10.11.4 Tube-parameters

In triodes, the plate current I_a depends on the grid voltage U_g and the plate voltage U_a . This bi-variant correspondence can be depicted via a pseudo-3D-graph. Due to the perspective-related warping, additional sectional views are also required. **Fig. 10.11.3** shows the context using an idealized performance map. The sectional views of the bent "working area" are derived first for constant plate voltage (U_a = const), second for constant grid voltage (U_g = const), and third for constant plate current (I_a = const). In the sectional views the slope of the curves (i.e. the partial derivative) yields the three **tube parameters** transconductance (S), internal resistance (R_i) and gain (μ):

$$S = \left.\frac{\partial I_a}{\partial U_g}\right|_{U_a = const} \qquad R_i = \left.\frac{\partial U_a}{\partial I_a}\right|_{U_g = const} \qquad \mu = -\left.\frac{\partial U_a}{\partial U_g}\right|_{I_a = const}$$

The transconductance increases (for U_a = const) with growing grid voltage; the internal resistance decreases (for U_g = const) with growing plate voltage; the gain remains (in this idealized example) independent of the grid voltage (for I_a = const).

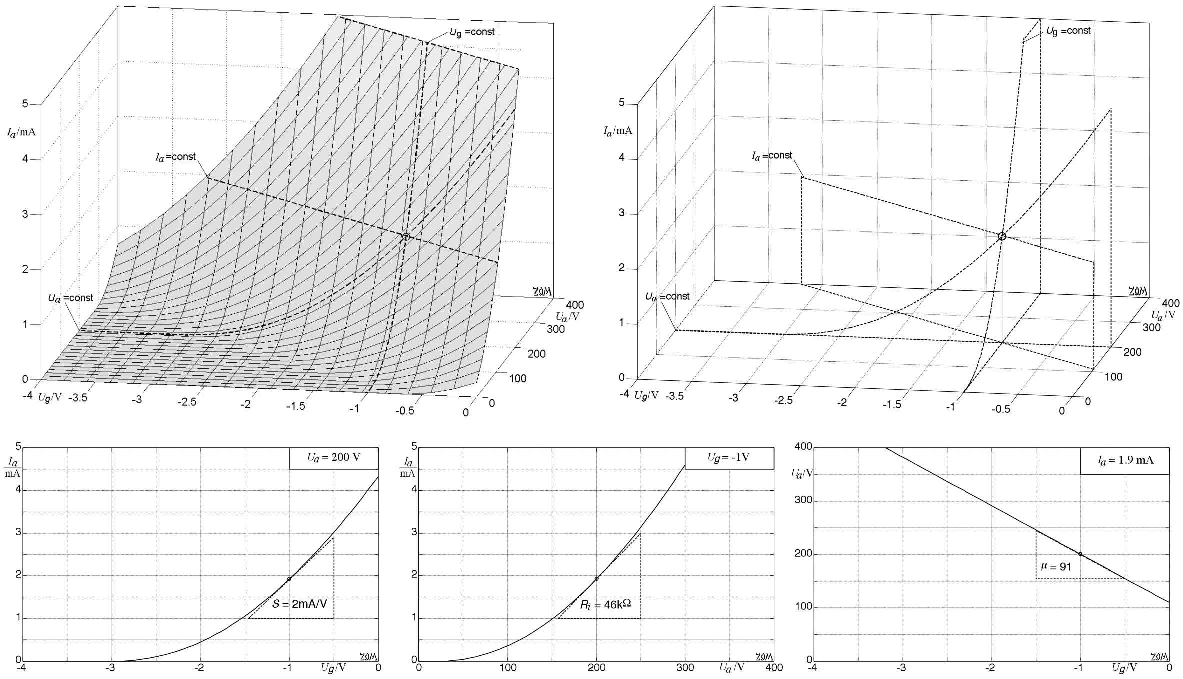


Fig. 10.11.3: Tube-parameters: pseudo-3D-picture (top) with sectional views (bottom).

The theory of quadripoles would – given the two input and two output terminals – in fact require 4 quadripole parameters. However, due to the normally negligible input current, three are sufficient♣. Moreover, these three parameters (S, R_i, μ) are interdependent such that in the end only 2 of them are required to describe the transmission behavior. Additionally, for some triodes the gain μ is almost independent of the plate current, plus it is possible to calculate e.g. the internal impedance from the transconductance:

$$S \cdot R_i = \mu = 1/D$$ Barkhausen formula, D = "Durchgriff"

♣ It was already shown in Chapters 10.1.3 and 10.2.2 that the gird current must not generally be ignored.

If we do not consider the grid current, three static parameters (U_a, I_a, U_g) and three dynamic (or differential) parameters (S, R_i, μ) remain. The static parameters describe the behavior at the operating point and the dynamic parameters describe the behavior at small drive levels. Only with linearization (i.e. replacing the curved transmission characteristic by the tangent), we can obtain a linear equivalent circuit with signal-independent components. In it, the tube is replaced by a controlled source with internal resistance (**Fig. 10.11.4**):

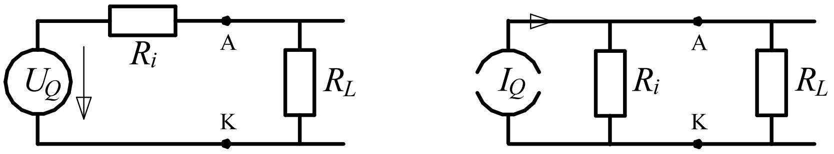


Fig.10.11.4: Two tube-equivalent-circuits for small drive levels (small-signal-EC) with equivalent behavior.

Source voltage U_Q und source current I_Q are interdependent via the internal resistance ($U_Q = I_Q \cdot R_i$), R_L is the load resistance at the plate. R_L combines the total external plate load i.e. plate resistance (from plate to supply voltage) plus in parallel the input impedance of the subsequent stage. The AC-values U_Q and I_Q are "controlled" by the alternating voltage at the grid $\tilde{U}_g$:

$$U_Q = -\mu \cdot \tilde{U}_g \qquad I_Q = -S \cdot \tilde{U}_g \qquad \tilde{U}_a = \frac{U_Q}{1 + R_i / R_L} = I_Q \cdot \frac{R_i \cdot R_L}{R_i + R_L}$$

The ratio of the alternating voltage at the plate $\tilde{U}_a$ and the alternating voltage at the grid $\tilde{U}_g$ yields the alternating voltage gain v_U:

$$v_U = \frac{\tilde{U}_a}{\tilde{U}_g} = \frac{-\mu}{1 + R_i / R_L} = -S \cdot \frac{R_i \cdot R_L}{R_i + R_L}$$ Alternating voltage gain

The alternating voltage gain v_U, (also called operational gain) needs to be distinguished over the gain μ; μ is also called the open-loop gain (see the above tables). Under regular operating conditions (i.e. with a plate load R_L) the gain is smaller than the open-loop gain. Of course, both formulas given for the calculation of v_U lead to the same result. For tubes featuring a μ almost <u>in</u>dependent of current (the ECC83 belongs to this group), the first formula would be more conducive because with it only the internal impedance remains as current-dependent (i.e. operation-point-dependent) variable. The larger the plate current I_a, the smaller R_i, gets and the larger the amplification v_U becomes. On the other hand, the (static) plate voltage drops with increasing voltage, and so does the maximum possible alternating voltage at the plate.

Let us quickly repeat, just to be clear: without any drive signal we obtain the static values for the operating point (U_a, I_a, U_g). With a drive signal, the small dynamic alternating values $\tilde{U}_a, \tilde{I}_a, \tilde{U}_g$ are superimposed on top of (i.e. added to) the static values of the operating point. "Plate voltage" always signifies the voltage between plate and cathode, and correspondingly the "grid voltage" always is the voltage between grid and cathode. Nonlinear behavior (distortion) cannot be covered via the small-signal equivalent circuit. Often, tube data sheets merely give the three dynamic tube parameters for a single operating point that may or may not fit. For the **ECC83** we find, for example, data at I_a = 1.2 mA: a reasonable fit for typical input stages. For the ECC81, however, the parameters in the data sheet are specified at 10 mA; this value is normally not a good match at all because preamps and intermediate stages mostly operate with smaller currents.

 Translation into English by Tilmann Zwicker

Fig. 10.11.5 compares tube parameters within the range of plate currents typical for amplifiers. Special consideration is required because: 1) the data sheets on which the comparison is based are most often of a very small format and not precisely drawn, 2) the nominal curves for the same types of tubes from different manufacturers are not an exact match, and 3) there is significant production scatter. In the top right figure, the dependency of the open-loop-gain on the current is shown, below that we see the gain at 91 kΩ (a value resulting from connecting a 1-MΩ-pot via a coupling capacitor to a 100-kΩ-plate resistor). The largest gain is obtained by the **ECC83** (12AX7, 7025) – therefore this type is often found in the input stages of amplifiers. Since this tube can be overdriven with more sensitive pickups, the **12AY7** may also occasionally be found – however compared to the ECC83 the 12AY7 requires a more negative grid voltage at the same plate current. Given its parameters, the **ECC81** (12AT7) would be a suitable replacement of the ECC83; however the data sheet does not feature the small hum and noise values as they would be necessary for input stages.

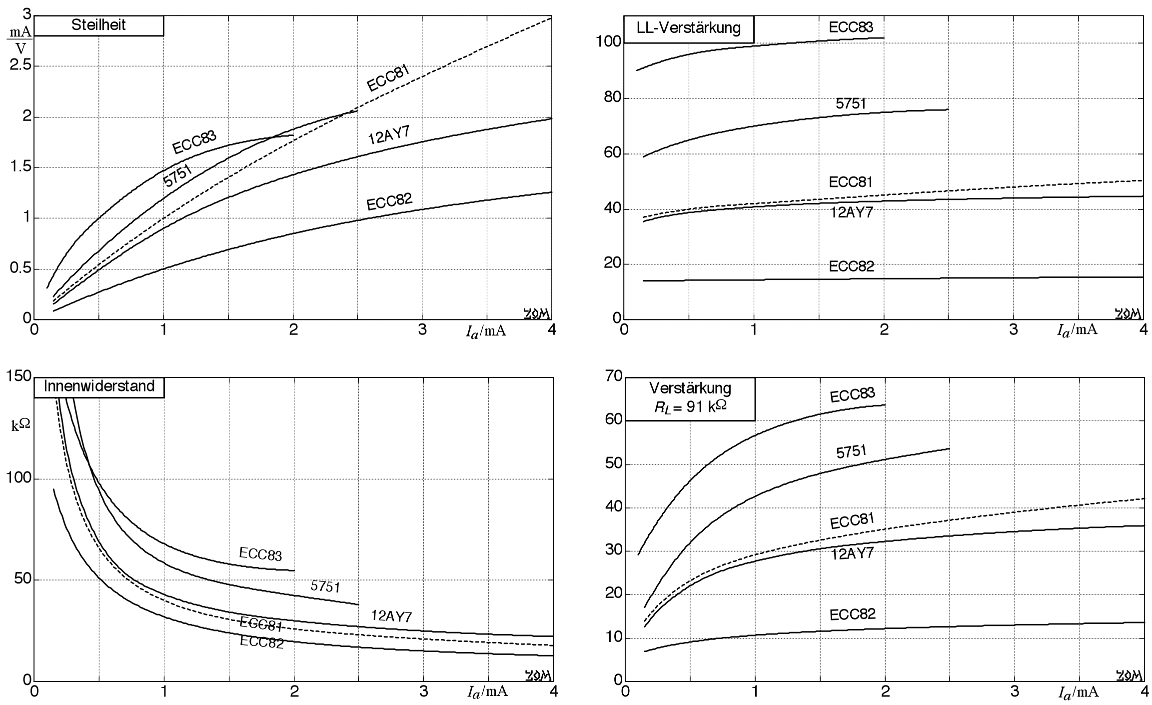


Fig.10.11.5: Comparison of tube-parameters, for 250 V plate voltage. Taken from manufacturer data sheets.

Other than from the plate current, the tube parameters also depend on the plate voltage, but this effect is relatively weak (**Fig. 10.11.6**).

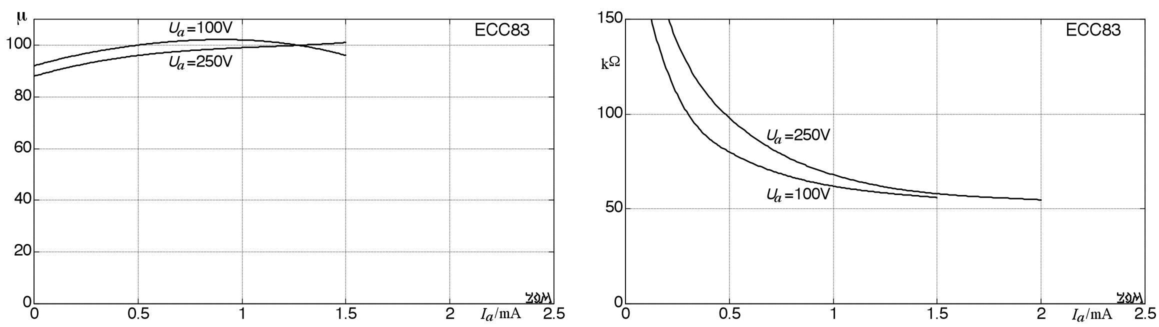


Fig.10.11.6: Tube parameters dependent on the plate voltage. Taken from manufacturer data sheets.

The two transmission-parameters transconductance S and open-loop gain μ are defined for short circuit and open loop, respectively, at the plate. These are operating conditions that do not appear in practice. In real circuits the **plate resistor** R_a interconnects the static values plate voltage U_a, plate current I_a, and supply voltage U_B: $U_a = U_B - R_a \cdot I_a$ (for the dynamic values see Fig. 10.11.4). In **Fig. 10.11.7**, the **load plane** – a slanted area in the 3D-representation – intersects the characteristic area in a line (dashed in the figure), the projection of which onto the U_g/U_a-plane below shows the dependency on the grid voltage. We do not achieve a distinction between static and dynamic plate load yet (there's only R_a, no coupling capacitor, no additional load) – still: we get the whole range and thus real large-signal-behavior. Almost, that is, since the grid current remains not considered. It is here where the beautiful tube models find their limitations, because no data sheet tells us anything reliable about the grid current. The latter is subject to too much scatter to be specified in the data sheets. That is why it is not possible to reliably describe the U_g/U_a-development in the right corner (U_g > -0.5V), why distortion models always remain limited to idealized characteristics, and why every individual tube can sound different when overdriven. Less emphatically: that is why tubes of the same type differ in particular in their non-linear behavior. The differences can be very large: grid currents of tubes of the same type can vary by a factor of 20! We may neglect the grid currents only as we drive the tube with a low-impedance signal generator in the lab. With a high impedance source (such as a guitar pickup or a preceding tube in common-cathode-configuration driving the tube), the individual grid current is significant.

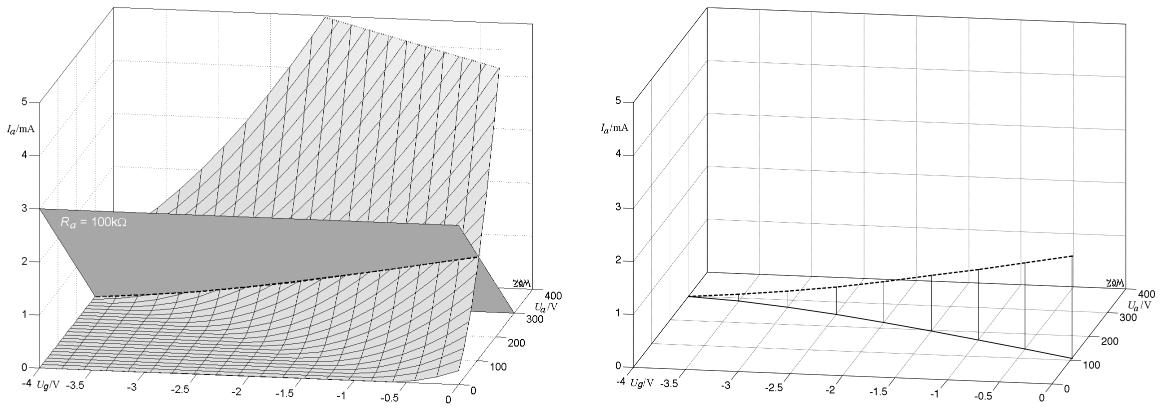


Fig.10.11.7: Load plane for R_a = 100 kΩ (left); projection onto the U_g/U_a-plane (right).

Based on measurements, **Fig. 10.11.8** shows how much the grid currents can vary. However, the figure must <u>not</u> be interpreted such that e.g. tubes manufactured by Siemens would generally have a strong grid current; another ECC83 by Siemens may well have a much smaller grid current.

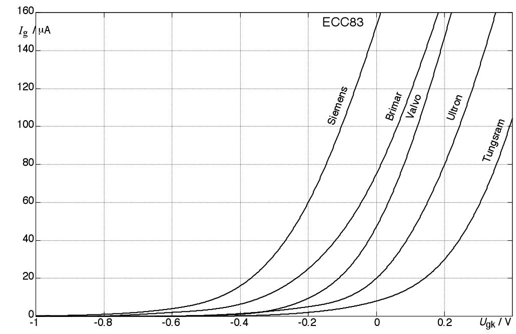
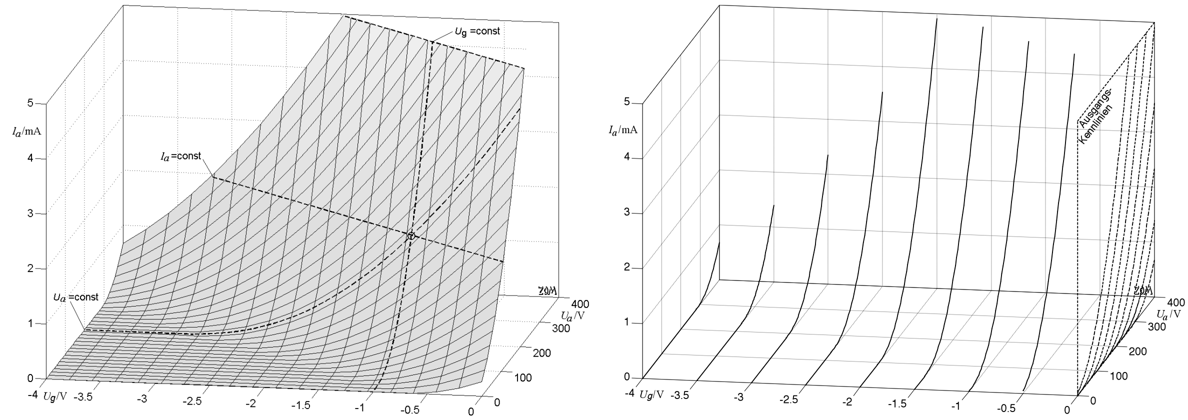


Fig.10.11.8: Grid currents for five different ECC83.

Data sheets do specify an operating point with associated transconductance. This does not help much, however, if the tube is deployed using a different operating point, and thus there are supplementary diagrams. For the triode, the grid and cathode define the input port, and plate and cathode define the output port. Grid voltage and grid current are the **input signals**, while plate voltage and plate current form the **output signals**. **Fig. 10.11.09** shows a characteristic area, selected characteristic curves (for U_g = const), and the projection of these curves onto the right-hand boundary plane. The axes of this boundary plane represent the output signals of the tube, and thus the curves are called "**output characteristic curves**".



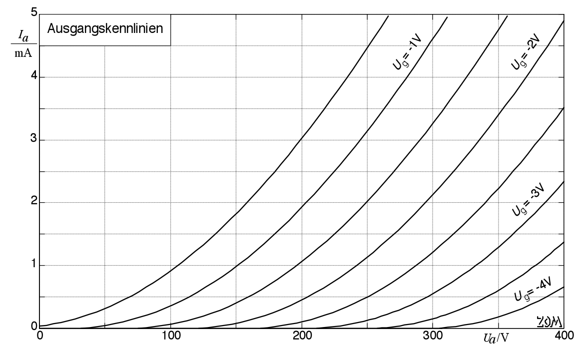


Fig. 10.11.09: Characteristic area and batch of characteristic curves for a triode. The lines of constant grid voltage are projected onto the left boundary surface (upper right); this results in the output characteristic curve diagram (left)

Alternatively, the curves for constant plate voltage may be projected onto the boundary area towards the back (**Fig. 10.11.10**). Since in this case one of the axes belongs to the input values while the other belongs to the output values, these characteristic curves are designated "**transmission characteristic curves**", or transfer characteristic curves. As a supplement, further characteristic curve diagrams are customary, for example for a special plate load (see Fig. 10-11-7).

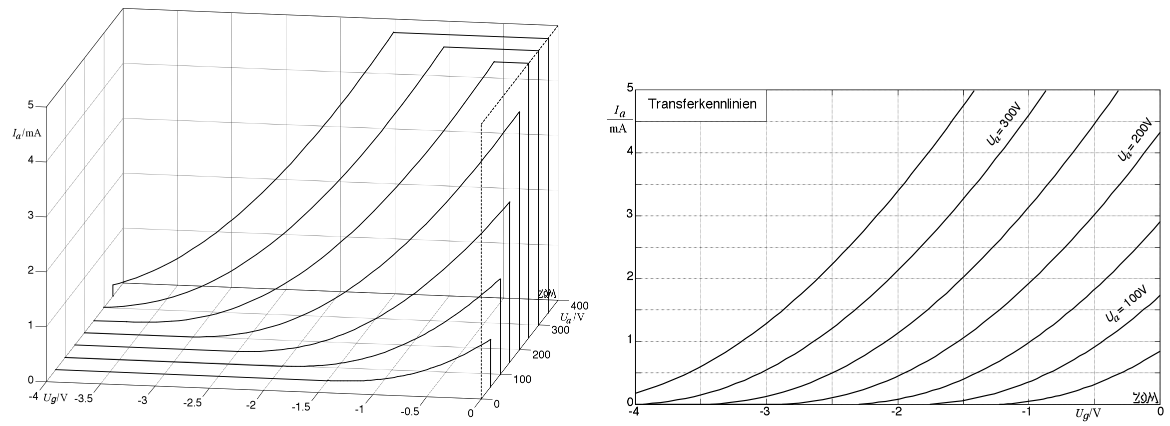


Fig. 10.11.10: Transfer characteristic curves for constant plate voltage.