5.6 Instruments for measurements on pickups

How do I measure an electric pickup parameter? In most cases presumably with an instrument the inner workings of which are not really known to the user. A popular choice is the so-called RLC-instruments able to meter R (resistance), L (inductance) and C (capacitance). If the pickup were an ideal basic two-terminal network, there would be no objections against this approach. Basic two-terminal networks consist either of an ohmic resistor, or of an ideal inductor, or of an ideal capacitor. In a pickup, however, all three of these elements operate in conjunction – the pickup thus is a composite two-terminal network.

In the simplest case the pickup impedance is modeled via an electrical resistor R connected in series to the inductance L of the winding, with the capacitance of the winding connected in parallel to this series connection. The resistor R is the DC-resistance of the wound copper wire as was already described above – it is also called copper resistance. As has been elaborated in the chapter *Magnetodynamics*, the *DC*-resistance of an ideal inductor is zero; the *DC*-resistance of an ideal capacitor is infinite. Indeed, at $f = 0$ Hz only the value of R remains, since the other two components in the network do not contribute anything at this frequency. Consequently, if R is to be measured, this should be done at 0 Hz – kind of obvious, isn't it. However, RLC-instruments do not work at 0 Hz but at other frequencies, e.g. at 1 kHz. They will determine the real part of the complex impedance $\underline{Z}$ – which may well be different from the copper resistance.

The formal description of the impedance works best with the aid of the complex notation [see e.g. 18, 20]. The **complex impedance** $\underline{Z}$ of an *RL*-series-connection (i.e. to begin with without the capacitance C) is:

$$\underline{Z} = R + j\omega L \qquad \mathrm{Re}(\underline{Z}) = R; \qquad \mathrm{Im}(\underline{Z}) = \omega L;$$

Complex impedance

The real part of the complex impedance is R, the imaginary part is ωL (the imaginary unit j is not a section of the imaginary part!). As evident, the real part is independent of the frequency and can – *for this specific two-terminal network* (!) – measured at any frequency. As soon as the capacitance is connected, however, this situation changes: the capacitance C is, in the simple equivalent circuit, connected in parallel to the *RL* series circuit. The complex impedance $\underline{Z}$ of this *RLC* is calculated as:

$$\underline{Z} = \frac{R + pL}{1 + pRC + p^2 LC} = \frac{R + p(L - R^2 C) + p^3 L^2 C}{1 + p^2(2LC - R^2C^2) + p^4 L^2 C^2} \qquad p = j\omega$$

Breaking down this complex impedance as a sum of a real part and an imaginary part yields a value which an RLC-instrument will show as loss-resistance if a coil is to be measured:

$$\mathrm{Re}(\underline{Z}) = \frac{R}{1 - \omega^2(2LC - R^2C^2) + \omega^4 L^2 C^2}$$

real part of the *RLC*-circuit

This real part is not constant anymore but dependent on the frequency! For DC i.e. at $\omega = 0$, the correct DC-resistance R is still the result, however for every other frequency a diverging and thus incorrect value is measured.

These deviations are not always dramatic – BUT they should be looked against the background that an "expert" for example *has* to know that the Texas-Special-Pickup sports 6210 Ohm whereas the 'Vintage Reissue Pickup" throws *a mere* 6100 Ohm (i.e. a full 1,8% less!) into the ring. Incidentally, the expert hopefully is also aware of the fact that the same 1,8% resistance change can also be caused by a temperature change of as little as 4,5°C ☺. How large the differences can be due to the instrumentation is shown by **Fig. 5.6.1**: using an RLC-Instrument working with 1000 Hz to measure the Stratocaster-coil-resistance will give a value which is too large by 6%. Which amounts to about the difference between a '80s-Standard-Pickup' and a 'Late-60s-Pickup. At the same temperature …..

Pickups with a relatively low resonance frequency (e.g. Gibson P90), on the other hand, show significantly larger deviations (Fig. 5.6.1). Connecting a cable changes the real part, as well, even if the **cable** is defined as ideal capacitance having exclusively an imaginary effect (in the sense of the imaginary notation system ☺). For the P90 pickup, the addition of a cable of 600 pF has the effect that at 1 kHz the real part of the impedance increases by 40%.

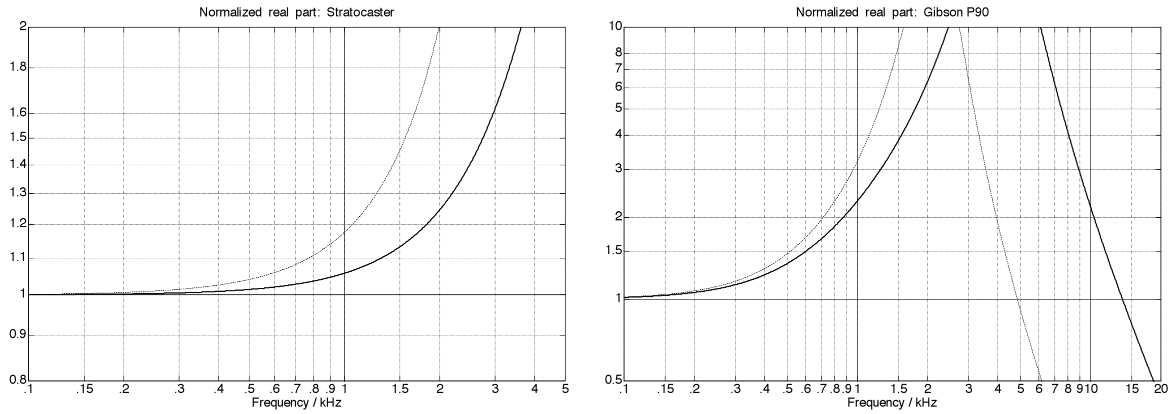
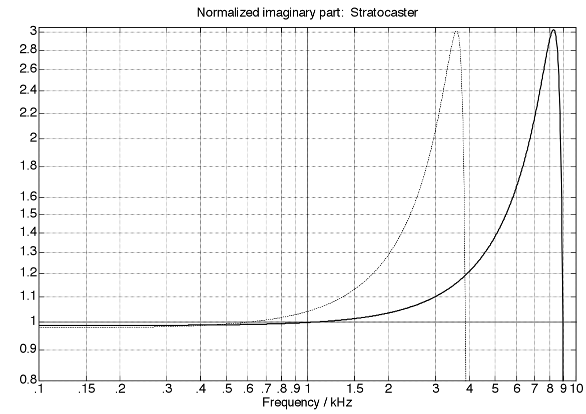


Abb. 5.6.1: Real part of the pickup impedance referenced to R_{Cu}. Left: Stratocaster, right Gibson P90. At f = 1000Hz the real part (without cable) diverges by 6% respectively 130% from the 0-Hz-value (———). Narrow lines: with 600-pF-cable. To clarify at which frequency the impedance meter is operating, the measuring frequency can be checked e.g. via an oscilloscope during the measurement.

Besides the DC resistance R, the **inductivity** L is the second important electrical parameter. If only R and L were cooperating in a pickup, we could measure L without any issue as imaginary part of the impedance – at any frequency except 0 Hz. However, the capacitance connected in parallel has the effect that below the resonance frequency the normalized imaginary part rises; above the resonance frequency it even becomes negative. An RLC-instrument, which displays in the "coil measurement" setting merely the imaginary part of the impedance divided by $2\pi f$, will follow the curve shown in **Fig. 5.6.2**. Up to 1000 Hz the deviations for the Stratocaster pickup are actually not too significant yet; for higher frequencies, the error keeps mounting – as it does for pickups with lower resonance frequency.

The real problem with inductance measurements starts if the pickup impedance should be described by more than one inductivity. As we will see in the chapter about equivalent circuits, this comes into play especially if eddy-current losses can not be ignored, i.e. for pickups with slugs made of soft iron or nickel, and/or with metal covers. In complete analogy, a mechanical system including 3 independent masses connected via 2 independent springs could not be characterized for oscillations of every frequency by one and the same spring stiffness, either.



Imaginary part of the impedance of the *RLC*-circuit:

$$\mathrm{Im}(\underline{Z}) = \frac{\omega(L - R^2C) - \omega^3 L^2 C}{1 - \omega^2(2LC - R^2C^2) + \omega^4 L^2 C^2}$$

Fig. 5.6.2: Imaginary part of the pickup impedance (Stratocaster), referenced to *ωL*.
Thin line = 600-pF-cable added.

In such a case a possible way would be to first define a suitable **equivalent circuit**, and then to determine the element values in this equivalent circuit via measurements. RLC-meters in fact use the same approach, and in some cases even include options: to measure a coil two equivalent circuits are offered – an *RL*-series circuit and an *RL*-parallel circuit. These two are however not compatible. For example, the series connection of a 6861-Ω-resistor and a 2-H-coil may be described at 1 kHz by an equivalent parallel circuit of a 30-kΩ-resistor and a 2,6-H-coil. The equivalence is valid only for 1 kHz; at every other frequency different values will result for the elements. Both the *RL*-series circuit and the *RL*-parallel circuit are moreover too simple for a pickup; suitable equivalent circuits should at least include a capacitance (see also the chapter on equivalent circuits).

As an alternative to measuring the inductivity with an RLC-meter it is possible to draw the frequency response of the amount of the impedance in a double-logarithmic representation. Since the impedance is dependent on the frequency according to a power function, curves result which – in sections – can be approximated by straight lines. Or so the theory according to Bode says. However, this only holds for simple networks such as an *RL*-series circuit (**Fig. 5.6.3**). Or so the author says.

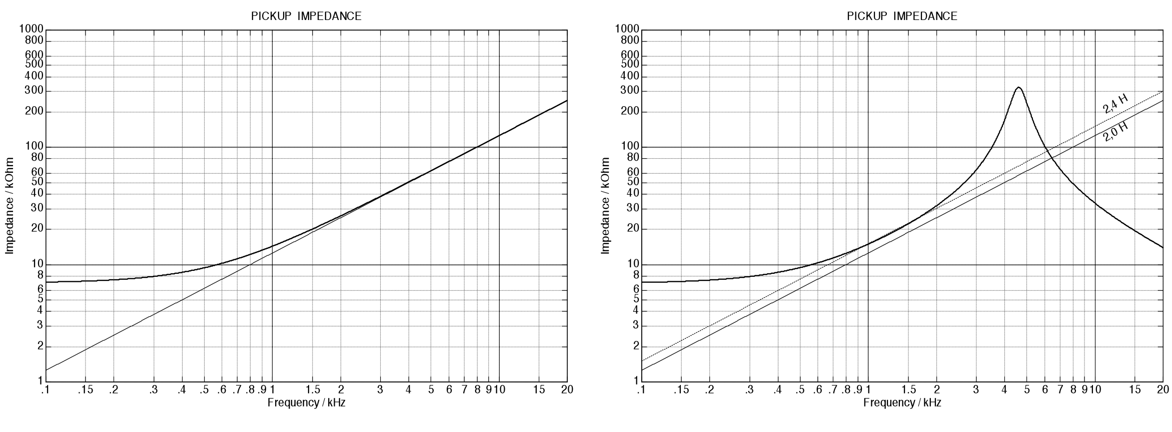


Fig. 5.6.3: Amount of the impedance of an *RL* series circuit (left), and of a *RLCR-equivalent circuit* (right).

Plotted in the left part of **Fig. 5.6.3** is the amount of the impedance frequency response of an *RL*-series connection (R = 7 kΩ, L = 2 H). The curve approximates towards low frequencies a horizontal straight line Z = 7kΩ), whereas towards high frequencies we get an increase according to the slanted straight ($Z = 2\pi f L$). The inductivity L can be determined graphically from this measurement by shifting the approximative straight line to best match the curve. The proportionality coefficient L is the inductivity.

However, as soon as a capacitance C (600 pF) and a dampening resistor R_p (1 MΩ) are also included, this high-frequency approximation is not possible any more (Fig. 5.6.3 left). One can try the approximation at medium frequencies (e.g. at 1,5 kHz) but this will result in a inductivity result which is 20% too large. In fact, that would not be a dramatic error but it all depends on the desired measurement accuracy. DUCHOSSOIR specifies the following, for example: *Late-60s-Strat*: 2,2 H, *Vintage-Reissue*: 2,3 H, *1980s-Standard*: 2,37 H, *Texas-Special-Neck*: 2,47 H, *Texas-Special-Middle*: 2,50 H. If indeed such small differences (as far as they are of any significance to begin with) are to be determined, 20% tolerance would be unacceptable. As a precaution it is noted here that determining the intersection point with the straight line dropping off at high frequencies (due to capacitances) brings an improvement only in theory: in practice there are parasitic disruptive effects which falsify the theoretically expected $1/f$-drop-off.

Measuring the **pickup quality factor** Q with an RLC-Meter is even more misleading that the measurement of R and L. What is actually measured here is the coil quality ($Q_L = 2\pi fL/R$) and thus a frequency dependent parameter. DUCHOSSOIR assumes, in his books on the Fender Stratocaster and Telecaster, relatively arbitrarily f = 1000 Hz. He notes: *a pickup with a higher Q emphasizes a narrower frequency band, and vice versa a pickup with a smaller Q emphasizes a wider frequency band.* This clarification would hold if Q were meant to be the resonance quality factor, however, DUCHOSSOIR does not list resonance quality factors, but the coil quality. The influence of the latter on the resonance emphasis cannot be described by a simple function. Fig. 5.5.9 shows how changes in the coil quality have only small effects on the resonance emphasis. If on the other hand both R and L are changed similarly, e.g. both by 50%, Q_L remains constant but the resonance emphasis drops by about 2 dB on the Stratocaster.

As a closing example a pickup from a **Gretsch** Tennessean is investigated. Its DC-resistance amounts to 3260 Ω, however taking an impedance measurement at 1 kHz yields 7155 Ω in series with 1,2 H. An equivalent circuit built from these two components indeed shows the same impedance at 1 kHz (**Fig. 5.6.4**) but behaves much differently at other frequencies.

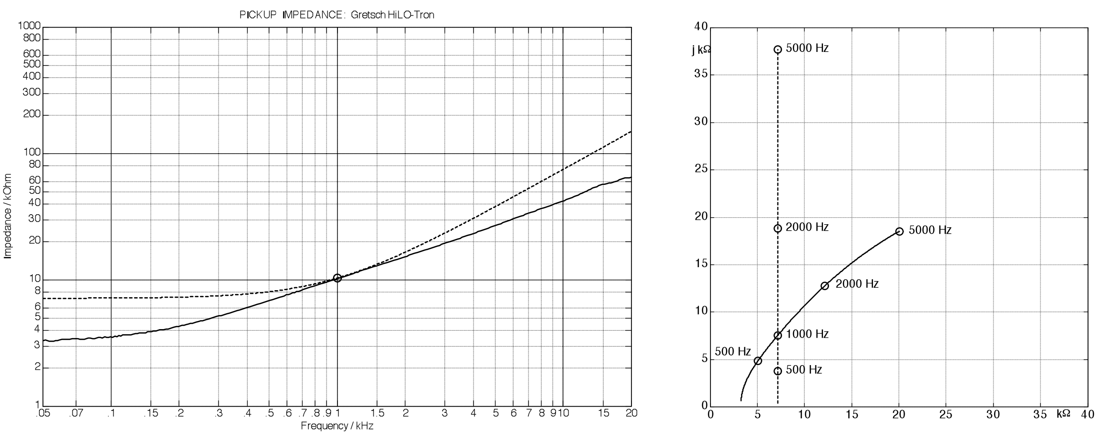


Fig. 5.6.4: Measured impedance amount of a Gretsch pickup (——). A RL-meter operating at 1000 Hz measuring frequency shows 7155 Ω and 1,2 H. Measuring such an RL-series circuit (-----) reveal, however, major differences. The right figure depicts the impedance locus (50 – 5000 Hz). The reason for these considerable deviations is the strong eddy current dampening of this special pickup.