10.2 Intermediate amplifier

In the signal path, the intermediate amplifier operates between input stage and power stage – but it is not the tube immediately ahead of the power tubes that is meant here (that would be the tube commonly known as *phase inverter* in push-pull arrangements, see Chapter 10.4). In the classical guitar amp, the typical intermediate amplifier is the second amplification stage. Between the first and the second stage we find the tone-filter … or the volume control … or both. In fact even in the classic amp-forefathers we already find different concepts.

Which are the (dis-) advantages of these various topologies, and what are the sonic differences? That is quite difficult to answer. It is easier to address the question what the reasons could have been to implement the respective topology. **Fig.10.2.1** shows the most important ones – there are more but we will not investigate them here. In almost all guitar amps, the signal from the pickup is directly fed to the first tube. This is because any circuitry connected between pickup and the first tube would have to be high-impedance and thus would unduly increase noise. If the volume control is located directly after the first tube and the tone-filter subsequently (as shown in the first variant), then the source circuit (the volume control) feeding the tone-filter would have an internal impedance that depends on the position of the potentiometer's center-tap. Moreover, the potentiometer load (= filter-input) would be frequency-dependent. The effect of the filter would therefore not only depend on the settings of the tone control, but also on the setting of the volume control. Presumable it was this interdependency that precluded the corresponding topology from become really widespread.

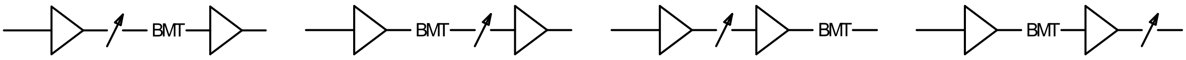

Fig. 10.2.1: Some obvious circuitry-topologies. BMT = tone-filter, arrow = volume-pot.

We will look more closely at the second and third topology-variants; these two are found most often in tube amplifiers. The fourth variant would work without any problem, as well, but was apparently not seen as directly superior and was thus rarely used. Variant two and three differ in the position of the tone-filter: ahead of the volume control or after it. The **sequence** of the subsystems in a guitar amp would be rather unimportant if the amp were a linear system. However, as Chapter 10.1 has shown, non-negligible harmonic distortion happens as early as the very first amplifier stage; the system is non-linear in quite a complicated way. Moreover, a further non-linear effect needs to be considered: the noise that every component generates. Non-linear system need to be source-free i.e. they must not include any noise-sources, either. If the volume-pot is positioned late in the signal-flow (close to the power amp), almost no noise will be audible when the volume control is turned down. However, there is now considerable danger that one of the preceding amplifier stages will be overdriven in case the connected guitar has a high-output – and this danger cannot be reduced by turning down the volume control. If, conversely, the volume control is located directly after the first stage, any potential overdrive of subsequent stages is fully controllable – but there may be a considerable noise level even with the volume set to zero. Of course, no guitarist plays his or her amp with the volume fully turned down so this would probably not be a problem. Rather, the sales department that makes demands here: in the music store, it's no good if the amp creates such a racket even though no-one is even playing through it. Still, the amp needs to be "clean" at low volume. Only later amplifier generations include "Fat"- and "Boost"-switches, and master-volumes to get more sound-options; the early amplifier-variants had to do without that. Obviously, "sound" won out over "noise": in the circuits, the volume control was close to the input (mostly before the second tube stage).

10.2.1 Intermediate amplifier in common cathode-circuit

The standard version of the intermediate amplifier contains *one* tube (almost always a triode) in common-cathode configuration. The circuit is similar or even identical to the first preamp-stage. And why not – the signal has been attenuated by tone-filter and/or volume control and needs to be re-amplified, with the common-cathode configuration being highly suitable. Sometimes, the developers see a need for an impedance conversion in the second amplifier stage – this aspect we will cover in the next section (10.2.2).

In the **common-cathode circuit**, the cathode is connected to "common" i.e. to ground. The required grid-offset is usually generated "automatically" by a cathode-resistor (Chapter 10.1). A capacitor is connected across this resistor in order for the latter to be active only for DC, and to avoid any AC-voltage across it (which would introduce negative feedback). As long as there is not grid-current, this circuit features very high input impedance – although a non-negligible input capacitance (100 pF minimum) does require consideration. The output impedance (internal impedance) results from the parallel connection of the internal impedance of the tube (about 60 kΩ) and the plate-resistor (100 kΩ); the gain factor is about 35 dB (or a bit less if there is significant loading).

Fig. 10.2.2 shows two famous amplifier concepts in comparison: in the Fender circuit, the volume potentiometer directly follows the tone-filter and feeds the intermediate stage, while in the VOX, the intermediate stage is placed between volume pot and tone-filter. **Fender** follows the simple line of thinking: take care of all control efforts at one and the same location. The interaction between the directly connected volume control and tone-filter remains within reasonable limits because the pot is of relatively high impedance (1 MΩ). With the **VOX**, we find an entirely different approach: a special intermediate amplifier with high-impedance input (common cathode configuration) and low-impedance output (common-plate configuration, see 10.2.2) follows the volume pot.

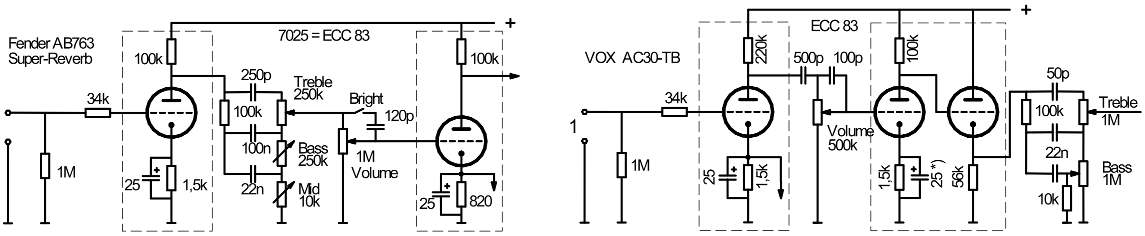

Fig. 10.2.2: Comparison between a typical Fender-circuits (left) and a VOX-circuit (right).
***)** There are VOX amps that do not include the cathode-capacitor for the 2nd tube.

Pushing the discussion of the tone-filter into Chapter 10.3, we will first analyze the 2nd tube-stage of the **Fender circuit**. Both 1st and 2nd tube-stages are fundamentally similar but there are differences regarding the cathode circuit: in the Super Reverb (under scrutiny here), the cathode-RC-circuit also feeds the corresponding cathode of a tube in the other input-channel. Other Fender amplifiers include the same component-saving detail. In the figure, the second tube is not included but an arrow indicates the connection to it. For the grid-offset of the tube(s) to remain at the desired value, the value of the cathode-resistor common to both tubes is approximately halved at 820 Ω (instead of 1,5 kΩ). Since both triodes are feeding relatively high impedance circuits, they have similar voltage gains. Given a regular ECC83, each triode will yield about 32 – 34 dB. The harmonic distortion, however, will be different because the source impedances (ahead of the grid) differ.

10.2.2 Intermediate amplifier with cathode-follower

The VOX-circuit (Fig. 10.2.2) differs from the Fender-circuit not just in the sequence of the partial systems but also in the build of the second amplifier stage. It deploys *two* triodes: the first generates the required voltage gain while the second acts as a current amplifier (impedance converter = cathode-follower = common-plate circuit) and achieves a low output-impedance (= internal impedance). Strictly calculating the internal impedance according to text-books we get $1/S$ (S = transconductance); for the present circuit this would be 600 Ω. An output-impedance of such a low order would not be mandatory, though: the load imposed by the VOX-tone-filter is always larger than 100 kΩ. Before we go into further detail regarding the rather special dimensioning of the VOX-circuit, let us quickly review the history of the cathode-follower: Leo Fender outfits his tweed amps with this circuit from the mid-1950's (albeit not using the 12AX7 but the 12AY7, **Fig. 10.2.3**).

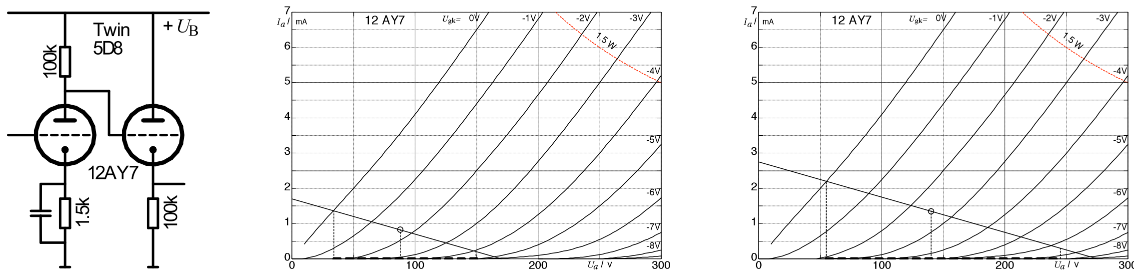

Fig. 10.2.3: Intermediate amplifier with cathode-follower; family of output-characteristics of the 12AY7, U_B = 170V … 275V.

For the 5D8-Twin, the layout specifies [Funk] a supply-voltage of U_B = 170 V, for the later 5E6-Bassman this has risen to 235 V, and in the 5E6-A we find even 275 V. With the increase of the supply-voltage, the quiescent current of the triodes also mounts; this is indicated in Fig. 10.2.3 as a dot on the load-line. For U_B = 170 V, the travel of the plate-voltage of the first triode is limited to about 35 V towards small values by the U_{gk}=0V-characteristic. For even smaller U_a (i.e. larger I_a), the grid would have to become positive relative to the cathode but this is only possible to a small extent: the grid-current is kept low by the high-impedance feed. If the first tube were in blocking mode, its plate-voltage would be the same as the supply-voltage (with no load present). However, since in the second triode there is a grid current (200 µA), the plate-voltage of the first tube rises only to about 150 V. Corresponding characteristics result for a supply-voltage of 275 V (**Fig. 10.2.4**).

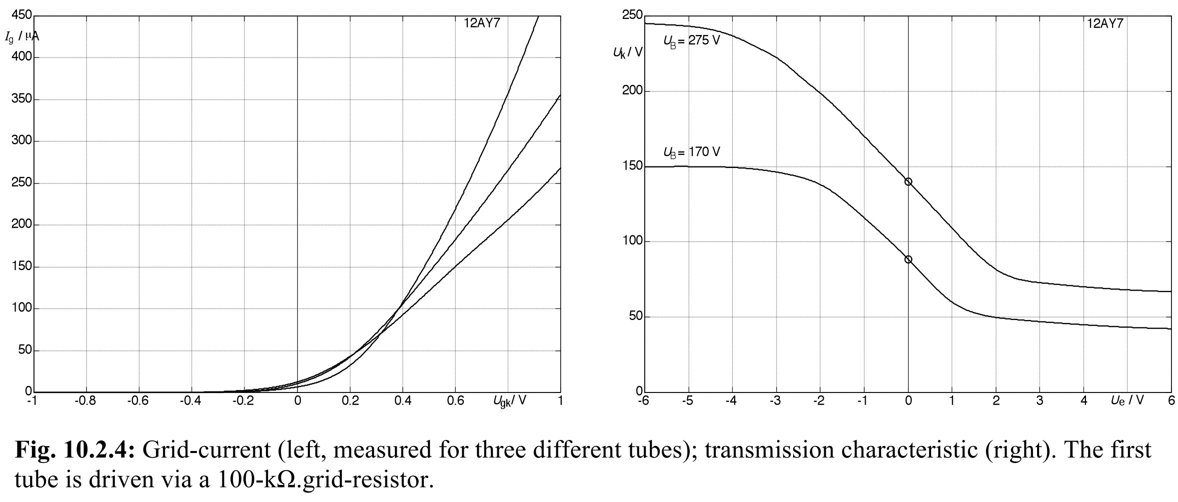

Fig. 10.2.4: Grid-current (left, measured for three different tubes); transmission characteristic (right). The first tube is driven via a 100-kΩ.grid-resistor.

With the change from the E- to the F-series, Fender replaced the **12AY7** by the **12AX7** (= 7025 = ECC83) – presumably because the latter has higher gain, or simply in order to standardize. Bassman 5F6, Super 5F4, and Twin 5F8 still included the common-cathode/plate-circuit for their intermediate amplifiers but received the 12AX7 instead of the 12AY7. In the Super 5F4 the associated components remained identical; for the other amps R_{k1} was decreased from 1.5 kΩ to merely 820 Ω. The differences between the two double triodes are shown in **Fig. 10.2.5**: the 12AX7 sports the larger open-loop-gain (μ = 100 vs. 44) but also has the larger internal impedance: 63 kΩ vs. 25 kΩ. Since the tubes are not operating under open-loop conditions, the gain in reality differs not that much but still considerably: 50 vs. 30, i.e. 34.0 dB vs. 29.5 dB.

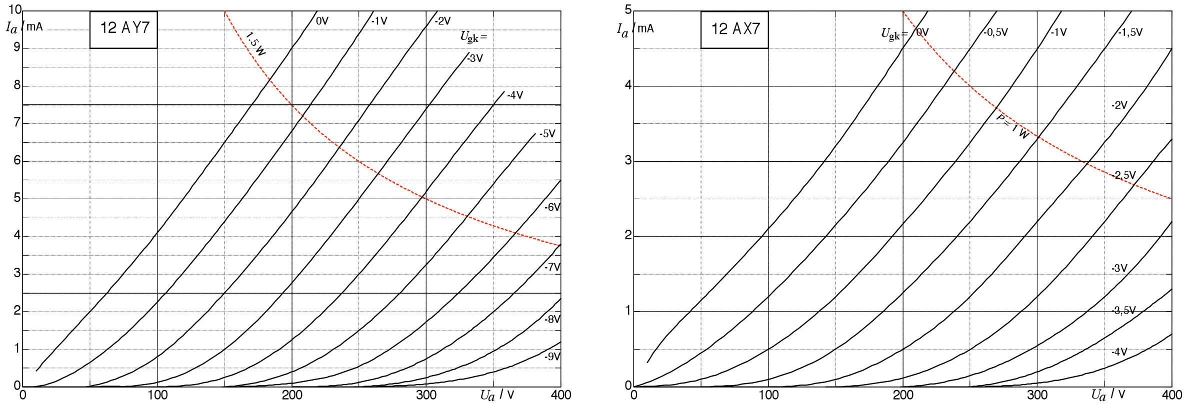

Fig. 10.2.5: Output characteristics (according to data sheets) of the 12AY7 (left) and the 12AX7 (right).

The transmission characteristic of the 5F4-circuit is shown in **Fig. 10.2.6**. Besides the steeper slope (= higher voltage gain) it is especially the much stronger curvature that stands out – it is the reason for strong non-linear distortion. The change to the smaller cathode-resistor (5F6) balances the operating point somewhat but cannot change anything about the curvature. It may be due to this non-linear behavior that Fender's Super-Amp 5F4 received additional negative feedback – but the Bassman 5F6 (and its successor 5F6-A) had to do without the negative feedback. It needs to be noted that in particular this Bassman had a lasting influence on the British amplifier industry: it was the amp that Jim Marshall modeled his JTM amps after from 1962 (with cathode-follower, with 820-Ω-resistor, without additional negative feedback).

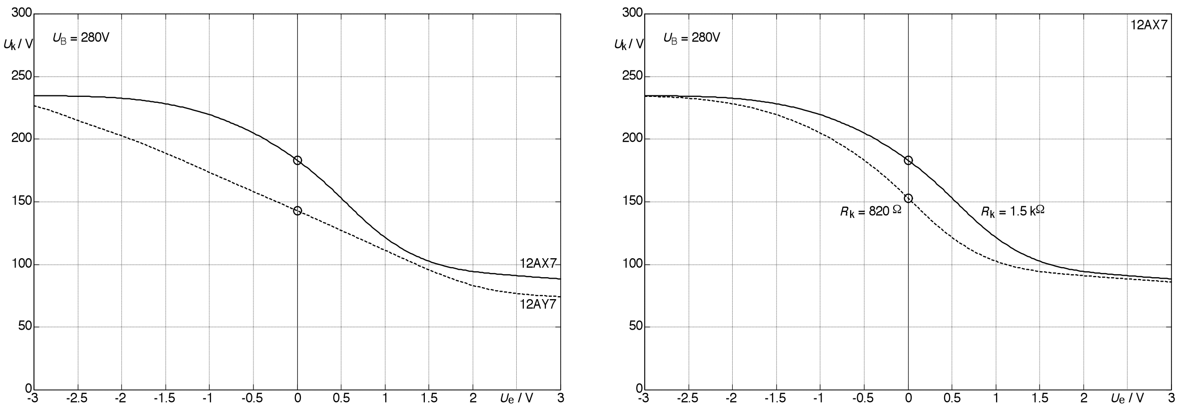

Fig. 10.2.6: Left: comparison 12AX7 vs. 12AY7 (1.5 kΩ // 25µF). Right: comparison 820Ω vs.1.5 kΩ (// 25µF). As in Fig. 10.2.4, the first tube was driven via a 100-kΩ-grid-resistor.

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The first cathode-resistor (Fig. 10.2.7) determines the operating point of the first tube but the individual tube data also have significant influence. In **Fig. 10.2.7**, we see the results of measurements taken from several 12AX7 (Siemens, Valvo, Brimar, Mazda, Ultron, TAD). There are clear differences in the transmission characteristics as well as in the time-functions – this of course does dramatic effects on the level-dependencies of the harmonic distortion. Still, the attributes *good* or *bad* may be assigned with great caution only. Whether single-sided signal-limiting is preferred or objected to is a matter of taste, and the same holds for whether new or old tubes are utilized. A stringent correlation between tube data and tube age must not be expected – a clear correlation between tube price and **tube age** may be, though.

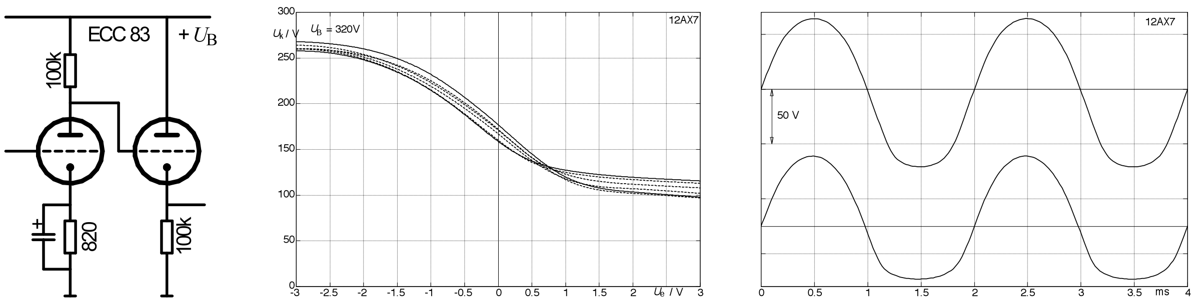

Fig. 10.2.7: Characteristics of 6 different 12AX7 tubes. Right: time functions (two different 12AX7).
First cathode-resistor = 820 Ω bridged with 25 µF; drive signal fed via a 100-kΩ-grid-resistor.

While we are on this subject: the opinion that **tubes produced back in the day** (NOS) are better, and consequently of course more expensive, holds only for the latter part. There might be something to the idea that the descendants of the old geniuses have plainly misplaced the recipes and do not know anymore how to build a high-quality tube. New tubes might have issues with microphonics, noise, a short lifespan, leaky seals, unsuitable getter♣, just to name a few criteria. But variations in the transconductance? The formula *higher transconductance = better* does certainly not work out, and a corresponding link to the price remains unclear, as well. The overdrive-behavior that is so important for guitar amplifiers is not specified in any data sheet for triodes, and, generally, neither is the grid current. A 12AX7 bought in 2008 may cost 6 € (advertised with tight bass, punchy mids and silky top end), or more than 13 € (tight bass, punchy mids and silky top end *with overall definition and brightness*). Or it could be priced at 25 € (great for warm clean tones and creamy overdrive). That is too expensive? Here is a 20-€-tube with "great warm clean tones and fat overdrive with smooth top end". Still not in your price-range? Hm … then maybe the 7-€-tube with "better gain and warm tone", or the 8-€-tube with "good gain, lots of treble and tight bass response"? Blimey – I've shelled out a 20-€-surcharge♥ for the tube-supplier scraping off the original labeling and replacing it by his company logo – shouldn't I be entitled a source to read up on the criteria that the tube (now knighted as "selected") will actually meet? Not a chance - "good gain", or "slightly better gain than Nr. 5" … that'll have to do. Or simply: "comes in the original RCA-boxing". That will set you back at least 30 €, though. But the real winner is: "*12AX7; enlarged grid giving a better articulation in the bass-range. The helix-shaped heating filament takes care of excellent noise-behavior and lowest microphonics*" – at no less that **42 € per piece**! Hopefully that extended bass-range is worth this kind of money-drain – given that the regular 12AX7 already extends down to 0 Hz. Of course, this sort of premium-stuff might be exactly what you were searching for forever. But then, the 5-€-no-name tube might have done the exact same trick. Faites vos jeux, ladies and gentlemen.

♣ materials that bind gas residues and improve the vacuum that way.
♥ Dear lawyers (including partners and colleagues in your firm scattered throughout the ROW): this is all just irreal satire. Ain't no spondu-licks coming through these tubes …

But now back to our actual topic: **Fig. 10.2.8** shows the harmonic distortion of the signals in Fig. 10.2.7. The differences between the left and right sections in Fig. 10.2.8 are due to just swapping tubes: take out the 12AX7 – plug in another 12AX7. Left, the 2^{nd}-order distortion dominates up to -2.5 dBV; above that we see mainly 3^{rd}-order distortion. Right, things are very different: 2^{nd}-order distortion up to -11 dBV; from there on, about the same share for 2^{nd}- and 3^{rd}-order distortion. The closer the operating point gets to the end of the characteristic, the more dominant the 2^{nd}-order distortion becomes for small drive levels. An ideal one-way rectifier (as an extreme example) would show only even-order distortion ($k_3 \equiv 0$).

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Fig. 10.2.8: Harmonic distortion of the signals of Fig. 10.2.7. 1st tube driven via a 100-kΩ -grid-resistor. Harmonic distortion attenuation $a_k = 20 \cdot \lg(1/k)$, k = harmonic distortion factor. Larger dB-values indicate smaller non-linear distortion. These figures are reserved for the printed version of this book.

Given such variances, wouldn't it be worth the while to use **selected tubes**, after all? That question is reason enough to check some offerings. A sample of 6 tubes sourced from a tube supplier was measured using the circuit seen in Fig. 10.2.7; the results are shown in **Fig. 10.2.9**. The small signal gain varies from v_U = 34.8 to 35.6 dB, and the operating points differ by as much as 20 V. The differences in the maximum and minimum achievable voltage are of similar magnitude, and thus in the symmetry of the curves, as well. "Asymmetry" would be the better term: in this circuit, this type of tube will be the source of pronounced single-sided distortion. Not that that's entirely undesirable in a Marshall amp … however, the precise reproduction of special distortion characteristics clearly is NOT warranted by the "selection" of tubes – as can easily be seen from **Fig. 10.2.12**. Except for the attribute "selected tube", no actual selection criteria are made public, and we can only speculate what the basis of the surcharge asked for these tubes could be. Maybe there is a selection for reduced microphonics – not entirely useless, but not a first priority in an intermediate amplifier stage, either.

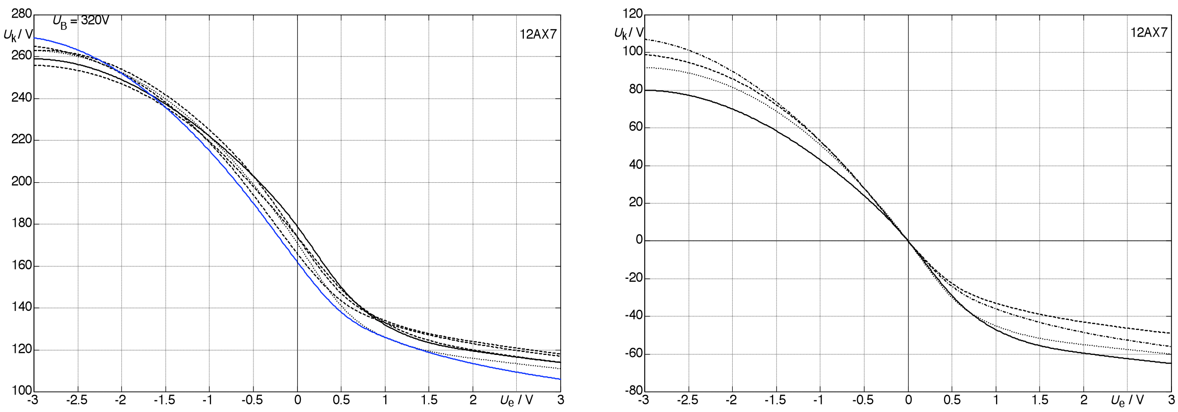

Fig. 10.2.9: Characteristic of 6 selected 12AX7 (supplier A); 4 of them in normalized presentation (right).

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Fig. 10.2.10 shows measurements taken from 6 tubes provided by another supplier. The curves are indeed closer to each other although there are still differences in the details. Small signal gain is between 35.7 and 36 dB – a better match compared to our first example. The voltage limits, however, include a similar scatter so that we do not have a uniform distortion characteristic across several tubes, either (Fig. 10.2.12).

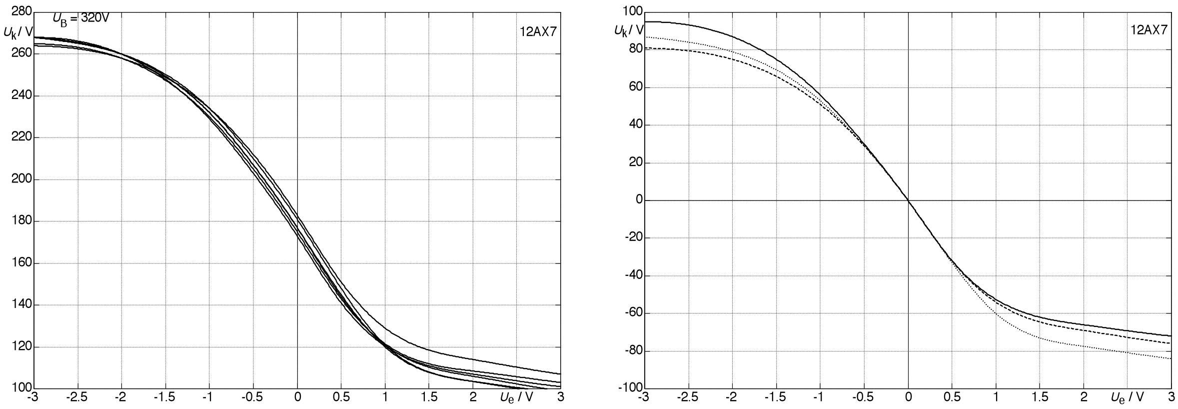

Fig. 10.2.10: Characteristic of 6 selected 12AX7 (supplier B); 4 of them in normalized presentation (right).

Last, let us take a look at 4 unselected tubes (all 4 from the same manufacturer), bought at a low price from a component discounter (**Fig. 10.2.11**). The small-signal gain v_U varies between 33.3 and 33.4 dB i.e. the gain factor this is 2 dB less than in the other samples. This can by no means be seen as a general deficit: whether the user prefers or dislikes the corresponding (small) reduction of distortion is a purely subjective rating.

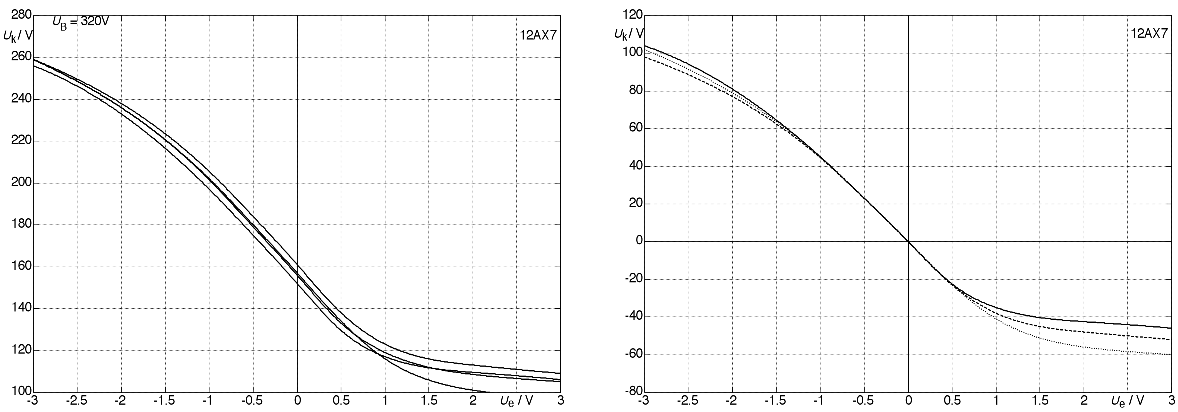

Fig. 10.2.11: Characteristic of 4 unselected 12AX7; 3 of them in normalized presentation (right).

In **Fig. 10.2.12**, again normalized transfer characteristics and harmonic distortion are brought face to face. The first sample of "selected" tubes shows measurable variance in the gain and – in particular – strong differences in the harmonic distortion; a common characteristic, however, cannot be established. The second and the third samples show a group-specific characteristic, but the variations within each group are still considerable – whether with or without "selection".

Of course, these measurements do not allow for the conclusion that *all* selected tubes offered on the market do not merit the term; the samples used here are too small for that. Still, inquiring about what the selection process in fact entails would appear to be highly advisable.

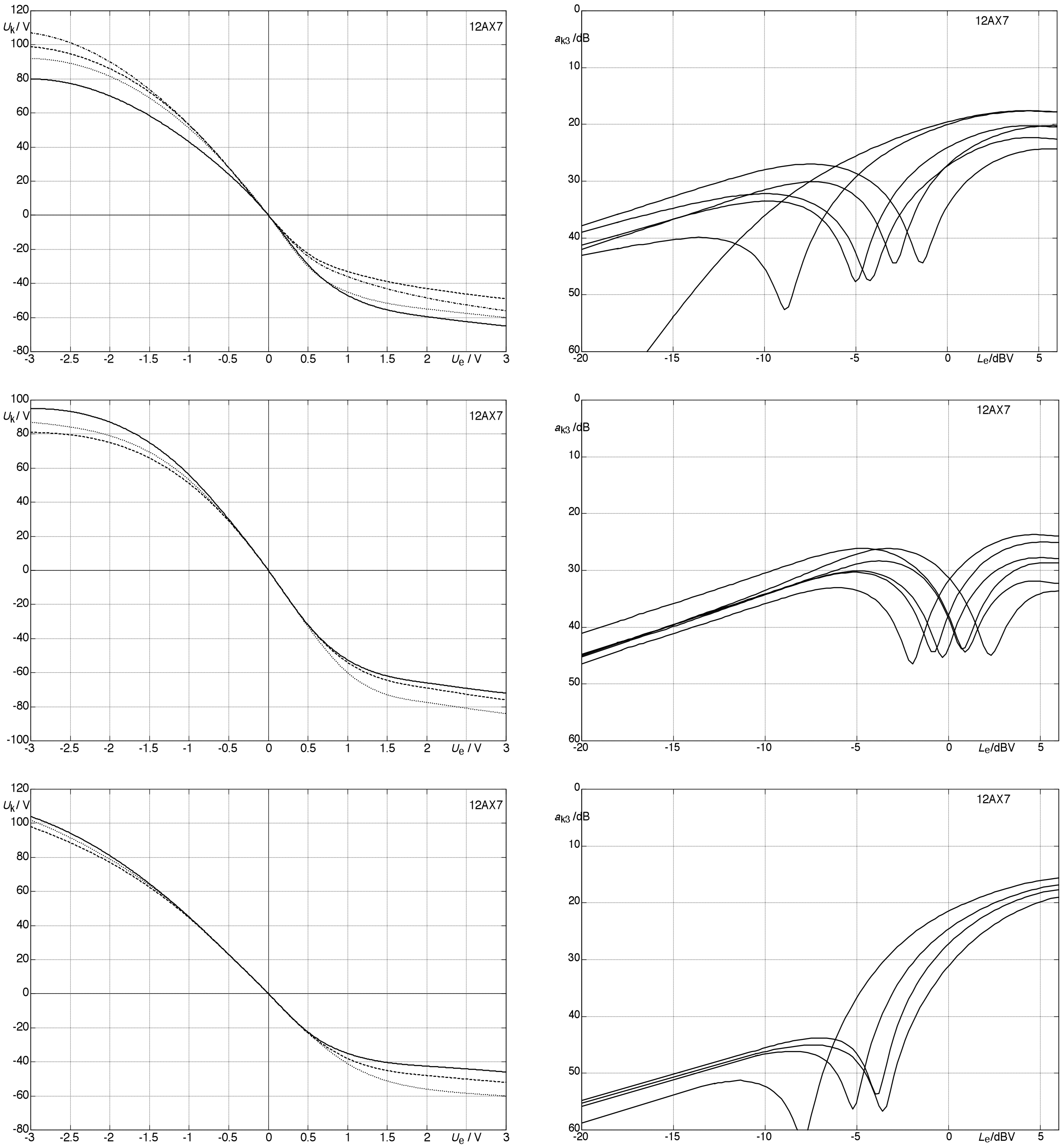

Fig. 10.2.12: Normalized transmission characteristics (left); harmonic distortion (right). Comp. Figs. 10.2.9-11.

Starting from the first Fender-circuits, the cathode-follower was subjected to two important changes until it arrived in Jim Marshalls JTM: 12AY7 → 12AX7, and 1500 Ω → 820 Ω. For the **VOX AC-30TB**, a third modification was added: the cathode-resistor at the cathode-follower tube was reduced from 100 kΩ to 56 kΩ, with the result that even without any drive signal, no less than 3 mA already flow through this tube. That is no laughing matter for a tube specified to carry 1,2 mA in its operating point. It won't be destroyed, but such a high current cannot be generated without the presence of a grid-current. This cathode-follower tube does not have a high-impedance input anymore but represents a non-linear load for the plate-circuit of the preceding tube. The latter is required to deliver a grid current of almost 1 mA which, considering that the plate resistor has a value of 100 kΩ, is no mean feat, and which will be the source of a special non-linearity. As is always the case with this special amplifier type, that might, however, not be generally undesirable.

Fig. 10.2.13 depicts the measurement results taken from the **VOX-circuit**: even without drive signal, the cathode-follower requires a grid-current of 185 µA. Measuring the differential input impedance (AC-resistance) of the cathode-follower resulted in the surprisingly small value of a mere 90 kΩ! This impedance-converter apparently does not feature the "extremely high" input-impedance typically found in such circuits, but is – due to its relatively high quiescent plate-current – even of quite low impedance. At high plate-voltages (U_{a1}), it loads down the preceding stage just like a 90-kΩ-resistor, and reduces the voltage gain of that stage by a quite sizeable 28%. With decreasing plate-voltage (U_{a1}), the input-impedance of the cathode-follower increases, after all; it therefore represents a non-linear load impedance. The transmission characteristic is strongly curved and the output-voltage swing is relatively small. This means that for large output voltages, the cathode-follower cannot provide enough current, and for small input voltages, the first tube is not sufficiently low-impedance. Not when using the 12AX7, anyway.

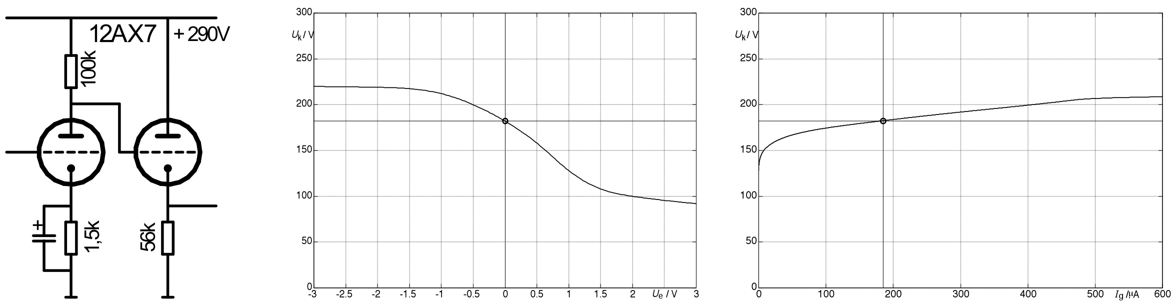

Fig. 10.2.13: Lefts: VOX AC-30TB. Middle: transmission characteristic of the overall circuit. For the measurement, the first tube is driven via R_{g1} = 100 kΩ. Right: grid-current of the cathode-follower tube.

Fig. 10.2.14 compares the summation- and the distortion-levels. The left-hand section shows the situation at the un-loaded 1st tube while the right-hand section describes the non-linear loading. The reduction of the summation level L_Σ by 2,8 dB and the growth of the distortion is clearly visible. Already at an input level of -15 dBV (178 mV), the 2nd harmonic (distortion) is a mere 30 dB below the level of the primary signal (i.e. k_2 = 3,2%). It will come as no surprise that the **internal impedance** (output impedance) of this cathode-follower is not at a by-the-book-value of 600 Ω but brings no less than 7 kΩ to the market: the operating point is not positioned by-the-book, either! Nevertheless: 7 kΩ are o.k. for the VOX-circuitry.

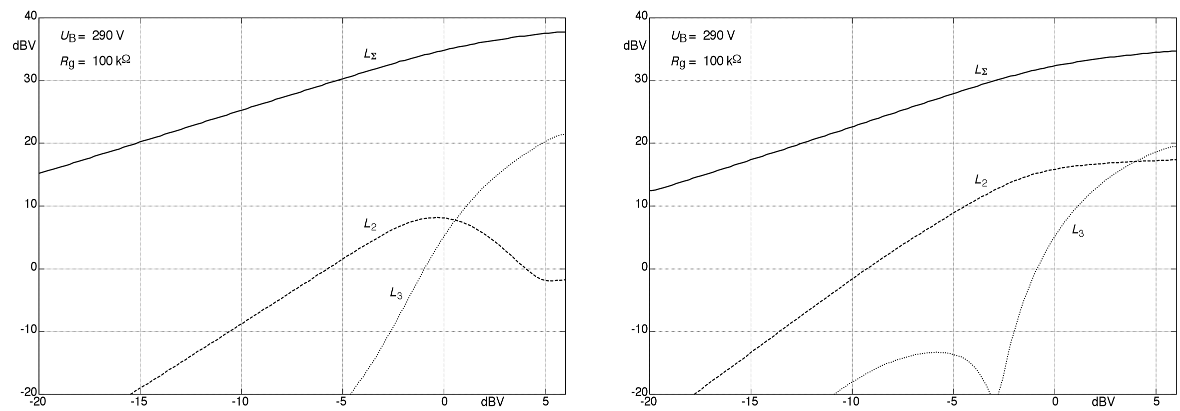

Fig. 10.2.14: Output-summation-level L_Σ, L_2 and L_3 of the VOX-circuit. Left: first half of the intermediate amplifier only (i.e. without cathode-follower). Right: complete circuit with cathode-follower.

The unusual selection of the operating point of the cathode-follower is the reason for strong 2nd-order distortion (k_2) showing up in the intermediate amplifier of the VOX. It is, however, difficult to surmise that there is any intentional design in this – the details too clearly fail to be reproducible. The non-linearity depends strongly on the supply-voltage, and on the individual tube in use, and it therefore appears – from one individual amp to the next - with varying distinction. (**Fig. 10.2.15**).

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Fig. 10.2.15: Level (left) and harmonic distortion (right) of the VOX intermediate amp; 8 different 12AX7. Grid-resistor in the first tube: R_{g1} = 100 kΩ. Supply voltage: U_B = 290V (compare to Fig. 10.2.13).
These figures are reserved for the printed version of this book.

All distortion measurements of the VOX intermediate amplifier were done with R_{k1} being bridged with a capacitor. During the history of the AC-30TB-circuit, there has, however, been a variant that fails to include this capacitor. With C_k = 25 µF, practically the whole relevant frequency-range receives an increase in gain of about 7.5 dB, while the 0.68-µF-capacitor found in some Marshall amps boost only the mids and highs (compare to Chapter 10.1). The treble-loss occurring upwards of 10 kHz happens in the first tube (R_{g1} plus Miller-effect). **Fig. 10.2.16** compares the frequency-responses measured with and without the cathode-capacitor.

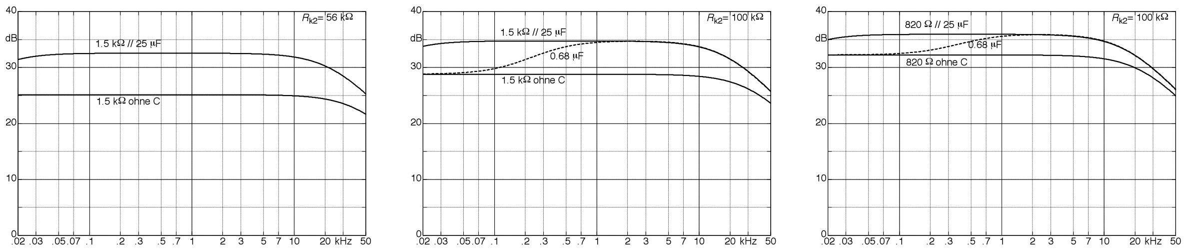

Fig. 10.2.16: Effect of the cathode-capacitor. In the VOX-circuit (left), the cathode-resistor is either bridged with 25 µF or left without a capacitor in parallel.

In the framework of discussing nonlinear distortion, the actual drive level is, obviously, of significance – there is no consistent benchmark for this, though. Guitar, playing style, setting of the tone- and volume-controls … all this determines the voltage arriving at the cathode-follower. Subtle playing may bring down the voltage level to below -20 dBV: in this case the non-linearity of the cathode-follower does not play any role. However, just turning up the volume control halfway generates – with a Stratocaster played in a normal way – easily voltage amplitudes of in excess of 1 V at the grid of the first tube in the two-tube-cathode-follower circuit. In particular the picking-attack will generate strong non-linear distortion in this scenario.