5.9 Equivalent Circuits

The vibration of a string is always a composite from partials of different frequencies. The conversion of mechanical into electrical vibrations in the pickup includes a frequency-dependent weighting: spectral components in the vicinity of the resonance frequency are emphasized, and those of higher frequency are attenuated. The pickup can therefore be considered as a system with frequency-dependent transfer-function i.e. as a filter. According to the teachings of the theory of electrical system (systems theory, e.g. [7]), the transfer behavior of a linear system is unambiguously described by its transfer function. Linear systems with identical transfer function have an identical filter effect, even if they are differently constructed. The construction of a magnetic pickup seems to be simple (a wound wire) – the frequency-dependent filter effect can, however, not be visualized this way. The telecommunication engineer is more familiar with passive filter networks, i.e. networks consisting of coils, capacitors and resistors. In the case of the pickup we use such networks as replacement for the original system: as long as the network in its transmission parameters is equivalent to the pickup, it represents a replacement (a model) the behavior of which is investigated in place of the pickup.

5.9.1 Models and analogies

The approach in physics is to try to explain natural phenomena and make them accessible by a mathematical description. Influencing factors, states and effects of real processes are, however, so diverse that a complete description is impossible. For this reason, simplified systems (**models**) are developed which are equivalent to the reality in a number of (but not all) characteristics. The model-boundaries define what is to be reproduced and what is not. Famous examples of physical models are the simple law of inertia (Newton) which is not valid for relativistic considerations, or models of atoms. The model is the compromise between the exact mathematical description which cannot be realized, and the variations existing in the real world which are, however, to complex to be describable.

The **analogy** (the analogon) is a model-like description in a related area which is usually better understood. To understand the resonance effects in a spring-mass-system, the electrical engineer finds an illustration via an electrical resonance circuit; the mechanical engineer, on the other hand, will probably prefer the opposite approach and look at an electric resonance circuit using an electro-mechanical analogy. For all models and analogies, the respective ranges of approximations and definitions need to be considered: if, for example, an electro-mechanical analogy models merely the transversal movements in one plane, then torsion-vibrations will remain without consideration. The idealized spring has a single elasticity (Hooke) - and therefore is without any mass, which is in sharp contrast to the real spring. In every model it is necessary to find a compromise between complexity and accuracy. Strong simplifications lead to clear, simple structures; however, these may not be able to reflect the effect under investigation with sufficient accuracy, or even to describe it at all. On the other hand, a highly exact model may result in too great a variety of parameters the calculation of which may take too long, or the complexity of which goes beyond the imagination. Purposeful limits for the accuracy of approximation (and therefore for the complexity) are given by the reachable measurement accuracy, the reproducibility, or whether or not a model-specific inadequacy is in fact audible.

Two approaches are often found when models are put together: **inductive**, concluding generally applicable statements from a single finding (bottom up), and the **deductive** conclusion from the general finding to the single event (top down). Both approaches may be used in parallel. The laws of magnetism and those of electrical networks can be applied to all magnetic pickups. The specific equivalent circuit, which would be not sufficiently accurate to generalize, may be supplemented by additional components and thus be improved in its precision (and general applicability).

Models and analogies have led to an adaptation and broadening of the meaning of familiar terms. For example, the term '**flow**', as it would be used in the context of water circulation, relates to a macroscopically visible matter movement. In an electrical circuit, however, the term is directed to the microscopic movement of electrons, while in a magnetic circuit there is no movement (flow) at all (*panta rhei ?*). Nevertheless, we imagine a magnetic flow including flow-lines, flow-density, turn-offs and junctions - very much in analogy to the electrical <u>circ</u>uit … which in itself is not always happening in a <u>circ</u>le, anyway. ☺

5.9.2 Equivalent Circuits for Electrical Impedances

Regarded from the point of instrumentation, there are two pickup characteristics which are of fundamental significance: its electrical impedance and its transfer behavior. Naturally, in the end only the latter is of interest but the corresponding required system parameters can only be determined with much effort. The impedance, on the other hand, can be determined easily and accurately, and forms a good starting point to arrive at the transfer parameters via calculations.

The **impedance** Z is the complex, frequency-dependent resistance of a two-pole element. The term **two-pole** points to the fact that $\underline{Z}$ is to be determined in relation to two poles (junctions, terminals) in an electrical circuit. If a circuit includes more than two terminals, it is possible to define two-terminal-network impedances between any two of these terminals. Using the complex number terminology (designated by underlining the respective character in a formula), magnitude and phase of the impedance can be described elegantly and economically. For this purpose, two different but each individually complete ways exist: the polar and the Cartesian form. In Cartesian coordinates $\underline{Z}$ is constituted from a real and an imaginary part, while in polar coordinates a radius (= amount, magnitude) and a phase-angle.

The impedance of a purely ohmic resistor is real and independent of frequency: $\underline{Z}_R = R$. The impedance of an ideal inductance (wound up wire, coil) is imaginary and dependent on frequency: $\underline{Z}_L = j\omega L$. j is the imaginary unit $\sqrt{-1}$, which in mathematics also is designated with i. The product $j\omega$ is the **complex frequency**[♣], often also termed p or s. The impedance of an ideal capacitance is imaginary and frequency dependent: $\underline{Z}_C = 1 / j\omega C$. If two two-terminal networks are connected in series their impedances add up; if they are connected in parallel their admittances are added. The **Admittance** $\underline{Y}$ is the inverse of the impedance $\underline{Y} = 1 / \underline{Z}$. (This is elaborated on e.g. [7, 18, 20]).

For a real resistor and an inductivity connected in series, their impedances have to be added up: $\underline{Z} = R + pL$. In this example R is the real part of the impedance and L is the imaginary part. The j contained in p is not counted as part of the imaginary part.

♣ $p = \sigma + j\omega$; here: $\sigma = 0$, i.e. $p = j\omega$ (steady state).

The **magnitude** of the impedance is calculated taking the square-root of the sum of the squared real and imaginary parts. To mark the result as magnitude, two vertical lines are added, or the symbol in the formula is written without underline. The latter form is unfortunately somewhat dangerous, because complex values are sometimes found in literature where the underline has conveniently been dispensed with.

$$|\underline{Z}| = Z = \sqrt{\mathrm{Re}^2\{\underline{Z}\} + \mathrm{Im}^2\{\underline{Z}\}}$$ Magnitude of the complex impedance $\underline{Z}$

Equivalent circuits for impedances have the same impedance as the system they replace. Let us take, for **example**, an ohmic resistor: ideally its impedance♣ should be purely real ($\underline{Z} = R$). However, at high frequencies the contact caps of the resistor act as a small capacitance; the magnitude of the impedance decreases with increasing frequency. This behavior could be reproduced by an equivalent circuit with a capacitor connected in parallel to the resistor. On the other hand, the resistor may be built of a wound-up wire; in that case the resulting inductive component would have to be reproduced by a coil connected in series – possibly in conjunction with the capacitor mentioned above. For DC-considerations neither coil nor capacitor are required; they do not hurt either, though, since the DC-resistance of the coil is zero (i.e. no effect in a series connection), and the one of the capacitor is infinite (i.e. no effect in a parallel connection). At 50 Hz, the contribution of the coil and the capacitor may be so small that it can neglected. Starting from which frequency the consideration is required depends on the desired accuracy.

In a **guitar pickup** the inductive component of the wound-up wire has a significant effect already from 100 Hz. Consequently, the equivalent circuit will require at least an inductance on top of the pure wire-resistance. The calculation of the inductance is in fact not entirely trivial. Even very simple, symmetrical structures will require an extensive integration which can quickly reach an undreamed of scope. Strictly speaking, every one of the 10000 turns?? would have to be broken down into differentially small wire-pieces which all interact with all other wire-pieces and form a complex inductance and capacitance. As a first approximation, however, it is sufficient to supplement the ohmic pickup resistance with an ideal coil and an ideal capacitor. The **quality of the modeling** can easily be checked by measuring the frequency characteristic of both impedance of the pickup and that of the equivalent circuit (put together from a resistor, a coil, and a capacitor). The two measurements should agree within the desired measurement accuracy. Even simpler is *calculating* the impedance of the equivalent circuit using methods of systems theory. This approach removes the obligation to acquire an ideal coil which does not include the inadequacies which are the reason we are making the effort to start with! If we find that the object under measurement and the model differ too much, the model needs to be improved with other parameters or with another – and possible more extensive – structure. Moreover, the purpose of the model must never be forgotten: it is supposed to reproduce the frequency response of the impedance. The model cannot and will not reproduce the transfer behavior or the non-linear distortions.

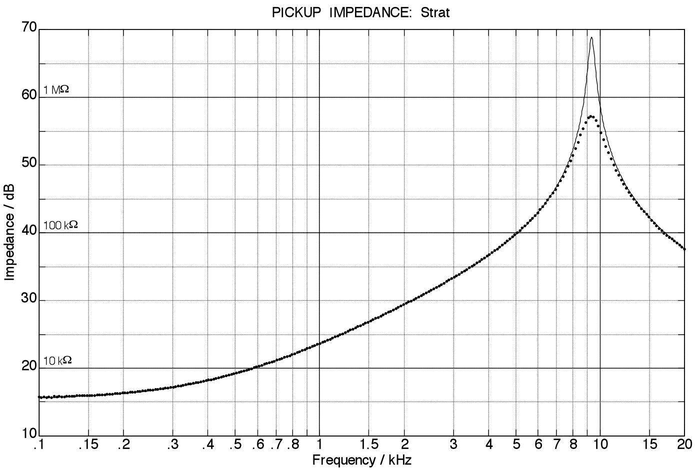
♣ <u>Purely</u> real numbers are a sub-set of the complex numbers, as are <u>purely</u> imaginary numbers.

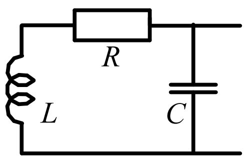
5.9.2.1 Singlecoils with weak dampening of eddy-currents

The typical Stratocaster pickup consist of 6 magnets, two coil flanges, and would-up wire. The impedance of such a pickup can be reproduced in the frequency range up to 20 kHz with good accuracy with few circuit elements. As already discussed, the term „*reproduce*" means putting together an **impedance-equivalent circuit** consisting of few ideal, concentrated elements (R, L, C). This equivalent circuit, described in the form of an **equivalent circuit diagram**, approximates the pickup impedance in the framework of purposeful accuracy limits, e.g. 5%.

Fig. 5.9.1 shows an electrical equivalent circuit diagram (ECD0) of a Stratocaster pickup as well as the corresponding impedance frequency plots. For the measurements, the pickup was connected via short leads and without further components (i.e. without potentiometers) to an impedance meter. At very low frequencies the impedance is determined by the copper resistance R; at a few kHz there is a resonance maximum and at high frequencies an impedance drop-off occurs which is due to the capacitance. There is a general correspondence between the measurement (of the real pickup) and the calculation (based on the equivalent circuit diagram). The emphasis of the resonant peak is different, however. Obviously, the pickup contains an additional dampening which the simple equivalent circuit ECD0 does not model (eddy currents in the magnet, see chapter 5.9.2.2).

There are several possibilities to extend ECD0 by real dampening restores. Seen from the point of networks theory, the corresponding impedance function is a *second*-order broken rational function, since the network includes *two* independent storage elements (namely L and C). In a fraction, containing (in numerator and denominator) the complex frequency variable p with not more than the power of 2, five polynomial coefficients can be chosen freely – corresponding to five components which may be selected freely. Therefore, apart from L and C, a maximum of three dampening resistors may be determined independently from each other in a 2nd-order system. It is not difficult to draw *more* than two additional resistors into ECD0; the resulting new circuits can, however, be transferred into simpler circuits (with a maximum of three resistors) using equivalence-transformations. There are in fact even several possibilities to extend ECD0 by merely one single resistor – these support various physical interpretations differently, although they are equivalent regarding the impedance modeling.





Equivalent circuit diagram

Fig. 5.9.1: Stratocaster-impedance, ECD0 Measurement (…), ECD-calculation (----**).**

In **Fig. 5.9.2** we see two equivalent-circuit diagrams containing *two* resistors each. To arrive at the left ECD, the overall circuit of Fig. 5.9.1 was supplemented by a resistor connected in parallel, while for the right-hand ECD, the resistor is connected in parallel to the coil. The impedance of both ECDs approximates the measurement curve of Fig. 5.9.1 so perfectly that no difference at all can be seen anymore. Several questions result: do both ECDs have the exact same impedance? Which ECD is correct? How do we arrive at the values of the components?

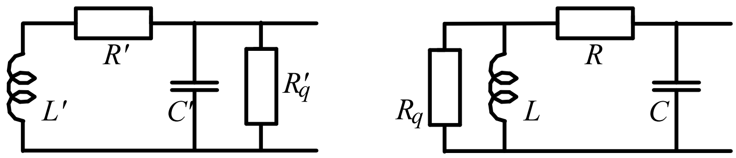


Fig. 5.9.2: Extended Stratocaster ECD (ECD1)

The following considerations require simple knowledge in network analysis as it is e.g. imparted in [18, 20]. The **impedance** of a resistor is *R,* that of an inductance is *pL,* and that of a capacitor is 1 / *pC.* For the series connections of two-poles, their impedances are added; for parallel connections the sum of the admittances (inverse) is used. In both the ECDs a section of the circuit consisting of two resistors and a coil is connected in parallel to a capacitor. If both ECDs are supposed to have the same impedance, and if the capacitance is supposed to be of the same value for both ECDs, then these two partial circuits need to have the same impedance, as well. Without compromising the accuracy, it is therefore possible to limit the issue of identifying the ECD-impedances to calculating the impedances of the respective sections of the circuit mentioned above:

Fig. 5.9.3: As above, without *C.*

$$\underline{Z}' = R'_q \cdot \frac{pL' + R'}{pL' + (R' + R'_q)} \qquad \underline{Z} = \frac{pL(R + R_q) + R \cdot R_q}{pL + R_q}$$

Impedance functions

It is a necessary (but normally not sufficient) requirement for the identity of the impedance function that the impedances for $f = 0$ and for $f = \infty$ must be equal. It follows that:

$$R = \frac{R' \cdot R'_q}{R' + R'_q}; \qquad R + R_q = R'_q .$$

Introducing these requirements into the impedance function described above, we obtain the still missing requirement for the relationship between the inductances:

$$L'/L = (1 + R/R_q)^2$$

These equations enable us to set up an *impedance-equivalent* ECD from the respective other ECD.

It may be surprising that the two ECDs need different inductances for identical impedances. However, surmising that the imaginary part of an impedance would be determined solely by the reactances (*L* and *C*) is only correct for a series connection. As soon as there is a parallel connection, the imaginary part is determined by the real resistances, as well. Understanding this has strong implications on how the component values need to be interpreted. Let us use a simple concrete example to exemplify this problem:

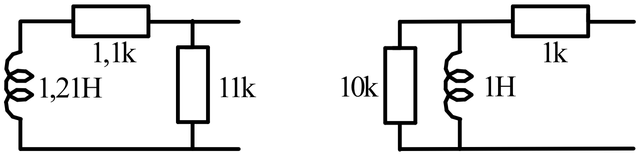


Fig. 5.9.4: Impedance-equivalent circuits

Regarding their impedances, the equivalent-circuit diagrams shown in **Fig. 5.9.4** are fully identical, although the inductances differ by 21%. For the Stratocaster pickup, the differences are significantly smaller, but as soon as additional iron parts are introduced into the magnetic circuit (as e.g. in the P90), considerable differences result. In the end, this means that a precise **pickup-inductivity** can only be given if the corresponding equivalent circuit is specified. It is merely for very simply constructed pickups that the component values differ so little that stating the ECD-topology may be dispensed with.

We can now answer the question posed above: both ECDs shown in Fig. 5.9.2 feature exactly the same impedance, both ECDs are correct, and he values of the components can be derive via a regression-process. If you want avoid deploying the big guns, you may vary the ECD-component values until the measured impedance curve and the ECD-impedance correspond with the desired accuracy. It is not as easy to answer the question which ECD is more purposeful. An additional question could lead the way: which is the purpose of the ECD? Normally, an ECD is put together in order to obtain a clear basis for calculations, and to be able to recognize simple correspondences at a glance. The real use of an equivalent circuit for the impedance only reveals itself once the equivalent circuit for the transmission has been derived from it. Since the theory required for this process is only discussed later (see chapter 5.9.3), we will just take a quick look here: the pickup parameter measured in the easiest way is the DC-resistance R_{DC}. With $R = R_{DC}$, it can be directly included in the equivalent circuit if the right-hand version shown in Fig. 5.9.2 is preferred. It may also be explained using an equivalent circuit diagram of a transformer that resistive losses are considered with a connection in parallel to *L* and not with a connection in parallel to the series connection *R'L'*. May be … but doesn't have to be. From a network-theory point-of-view both circuits are equal, and the preference is a matter of taste. The following considerations use the $(R_q //L)+R$ -structure (**Fig. 5.9.5)**, and the result perfectly approximates the measured curve (Fig. 5.9.1) – to the width of a line.

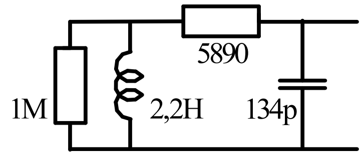


Fig. 5.9.5: Equivalent circuit diagram for the impedance of a Stratocaster pickup

5.9.2.2 Eddy currents in non-magnetic conductors

As a time-variant magnetic flux penetrates a conductor, it induces an electric circulating voltage which results in annular eddy currents. The vibrating string changes the magnetic resistance in the magnetic circuit and modulates the magnetic flux such that an alternating field is superimposed over a constant field. According to the law of induction the flux $d\Phi/dt$ changing over time leads to a voltage U which – depending on the electrical conductivity $\sigma = 1/\rho$ – causes a current I.

Non-magnetic (i.e. non-ferromagnetic) conductors are found in pickups predominantly in the form of assembly and **shielding sheet metals**. Not all pickups are fitted with them: the typical Stratocaster pickup has a plastic cover but the Gibson Humbucker is mounted to a metal plate and shielded with a metal cover. These metal sheets do have an influence on the magnetic field even if they are not ferromagnetic (!), and therefore also on the transfer characteristic of the pickup. The eddy currents flowing within them draw their energy from the magnetic circuit which receives a corresponding dampening effect.

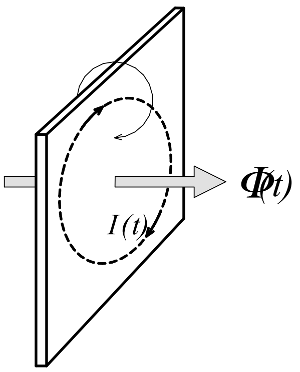


Fig. 5.9.6: The electrically conductive plate is penetrated by a magnetic flux $\Phi(t)$ which increases over time. The result is an annual eddy current $I(t)$ in the direction as drawn. This current flows in the plate as a whole, not only on the indicated circle. It causes a secondary magnetic field (as indicated at the upper edge) which attenuates the primary field.

A time-variant magnetic flux $\Phi(t)$ inducing an eddy current $I(t)$ in a current-carrying plate is shown in **Fig. 5.9.6.** This eddy current again generates itself a magnetic counter-field which attenuates the primary field such that a smaller voltage is generated in the pickup coil (not shown). Since eddy currents depend on the temporal change of the magnetic field, they have an effect particularly at high frequencies (skin effect, see below). Therefore, metal sheets do not only provide shielding against electrical interference but they also deteriorate the **treble response**. This is not necessarily a disadvantage – a full, warm sound may in fact be the objective of pickup design. For a brilliant, treble-laden tone, however, eddy currents must not have too big an effect.

There are several **measures** to get a handle on the eddy-current dampening. Size, thickness and distance of the dampening metal sheet play a role, as does the material used. The eddy current emerges as the quotient of induced voltage and electrical resistance. The induced voltage depends on the magnetic flux; metal sheets in areas of weak magnetic alternating flux attenuate less than sheets in areas of strong alternating flux. Sheet metal bent into a ring-shape (e.g. for covers) may enclose a large surface with strong alternating flux; in such a case it should be checked whether a slot could not interrupt the current flow. Thin sheets offer higher resistance than thick ones; German silver (nickel silver) has a higher resistance than brass. Gold-plated covers have better conductance (dampen more) than chrome plated covers - if the gold layer is thick enough.

The following table offers an overview of the specific resistances of common sheet metal materials. **German silver** is often used in higher quality pickups. This metal of a silvery shine is corrosion-resistance and of relatively high resistance.

Material	ρ in $\Omega mm^2/m$		Material	ρ in $\Omega mm^2/m$
Copper	0.018		Brass (Cu, Zn)	0.08 (0.06 – 0.12)
Gold	0.022		Bronze (Cu, Sn)	0.08 (0.02 – 0.14)
Aluminum	0.029		Steel for strings (ferromagnetic!)	0.20
Nickel	0.070	(ferromagnetic!)	German silver (60 Cu, 17 Ni, 23 Zn)	0.3
Iron	0.098	(ferromagnetic!)	Alnico-Magnet (magnetic source!)	0.6
Chrome	0.12		Chrome-nickel (70 Ni, 30 Cr)	1.2

Table: Specific resistance ρ of metals

Fig. 5.9.7 schematically shows a pickup winding next to which a sheet metal forms a short-circuit winding. The elements of the pickup winding are the DC resistance R (copper resistance), the winding capacitance C, and the winding inductivity L. The Short-circuit winding is characterized by R_K and L_K. Due to the incomplete flux-coupling k we will not find the same flux $\Phi(t)$ penetrating both windings i.e. k < 1. The eddy-current resistance R_K is transformed up as R_w and attenuates a part of the winding (in the transformer-free equivalent circuit on the right-hand side). The eddy currents induced into the sheet metal thus reduce the coil inductance and increase the coil losses. The stronger the coupling (i.e. the closer the sheet is positioned to coil) the larger the part of the coil which is shorted by R_w and the larger R_w itself. In addition, R_w depends on the specific resistance of the sheet metal.

At low frequencies, the parallel-connection of R_w and $(1 - \sigma)L$ has the effect of an inductance, at high frequencies it has the effect of a resistance. The cutoff-frequency between inductive and resistive behavior is $f_g = R_w / [2\pi(1-\sigma)L]$. As a simplification, the eddy-current losses can be neglected below f_g while above f_g the resistance increases from R to $R + R_w$, and the inductivity decreases from L to σL (compare to Fig. 5.9.8).

$R_w \approx R_K \cdot N^2 \cdot (1-\sigma)$ N = number of turns of the winding $\sigma = 1 - k^2$ = degree of scatter

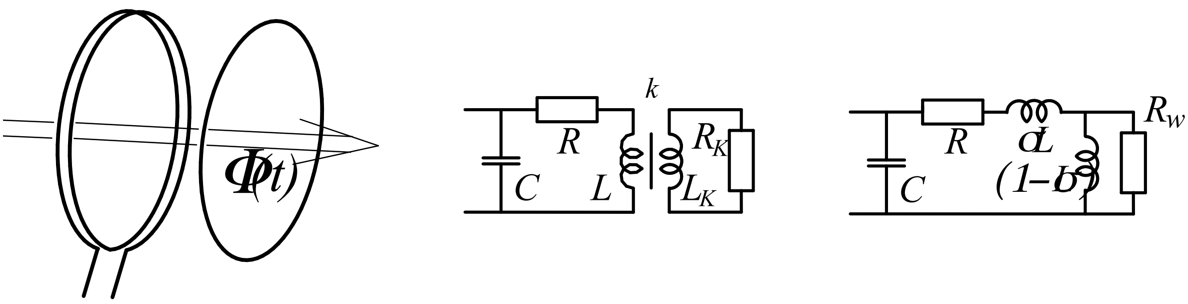


Fig. 5.9.7: Pickup coil with short, equivalent circuit diagrams [4].

Fig. 5.9.8 shows the frequency response of the impedance-magnitude for the equivalent circuit of Fig. 5.9.7 – without capacitance, though (i.e. $C = 0$). For the left section the degree of coupling k was varied. As the short circuit winding is brought closer to the pickup coil, the coupling increases while at the same time the degree of scatter decreases. The treble loss becomes stronger and the impedance level of the circuit is reduced. The left section of the figure shows the effect of the variation of the resistor R_w for fixed coupling, which is equivalent to a change in the thickness of the sheet metal, or of its material type. This measure changes the cutoff frequency f_g: with increasing resistance (thinner sheet metal, higher material resistance) f_g increases.

$$f_g = \frac{N^2 \cdot R_K}{2\pi \cdot L}$$

Cutoff frequency of the parallel connection of R_w and $(1-\sigma)L$

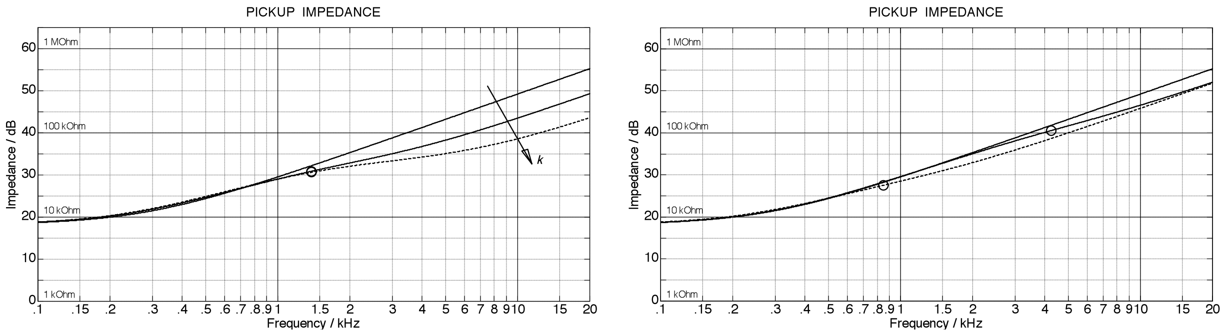


Fig. 5.9.8: Effect of changing the coupling (left) and varying R_w (right). The cutoff frequency is marked by a circle.

Fig. 5.9.9 shows impedance measurements for a Jazzmaster pickup. First a 1mm strong **sheet metal made of brass** was brought in close proximity (2,5 mm) to the pickup and the impedance measurement taken. Subsequently, the brass plate was replaced by an equally strong **copper plate** (positioned at the same distance). The differences in the impedance frequency plot are relatively small but still readily identifiable (at 1 – 3 kHz), and moreover in good agreement with the results from the equivalent circuit diagram (Fig. 5.9.10).

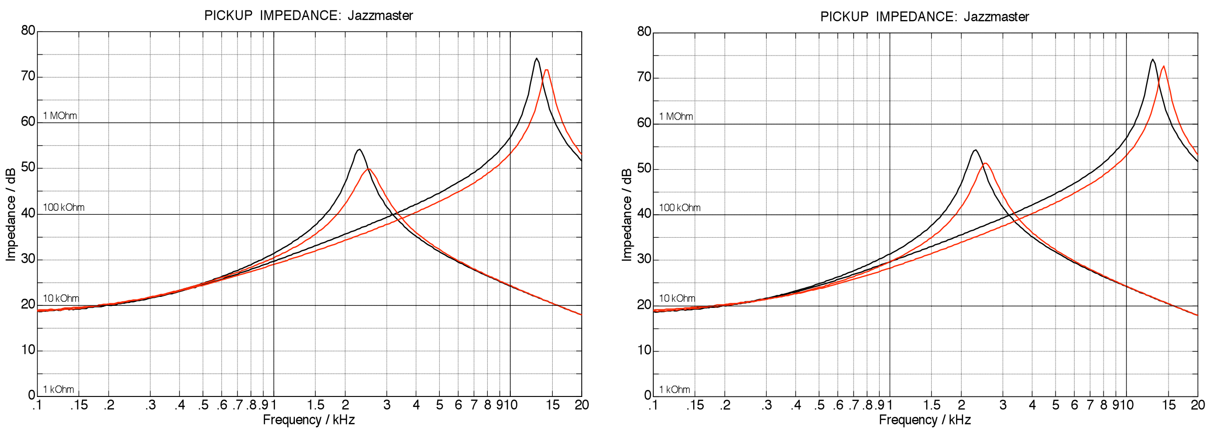


Fig. 5.9.9: Measured impedance chart for a Jazzmaster pickup. The pickup was unloaded (high resonance frequency), or loaded with 1 nF (resonance at 2,5 kHz. With the sheet of brass (left) or copper (right) respectively, the impedance drops and the resonance frequency increases.

The equivalent circuit diagram for the impedance of the Jazzmaster pickup with eddy-current dampening is shown in **Fig. 5.9.10**. The ECD on the left refers to the pickup without any dampening sheet metal. The only eddy-current losses are due to the six alnico magnets; they can be modeled by a 72-kΩ-resistor (see the next chapter). The additional dampening effected by the brass sheet (middle section of the figure) is modeled by the 4-kΩ-resistor shunting about 1/6 of the overall inductivity (0,8 H). As is obvious, *magnetic* losses cannot be always modeled by the same *RL*-element. This is because the magnets and the brass sheet influence each other. Every eddy current changes the field geometry and with it the individual coupling effects. The dampening caused by the copper sheet is modeled via the right hand section of the figure. The conductivity of copper is about four times higher than that of brass, and consequently the 4-kΩ-resistance needs to be decreased to 1 kΩ. The partition of the coil remains since the coupling effects to the brass sheet and the copper sheet are about the same.

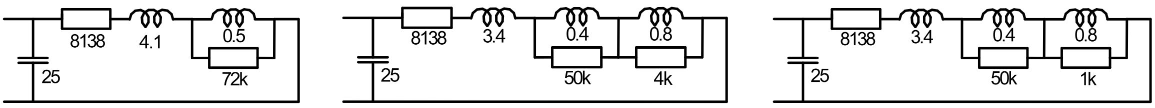


Fig. 5.9.10: Equivalent circuit diagrams for the measurements of Fig. 5.9.9. Left: pickup without sheet metal; middle: with brass sheet; right: with copper sheet. Capacitances are in pF, resistances in Ω, inductances in H.

During the experiments just elaborated sheet metals were brought into proximity of the pickup since their geometry quality could easily be established. Of course, there is no 1-mm-sheet-metal over or under to the Jazzmaster pickup in reality because the pickup is housed in plastic. However, many pickups do have metal bases or metal covers which indeed change the electrical pickup characteristics. The effects of (per se non-magnetic) shielding materials are shown by impedance measurements with a Hoyer-pickup (from the 1960s). The P90-like coil of this pickup is shielded by a metal cover on the surface towards the strings. **Fig. 5.9.11** shows the effects of this shielding on the impedance frequency plot. The eddy currents do not only dampen and attenuate the resonance peak more strongly; the resonance frequency increases, as well.

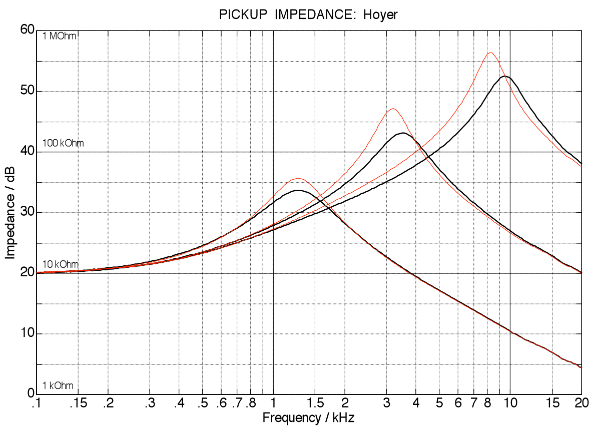


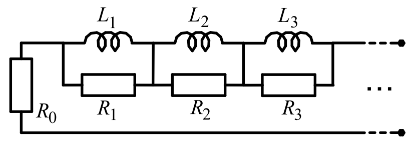
Fig. 5.9.11: Frequency response of the impedance of a Hoyer pickup. The bold lines represent the original condition while the thin lines refer to the cover taken off. The pickup is loaded with 4700pF, 700pF, 0pF, respectively.

The eddy-current dampening effect due to the shielding cover attenuates the high frequencies and reduces the reproduction brilliance. If this is thought to be a disadvantage, the cover may be replaced by one made of plastic.

5.9.2.3 Equivalent two-terminal networks

Magnetic pickups may be represented as two-terminal network or as four-pole network. The basis for the design of a **two-terminal equivalent circuit diagram** is the (frequency dependent, complex) resistance – the **impedance** – measured at the two terminals. In addition, the transfer characteristic may be described by way of this equivalent circuit diagram being extended by two further terminals yielding the four-pole equivalent circuit diagram (chapter 5.9.4). Circuits (networks) are equivalent with respect to impedance if their impedance-functions $\underline{Z}(f)$ correspond; topology and component values may in fact be rather different.

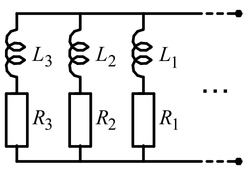
The higher the order n (the number of independent storages) of the network, the larger the number of possible impedance-equivalent but structurally different networks is. In network synthesis three topologies are of particular significance: the resistance partial fraction circuit (**RPFC**), the conductance partial fraction circuit (**CPFC**) and the continued fraction circuit (**CFC**). For the RPFC (**Fig. 5.9.12**), the network analysis is done via series connection of individual impedances, for the CPFC (**Fig. 5.9.13**), this is done via a parallel connection of individual admittances, and via alternating series and parallel connections for the CFC (**Fig. 5.9.14**).



$$\underline{Z} = R_0 + \sum_i \frac{1}{1/R_i + 1/pL_i}$$

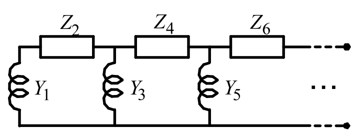
Fig. 5.9.12: Resistance partial fraction circuit (RPFC)

The RPFC is highly suitable to describe magnetic pickups. The DC-resistance is - as R_0 - directly found in the diagram, the values L_i are easily interpreted as components of the overall inductance, and the loss resistances can be attributed via the transformer-equivalent. If all resistances R_i ($i \geq 1$) are finite, the impedance approaches a real, constant value at high frequencies. If one of the resistors is omitted (R_i=∞, $i \geq 1$), the impedance approaches - for high frequencies - a straight line increasing proportionally with the frequency. The CPFC delivers the same impedance, but the large inductance values occurring here are more difficult to interpret, and *R*DC is not immediately evident, either. The CFC shown in Fig. 5.9.14 yields *R*DC in a straightforward manner but is not used due to the high inductivity values.



$$\underline{Z} = \frac{1}{\sum_i \frac{1}{R_i + pL_i}}$$

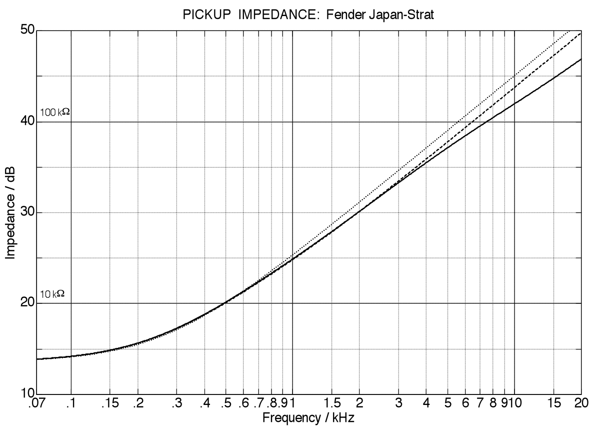
Fig. 5.9.13: Conductance partial fraction circuit (CPFC)



$$\underline{Z} = Z_6 + \cfrac{1}{Y_5 + \cfrac{1}{Z_4 + \cfrac{1}{Y_3 + \cfrac{1}{Z_2 + 1/Y_1}}}}$$

Fig. 5.9.14: Continued fraction circuit (CFC)

Understanding the impedance frequency plot of a resistance partial fraction circuit (**Fig. 5.9.15**) is made easy by - as a first step - assuming all resistances except $R0$ to be infinite. What remains is merely a series-RL-circuit the impedance value of which can be approximated by R_0 at low frequencies and by $\omega(L_1 + L_2 + L_3)$ at high frequencies. For magnetic pickups the impedance growth towards high frequencies is not proportionally to ω but with a shallower slope, and this behavior can be modeled by decoupling the partial inductances using the resistors coupled in parallel. The effective inductance now decreases with increasing frequency and the phase angle does not approach 90° but a smaller value.



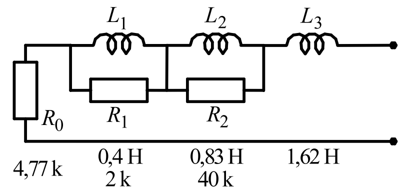


Fig. 5.9.15: resistance partial fraction circuit, magnitude of frequency response. For the upper curve, $R_1 = R_2 = \infty$ was assumed, for the middle curve $R1 = 2$ kΩ, $R2 = \infty$, and for the lowest curve $R1 = 2$ kΩ, $R2 = 40$ kΩ.

The differences between the curves shown in Fig. 5.9.15 may seem rather small. However, the magnitude by itself is not adequate to unambiguously describe a network. As soon as a **capacitor** is connected (capacitance of the coil, or of a cable), real and imaginary part change in different manner. It is therefore necessary to precisely model both real and imaginary part and not only their magnitude. Depicted in **Fig. 9.5.16** are impedance frequency plots as they result from a capacitor of 1 nF being connected to the terminals of the CPFC according to Fig. 9.5.15. For the dashed line, again $R_1 = 2$ kΩ, $R_2 = \infty$ was set, the solid lines refer to the unchanged circuit ($R_1 = 2$ kΩ, $R_2 = 40$ kΩ). Although the magnitudes of the impedances of the circuits without capacitor are almost identical at 3 kHz, there are large differences with a capacitive load. This clearly demonstrates that a high precision is necessary when putting together an impedance-equivalent circuit diagram.

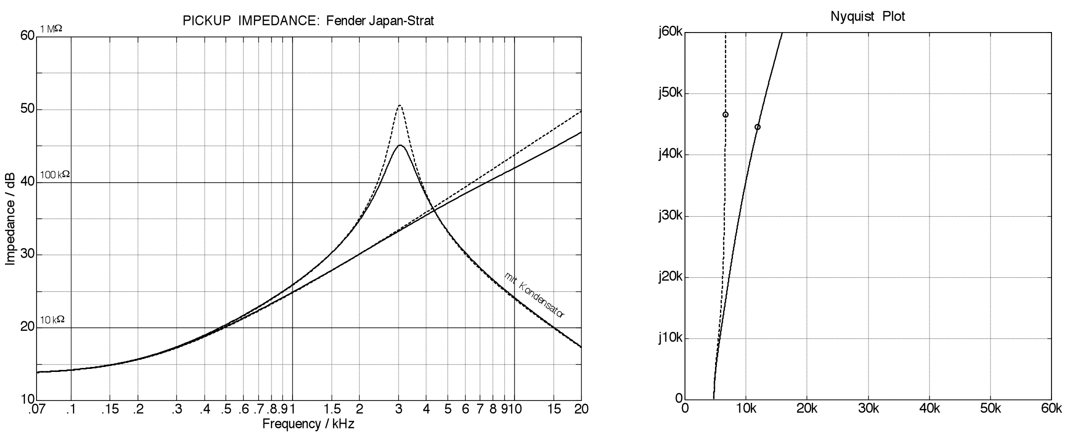
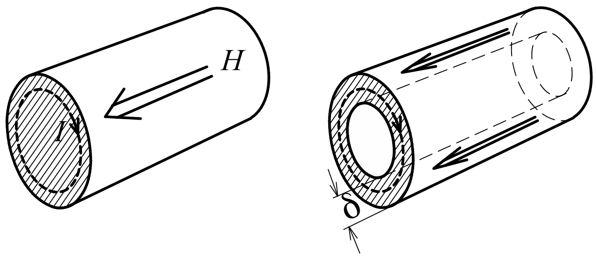


Fig. 5.9.16: Frequency responses of the impedance magnitude of the circuit according to Fig. 5.9.15, with and without capacitive load; Nyquist plot of the impedance without capacitive load (right, marking at 3 kHz.

5.9.2.4 Eddy currents in the magnetic conductor

As a ferromagnetic, *electrically conductive* material is brought into a time-variant magnetic field, there are two effects: the (relative to air) higher permeability of the material increases the magnetic flux density, and at the same time eddy currents diminish this permeability. Since eddy currents are proportional to the temporal changes of the magnetic field, the effective permeability (and thus also the inductance) decreases with increasing frequency. As we have already shown for the non-magnetic conductor, the eddy currents generate active power drawn from the primary field – the pickup receives a dampening♣.

Fig. 5.9.17 depicts a cylindrical magnetic conductor axially permeated by a magnetic field *H*. Examples for such a scenario are the magnets as they are found in typical Fender pickups under each string, or the pole-pieces (slugs) of a pickup with a bar magnet. If the field is flowing in the direction as indicated and increases over time, it induces a clockwise flowing eddy current *I*. This eddy current weakens the primary (generating) field, especially close to the axis. As a simplification we can imagine that the axial area is left without any field at all, and a magnetic flux remains only in a thin border layer with a **depth penetration** δ (**skin effect**). δ depends on the electrical conductivity ρ, on the frequency *f*, and on the permeability μ. Permanent magnets show practically no skin effect in the audio range due to their small reversible permeability (μ_r = 1.1 – 5) and their relatively bad conductivity (≈ 0.6 $\Omega mm^2/m$). Steel behaves less favorably: at 2 kHz we get merely $\delta \approx 0.4$ mm (with μ_r = 100). The magnetically effective cross-section is thus reduced to 1/7th!



$$\delta = \sqrt{\frac{\rho}{f \pi \mu_r \mu_0}}; \quad [5]$$

Fig. 5.9.17: Cylinder with axial magnetic field *H*, eddy current *I*, and border layer with penetration depth δ.

The penetration depth δ (also called conductive-layer thickness) determines both the cross-sectional area for the eddy current and the magnetically effective cross-section area. Both areas are reciprocal to the *square-root* of the frequency, and since the square-root is an irrational function, the impedance cannot be described with a rational function (i.e. a function with a finite number of polynomial sections) – and therefore cannot be modeled with a finite number of components. An equivalent circuit diagram as given in Fig. 5.9.7 is only possible below the approximated cutoff frequency. For **magnets** (with small μ_r), this cutoff lies above the relevant frequency range, and consequently a single loss resistor is sufficient. The common pole pieces (with a larger μ_r) require a more elaborate modeling including several R//L-two-terminal networks. Of course, the desired accuracy plays a role, as well: the circuit behavior can always be reproduced in principle with one coil, one capacitor and two resistors – however depending on the situation there may be considerable differences to the original.

♣ See the theoretical derivation in chapter 4.10.4

Apart from eddy currents there is a further source for losses: the **remagnetization** of the iron and magnetic parts requires energy which is taken from the magnetic field, as well, and thus requires a load resistor in the equivalent circuit diagram. Since the magnetic field changes direction twice with every period of the signal, the remagnetization losses increase with rising frequency. Other lossy mechanisms do exist – however, these are of minor importance.

The following measurements were taken from the „screw-coil“ of a **Gibson** humbucker (PU490). The pickup was disassembled and the screw-coil removed. Unscrewing the 6 screws leaves a coil without ferromagnetic parts. Its impedance can be described rather perfectly by a resistor (4379 Ω), an inductance (1125 mH) and a capacitor (43 pF). **Fig. 5.9.18** shows the magnitude frequency response of the impedance with and without coil capacitance. In conjunction with the inductance, the capacitance causes a resonance maximum at 23 kHz.

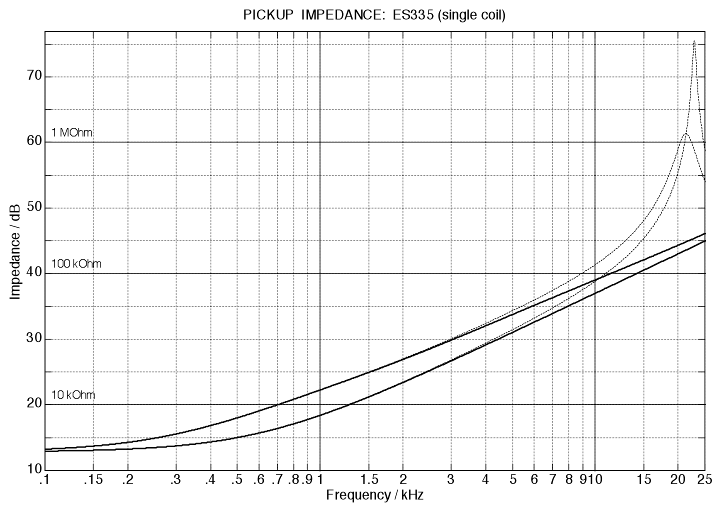
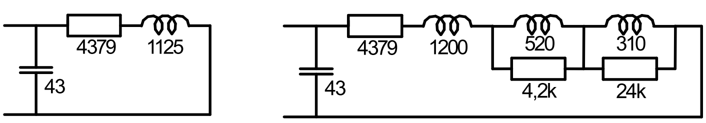


Fig. 5.9.18: Calculated magnitude of the impedance of a coil, with (---) and without (—) coil capacitance. The curve with smaller impedance belongs to the coil with all iron removed, the curves above it refer to the coil with mounting block and 6 screws.

Adding in the mounting block located beneath the coil does not change the impedance frequency plot much. Not until the 6 screws are moved in place does the inductance increase significantly: the impedance curve slides upwards. However, it does not run in parallel with the original course. The reason is the appearance of the eddy current which – with rising frequency – increasingly displace the magnetic field out of the screws and partially undo the inductivity gain. Since the impedance increase of the upper curve (with iron) is not anymore proportional to the frequency, and approximation with several *RL*-sections is required (**Fig. 5.9.19**). The influence of the iron screws is considerable, as the transfer frequency responses shown below in Chapter 5.9.3 also show. If eddy-current losses are undesirable, it is possible to moderate their effects by lamination of the sheet metals or the ferrite materials.



For a high degree of accuracy of the approximation, more than two R//L-two-terminal networks are required.

Fig. 5.9.19: Equivalent circuit diagrams for a PU-490 coil without (left) and with (right) 6 pole-screws and mounting block. Capacities given in pF, resistances in Ω, inductances in mH. The frequency response of the impedance is shown in Fig. 5.9.18.

As already mentioned, the ECD of Fig. 5.9.19 is only one of several equivalent options. The more components an ECD includes, the more topologies are possible. It is purposeful to divide the total inductance into a series connection of *R//L*-two-terminal networks (RPFC, Chapter 5.9.2.3). Alternatively, a parallel connection of *RL*-series circuits could also be used (CPFC), but here the inductances require very large values, e.g. 100 H. Although the total impedance can be perfectly approximated that way, it is difficult to interpret such a circuit. The series circuit above mentioned series makes more sense: at first glance the inductivity decreasing with increasing frequency is evident.

While the *magnetic* losses were already extensively discussed, the **dielectric losses** may be looked at in a more concise manner. Non-conductors cannot carry any current – and thus no eddy currents, either. In the case of pickups, non-magnetic non-conductors are all insulators, i.e. coil bobbins and the wire insulation. These materials are in fact the source of dielectric losses – this effect is rather indistinct, however (Chapter 5.5).

Magnetizable non-conductors ($\mu >> 1$) are, for example, **ferrites** i.e. ferrimagnetic materials. They may be (but don't have to be) used for field-guiding parts (polepieces) and/or magnetically hard ferrite magnets. The electric conductance of ferrite magnets (e.g. barium ferrite) is very small which makes for almost no eddy currents at audio frequencies. The resonance dampening consequently is less compared to alnico magnets. Since the reversible permeability μ_{rev} of alnico magnets is – by a factor of 3 to 4 – larger that that of ferrite magnets, it is possible to create a larger coil inductance with alnicos ... but: the much higher conductance of alnico leads to eddy currents and thus again to a reduction of the inductivity (see Fig. 5.9.9). How large the differences individually are depends on where the magnets are mounted and which alternating flux penetrates through them. For example, the alnico magnets mounted underneath the coil of the P-90 increase (!) the resonance frequency by as little as 5%. Therefore no big differences could be expected if the alnicos were to be replaced by ferrite-magnets. A stronger effect would occur, on the other hand, from exchanging the cylindrical alnico magnets (penetrated by an alternating field) of a Stratocaster pickup for ferrite magnets: the resonance frequency would rise by about 10 – 15%. However, for many pickups of this type, these considerations have to remain a pure thought experiment, because pushing the magnets out of the coil is dangerous, and the pickup may be irreversibly destroyed.

Material	ρ in $\Omega\text{mm}^2/\text{m}$		Material	ρ in $\Omega\text{mm}^2/\text{m}$
Steel for strings	0.20	(ferromagnetic)	Hard ferrite (oxide magnet)	about 10^{12}
Nickel	0.070	(ferromagnetic)	Alnico-Magnets	about 0.4 – 0.7
Iron	0.098	(ferromagnetic)	Magnetically soft ferrites	about 10^6 (up to 10^{12})

Table: Specific resistance ρ of magnet materials.

5.9.2.5 Singlecoils with strong eddy-current dampening

As soon as pickups contain other metal parts in addition to the magnets it is necessary to check whether the equivalent circuit diagrams introduced in Chapter 5.9.2.1 are still of sufficient accuracy. The magnetic alternating flux does not only induce a voltage into the coil but into all other metal parts as well, and this leads to **eddy currents**. In this process, the metal parts act like a shorted secondary coils. The resistance of this short (a few milliohm) is transformed upward with the squared winding transmission ratio (e.g. 5500^2) and results in a non-negligible cross-resistance in the equivalent circuit diagram. **Fig. 5.9.20** shows an impedance measurement for a pickup from Hoyer guitar (made in the 1960s). Underneath the coils there are two bar magnets held by the base-sheet, and in addition there is a shielding cap put over the pickup. In **Fig. 5.9.21** we find a simple ECD containing the winding resistance *R*, the winding inductance *L*, the winding capacitance *C* as well as an additional dampening resistor R_q. Using this diagram, the measured curve can be approximated at 0 Hz and around the resonance; the agreement at 1 kHz is merely moderate, however.

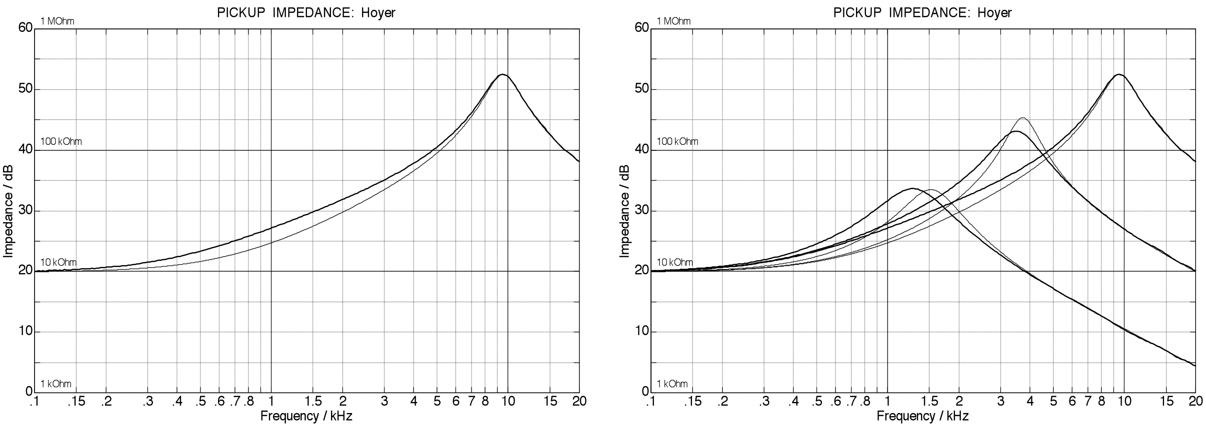
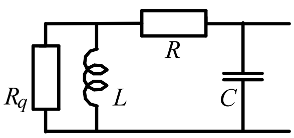


Fig. 5.9.20: Hoyer-pickup, impedanc frequency response. Measurement (——), ECD1-calculation (––––).
On the left readings for the unloaded pickup are shown, on the right loads are connected: 4700pF, 707pF, 0pF.



L = 2,17 H R = 9850 Ω

R_q = 540 kΩ C = 125 pF

Fig. 5.9.21: Hoyer-pickup with metal cover. Equivalent circuit diagram ESB1.

The differences grow more noticeable as a customary **guitar cable** is connected to the pickup. Its effect is purely capacitive in the audible frequency range; depending on the length there will be a cross-capacitance of 300 – 1000 pF. The instrument used for the measurement allows for a connection of 0 pF, 707 pF, 4700 pF. The larger the capacitance, the lower the resonance frequency is. In the right part of the figure curves for different capacitive loads are given: the eddy-current losses lead to clear deviations between measurement and calculations. The equivalent circuit diagram presented in Fig. 5.9.21 (with a topology designated **ECD1**) needs to be extended by additional components in order to achieve better agreement.

To obtain a better approximation it is necessary to model the eddy-current losses with the equivalent circuit diagram of a loosely coupled transformer (Chapter 5.9.2.2). There are several equivalent possibilities for this. As already shown in Chapter 5.9.2.3, the series connection of *R//L*-two-terminal networks is particularly easy to interpret; it is used again here. **Fig. 5.9.22** shows the extended equivalent circuit diagram (**ECD2**).

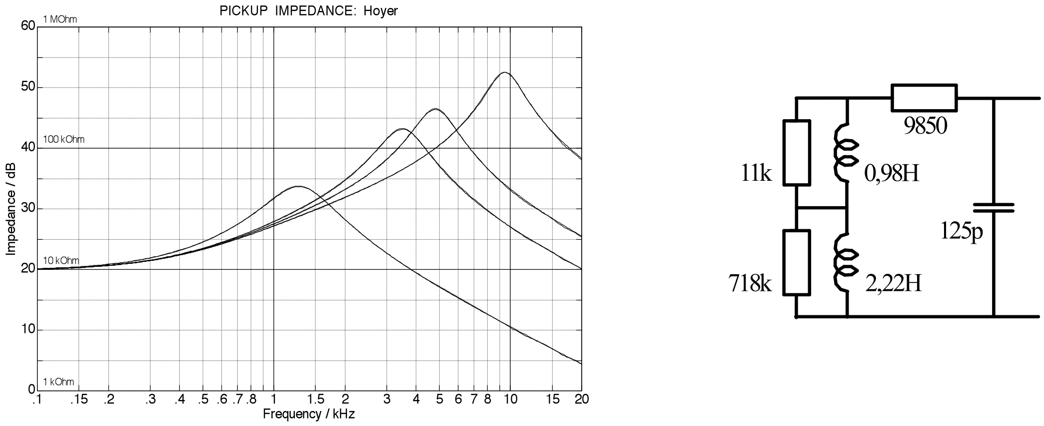


Fig. 5.9.22: Hoyerpickup, impedance frequency plot; 4700, 700, 330, 0 pF load; measurment and calculation are not distinguzishable anymore. ECD2 on the right.

Whether the eddy-current losses indeed need to be modeled depends on the construction of the pickup and the desired accuracy. In many cases (such as for the Stratocaster pickup) already ECD1 delivers very good results. On the other hand, for pickups with additional metal parts more or less significant discrepancies between measurement and calculation should be expected. **Fig. 5.9.23** shows the impedance frequency plots of a P-90 pickup with a capacitive load (0pF, 330pF & 1000pF): with ECD1 there are clearly visible deviations, while for models of higher order a perfect agreement between measurement and calculation can be achieved for the p-90 as well.

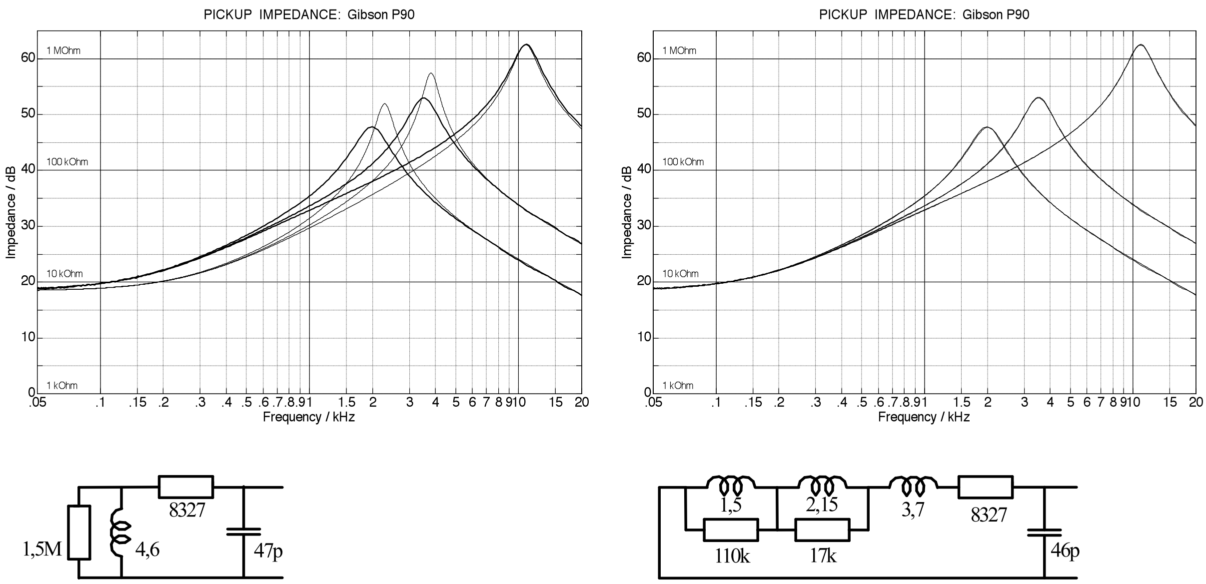


Fig. 5.9.23: Gibson P90, impedance. Measurement (——), ECD-calculation (______). Left: ESB1; right: ESB2. Pickup without coaxial cable. Component values in H, Ω, F.

At this point we will take another look at the effect of load capacities. Every pickup is loaded with a capacitance – in fact only this way it receives its charachteristic resonance. When putting together the equivalent circuit diagram and during the approximnation process, it is necessary to keep this load in mind. The following example includes a simple circuit: a coil of 2 H having a copper resistance of 5 kΩ has a dampening resistor connected in parallel to it. In one case, this resistor has 3 MΩ, in the other it has 300 kΩ. The corresponding frequency response of the impedance magnitude (**Fig. 5.9.24**) shows a difference only at higher frequencies; at 3,5 kHz both magnitudes are almost identical. However, connecting a 1-nF-capacitor in parallel causes considerable deviations between the two magnitude curves.

Without the parallel-connected load capacitor, the impedance magnitude at 3,5 kHz is mainly formed by the imaginary coil-impedance – compared to it the parallel dampening resistor is of high impedance and negligible. A load capacitor connected in parallel compensates the imaginary part created by the coil, and the real part becomes dominant. In the Nyquist curve on the right (showing the real part of the impedance on the abscissa and the imaginary part of the impedance on the ordinate – with the frequency as parameter) sections of two clock-wise curved circles are shown; due to the different coordinate scaling they are distorted to ellipses. For 0 Hz both circles start at about 5 kΩ (more precisely at 5//300 and 5/3000, respectively) and turn upwards in a clock-wise manner. In both curves, f = 3,5 kHz is marked as a dot. The points for which the distance to the origin is constant are indicated with a *dashed* line (this is in fact a circle, but again the different scaling on the coordinates distorts it to an ellipse). As is clearly evident, both indicated 3,5-kHz-points have an almost equal distance to the origin – the magnitude of their impedances therefore is almost identical, but the real parts of their impedance differ by almost a factor of two. This shows that the magnitude of the impedance alone does not give a complete description.

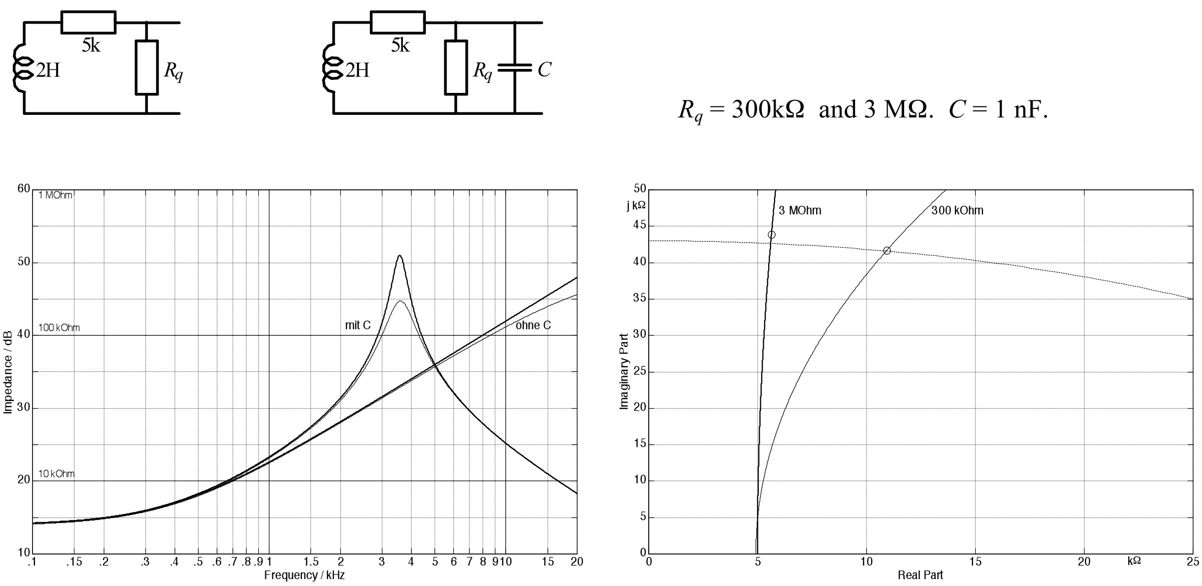


Fig. 5.9.24: circuit (above), frequency response of the impedance magnitude)left); Nyquist curve of the impedance (right). Thin line: 300 kΩ, bold line: 3 MΩ.

5.9.2.6 Gibson Humbucker: coil with screws

Seth Lover, developer at Gibson, reports in [13] that every pickup coil had 4500 turns of thin enameled copper wire. He states an AWG-#42-diameter which equals 64 µm. On the other hand, he also notes that the wire diameter was subject to tolerances dictated by manufacture: "*The DC resistance varied, because the diameter of the wire was not constant. As the diameter decreases the resistance increases, but if the inductance remains within certain tolerances, then it's OK*" [13]. A further manufacturing issue with early Gibson pickups were shorts within the winding (*short turns*) which apparently were due to insufficient insulation; these reduced the resonance emphasis and thus the treble content in the signal. Regarding the magnet material, Set Lover remarks [13]: "*We also used Alnico II and III, and the reason is, that you couldn't always buy Alnico V, but whatever was available we would buy as they were all good magnets*". ISO 9000 hadn’t arrived yet.

We can assume that the early Gibson pickups were subject to substantial manufacturing tolerances, and that therefore their transmission characteristics (i.e. their sound) included inter-individual variances. Tom Wheeler writes in his Guitar Book [14]: "*Later Humbuckers have slightly smaller magnets and other minor differences in construction*", and he does add about the color (!) of the cosmetics "*The color of the bobbin has no direct bearing of the tone*" [14]. Seth Lover, however, does not remember any changes [13]: "*No, we kept the pickups pretty much the same, they were all identical. ... Actually the PAFs weren't any better than the later pickups that were built right.*" Seems to be all a question of the point of view. Tom Wheeler [15]: *"The PAF's popularity, which is unsurpassed, is a blend of performance and snob appeal*".

The patent for the Gibson-Humbucker talks about two corresponding coils. A magnetic field emanating from an interference source induces the same interfering voltage into both coils, and the out-of-phase (reverse poled) connection of the two coils causes the two interference voltages to cancel each other out. Production units of the pickup, however, sported two different coils: they included a “slug”-coil and a “screw”-coil. The slug-coil contains 6 cylindrical pins (pole pieces) of a diameter of 4,8 mm. The pins are positioned such that their upper surface is flush with the string-facing surface of the coil while their lower surface extends 3 mm out of the bobbin. The screw-coil holds, instead of the pins, 6 round-head screws of a length of 21 mm and a diameter of 3,2 mm = 1/8”. The sensitivity of the pickup can be adjusted for each string individually by rotating the screws.

The following measurements and calculations refer to a bridge pickup of a 1968 Gibson ES 335 TD – it was taken out of the guitar and disassembled (with rather mixed feelings!). The screw-coil (**Fig. 5.9.25**) is penetrated by 6 screws which are screwed into an iron block at the lower side of the coil. Unscrewing all 6 screws allows for taking off the iron block such that a coils without any ferromagnetic parts remains. The impedance frequency plot of this coil is shown in **Fig. 5.9.26**. In the low frequency range, the impedance is determined mainly by the copper resistance, and in the middle frequency range by the reactance of the coil ωL; in the high frequency range the reactance of the capacitance $1/(\omega C)$ is the main factor. At the upper end of the frequency range a pronounced resonance is clearly visible.

$$\omega_{\text{resonance}} = 1\big/\sqrt{L \cdot C}\,; \qquad f = \omega/2\pi \qquad \text{Resonance frequency}$$

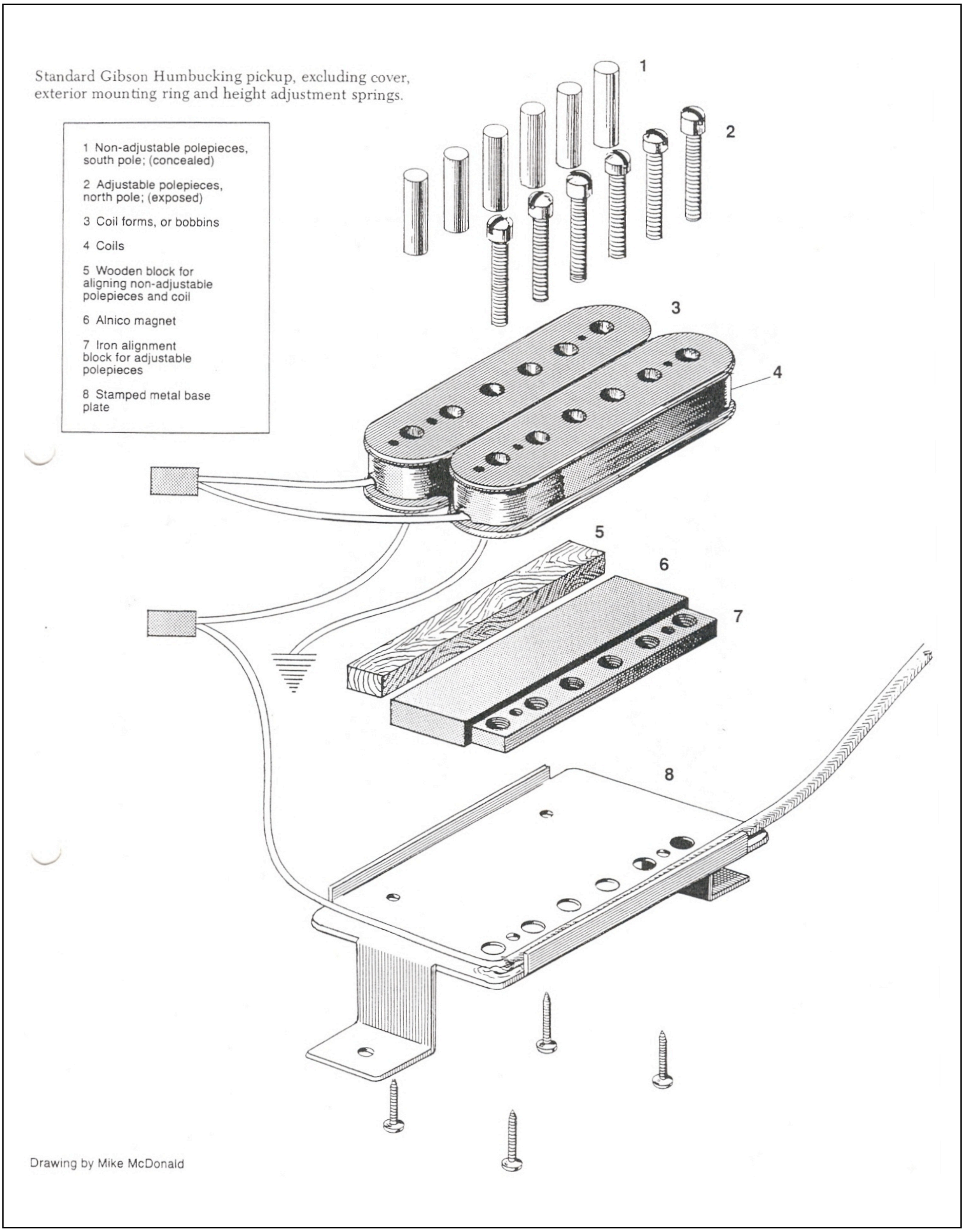


Fig. 5.9.25: Exploded view of a Gibson-Humbuckers (according to Mike McDonald)
1 = fixed pole pin, south pole (not accessible); 2 = adjustable pole screw, north pole;
3 = bobbin; 4 = coil; 5 = wooden spacer; 6 = alnico bar-magnet;
7 = block with threads for the pole screws; 8 = metal base plate.

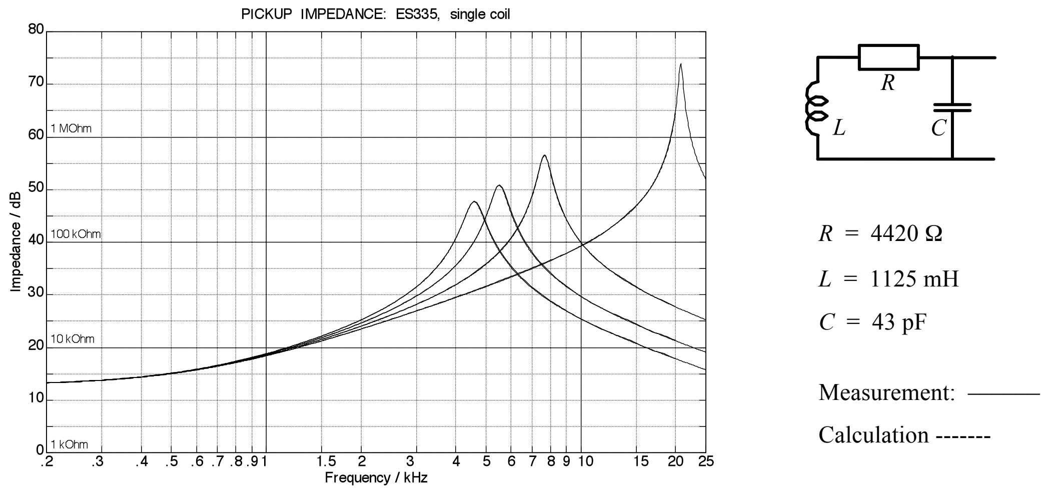
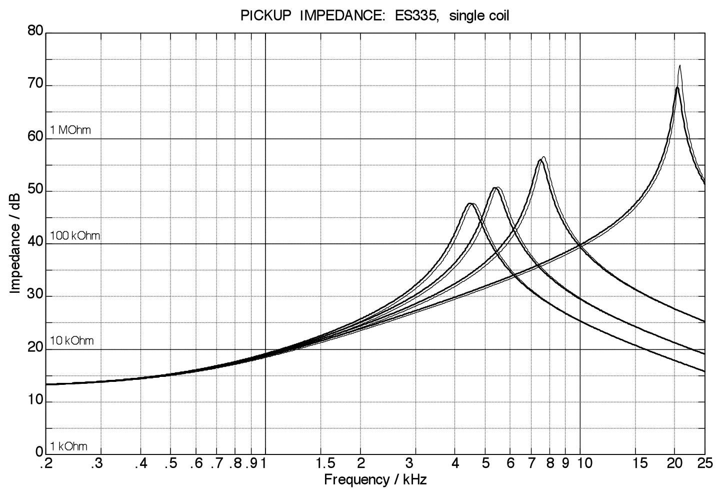


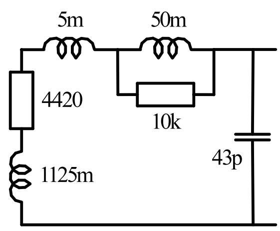
Fig. 5.9.26: Magnitude of pickup-impedance frequency plot. Screw-coil without metal parts. Measurement and calculation (equivalent circuit diagram) are practically identical. The pickup was loaded with 0/330/700/1030 pF.

The measurement gives a DC resistance (copper resistance) of 4420 Ohm. The inductance of the winding determines the impedance increase at middle frequencies. The cutoff-frequency at which the inductive reactance corresponds to the ohmic copper resistance is f_g = 625 Hz. Below f_g, R dominates, above, L dominates. The wound-up coil wire does not only show inductive but also capacitive behavior (winding capacitance), due to the neighboring coils. Inductance L and capacitance C result in a resonance maximum in the frequency response at the resonance frequency $f \approx 1/\left(2\pi\sqrt{LC}\right)$. The larger the capacitance is, the lower the resonance frequency is located. The measurements were taken without and with a load (in the form of an external additional capacitor) connected to the pickup; this way the resonance frequency of 21 kHz at 0 pF could be lowered to 7.7 kHz (330 pF), 5.5 kHz (700 pF), and 4.6 kHz (1030 pF). The resonance shift gives additional information about the quality of the modeling. As can be seen from Fig. 5.9.26, the measurement and the calculation agree to the line width. The shown equivalent circuit diagram (**ECD**) is therefore well suitable to model the impedance behavior of the pickup coil.

In the real pickup coil, resistance, inductance and capacitance are of course not concentrated into one single point but differentially distributed. Every little piece of wire of the length *dl* contains a partial resistance *dR* and a partial inductance *dL*, and forms a partial capacitance *dC* with all other pieces of wire. Measurement and simulation (calculation) do however show that a modeling of the impedance by concentrated elements (*R, L, C*) is fully sufficient. Whether the transmission characteristic of the pickup can equally well be described this way needs to be investigated separately (see below).

Next, the screw-coil is to be looked at in conjunction with the iron **block**, but still without screws. For the measurements, the block was fixed in its normal position underneath the coil using sticky tape. The ferromagnetic behavior of the block reduces the magnetic resistance in the magnetic circuit; permeability and inductivity are increase that way.





ECD: Screw-coil with iron block (compare to. Abb. 5.9.26).

Fig. 5.9.27: Frequency response of the pickup-impedance magnitude. Screw coil with/without iron block. ECD.

Fig. 5.9.27 shows a comparison of the impedance frequency plots with/without the **block**. The inductivity is increased by the presence of the block, which leads to a lowering of the resonance frequency. This is not a pronounced effect, though, and could be ignored for a simple model. A precise model requires that on top of the inductance increase, the **iron losses** are reproduced, as well. To re-magnetize the iron, energy is necessary which is taken out of the electrical circuit (re-magnetization losses). In addition, the time-variant magnetic field causes **eddy currents** to be induced in the iron – again these are fed energy from the resonant circuit. Coil and block may be though of as a transformer coil: the block represents a short-circuit winding withdrawing energy from the pickup coil. In the end, the block is made warmer; this effect is however so minute that the temperature-rise will not be noticeable. Still, the dampening effect in the resonance circuit can be seen in the frequency response of the impedance: the impedance maximum is slightly reduced.

Modeling the iron losses is complicated. In the above example it could be dispensed with, as well, since the effect is so weak. However, when inserting the screws into the coil, substantial iron losses occur which may not be ignored anymore. A fundamental discussion is therefore necessary. In every electrically conductive material a time-variant magnetic field causes eddy-currents; these flow on a circular path within the conductor. Since the cross section of the block is relatively large, the eddy currents meet merely a rather small resistance, and the load is of relatively low impedance. With increasing frequency, however, a displacement of the current happens which is called '**skin effect**'. The eddy currents do not flow in the whole block anymore, but only along the surface of the block. The cross-section available to the current flow is reduced and the resistance increased. This resistance increase has a dependency on frequency described with the square root. Since the square-root, however, is not a rational but an irrational function, it is not possible to model the corresponding behavior with a finite number of RLC-elements. An infinite number of elements are not a practicable solution, though. Again, an approximation presents itself as a way out: the skin effect may be modeled by a special RL-two-terminal network. The higher the requirements regarding accuracy, the more components need to be put into his two-terminal network. For most pickups, however, 3 – 7 elements will suffice (Chapter 5.9.2.2).

The block is modeled in **Fig. 5.9.27** by three additional components (5 mH, 50 mH, 10 kΩ). The two coils increase the overall inductivity (ferro-magnetic effect of the block), at high frequencies, however, the 50-mH-coil does not have its full impact anymore due to the resistor connected in parallel (modeling of the skin effect). With this ECD, the reproduction of the impedance is of such accuracy that it agrees with the measurement up to line-width.

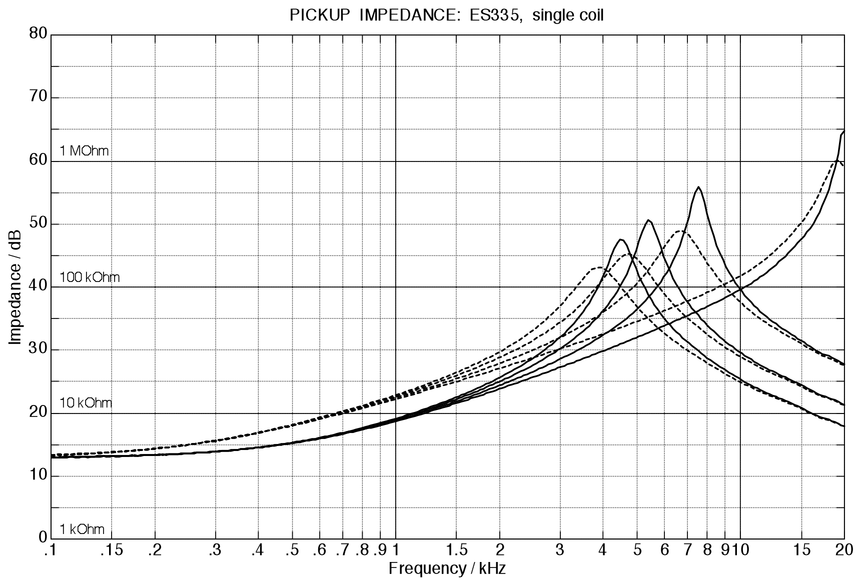


Fig. 5.9.28: Comparison: screw-coil with block, without (——) nd with **screws** (-----).

The impedance changes clearly once the 6 **pole-screws** are inserted into the bobbin **(Abb. 5.9.28)**. The ferromagnetic screws are positioned in the area of strong magnetic alternating flux; they substantially reduce the magnetic resistance and thus increase the coil inductivity. On the other hand, the screws also produce losses, which is why the ECD requires additional (ohmic) loss resistors.

Further difficulties arise from combining coil, screws, and block: the screws change the distribution of the magnetic field in space. With the screws, the magnetic field permeates the block in a different manner than without the screws. Consequently, the block-ECD, which is valid for the setup without screws, cannot be used once the screws are added. Let us be reminded at this point that the equivalent circuit diagrams present here do not model the distribution of the field in space but are equivalents for the impedance. It is only possible to explicitly identify the resistor *R* effective for DC. All other elements of the ECD are the result of an approximation without physical correspondence.

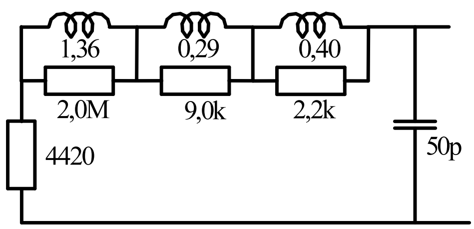


Fig. 5.9.29: Equivalent circuit diagram (ECD) for “screw-coil with blocjk and screws”, Gibson-Humbucker. Compare to Fig. 5.9.30.

In **Fig. 5.9.29** we see an equivalent circuit for the screw-coil with block and screwed-in screws. The impedance frequency plot is very well approximated with it, as shown by measurement (——) and calculation (-----) in **Fig. 5.9.30**; both families of curves are practically identical.

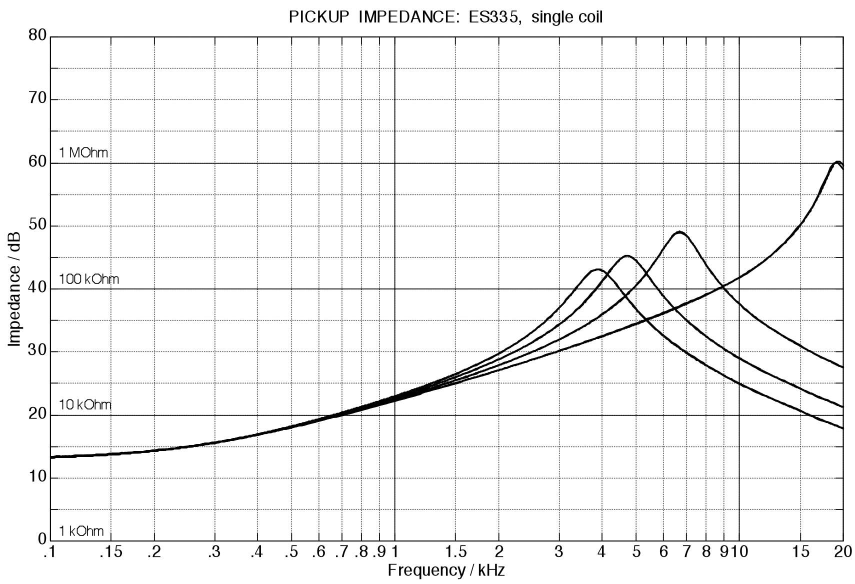
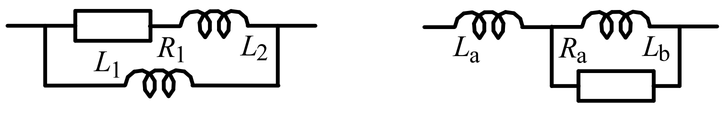


Fig. 5.9.30: Frequency response of impedance: “screw-coil + block+ screws”.
Measurement (—) = calculation (----).

The circuit according to Fig. 5.9.29 is not the only one possible – there are several equivalent replacements with the same high quality of approximation. **Fig. 5.9.31** shows two simple equivalent circuit diagrams, both including a resistor and a two independent coils each. Consequently, the impedance functions are of 2nd order and include the frequency to the power of 2, 1 and 0. Equating the corresponding polynomial coefficients (comparison of coefficients), we obtain 3 requirements for the 3 components; this enables the conversion of the component values from one circuit into the components of the other. For circuits of higher order (i.e. additional coils), there are still more different topologies with the same impedance frequency plot. Which equivalent circuit is used in the end remains a matter of taste. The supplement via series connection of RL-parallel-circuits as proposed in Fig. 5.9.29 appears more purposeful than the parallel connection of RL-series circuits, though (see also Chapter 5.9.2.3).



$$L_1 = L_a + L_b$$
$$L_2 = L_a \cdot \left(1 + L_a / L_b\right)$$
$$R_1 = R_a \cdot \left(1 + L_a / L_b\right)^2$$

Fig. 5.9.31: Two equivalent circuit diagrams wth equal imepdance frequency response.

The only purpose of the equivalent circuit diagrams present here is to deliver impedance frequency plots equal to those obtained in measurements, and to create the basis for equivalent circuit diagrams of the transmission. As soon as a purposeful compromise between component-complexity and accuracy was found, the approximation was successfully applied and not optimized further.

The consideration about impedance related to the coil with screws and block. Now we add the bar-**magnet**, finally transforming the coil which by itself is insensitive to string vibrations into a pickup. The effects of the magnet on the transmission behavior are of existential importance; its influence on the impedance is, however, very small. It does belong to the group of ferro-magnetic materials but its permeability at the operating point is relatively small, and moreover it is not within the coil but positioned to the side of it. **Fig. 5.9.32** shows the frequency response of the inductivity with and without magnet. Adding the magnet makes for a slightly larger inductivity (compare to Fig. 5.9.33), for a quality factor which is a bit reduced, due to the eddy currents induced in the magnet, and in the end for a slightly better coupling of the two coils.

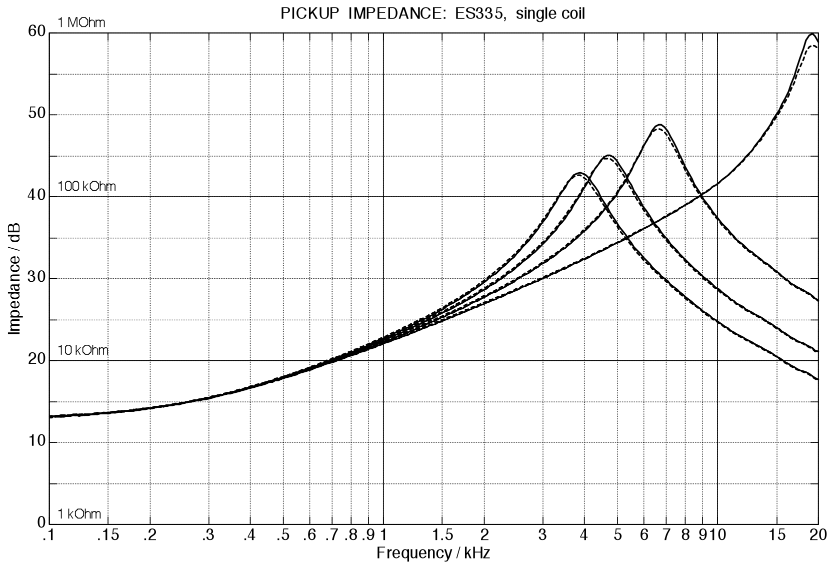


Fig. 5.9.32: Frequency response of the impedance: “screw-coil + block+ screws”;
without (——) / with (-----) **magnet**

The effects of the magnet on the inductivity show most at mid-range frequencies. **Fig. 5.9.33** depicts an enlarged part from Fig. 5.9.32. The inductivity increase amounts to merely 2 – 3 %.

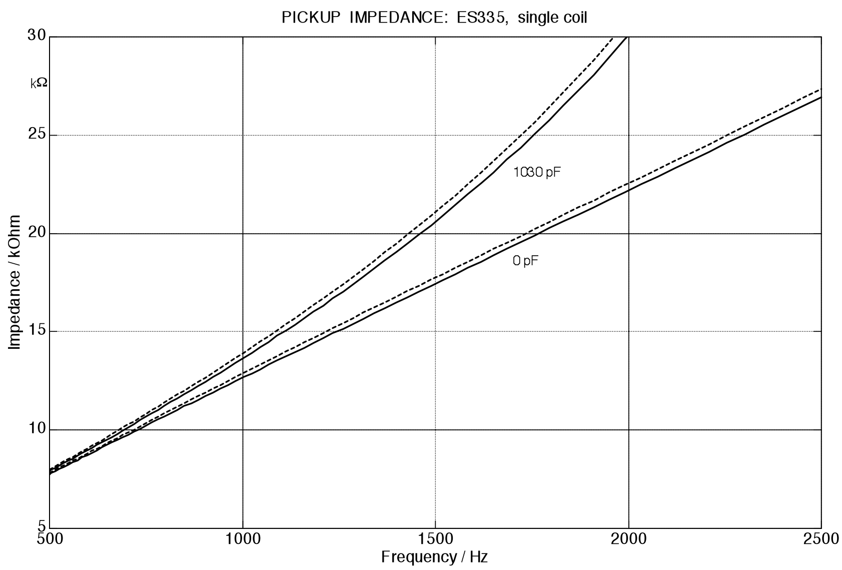


Fig. 5.9.33: Enlarged section from Fig. 5.9.32, without (——) / with (-----) magnet.

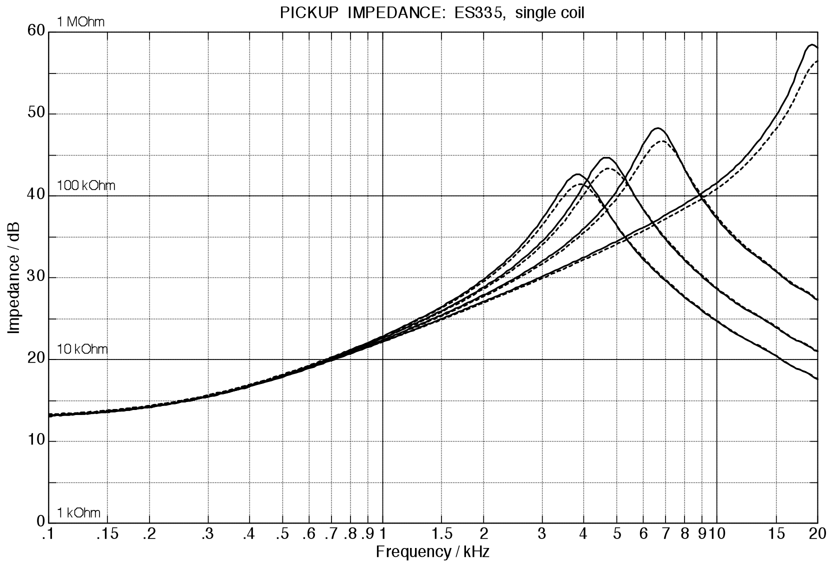


Fig. 5.9.34: Impedance: screw-coil + block+ magnet; without (——) / with (-----) **sheet metal**

As a next step, the sheet metal forming the base plate of the pickup is added in. It consists of German silver, which is a non-ferro-magnetic material. Its specific resistance is 0.3 Ωmm²/m, compared to 0.018 Ωmm²/m for copper. Still, even with this higher resistance eddy-current losses cannot be completely avoided, as **Fig. 5.9.34** shows. The resonance quality factor has again gone down compared to that of Fig. 5.9.32.

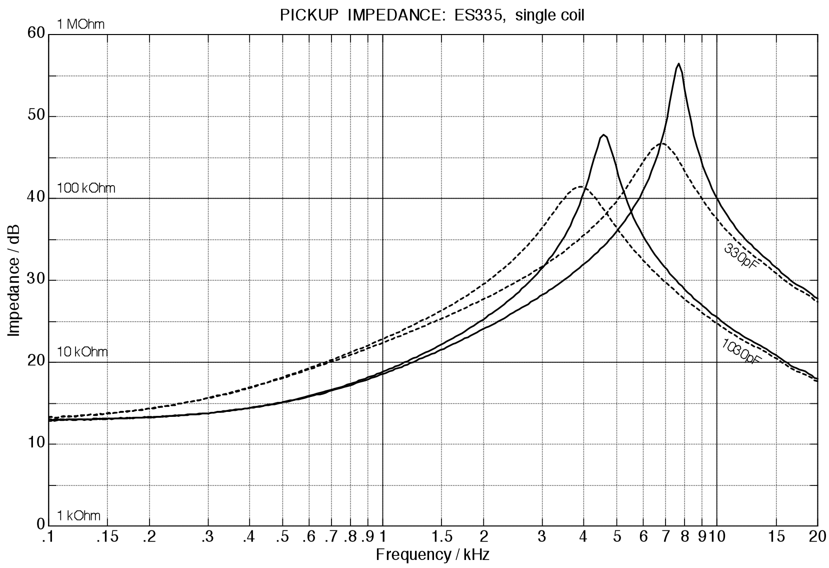


Fig. 5.9.35: Impedance: screw-coil without any metal parts (——);
screw-coil + block + screw + mgnet + base plate (-----); loaded with 330 pF and 1030 pF.

Fig. 5.9.35 indicates a summary of the influences of the metal parts on the impedance. The increase of the inductance is due to the screws, the decrease of the emphasis is caused by the screws and the base plate. The metal pickup cover had been removed in the past – it would have further reduced the emphasis.

Now, the fully assembled **slug-coil** is mounted next to the screw-coil, but it is not yet electrically connected. The measurements are still directed to the screw-coil; the objective is to clarify whether the magnetically soft slugs increase the inductivity of the screw-coil. As **Fig. 5.9.36** shows, this is not really the case; the two measurements differ merely by the line width. The ferromagnetic slugs are positioned so far away from the screw-coil that they have little disturbing effect on the latter's magnetic field. The magnetic coupling of both coils is, however, not zero (Chapter 5.9.2.8)!

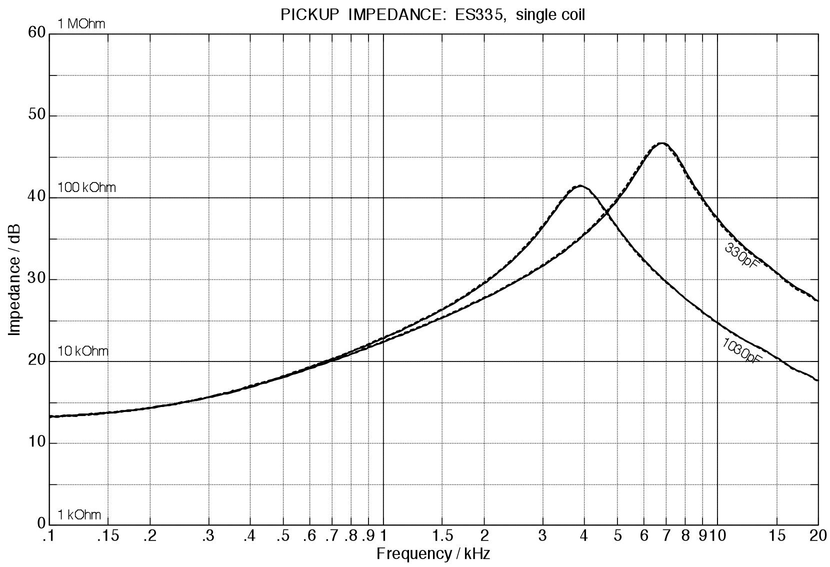


Fig. 5.9.36: Impedance: complete screw-coil without (——) and with slug-coil next to it (-----); loaded with 330 pF and 1030 pF.

Finally, **Fig. 5.9.37** shows the equivalent circuit diagram for the impedance of the complete screw-coil. We thus have arrived at an impedance model for an individual specimen of a humbucker taken from a ES-335-TD made in 1968. On the basis of this pickup we could exemplify the influences of various pickup components; however, we must not expect that <u>every</u> Gibsom Humbucker can find its exact description in this equivalent circuit diagram. Manufacturing tolerances and modifications have led to different versions and thus to different data.

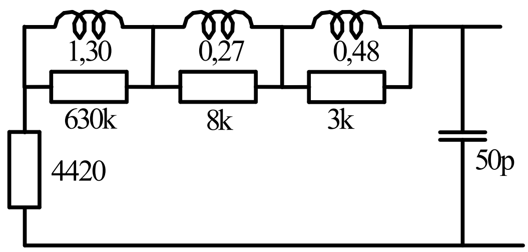


Fig. 5.9.37: Equivalent circuit diagram for the impedance of the screw-coil of the fully assembled pickup.

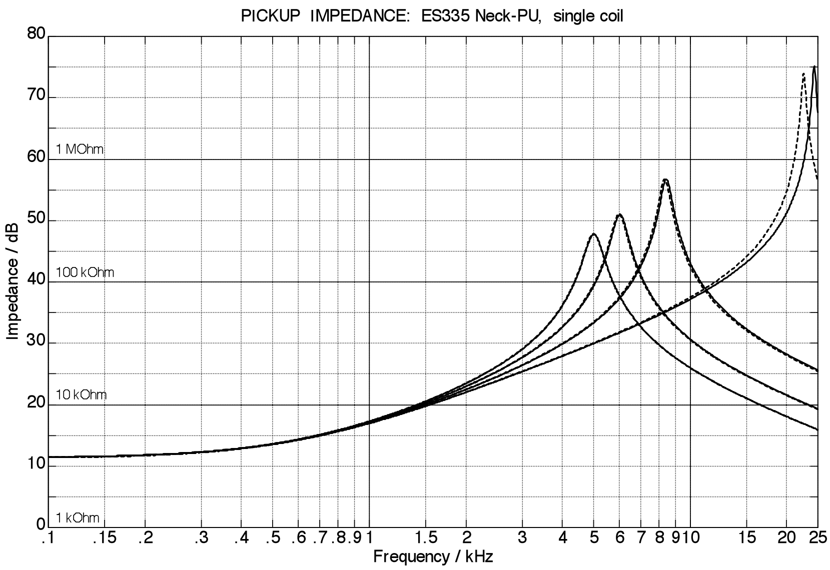
5.9.2.7 Gibson Humbucker: coil with slugs

The Gibson Humbucker contains *two* coils: a coil with screws, and a coil with slugs. In order to accomplish the hum-suppression, both coils should feature the same electrical characteristics. Comparative measurements yield an inconsistent picture (**Fig. 5.9.38**): the neck pickup of the ES-335 under investigation indeed had two equivalent coils, while for the bridge pickup (of the same guitar) there were differences. The slug-coil featured an 11% smaller DC resistance and a 13% smaller inductivity compared to the screw-coil; most probably the coils differ in the number of turns. We cannot determine anymore whether this **lack of symmetry** was on purpose, or happened by accident during manufacture (in 1968). In any case it seems not entirely undesirable; otherwise Gibson would not offer, in the form of the new “Burstbucker”, a pickup which replicates the uneven number of turns found in old humbuckers.

Slug-coil:
0,98 H, 3928 Ω, 47 pF.

Screw-coil:
1,13 H, 4420 Ω, 47 pF.

Fig. 5.9.38a: Comparison screw-coil (---) vs. slug-coil (——). Only bobbin and wire for a ES335-**bridge**-pickup.
1000pF, 700pF, 330pF, 0pF.



Slug-coil:
0,95 H, 3693 Ω, 40 pF.

Screw-coil:
0,96 H, 3660 Ω, 47 pF.

Fig. 5.9.38b: Comparison screw-coil (---) vs. slug-coil (——). Only bobbin and wire for a ES335-**neck**-pickup.
1000pF, 700pF, 330pF, 0pF

The impedance frequency plots shown in Fig. 5.9.38 were measured with the coils taken off the pickup assembly, i.e. there were only the bobbins wound with the wire, and no metal parts were included. In the assembly process, the inductances increase due to the effect of the ferro-magnetic metal components (Fig. 5.9.39).

6 ferro-magnetic metal cylinders ("slugs") are inserted into the **slug-coil** (∅ = 3/16" = 4,8 mm), and 6 ferro-magnetic metal screws are screwed into the **screw-coil** (thread-∅ = 1/8" = 3,2 mm, head-∅ = 3/16" = 4,8 mm); in both coils the inductance is increased by these metal parts, while the resonance emphasis is decreased – but not in the same way. With the neck pickup (having rather similar "empty" coils, Fig. 5.9.38b) there is a larger inductivity increase at low frequencies in the screw-coil; from 1 kHz, however, the slug-coil features the larger inductivity. The resonance emphasis of the screw-coil decreases more strongly that of the slug-coil (**Fig. 5.9.39b**). These effects also appear for the coils of the bridge pickup (**Fig. 5.9.39a)** but the different numbers of turns hamper any analysis.

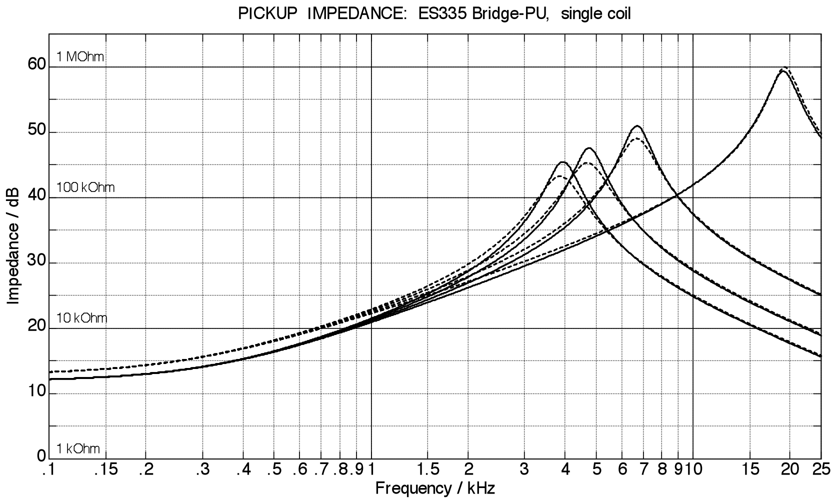


Fig. 5.9.39a: Comparison: screw-coil with screws, with block (---); slug-coil with slugs (——). Without bar magnet and base plate ES335-**Bridge** pickup. 1000pF, 700pF, 330pF, 0pF.

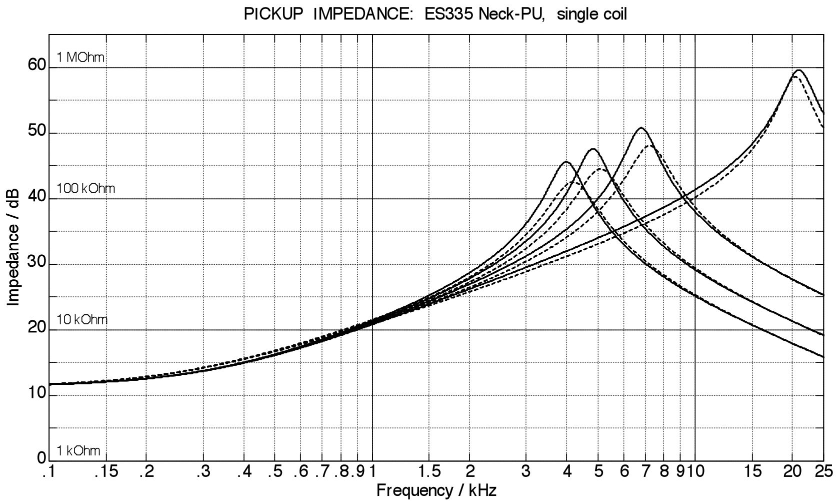


Fig. 5.9.39b: Comparison: screw-coil with screws, with block (---); slug-coil with slugs (——). Without bar magnet and base plate ES335-**Necl** pickup. 1000pF, 700pF, 330pF, 0pF.

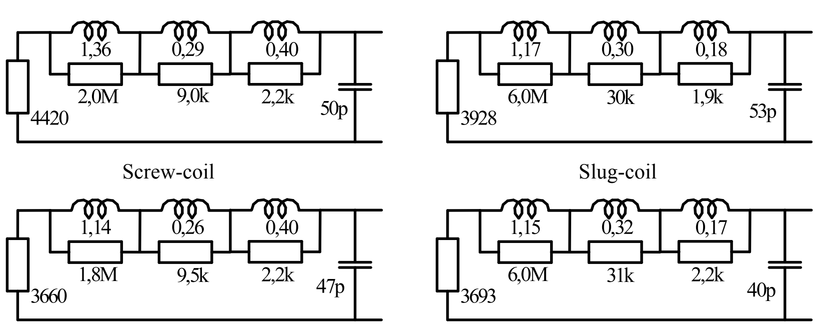


Fig. 5.9.40: Equivalent circuit diagrams for the impedances in Fig. 5.9.39 Bridge pickup (top) Neck pickup (bottom)

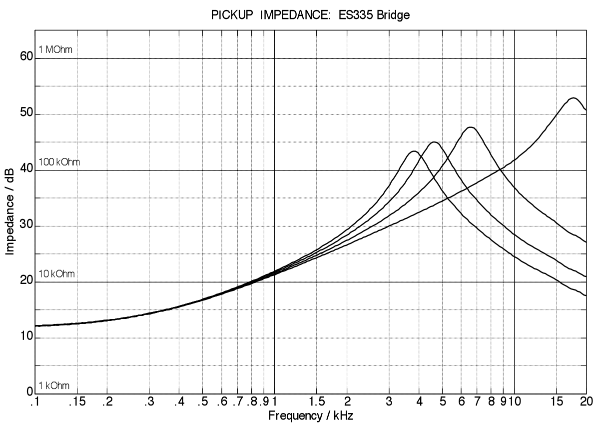
5.9.2.8 Gibson-Humbucker: coil-coupling

The two coils of a typical Gibson Humbucker (e.g. 490R; but not P-100) are connected in series. Therefore, it could be expected that their impedances add. For the DC resistance this assumption is correct; for frequencies which are not zero, however, there are deviations. The measured impedance of the series connection is larger than the sum of the individual impedances. The reason for this is the magnetic coupling of the two coils, and a different provision for the addition results (compare Chapter 5.5.2).

Two series-connected inductivities L_1, L_2 carry the same current $\underline{I}$. If there is no magnetic coupling, a voltage $j\omega \cdot \underline{I} \cdot L_1$ and $j\omega \cdot \underline{I} \cdot L_2$ across them is created, respectively. However, if the magnetic flux generated in one of the coils partially or completely penetrates the other coil, it will induce an additional voltage there, depending on the coupling factor [20, Band II]. The coupling factor k is zero for non-coupled coils; it is +1 for coils ideally coupled in the same sense and -1 for coils ideally couple in the inverse sense. Ideal coupling is not possible in reality; therefore, the magnitude of the coupling factor needs to be always smaller than 1. Equal-sense coupling implies that the coil voltage is increased by the coupling – this is the case for humbuckers ($0 < k < 1$). As two coils coupled by a joint magnetic field are connected in series, the overall inductivity of this series connection is

$$L_\Sigma = L_1 + L_2 + 2k \cdot \sqrt{L_1 \cdot L_2} \approx (L_1 + L_2) \cdot (1 + k) \qquad \text{Summed inductivity}$$

In **Fig. 5.9.41** we see the frequency responses of the impedances of the (separately measured) coils of a Gibson Humbucker. The pickup was fully assembled and the coils isolated against each other. A distinct non-symmetry is recognizable with the screw coil having a higher impedance. Connecting the two coils with the customary polarity in series results in an overall impedance which is not the sum of the individual impedances but one which has an about 20% larger value. Only at very low frequencies the overall impedance corresponds to the sum of the sum of the individual impedances (**Fig. 5.9.42**). The coupling factor of the two coils thus amounts to 20%, i.e. a fifth of the magnetic flux created by one coil penetrates the other coil as well and induces a voltage there. If one coil would be connected with reverse polarity, the overall voltage would decrease by 20% – no measurements for this are shown here.



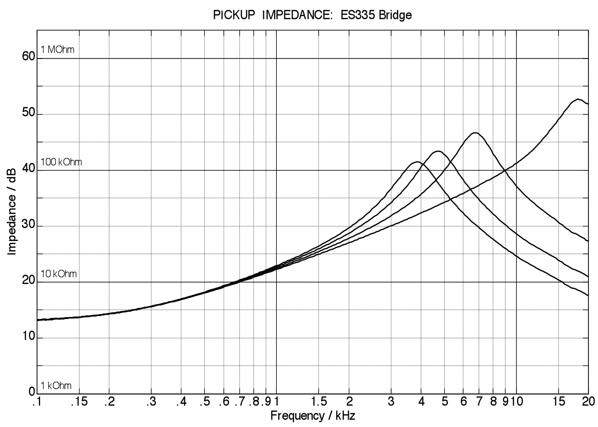


Fig. 5.9.41: Frequency repsonses of impedances: ES-335-bridge-pickup, slug-coil (left), screw-coil (right). Capacitive load: 1030 pF, 700 pF, 330 pF, 0 pF. For the measurement, the coils were insulated against each other.

In the left part of **Fig. 5.9.42**. the calculated sum of the individual impedances is shown; the solid curve depicts the measurement results. In the right-hand section of the figure, the equivalent circuit diagrams of the individual coils formed the basis of the calculated curve for the sum (Chapter 5.9.2.6 and 5.9.2.7), with all inductances and loss resistances being increased by k = 20%. With this, the agreement with the measurement results is much better – the only discrepancy shows for the connected coils without capacitive load at the 15-kHz-resonance. Apparently there is also a capacitive coupling of the two coils which, however, can be ignored in the framework of practical operation.

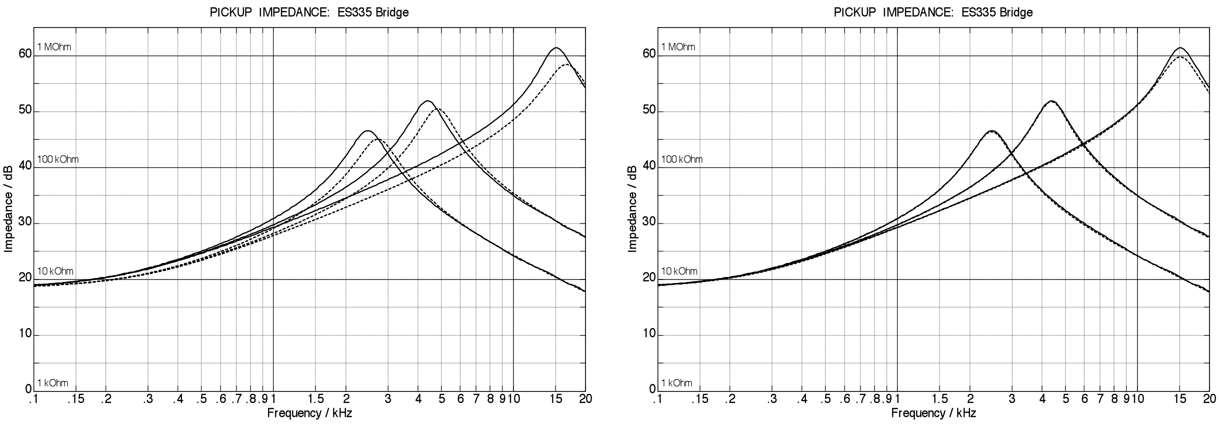


Fig. 5.9.42: Frequency response of the impedances: ES-335-bridge-pickup. Model wthout coupling of magnetic fields (left), with 20%-coupling of the magnetic fields (right). External capacitve load: 1030 pF, 330 pF, 0 pF. Replacing the bar magnet (Alnico 2 vs. Alnico 5) may change the coupling factor; no measurements shown here.

In principle all pickup coils of a guitar are magnetically coupled. However, since the coupling factor decreases rapidly with increasing coil distance, the magnetic field coupling has any significance only for the neighboring humbucker coils. Just to be safe, a Stratocaster (3x singlecoil) was also analyzed: indeed, the coupling factor could be measured but at k = 0,5% has no significance at all.

5.9.3 Equivalent circuit diagram for the transmission

In the previous sections we presented two-terminal equivalent circuits modeling the frequency response of a pickup. The actual aim is, however, to describe the sound of the pickup – or, more precisely, its transfer characteristics. Using the two-terminal-network theory discussed in chapter 5.9.2, the electrical circuit (the network) is investigated regarding two *terminals* (network nodes); for a pickup, these are the two connecting terminals at which a complex impedance is measured. In contrast, for the **quadripole theory** two of the network nodes are defined as input port and the other two as the output port; therefore occasionally the term **two-port-theory** is found instead of quadripole theory. At each of the two ports two-terminal impedances may be defined, but more important is how the signals at one port depend on the signals at the other. For an electrical network, the signals at the ports are voltage and current. Between the nodes of every port we find a voltage $\underline{U}$ that as a special case may be zero, while the currents $\underline{I}$ flow in the connecting wires to external systems; again $\underline{I}$ may be zero as a special case.

In order to make the complicated transfer behavior of a pickup describable, it needs to be simplified. This is achieved by defining the pickup as a linear, time-invariant system of finite order. **Linearity** implies among other things lack of sources and proportionality between input and output signals. “Lack of sources” means that the pickup does not contain any signal source – which is a matter of course in the framework of the usual approach, save for noise disturbances (Chapter 5.12). “Proportionality” stands for an output signal multiplied by k if the input signal is changed by the same factor of k. This is only approximately true for a pickup, as distortion measurements show (Chapter. 5.8). For small levels, a pickup is a linear system but for strong string vibrations a non-linear model is required. **Time-invariant** means that the pickup always behaves in the same way: a condition generally met with good approximation. The **order** n of the model marks the number of free energy storages, in other words the number of independent capacitances and inductances within the equivalent circuit. The more precise the model is supposed to be, the higher the order will be (it does – in this context – not indicate the contrary of disorder). For usual equivalent circuits of pickup an order of $n = 2 \dots 5$ is to be expected.

Using the simplifications mentioned above we can determine a broken rational transfer function of n-th order, which maps the input signal onto the output signal. The output signal is the voltage at the output terminals – but what is the input signal? If one does not want to immediately go back to the action potentials of the guitarist, we could define the **string vibration** as the input signal. This, however, is a spatially distributed vector field difficult to describe. Again, several simplifications are required: measurements of the aperture (Chapter 5.4.4) suggest that only the string section vibrating directly in front of the magnet causes the significant change in the field, and within this again predominantly the magnet-axial (fretboard-normal) component. Movement of the string changes the magnetic resistance and modulates the flux generated by the permanent magnet. A DC-source and a time-variant impedance may model this process in the equivalent circuit, or one can imagine the magnetic AC-flux as being generated by an AC-driven **transmitter coil**. This transmitter current is then imagined to be proportional to the string movement; the latter in turn can be presented in several ways: as deflection, velocity or acceleration.

The **transfer function** describes the projection of the string movement (the input quantity) on to the pickup voltage (output quantity) as a complex frequency function $\underline{H}(j\omega)$. The **spectrum** of the pickup voltage $\underline{U}(j\omega)$ is a complex frequency function, as well, in contrast to $\underline{H}(j\omega)$; however, it is not a system quantity but a signal quantity. $\underline{U}(j\omega)$ is dependent on the input signal but $\underline{H}(j\omega)$ is not. For an excitation with a known input spectrum $\underline{E}(j\omega)$, the corresponding output spectrum $\underline{U}(j\omega)$ can be calculated in the linear model:

$$\underline{U}(j\omega) = \underline{E}(j\omega) \cdot \underline{H}(j\omega)$$

From a systems theory perspective, each one of the three motional quantities of the string (deflection, velocity, acceleration) could be defined as input quantity, but using the **string velocity** is particularly purposeful and can be interpreted well. The pickup-transfer-function used in the following is thus the velocity→voltage-transfer-function $\underline{H} = \underline{H}_{\mathrm{Uv}}$, the first index (U) of which points to the generated output-quantity while v yields the input quantity which causes the effect. For the magnetic pickup, $\underline{H}_{\mathrm{Uv}}$ is a **low-pass function** which sometimes raises the question whether such a pickup can actually generate a “0 Hz”-signal. In this respect, we need to consider that – as pointed out above – the output spectrum is not only dependent on $\underline{H}_{\mathrm{Uv}}$, but also on the input spectrum. At 0 Hz, the string is without movement, its velocity is thus zero and therefore the output voltage is zero as well – although $\underline{H}_{\mathrm{Uv}}$ is not zero.

In order to now put together a purely electrical transfer equivalent circuit we need to find an electrical input quantity matching the string velocity. The cause for the induced pickup voltage is the changing magnetic flux, the instantaneous value of which depends on the distance of the string to the magnet: the closer the string to the magnet, the larger the flux. Since the distance is equivalent to the integral of the string velocity over time, and since the spectral operation corresponding to this is a division by $j\omega$ [6], it is possible to use as equivalent model a **transmitter coil** positioned on the pickup. This coil – excited by a current source with a $1/f$-characteristic - generates a magnetic alternating field.

$$\underline{v} \rightarrow \underline{I} \rightarrow \underline{U}; \qquad \underline{H}_{\mathrm{Uv}} = \underline{H}_{\mathrm{Iv}} \cdot \underline{H}_{\mathrm{UI}}; \qquad \left. \underline{H}_{\mathrm{Iv}} = \frac{\underline{I}}{\underline{v}} = \frac{const \cdot \Phi}{j\omega \cdot \xi} = \frac{const}{j\omega} \right\} \underline{I} = \frac{const \cdot \underline{v}}{j\omega}$$

In other words: to obtain a frequency-independent velocity-amplitude, the amplitude of the deflection is reciprocal to the frequency, and so is the amount of the magnetic AC-flux. Whether this AC-flux is generated by a moving string or instead by a current-excited transmitter coil is – in the framework of this model – equivalent.

In the following the velocity→voltage-transfer behavior of the pickup is presented with a low-pass-model. The input quantity is generated by an ideal current source with frequency-reciprocal amplitude $I \sim 1/f$ while the output quantity is the pickup voltage.

Special emphasis is put on the fact that per pickup in the two-terminal- and in the quadripole-equivalent-circuits one and the same components are used. If the basic models are viable it needs to be possible to derive a two-terminal-equivalent circuit from an impedance measurement (doable with little effort), and to further determine – with the components calculated for the two-terminal-equivalent – also the quadripole-equivalent-circuit and the transfer function $\underline{H}_{\mathrm{Uv}}$. As a precaution it is mentioned again that $\underline{H}_{\mathrm{Uv}}$ is not identical to the spectrum of the pickup voltage; for the latter the velocity spectrum is required on addition (Chapter 1 – 3).

Fig. **5.9.43** shows the quadripole-equivalent circuit for a **Stratocaster** pickup. Structure and component values are taken from the two-terminal equivalent circuit (Fig. 5.9.5). The alternating field caused by the string may be imagined to be generated by a transmitter coil driven by an impressed current $\underline{I}$. In the left-hand picture, the transmitter coil is the primary winding of the transformer with the current source marked by the broken circle. The current source may be transformed over to the right-hand side of the transformer (right-hand picture); this merely changes the amount of the current, and the primary winding becomes redundant and is dropped. From the transformer, only the pickup inductance (2,2 H) remains.

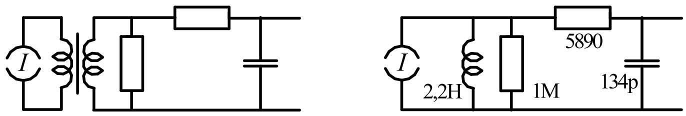


Fig. 5.9.43: quadripole-equivalent-circuit of a Stratocaster pickup.

We can now define the quotient of output voltage and input current as the transfer function: $\underline{H}(f) = \underline{U}_2(f) \;/\; \underline{I}_1(f)$. If the current amplitude is equal at all frequencies, the result is a band-pass-characteristic ($\underline{H}_{U\xi}$, **Fig. 5.9.44,** left-hand side). However, an excitation with frequency-reciprocal current amplitude is more easily interpreted since it yields a **low-pass-characteristic** ($\underline{H}_{Uv}$). The left-hand section of Fig. 9.5.44 shows the results of measurements taken for field-coupling with a small transmitter coil (constant current amplitude) wound around the 6 magnets extending from the Stratocaster pickup; the pickup was loaded with 4700, 1000, 330, and 0pF resp. In addition, calculations based on the equivalent circuit shown in Fig. 5.9.43 are included. The two sets of curves are practically identical; any differences are hardly noticeable. Using a frequency-reciprocal current amplitude $I \sim 1/f$ instead of the frequency independent current brings us to the right-hand section of the figure ($\underline{H}_{Uv}$, low-pass ECD).

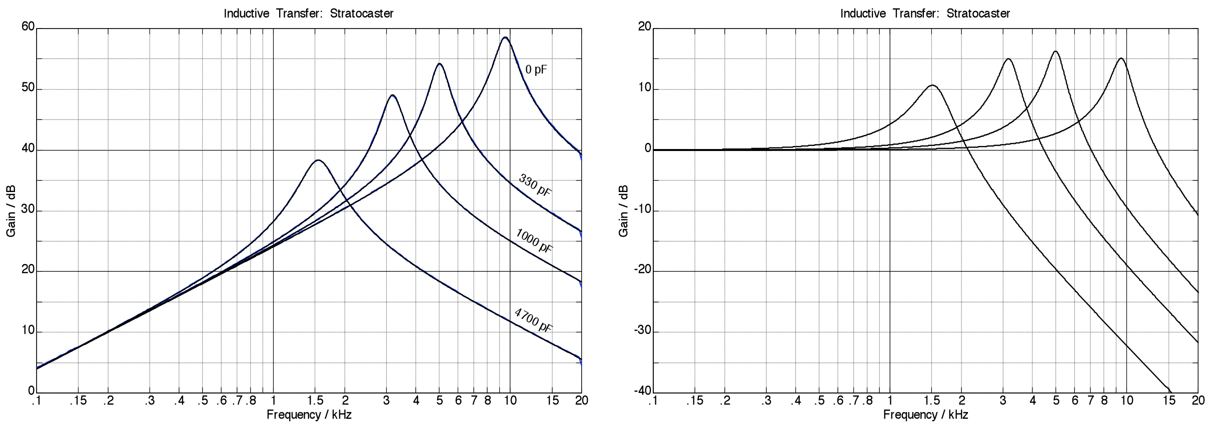


Fig. 5.9.44: Transfer function for current impression (= field impression); left: band-pass, right: low-pass

The low-pass transfer function shown on the right are **normalized** such that for low frequencies we obtain a transfer factor of 0 dB. Using the field coupling, only *relative* frequency responses can be measured since the strength of the static magnetic flux is not captured. The absolute scaling (i.e. the vertical position of the plots) may be determined on the shaker test stand (Chapter 5.4.5). Given a capacitive load, every magnetic pickup shows a low-pass characteristic (LP-ECD) including a resonance arising from the pickup inductance and the capacitance of the pickup plus cable. The resonance emphasis is high for a purely capacitive loading; it drops off with the resistances of typically connected potentiometers (Chapter 9) coming in.

As already shown, various transfer functions ($\underline{H}_{Uv}$, $\underline{H}_{U\xi}$, ...) may be defined from a systems-theory point-of-view. However, besides the analytical description also a visual recognition and evaluation of the shape of the frequency dependency is desirable, and here we find a similarity between the third-octave spectra often used in acoustics on the one hand, and the velocity→voltage-transfer-function $\underline{H}_{Uv}$.

In **Fig. 5.9.45** we see the third-octave spectrum of the pickup voltage of a Stratocaster. The guitar was in its original condition and externally loaded with 700 pF (cable). All strings were plucked repeatedly in quick sequence while being slightly dampened at different neck positions with the left hand. The left hand at the same time fingered various bar chords without pushing the strings fully down onto the frets. This generated a wide-band noise-type signal without too many tonal components (which could have disturbed the spectrum). The **third-octave spectrum** obtained via main- and auxiliary-third-octave analysis (according to DIN) is shown as a **polyline**. Between 100 Hz and 4 kHz there is a nearly horizontal characteristic while below 100 levels drop off – the fundamental frequencies of the strings do not cause us to expect anything else. Above the pickup/cable resonance (3 kHz) we find a treble attenuation. Except for the low frequency range, this analysis matches a low-pass model quite well while no similarities are recognizable to a 3-kHz-band-pass.

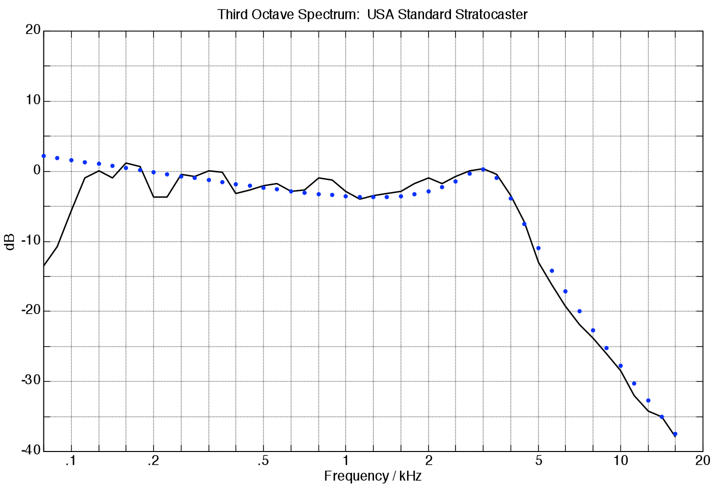
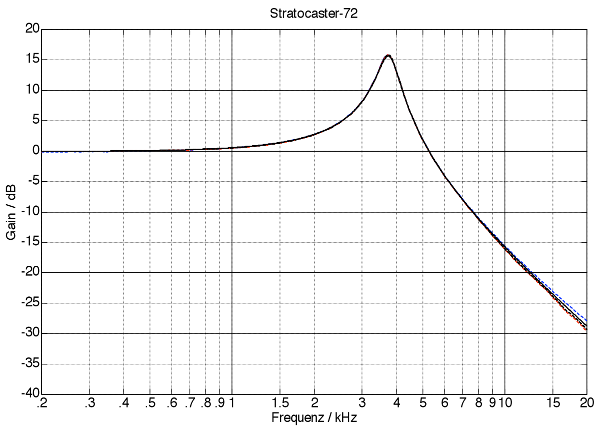


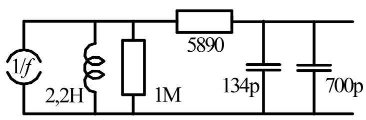
Fig. 5.9.45: Fender Stratocaster. Measured levels of third-octave spectrum (line); calculated LP-transfer function (dots). The pickup was loaded with an external capacitance (700 pF).

As a supplement, the $\underline{H}_{Uv}$-transfer function is indicated **as dots** in Fig. 5.9.45. It was calculated on the basis of the quadripole equivalent circuit (Fig. 5.9.45) to which a slight treble attenuation of 1,8 dB/Oct. was added. Both plots globally show strong similarities; moreover the two do not have to correspond in detail since these are two fundamentally different quantities. Of course, the third-octave-level spectrum depends on the strings and the way the playing style while the transfer function does not. The latter is a system quantity and as such gives the transfer characteristic in a time-invariant and signal-independent manner: the pickup resonance is, for example, independent of which music the guitarist is playing at the time. The voltage spectrum, however, is dependent on the string excitation and the transfer characteristic.

That the correspondence in Fig. 5.9.45 nevertheless is so pronounced indicates that the choice of the low-pass transfer function is a good one. Although the other choice for the band-pass transfer function would be scientifically also possible, a visual analysis is much more difficult.

The quadripole equivalent-circuit-diagram describes the transmission from the magnetic field excitation (input port) to the connectors (output port); it can serve to determine – with little effort – the transfer function ("frequency response") of the pickup. The components of the quadripole-ECD **are the same** as those of the two-terminal equivalent circuit and may be determined via impedance measurement and curve fitting, or via special methods of network analysis. The magnetic alternating-field-source corresponds, in the electrical quadripole-ECD, to an AC current source fitted in parallel to the inductance dampening the eddy-currents (**Fig. 5.9.46**, right hand section).





Quadripole equivalent circuit diagram.

Fig. 5.9.46: Calculated and measured low-pass transfer-function. Stratocaster pickup, 700pF.
Measurement: using coupling of themagentic field; calculation: using the quadripole ECD shown on the right.

Comparing the measurement and the calculation shows how accurate the quadripole-ECD is. To achieve the coupling of the magnetic alternating field there is a choice from several possibilities:

1. Using a **pair of Helmholtz coils** we can generate a homogeneous, quantitatively well defined field which however is in its shape very different from the locally limited AC-field caused by a string.
2. A small **coaxial coil** positioned on a magnet (e.g. Stratocaster) or pole-screw (e.g. P-90) yields a locally limited field, which however does not yet correspond to the field generated by a string.
3. Much closer to reality is the excitation with a tripole-coil. For this, we wind …..

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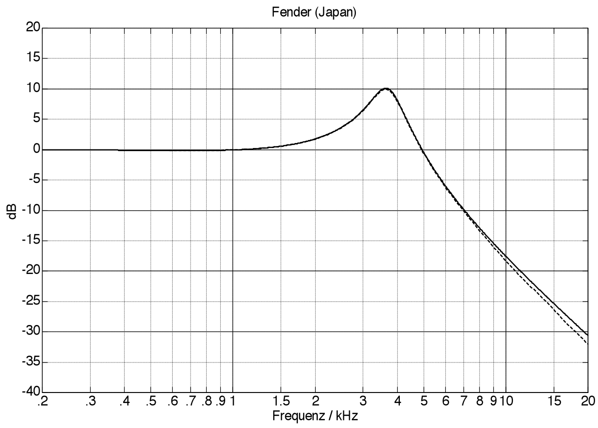
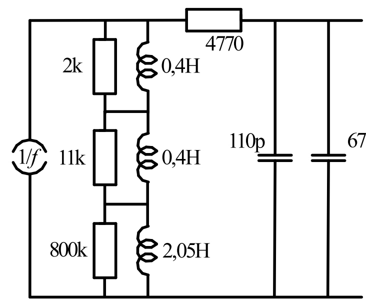
Fig. 5.9.46 contains 4 plots: one each for the measurement with Helmholtz-, coax- und tripole-coil plus one calculated from the quadripole equivalent circuit diagram. Up to 10 kHz all four correspond perfectly (ΔL < 0,5 dB). Only in the highest octave we find differences: the excitation with the Helmholtz-coil (dashed line) yields the highest levels while the lowest levels are given by the other two excitation coils with the calculation (solid line) positioned in between. The pickup ware loaded merely with a capacitance; further loading (controls, amplifier) would reduce the resonance emphasis for all plots in a similar manner.

The transfer functions depicted in Fig. 5.9.46 are normalized in such a way that their position accommodates a level of 0 dB at low frequencies. While the shape of the curves is thus set, the **absolute scaling** remains undetermined. To know the vertical position of the transfer curves, measurements with a real vibrating string are required – these need to be taken at merely one single frequency, though. It is purposeful to choose a frequency at which few artifacts can be expected.

As has been shown, the results of measurement and the calculation agree very well for the original Stratocaster pickup, which features only little eddy-current losses. This agreement is not as good for the pickup variant manufactured in Japan (**Fig. 5.9.47**) the construction of which is based on a bar magnet and 6 iron slugs rather than on 6 cylindrical alnico magnets. In the low and middle frequency ranges a perfect agreement does remain between the measurements with a tripole excitation (----) and the calculation while for higher frequencies there is a larger difference although this range is less important for electric guitars.

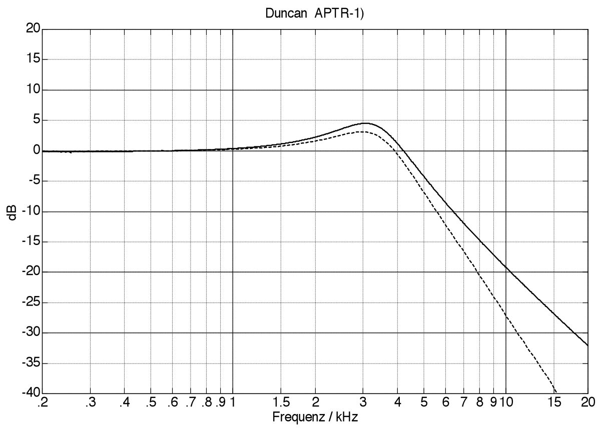


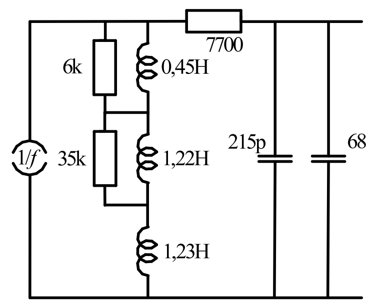


Quadripole equivalent circuit diagram.

Fig. 5.9.47: Calculated and measured lowpass-transfer function. Fender-Japan-Strat, 670pF load.
Measurement with tripole-coupling (---), calculation with the quadripole ECD shown on the right.

The situation turns out differently for the Telecaster neck pickup (**Fig. 5.9.48)**: there is a clear divergence between measurement (----) and model calculation. We can pinpoint the reason in the metal cover the eddy-currents of which necessitate a modified equivalent circuit diagram (see Chapter 5.10).





Quadripole equivalent circuit diagram.

Fig. 5.9.48: Calculated and measured lowpass-transfer function. Telecaster (S. Duncan), 680pF load.
Measurement with tripole-coupling (---), calculation with the quadripole ECD shown on the right.

The equivalent circuit diagrams shown in Fig. 5.9.47 and 5.9.48 contain *three* different inductances. Whether this effort is justified can be determined on the basis of the desired accuracy. Using the Gibson screw-coil discussed in Chapter 5.9.2.6 as an example, **Fig. 5.9.49** compares the transfer function derived from a 4^{th}-order model (n = 4, Fig. 5.9.37) with the transfer function calculated on the basis of a simple 2^{nd}-order low pass (n = 2). Whichever way we approach the alignment (whether going for identical maxima – left-hand section – or for equal high-frequency asymptote – right-hand section): the resonance of the 2^{nd}-order plot comes out too broadband. In other words: if we are looking for more than just a coarse approximation, the more exact modes should be preferred – the effort is manageable.

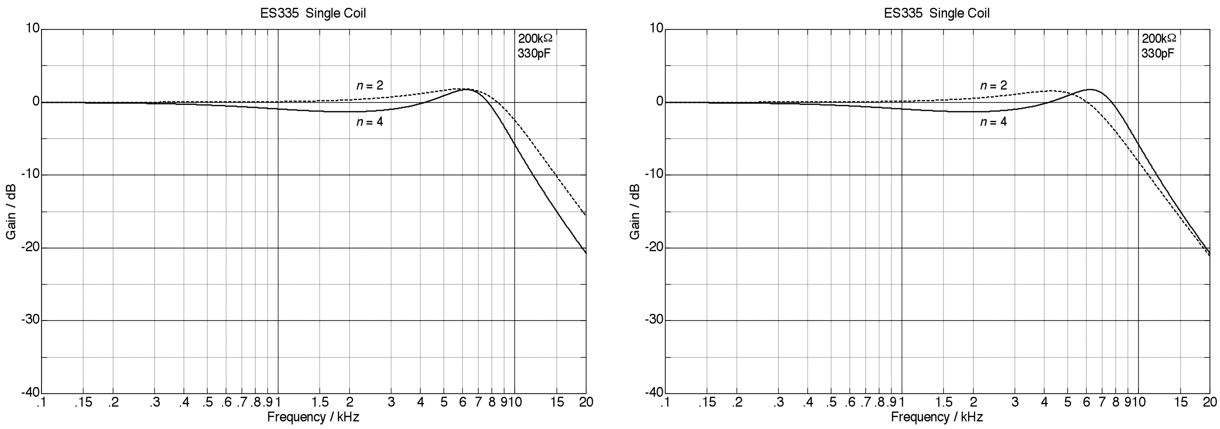


Fig. 5.9.49: Transfer functions calculated on the basis of models of different complexity.

5.9.4 Pickups connected in combination

Connecting two pickups in parallel changes the sound in two ways: due to the halving of the inductance the resonance frequency rises by 40%, and in addition we get an interference filter similar to a humbucker – although with a larger distance of the coils and negligible coil coupling. **Fig. 5.9.50** shows the frequency responses for a coil distance of 6 cm; this interference filter is shifted further towards lower frequencies for the combination of neck- and bridge-pickups (d = 12 cm). The resonance emphasis grows because the source impedance is cut in half.

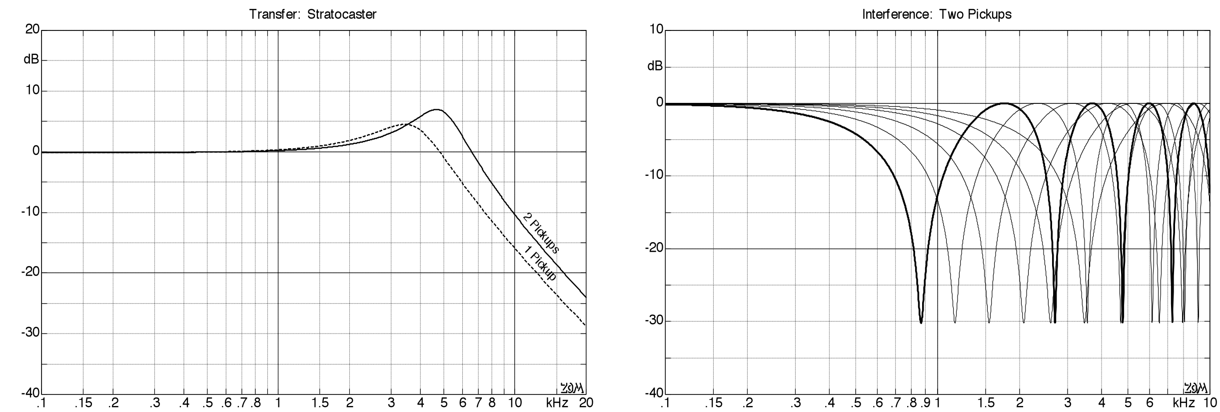


Fig. 5.9.50: Transfer frequency response and interference filter (d = 6 cm), pickups cinnected in parallel. The interference effect is specific to the string; the bold line holds for the E2-string.

5.10 Determining the transfer behavior

In Chapter 5.9 the purpose of an equivalent circuit diagram has already been explained; it is supposed to represent the transmission characteristics of a pickup in a form easily understandable to the electronics expert. How far this is successful shall now be examined for some selected pickups via control measurements. First, we have to specify which **transmission** is meant. The generated *effective quantity* is the electrical voltage created at the pickup terminals for a defined electrical load, and the *source quantity* generating this effective quantity is the string velocity perpendicular to the fretboard. These two quantities give the **transmission coefficient** H_{Uv}. We could, in addition, also use the string velocity in parallel to the fretboard, or the strain-wave velocity running along the string – but for the following, let us limit ourselves to the string velocity oriented perpendicular to the fretboard (fretboard-normal velocity).

To model the transmission behavior the string-plucking guitarist is advantageously replaced by a source which can be described more precisely. Such a source could be a generator coil creating the magnetic field, positioned coaxially with the pickup coil or orthogonally to it, or it could be a short string moved by a shaker, or an impulse-excited, laser-monitored long string. It may be noted already in advance that all control measurements confirm the suitability of most of the equivalent circuit diagrams – modifications are required merely for pickups with strong eddy-current dampening.

5.10.1 Measurements using a shaker

For the shaker-measurements, a string of 10 cm length is driven by a B&K-Shaker (Type 4810) such that it vibrates – along a sinusoidal curve – orthogonally to its longitudinal axis while keeping its shape (no string bending). The string acceleration is frequency-selectively monitored via a PCB-impedance-measuring head (Type U-288) connected to a DFT-analyzer. In most cases a D'Addario PL-026 string of 0,66 mm diameter was used; the measurement frequency was in the range of 50 – 100 Hz with a deflection amplitude of 0,2 – 0,5 mm. Any non-linearity of the drive-system was suitable compensated for if necessary.

Shaker-measurements allow for a relatively precise determination of the absolute pickup-sensitivity, but can only be carried out in the low-frequency range due to structural resonances. While the **passive** two-terminal networks of an equivalent circuit diagram (*R, L, C*) may be identified via measurement of the pickup impedance, the shaker-measurement enables us to calibrate the **active** source contained in the ECD. Indeed, pickup excitations via alternating magnetic fields (Chapter 5.10.2 – 5.10.4) merely allow for determination of the magneto-electric transmission coefficient; conversely, the shaker-measurements described here make possible the identification of the mechano-electric transmission coefficient H_{Uv} - though limited to the low frequency range where H_{Uv} is independent of frequency. Typically, we find H_{Uv} to be about 0,1 – 0,3 Vs/m for the Stratocaster pickup. The precise value is of course dependent on the individual pickup and on the distance between string and magnet; moreover the string diameter needs to be considered.

From the point of view of systems theory we could state: the impedance-measurement allows for the specification of poles and zeros in the transmission-function; the shaker measurement adds the basic amplification. Or we could say: with the impedance measurement the shape of the transmission frequency response can be determined while the shaker-measurement yields its absolute position.

The string velocity is not only applicable as source quantity at low frequencies but also across a broad frequency range. Proof is found in **Fig. 5.10.1** comparing the time-function of the string velocity (left-hand section) to the voltage generated by a Telecaster-Bridge-pickup (right-hand section). The pickup was mounted at a distance of 2,5 mm below the string, and loaded with 110 kΩ and 330 pF. The ray of the laser-vibrometer struck the string on the (extended) axis of the magnet with the string vibrating in the direction of the axis of the magnet, and thus also in the direction of the laser beam. The velocity-signal generated by the laser-vibrometer was filtered with a 2nd-order low-pass in order to model the filtering happening within the pickup. The sameness of the two plots is impressive proof that the pickup indeed does detect the string velocity, and allows for an absolute scaling of the transmission coefficient of **0,29 Vs/m** in the low-frequency part of the oscillation.

As a comparison, shaker measurements were available which, however, were taken with 2,00 mm string/magnet-distance and with a 0,66-mm-string. They had yielded a transmission coefficient of 0,31 Vs/m. Matching the string diameter (0,66 mm → 0,70 mm) increases this value to $0{,}31\cdot(0{,}70/0{,}66)^2$ Vs/m = 0,35 Vs/m, and matching the string/magnet-distance (2,0 mm → 2,5 mm) decreases it to **0,30 Vs/m** (Chapter 5.4.5). Consequently, the absolute sensitivity determined with little effort via the shaker is a very good match to the value obtained from the laser-vibrometer-setup.

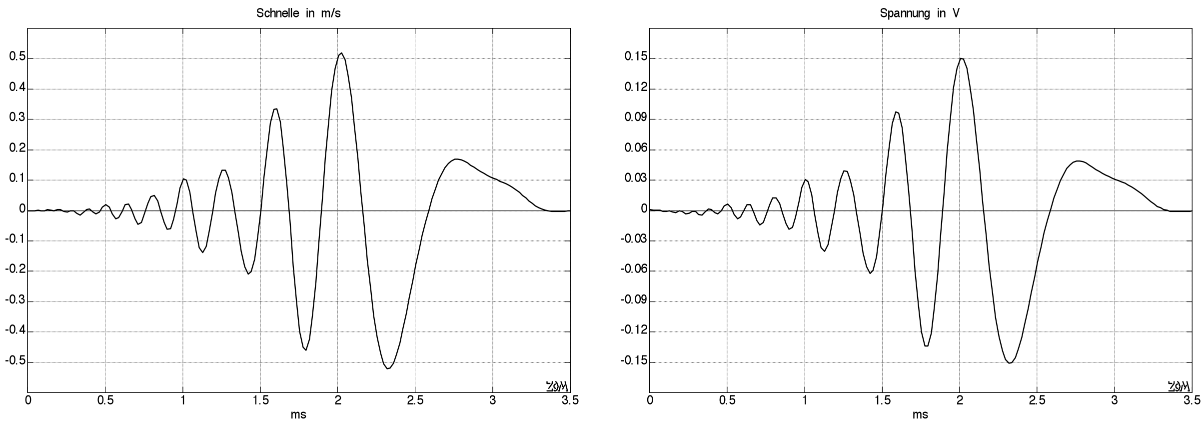


Fig. 5.10.1: String velocity obtained via the laser-vibrometer (left); corresponding pickup voltage (right). For string diameter and string/magnet distance see the text. Pure transversal wave.

Measurements using the shaker make possible a relatively effortless determination of the transmission coefficient. The following hints are helpful to limit measurement errors to an acceptable level:

- the pickup needs to have sufficient distance to the shaker to avoid direct magnetic coupling;
- the string needs to vibrate with a constant shape and must not develop any “life of its own”;
- the pickup needs to be mounted with non-magnetic materials to avoid any eddy-currents;
- the “magnetic history” of the string influences the result and should be recorded exactly;
- a DFT-window with small level-error (picket-fence-effect) may be dispensable for transmission measurements because the resulting error compensates itself (it shows in both channels in the same way), but it is still strongly recommended to make comparisons with other measurement approaches;
- the pickup should be mounted as rigidly as possible since, with a string-excursion of e.g. merely 0,5 mm, a vibration of the pickup of as little as 50 μm in amplitude can already cause ugly measurement errors.

5.10.2 Measurements with the Helmholtz-coil

Using a pair of Helmholtz-coils, it is possible with only little effort to generate a parallel magnetic field the strength and flux density of which can be precisely calculated. We need to consider, however, that magnetic fields around strings are everything but parallel – it is therefore easily possible that measurements employing the Helmholtz-coil yield other results compared to measurements where the pickup is excited by a vibrating string.

For the following measurements two oval Helmholtz-coils were wound; they had a size of 33 cm x 27 cm and 175 turns. The resistance of both (in parallel connection) is 7 Ω, they were driven by the AF-100 frontend of a Cortex workstation at L_U = 18 dBV for 600 Ω source-resistance. With these values a flux density of 6,5 μT_{eff} resulted in the low frequency range at the measuring position. Since the (inductive) coil impedance could not be expected to remain small relative to the source impedance across the whole measurement range (which would have resulted in perfect current impression), the actual current was monitored (**Fig. 5.10.2**) and any deviations were **compensated for** arithmetically. Still, we are confronted with differences compared to the results obtained with other measuring methods. A more in-depth analysis of the coil impedance showed a **resonance** at 44 kHz, i.e. capacitive currents having a field-amplifying effect♣. Given this situation, the share of the inductive current was now determined for a coil-equivalent circuit (Fig. 5.10.2, ----), and only the deviation of this share was arithmetically compensated for the subsequent pickup measurements.

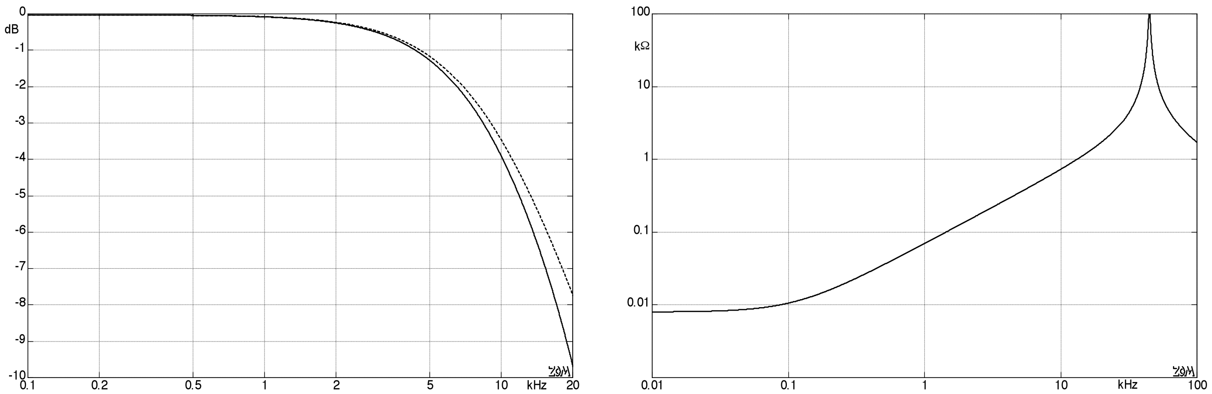
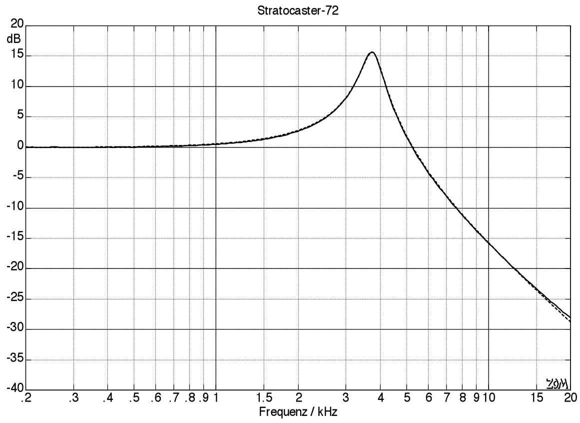


Fig. 5.10.2: Current flowing into the terminals (600 Ω source impedance, ——), inductive current (----). The right-hand graph shows the frequency response of the amount of the Helmholtz-coil impedance.

Measurement and calculation are compared in **Fig. 5.10.3**. The measurements took place within the parallel field of the Helmholtz-coils; the axis of the Helmholtz coils and that of the pickup coil coincided. The compensation mentioned above resulted in operating conditions which were equivalent to the operation with impressed magnetic flux density. The results of the calculations were obtained using a quadripole equivalent circuit diagram. The component values of this ECD were derived from the impedance frequency responses, as they were determined in Chapter 5.9.2. The basic correspondence of the curves shows that the transfer behavior of the magnetic pickup, from magnetic field to voltage, can approximately be derived from a simple measurement of the impedance frequency response. The absolute scaling cannot be determined that way but can be achieved at a single low frequency using the shaker (Chapter 5.10.1).

♣ For a parallel-resonance-circuit, the current in the terminals is smaller (!) than the current in the res. circuit.



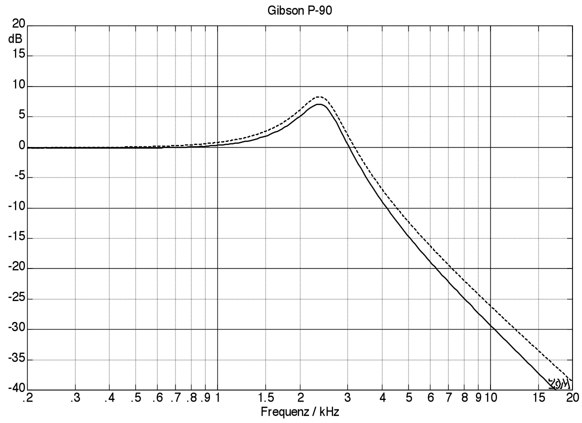
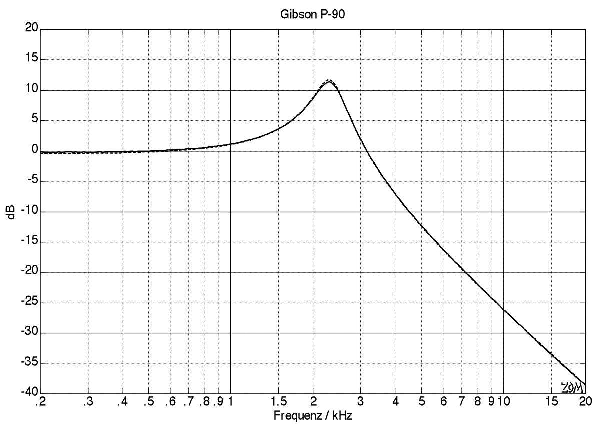


Fig. 5.10.3: Pickup transmission factor G_{Uv}: measured with Helmholtz-excitation (——), calculated with ECD (---). Fender Stratocaster (left), Gibson P-90 (right), each loaded with 700 pF.

The **Stratocaster**-pickup has little eddy-currents and for it we find a very good correspondence between measurement and calculation, while significant differences are observed for the **P-90**. Other than the capacitive coupling which could be the reason for small differences in the highest octave, it is in particular the different field geometry that is responsible for the discrepancies. The **brass plate** used as mounting base below the P90-coil influences the coupling factor stronger for the parallel Helmholtz-field incident than for the focused string-field. As one removes the brass plate from the P-90, the Q-factor increases, and measurement and calculation correspond (left-hand section of **Fig. 5.10.4**).



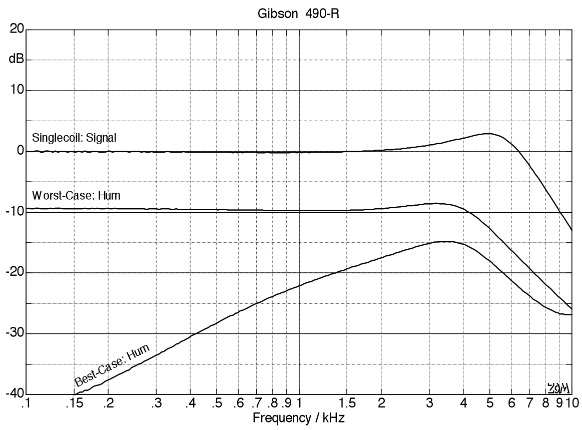


Fig. 5.10.4: Pickup transmission factor G_{Uv}: Helmholtz-measurement (——), ECD-Calculation (---). Gibson P-90 w/out brass plate, 700-pF-load (left). Gibson 490-R, 330 pF // 200 kΩ load (right).

The Helmholtz-field turns out to be totally unsuitable to measure the velocity/voltage-transmission coefficient of a **humbucker**: the out-of-phase connection between its two coils is designed to render such parallel fields ineffective. **Fig. 5.10.4** shows how well or how badly the design succeeds in that respect. The upper curve was taken in single coil mode, the lower in humbucking mode with an axis-parallel field (the direction of the magnetic field was in parallel with the coil axis). At least in the lower-frequency range the compensation works well. However, as the pickup is turned by 90°, barely 9 db of compensation dampening remain. This appears somewhat weak, especially since the pickup is manufactured by *the inventor of the humbucker* (Gibson advertisement). More details regarding hum suppression are explained in Chapter 5.7.

5.10.3 Measurements with a coaxial coil

For these measurements the pickup is excited by a generator coil the axis of which coincides with the axis of the pickup (thus the designation coaxial coil). **Fig. 5.10.5** shows a cross-section through the setup: a small coil (e.g. 6 mm ∅) carrying a sinusoidal current is positioned over the magnet of a singlecoil-pickup (e.g. Fender Stratocaster). The magnetic field of the small coil is – as a contrast to the Helmholtz-field - focused and thus more similar to the magnetic-field of the string. For the Stratocaster pickup already the Helmholtz-measurement was useable – the coaxial excitation works similarly well. We do get effects of capacitive coupling above 10 kHz but these are negligible. For the P-90 the Helmholtz-excitation gives clearer divergences re. the ECD-model; the coaxial excitation results in a better agreement because the magnetic AC-flux is mainly concentrated on the upper side of the winding und therefore the brass plate located below the pickup has merely a weak effect.

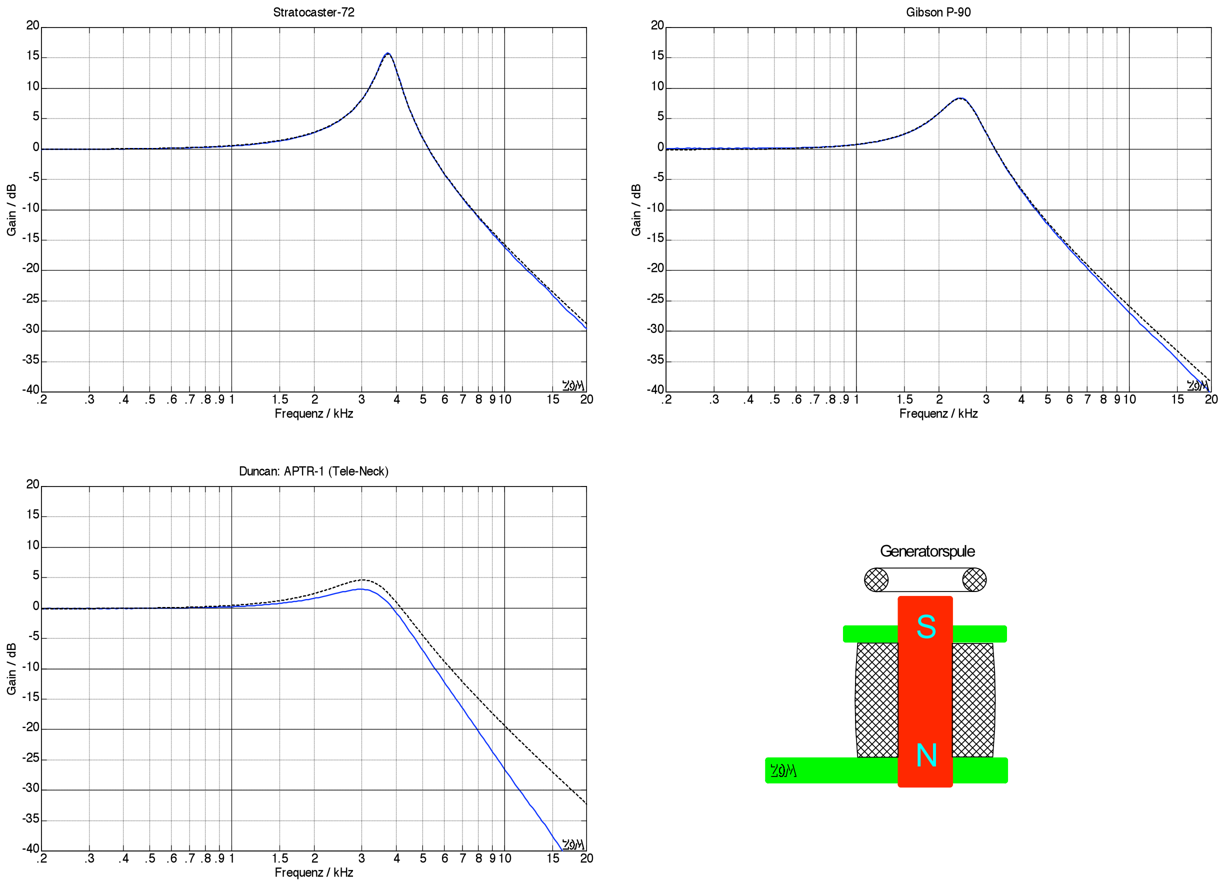


Fig. 5.10.5: Pickup with coaxial generator coil (cross-sectional drawing for a Stratocaster pickup).

For the Telecaster neck pickup, we see clear differences between the measured curve and the transmission function derived from the two-terminal equivalent circuit diagram. These differences are due to the eddy-current dampening of the metallic pickup cover. Apparently one does arrive at a limit regarding modeling for pickups when confronted with such strong dampening, and a modification of the simple quadripole-equivalent-circuit-diagrams introduced in Chapter 5.9.3 is required (see Chapter 5.10.5).

5.10.4 Measurements with the tripole coil

The coaxial coil introduced in the previous chapter generates an alternating magnetic field which is a much more locally effective field than the field of the Helmholtz-coils. However, there are still differences compared to the field distribution of an oscillating string. A further optimized approximation of the field geometry of the string can be achieved with a tripole-coil, i.e. a layout …..

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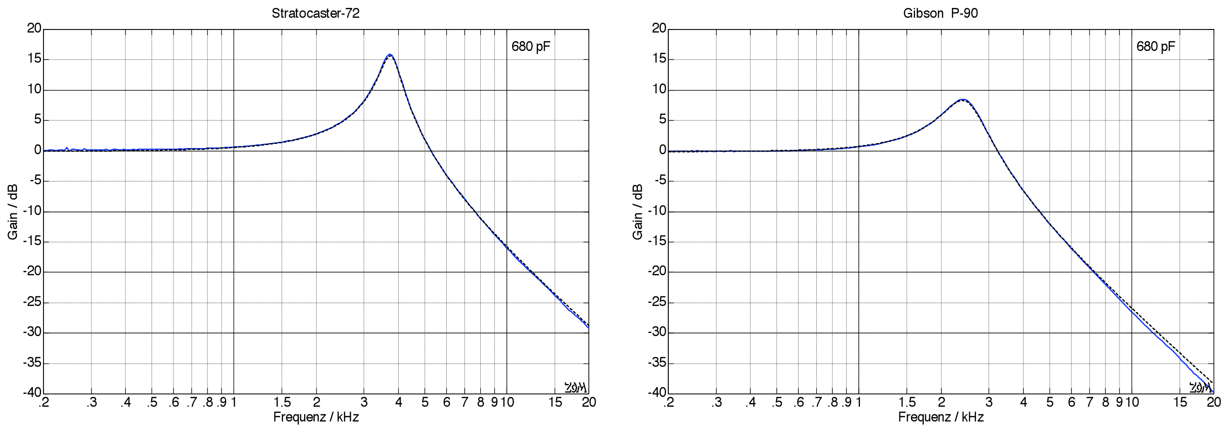


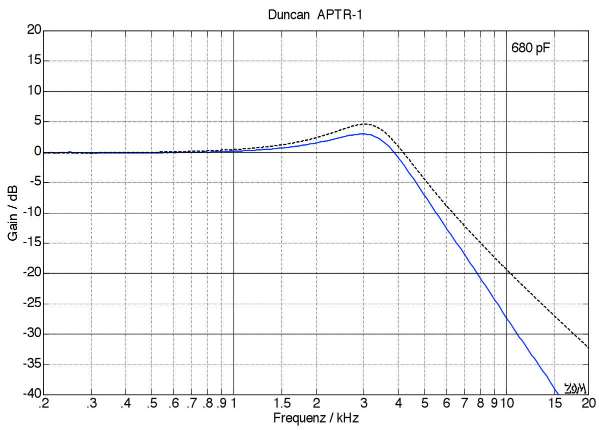


Fig. 5.10.6: Tripole coil excited by alternating current, measurement (——), ECD-model (---).

While the correspondence between measurement and model-calculation is again good for the Stratocaster- and P90-pickups, significant divergences appear for the Telecaster-neck-pickup. The cause is found in the metal **shielding cover**. Although it is made of non-magnetic material, this cover introduces a dampening due to the eddy currents induced into it. The effect is mainly felt in the treble range. The equivalent circuit diagram (ECD) derived from the impedance obviously requires modifications in order to account for eddy-currents close to the strings, and to better model the frequency dependence of the mechano-electric coupling. At this point we can also look into the question whether the tripole-excitation always yields results which are equivalent to normal operation (string oscillation). It may be as well that the ECD-model given above is closer to reality. Measurements with the laser-vibrometer give clarifications regarding these issues (Chapter 5.10.5).

5.10.5 Measurements with the laser-vibrometer

The measurement methods presented in the previous three chapters (5.10.2 – 5.10.4) deliver nicely agreeing results for pickups that feature a small level of eddy-currents. However, as soon as pickups with eddy-current-dampening (e.g. P-90) are the subject of the measurements, we see differences at higher frequencies. We could ignore these differences because the transfer behavior at 10 – 20 kHz is not really that important due to the lowpass filtering. On the other hand, we could consider the divergences as an indicator that an extension of the overhead towards the limits of our models might be in order and that decreasing the differences would be worth the effort. Still, none of the measurement approaches proves that the velocity/voltage-transfer-function indeed shows the identified frequency response. In the end, all three methods yield merely the magnetic-field-to-voltage-transfer-function, or – to put it even more radically – the current/voltage-transfer-function. Considerably more insight is offered by measurements with the laser-vibrometer which do require a higher effort regarding instrumentation but directly capture the desired source quantity (the string velocity).

Laser-vibrometers take advantage of the **Doppler-Effect**: the frequency of a reflected wave changes if source and reflector move relative to each other. If source and reflector get closer, the reflected beam of light has a higher frequency than the ray emitted by the source (laser). If source and reflector move away from each other, the frequency is lower. Given v = speed difference between source and reflector, the relative frequency change corresponds approximately to $\Delta f / f_0 \approx v/c_{\text{light}}$. As one points the laser-beam at the oscillating string, the voltage generated by the laser-vibrometer corresponds to the string velocity in the direction of the beam. String movements along the string (i.e. perpendicular to the laser beam) are not detected. This means that strain-waves (if we discount a minimal transversal contraction) are not detected by the laser-vibrometer – but they are by the pickup. When performing laser-based control measurements on a pickup, we need to ascertain as a consequence that either exclusively transversal waves are generated, or that the two wave-types clearly happen separately. For the following experiments using a string of a length of 28 m could ensure a sufficient mode decoupling. This string is deflected on one end by a short transversal impulse. Below the string the pickup is positioned at the regular distance (2 – 5 mm), and above the string we have the laser-vibrometer. Fig. 5.10.1 could already drive home the point that a magnetic pickup indeed samples the transversal string velocity at the given point – this is the same with a laser-point. Transforming the voltage given by the pickup as well as that given by the laser-vibrometer into the frequency domain puts us in the position to determine the **transmission function** of the pickup. In principle, that is ……

Unfortunately, we may not conclude from the fact that the laser-vibrometer can carry out highly precise measurements that the pickup measurement automatically is also free of measurement artifacts. It is necessary that exclusively a transversal wave of plane polarization propagates in the string – but this is not easily accomplished. Structural resonances in the string bearing continuously lead to undesired strain-waves which falsify the measuring result. After carrying out extensive pre-experiments, an experimental setup could be developed which includes strain-waves artifacts only at very high frequencies. Since the pickup operates as a low pass, the remaining interferences are tolerable or insignificant. A similar situation exists for the inevitable offsets in the circuits, which cause voltage drifts at low frequencies. The offset compensation chosen for the experiments was sufficiently potent, and the remaining error was insignificant (Cortex-Workstation CF-90, CF-100). The T_{Uv}-values given in the figures belong to individual measurements which were not always carried out with a string-to-magnet distance of 2 mm.

Fig. 5.10.7 compares the results of the laser-measurements with the ECD-model-calculations. During the measurement the pickup was loaded with an RC-circuit; this was considered correspondingly in the calculations. While the resonance-emphasis is, generally speaking, correctly reflected, all measurements give relative to the calculations a characteristical **treble-loss** amounting to about 1 dB at 10 kHz.

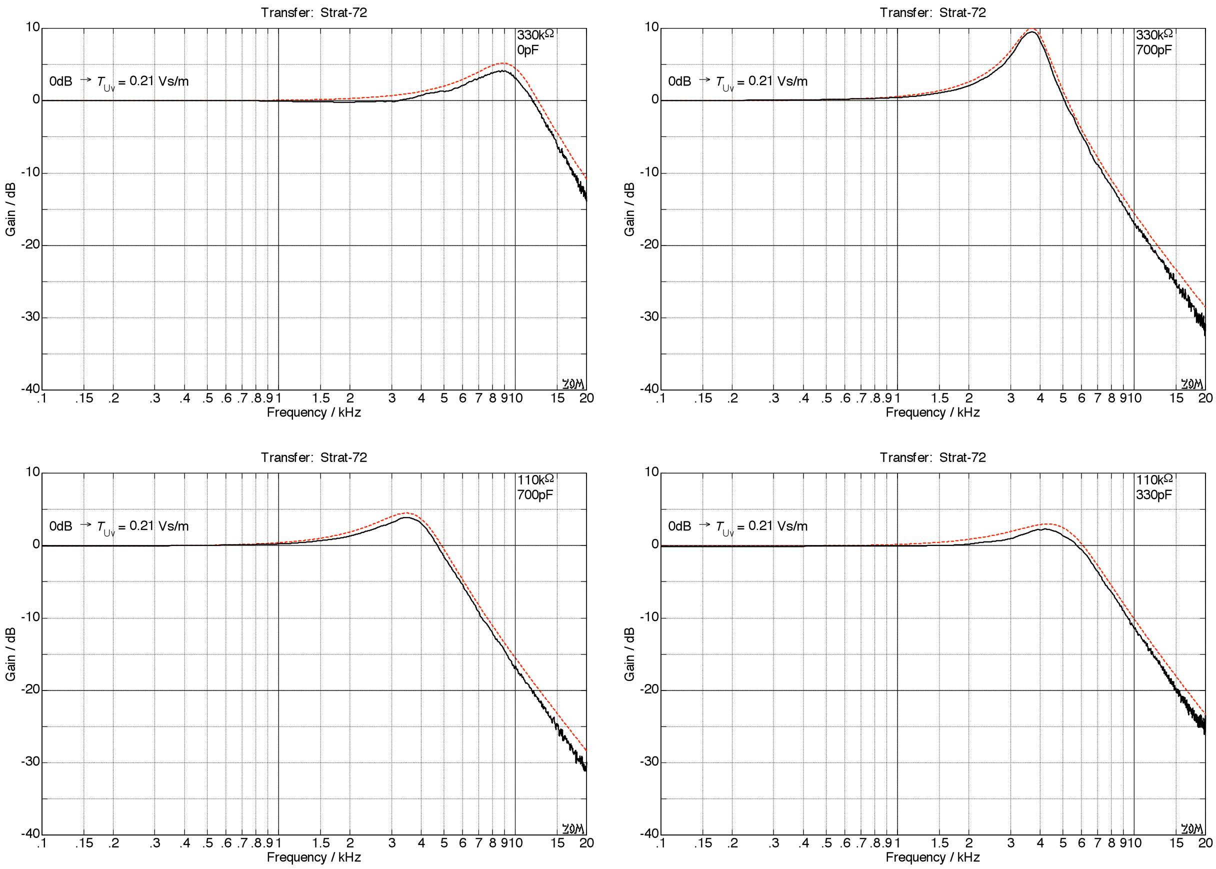


Fig. 5.10.7: Transversal-wave transmission-factor: laser-vibrometer (——), ECD-model-calculation (----).

In **Fig. 5.10.8** corresponding measurements and calculations are depicted for a coaxial humbucker (Fender Noiseless Stratocaster). Despite the different construction and the so-called "beveled magnets" (Chapter 5.4.6), the level differences in the treble range turn out to be analog those in Fig. 5.10.7.

Fig. 5.10.8: Transversal-wave transmission-factor: laser-vibrometer (——), ECD-model-calculation (----). This figure remains reserved for the print version of this book.

Further measurement results are shown in **Fig. 5.10.9**; they feature similar divergences between measurement and model-calculation in spite of different pickup build. The Duncan APTL-1 and the Fender Telecaster bridge pickup are seated on a ferromagnetic assembly plate; their cheapo-counterpart uses a ferrite bar-magnet instead of 6 alnico magnets; the Jazzmaster pickup sports a relatively large winding-surface and short magnets; for the P-90 two bar-magnets are located beneath the coil – the differences between measurement and calculation still amount merely about 1dB in the relevant frequency range (only slightly more for the P-90). Consequently, it is possible to derive the transmission-behavior of all pickups of this simple singlecoil-type from the impedance frequency response. It may be – if necessary – supplemented by a slight treble attenuation the cause of which can be found for the most part in the aperture window (Chapter 5.4.4).

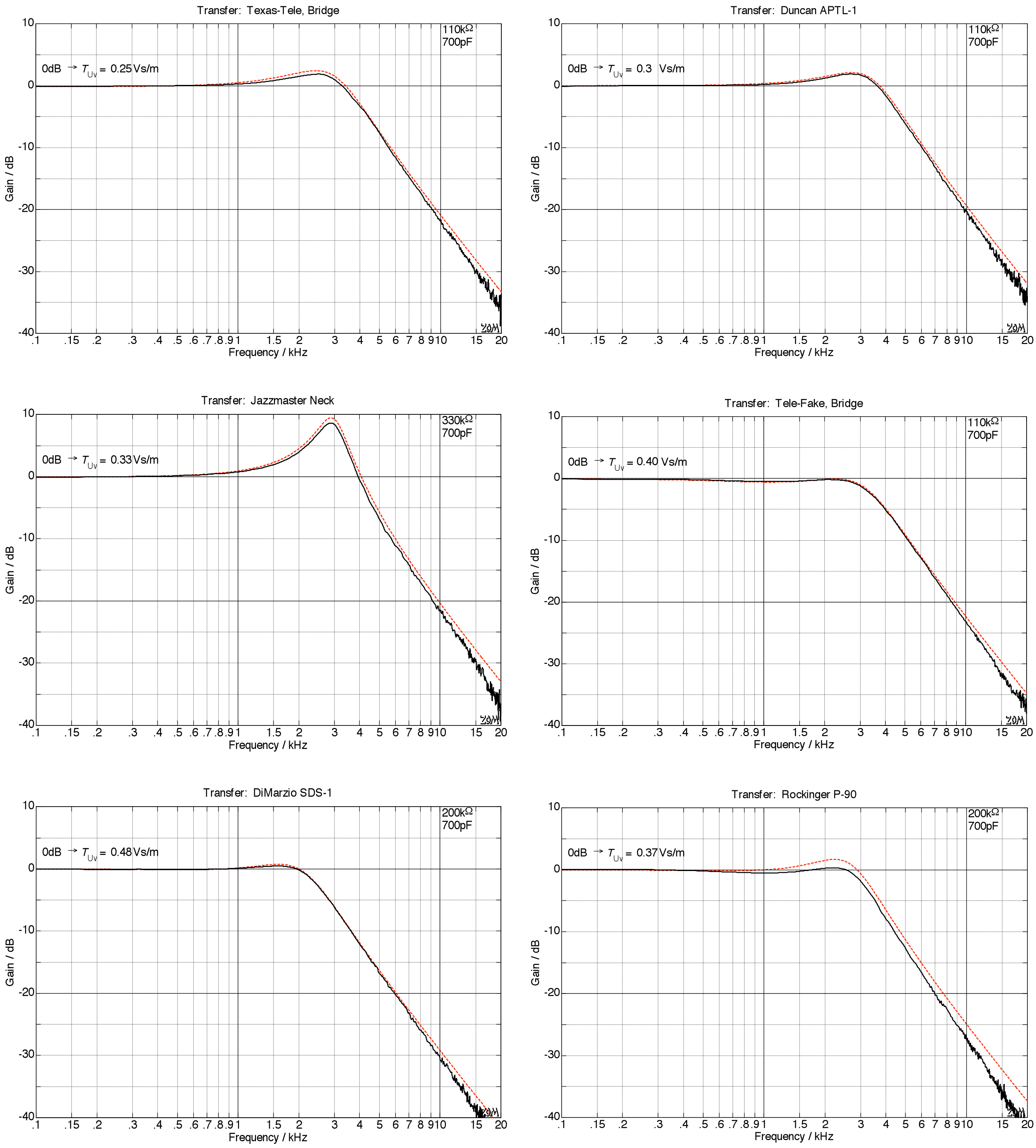
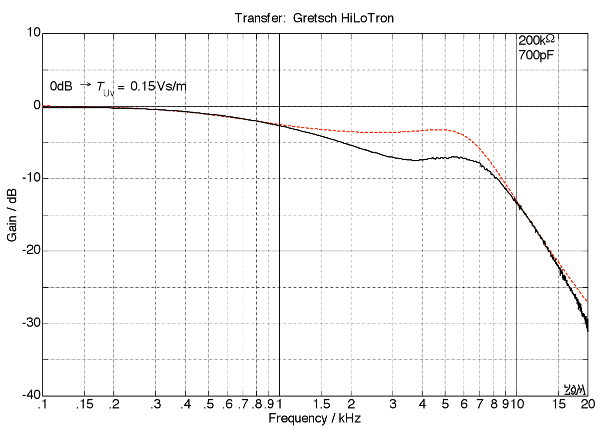


Fig. 5.10.9: Transversal-wave transmission-factor: laser-vibrometer (—–), ECD-model-calculation (----).

But not all singlecoil-pickups show the aperture-induced differences between measurement and model-calculation as depicted on Fig. 5.10.9. The Gretsch HiLoTron has a striking comb-filter-like interference curve, and the Telecaster-neck-pickup gives serious discrepancies at high frequencies – in these cases it is not possible to draw conclusions regarding the transmission behavior from the impedance-equivalent-circuit-diagram. The reasons are found in the magnetic field – but they are highly individual.

Let us first take a look at the HiLoTron-pickup which first entered service in the late 1950s in Gretsch guitars (e.g. Tennessean). Tom Wheeler writes in his book "American Guitars" that the pickup was developed by "fulltime Gretsch personnel". However, with No. 2683388 there was a patent already in 1954 which shows the exact same construction. Inventor is Ralph Keller who is designated as "assignor to Valco Manufacturing Co.". Valco (the successor to National and Dobro) manufactured guitars for other companies in the 50s, including Gretsch. Maybe somebody among the "fulltime Gretsch personnel" took off the vinyl-cover and checked out the pickup? Or – as it does happen now and again – the time was ripe and two inventors had the same idea at the same time without knowing from each other (they were both from Chicago, though ….).

Anyway, it's all **Ralph Keller's** glory, who on the other hand also has to take the rap for the justifications he gives in his patent: *The most important advantage stems (...) from the generally parallel relation of the magnetic lines of force with the instrument strings as compared with the perpendicular relation between the magnetic field and the strings which is common in many currently used pickup devices. (...) As a result, a wide area of the magnetic pattern is efficiently activated by the moving strings whereby to produce substantially greater and more effective variations in the reluctance of the magnetic field. (...) Consequently, (...) the pickup produces substantial improvements in the tone color of the instrument due to the capturing of additional overtones or harmonics which are not ordinarily reproduced when the pickup point is limited to a single point or relatively restricted area on the strings*. In short: according to Ralph K. the aperture-window should be as long as possible in order to capture as many harmonics as possible. This assumption (which was also taken up by Leo Fender♣ at the beginning of the 1960s when he designed the Jazzmaster pickup) is however not in agreement with systems theory: the longer the (actually effective) impulse response, the more the system has a narrow-band character. This is a fundamental aspect of the reciprocity of time and frequency as elaborated e.g. by Marko or Küpfmüller. In the case of the HiLoTron-pickup, the measurement of the transmission function shows – compared to the curve derived from the impedance ECD – a string specific interference gap at 5 kHz (**Fig. 5.10.10**).



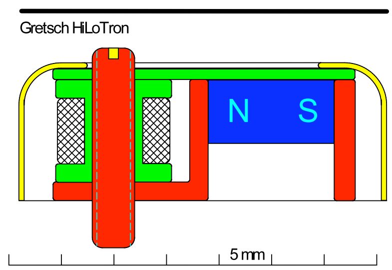
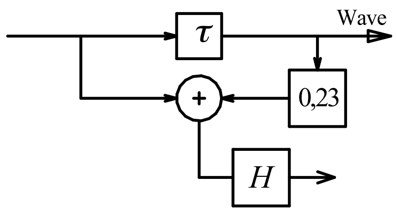


Fig. 5.10.10: Gretsch HiLoTron. Laser-vibrometer (——), ECD-model (----).

♣ Compare to Chapter 5.1

The horizontal position of the bar-magnet indeed lets the string be sampled "across a wide range", or more precisely at two relatively distant points – this leads to comb-filter-like superpositions (**Fig. 5.10.11**). As the string vibrates perpendicular to the fretboard, **two air-gaps** change: one (as usual) over the pole-screw, and a second one over the south pole of the bar magnet. The air gap bordering the pole-screw is the smaller one and therefore the transversal wave occurring here causes a larger *relative* distance change. In other words: at this position the pickup is more sensitive. Increasing the string-to-pickup-distance makes the pickup become less sensitive, as is to be expected; the interference effect becomes stronger, however (due to the air gaps becoming more similar).



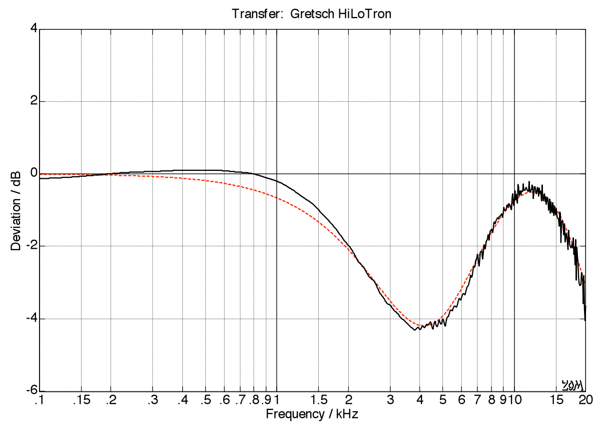


Fig. 5.10.11: Block diargam (above). Difference between laser measurement and ECD-model (——), frequency response of interference filter (----, right).

Fig. 5.10.11 models the delay-time between the two air-gaps with $\tau(\omega)$ (due to the dispersive wave-propagation τ is frequency-dependent). Optimization of the parameters resulted in an effective distance of the two sampling points of 23 mm which is in good agreement with the dimensions. A real factor takes care of the smaller sensitivity of the second "channel"; it amounts to 0,23 in the example. Although the magnetic polarity at the two sampling points is opposite, the two channels need to be *added* (constructive interference): bringing the string closer to the pickup decreases the magnetic air-gap resistance in both cases and thus increases the magnetic flux. Of course, in reality the sampling does not happen at two ideally small points but in two areas with finite dimensions each. Model and measurement will therefore not match exactly. That for the chosen example the differences are nevertheless as small as a few tenths of a dB (Fig, 5.10.11) is a nice confirmation of the model. **Fig. 5.10.12** shows the measurement results compared to the complete model, and also the dependency on the string.

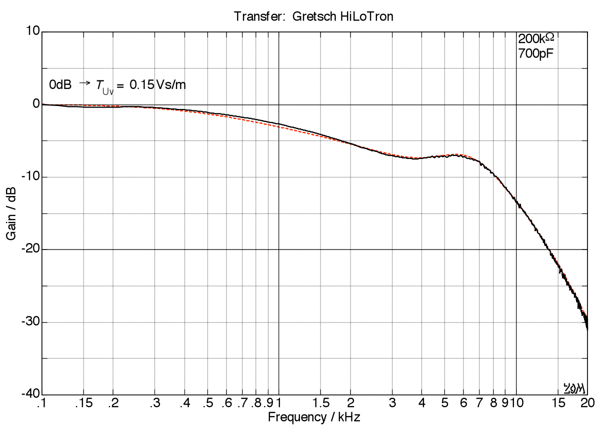


Fig. 5.10.12: Comparison measurement/model (left), string-specific transmission function H_{Uv} (right).

The “two-location-sampling” gives the HiLoTron-pickup its very own transmission characteristic which is unique in this form. Compared to a humbucker, the interference gap is much less pronounced, and the low coil inductance results in a brilliant, treble-rich sound. We find an entirely different situation for the **Telecaster** pickup. While here, as well, the measurement results differ from the model-calculations based on the impedance equivalent circuit diagram, they do so in a different way and due to different causes (**Fig. 5.10.13**).

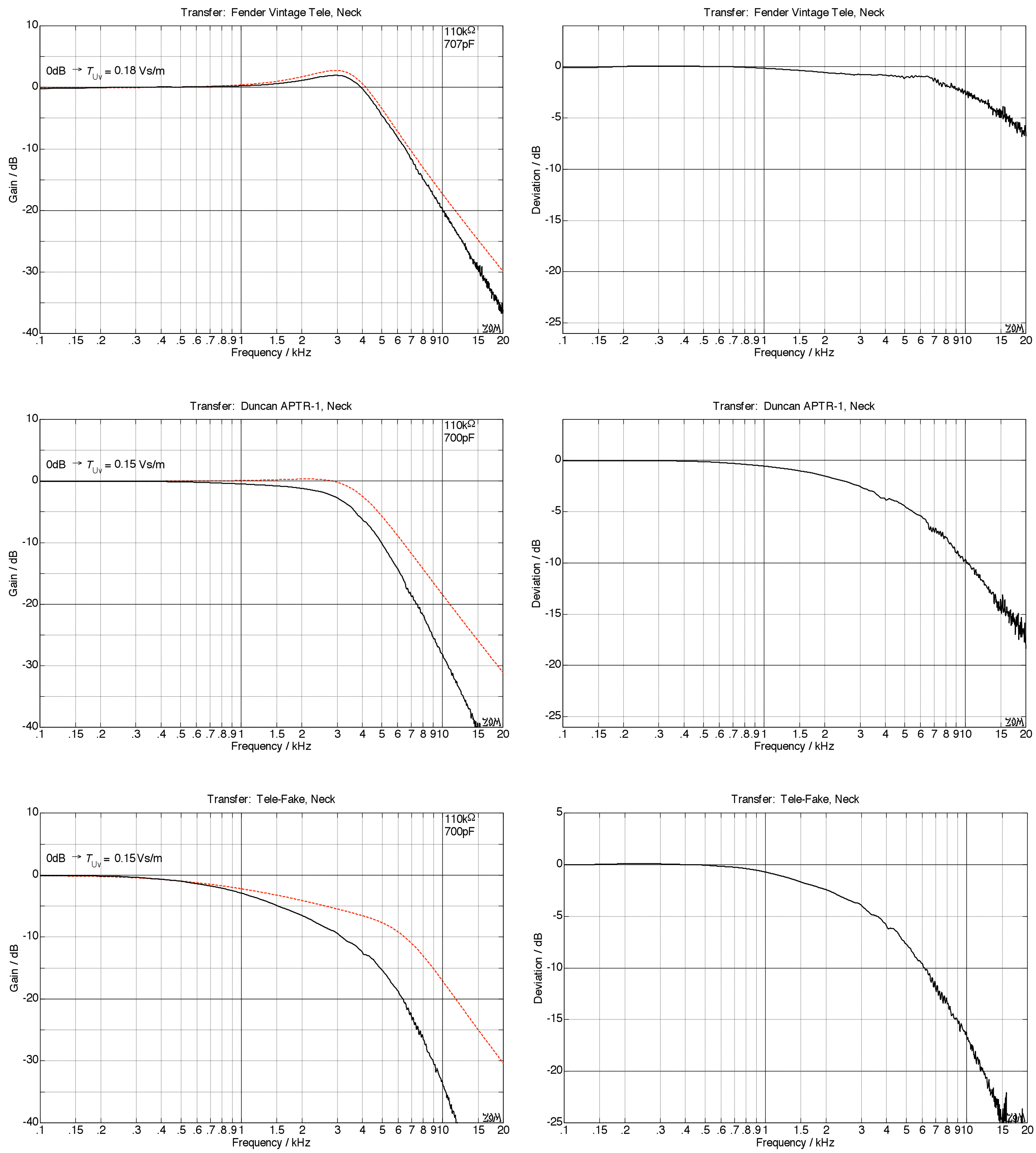


Fig. 5.10.13: Transversal-wave transmission factor: laser-vibrometer (——), ECD-model calculation (----). Right-hand column: difference between measurement and ECD-model calculation.
1st line: original Fender pickup, Telecaster retrofit set. 2nd line: Duncan APTR-1 ("for Tele®").
3rd line: “cheapo” copy, guitar with Telecaster-like body and similarly looking pickup

Measuring the three Telecaster neck pickups first resulted in three different impedance frequency responses. From these the different transmission frequency responses can be calculated (as shown in Fig. 5.10.13); however, the measurement results diverge significantly. The reason for the discrepancies are **eddy currents** induced by the alternating magnetic field into the metal **cover** (Chapter 5.9.2.2 and 5.9.2.5). While the measurement of the pickup impedance does capture eddy-current dampening, it only succeeds so with regard to the impedance – and not (or only partially) in terms of the effect on the transmission.

An experiment exemplifies this: the influence of the cover on the impedance frequency response is shown for a Duncan pickup (APTR-1, "for Tele®"), and we can see effects merely in the range of the resonance. Operating the pickup without cover we can calculate H_{Uv} in the usual way; any differences to the calculation can again be explained by the aperture dampening. **With cover**, two measurement conditions can be distinguished: **normal** (string above the cover) and **upside-down** (pickup turned over). Of course the impedance frequency response will be identical in both cases; the string has no measurable effect. Not so for the transmission frequency response where differences appear. Upside-down, when no cover metal comes between string and coil, we do get an entirely different measurement curve compared to "with cover", but the differences between calculation and measurement are similar for both cases. In normal configuration (Fig. 5.10.13) the difference between measurement and model calculation amounts to 10 dB already at 10 kHz. Apparently the positioning in space offers another degree of freedom which the model calculation does not cover. An extended model with three coupled, lossy coils would have to be supplemented (the cover acts as a shorting ring), but the usefulness is not in any reasonable relationship to the required effort.

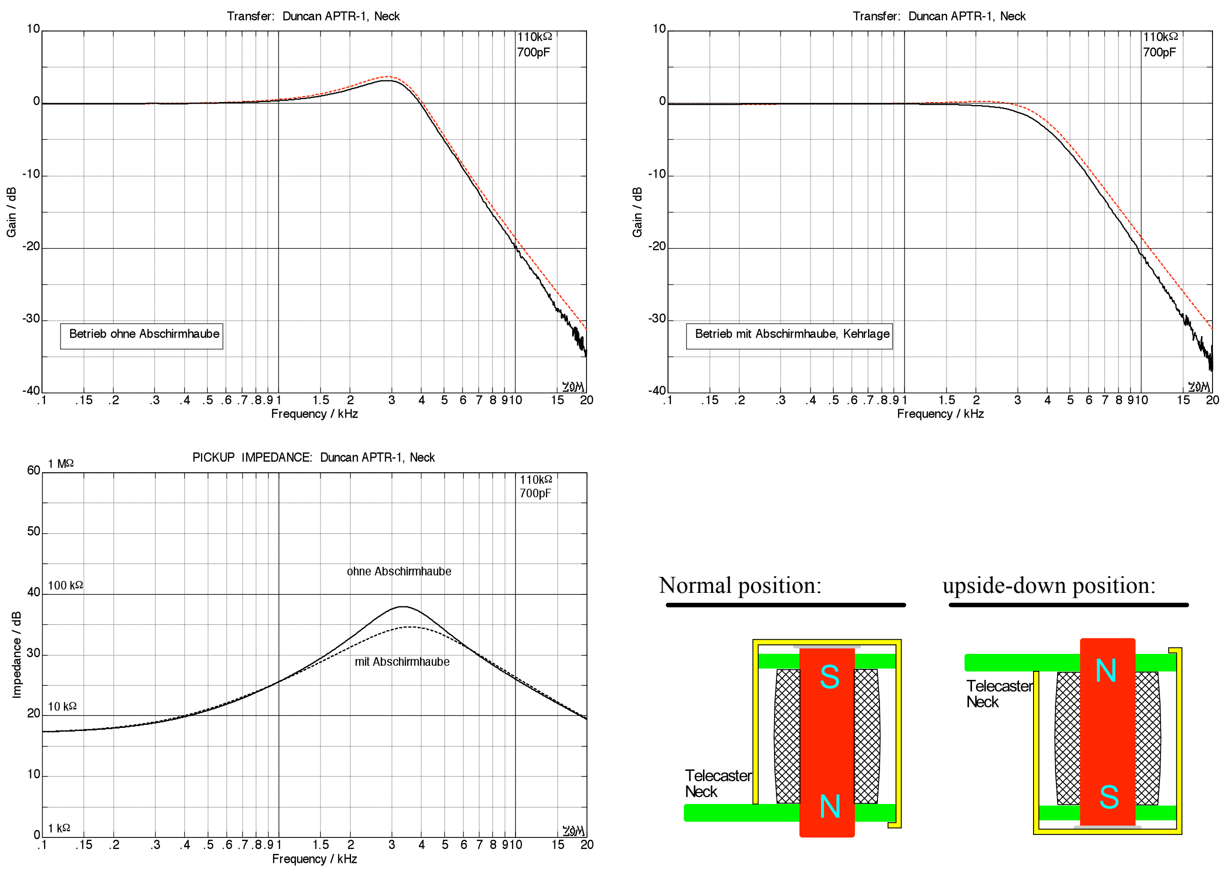


Fig. 5.10.14: Duncan APTR-1, with and without shileding cover (operation of normal position; see Fig. 5.10.13.

All three pickups mentioned in Fig. 5.10.13 find use in similarly looking guitars but their transmission characteristics differ tremendously: the treble reproduction diverges by 12 dB! Where do these differences come from? Without cover, the vintage Tele and the APTR-1 show a similar behavior (Fig. 5.10.15) – as one would expect it due to the similar build. The cheap copy fitted with a bar-magnet does not entirely reach the resonance emphasis presented by the competitors (due to the eddy-currents in the iron slugs), and arrives at a somewhat worse treble reproduction. However, only as the **covers** are mounted, the large differences arrive: the similarity is only in the looks but the electrical characteristics differ significantly. The cover of the Fender pickup is made of 0,5-mm-thick German silver; the other two are made of chrome-plated brass.

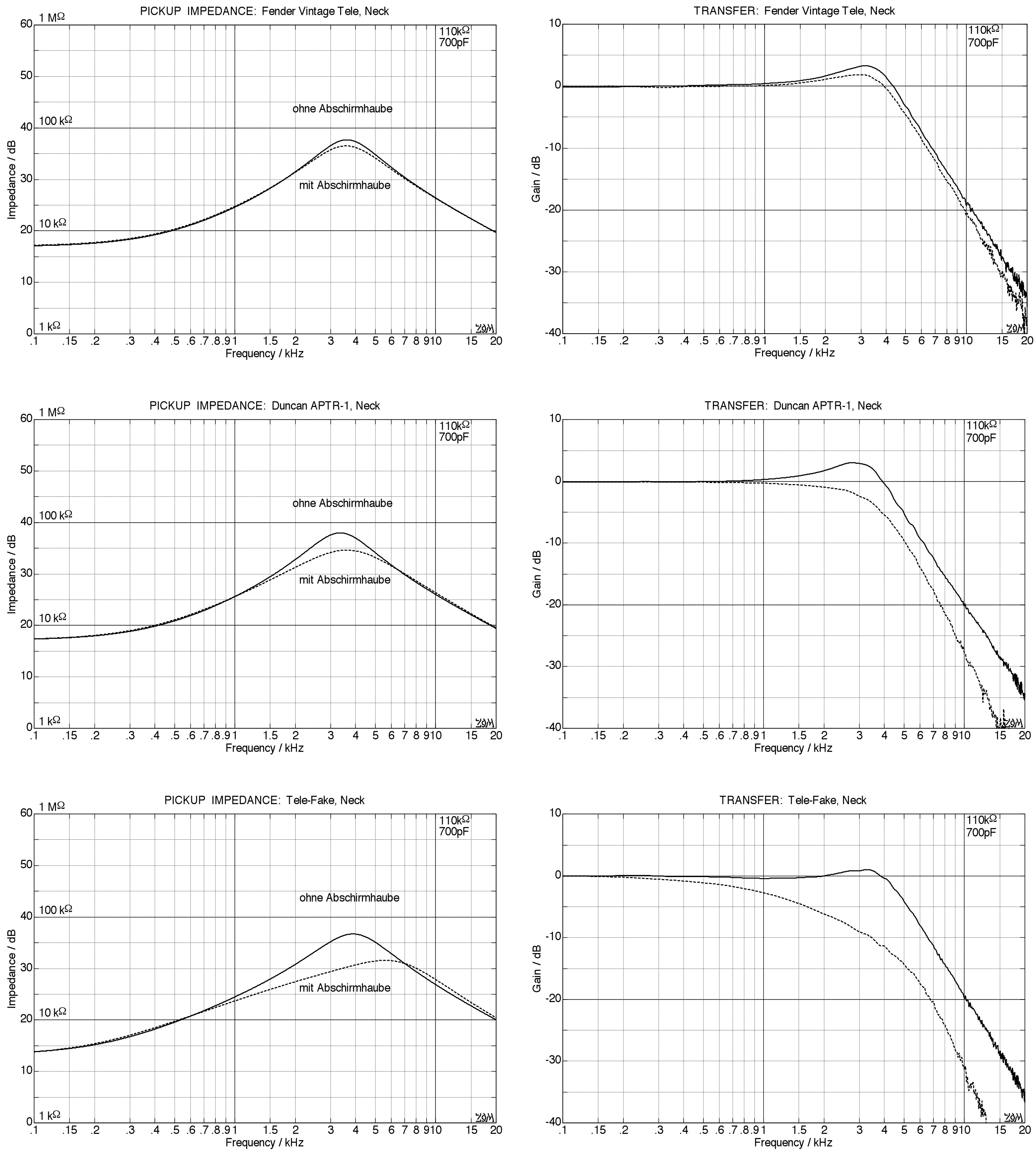


Fig. 5.10.15: Impedance- und transmission-frequenca-responses: pickups with/without cover.

The different conductivity of these metals (Chapter 5.9.2.2) gives varying eddy-current-dampening. The cover of the cheap imitation has a thickness of 0,8 mm and is even more efficient than the one of the APTR-1 (which has 0,5 mm). Of course, it is now a matter of individual evaluation whether one prefers shining treble or boxy mids. However: for the original Fender pickup it was possible to attenuate the treble if so desired. That does not work the other way ‘round. In the Seymour-Duncan brochure the phrase "For tone that sets you apart" is found above the picture of the APTR-1. Apart … to where, now? Be careful what you wish for …. ☺

Humbucker

Humbuckers sample the string vibration at two positions using their two pole pieces per string. Due to the delay between these two points, phase shifts occur and **interference cancellations** happen if the delay matches half a vibration-period. Since the phase-velocity of the propagating transversal wave is different for each string, the humbucker interferences are **string-specific**. Fig. 5.10.16 compares laser measurements and model calculations. The curves shown in the first line of the figure are practically congruent which is impressive proof for the high quality of the model. Three components were considered in the calculation: the aperture filter (**Ap**), the interference filter for a pole distance of 19 mm (**Notch**), and the low pass transmission (**RLC**) derived from the impedance frequency response. Recalculated for a scale of 63 cm, the fundamental frequency amounts to f_G = 130 Hz, the string diameter is 0,7mm.

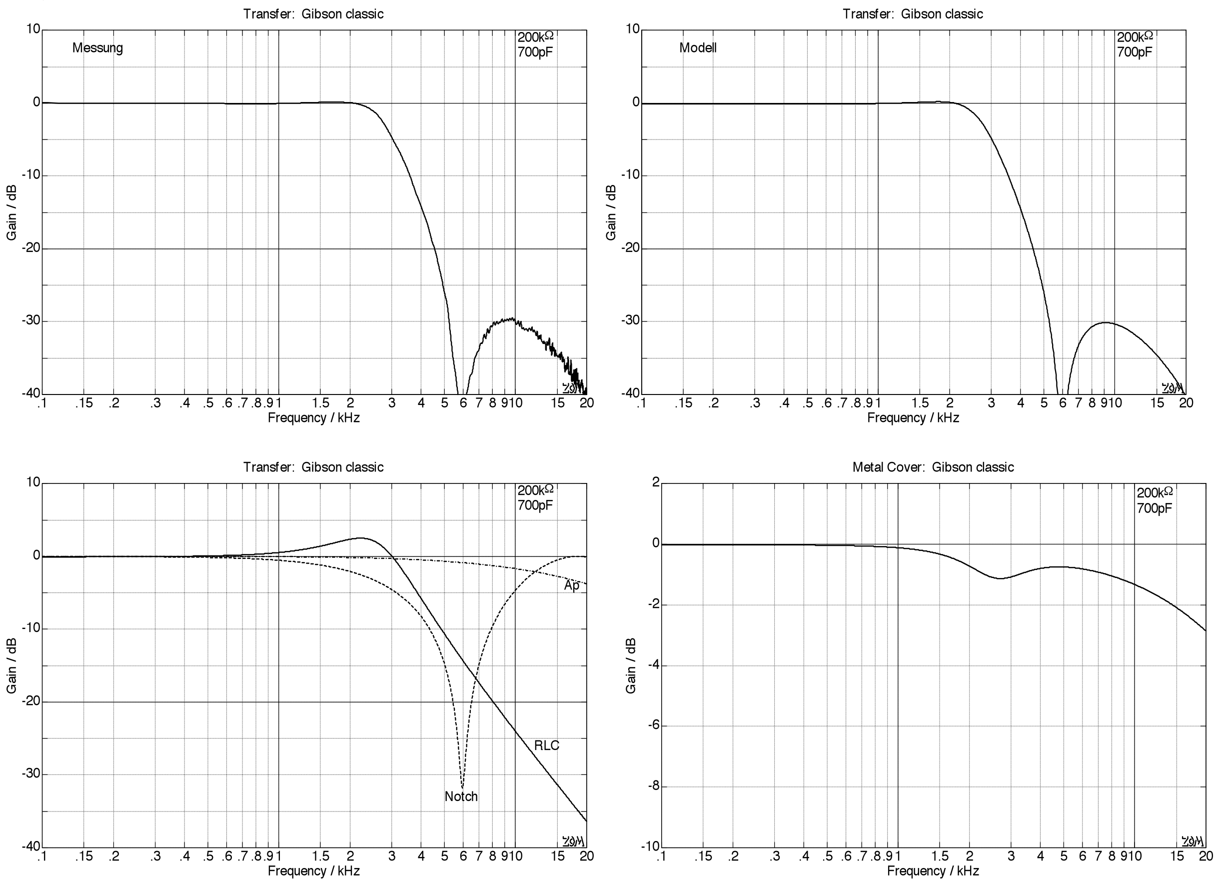


Fig. 5.10.16: Gibson-Humbucker ('57 classic). Laser-measurement (upper left), model-calc. (upper right.). Components of the model-calculation (lower left). The treble attenuation of the metal cover is shown lower right.

The measurements and calculations depicted in Fig. 5.10.16 were done for the string used on the test-bench; **Fig. 5.10.17** gives the transmission frequency responses for real guitar-conditions. The left-hand part of the figure relates to a long-ish guitar cable (700 pF), the right hand part holds for a load capacity of 330 pF (Chapter 9.4 and 9.6). The interference gap for the low E-string (E2) is located at 3 kHz i.e. just at the range which would be particularly emphasized by a Fender singlecoil. In conjunction with the treble attenuation caused by the LC-low pass, a transmission frequency response results for the Gibson Humbucker (and its innumerable copies) which evokes a Tschebyscheff-low-pass: that's how treble is efficiently cut. Another 5 dB are lost in the treble range if (as it was the case for many Gibson guitars in the 70's and 80's) potentiometers of 100 kΩ ("Tone") and 300 kΩ ("Volume") are utilized rather than 500-kΩ-versions. Tone is in the eye of the beholder ….

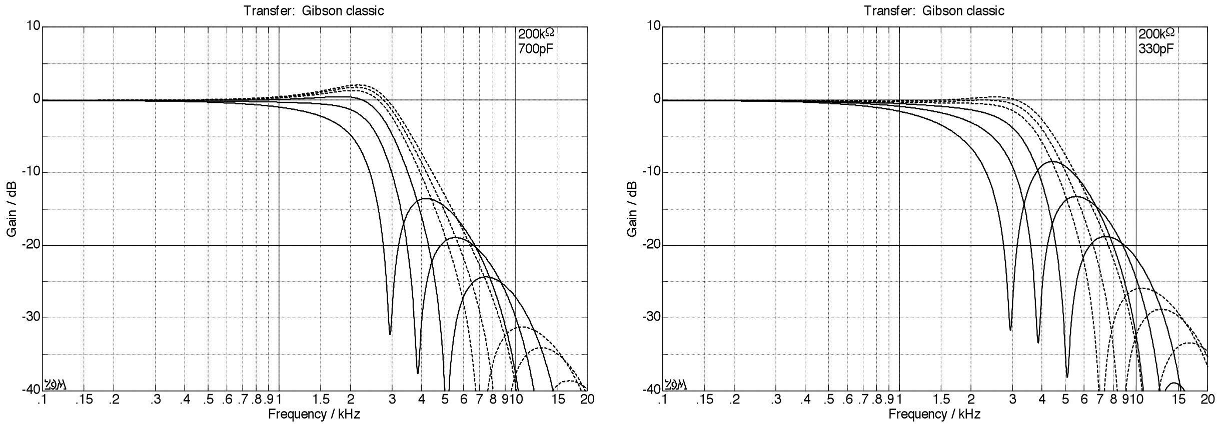


Fig. 5.10.17: Gibson-Humbucker ('57 classic). Stringspecific transmission function, with varying *C*. Due to the dispersive wave propagation the second interference gap is not at trice the frequency but considerably higher: high-frequency components run disproportionally faster (Chapter. 1.3.1).

Not all humbuckers feature the pole-distance of 19 mm as given by the Seth-Lover-developed Gibson Humbucker. For the Fender Humbucker (incidentally also developed by Seth Lover) we find 20 mm and for the Gibson Mini-Humbucker 13 mm, while for humbuckers in a single-coil format the distance is as small as 6 – 9 mm. In the same way that the pole-distance decreases, the notch-frequency increases. If the magnet poles are reduced to narrow blades with a separation of the (middle of the) blades of 7,5 mm – as it is the case e.g. for the **Joe-Barden-**pickup or the **DiMarzio** DP-184 – the notch frequency is pushed to higher ranges.

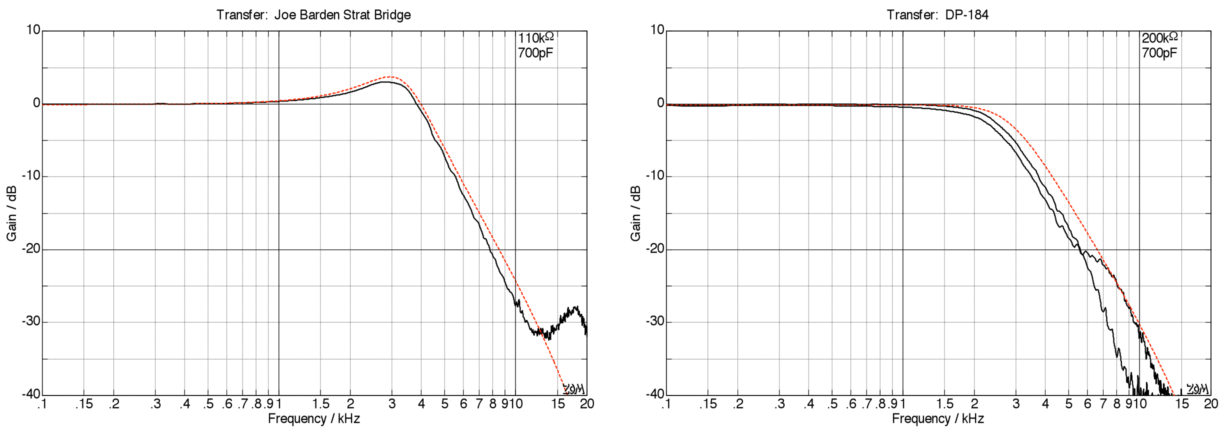


Fig. 5.10.18: Transmission frequency repsonse: humbucker of 7,5 mm blade-distance (Joe Barden, DiMarzio). Laser-measurement (–––), model-calculation (RLC, notch, aperturefilter ----). String diameter 0,7 mm, f_G = 130 Hz.

Without dispersion a 0,4-fold pole-distance-decrease would increase the notch-frequency by a factor of 2,5, in reality, however, it increases (string-specifically) by a factor of 4 to 5. The corresponding theory (dispersive wave propagation, Chapter 1.3.1) is a good match to the measurement results. In addition there are effects that are more difficult to model such as non-negligible inductive and capacitive coupling between the two coils – in particular relevant for humbuckers with small pole- or blade-distance. Under some conditions the transmission characteristic can be dependent on the propagation direction of the transversal wave (Chapter 5.11). Simple transfer-models give the resulting complicated frequency responses merely with modest accuracy (**Fig. 5.10.18**). The maximum showing in the 18-kHz-range for the Joe-Barden-pickup (which could be interpreted as a dipole-resonance) is indeed due to the coupling-resonance of the two coils. For the sound this side-maximum is insignificant.

5.10.6 Measuring accuracy (or rather measurement inaccuracy)

Test-stand-measurements support objective measurement data but they are carried out in an un-typical situation ("in vitro"). There are differences to the behavior of the actually played guitar ("in vivo"), and in addition we need to consider that all measurements contain errors. Having doubts about the value of measurement results is therefore permitted. On the other hand, subjective evaluations (e.g. given while playing a guitar) need to be questioned, as well: they may have been expressed by a hard-of-hearing guitarist, or by somebody playing under-the-influence, or may have been written up by a guitar-tester in dire need of money. Even a combination of all three conditions is conceivable. An evaluation may also simply have been given in a special (possibly non-reproducible) mood; thus it expresses a subjective opinion of little relevance to the public. Chapter 8 addresses the world of psychoacoustics while the following paragraphs deal with the measurement errors occurring with bench-tests.

1) Most of the pickups investigated show a rather poor production quality: each single magnet generates a different flux density, the air-gaps are different, the mounting plate is distorted, or the magnets are lopsided. Even simple distance measurements become problematic – plus regular measuring tools made of steel cannot be used due to the magnetic attraction forces. For dynamic measurements non-ferrous metals need to be excluded as well, since eddy-currents generated within them lead to undesirable dampening. On the other hand, using a test bench put together exclusively from regular plastic easily leads to measurement tolerances of 0,1 mm – for critical distance measurements this may often be already too much. Even much more difficult are diameter measurements of strings: to determine the cross-sectional area of a 10-mil-string with an accuracy of 1%, we need to measure the diameter with an accuracy of 1,3 μm. Normal micrometer screws reach 10 μm tolerance which leads already to an error of 8% for the area.

2) For electrical measurements, the situation is somewhat more positive: voltage- and current-values can be taken with an error of about 1%; in individual cases even more precisely. Measuring magnetic quantities brings again a decrease in accuracy: errors of 5% are probably the typical range.

3) An even greater problem resides with the **string-magnetization**: magnetic pickups work only with ferromagnetic strings, and their operating point moves along a hysteresis loop. The transmission factor of a pickup can change by as much as 3 dB (!) if the string is brought close to the pickup magnet and then moved away again to its rest position … plus there are many paths within the three-dimensional space to get to a specific location! An example shall exemplify the associated difficulties (**Fig. 5.10.19**): in the left-hand section of the figure the

pickup (a Gibson Humbucker) is moved along the strings across the cranks of the rotating string (motor-test-bench). The paths “to and from” yield two different curves (—— d = 2 mm, ------ d = 4 mm). The right-hand section shows the voltage-level curve as a function of the distance d; the crank was rotated across the slug-coil of the humbucker (left maximum in the left section). It required many complementing measurements to arrive at meaningful and practically relevant measurement curves – and to arrive at the “subjectively correct objectivity”.

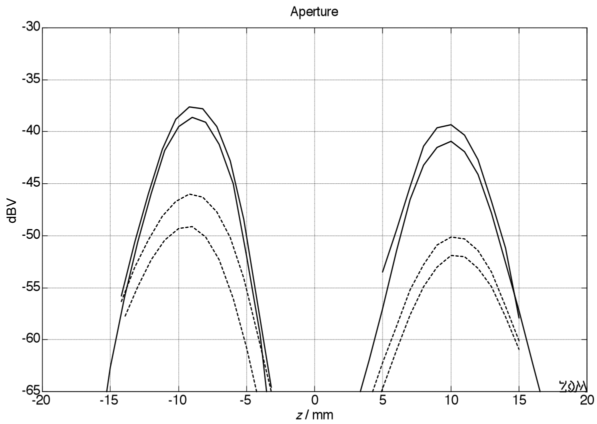


Fig. 5.10.19: Dependency of the voltage level on the pickup shift along the string (left) and on the string-to-magnetic-pole distance (right). Motor-testbench (Chapter 5.4.4).

4) In order to see whether the data collected from an individual pickup are indeed **representative** for this type in general, it would in fact be necessary to pick a sample including more than just one single element. However, the price per unit of € 186 (in 2003) is prohibitive for such an approach, and – as “extrapolation” – the speculation remains that all pickups of this type received the same more or less crooked and messy assembly. (Here, the business administrator nods, and with a stern expression points to the fact that a single alnico magnet is already as expensive as 40 cents: “one needs to make a little profit, after all”.)

5) We may be critical regarding the motor-test-bench, and note that
- the string-crank we used does not represent an infinitesimal short impulse, that
- a rotational movement is happening, and that
- transformation in the frequency domain requires a linear system.

Moreover, the string does not maintain its cylindrical shape at the crank but gets minimally bent (steel wire cannot be cranked in another way). For 1 mm crank amplitude and a desired measuring dynamic of 40 dB, the required production tolerance is as small as10 μm. …. Or maybe 60 dB were desired – in that case you need to bump it all up to 1 μm tolerance. … Oh, right: and please do install the whole shebang on plastic bearings free of friction and mechanical play …..

6) The **shaker-test-bench**, as well, includes typical artifacts: the string does not vibrate in one plane but along a slightly elliptical path; the magnetic drive of the shaker generates a magnetic crosstalk; measurements are limited to the low-frequency range due to self-resonances; the drive is non-linear and time-variant due to it heating up. Plus much more.

7) The **laser-vibrometer** operates with sufficient accuracy if mounted on a heavy stone-table (this was the case for our experiments). In order to keep the noise low, a suitable narrow-band-filtering is required, as discussed e.g. in chapter 6.

8) In order to be able to exactly specify the effective coil surface, a wire as thin as possible should be used for all **measurement coils**. However, the thinner the wire, the greater the risk of damage (as a compromise, 60 – 80 μm magnet wire could be used).

9) Measurements which include forming the integral of the measurement signal (e.g. to derive the velocity from the acceleration) are falsified by **amplifier offsets**. Even for low-offset op-amps sometimes just moving the air above the housing of the op-amp is sufficient to produce measurable drift-effects. With a corresponding effort, this problem proves to be just about manageable.

In the end, we obtain some relief from comparing the individual measurement results: it ain't all that inaccurate. As long as one does not approach the problems with excessive expectations, and as long as one avoids real blunders (which do wait to happen, though), the test–bench–measurements yield reliable results. The comparison of measuring results taken over many years corroborates the (subjective) assumption that the typical accuracy of a test-bench is comparable to that of a precision-SPL-meter, and amounts to about 1 dB.

5.10.7 FEM-calculations

Besides unwavering faith ("ONLY pre CBS"), listening experiments ("vintage vs. new") and measurement ("3D-laser") – and maybe sheer ignorance – the only other way to describe the function of a pickup "exactly" seems to be mathematical/physical finitization. The magnetic field is cut into hundreds of thousands of fragments (the finite elements) for which a computer calculates (for hours) the exact field-distribution. The more expensive the software and the larger the number of elements, the better this works. And so the ambitious hobby-scientist enthusiastically posts his colorful fluxograms on the Internet – to deliver the definitive proof why the Strat pickup sounds differently than the XY-90. Please heed two words of wisdom from a professional scientist who threw in the towel after half a year: forget it.

It isn't that these finite models are generally bad – the problems lie in the data entered by the user. But first things first. Field calculations are simple if direct current flows through a straight wire of infinite length. That ain't the case for a gittar pickup? Okay then. Let's open the toolbox for permanent magnets and click on "cylindrical magnet". Go to "Mesher", on to "Solver", do a color plot …. and off into the bin it goes. Any questions? Sure – lots!

The field of *one* **cylindrical magnet** is a relatively simple one because it features rotational symmetry. One might be able to ignore that a pickup includes 6 of them (let's "approximate"), and as well that there is a string; oh … 6 strings, even. Didn't someone say checking out a string-less guitar: "*for a beginner that will suffice.*" But seriously, the magnetic field without string is of course only of any use as a starting point. Statements regarding the transmission behavior work only with inclusion of the string. That, however, makes the rotational symmetry go out the window; the calculation effort rises dramatically. We could see that as a challenge: those with lots of experience with the cross-linking should be able to master the geometry, set the boundary elements correctly (a job not at all trivial), and have the field calculated with string. Now, this field needs to travel through air, with the relative permeability $\mu_r = 1$. And through a steel string with a high permeability (due of the ferromagnetism). And through a permanent magnet with a rather small μ_r. Limiting the effort, a search leads $\mu_r = 4$ for alnico and to $\mu_r = 40$ for steel. Again: off into the bin it all goes.

Your regular FEM software will model ferromagnetic materials with a *BH*-characteristic. One *BH*-characteristic, that is. That's because that way you don't have to distinguish which branch of the hysteresis-curve holds the operating point. So, the simulation gives us an approximate impression of the field shape – but what about being accurate? Will the big effort bring ultimate perfection? Well, both the string and the magnet are magnetically hard, and therefore the two hysteresis-branches differ considerably: off then to get more computer power (if one gets that kind of support to begin with ….) and to calculating the two branches. Two? I.e. merely the boundary curves which in fact each hold an infinite number of *BH*-pairings? Now the "Solver" can't manage it anymore, the iteration fails to converge, the software capitulates. Ah – but the newest release takes care of this issue as well! Super! So now we have two different non-linear performance maps of the materials, and can only hope that magnet and string abide by these. Does the newest release include a button for **anisotropy**, i.e. the fact that the magnetic characteristics of metals are dependent on direction? In the simple model, isotropy is used as a basis, but the string was *drawn* during the manufacturing process and therefore subjected to significant mechanical stress in one direction – so at least we should check whether it really acts isotropically. Alnico-V-magnets are certainly anisotropic, ceramic magnets often as well. Plus, unfortunately only a small part of the magnetic flux flows through the cylinder in the axial direction while a significant part penetrates the cylinder mantle at an angle. In conclusion: no final perfection, and in spite of mathematical overkill we merely have a rough approximation.

As the proud owners of colorful fluxograms with increasingly fine resolution and barely visible finitization we now believe we have the license for carrying out the final step: the **dynamic analysis**. Now the sting is to vibrate i.e. it changes its distance to the magnet. We suggest our desire to the FEM-software in the form of discretization: instead of one string/magnet distance we do an overnight calculation-run for 10 of them (not more, let's start small and not exaggerate). This yields 10 different magnetic fluxes, and as difference between them we obtain the quantity on which the induced voltage depends: the change of the magnetic flux over time.

The highly optimistic assumption at the basis of this result is that material data we use are close to reality – although rarely anybody will have tensorial data of anisotropic ferromagnetics at their disposal. Let us imply that we would indeed have access to such numbers – how do we continue? Eddy currents form in the magnet, and they displace the magnetic field which we have just calculated with much effort! So: either we limit ourselves to 82,4 Hz (that's at least something, isn't it?), or we justify even (much!) more calculation effort and do a truly dynamic run. But then we realize at some point that the difference of two approximately correct numbers will have a mightily big error margin. So again and finally: off it all goes into the bin.

For all those still not convinced (because 5 months of work have been already invested, and because the nice software support people were so kind to eradicate all programming errors): as the magnetic field changes (which it does due to the vibration of the string), the *BH*-point does not run along the hysteresis-family of curves. The gradient of the hysteresis curve is the **differential permeability** but what we need is the **reversible permeability** which is smaller that the differential one (Chapter 4.10.3). In the end we have therefore now a hodge-podge collection of approximated dependencies the difference of which is not the mathematical "ultima ratio" but still remains a coarse estimate. Not bad if you have nothing else to do … but don't show it, will you?!

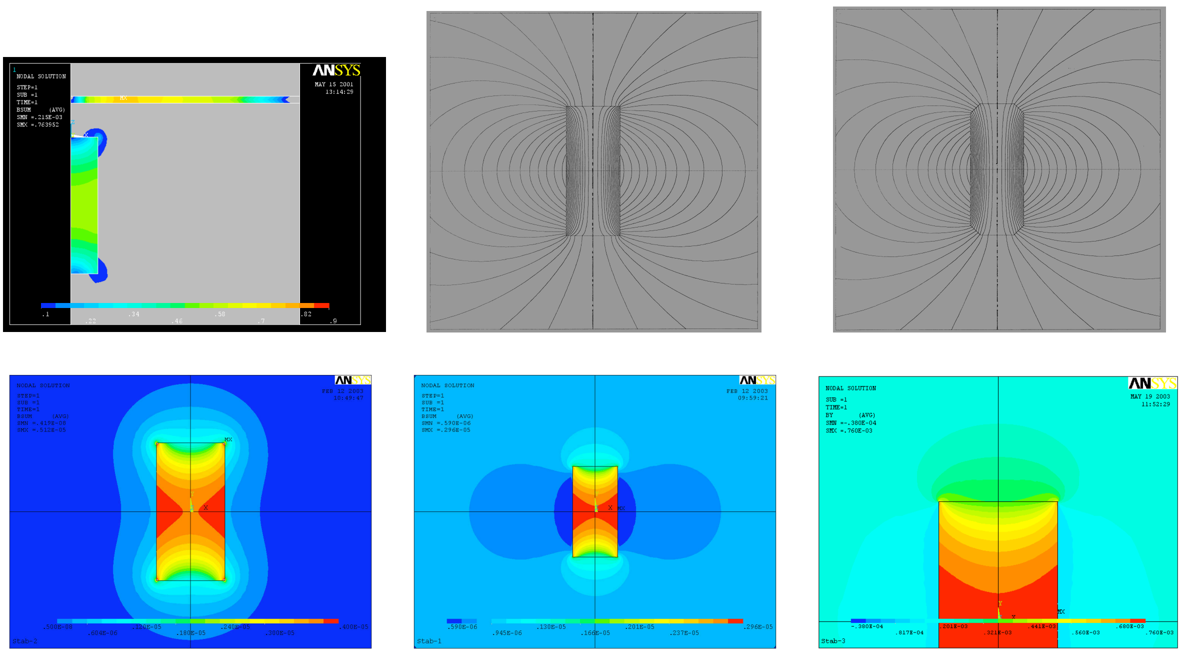


Fig. 5.10.20: FEM-graphs

5.11 Pickup-directionality

Magnetic pickups predominantly detect string vibrations perpendicularly oriented to the surface of the fretboard. The string swings back and forth between areas of higher and areas of lower magnetic field strength causing flux changes in the pickup coil. A motion in parallel to the fretboard makes the sting move merely in areas of approximately equal field strength such that only a small voltage is induced. Other than the polarization of the string vibration it is also the propagation direction of the wave, which we need to consider (in particular for humbuckers).

5.11.1 Polarization-plane of the string

The polar diagram shown in Fig. 5.11.1 tells us about the dependency of the pickup voltage on the angle of the oscillation plane of the vibrating string. To do the measurement, a D'Addario string (PL-026, diameter 0,66 mm) was sinusoidally deflected. The amplitude was 0,4 mm and the distance between string and magnetic pole was 2 mm. The string was centered above the magnetic pole (on the magnetic axis) of a Telecaster bridge pickup.

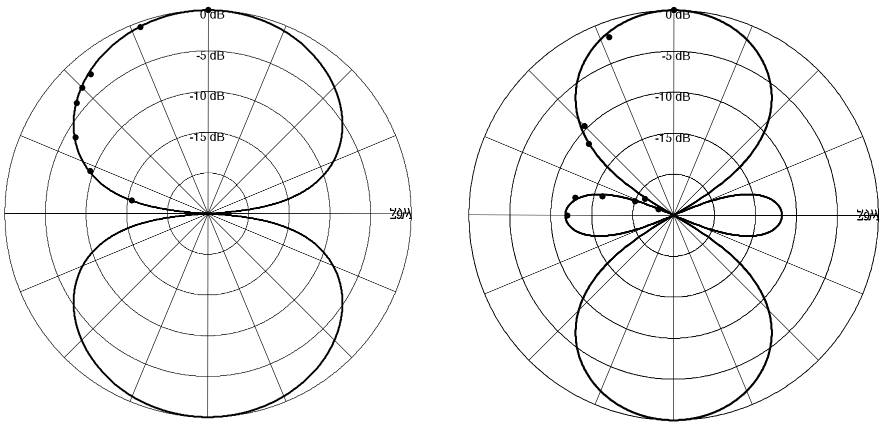


Fig. 5.11.1: Polar diagram of a magnetic pickup (Fender Telecaster, bridge). The line represents the model calculation, the dots show the measured results. 1st harmonic (left), 2nd harmonic (right).

Above the centre of the magnetic pole the **1st harmonic** shows a cosine-shaped dependency with a maximum sensitivity for fretboard-normal oscillation and complete cancellation for fretboard-parallel oscillation. The angle-dependency of the **2nd harmonic** has a zero at 63° and a secondary maximum at 90°. Let us consider for an axially symmetrical magnetic field, a sinusoidal, centered oscillation oriented normally to the axis of symmetry yields. It will yield a field shape which can include – due to the symmetry (even function) – exclusively even powers of the series expansion. In other words it holds exclusively even-numbered harmonics save for a DC component that remains unimportant for the present point of view. However, this changes as soon as the string does not follow a centered path of movement anymore – it may be shifted by string bending or, it may have been positioned eccentrically already during production. Fig. 5.11.2 indicates string positions of an American Standard Stratocaster built in 2002. The distance of the magnetic axis is 10,4 mm uniformly *for all three pickups*. Since the strings are nut running in parallel but diverge from nut to bridge, it is not possible that all 6 strings are centered above the magnets, and therefore the transmission coefficient is not only dependent on the oscillation direction of the string but also on the string position. The latter may be shifted in *two* dimensions.

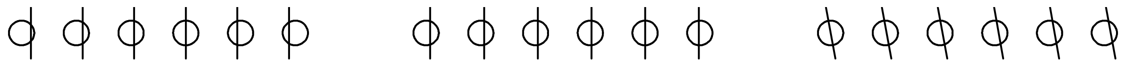


Fig. 5.11.2: String positions over the magnetic poles: neck, middle and bridge pickups (left to right). The strings do not run straight across the bridge pickup but at an angle.

Polar diagrams such as the one given in Fig. 5.11.1 are therefore valid only for their individual case – a generalization is possible to a limited extent only. To detect the dependency of the transmission coefficient on the string position, a number of pickups were measured on the text bench (**Fig. 5.11.3**). The string was subjected to a sinusoidal deflection at a frequency of 85 Hz and shifted while keeping a constant distance over the magnetic poles. Despite the fact that the pickups are of different build (Chapter 5.1 – 5.3), the resulting curves are similar. The pickups differ in their absolute sensitivity (loudness), and moreover the transmission coefficient is dependent on the string position. It is not surprising that the voltage level is largest right on top of the magnetic pole and smallest in between two poles – for a Telecaster the level difference for these two conditions amounts to 5 dB, and it is somewhat smaller for the other pickups. In the figures only one half of the respective pickup is shown since the curves are symmetric relative to the middle of the pickup. The Stratocaster pickup is the one exception since its magnetic poles protrude – in the original condition – differently from the pickup housing (staggered magnets). They were, however, adjusted for equal height during the measurements.

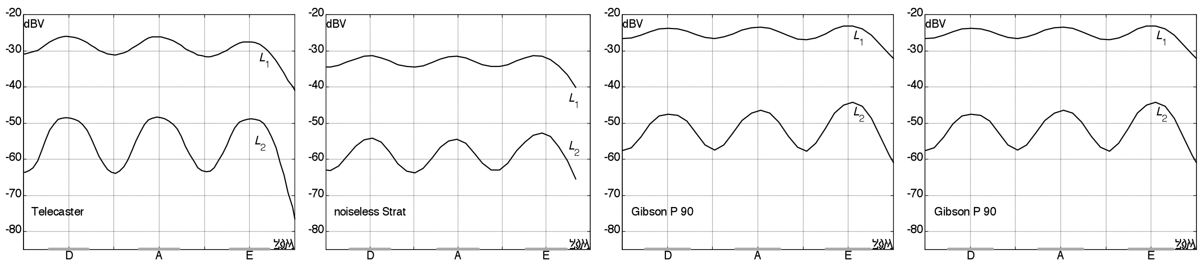


Fig. 5.11.3: Location dependency of the level of the 1st and 2nd harmonic; string motion normal to the fretboard plane. Amplitude 0,4 mm, string-to-magnet distance 2 mm, intrinsic distortion of the shaker compensated for.

Fig. 5.11.4 depicts corresponding results for string vibration polarized in parallel to the fretboard plane. There are general similarities but also significant differences to the fretboard-normal motion. However, we must not be tempted to explain inter-individual sound differences from these diagrams. In **listening experiments** we found neither a sideways shift in the string position (keeping the string-to-magnet distance constant) nor a change in the string vibration polarization to have any *significant* effects. That does not exclude certain smaller effects becoming apparent in the sound for individual cases but it does qualify the significance (or rather insignificance) of such effects. For example, the sound changes much more, as the string is plucked at a different position of with a different pick. A big difference is heard between picking a string in a fretboard-parallel motion and "plucking" it perpendicularly such that it hits the fretboard; this difference, however, stems from the strings hitting the frets i.e. from the mechanical vibration (and not the directionality of the pickup).

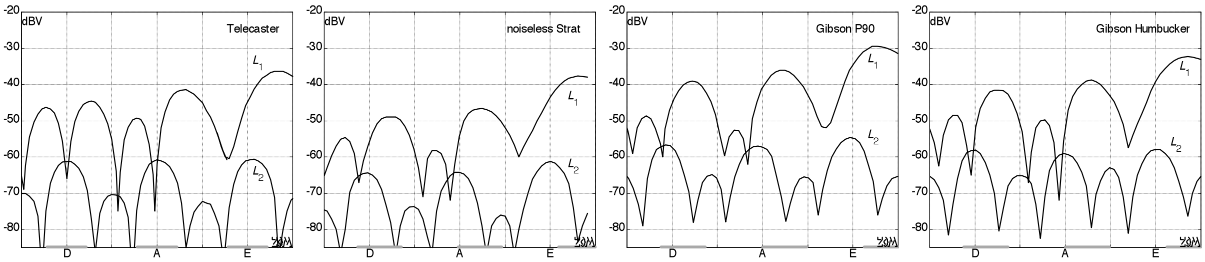


Fig. 5.11.4: Location dependency of the level of the 1st and 2nd harmonic; string motion parallel to the fretboard plane. Amplitude 0,4 mm, string-to-magnet distance 2 mm, intrinsic distortion of the shaker compensated for.

Fig. 5.11.5 shows the results for the measurements of all 4 pickups on top of each other. The curves were vertically shifted such that the divergences are minimal. For fretboard-normal oscillation there are only minute differences for the 1st harmonic; larger differences exist for the minima of the 2nd harmonic but this is insignificant due to the much lower level compared to the 1st harmonic. Fretboard-parallel string vibration causes more pronounced differences since zeros in the transfer function (i.e. cancellations) are passed through and thus small imbalances in the magnetic field can have effects on the voltage level. The difference in the height of the maxima in the right-hand figure is due to the finite number of magnets, which causes a magnetic field diverging toward the outer range. If a large number of magnets were lined up we would see maxima of equal height (save for the outer magnets).

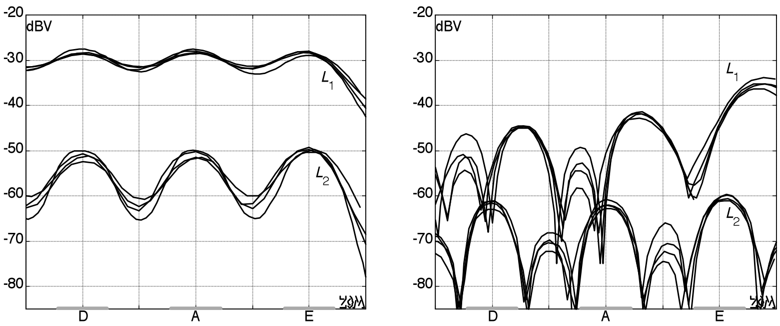


Fig. 5.11.5: Location dependency of the level of the 1st and 2nd harmonic; string motion normal to the fretboard plane (left), parallel to the fretboard plane (right).

In the range of the E-string all curves have a similar shape, despite the fact that:

- the Telecaster magnet is cylindrical with a plane face,
- the Stratocaster magnet is beveled with a wraparound,
- roundhead screws focus the field of a bar magnet for the P90,
- for each string a slug and a screw focus the field for the humbucker.

Towards the middle of the pickup we do see (for the string vibration in parallel to the fretboard plane) difference of in excess of 10 dB but their relevance immediately needs to be put in question again: 1) the real string does not vibrate exclusively in the fretboard-parallel plane; 2) if indeed this difference were of any significance, the A- and the D-string would sound differently than the E-string which could not be confirmed at all in listening tests. In fact, all three strings generated e.g. for the Stratocaster the expected sound without any string-specific special feature (of course, the pitches did differ).

5.11.2 Direction of the wave-propagation

As discussed in the previous chapter, magnetic pickups have directionality with regard to the orientation of the string-oscillation. However, under certain conditions the transmission characteristic of the pickup also depends on the propagation direction of the wave travelling along the string. This effect does not manifest itself in axially symmetrical pickups, but as soon as the design is asymmetrical, the wave running in one direction can generate a different induction voltage compared to the wave running in the other direction.

Fig. 5.11.6 explains the context with a simplified block-diagram. A string is sampled at two locations. A transversal wave propagates along the string; its direction is defined as “forward” with the index V (from the German “vorwärts”) and “reverse” with the index R. Between the two sampling points we find a **phase-delay** τ that may show any kind of dependency on frequency (dispersion). A humbucker readily serves as practical example – with it the distance between the sampling points typically amounts to 19 mm.

Fig. 5.11.6: Block-diagram for a string oscillation sampled at two locations.

The two sampling signals (induction voltages) each run through a filter, the transfer-function of which is defined by $\underline{H}_1$ and $\underline{H}_2$, respectively; subsequently the two signals are added. In a first step the overall transfer function can be set to:

$$\underline{H}_V = \underline{H}_1 + e^{-j\omega\tau} \cdot \underline{H}_2; \qquad \underline{H}_R = \underline{H}_2 + e^{-j\omega\tau} \cdot \underline{H}_1$$

however this would lead to different points of reference: for the forward traveling wave this would be the input of $\underline{H}_1$ and for the reverse wave it would be $\underline{H}_2$. It is conducive to chose the **pickup mid-point** as reference for the time, and thus to reformulate the transfer functions accordingly:

$$\underline{H}_V = e^{+j\omega\tau/2} \cdot \underline{H}_1 + e^{-j\omega\tau/2} \cdot \underline{H}_2; \qquad \underline{H}_R = e^{-j\omega\tau/2} \cdot \underline{H}_1 + e^{+j\omega\tau/2} \cdot \underline{H}_2 .$$

For the filters (pickup RLC low pass) several special cases need to be distinguished: $\underline{H}_2 = \underline{H}_1$, $\underline{H}_2 = k \cdot \underline{H}_1$, and $\underline{H}_2 \neq \underline{H}_1$. The case of identical filtering ($\underline{H}_2 = \underline{H}_1 = \underline{H}$) correspond to axially symmetrical structure, and the two transfer functions are **identical**: $\underline{H}_V = \underline{H}_R$. The Gretsch humbucker “Filter-Tron” is an example for a real case of this kind:

$$\underline{H}_V = e^{+j\omega\tau/2} \cdot \underline{H}_1 + e^{-j\omega\tau/2} \cdot \underline{H}_2 = 2\cos(\omega\tau/2) \cdot \underline{H} = \underline{H}_R; \qquad \underline{H}_1 = \underline{H}_2 = \underline{H}$$

The second special case comes with the two transfer functions differing by a *real* factor k: $\underline{H}_2 = k \cdot \underline{H}_1$. The two expression in brackets are the conjugate complex of each other, and the two transfer functions are **equal in their magnitude**; $|\underline{H}_V| = |\underline{H}_R|$. The phase functions differ, however, which needs to be considered when superimposing waves:

$$\underline{H}_V = \underline{H}_1 \cdot \left(e^{+j\omega\tau/2} + k \cdot e^{-j\omega\tau/2}\right); \qquad \underline{H}_R = \underline{H}_1 \cdot \left(e^{-j\omega\tau/2} + k \cdot e^{+j\omega\tau/2}\right); \qquad \underline{H}_2 = k \cdot \underline{H}_1$$

The third case can be described by a complex factor ($\underline{H}_2 = \underline{k} \cdot \underline{H}_1$) and includes different overall transfer functions for each of two waves travelling in two directions. This scenario is the one of all humbuckers with **different coils**, and for humbuckers in singlecoil-mode for which the coupling of the magnetic field is non-negligible.

$$\underline{H}_V = \underline{H}_1 \cdot \left(e^{+j\omega\tau/2} + \underline{k} \cdot e^{-j\omega\tau/2}\right); \qquad \underline{H}_R = \underline{H}_1 \cdot \left(e^{-j\omega\tau/2} + \underline{k} \cdot e^{+j\omega\tau/2}\right); \qquad \underline{H}_2 = \underline{k} \cdot \underline{H}_1$$

Fig. 5.11.7 shows an example for strong differences between the two filter functions: a DiMarzio **DP-184** was operated in "split mode", i.e. only one of its coils was connected while the other was left open (electrical idle). We may not conclude from this type of operation that the coil in idle does not contribute: due to the unavoidable winding capacitances (in this case around 500 pF), currents are also flowing in the disconnected coils – they generate a magnetic field which has effects on the other (connected) coil. The split-mode distinguishes itself from true single-coil operation in particular in the range around the resonance frequency. While the connected coil represents a low-pass system (e.g. $\underline{H}_1$), the idle coil works as a band-pass ($\underline{H}_2$), and consequently $\underline{H}_1$ and $\underline{H}_2$ differ significantly, with a resulting strong dependency on direction.

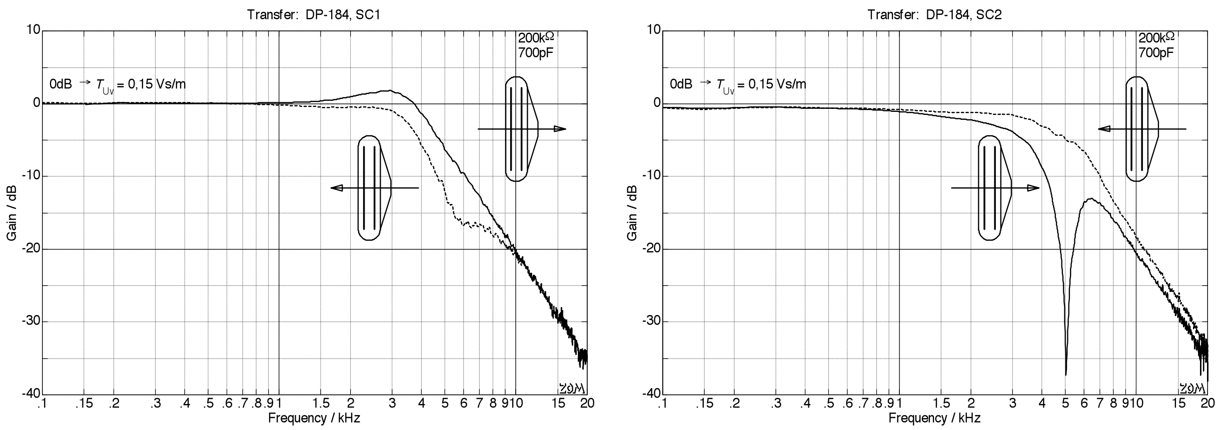


Fig. 5.11.7: Transmission measurement (laser-vibrometer): DiMarzio DP-184 in singlecoil-mode.

We observe directionality, as well, when connecting the two coils in series (**Fig. 5.11.8**), although the differences are smaller than those experienced with single-coil operation. Based on the measurement results, we may assume that both coils have the same number of windings, but obviously the wire diameter is different leading to different DC-resistances (3757 vs. 5100 Ω) and different winding- and coupling-capacitances.

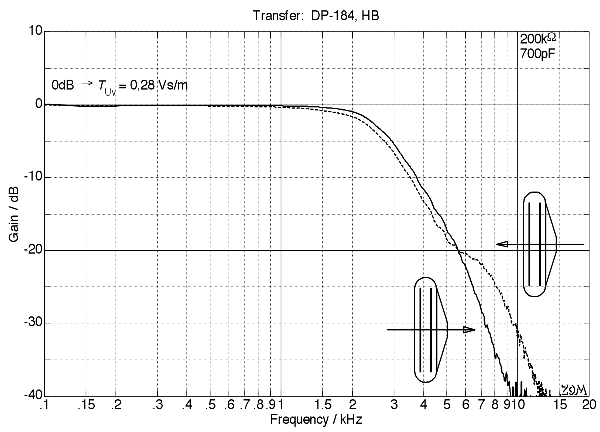


Fig. 5.11.8: : Transmission measurement (laser-vibrometer): DiMarzio DP-184 in humbucking-mode

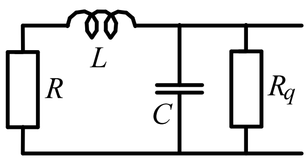
5.12 Pickup noise

Every pickup generates undesired noise. The magnetic pickup converts magnetic interference fields into noise voltages (Chapter 5.7), but it also creates already without the presence of any magnetic field a broadband noise. As the term “broadband” indicates, the spectrum of this noise is distributed continuously from very low to very high frequencies. The reasons are conducting electrons in the copper wire which can move freely and perform stochastic movements. The superposition of all these charge-movements leads to a noise voltage having a normal (= Gaussian) distribution and being measured as an RMS-value $\tilde{U}$. For a given absolute temperature T, a measurement bandwidth B, and with Boltzmann’s constant k, the resistance R yields:

$$\tilde{U} = \sqrt{4kTBR} = 0{,}127\mu\mathrm{V} \cdot \sqrt{B/\mathrm{kHz} \cdot R/\mathrm{k}\Omega}$$ Thermal noise voltage

For example, a 10-kΩ-resistor would generate a noise voltage of 1,27 µV for a measurement bandwidth of 10 kHz. However, this calculation is only valid for real (i.e. purely ohmic) resistors without any loading. As a first consideration it will suffice to model the magnetic pickup via its coil resistance R, its inductance L, the load capacity C (predominantly contributed by the cable, and the cross-resistance R_q (**Fig. 5.12.1**). R_q is made of three parallel resistors: the amplifier input resistance (typically about 1 MΩ), the volume potentiometer of the guitar, and the tone potentiometer connected via a “tone”-capacitor. With respect to noise voltages, this “tone”-capacitor may be seen as a short so that all three resistances are connected in parallel. For a typical Stratocaster pickup we find, for example: R = 6000 Ω, L = 2,2 H, C = 0,7 nF, R_q = 111 kΩ. Merely the ohmic resistances in the circuit generate thermal noise; it is modeled for R via the series-connected noise voltage source U, and for R_q via the parallel-connected noise current source I. Both noise processes run independently of each other so that their effects can be superimposed after separate calculation. We do need to consider that the two RMS-voltages have to be added according to the **Pythagorean** law – as it is required for interacting incoherent signals. For the calculation we first omit the current source and obtain the terminal voltage generated by U; subsequently a short replaces the voltage source and the terminal voltage generated by I is calculated. The two terminal voltages are each squared and then added; the square root of the result is the actual noise voltage.

The spectral distribution of the noise is shown in the **noise spectrum** with the frequency running along the abscissa. Along the ordinate we find the noise power spectral density (W/Hz), or the normalized square-root of it – the so-called **noise voltage density**



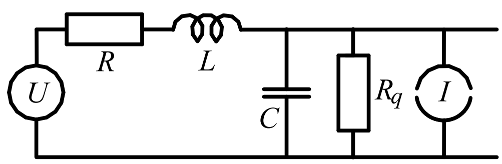


Fig. 5.12.1: Equivalent circuit diagram of pickup; left without, right including noise sources. The ECD is the basis for the noise spectra shown in Fig. 5.12.2.

The thermal noise power of an ohmic resistor R amounts to $4kTB$ and is independent of the resistor value. The noise power referenced to the bandwidth B is called the power spectral density **PSD** = $4kT = 1{,}62 \cdot 10^{-20}$ W/Hz, with 293K (room temperature) used for T. Since the power spectral density has the same value for each frequency region (i.e. it is independent of f), this noise is termed **white noise**; as is the case for white light, “all frequencies are contributing”. In circuit technology, the noise voltage density e_n is normally used instead of the PSD; it is obtained by dividing the noise voltage $\tilde{U}$ by the square root of the bandwidth: $e_n = \sqrt{4kTR}$. A 6-kΩ-resistor generates white noise with a noise voltage density of $9{,}85\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$. In Fig. 5.12.1, this value characterizes the noise voltage source designated U. However, the noise arriving at the terminal is not a white noise anymore but it is low-pass filtered by L and C. The left-hand section of **Fig. 5.12.2** shows, in the lowest curve, the frequency dependency of the noise voltage density generated by R and found at the output terminals. The resonance emphasis caused by the low pass is clearly recognizable at 3,8 kHz.

The second noise source is the cross resistance R_q. Its noise is expediently modeled via a parallel-connected noise current source, the spectral noise current density i_n of which is e_n / R_q. 111 kΩ yields $382\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$. To calculate the terminal voltage generated by this resistance, i_n needs to be multiplied with the absolute value of the circuit impedance; this result is given in the left part of **Fig. 5.12.2** by the middle curve. Below 1,8 kHz, the noise contributions of the coils resistance R dominate, and above this frequency the noise contributions of the potentiometer/amplifier-resistances R_q. The latter in fact deliver the overall largest share of the noise. For the figure, a constant percentage bandwidth of **1/12th of an octave** was chosen. The relative 1/12th-octave-bandwidth is 5,8% corresponding to 5,8 Hz absolute bandwidth at 100 Hz, and to 58 Hz at 1 kHz. A noise voltage density of $9{,}85\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ generates – for a bandwidth of 5,8 Hz – a noise voltage of 23,7 nV (corresponding to a voltage level of −152,5 dBV). In the right-hand section of Fig. 5.12.2, the white-noise-levels of amplifying devices (tube, FET, operational amplifier) for $5{,}5\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ (ECC83, LT1113), and $18\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ (TL071), respectively, are shown as dotted lines. The TL071 downgrades the pickup noise below 2 kHz while the ECC83 and LT1113 add almost no noise at all. For **FET-operational amplifiers** and **tubes**, the effects of noise currents ($10\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$) can be ignored. Using a bipolar-transistor op-amp such as a NE5532 having about ca. $500\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$ would, however, not be purposeful, despite the good e_n-value.

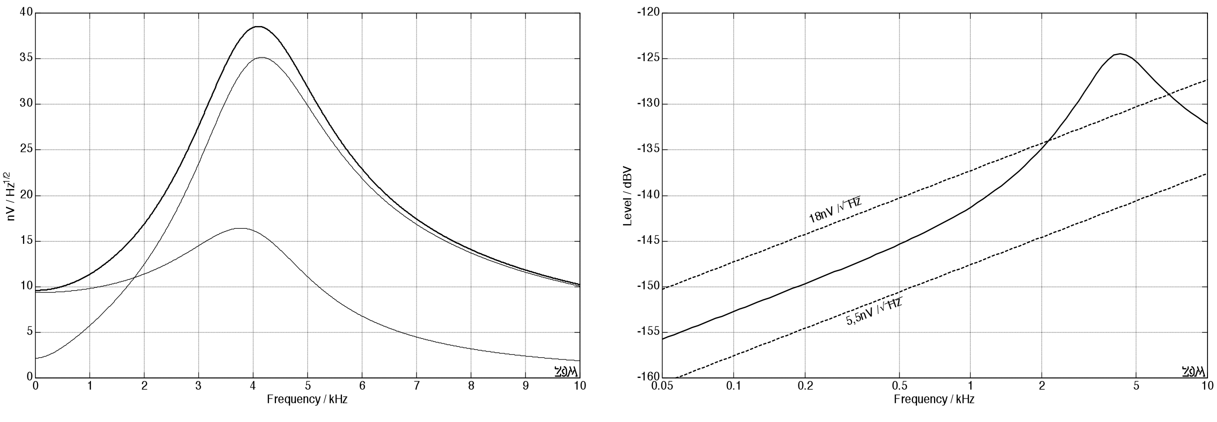


Fig. 5.12.2: Noise voltage denstity of a pickup (left), 1/12th-octave-level (right). Calculation done for the ECD of Fig. 5.12.1 with R = 6kΩ, L = 2,2H, C = 700pF, R_p = 111kΩ. => $U_{overall}$ = 2,2 μV.

5.13 Pickup microphonics

That a pickup is "microphonic" means that it is susceptible to air- and structure-borne sound. Actually, a pickup should only react to string oscillations, but whether it was conscious or subconscious, some designers have included rather efficient microphones into their guitars: as one speaks to one's instrument ("god-awful acoustics" …"dropped that bloody slide AGAIN" … "who the **** came up with these lyrics"), everyone can hear it coming over the speakers. In most cases it was probably an overambitious developer who sought to shield against hum, but in fact added – in the form of a **sheet-metal housing** – a microphone membrane. Which on top of everything is totally a lame duck to keep out magnetic fields at low frequencies.

Maybe we could simply pass over the whole subject with an "I never talk to my guitar"-approach, but all too often the issue develops a life of its own and ends in a high-pitched whine. Like it is the case with (proper) microphones, **feedback** develops as soon as the loop-gain increases over 1. Especially shielding covers made of steel sheets are dreaded. Even Seth Lover, famous developer with Gibson, sought to encase his PAF with a housing made from steel sheet metal. He had very correctly recognized that the relatively bad conductivity of this material leads to low eddy-current losses. Because steel is difficult to solder, German silver was in the end used – the standard in the premium range. It is not known exactly which type of steel Seth Lover originally wanted to use: there are indeed non-magnetic steel variants, but most are ferromagnetic and covers made from them – as they are stimulated by airborne sound – would induce significant voltages in the pickup coil, just as the string does. In the early days, when guitar amps were not operated much in overdrive mode, this would have not grown into too much of a problem. However, amplifier power and loop gain increased rapidly and significantly … and suddenly guitars had pickups whistling catastrophically. *"There was a pickup for sound-hole-mounting designated 'GM100' which had – probably due to blatant ignorance – the whole housing made of steel sheet metal. In terms of microphonics, it broke all records [Lemme]"*. Come to think of that this pickup was supposed to be mounted on a feedback-prone acoustic guitar ….. it's howl-scream-whistle-city ….

Even using 'non-magnetic' brass sheets would have been – cosmetically – rather counter-productive due to the yellow, quickly oxidizing color. Such covers were therefore nickel-plated (yellow-ish color) or chrome-plated (blue-ish color). **Nickel**, however, is ferro-magnetic and a similarly good conductor for magnetics as is electric sheet metal. On the other hand, c**hrome** indeed is paramagnetic i.e. practically non-magnetic, and so is aluminum. Still, it is not sufficient to just use nonmagnetic materials: moving a conductor (the sheet metal) within a magnetic field induces an **eddy current** in this conductor – and this eddy current again generates a magnetic AC-field which generates an AC-voltage in the pickup coil.

In a much-simplified model we can describe the cover mechanically as a spring-mass-system. Below the resonance frequency, the spring is contributing more, while above the resonance, the mass does. Together, sound-pressure and surface area of the cover generate a surface-normal force which below the resonance has (cooperating with the spring) the effect of a frequency-independent pressure-displacement-function. Above the resonance, the system is mass-inhibited and the pressure-displacement-function is proportional to $1/f^2$. Since for a ferromagnetic cover it is not the displacement but the velocity which determines the induction effect, an overall band-pass-shaped transmission results. The maximum voltage happens at the resonance of the cover. If that has low dampening (this seems to be the normal case for sheet metal), tremendous amplification factors (Q-factors) can appear. For non-magnetic metals a velocity-proportional eddy-voltage is generated which is transformed upwards according to the number of turns in the coil.

A simple experiment can help us estimate resonance frequency and Q-factor: given there is enough gain set in the amp, tapping on the pickup cover with a non-magnetic item (such as a pick) will generate a noise from the speaker. A short "tock" or "tuck" advantageously indicates a low resonance frequency and a strong dampening; less desirable is a higher pitched "bing", because it would stand for low-dampening and a resonance frequency in the 2 – 3 kHz-range: rather fatal since here also the pickup resonance resides.

Everything has at least two sides to it, though: such a pickup casing resonance may give a guitar a characteristic sound, as long as it does not (yet) lead to unwanted whistling. The guitarist may indeed have bought that specific guitar due to that specific sound. Moreover, since a pickup casing has 6 walls, there is a good probability that not just one but several resonances are in the game. Although designed to be of wondrous shielding quality, a pickup with a complete metal sheet surround may reveal undreamt-of sound qualities … again: only as long as the amp is not turned up too far. A wah-pedal in facts does something quite similar in that it creates a resonance emphasis (which can be altered with the pedal position). We have now arrived in an area where it is the turn of the "vintage guru": "the original PAF-pickups did not have potted coils so that the resonances and all that were much stronger, much more authentic; the harmonics could unfold much more freely. Everything breathes and sings, and is not as clean as the later high-tech-replicas behave." All bullshit? Well, there may be a grain of truth in there, or a grain of salt. Either way, about 3000 PAF pickups were installed on the '58 and '59 Les Paul's alone. They will not generally be without housing resonances, and among them there may well have been one with optimal structural resonances. Whether this is audible, remains speculation, plus: what is "optimal"? To be on the safe side, Gibson does today pot the '57 Classic Humbucker with wax. The BurstBucker, however, comes with "non-potted" coils; just like back-in-the-day without wax. In particular if wax gets between the coil bobbin and the metal cover, it can dampen resonances.

Speculations about the relevance of resonances in the pickup housing can find support or be rebutted to a fair extent by measurements. An experiment carried out in the anechoic chamber should give objective **transfer data**. Several different pickups were mounted 1 m in front of the mouth of a horn loudspeaker and the transfer coefficients were determined with the substitution method. A Brüel&Kjaer-microphone (4190) served as reference for the sound pressure level measurements. It became quickly apparent that the pickups did not only react to airborne sound but also to the electromagnetic fields originating from the speaker and the speaker cable. While this is certainly also a noteworthy characteristic, it was undesirable for the given experiment, and a grounded grid between speaker and pickup ensured that only the airborne sound had any substantial effect on the pickup.

Fig. 5.13.1 shows the free-field transfer factor of a select number of pickups. The smallest sensitivity to airborne sound is found in the G**ibson Toni Iommi**; obviously it was designed for high-gain applications i.e. strong overdrive. The whole pickup housing is potted with a hard material: there are practically no vibrations in the metal sheets. The Gibson '57 Classic proves to be already more sensitive and yields about 50 nV/Pa at 3,4 kHz; i.e. at 1 Pa sound pressure (= 94 dB_{SPL}) the pickup generates 50 nV. Without cover, that is! Putting a cover in place, we get – depending on the way the cover is fastened – a serious increase of the sensitivity to airborne sound.

The main resonance (1,35 kHz) depends strongly on the individual mounting. It is easy to imagine that over the decades almost every frequency had the honor of being the dominating pickup-housing resonance of a Les Paul – which raises the question about a pickup-housing main-resonance.

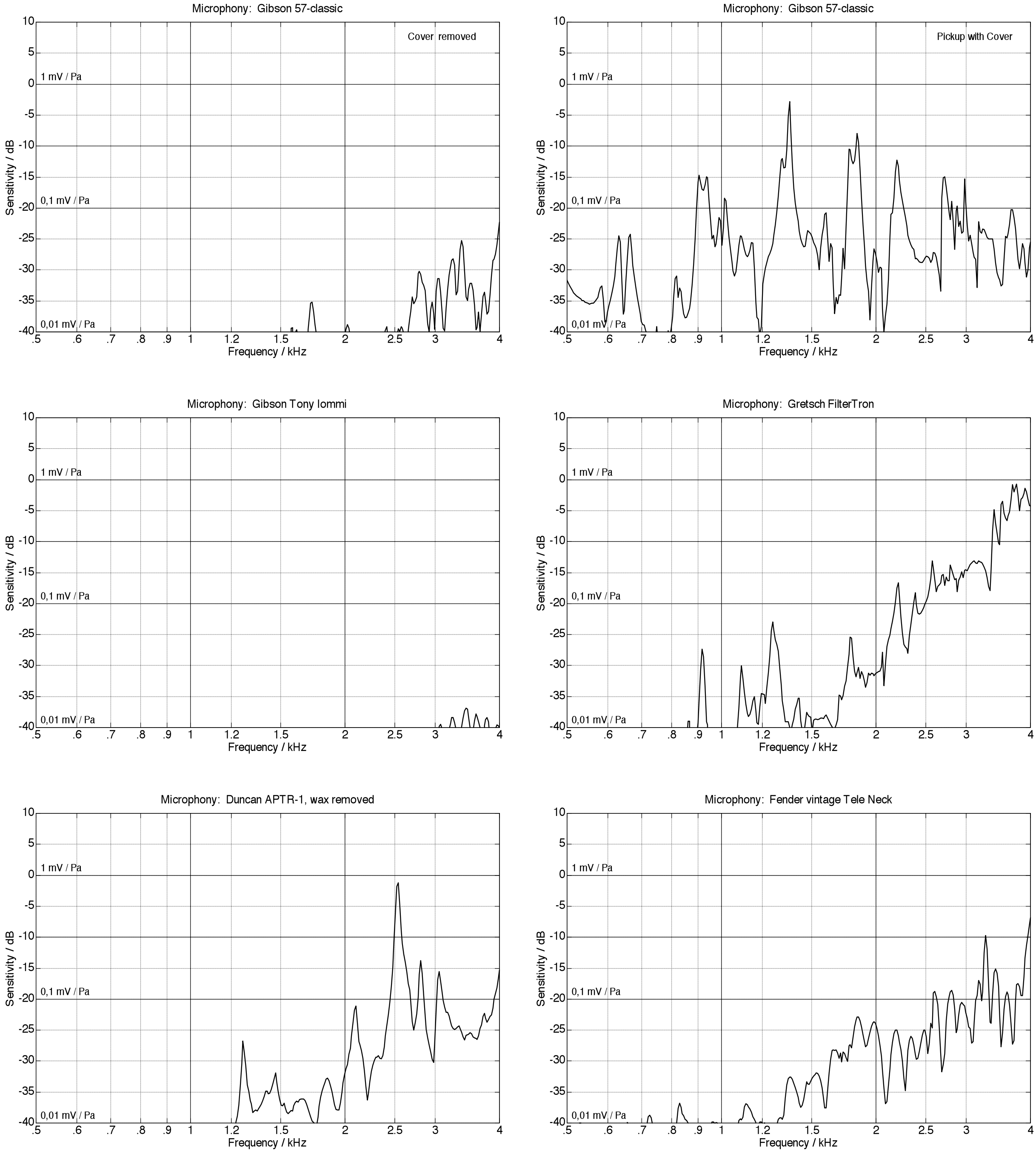
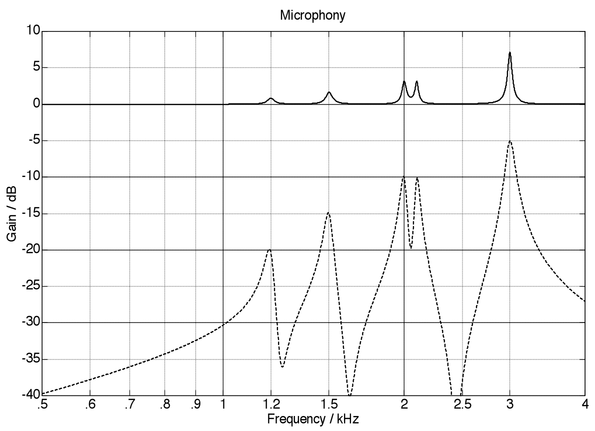


Fig. 5.13.1: Transfer factor for airborne sound (free field). The plots characterize individual pickups, with the inter-individual differences for pickups of the same type being considerable.

In normal operation and depending on string-material, action, and playing style, pickups generate induction voltages up to about **2 V**. Typical guitar loudspeakers are rated by their manufacturer at e.g. 100 dB (1W, 1m) which implies as a rough approximation SPL levels of e.g. 114 dB and a voltage of **10 mV** induced by the corresponding airborne sound. This voltage generated by airborne sound is therefore merely 1/200 of the voltages induced by the string vibrations. Still, it would be premature to conclude that resonances in the pickup housing are generally insignificant. Depending on the specific playing scenario entirely different relationships may arise. An opinion often expressed amongst guitar players is that “pickup-whistling” (i.e. unwanted pickup feedback) would be a problem only for guitar-amplification systems which generate very high SPL values: “In front of two Marshall stack it’s gotta whistle”. This is however not correct as such. The determining factor here is the **loop gain** i.e. the amplification-gain which signal is subjected to after having gone through the loop once: from the guitar through amp and speaker, and through the room (as airborne sound) back to the guitar.

Some numbers shall be given to exemplify: a guitar generates e.g. a voltage of 0,1V (due to the movement of the string) which is amplified to 2V by the amp. For the 8-Ω-speaker, this translates into 0,5W and results in an SPL of 97dB at a distance of 1m in front of the speaker. If this sound now hits the pickup, the latter will generate e.g. 1.4mV due to its sensitivity to airborne sound – in addition to the 0,1V mentioned above. The loop gain is 0,014 and thus substantially smaller than 1. The guitarist may now turn up the amp, either to get more loudness or to obtain more distortion, or he/she may add frequency-selective additional amplification with tone controls or an equalizer. The loop gain will increase and approach 1; in fact it may easily exceed 1. This is when pickup-feedback (i.e. whistling) occurs. Looking at the system very theoretically, an additional special phase condition would also need to be met, but that is always possible because of the manifold sound paths in regular room.

The sensitivity of the pickup to airborne sound will become apparent as sound coloration already at a gain which does not generate feedback. One can look at this as if there was, on top of the desired signal path, a signal decoupling into an additional effects channel. As there is a sufficient level in that effects channel, changes in sound will become audible. A model including a forward signal loop (sound pressure results in a voltage, $\underline{H}_{\mathrm{Up}}$) and a feedback path (voltage results in sound pressure, $\underline{H}_{\mathrm{pU}}$) is shown in **Fig. 5.13.2**). The feedback path contains 5 places of resonance (dotted line); in the curve on top we see the consequences on the overall frequency response. For a maximum loop gain of 0,1 ($\hat{=}$ –20 dB) there will be no audible effect; however, for a loop attenuation of merely 5 dB (corresponding to a loop gain of -5 dB) pronounced effects will appear. It is not possible to generally determine how clearly the resonance will bear down in the specific case, because sufficient signal energy needs to be present in the respective frequency band – and more room remains again for speculation.



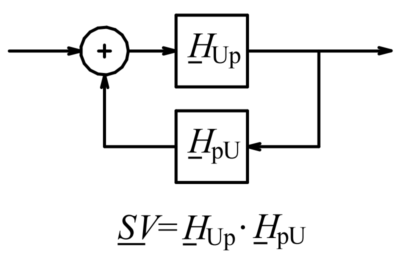


Fig. 5.13.2: Model of a signal loop and consequences of resonances on the overall transmission. The loop gain $\underline{SV}$ is the product of the forward- and the feedback-amplification.

In order to obtain at least some very rough data under regular operational conditions, a guitar amplifier (**VOX AD-60-VT**) was analyzed in the anechoic chamber. A guitarist had set the control such that, with a Les Paul (Historic Collection), a "slightly distorted, crunchy sound" resulted. All effects incorporated in the amp were switched off. A measurement microphone (B&K 4190) was positioned 1 m in front of the loudspeaker incorporated in the amp and captured the sound resulting from a signal of 1 mV_{eff} fed into the input "High" (**Fig. 5.13.3**). A sound pressure level of just 1 Pa (94 dB) was generated at 2,5 kHz; the voltage gain was about 500 (54 dB). Voltage-to-SPL transfer coefficient was H_{pU} = **1 Pa/mV** at this frequency. In combination with the Duncan APTR-1 described in Fig. 5.13.1 the condition for an oscillation ($H_{Up} \cdot H_{Pu} = 1$) would already be almost met – the 2,5-kHz-spike of this pickup almost reaches H_{Up} = 1 mV/Pa. To be fair, we need to remember again that all the wax with which the potting was done had been removed. With the wax in place the sensitivity to airborne sound would be less.

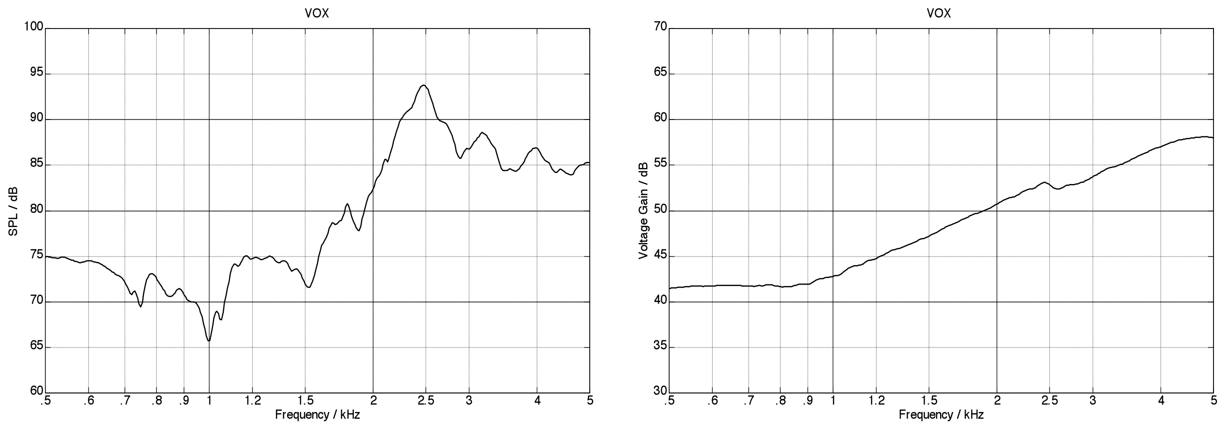


Fig. 5.13.3: SPL generated at 1 m distance for 1 mV input (left); gain factor up to the loudspeaker (right).

The sensitivity to airborne sound of the Les Paul guitar mentioned above was also determined in the anechoic chamber; see **Fig. 5.13.4**. All strings were removed and the guitar was positioned in 1 m distance in front of a horn loudspeaker. The guitar was loaded with 670 pF (cable) and 1 MΩ and all control set to "10". For the somewhat more sensitive bridge-pickup (**Gibson BurstBucker #2**), we found a maximum sensitivity to airborne sound of just short of 0,1 mV/Pa. The neck pickup was loess sensitive by 5 dB. Unwanted feedback will not appear under this condition since the smallest loop attenuation is 27 dB. For the same reasons, any influence on the sound is not to be expected, either! (Compare to Fig. 5.13.2)

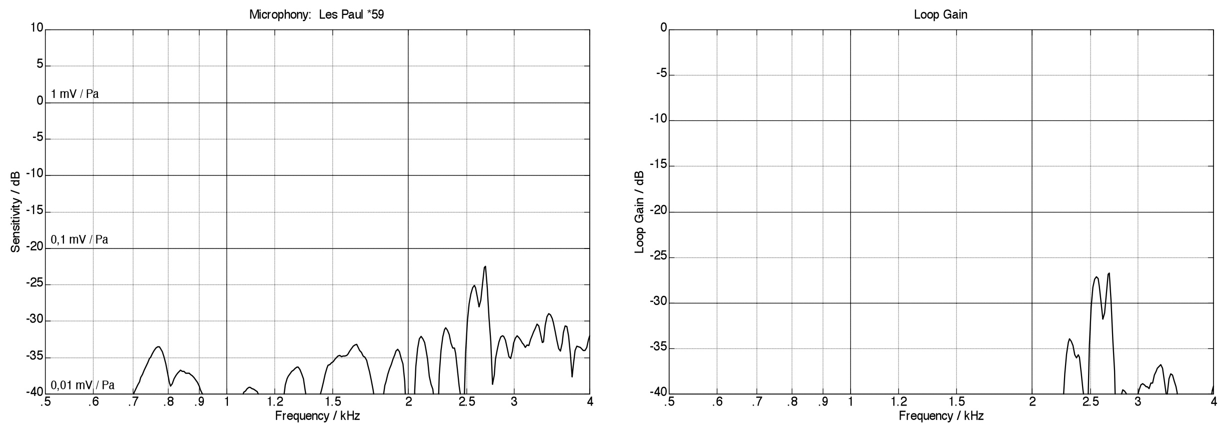


Fig. 5.13.4: Gibson Les Paul '59: Transfer factor for airborne sound (left), loop gain factor (right).

As the gain is increased by 6 dB (relative to Fig. 5.13.3), a much more distorted guitar sound is already generated for normal playing – well usable for *lead-Sounds a la Beano Blues-Breaker*♣. The maximum loop attenuation is 21 dB and thus still well in the green. Not unless all three volume controls (gain, volume, master) of the VOX amp are maxed out (introducing an additional 26 dB of gain), the setup generates nothing but piercing whistling noises. Under this condition it makes moreover no difference where the guitar is positioned in the room relative to the amp – it remains "mission impossible". The guitar would have to be removed from the room, or the pickup selector switched to the neck pickup – the slightly less sensitivity to airborne sound of that pickup♦ enables the guitarist to find a few positions which are not subject to feedback. From the point of view of the conservative musician the resulting messy sound is not actually desirable. Although: only now – so the control engineering approach says – do the resonances of pickup-housing have an effect on the overall frequency response.

From the carried-out experiments the following results can be derived:

1) A metal pickup housing with well-done dampening has little resonances and does not change the pickup transfer characteristic in the case of distortion-free reproduction (clean sound, stage volume) at all. (here we are not considering that a cover may cause eddy-current-dampening → Chapter. 5.9.2.2). Even at "normal distortion" there are no effects on the sound. At extreme gain-settings (ultra-distortion) some effects are conceivable – however: an entirely distorted guitar sound is not really the right condition to be able to discern subtle sound differences.

2) Pickup covers with weakly dampened resonances may have a sound-altering effect, depending on the amplification. However, going on stage with such a caterwauler is a bit of a ride on a cannonball: you never know at which point things will go sideways. If the loop attenuation is high enough, you won't hear any difference, there will be no effect of the housing resonances, but as they become audible, the limit towards uncontrollable pickup feedback is just a hair away, as well. This is of double (or triple) validity for thinline and full-bodied electric guitars: their sensitivity to airborne sound is even larger than that of a badly dampened pickup. Now, there are guitarists who are looking exactly for this borderline situation, and some have even reached true mastery in that battle with the unbridled resonance-power. So if a special guitar is said to have that very special unique sound drawing upon the pickup housing resonances: impossible it is not from the point of view of physics. With the single exception of the Gibson Toni Iommi, all the potted pickups examined in the framework of this book showed – upon opening them up – a interior distribution of the wax of … shall we say (to remain safe from the attorney assault): the wax distribution was following artistic considerations. As such, every guitar again is a unique specimen. But we already knew that, didn't we … even without the whole physics shebang.

What remains is a matter of faith. *Thesis: "The pickup covers, as well, add a material-specific resonance to the sound. If you love that throaty and nasal PAF-sound (a la Allman Brothers or even Peter Green), you should absolutely use covers on the pickups"* [U. Pipper, Gitarre & Bass, 9/2005]. That's one way to look at it. *Anti-thesis: "You may have heard that I remove the covers from my pickups; the improvement in the sound is unbelievable"* [Eric Clapton, in Bacon/Day]. That's the other side of the faith.

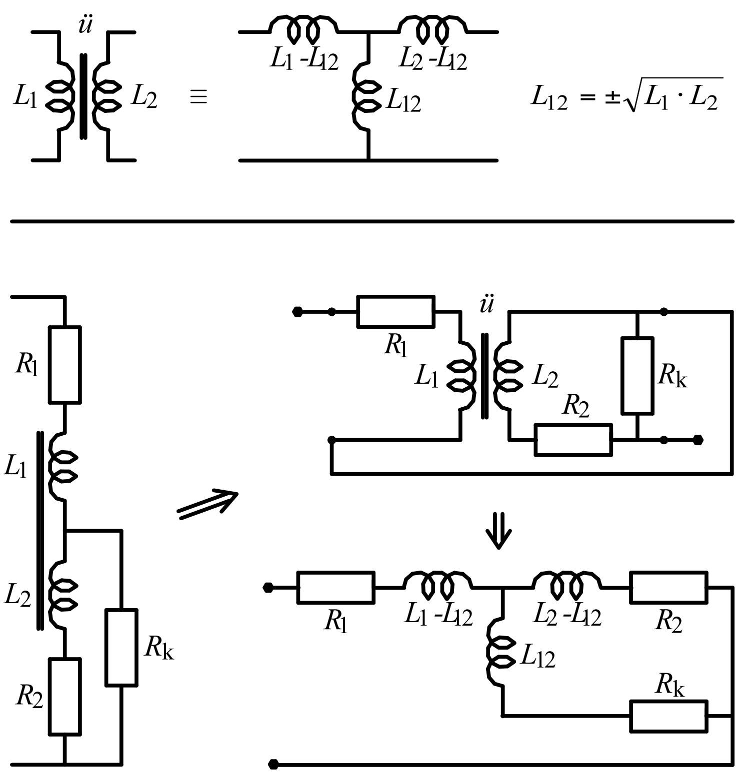
♣ Back in the day, the original setup included a Marshall combo amp.
♦ All these statements relate to one specific individual guitar.

5.14 Pickups with shorts in the coil-winding

The coil of a magnetic pickup is made of very thin copper wire carrying an even thinner layer of varnish for insulation. The insulation resistance of the varnish would still be sufficiently high with a thickness as small as 4 µm, but to keep the insulation layer undamaged is somewhat of a challenge. This was especially true in the old days when the magnet wire was often directly wound onto the magnet rods and it could happen that the insulating layer was abraded and shorts were introduced. Moreover, some of the insulating varnishes used back then became brittle over the decades and came loose from the copper. It is also conceivable that already the application of the varnish sometimes was sub-par or even faulty. Last, if the quality control was done merely using an ohmmeter with a tolerance of 20% [Duchossoir, Strat], much room remains for undetected shorted turns in the coils.

How does the transfer behavior of a pickup change it one or several windings are shorted out? If indeed merely *a single* winding is shorted, the effects are negligible, but in case a wire establishes contact to the next whole layer of the winding (or even the layer beyond that) we would be confronted with a possibly substantial defect. It shows some naïveté if a pickup manufacturer still writes in the year 2011 that it's ok if a few hundred of 8000 turns of a pickup are shorted out: indeed a few percent change in the DC resistance may be insignificant, but the pickup operation is based on AC. And with AC a short in the winding brings with it a resistive load and therefore a treble-loss.

It is purposeful to interpret a partially shorted inductance as a transformer (**Fig. 5.14.1**). Of the N turns of the winding, n are shorted; they N-n non-shorted turns form the primary inductance L_1, while the remaining (shorted) n turns form the secondary inductance L_2.



$R = R_1 + R_2$; $R_2 = R \cdot n/N$;
$L_2 = L \cdot (n/N)^2$;
$L_1 = L \cdot (1 - n/N)^2$;
$L_{12} = -\sqrt{L_1 \cdot L_2}$:

$R_k = 0$ yields an input impedance $\underline{Z}$ of:

$$\underline{Z} = \frac{R_1 R_2 + p(R_1 L_2 + R_2 L_1)}{R_2 + pL_1}$$

Fig. 5.14.1: T-equivalent circuit diagram of the transformer with hard coupling (top); ECD with short in the winding (bottom)

The copper-resistance (DC-resistance) of the full winding is R. R_1 belongs to the primary winding and R_2 to the secondary winding. The resistance occurring between two turns (the short resistance) is R_k. For a perfect short, R_k will be zero, but in the general model we will assume an arbitrary value. A hard-coupled transformer without flux leakage can be described by its T-equivalent-circuit-diagram, with L_{12} being the **mutual inductance**. The latter is positive for a concordant coupling, and negative for a inverse coupling. Interpreting the shorted inductance as transformer leads to a inverse coupling: L_{12} is negative.

From the ECD shown in Fig. 5.14.1 we can calculate the pickup impedance $\underline{Z}$. For an ideal short (R_k = 0) it may be simplified to the given formula. The DC-situation (f = 0) yields $\underline{Z} = R_1$; however, towards high frequencies ($f \rightarrow \infty$), $\underline{Z}$ does not remain inductive but converges to a real final value. With a further simplification (for $n << N$) we get $R{\cdot}N/n$ for this final high-frequency end value. If e.g. 4% of a pickup winding is shorted, the end-value is 25 x R (i.e. 25 x 6 kΩ = 150 kΩ for a typical Strat pickup). This only seems like a sufficiently high resistance – for a capacitive load, the effect is substantial and the resonance emphasis drops strongly (**Fig. 5.14.2**). As a consequence of the reduced Q-factor (compare to Chapter 5.9.3) the resonance emphasis of the transfer function goes down, as well. This is depicted in **Fig. 5.14.3** with a Stratocaster pickup serving for the example. A short across 2 layers of winding is approximately equal to n = 280; the corresponding loss in brilliance is not negligible anymore.

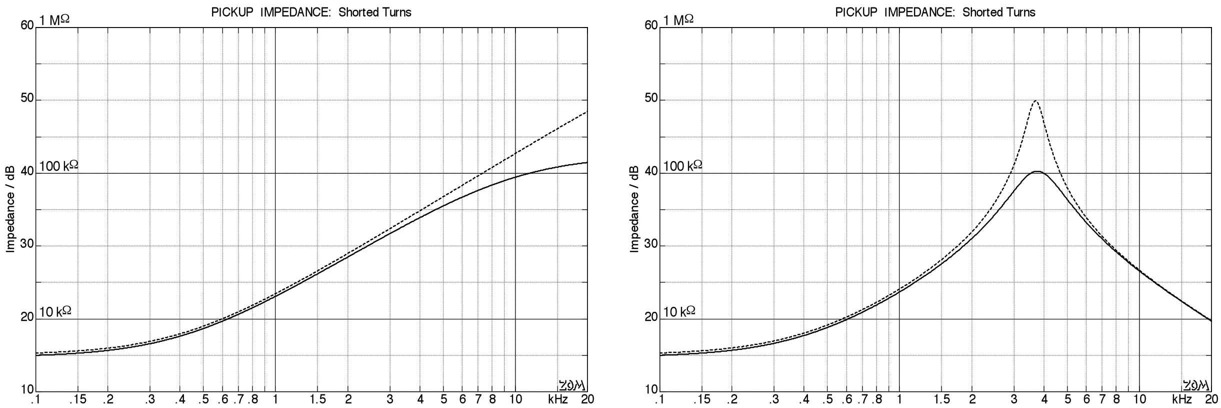


Fig. 5.14.2: Short in the winding. Left: without parallel capacitance; right: with parallel capacitance (850 pF). Stratocaster-Pickup: R = 5700 Ω, L = 2.2 H, N = 7600, n = 280. Without (----) and with (——) short.

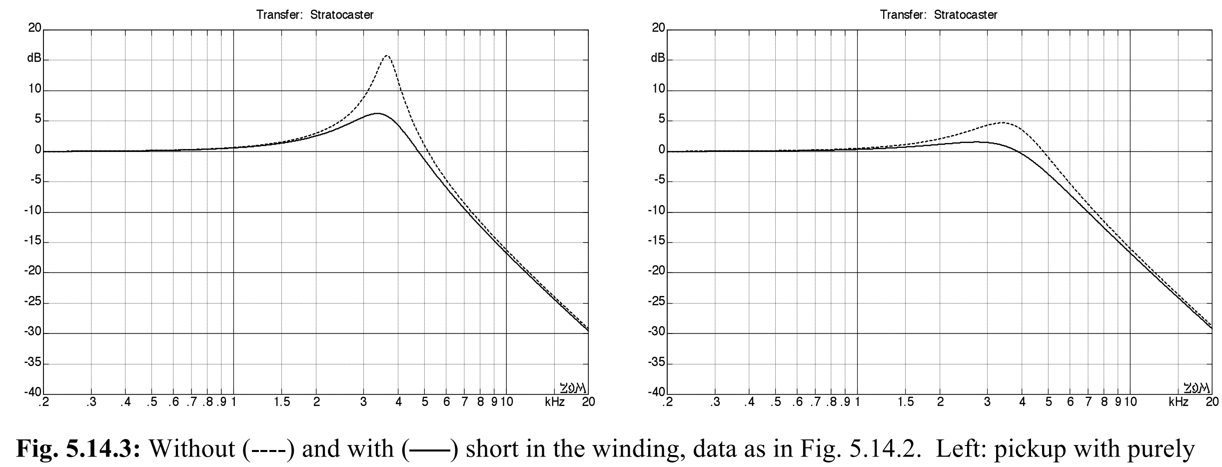


Fig. 5.14.3: Without (----) and with (——) short in the winding, data as in Fig. 5.14.2. Left: pickup with purely capacitive load (850 pF), right: 110 kΩ load resistance added (potentiometers + amp).

So. More than 160 pages about magnetic pickups – quite a heavy load. To conclude, let's bring in a goodie for those who persevered (no, not that Thorben-guy, he was not available – and he's had it, anyway). But we have Mr. **Chris Kinman**, well-known pickup manufacturer. He had some news for his followers published on his website around Christmas in 2010 which we may look into here:

Chris K. was repairing two '64 Strat pickups both of which had succumbed to broken coil wiring. For one of the two, the fracture had occurred right on the outside of the pickup; so that one is dealt with easily but the other's gonna be a lot of work: it has to be rewound entirely. Some original wire (i.e. the real Voodoo-stuff) was brought in, the rewinding done … however the two pickups sounded differently. That remained the case even after the magnets had been re-magnetized. Writes Chris: *"This experiment exploded the myth that aged magnets were the reason for this massive difference in sound. Another well known pickup manufacturer claims weaker magnets are the reason that old pickups sound sweet, but I can not confirm that claim when I deliberately degauss magnets."* Well, he's right on target: magnets do not age (he could have read up on that in Chapter 4, by the way). That **vintage sound** must still have some reason, though, and here it comes: *"It turns out that Formvar insulation is not age stable, it's an unsophisticated old technology coating that degrades over time, unlike modern Polyurethane coatings which seem to go on forever. ... So there you have conclusive scientific proof for aging of old Fender pickups, Formvar wire degrades in time. It definitely is not due to aging of magnets."* The "scientific proof" then uncharitably hides behind an impedance plot which indicates at the resonance frequency (3,2 kHz) a maximum value of merely 41.25 kΩ♣, but even given this there are still differences between the two pickups: the *"1964 original Strat pickup that has aged excessively"* indeed shows only 36 kOhm at the most. Approximately, that is – since the 4,46 kΩ per scale-division chosen by Chris K. makes it difficult to interpolate. Anyway, the older the pickup, the smaller the Q-factor will get because the aging insulating varnish encourages shorts in the winding. With the decreasing Q the *"ice-pick brittleness"* goes away and the aged sound (***<u>less treble</u>***) is in reach. That sound is – according to Chris K. – simply due to shorts in the coil winding. Conclusion: anybody who would like to play a 1954 Strat but would rather invest money in old Aston Martins does not really have a problem. Just buy a new Strat, turn down the "Tone" control a bit: voila – aged sound. However: it is now psychologically prohibitive to ever again read music "trade journals" because there the investor may find the statement that the old Strats have an unequalled brilliant sound (***<u>more treble</u>***).

Good advice? You are very welcome. As a return service, someone could pay a visit to Chris Kinman and show him how correct impedance measurements are done. Having said that, he actually deserves much credit because he does make the effort and takes some decent instrumentation to the pickups. Many manufacturer seem not to do even that …

♣ With a purely capacitive load, that should be (without the potentiometers) about 300 kΩ sein, and with the pots still about 88 kΩ.

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