internal conductor is surrounded by a concentric shielding braid or stranded wire. Depending on geometry and the dielectric, capacities of 50 - 200 pF/m will occur – which is already more than what the two-wire line exhibits but still immaterial for the typical small lengths in the guitar interior. But then, there's Gibson. Many of the pickups of this manufacturer sport a coaxial cable with astounding characteristics. When we measured the 50-cm-long cable of a **P90** pickup for the first time, our spontaneous reaction was: our PM6303 instrument is clearly broken. The display showed 700 pF in parallel with 500 kΩ at 1 kHz – which is a whole order of magnitude away from the expected value. However: Philips again proved to be dependable: the instrument worked flawlessly. The cable capacity was indeed that high (**Fig. 9.13**). Typical insulators have a dielectric constant of between 2 and 4 – this could not explain such a large capacitance. There is however a substance with a high dielectric constant of about 80 that could help to explain what was going on: water! If indeed the fibrous insulating material is hygroscopic und absorbs water, such a large capacitance could actually result. We tried and heated the cable to 75° C for 5 hours – and, alas, the (cooled down) capacitance dropped to 160 pF.

Such a "special" cable hits back in several ways: the high capacitance exceeds possibly even that of the guitar cable and this audibly reduces the resonance of the pickups, plus the high losses dampen the resonance. These effects are dependent on humidity! in the humid basement the guitar sounds duller than in dry, heated rooms – and this is due to a cable, not due to the wood! We would have liked to print here a comment by the manufacturer .... but those concerned preferred not to reply to an inquiry.

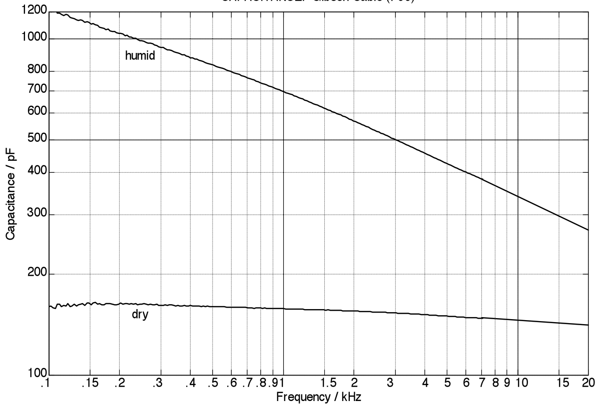


Fig. 9.13: capacitance of a 50 cm long Gibson pickup cable (pickup disconnected). The two curves were measured at different points in time.

9.4 Guitar Cables

Guitar pickups are usually connected to the guitar amplifier via a cable several meters long. In more rare cases an amplifier is already built into the guitar or even into the pickup - wireless connections are also used. The customary guitar cable determines the sound. Its capacitance generates - in cooperation with the capacitance and the inductance of the pickup coil - the **pickup resonance** which lends a characteristic color to the transmission.

The guitar cable holds an internal conductor (in some cases two). This is constructed as a thin, flexible stranded wire (sometimes two) outwardly insulated cylindrically e.g. by foamed polyethylene. Around the insulator there is a concentric braided shielding which sometimes holds conducting synthetics in addition. For high-quality cables double shielding is customary. Every differential little piece of cable can be described by four elements: a series resistance, a series inductance, a parallel capacitance and a parallel resistance.

The series resistance amounts to just a few Ωs - it may with very good approximation be fully neglected re. the source impedance (kΩ). The series inductance (ca. 1 µH) is so small, as well, that is will not play any role here. As a rule, the parallel resistance is large (> 100 MΩ) to the extent that it, too, will have no audible effect. On the other hand, charge displacements and corresponding very small mechanical deformations will occur in the dielectric (the insulating synthetic). This will lead to mounting energy losses with increasing frequency. Such effects cannot be captured with a normal **insulation measurement** which is normally done with direct current. For this reason, more elaborate equivalent circuits feature not just one simple (real) parallel resistor but a complicated **RC-array** modeling the complex parallel conductance. On other words: the **cable capacitance** is frequency dependent to a small degree and decreases a little with increasing frequency, while the **cable losses** are strongly frequency dependent and mount with increasing frequency.

Lossy capacitances are described in a simplified manner by an RC equivalent circuit. In the lower frequency ranges an RC parallel circuit is employed while in the higher frequency ranges an RC parallel circuit is used. The energy stored in the capacitor can be recalled, however the resistor irreversibly converts electrical energy into thermal energy – thus the term **loss**. In the complex admittance plane, the admittance real component represents the conductance due to the loss while the admittance imaginary component is the susceptance due to the capacitance. Instead of the Cartesian coordinate system with conductance and susceptance the polar coordinate system with magnitude and phase may also be used. The magnitude is the admittance while the tangent of the complementary phase angle ∂ is the dissipation factor *d*.

$d = \tan \partial = 1/R \cdot 1/(\omega C) = 1/(\omega RC)$ ∂ = dissipation angle (Fig. 9.14)

For high quality capacitors the parallel resistance *R* is very large, and consequently the parallel conductance *1/R* very small. The result is a very small value for ∂. Data sheets show e.g. values of $d = \tan \partial \approx 10^{-4}$. Inserting into the above formula a frequency-<u>in</u>dependent resistance *R* and a frequency-<u>in</u>dependent capacitance *C* should lead to reciprocal dependency of tan ∂ on frequency. However, in reality tan ∂ is more or less constant at lower frequencies, and for many insulators even an increase with frequency is found (see also Chapter 9.2, tone capacitor).

The measurements are in clear contradiction with the formula shown above. If frequency dependent components (the function of which is difficult to understand) are to be avoided, the only solution is to extend the equivalent circuit to multiple components. Depending on the desired accuracy a rather large RC array may be required. Fig. 9.14 shows one simple and two extended equivalent circuits.

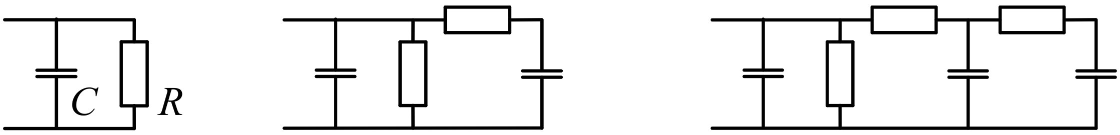


Fig. 9.14: Two-pole equivalent circuits of different complexity for a guitar cable. (see also 5.9.2).

Cable capacity and pickup inductivity cooperate to generate a **resonance** in the frequency range between 2 and 5 kHz. The cable capacity is an indispensable partner in this resonance circuit and determines the sound. Cable losses dampen the resonance – however this is negligible for good cables. As has been discussed already, it is not proper to use the (very high) insulation resistance for considering the cable loss; rather a loss simulation dependent on frequency is required. Since the pickup/cable resonant circuit has its highest impedance at resonance frequency, a dampening resistance in parallel has the biggest effect. High quality cables will yield loss resistances > 50 MΩ in the frequency range of the resonance. Compared to other losses and in particular compared to typical potentiometers used in guitars (250 kΩ), **such cable losses are consequently negligible**. This does not mean that cable losses are negligible in general. For radio-frequency transmission other criteria are valid. Guitar cables however are operated in the audio range – and here only the cable capacitance is of importance. High quality cables cost a couple of $/m – add some high quality plugs and the cost can be some $ 20.-. That should be it. "Monstrous" prices are not justifiable from a physics point of view.

The **cable capacity** usually is around 100 pF/m (+/- 30%). Normally used cable lengths thus yield capacitances of **300 - 600 pF**. For very long cables this could rise to up to about 1,5 nF. Special low-capacitance cables go as low as 70 pF/m. For comparison measurements we had access to a 40 year-old guitar cable (i.e. truly "vintage" ☺). It was 4 m long and sported a rather remarkable 1050 pF, plus a similarly noteworthy loss resistance of only 500 kΩ. Compared to the low-capacitance cable mentioned above with 4 x 70 pF = 280 pF there is a large and clearly audible difference. The effects of the low loss resistance can be (just) audible for high-impedance guitars, as well. The "vintage" cable is however not typical for modern cable production.

Next to the above elementary electrical parameters there are some other properties of importance: shielding effect, mechanical resilience, flexibility, safety against fracture, flexural strength and **low noise performance**. It may be surprising that a cable can generate noise. Bending and straining changes the mechanical tensions in the insulator which can lead to charge displacements. The latter can manifest themselves as crackling noise (tribo-electric effect) - for high quality cables this is not audible, though.

The sound of an electric guitar can audibly change when the **cable is switched**. Unless very low-quality cables are used, the reasons are **solely** found in the different cable capacitances. Relaxation phenomena (orientation polarization, inertia of dipole rotation in the frequency range f > 1GHz), dispersive signal-propagation or non-linear effects are insignificant in the audio range. Physics are neither applicable nor competent in the area of esoterism – nor are psychoacoustics.

Old **coil cords** could often be stretched to 5 m. The actual cable length was even longer – 8 m were probably not untypical. Capacitances of about 2,1 nF and loss resistances of 250 kΩ could be the result. If someone would like to reproduce specifically these old "vintage" characteristics but is shying away from laying 21 m of modern cable 21 x 100 pF = 2,1 nF) could solder an additional capacitor to the cable. The effect of the loss resistance can be reproduced by turning down the tone control to some degree. The final evaluation should be done via a listening test. To exclude prejudice and bias, a blind test with direct A/B-comparison is recommended.

A very flexible solution can be obtained by connecting different capacitors via a **rotary switch** to a short low-capacitance cable – the resonance frequency is now adjustable. The connection of a capacitor is indispensable in particular if a usual magnetic pickup is to be connected to an amplifier (e.g. an on-board pre-amp) *without* a long cable. The resonance frequency of the pickup without the loading by the cable capacitance is too high such that the sound becomes "glassy" or "too sharp". If this sound is not actually desired, a capacitor of 300 - 1000 pF needs to be connected in parallel to the pickup in lieu of the cable.

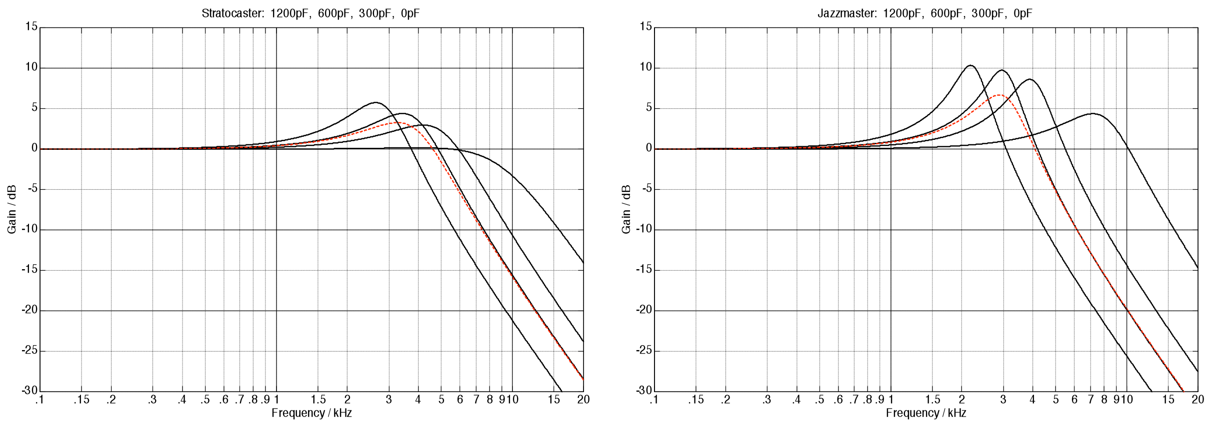


Fig. 9.15: Low-pass transmission for varying cable capacitances: 1200 pF, 600 pF, 300 pF, 0 pF. The solid lines show loss-free cables, the dotted line refers to a 500 kΩ loss resistance. For modern high quality cables the loss resistance of R>50 MΩ in the range of the resonance frequency is certainly negligible.

In **Fig. 9.15** we see the influence of the cable capacity on the H_{Uv}-transmission function (low-pass model). Elongating the cable has the effect of a capacitance increase proportional to the length increase. This reduces the resonance frequency. The resonance peak at the same time becomes stronger. The figure is meant to exemplify the effect in principle. Additional data are found where the specific pickups are discussed.

Fig. 9.16 depicts the loss factors for a number of guitar cables. The five lines in the upper region of the figure are the results of guitar cables from old production, and of modern microphone (!) cables. These cables can result in an audible dampening of the resonance. The cables of the makes Horizon, Straight, Klotz LaGrange and Gibson will clearly not decrease the resonance peak, nor will the RG58-CU used in measuring and instrumentation (it would however not be flexible enough as a guitar cable). The rather thin George-L's-cable can be seen as a borderline case: the dissipation factor should not exceed 2% in the range of the resonance frequency (2 - 5 kHz).

Microphone cables are generally not suitable as guitar cables. They are usually a two-wire line and optimized for connection to a differential amplifier input; the issue of low capacitance is not much considered. The survey measurements revealed microphone cables sporting a rather sizeable 250 pF/m and dissipation factors of 10%. When operating a dynamic 200-Ω-microphone one can still get very good results with a 10-m-long-line, but for a high-impedance guitar such a cable should not be used. This does not imply that microphone cables are generally unsuitable for electric guitars – there are indeed also very good microphone cables. The suitability should therefore be checked in the specific situation.

It should be general knowledge that **loudspeaker cables** are unsuitable for guitars. Most often speaker cables are constructed as thick stranded cables, and they are not shielded. The pickup might be susceptible to noise, but at least the cable should be silent.

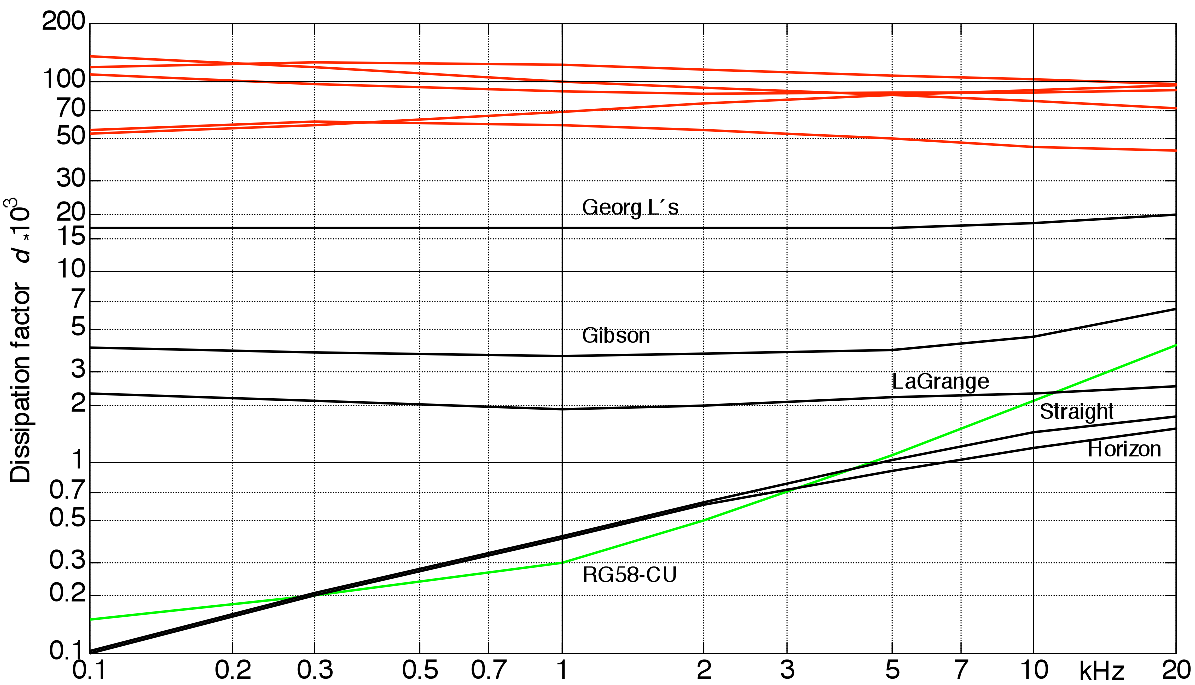


Fig. 9.16: Dissipation factors of guitar cables. The sample shows just a few examples, there are many more manufacturers.

It is no surprise that inconceivable nonsense is sometimes found in advertisements – rather this appears almost to be part of the specific charm of the genre. In contrast, editorial test reports published regularly in musician's magazines carry a high weight since one assumes an independent expert author to be behind it. To illustrate here an excerpt from a well-respected guitar and bass magazine: in an issue in spring 2000, the well-known author notes, in the framework of a test of instrument cables, with some prudence: *"According to the manufacturer, the Monster-Cable Performer 500 Rock supposedly is distinguished by an aggressive sound, while the Bass Instrument Cable (Performer 500 Bass) supposedly has a particular strength in the low frequency range and achieves an extended-dynamic performance.*" Supposedly! This wording leaves room for interpretation of the kind we know to be smart when dealing with the tourist industry: "given that the hotel is located in the immediate vicinity of the airport, it supposedly is relatively quiet." If you still go there, it's your own fault. In the next issue of the same magazine the same author writes: *"While the cables for bass and Rock distinguish themselves through emphasizing the cutoff frequencies and aggressive presence, respectively, the Performer 500 Jazz establishes itself audibly more succinct in the lower mid frequencies and presents the character-defining timbre-range with extensive emphasis but remains pleasant and round .... compared to other Monster Cables, the Studio Pro 1000 appears a tad softer - this can be traced to a particularly balanced transmission without any emphasis or peculiarities."*
So much for diplomatic restraint: here is the opinion of the man carrying out the test. Of course, he is entitled to it and may publish it. However, he will then have to put up with the question whether he indeed has any clue at all of the electric function of a cable. "Without any emphasis"? Does that mean the cable has no capacitance? That would probably not work, and it is not desirable, either. What actually is the capacitance of these wonder-cables? One could easily and cost-effectively measure them and publish the result - the reader would take away much more than he will profit from speculations about cutoff frequencies. In any case the price of these wondrous cables does not remain in the dark (remember, this is in 2000, and below we are using a conversion rate of slightly more than 1 $ to the EUR):

- Performer 500 Monster Bass Guitar Cable 6,4 m: ca. $ 70.-
- Performer 500 Monster Rock Guitar Cable 6,4 m: ca. $ 70.-
- Performer 500 Monster Jazz Guitar Cable 6,4 m: ca. $ 85.-
- Studio Pro 1000 6,4 m: ca. $ 180.- No typing error: **onehundredandeighty bucks!**

It is of course understood that a Jazz-cable will be more expensive than a Rock-cable. If that weren't the case, the marketing manager should be laid off without notice. The step size is o.k., as well: one quarter more expensive. You do see it the same way, dear Jazz guitarists, don't you? But what about the actual level of these prices?? The very high-grade Klotz LaGrange cost at the time about $30.-. Same length of 6,4 m, and a capacitance of 67 pF/m, with two Neutrik plugs. And that cable, as well, will not have been sold without profit ....
It may be that the special capacitance of the Monstercables generated a special sound during the test which led to the mentioned description. Of course nobody will will imply that the Author may have simply copied the advertisement texts provided by the manufacturer and then signed with his name. However the special capacitive load could have been achieved at less expense: for $180.- one could buy 1000 capacitors and as many resistors to go with them. That would have been sufficient for a whole lot of set-ups to emulate ANY cable, even the Monster-ones. And a loc-cap cable with two Neutriks would have been thrown in ...

To cite an author/tester from another magazine: "The idea of an instrinsic sound of cables as propagated by the industry is, in my opinion, a load of total BS." Stated by a well-respected studio owner and regular author with this other magazine.

9.5 Mounting plates

Since the magnetic alternating field is not limited to the interior of a pickup, it is possible that metal parts mounted in the vicinity of the pickup influence the mechano-electric transmission parameters. Examples for such parts are the rectangular bridge plate of the Telecaster lead pickup, or pickguards made from metal. The **eddy currents** induced in these part dampen the pickup and reduce the inductivity *L* and the resonance peak. Some **Stratocaster** pickguards are entirely made of plastic – no eddy currents can happen here. However, often more or less thin metal foil or even metal sheets are glued underneath the pickguard for shielding purposes. The thicker these foils or sheets, the more they dampen the resonance. Particularly "efficient" in this way are pickguards entirely fabricated from metal (e.g. aluminium). The dampening effect can be audible in a direct A/B comparison – the range of brilliance that is so important to the "Fender Sound" is attenuated by about 2 dB. (**Fig. 9.17**)

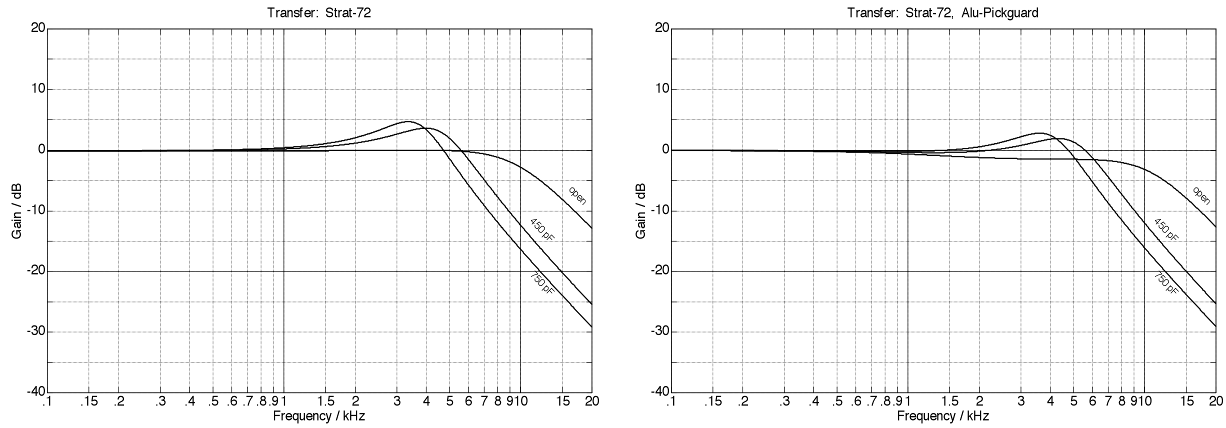


Fig. 9.17: Transfer characteristic of a Stratocaster pickup without and with aluminium pickguard

Similarly, the transfer characteristics of the **Telecaster** bridge pickup will change if a well conducting bridge plate is mounted (**Fig. 9.18**). The differences resulting from the comparison between two bridge plates are however so small that they will normally not be registered. If that happens nevertheless: a thin slit in the bridge plate effectively prevents the eddy currents from flowing.

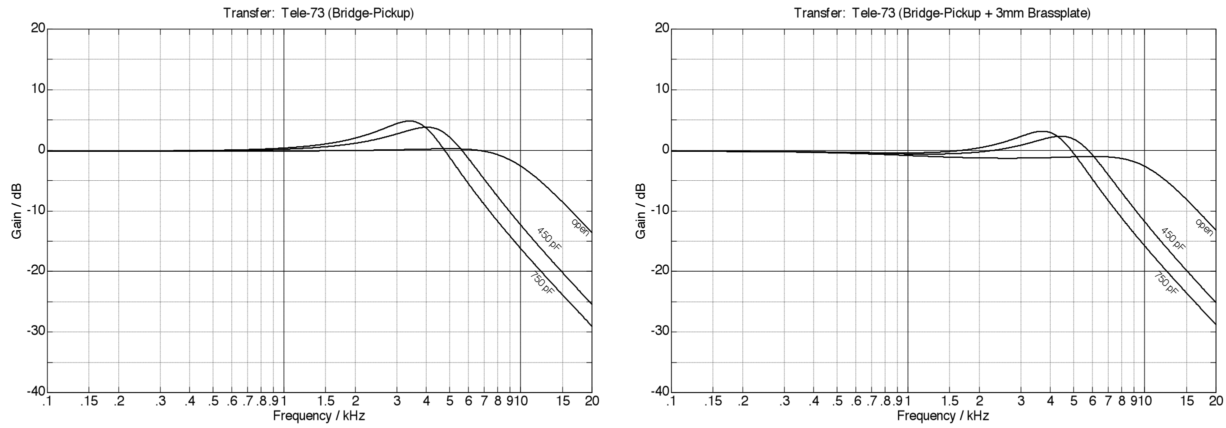


Fig. 9.18: Transfer characteristic of a Telecaster pickup without and with brass bridge plate (Gotoh).