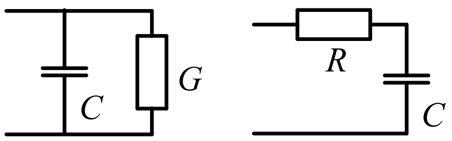
9.2. Tone capacitor

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.

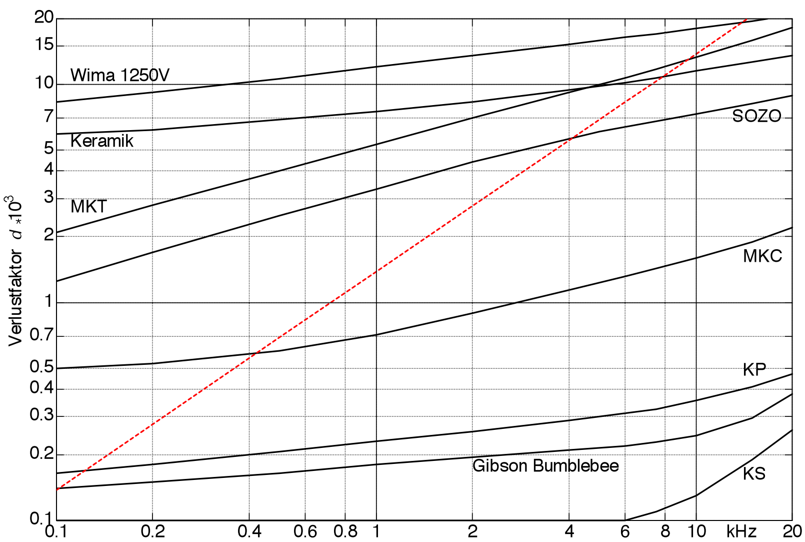


Fig. 9.9: Dissipation factor *d(f)*. Measurements of various 22-nF-capacitors. The high-frequency equivalent circuit results in the dashed straight line (10Ω in series with 22 nF).
MKC = Polycarbonate
MKT = Polyester
KP = Polypropylene
KS = Polystyrene = Styroflex

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.

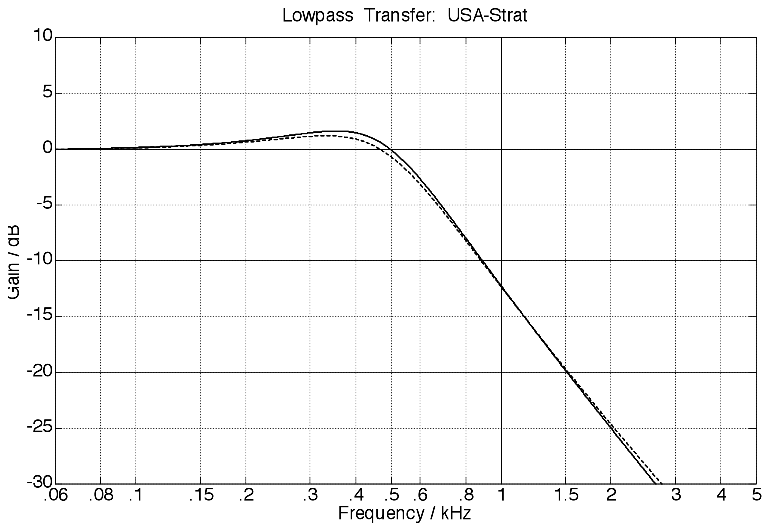


Fig. 9.10: transmission factor of the Stratocaster, tone control full down two different capacitors (solid line = lossless)

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.

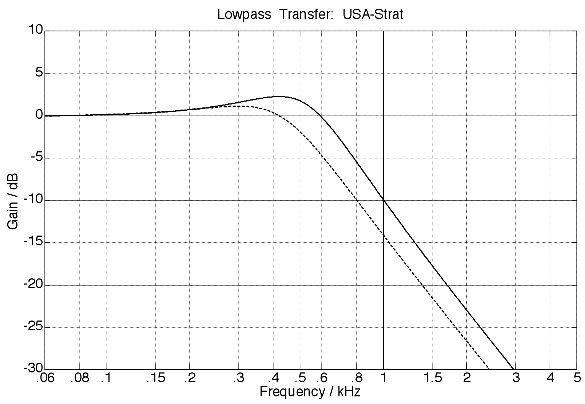


Fig. 9.11: transmission characteristic for a Stratocaster, tone control turned down, two different capacitors: 60 nF and 40 nF. When the Strat was released originally, Fender fitted 100 nF capacitors, from 1970 50 nF were used, followed by 22 nF from 1983. The smaller the capacitance, the higher the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

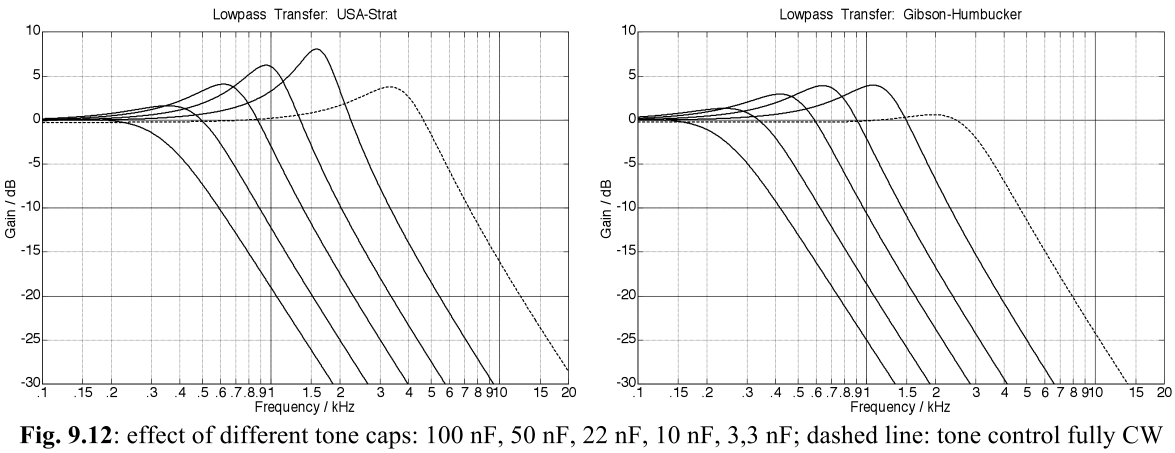


Fig. 9.12: effect of different tone caps: 100 nF, 50 nF, 22 nF, 10 nF, 3,3 nF; dashed line: tone control fully CW