10.1.2 Tube input-impedance

Together with the cable capacitance, the input impedance of a guitar amplifier is connected in parallel with the source impedance of the guitar pickup. Looked at in a simplified manner, the amplifier input may be represented by a high-value resistor: for guitar amps about 1 MΩ is customary. The resulting damping effect on the pickup-signal is small. If, however, the input impedance of the amp is significantly lower, an audible damping effect does happen that makes itself felt (or rather heard) as a loss in brilliance. Entirely different scenarios may occur with effects boxes (e.g. treble booster, distortion device, or wah-wah) connected between guitar and amp. Their input impedance often is rather low but this needs to be seen as part of the effect.

Aside from the regular standard input (designated "1" or "Hi"), many classic tube amps offer a second input of lower sensitivity ("2" or "Low"). Due to the smaller input impedance (typically 136 kΩ), this second input makes the guitar sound less brilliant. Also, a 50%-signal-attenuation involving a voltage divider with two 68-kΩ-resistors is included, reducing down preamplifier distortion. When the **standard input** ("1") is used, the two 68-kΩ-resistors are connected in parallel with each other, and in series with the tube input. They have the effect of a low-pass filter that however only cuts out high-frequency radio transmissions – in the audible range, the low-pass effect is insignificant.

The **input capacitance** of customary guitar amplifiers is small but not always negligible compared to the cable capacitance. For a tube amplifier, the input capacitance of the preamp-triode will be around 80 – 150 pF due to the **Miller-effect**. Depending on the wiring within the amp, further line capacitances of about 50 pF may need to be added. With the standard input-circuitry for tube amps, the guitar is galvanically coupled to the grid of the first tube – there is no coupling capacitor. Only few amps (in particular very old ones) generate the grid bias via the leakage current of the grid, and therefore separate guitar and tube via a coupling-capacitor of 10 – 20 nF. The effect of this capacitor is negligible in the framework of the linear model – the operating point of the tube in this configuration is, however, not very stable at all.

The tube grid is connected neither to the plate nor to the cathode, and since the glass container insulates very well, we could indeed surmise a tube input of very high impedance. However, while plate and cathode are not connected, there is still an electric current flowing between them. This is due to the glowing cathode emitting electrons that fly – through the vacuum in the glass container – to the positively charged plate. A flow of electron is an electrical current: negative charges flowing from the cathode to the plate make (applying the technical current direction) for a positive current from plate to cathode. The electrons travelling from the cathode land on the plate and not on the grid because the plate is charged positively relative to the cathode, and the grid negatively – for the customary **operating point**, anyway. A cathode-current of e.g. 0,8 mA (Fig. 10.1.1) flows in the absence of an input signal, and with this the grid-potential is 1,2 V more negative than the cathode-voltage. However, in the case that the grid becomes positive relative to the cathode, the electrons find two attractive landing sites: the highly positive plate and the weakly positive grid. Since the plate-surface is much larger than the grid-surface, and since the plate-voltage is much higher than the grid-voltage, most of the electrons will fly to the plate. However, a small part of them does land on the grid and causes a **grid-current**. This grid-current exits the grid as a negative electron flow, i.e. it enters the grid as technical current.

There are several reasons for the **flow of this grid-current**: finite insulation resistances grid/plate and grid/cathode, ionization of the remaining gas in the glass container (deficient vacuum), thermal grid-emission due to high grid-temperature, and the already mentioned pickup of a part of the electron cloud emitted by the cathode. The individual effects superimpose (in part with inverse signs) and result in a non-linear input characteristic; the grid-current depends on the grid/cathode-voltage U_{gk} in a non-linear fashion. For input voltages[♣] U_e of above about +0,7 V ($U_{gk} > -0,5$ V) there will be an observable grid-current leading to a voltage across the grid-resistor R_g. Consequently, the grid-voltage U_g decreases. This effect makes itself felt especially for strongly positive input voltages: for example, we may find only about +1,2 V instead of +4 V at the grid (**Fig. 10.1.2**).

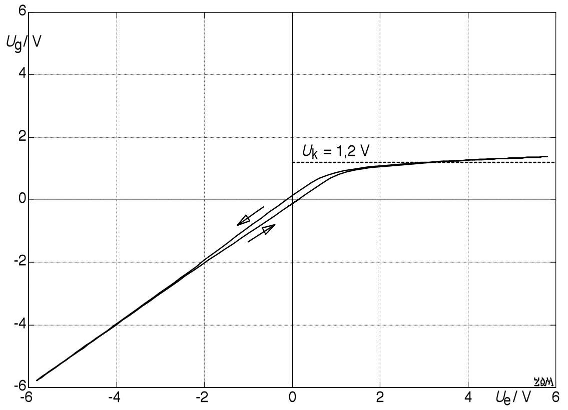

Fig. 10.1.2: Non-linear correspondence between input voltage U_e, grid-voltage U_g, and grid-current I_g.

Measurements of real tube voltages and tube currents show a hysteresis caused by capacitive coupling between plate and grid. Within the tube, the grid/plate-capacitance (about 1,6 pF) has an effect, and external stray-capacitances depending on the build of the circuitry weigh in. In conjunction with the grid-resistor, a low-pass in the feedback branch is created, i.e. the plate-voltage is (approximately) differentiated and the result superimposed onto the generator voltage. Since the plate-voltage is strongly limited for the drive signal shown in the figure (Chapter 10.1.3), this feedback becomes effective predominantly close to zero. Idealized characteristics are shown in **Fig. 10.1.3**: U_{gk} is the voltage between grid and cathode i.e. the actual control voltage of the tube. For the example it amounts to about -1,2 V in the operating point (i.e. without drive signal).

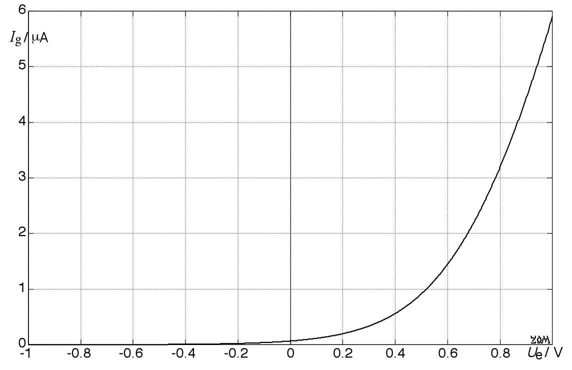

Fig. 10.1.3: Grid-current depending on the input voltage (or on the grid/cathode-voltage).
The right-hand picture shows measurements (----) in addition to the idealized curve.

[♣] U_e between input and ground, U_g between grid and ground, U_{gk} between grid and cathode.

In order to assess the non-linear behavior, it is of course the magnitude to the actual input voltage that needs to be considered. If this were no larger than 100 mV, we could ignore the non-linearity. However, normal magnetic pickups can easily generate voltages in excess of 0,5 V, and even 4 V is not unheard of – therefore the non-linearity merits a discussion. The distribution function of the occurrence of pickup voltages is shown in **Fig. 10.1.4**. It may be nicely described by a Laplace-distribution (just like speech): the larger the amount of the pickup voltage, the less frequent it occurs♣. “Loud” pickups (Chapter 5.4), heavy strings and a strong picking attack may generate considerable voltages. The distribution function of this special example shows that 95% of all voltage values are smaller than 1 V, and 98% are smaller than 2 V. The relatively low likelihood of crossing these borders must not lead to the conclusion that the non-linearity may be neglected. Strong amplitudes especially happen with the plucking of a string (**Fig. 10.1.5**), and the immediate subsequent attack-process in the signal is analyzed by the hearing system with particular precision. The two signals shown in Fig. 10.1.5 do sound differently. However, the amplitude-limited signal – surprisingly – does not sound more distorted but less trebly than the original signal. The plate-voltage looks entirely different, again (Chapter 10.1.3), and what always holds is: the isolated portrayal of an individual non-linearity says little about the output signal of an amplifier.

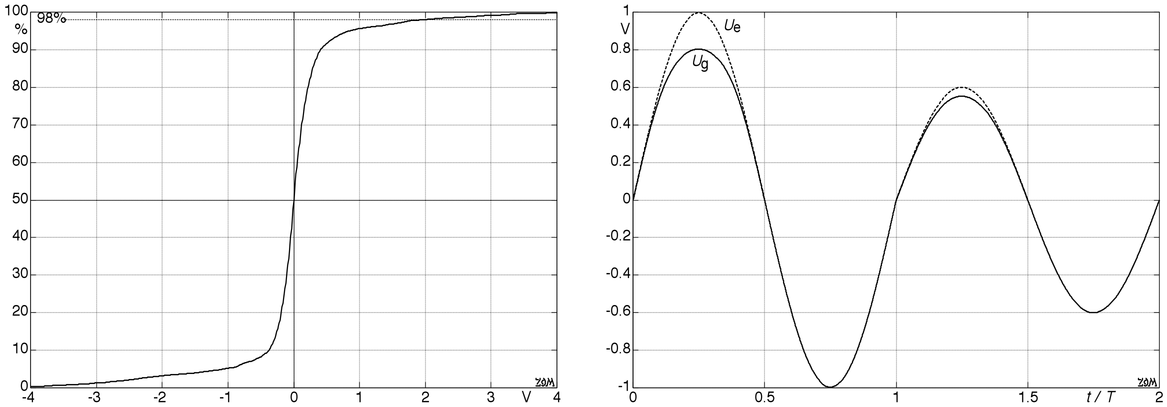

Fig. 10.1.4: left: Distribution function (cumulative) of the pickup voltage (Strat, SDS-1 in bridge position). Right: Non-linear correspondence between input voltage U_e and grid-voltage U_g for a sine signal.

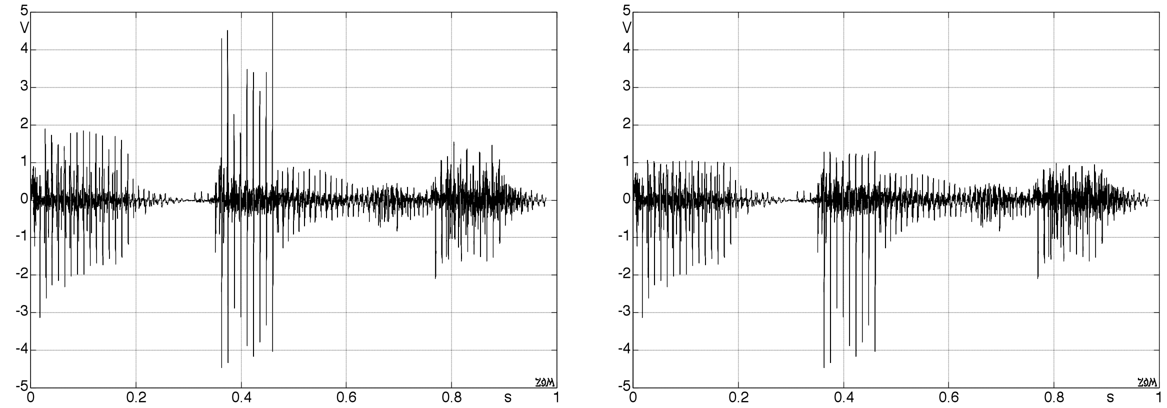

Fig. 10.1.5: Voltage-over-time at the terminals of an SDS-1 pickup (left); with limiting similar to a tube (right).

♣ Strictly speaking, the probability density is zero for discrete values of the continuously distributed voltage; to arrive at a probability (other than zero), integrating over a range is required.