10.10.4 Comparison: harmonic distortion

Transistors generate 3rd order distortion (= bad) while tubes generate 2nd order distortion (= good) – that's correct, isn't it? Nonsense. Some things may be square (aka 2nd order), and others hip, but tubes are … well, they are cylindrical. Tube as well as bipolar transistor as well as field-effect transistors have progressively curved characteristics and therefore generate both 2nd *and* 3rd order distortions (and many more). A big difference is that for the tiny transistor, very soon extended circuits established themselves that included negative feedback across several stages. Meanwhile, for tubes, the single stage with little negative feedback (or none at all) continued to dominate. There are exceptions (e.g. power stages), but in input stages we almost always find single tubes – mostly with a cathode resistor bridged by a capacitor i.e. without any substantial negative feedback. The contrary happens in an **operational amplifier (OP)**: here there are 20 or more transistors concentrated in a tiny space – something entirely impossible with tubes but doable with transistors in an "integrated amplifier" on a chip of 1 mm^2. The strong negative feedback in typical OP-circuits results in symmetrical signal clipping i.e. in strong odd-order distortion (k_3, k_5, k_7, ...). Thus, it is the circuit that determines how an amplifier distorts, and not primarily its amplifying elements.

The transfer characteristic of a bipolar transistor from base-emitter-voltage (U_{BE}) to collector-current (I_{C}) may be approximated by an exponential function:

$$I_C = K \cdot e^{(U_{BE}/26\mathrm{mV})}$$

Simplified transistor characteristic

The constant K is the value on which the blocking behavior of the transistor depends. The collector current rises progressively with increasing base-emitter-voltage, and since this function is not point-symmetrical to any strong degree, the dominant distortion is the 2nd order one and not the 3rd order one (**Fig. 10.10.15**).

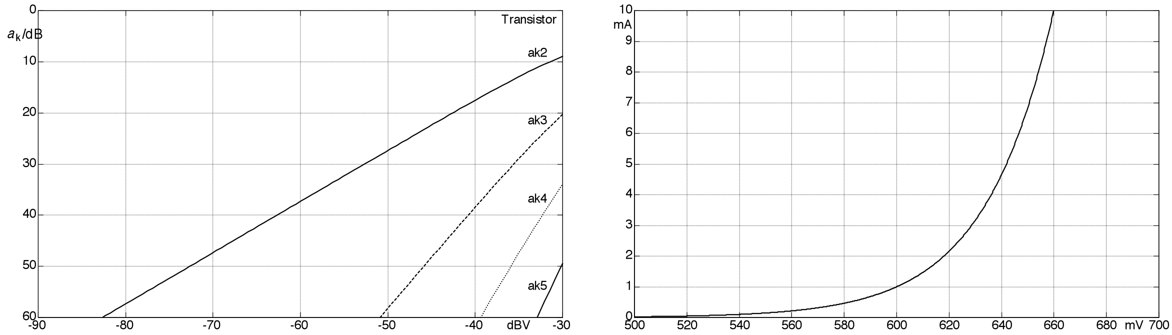

Fig. 10.10.15: Harmonic distortion for a bipolar transistor (left); transfer characteristic (right) .

The figure shows that the 2nd order harmonic distortion increases proportionally to the drive level while the 3rd order distortion rises with the 2nd order of the drive level. At $U_{\mathrm{BE}} \approx 2.5$ mV the 2nd order distortion exceeds 3%; the 3rd order distortion amounts to merely 0,1%. It needs to be considered, however, that the above equation holds for the small-signal behavior that reaches its limit at the latest when the collector voltage approaches the residual voltage (when the transistor conducts best). The collector current cannot increase indefinitely and as it reaches its limit, the characteristic (initially arched to the left) turns to the right. As a consequence of this change in the direction of the arch, the collector-current receives a limitation in *both directions* and odd-order sections of the function gain in weight, and with them the odd-order distortion products. For strong overdrive, the dominant harmonic distortion will generally not be the 2nd order distortion but the 3rd order distortion.

A **triode** distorts similarly, although the functional relations are of a different kind (Fig. 10.1.12), and the following analysis will be dedicated not to the transistor but to this triode. The basic behavior has already been presented in Chapter 10.1.4; now special guitar amplifiers will be targeted. Fender's **Super-Reverb** (AB 763) features a 7025 (ECC83) at the input in a typical wiring – at low drive levels the 2nd order distortions dominate (**Fig. 10.10.16**). Fig. 10.1.13 has already demonstrated that the drive-level-dependency of the harmonic distortion varies with the individual tube-specimen but at low signal levels (e.g. -20 dBV, equivalent to 0,1,V) the 2nd order distortion always is stronger. "Typical for tubes", one could think, however this holds true only for the first tube stage. The right hand picture shows the distortion measured at the second plate, and here the 3rd order distortion dominates that – according to some gazettes for musicians – is reserved for the transistor. Taken individually, each triode generates predominantly 2nd order distortion at low drive levels. However, since the **signal phase is inverted** from grid to plate, the 2nd order distortions compensate each other to a large degree for two tube stages. In other words: the first triode generates a concave downward characteristic while the second triode generates a convex upward characteristic, and the result in a series connection is an S-shaped overall characteristic that predominantly generates 3rd order distortion products (odd functions result in odd-order distortion).

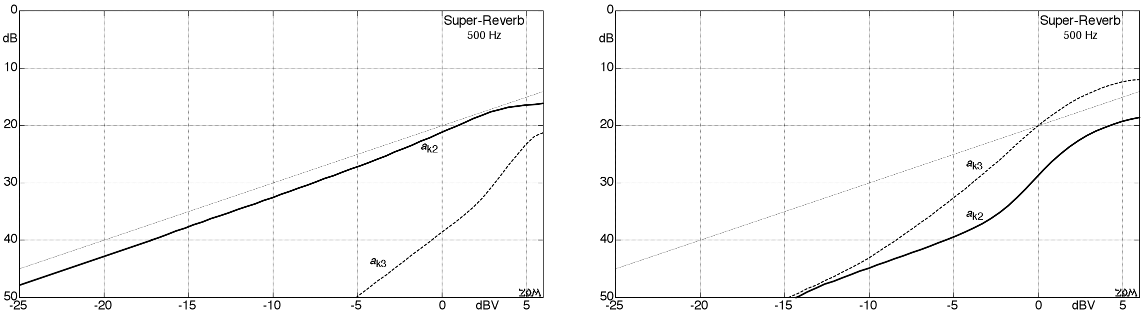

Fig. 10.10.16: Super-Reverb, harmonic distortion: input to 1st plate (left), input to 2nd plate (right).

Of course, the details of this k_2-compensation depends on the network located between first and second tube (in this case the tone stack and the volume control); the measurement was done at the not untypical setting of B = 2, T = 7, V = 7.

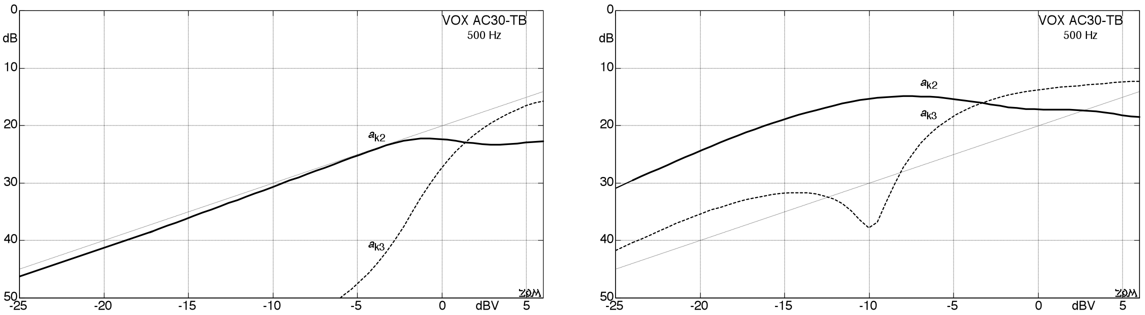

Fig. 10.10.17: VOX AC30-TB, harmonic distortion: input to 1st plate (left), input to 2nd plate (right).

An entirely different harmonic distortion situation is seen in the **VOX AC30-TB** (**Fig. 10.10.17**): although the first tube stage behaves similarly to the Super-Reverb especially at low drive levels, the distortion rises dramatically in the second stage (cathode-follower, Chapter 10.2.2). These are the effects of a very unusual choice of component values that leads to a nonlinear operation with strong grid-current (control setting: V = 12:00 h, B = 10:00 h, T = 12:00 h).

Another again different situation is found at the loudspeaker output (**Fig. 10.10.18**). For the VOX, 3rd order distortion dominates for strong drive levels (“… it’s a tube amp so it has to be k_3.” ☺), for the Fender we find k_2 and k_3 to be of a similar magnitude (“... strange, are there any transistors in the Super Reverb?” ☺). The details of this behavior depend on the specific individual tubes used and, for the Fender, additionally on the quiescent current and the degree of asymmetry in the phase-inverter. As the latter’s plate resistors are changed (100 kΩ and 82 kΩ, respectively), the k_2 changes, as well. Altogether we see a rather “multivariant” scenario.

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Fig. 10.10.18: Harmonic distortion, input to loudspeaker: Super-Reverb (left), AC30-TB (right).
This figure is reserved for the printed edition of this book.

What is the reason for the basic difference? The Fender uses the **6L6-GC** while the **EL84** is deployed in the VOX. The offset voltage of the grid is about -10 V for the EL84 and -45 … -50 V for the 6L6GC. In the Fender, the phase-inverter thus needs to deliver five times the voltage and, for high drive levels, is not able to do this as well compared to the VOX. Consequently, the operating points shift (chapter 10.4.3, 10.4.4, 10.5.12), the duty cycle changes, and the 2nd order distortions differ. In summary: with a typical singlecoil pickup, the Fender generates pure power-amp distortion with a dominant k_3. Conversely, in the VOX both the cathode-follower (k_2) and the power amp (k_3) distort. The distortion rises somewhat more steeply in the Fender but still more gentle compare to the clipping of a transistor power amp with strong negative feedback (Fig. 10.10.19, lower left).

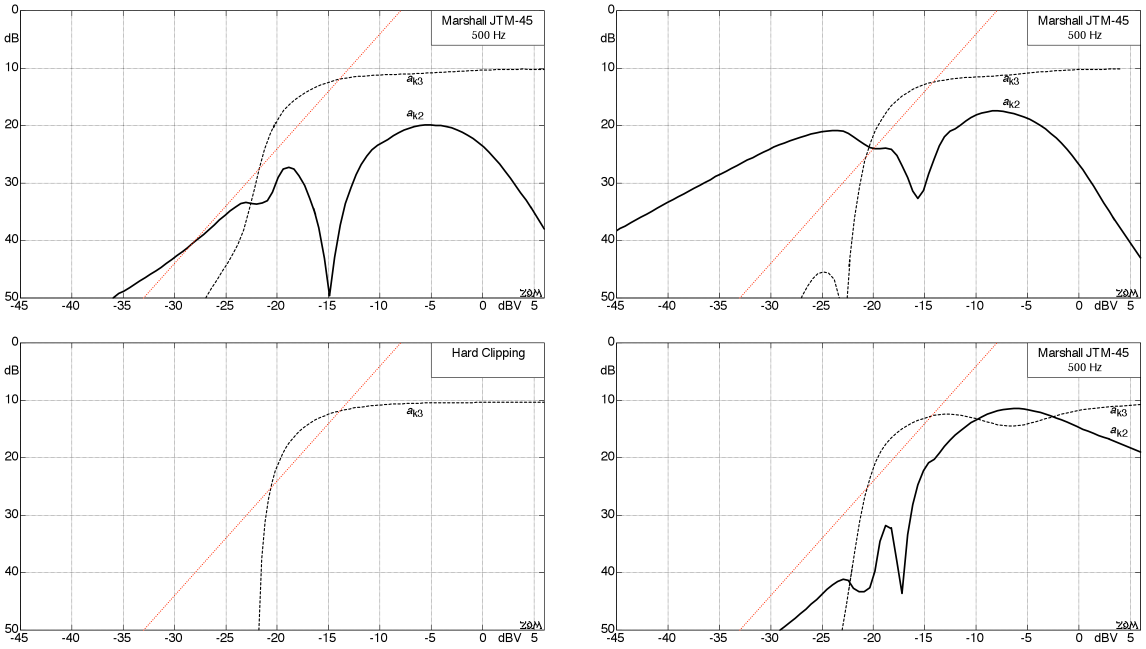

Fig. 10.10.19: harmonic distortion, input to loudspeaker: Marshall JTM-45 (KT-66, R_{aa} = 8 kΩ). Measurements with different tubes in the impedance converter (cathode-follower).

It was already noted in Chapter 10.5.12 that the **JTM-45** power amplifier has strong negative feedback and that the drive-level-dependent rise of the 3rd order harmonic distortion (k_3) consequently has similarities to a transistor power amp. **Fig. 10.10.19** shows the "overall" measurement from preamp input to loudspeaker output. Symmetric limiting should generate exclusively odd-order distortion but the measurement reveals even-order distortion (in particular 2nd order components a_{k2}), as well. These k_2-distortion-products are generated by the power amp but also in particular by the preceding tubes – and here the cathode-follower enters the picture. Its strange operating point with an uncommonly high grid current can make for strong distortion. "Can" – doesn't "have to", though. Swapping the cathode-follower-ECC83 for another ECC83 may change the 2nd order harmonic distortion by a factor of as much as 10 (or even more). We are not talking about damaged tubes here – no, these are brand new. Or they may have 100 h of "burn-in" under their belt, or be switched on in accordance with the moon-cycle, whatever. Take out one tube, put in another: 10 times the distortion. Or 10 times less if it's the other way round. Weird, ain't it? One might think that the developer was clobbered with this circuit botchery, but no, countless "expert"-journalists around the globe rave about it. Yes, it may indeed sound damn good. It may ……

Here a little story from way back in the day: at the Siemens R&D lab there was an infamous head of department who – as a tube circuit design was completed – took from his closet two borderline specimen for each tube type. He plugged them in and personally took measurements. If the great new circuit did now not perform so great anymore, the designer received a great talking-to and was sent back to rework the circuit. Well, Marshall & Son was not Siemens, apparently. Thank God, many will say: otherwise these distorting, screaming monsters would never have seen the light of day. Also, it is only fair to spread some blessing of early birth over 50-year-old developments – however why are there still no tubes in this century that are selected for just this strange c-follower? Rather, the "experts" elaborate about changing a transformer (RS vs. Drake), or whether yellow rather than orange capacitors should be used, or metal-film rather than carbon resistors, or 250 µF rather than 330 µF, even whether solid wire or stranded wire sounds better. No one ever thinks of better specifying the nonlinearities of the c-follower-tube that may actually make a real difference, for a change.

Finally, let us look at two amplifiers that do not include the cathode-follower: Fender's **Tweed Deluxe** (cathodyne, 6V6-GT), and the **Deluxe Reverb** (differential amplifier, 6V6-GT). Die Tweed power-amp has no negative feedback, and therefore the k_3 is stronger at low drive levels compared to the Deluxe Reverb (AB763) that does have feedback.

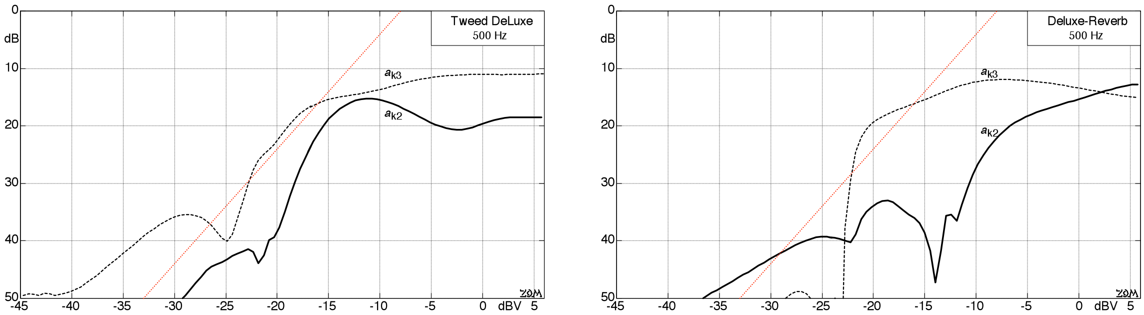

Fig. 10.10.20: harmonic distortion, input to loudspeaker: Tweed Deluxe (5E3), Deluxe Reverb (AB763).

Conclusion: clipping on both sides will generate odd-order distortion. With increasing negative feedback the k_3–rise will be steeper, but the really big differences are in the k_2: there is compensation of pre-amp-tube distortion as well as extreme dependency on individual tubes in the c-follower. Plus, of course, the individual push-pull-anti-symmetry plays a role.

The filter circuit in VOX amps known as **Cut-Circuit** merits special consideration. It was already an established custom to connect a small capacitor between the plates of the differential amplifier used as phase-splitter (Chapter 10.4.3); this reduces the gain in the highest frequency region. As this capacitance is increased into the nF-range, the treble is rigorously "cut"! However, in contrast to the treble controls used otherwise, this is a **non-linear low-pass**!

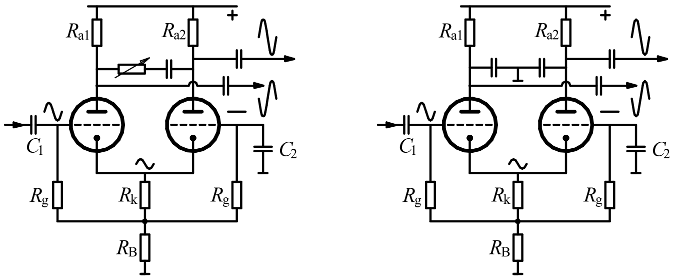

Fig. 10.10.21: Cut-circuit. With the pot turned down, the remaining capacitance may be interpreted as series circuit with intermediate grounding (Fig. 10.4.8).

Fig. 10.10.21 shows how the capacitance connected between the plates may be seen as series circuit (this works the same way with an RC-two-terminal-network, if the pot is not fully turned down). Both plate voltages are approximately equal in amount but out-of-phase so that "between them" we find zero volts. The large plate loading dramatically reduces the **slew-rate**, and therefore this low-pass has a non-linear effect. Another consequence is that the treble-loss cannot be compensated for in any further intermediate stage: the power amp generates less treble *even when overdriven* (!). 'Turning down Cut' therefore is different from 'turning down Treble'.

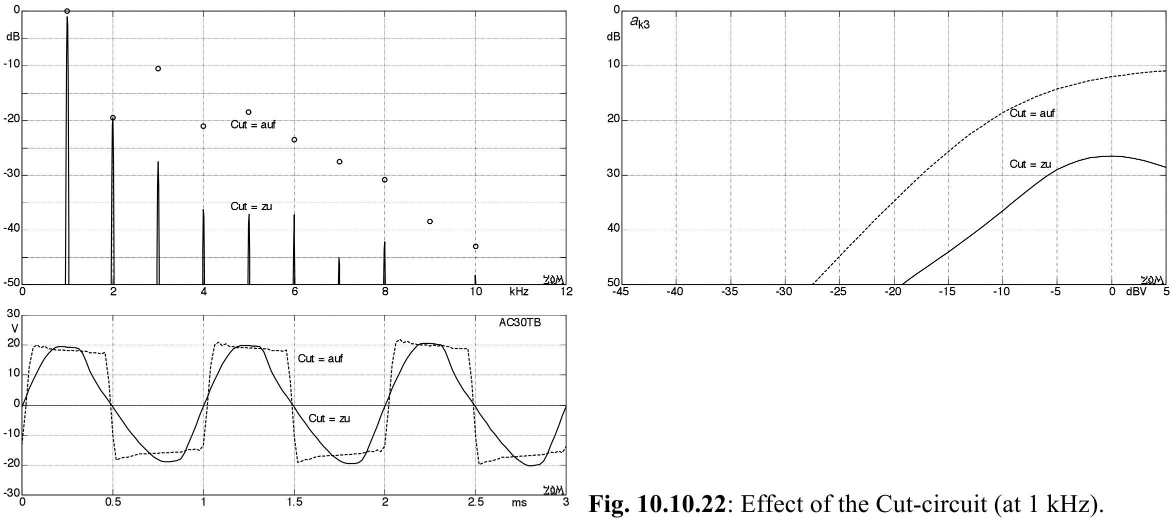

Fig. 10.10.22: Effect of the Cut-circuit (at 1 kHz).

In **Fig. 10.10.22** we see the results of measurements taken from an AC30-TB (from Normal-input to power amp). Even with strong overdrive, the power amp cannot do any "hard clipping": the shape of the curve is round and the high frequencies are attenuated. Conversely, if the Treble knob were turned down on e.g. a Fender amp, and the power amp strongly overdriven at the same time, the result would be a square output wave-shape. Here, the VOX offers an interesting alternative.