10.5.12 Special tube power-stages

In the following, a few selected tube power-stages are presented and discussed with respect to some parameters. In doing so, we will always consider that the behavior of every tube amp will depend on its individual components. All measurement curves shown were taken from a specific amp – even if an amplifier of the same type is built according to the same schematic, it can still behave differently.

VOX AC-30

The VOX AC-30 and its predecessor AC-15 are the guitar amplifiers often seen as "the" prototypes for the class-A push-pull power stage. We will not investigate the fact that there was a series of similar amps (e.g. from Gibson) – but we will look into the issue whether the AC-30 actually is powered by a class-A push-pull output stage. Technical literature consistently defines this type of operation via two aspects: the power tubes must not be driven into reverse operation, and the operating point must be located in the middle of the load line. What is the situation lined up in the VOX?

Four EL84 are employed in the AC-30, two each in a parallel configuration to double up the current. **Fig. 10.5.42** shows the output characteristic of this power pentode, with the operating point set to about 310 V / 47 mA – at least for the early variants. After the silicon rectifier had superseded the rectifier tube, voltages of more than 360 V found their way into the amp, but lets pick the "original VOX", the way it was built at the beginning of the 1960's, as object of our investigation. Without any drive signal, we find, at the operating point as given above, a power dissipation of 14 W per tube – mind you, that's 2 W in excess of what the datasheet allows. Still, that is just about tolerable (if we agree to a reduced life expectancy of the tube). However, a symmetric drive-situation (i.e. text-book class-A-operation) is not possible for this operating point: at a control-grid-voltage of about –10 ±6 V, the power tubes start limiting to *one side* of the signal, and therefore the provisional conclusion needs to be: **the VOX AC-30 does not feature a class-A push-pull power stage.**

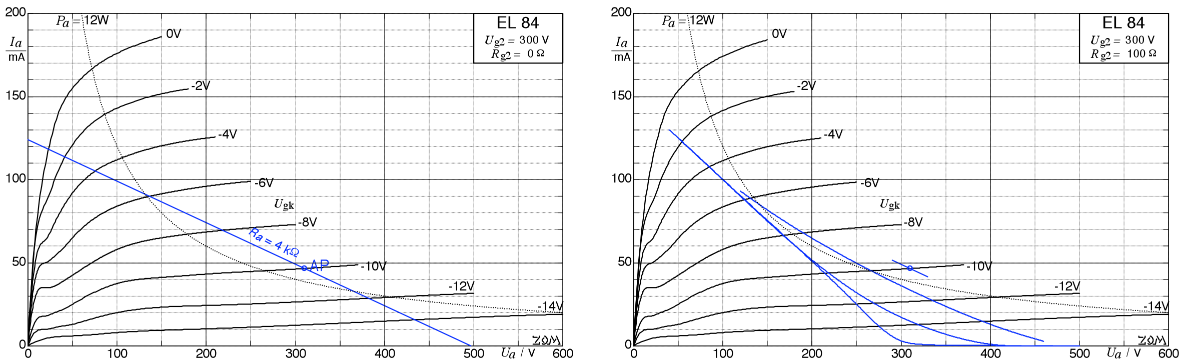

Fig. 10.5.42: Output characteristic of the EL84, ideal load line (4 kΩ) at a supply voltage of 310 V (left).
On the right measurement results for a VOX AC-30 are given (ohmic 8-Ω-load at the 8–Ω–output).

A more exact analysis of the load line confirms this diagnosis (Fig. 10.5.42, right hand section). For small drive levels the expected load line occurs, with a slope resulting from the 4-kΩ-load-impedance. For increasing drive levels, however, the OP wanders off into the lower ranges i.e. to smaller current values, and the slope changes from 4 kΩ to 2 kΩ. This indeed needs to happen, because the setting of the grid-current in the power tubes will polarize the coupling cap (Chapter 10.4.4), and also because each of the tubes now practically works in push-pull class-B mode (Chapter 10.5.3 & 10.5.5). If the AC-30 power stage indeed

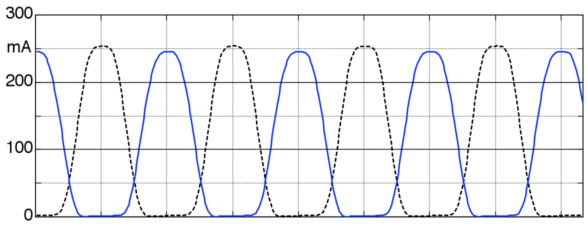

Fig. 10.5.43: Primary currents in the output transformer.

were a class-A push-pull circuit, current would have to flow during the *full* signal period. That is not the case, however, as the measurements shown in Fig 5.4.43. clearly prove. High drive-levels let current flow in the power tubes only during *half* the period, and therefore the AC-30 power stage is not a class-A power amp.

It is astonishing how tenaciously the fairytale about the allegedly unique push-pull class-A power stage keeps being repeated. In the book about VOX [Petersen/Denney 1995], this starts already in the introduction written by Brian May: *"The VOX AC-30 ... uses a Class A configuration."* Co-author Denney should know better: he has developed this amplifier, after all. The same with tube-vendor TAD: "*The sound of the class-A operation has been made legendary by the VOX AC-30! Class-A operation yields several advantages: a thick, 'three-dimensional' sound with pleasant, slight compression, singing sustain and harmonic, controllable distortion are typical*". Aspen Pittman opines in his collection of schematics: *"Contributing to the amp's smooth tone in both the clean and distorted modes is its very unusual Class A circuit designed by Dick Denney"*. Well, this power-stage circuit was not that unusual: two power pentodes, a common cathode resistor (i.e. automatic generation of bias-voltage) – we can easily find that years before in Fender amps (e.g. the Deluxe 5B3), and in Gibson amps (e.g. the GA-40); this was textbook-standard. It was only the value of the cathode resistor that varied – it set the **operating point** and made for a "hotter" or "cooler" operation of the amp (Chapter 10.5.8). And indeed, here the VOX does show a peculiarity: it operates at the hottest possible tail-end, with a power-dissipation of 14 W (average value) at the plate (the datasheet gives a maximum value of 12 W). However, a hot operation (or cathode resistor, respectively) does not automatically imply push-pull class-A.

Why push-pull class-A in the first place? To get the least non-linear distortion! Due to the superposition of differently-curved tube-characteristics, the non-linear components compensate each other, the THD decreases. Literature explicitly points out, however, that this only holds for triodes: *"For pentodes the push-pull A-circuit does not yield a significant improvement relative to the THD of the single tube [Schröder]"*. As a reminder: the EL84 is a pentode! The literature has more to in store: *"In a correctly balanced push-pull A-amplifier a capacitor is <u>not</u> required to bridge the cathode resistor. In a AB-amplifier it is, though [Langford-Smith]"*. The AC-30 does possess such a capacitor. Lastly: we find the voltage at the cathode resistor specified in the VOC-schematic; it is 10 V without input signal, and 12.5 V at full drive level. If this were a push-pull-A-circuit, this voltage would remain constant. An old **AC-15**-schematic from back in 1955 reveals a common cathode resistor amounting to 130 Ω, and R_{aa} = 8 kΩ for the load impedance at the plate. The Siemens-datasheet (from 1955) recommends, for a plate-voltage of 300 V, a common cathode resistor of 130 Ω, as well as R_{aa} = 8 kΩ. Coincidence? Of course not – the circuit designers were wise enough to follow the recommendations of the tube manufacturers. Siemens, Telefunken, Philips – they all specified R_k = 130 Ω and R_{aa} = 8 kΩ for the EL84-push-pull power stage. No, not for push-pull class-A configuration! These recommendations from Siemens, Telefunken and Philips are given for **push-pull class-AB configuration.** The AC-30 included four EL84 instead of two, i.e. double the current, and thus half the value of the cathode resistor. Old plans show an R_k of 80 Ω to begin with, but it soon was reduced to 47 Ω. Half of 130 Ω would have been 65 Ω – and so they opted for slightly higher output power (and slightly less tube endurance).

Also, the decision had been taken to do without any negative feedback (NFB). The typical Fender amplifier from the late 1950's fed back a part of the output signal to the input of the phase-inverter and reduced the non-linear distortion of the power stage that way. The AC-30 (from 1958) dispenses with that kind of negative feedback; for this reason, some presume that the distortion in the AC-30 would be "extremely high". Well, it's not – as **Fig. 10.5.44** shows. Granted, 5% THD is not exactly studio-standard, but the AC-30 was never intended to power studio monitors. At small drive levels, the harmonic distortion is a low as k_3 = 0.3%, and with increasing drive levels, the distortion gradually rises. This is in contrast to power-stages that feature strong NFB and, correspondingly, a sudden increase of the distortion at the drive-limit. Apparently, VOX-guitarists prefer the gradually rising distortion.

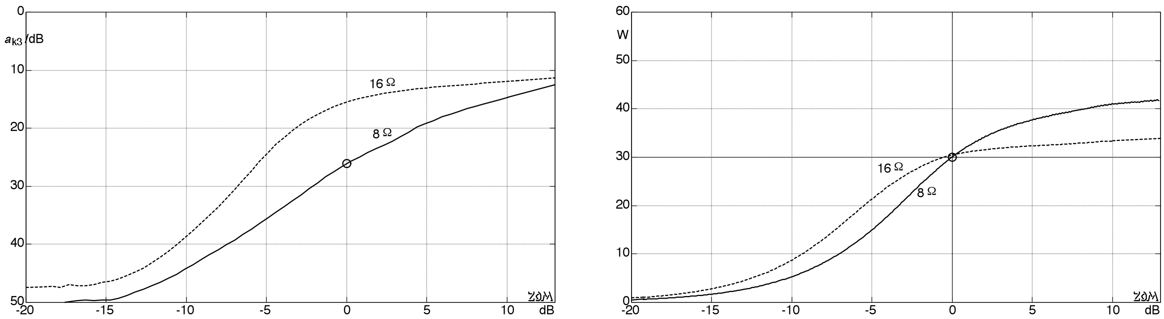

Fig. 10.5.44: AC-30, 8-Ω-output: distortion below signal (left), power (right); Abscissa referenced to P = 30 W.

It has already been mentioned that tube power stages cannot be described with *one single* characteristic curve because the operating points shift due to re-charging effects. **Fig. 10.5.45** shows corresponding measurements taken with varying drive levels. With increasing drive, the transmission characteristic flattens out, with a saddle-point appearing in the origin. For a load of 16 Ω (right hand part of the figure), the curves generally run steeper (high internal impedance ≈ current source). The flattening of the curves can be interpreted as a kind of compressor that reduces the gain of the power stage as the signal level increases. The load-dependency of the output voltage results in emphasizing the loudspeaker resonance and the high-frequency signal-components (compare to Chapter 11). In contrast, a power stage with strong NFB would have a drive-level-independent, sharply bent characteristic similar to the one discussed in Chapter 10.1.4. The maximum power-yield merits some attention, as well: with a stiff voltage-source (low internal impedance), the power-limit for a 16-Ω-load would be half of that for an 8-Ω-load ($P = U^2 / R$); the AC-30, however, reaches more than 80%.

Fig. 10.5.45: Characteristic curves of an AC-30 power stage. Left 8 Ω, right 16 Ω load (at the 8-Ω-output).
These figures are reserved for the print-version of this book.

This special power-stage characteristic is also documented by sweep measurements. For the latter, the AC-30 was connected to a Marshall 1960-AX – not your typical AC-30 speaker but able to take significantly more punishment than the fragile and overly expensive blue Celestions in the combo. **Fig. 10.5.46** shows the voltage level measured at the 16–Ω–output, on the bottom for small drive level and on top for overload.

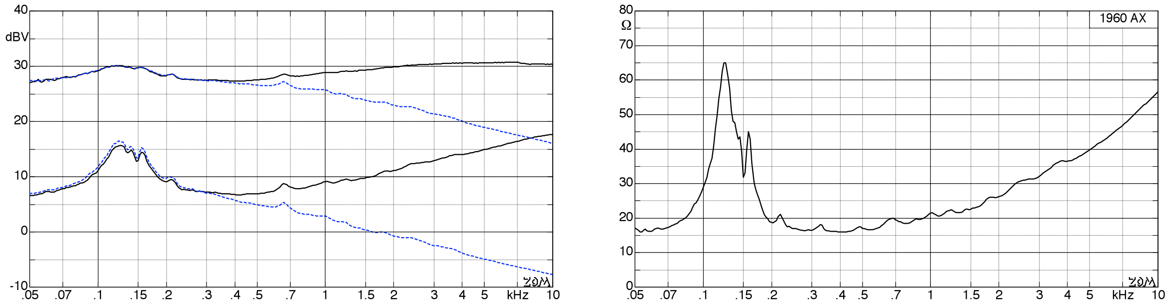

Fig. 10.5.46: Frequency response of an AC-30 power stage, 16-Ω-output loaded with 1960-AX,
Cut CCW (---) , Cut CW (——). Right: loudspeaker impedance (in a reflecting room). Compare to Chapter. 11.8.

It has been repeatedly noted that the power tubes deployed in the VOX do not only suffer when the amp is overdriven, but are under strain already with no input signal present at all. In **Fig. 10.5.47**, we see the power dissipation at the plate and at the control grid for drive levels rising by 30 dB. Without input signal, the power dissipation at the plate is about 14 W in each EL84. The strain on the plate decreases as the drive level rises, and after switching off the input signal there is a short peak in the strain. At idle, the **strain at the screen grid** is just below the allowable limit; with an input signal present, the limit value is very easily exceeded, especially with a high-impedance load (for typical loudspeaker impedances see Chapter 11).

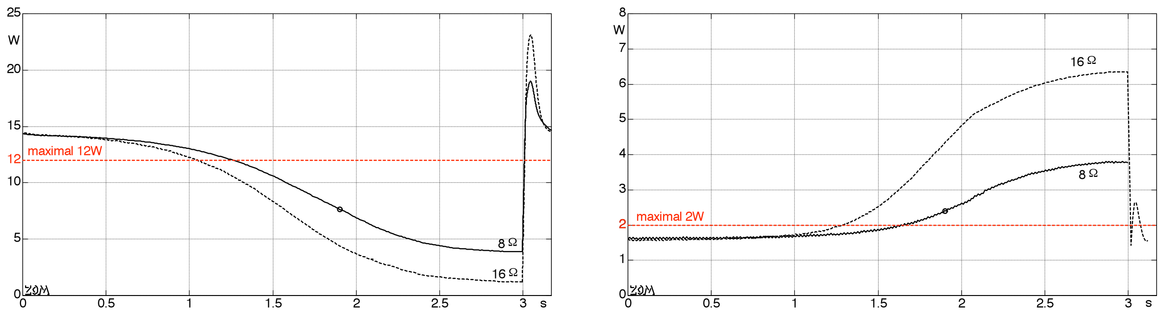

Fig. 10.5.47: AC-30: plate dissipation (left), screen-grid dissipation (right). The level of the sine tone at the input linearly rises by 30 dB from 0 … 3 s, at t = 1.9 s nominal power is reached for an 8–Ω–load. At t = 3 s the input signal is switched off, subsequently there are balancing processes in the capacitors of the power-stage.

The measurements for Fig. 10.5.47 were taken with an AC-30 that had a tube rectifier (GZ-34) in its power supply. Replacing the GZ-34 by silicon diodes will lead to an increase of the strain at the plate in idle to about 17 W; the peak after the switching-off reaches 30 W. The maximum stain on the screen grid exceeds 6 W for an 8-Ω-load, and 10 W for a 16-Ω-load! Since real loudspeaker impedances (including the so-called 16-Ω-speaker) can become higher than 16 Ω (Chapter 11.2), even stronger overload needs to be expected.

The **power supply** merits attention for another reason: the operating voltage for the power pentodes is directly taken from the cathode of the rectifier tube – the voltage has a corresponding ripple. This is not a problem at small drive levels, but it is for strong drive levels since clearly noticeable amplitude modulations result.

Abb. 10.5.48 depicts the time-function of the output voltage, with the 8-Ω-output loaded with a purely ohmic 8-Ω-load. As long as the output voltage is not limited, any fluctuations in the supply voltage represent a (superimposed) common-mode interference that is largely suppressed by the output transformer – the output voltage of the transformer remains un-modulated (left hand section of the figure). In overdrive-operation, however, an asymmetric limiting appears: the maximum plate-current depends on the supply voltage while the minimum plate-current does not (it is practically zero). As a result, an envelope depending on double the mains-frequency is generated – it may be seen, as a first approximation, as a 100-Hz-amplitude-modulation (AM). It is not that a 100-Hz-tone is superimposed onto the input signal; rather, the latter is changed (modulated) in its amplitude. The **envelope** over time (which does not actually exist but is an imaginary auxiliary line) is shown dashed in the right-hand section of the figure.

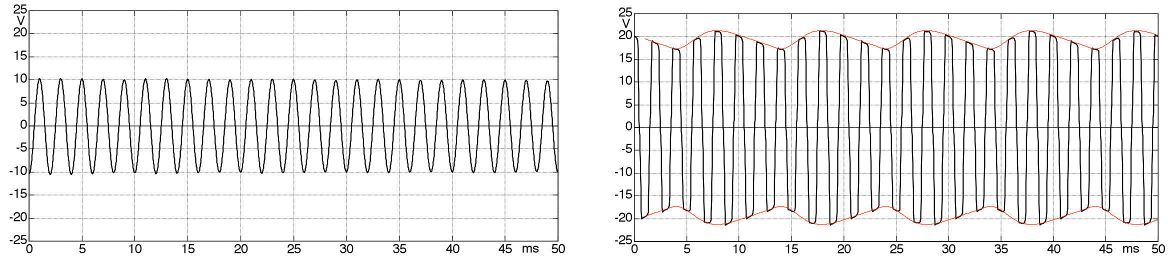

Fig. 10.5.48: Voltage at the 8-Ω-output for an 8-Ω-load. Drive level: half (left), overdriven (right).

Spectrally seen, this 100-Hz-modulation does not make itself felt as a line at 100 Hz. Rather, modulation-lines *next to* the signal-lines result. As a model, the AM can be illustrated as the multiplication 'signal x envelope', corresponding to a convolution in the frequency domain. Since the envelope is not of an exact sine-shape (Chapter 10.7), we not only get a single pair of additional lines (±100 Hz), but several pairs. The level-spectra related to Fig. 10.5.48 are shown in **Fig.10.5.49**: in the left-hand picture, the modulation lines (lateral lines) have a level of 45 dB below the carrier – the (3^{rd}-order) distortion (at 1.5 kHz) is 1%. For the overdrive operation chosen in the right-hand section of the picture, the 3rd-order distortion amounts to 20% with the level-distance between the modulation lines having decreased to 27 dB.

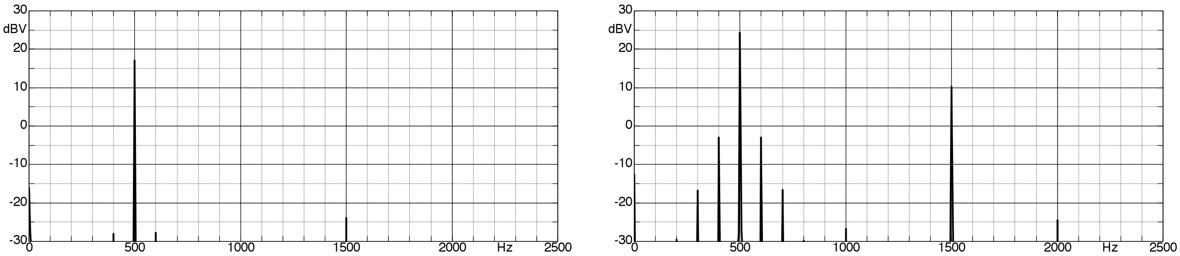

Abb. 10.5.49: Level-spectra related to Fig. 10.5.48.

Not every amplitude modulation that can be measured is necessarily audible – the AM shown in the right hand section of the figure can, however, be assumed to be noticeable as an additional roughness. In the area of psychoacoustics [12], the term "**roughness**" designates auditory perceptions created by fast signal fluctuations that could be labeled as a kind of buzzing sound. Measurements of harmonic distortion normally do not encompass modulation distortions; therefore, dedicated measurements are necessary for this type of distortion.

Marshall JTM-45

James Marshall opened his drum shop in London in 1960, and soon began to sell amplifiers alongside the drum kits. First, the rather expensive Fender amps and others, but from 1962 also the first Marshall amps that his technician Ken Bran assembled as close copies of the Fender (tweed) Bassman from 1959. Young guitarist James Marshall Hendrix was a customer, and both had laid the foundation of their respective careers: one went by the name Jim Marshall, the other called himself Jimi Hendrix. It was Eric Clapton, however, who first attracted worldwide attention to the Marshall amp. He recorded, together with John Mayall, an album the cover of which included a picture showing in the background a Marshall combo: the legendary JTM-45, with model number 1962.

What's so special about the JTM-45 power stage – what is it that creates the legendary sound? A sound – as Gitarre&Bass 7/06 puts it (for once not onomatopoetically but tribo-poetically⊕) – of a *"fat and creamy crunch-tone"*, but *"never a Marshall-typical distortion sound"*. Excuse me?!?! A non-Marshall-sounding Marshall? Although we are told that the JTM-45 includes *"all the ingredients responsible for the plexi-sound♣ that achieved legendary status later"*? Presumably, you can see these ingredients – but you can't actually hear them. 18 months before (G&B 2/05), the JTM-45 was described as *"even hotter and more aggressive"*, and 6 months before (G&B 2/06) with *"clear and fat, with a soft spectrum in the mids"*.

Clearly, fat may be hot – why not. How this hot-fat sound originates is subject of innumerably speculations. It starts with **Clapton's Les Paul** for which pertinent literature holds in stock a vintage of '58, '59. or '60. Shouldn't that be all the same to us? No way – that makes for one heck of a difference: after all, the frets changed over these production-years (they got wider), the neck angle also (it increased), and the cross-section of the neck, as well (it got more narrow). All this should be, of course, "tone-affecting", shouldn't it? And so we would expect E.C. to answer the question which model he bought back in the day (in June 1965 according to G&B 9/08) with an immediate: the '58, of course, because of the big neck that – as we all know – improves richness of tone and sustain [G&B Gibson-Special]. However, he does not answer anything of the like but merely notes: *"No idea"*. No idea? Geez, Eric (as musician, one is on a first name-basis right away), you should know that: the increased neck-angle of the '60-Paula (as this type of guitar is designated in circles of experts) alone would have ruined sustain, and the thin neck of the '60 "*has no acceptable vibration characteristic whatsoever [G&B 3/97]*". Very strange that Eric does not remember. Thank Eric we do have recordings surviving from those "Clapton is God"-times – Beano and such – so we should easily be able to pick out what the deal was. Here's the latest level of knowledge: *"Today the general opinion is that the guitar concerned was a '60-model since both Clapton and Peter Green describe the 'slinky' neck [G&B 9/08]."* Indeed these are tough times for guitar experts: on the one hand they continuously are required to explain that the smallest details of a Les Paul (varnish, frets, neck, pots or tone-caps) have an immense influence on the sound, but on the other hand there is not anyone in the world who could recognize, on the basis of these sound-specifics, and from listening to the Bluesbreaker-LP, the version of the guitar. The stopgap solution then is to reason the guitar-type from on memories regarding the neck-profile. What an odd, make-believe world of Gods and experts … and stopgaps.

Well then: we don't know any specifics about the guitar, but the amp is known: a **JTM-45, 2x12-Combo Type II**, in all likelihood fitted with alnico-speakers (G&B 9/2008).

⊕ Tribology = teachings of friction and lubricants

♣ Hopefully, the plexi *will* sound like a Marshall – or still not, either??

 Translated by Tilmann Zwicker

In all likelihood? Again, nobody knows exactly. Alnicos will yield *"particularly sweet and harmonically rich treble"*, that is known the latest since G&B 8/05, and so we should be able to hear from the Beano-LP whether alnicos or ceramics are at work. But again, the LP denies any analysis, and although ceramic-powered speakers sound *"entirely different"* compared to alnicos, nobody can pick out from the record which speakers were recorded. Unfortunately, it was just in those days that Marshall started to switch over to the ceramic-Celestions so that both types would be eligible. Again, let's ask Mr. Clapton – he should … no? Again, no memory? Well-well, dear Eric: did various substances abound that much already back then? Indeed?! Then we shall not insist. And on to a look into the expert literature: *"Because Clapton ran the amplifier at full volume, the Alnicos may have been damaged. He may have replaced them with the higher wattage, ceramic magnet Celestion Greenbacks."* This is the voice of Premier Guitar (February 2008). Clapton replacing his alnicos by ceramics? His alnicos, those that will produce – according to Premier Guitar – *"sweet warm tones and a smooth midrange"*? And that generate, according to G&B, *"particularly sweet and harmonically rich treble"* and do *"sound harmonic and with a bite"*. Entirely differently then, compared to the subsequent ceramic-Celestions that yield *"plenty of midrange crunch"* but *"...sounded very different from the Alnico type speakers used in other Marshalls [David Szabados]."* Of course nobody knows whether Eric did actually change the speakers: *"He may have"*, and he himself can't remember. That should be not a real problem, though, because there is that LP, and from it we should be able to pick out the speakers due to: *"sounded very different."* It remains difficult, though, because on the one hand the ceramics sound somehow very different – but not really, on the other hand, because otherwise we would be able to pick them out. In conclusion: we don't know anything in detail about the speakers, either.

We do know one thing, though: the **output transformer** was sourced either from Radio-Spares, or from Drake. That is certain: either / or. It is also known with certainty that the two transformers were not equivalent: the Drakes were *"rougher and more distortion-happy, more mid-rangy, darker than the R.S."*. Unfortunately we cannot pick out from the recording which transformer was on duty for Mr. Clapton, and therefore the retrofit-supplier offers replicas of both transformer, just to be safe. They cost about 250.-- USD (that's for one, not for both), thank you very much, plus customs and shipping, and there you are, another step nearer my God to Thee. You gotta understand why these transformer are so expensive: hand-made! Encouragingly, the core-sheets are not sawed out with a jigsaw – that would have made them seem a bit overpriced. Around 300 USD, that's o.k. – it's a detailed copy of the Clapton-gear, after all. In all likelihood – because we still do not know whether Drake or RS, and moreover the resident expert at G&B offers yet another variant: Mr. Clapton may have operated a pair of speakers having (in conjunction) an impedance of 8 Ω from the 16-Ω-ouput of the transformer. That's a factor of two, so a 100-%-mismatch – or is it 50%? Sorry, it is not easy to theoretically get a handle on these things, so we better draw some conclusions: Clapton's JTM-45-sound is legendary, we all agree on that. If you want to copy that sound, you acquire either a '58- or a '59- or a '60-Les Paul (allegedly differing audibly in sound), fit your JTM-45 with either a Drake- or an RS-transformer (allegedly differing audibly in sound), and install two alnico- or two ceramic-Celestions (allegedly differing audibly in sound) – and now you should firmly, certifiably reside in the midst of Beano-tone. Wow!

Clapton's Bluesbreaker-sound is great – how it originated is uncertain. Readily overlooked: a guitar player was involved of for the time extraordinary skill and talent, and of course studio technology will have had an influence. Clapton's Marshall-combo has disappeared – its specs are unknown. What remains is to use schematics and replicas, knowing that a schematic does not document all details. In the following we will analyze what the hand-drawn sketch in Doyle's Marshall-book reveals.

Marshall's (or rather Bran's) first amplifier was the JTM-45, with two **KT-66's** operating in a push-pull class-AB configuration in its power stage (with a few exceptions). For this mode of operations, the GEC-datasheet specifies an output power of 30 W. The number "45" after the JTM therefore is not an indication of the RMS-power but just promises a seemingly 50-%-advantage over the AC-30. The JTM-45 power stage includes a negative feedback which is relatively strong for a tube amp, with several consequences: non-linear distortion is reduced, loudspeaker resonances have less of an effect, and the amp may oscillate in the RF-range, in particular with the presence control turned down. Feedback functions as **negative feedback (NFB)** if the signal led back to the input is added to the control signal in opposite phase. In the high-frequency ranges, however, phase-shifts may occur (e.g. in the output transformer), and the negative feedback can turn into positive feedback: the amp will oscillate. These oscillations may only happen in a certain range of the drive-signal range where the specific gain and phase-shifts (both being drive-level-dependent) make for a loop gain of larger than 1. It is necessary to avoid such oscillations even if they are located in an inaudible frequency range to begin with: first, because they result in the operation of an illegal RF-transmitter, and second, because they put unnecessary strain on the power stage.

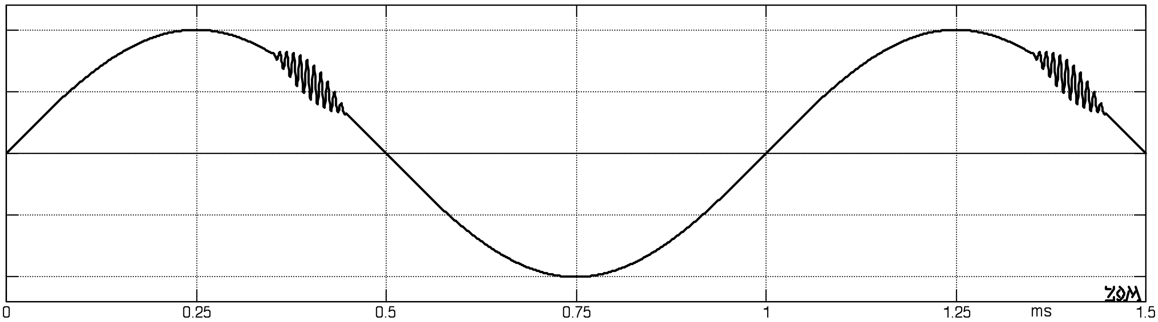

Fig. 10.5.50: 1-kHz-tone with superimposed RF-oscillation.

Fig. 10.5.50 depicts, in principle, the shape of an "RF-infested" audio signal. The RF (often around 150 kHz) is not always recognizable as a clean oscillation – it may result merely in a widening or a smearing of the curve of the audio signal. Small capacitors may be found in the circuit as a "brute-force bug-fix", soldered-in at "appropriate locations" to squash the malady. Much better would be a textbook RC-compensation reducing the loop-gain at high frequencies without adding significant phase-shifts (a LP with limited, defined attenuation at high frequencies). Sure, this is not a trivial topic because with every tube-replacement, the condition for the oscillation is newly negotiated – on top of also being dependent on the loudspeaker. Those who want to address this issue in a somewhat less sophisticated manner find a cooperative partner in the form of the Presence control. Just turn it to the right (up, CW) and the annoying RF is gone. It may be surprising that increasing the gain at high frequencies will choke the oscillation – however this reduces the loop gain that determines the tendency to self-oscillation.

Besides the signal-feedback via the NFB-network designed into the amp, another factor may support RF-oscillations: capacitive coupling of non-shielded components. In fact none of the components found internally in a Marshall are shielded, which is why even the position of individual wires can co-determine the tendency to oscillate. Incidentally, this is another detail that cannot be found in the schematic.

With the JTM-45 power stage operating in class-AB mode, there is, besides the choice of tubes, another degrees of freedom: the bias-current (or the offset-voltage at the grid). It would take us too far afield to show all significant characteristics for all appropriate tubes at several bias-current-settings, and therefore just a few examples shall do. **Fig. 10.5.51** shows measurements of the harmonic distortion (a_{k3}), without NFB in the power stage (left) and with NFB as found in the original circuit. In his comments regarding the Marshall circuit, Ken Bran does not make any secret of the fact that the Fender 5F6A-Bassman was used as a model. Therefore, it is not surprising that in both amplifiers, a 27-kΩ-resistor feeds back the signal to a 5-kΩ-presence-control. However, in the Bassman the 2-Ω-winding of the output transformer is the source, while in the JTM-45, the 16-Ω-winding is tapped for this. The negative feedback in the Marshall therefore is three times as efficient (impedances are transformed with the *square* of ratio of the windings). Whether this was by chance, or due to ignorance, or intentional … who would know 50 years later? In any case, for the successor-models of the JTM-45, the degree of NFB was reduced again – for whatever reason.

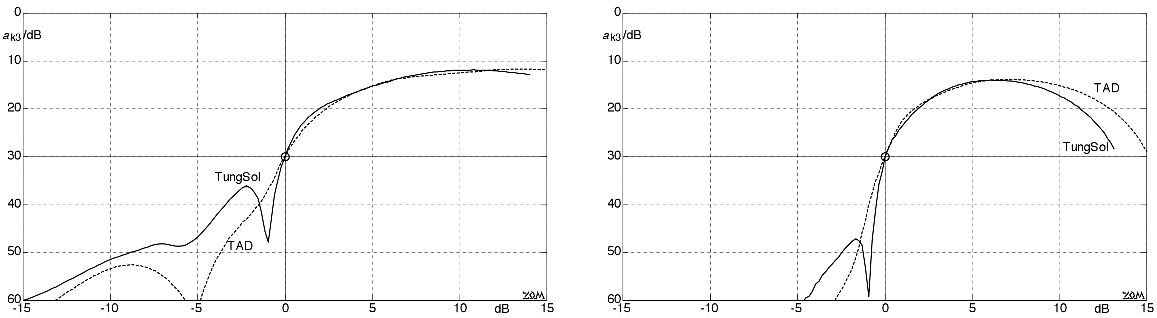

Fig. 10.5.51: JTM-45, harmonic distortion without (left) and with (right) negative feedback in the power stage. An 8-Ω-resistor was connected to the 8-Ω-output for the measurements, R_{aa} = 8 kΩ, f = 500 Hz.

In **Abb. 10.5.51**, the abscissa is set such that at 0 dB and for the specified loading, the signal is just starting undergo limiting. A THD < 1% (i.e. with the generated harmonics 40 dB below the signal) are surely irrelevant for the auditory perception – presumably, 30 dB difference (i.e. 3% THD) would still be inaudible in a guitar amp. There is no binding limit value, though, because too many parameters decide about the audibility of nonlinear distortions. At first glance, the JTM-45 power stage distorts similarly to a transistor power stage – due to the strong NFB. It remains practically distortion-free⊗ for the non-limited signal, and shows textbook increase of harmonic distortion above the drive-limit. This sentence should in fact be carved in stone: "Marshall's power amp distorts like a transistor power stage" – considering that all those amplifier gurus keep praising the specially-bred Marshall distortion! But then, where should we find something special when we have a copy of an American amp the circuit of which was taken from tube-manuals? The JTM-45 power stage includes a textbook differential amplifier as phase-inverter, two beam-tetrodes with a textbook drive-scenario, and an output transformer as it was offered to a clientele that we would call "hobbyists".♣ It must not surprise us that secret forces are entrusted to these "Radiospares-Deluxe-Transformer" by its fan base – it is, after all, in the sacred company of Ken Bran's special solder the atoms of which always automatically redirect themselves towards Hanwell. Caution, though, dear buddies: after lugging the amp around you gotta wait for 4 minutes – as we learn in the chemistry course, tin and lead have 4 valence-electrons … they are the so-called inert (passive) heavy metals, and the redirecting of the atoms will take a little while.

⊗ 60 dB level difference between the generated distortion and the signal corresponds to a THD 0,1%

♣ In fact, many guitar amp designers had/have a background in ham-radio.

Are you startled yet? Relax, there are, after all, differences to a transistor amp – we must not conclude a general equivalence from the similarity of two distortion-curves. The combination of power tubes and output transformer results in a special power- and distortion-characteristic that in this manner cannot be found in transistor amps. In the JTM-45, the two KT-66 operate towards an output transformer with a rather high primary impedance. Presumably, it first was the RS-Deluxe transformer – nobody can remember which transformer resided in Clapton's "Bluesbreaker"-amp. A: it's been a long time, and B: RS was not a manufacturer but a retailer, and therefore several manufacturers are possible. An American retrofitter (who is not adverse to selling his replacement-transformers) surmises that, in the original JTM-45, an RS-Transformer with R_{aa} = **6.6 kΩ** was at work. The magazine Gitarre&Bass supposes an RS-Transformer with **8.0 kΩ** included in the amp (7/2006), but also considers an 8-kΩ-Drake to be a possible candidate (9/2008). Why would there be such high impedances? The RS-transformer used to begin with was an all-round device intended for applications as universal as possible. Consequently it offered four different primary connections: for KT-66 and EL34 with additional ultra-linear connections R_{aa} = 6.6 kΩ; for 6L6, 6V6 and EL-84 R_{aa} = 8.0 kΩ, or R_{aa} = 9.0 kΩ. The Marshall JTM-45 did not have the ultra-linear configuration, but the KT-66 with R_{aa} = 6.6 kΩ or 8.0 kΩ is today seen as historically correct. By the way, what does the KT-66 datasheet specify? We find R_{aa} = 7 kΩ (ultra-linear), or 8 kΩ for the regular class-AB power stage; for both versions with a cathode-resistor, though. The JTM-45 did not include such a resistor! For this bias-variant, the KT-66 datasheet specifies **5 kΩ** but the supply voltages do not entirely match. Conclusion: neither the output-transformer manufacturer nor the tube manufacturer supplied any exactly matching guidelines to the Marshall developers. Anything else is speculation.

Measurements of the family of output characteristics show that R_{aa} = 8 kΩ is not really conducive for an instrument amplifier (**Fig. 10.5.52**). With a load of 8 Ω connected to the 8-Ω-output, the load line meets the output characteristic of the KT-66 at rather too low a point. In our example, the KT-66 has a scarily high residual voltage but that is another matter. With half the load impedance (right-hand section of the figure), we would close in much better on the ideal condition – and so the conclusion is: for the KT-66 in the JTM-45, ***R_{aa}* = 4 kΩ would be optimal**. That is, at least if a high-power yield is requested. For minimal harmonic distortion, higher primary impedances could be considered, too … but in a Marshall? A 4-Ω-load at the 8-Ω-output would be approximately equivalent to an 8-Ω-load at the 16-Ω-output, a variant also thought possible in Clapton's amp by G&B (09/2008).

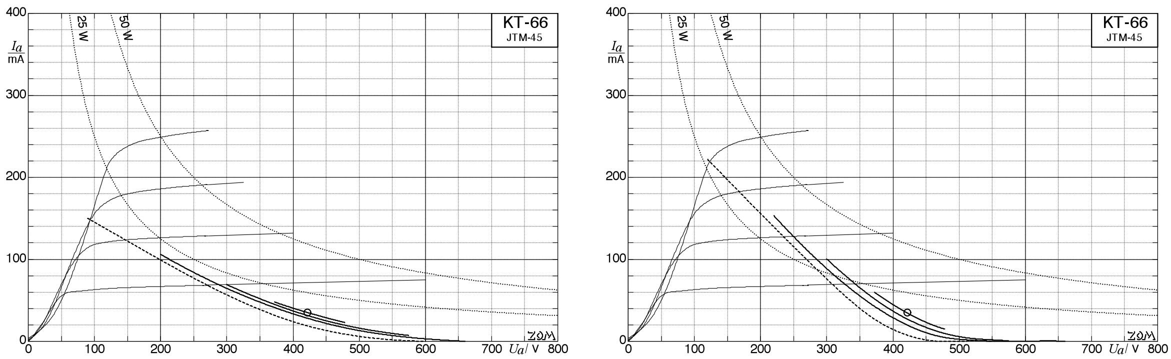

Fig. 10.5.52: Load characteristics, R_{aa} = 8.0 kΩ, 8-Ω-output at an ohmic load of 8 Ω (left), and at 4 Ω (right).

In its measured data, the TungSol-KT-66 corresponds approximated to the GEC-datasheet, while the TAD-KT-66 fails to deliver the required power due to its excessive residual voltage. On the other hand, the latter distorts somewhat less as already shown in Fig. 10.5.52. It is, however, not possible to say how long these evaluations hold: such data change too often.

 Translated by Tilmann Zwicker

Fig. 10.5.53 shows the output power of the JTM-45, dependent on the level of the input signal. Fitted with the TAD, it struggles to climb over the 30-W-mark even when overdriven (and loaded with the nominal impedance), while with the TungSol-tubes, it is o.k. to call it a "30-W-amp". Only when overdriven, and with a mismatched load, it gets close to 45 W. Its daddy, the Fender Bassman, could to offer more (Fig. 10.5.62), until Marshall later outperforms it again using the EL34.

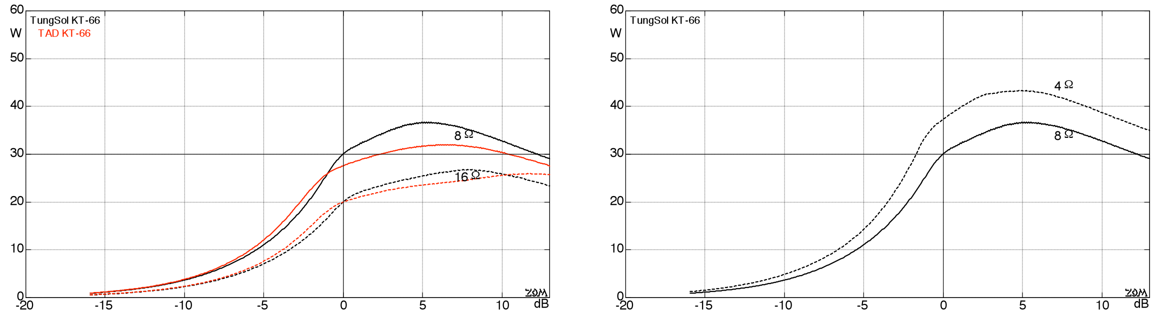

Fig. 10.5.53: JTM-45, output power at the 8Ω-output, loaded with 16 Ω, 8 Ω and 4 Ω, purely ohmic.

In **Fig. 10.5.54** we see the frequency response of the power-stage loaded with a real loudspeaker. With the presence control turned down, the characteristic is almost frequency-independent, despite the frequency-dependent load. As the power stage is overdriven (30-dB-curves) the presence control looses its effect. While the JTM-45 has strong negative feedback (NFB), this apparently was not seen as "the" secret of the Marshall-sound – otherwise it would have been retained in later models. But just that does not happen: rather, the NFB-tap drifts from the 16-Ω-winding to the 8-Ω-winding, and later even on to the 4-Ω-winding; at the same time Marshall increases the feedback resistor from 27 kΩ to 47 kΩ and later even to 100 kΩ. Both these changes reduce the NFB – that, however, affects the successors fitted with EL34's.

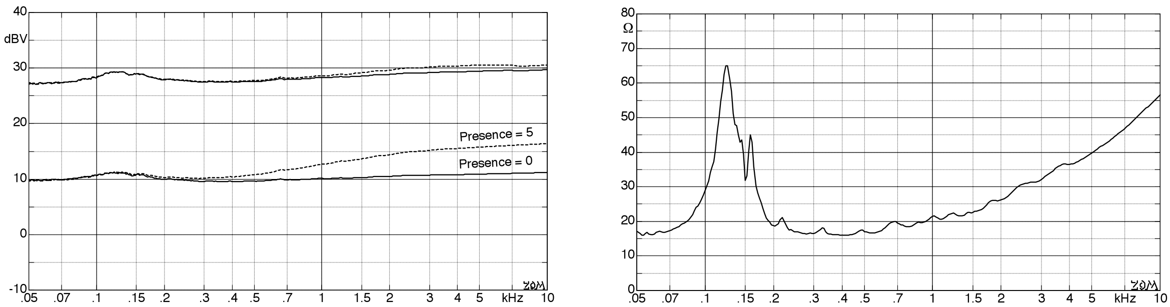

Fig. 10.5.54: Frequency response of a JTM-45 power stage, 16-Ω-output loaded with a 1960-AX speaker (left). Magnitude of the loudspeaker impedance: 1960-AX measured in a room with reflecting surfaces (right).)

We had seen in Fig. 10.5.52 that an 8-kΩ-transfromer does not really challenge the power tubes much. For the power-curves shown in the following, we therefore used a **4-kΩ-transformer**. Connecting the latter, at its 8-Ω-output, to a 16-Ω-load, we arrive approximately at the original conditions (R_{aa} = 8 kΩ). With an 8-Ω-load, the load line just about meets the "knee" of the output characteristic of the tubes (R_{aa} = 4 kΩ). Chapter 10.5.9 already illustrated the effects of such load changes: the smaller the load impedance, the higher the strain on the plate; the larger the load-impedance, the larger the strain on the screen grid. Valid for the JTM-45: R_{aa} = 8 kΩ is the presumed original value; R_{aa} = 4 kΩ would be optimized in terms of the power yield.

The strain on the power tubes is shown in **Fig. 10.5.55** for an ohmic 8-Ω-load at the 8-Ω-output. As the drive level mounts, the strain on both plates first decreases. Then, however, the strain on one of the two power tubes rises again. At the moment the input signal is switched off, we see a high peak in the strain resulting from charge-balancing processes in the coupling capacitors. Since this peak only has a short duration, it is not particularly dangerous to the tubes. Conversely, the screen grid is in more danger: as soon as the power stage is overdriven, the power dissipation in the screen grids mounts: ongoing overdrive does overload the tube for the duration, and its lifetime is shortened.

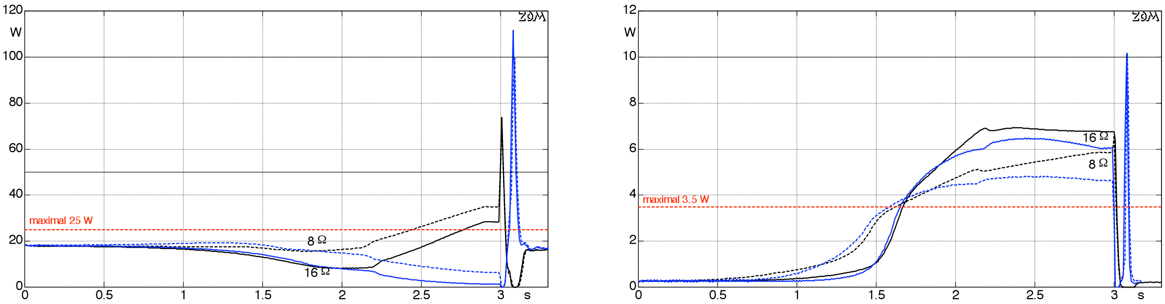

Fig. 10.5.55: JTM-45: power dissipation at the plate (left), and at the screen grid (right). From 0 to 3 s, the level of the input sine-tone rises linearly by 30 dB; at $t = 1.5$ s a power of $P = 30$W at an 8-Ω-load is reached.
At $t = 3$ s the drive signal is switched off; balancing processes in the capacitors of the power stage follow.
The power dissipation of one of the power tubes (TAD KT-66) is shown in black, the one of the other in blue.

The transmission characteristic from the input of the differential amplifier to the power output is shown in **Fig. 10.5.56**. As soon as the power amp is overdriven, the curve looses its point-symmetric shape, and the duty cycles change. The reasons for this are potential shifts in the differential amplifier (phase inverter) and the grid-current flowing in the power tubes. Until just short of the drive-limit, the output signal is proportional to the input signal as can be seen in the left hand picture. As overdrive occurs, the output voltage experiences limiting but also becomes increasingly asymmetric, and consequently the characteristic curve shifts (the average value needs to remain zero). Since the limited signal does now include several rather than a single frequency, phase-shifts occurring in the output transformer (acting as a high-pass) start to take an effect. The transmission characteristic is not memory-free anymore but decomposes into a rising and a falling branch. To retain sufficient clarity, Fig. 10.5.56 does not show the corresponding hysteresis-loops but average values. If a loudspeaker were to be connected rather than the ohmic load resistor, the complex impedance would result in even more complicated curves.

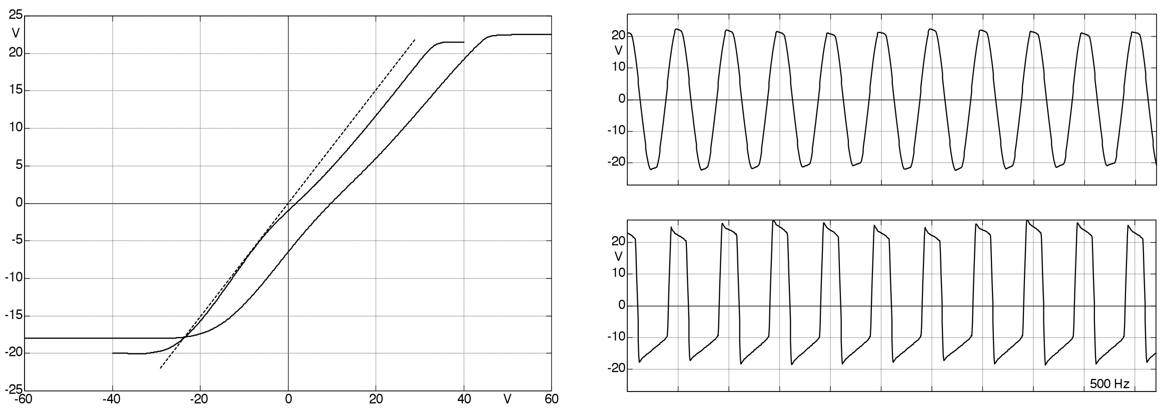

Fig. 10.5.56: Idealized transmission characteristic (left); time-function of output for ohmic nominal load (right).

The **output transformer** (OT) does influence both the frequency response and the non-linear distortion of the power stage – but there is no mystery about that. In order to conduct measurements as well as listening tests we put together a test-circuit that allows selecting between 10 different output transformers via a switch. Among others, we had in the running: a Marshall-JTM-45-transformer, a TAD MJTM45A, a Hammond 1750Q, an IGOT-JTM45 plus a few 4-kΩ-transformers. In the frequency range relevant for the guitar, all transformers showed practically the same frequency response. Regarding maximum power and harmonic distortion, there is no more than a just-about-noticeable difference between a 4-kΩ-OT und an 8-kΩ-OT. Consequently, these results cannot be the basis for advising a swapping of transformers. When comparing two OT's, the most important parameter is the transformation ratio. If two top-quality transformers produce audible differences in sound, this is most likely due to a different **transformation ratio**. However, turns-ratios can be set and checked very easily and precisely, and therefore any exorbitant pricing of a transformer is not justifiable merely on the basis of a special transformation ratio.

This is a good point to take a short side-trip into **advertising psychology**: as an exceptionally gifted transformer winder, what can you do to increase your turnover? You could write: "we are the best!" … but they all write that. Rather, you could motivate an independent trade-journalist to write an editorial contribution about, say, "Restoring Marshalls". You then find a well-known musician not happy with the sound of his/her Marshall – and off you go. Taking stock: a boring sound, odd harmonics (!), the worst Marshall since dinosaurs (of any kind) roamed the planet. After this diagnosis, on to the therapy: swap components! You will want to grab: genuine carbon-resistors, yellow or orange capacitors (depending on which supplier forks over a more generous subsidy), and of course: a new mains transformer (it supplies all that power, after all), and a new output transformer (all that music needs to pass through it), and, since we're at it, throw in a new choke. Ah – now we're in brown-sound-city: the best Marshall ever heard! Last, make the well-known musician rave about the unbelievable improvement in sound, and make him/her recommend that everybody installs these wicked transformers. Now, it only remains to hope that nobody checks www.tone-lizard.com/marshall-myths, where a discussion can be found mentioning – with relish – that for repairs frequently a damaged Marshall-transformer was exchanged for a low-cost no-name transformer … and *not a single complaint* was ever received. Delightful stuff.

It is normal and necessary that manufacturer advertise their products; that they hire musicians to praise the unrivalled sound may be criticized but there's not much that can be done about that. From a technical point of view, nothing stands against swapping a correctly working Marshall transformer for an expensive clone. It is easily conceivable that a guitarist feels better after the swap than before – but that has different reasons then.

The JTM-45 and its output transformer have achieved cult-status. Supply (meager) and demand (high) now regulate the price (enormous). In Doyle's Marshall-book we read, however, that the differences to the 5F6-A-Bassman are in essence due to the different loudspeakers (Celestion 12" vs. Jensen 10"), the different input tube (12AX7 vs. 12AY7), and the higher negative feedback in the power-stage of the JTM-45. The RS-output-transformer is not the reason for a special sound, as Doyle cites the design-director of Marshall. Hopefully, nobody still believes that a steel-chassis will make the amp sound different compared to an aluminum-chassis. You over there still do? Be informed that this is another myth. Aluminum has paramagnetic characteristics while steel is ferromagnetic?! So? The effects on the sound are about as dramatic as the color of the control-knobs is.

There is, however, a sound-determining parameter that has so far been investigated too little: the **2nd-order harmonic distortion**. In a transistor amplifier we usually pay close attention to symmetry, and consequently even in overdrive mode the 2nd-order distortion is reduced to insignificant levels. The tube power-stage, on the other hand, shows a rather different behavior (e.g. Fig. 10.5.56): as the overdrive increases, the duty-cycle changes and k_2 may not be neglected anymore. **Fig. 10.5.57** shows distortion measurements: the differences between the individual curves are rather substantial. What is the reason? These are different tubes (all KT-66). TungSol, TAD, and several original GEC-KT66 from the good old days. They are accredited with qualities that allegedly are not achievable anymore today, and so a pair of GEC-KT-66 may be offered (at the time of writing) for 280 Euro. That could be $699, as well, if we jump to the other side of the Atlantic (Ebay, December 2013). Stiff prices, indeed.

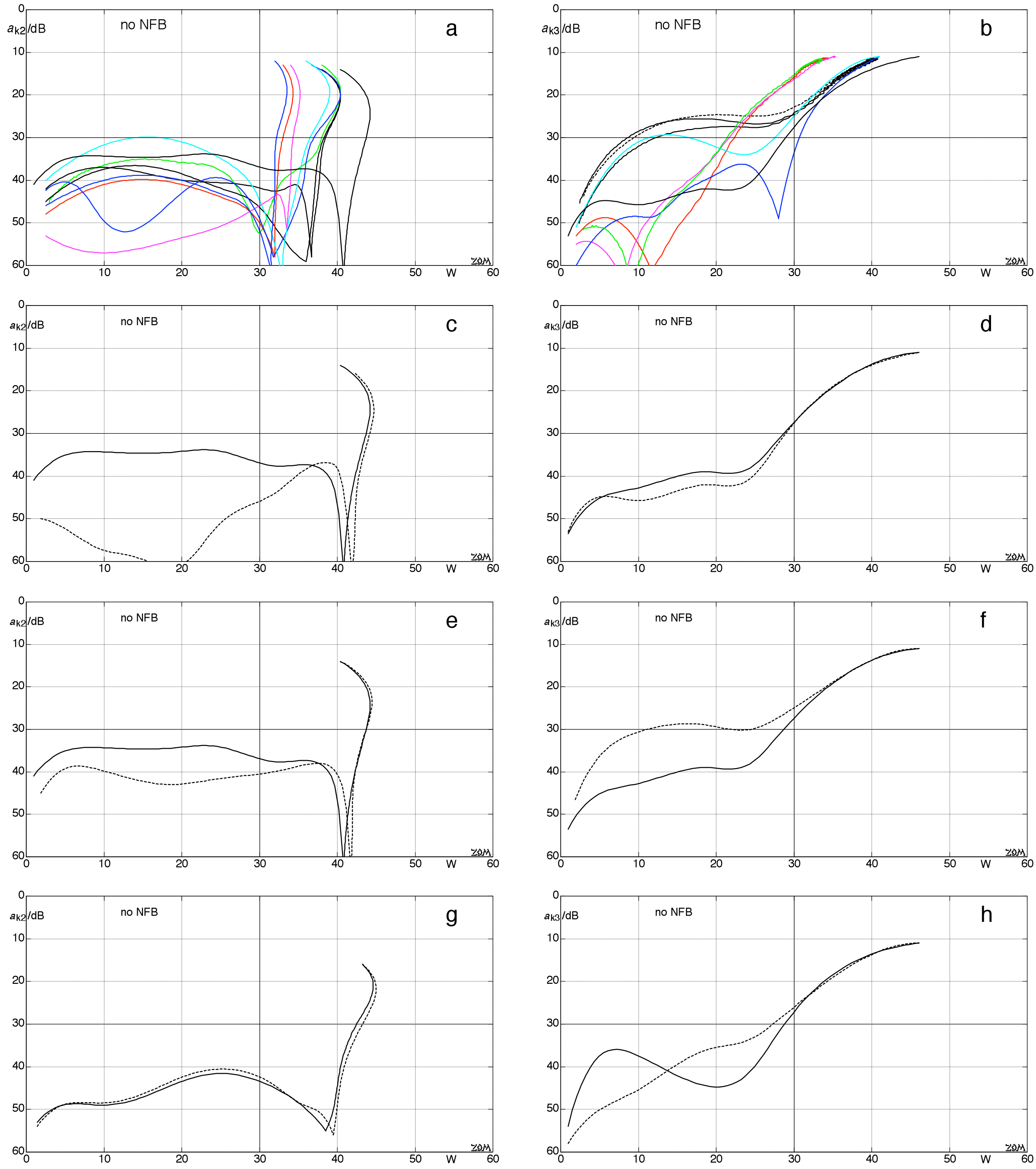

Fig. 10.5.57: 2nd order (left) and 3rd order harmonic distortion, KT-66, R_{aa} = 8 kΩ, 8-Ω-load at the 8-Ω-output.

The first line in **Fig. 10.5.57** shows the scatter-width across 8 different KT-66-pairs. For pairs **c and d**, only one plate-resistor was changed: 82kΩ/108kΩ were included rather than the usual 82kΩ/100kΩ (differential amplifier). Immediately, the power-stage anti-symmetry changes, as does the 2nd-order harmonic distortion. For **e and f**, the offset voltage at the grid of the power tubes was changed from -53V/-50V (13mA/13mA) to -48V/-48V (25mA/19mA). This KT-66-pair was 'matched' only to a rather lukewarm degree, despite a 4-digit-coincidence of the numbers on the sticker. Increasing the plate-current increases the 3rd-order distortion; the asymmetry in the current to some extent compensates for the disparity in the tubes (a_{k2}). For **g and h** another KT-66-pair was used, and the bias-current was changed from 13mA/13 mA to 17mA/17 mA. It is surprising that the KT-66 requires such a small bias-current for low distortion (it was operated with R_{g2} = 1.5 kΩ for these measurements).

The bias-current could be easily adjusted in this JTM-45; no potentiometer is, however, foreseen to set the symmetry. In fact, there are two values of relevance here: differences in the drive circuit (plate-resistors in the differential amplifier), and the offset-voltages at the grids of the power tubes. Of course, the respective individual KT-66 adds in, as well. Frequently, carbon film resistors are recommended in order to achieve the original sound. However, such resistors normally have a tolerance of ±10%! The variation of a plate resistor from 100 kΩ to 108 kΩ is comfortably covered by this tolerance span, but it will change k_2 (at c) by more than a factor of 10! If such variations are indeed considered to be relevant, it is not necessary to shell out more than 15.000.- Euro for an old JTM-45 – one or two potentiometers added into the circuit of a reissue amp will do fine (at a price of 3 Euro per piece).

The notion that KT-66's produced today will not match the original data holds, in this experiment, only for the TAD-tubes (which in the meantime may well be supplied by another manufacturer – we did not investigate this aspect). The TungSol-KT-66's are not generally worse than the original GEC-tubes – quite the contrary. We had 8 GEC-tubes at our disposal for the measurements. True vintage! Correspondingly, they were handled with great care. One of these tubes was practically useless, two others had a gain so low that they could not be used. The remaining KT-66's worked well but their data corresponded only very moderately, despite the "7500/7500"-marking on one pair and the "6500/6500"-marking on another pair. The seemingly 4-digit correspondence ("matching") did not keep the tubes from featuring different gain – which will influence the harmonic distortion.

The above observations warrant the warning not to acquire vintage tubes (so-called NOS) from unknown sources. This especially holds if the prices are significantly higher than those of new tubes. At present, a pair of KT-66 is about 65 Euro, and it would be unwise to pay much more. While it is indeed possible that vintage tubes on the market are well paired and have been used little, and also feature small grid-currents and a good vacuum, they may just as well be of abysmal quality. What can you do if (prepaid with an enormous sum) a parcel arrives from far-away lands with tubes for which merely the label is correct? It may be rather profitable to re-sell a cosmetically perfect replica (bought for a few Yuan) for $699 per pair – but let's mention that only in passing. It does of course not imply, that all NOS-tubes necessarily are fakes (for more information search the web for "faked tubes").

To avoid that the results shown in Fig. 10.5.57 are interpreted as stellar peculiarity of the JTM-45: please take note of another warning. Similar curves are to be found with Fender power stages, as well – this is not exclusive to Marshall! The plate resistors in the differential amplifier, the degree of pairing of the power tubes, the bias current, the negative feedback – all this determines the behavior of the power stage. The equation "vintage = great" does not compute!

Fender – VOX – Marshall, the holy trinity: sure, it will not command the respect of every guitarist, but the constantly recurring chorus in the "vintage"-columns of magazines has generated the widely held opinion that the primordial VOX (or the proto-JTM-45, or the ancient Bassman) is unequalled sonically, and easily justifies the $10.000 or 20.000 asked today for the old originals. And of course, it is alluring to elect the top dog of this troika: "compared to the 1959 Fender Bassman it is modeled after, the JTM outperforms its alter ego with ease" (Gitarre&Bass, 7/2006). Onto the podium – long live the myth.

How should we imagine the scenery at the beginning of the 1960's, when this legendary amp came to life? Maybe like this (as some would have it): 39-year-old Jim sits behind his drum kit, squeezing some sophisticated triplets between the screaming guitar-arpeggios, and thinks *'that doesn't sound like Hardrock at all – I'm gonna build 'em a new amp with the right brit-brown sound'*. And then he tells Ken: *'get on with it'* – and the result is the JTM-45 with its unparalleled distortion sound? Maybe it was like that, with Jim the Rocker? This image does not really fit the picture found in the books about Marshall: a friendly gentleman sporting suit and bow-tie who probably makes his sticks dance across the skins in a more gentle manner. Wikipedia sees the start of the **Hardrock**-era in 1969 but not in 1962. We know that Ritchie Blackmore, Jimi Hendrix, Pete Townshend and many others came to fame using Marshall amps, and it is easily imaginable that they voiced requests for more power – could that have been in 1962, though? Townshend played (according to Wikipedia) in a Dixieland-band in 1959, then graduated to Skiffle, and the Who gets off the ground only as late as 1964. Deep Purple forms in 1968, Hendrix starts his Experience in 1966, and Clapton plays with the Yardbirds in 1963, miles away from any Beano-like tone. It is also sufficiently well documented that Brian Poole (with his Tremeloes) was not an early exponent of Hardrock.

No contest: Jim Marshall has deservedly earned his medal as amp-pioneer – summa cum laude, without any doubt. That does not imply, however, that the JTM-45 was developed and optimized as distortion-heavy amp, even if this rumor is circulated within fan circles. Folks, read closely what Ken Bran states in the Marshall book: *"It was a bass amp we originally wanted ... but the guitar sound was too good to pass up."* The differences existing between the bass, guitar, organ and PA-variants of the early Marshalls are limited to two small bridging-capacitors to boost the treble. Had the JTM-45-circuit been developed to generate special distortion, it would have also distorted vocals amplified by the PA-version – except for the different treble gain, all these amps were identical. Many guitarists found (and continue to do so) that the JTM-45 sounds really good when overdriven, but already in the description of the distorted sound we find differences: according to Wikipedia, the Bluesbreaker combo (Model No. 1962) was the amp that *"first led to the breakthrough of the typical Marshall sound"*. However, in Gitarre&Bass (07/2006) we find the statement that this same amp produces *"never a Marshall-typical distortion sound"*. The author, writing a monthly column about vintage amplifiers, is somewhat of a Nostradamus-of-the-tube-amp (i.e. not looking into the future but backwards-oriented – we are talking *vintage* here!), and in terms of interpretation simply congenial. A sample: *"and the result (JTM-45) differed, in the end, strongly from a Fender Bassman"* (G&B 07/2006) **versus** *" the first of the so-called JTM-models were therefore rather authentic copies (of the Fender Bassman)"* (G&B 2/2005). Just like with Nostradamus: it all depends on the year. Not a problem for anybody bred and raised in Munich, Bavaria, and familiar with local poet Karl Valentin who wrote: *"it has expertly been calculated that the Lake of Starnberg* (a well-known beautiful lake south of Munich) *is, at the same time, deep, shallow, long, short, narrow, and wide.*

Fender Super-Reverb

A typical medium-power Fender amplifier holds two 6L6-GC's, and the Super-Reverb is a good example. The cathodes of the power tubes are connected directly to ground, and a separate diode generates the negative offset-voltage: no doubt at all – this is textbook-class-AB-operation. Ahead of the power tubes we find a differential amplifier, following them the output transformer with a connection to the negative feedback loop. All in all it is a model for the way Fender power stages looked like in the 1960's. Still, there are individual idiosycracies: the driver-tube may change (12AT7 instead of 7025), the coupling capacitors, too; small blocking capacitors are discarded, then they return again – and even a "Presence"-control is found in the 'Super' for a short time. The Super-Reverb investigated in the following has the AB-763-circuit originating in the 'Blackface-era' i.e. in the golden 1960's.

Fig. 10.5.59 depicts the output characteristics for ohmic loading of the 8-Ω-output (this specimen of the amp had a transformer with such a connection installed). For the specified load, the "knee" of the 0-V-curve is almost exactly met, indicating an optimum transformer dimensioning. As the drive level rises, the curve is shifted towards smaller voltages.

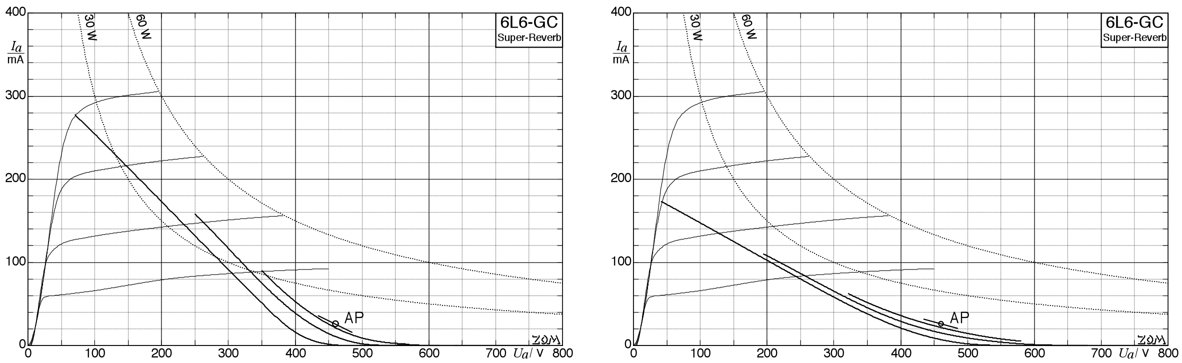

Fig. 10.5.59: Characteristics for ohmic load of 8Ω (left) and 16Ω (right).
Note: the output transformer used here also had an 8-Ω-output on top of the regular 2-Ω-output.

The negative feedback in this power stage is not as strong as it is in the JTM-45, and therefore the loudspeaker impedance is more clearly represented in the transmission frequency response (**Fig. 10.5.60**). For all these diagrams, it is important to recognize that the exact shape of the curve depends on the specific loudspeaker: the loudspeaker resonance, which is about 75 Hz in the given example, may rise to over 100 Hz with other speakers. This of course has an effect on the sound (compare to Chapter 11). If the power stage is overdriven, the influence of the speaker diminishes and the characteristic becomes closer to that of a voltage source. This is shown in upper curve of the left-hand picture.

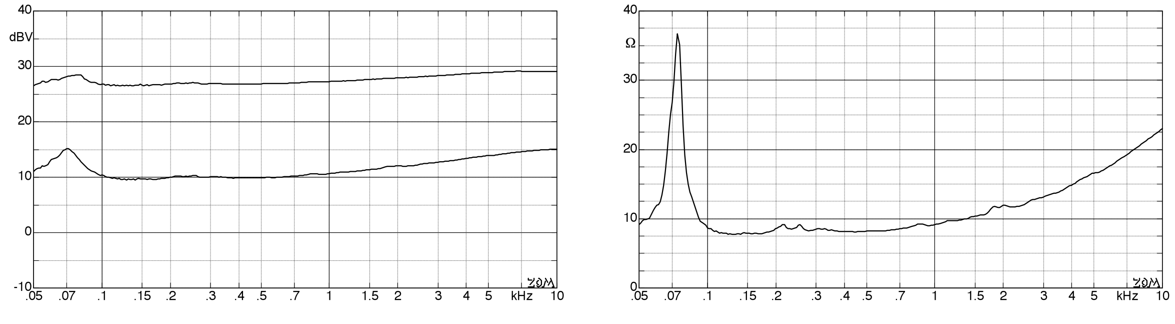

Fig. 10.5.60: Frequency response of a Super-Reverb power amp, 8-Ω-output loaded with 4xP10R (left).
Right: magnitude of the loudspeaker impedance (4xP10R, cabinet set up in reflecting surroundings).

The transmission characteristic of the power stage for 8-Ω-loading is shown in **Fig. 10.5.61**. As the drive level rises, the curve decomposes into two branches that slide apart. As has already been noted, the reason is the polarization of the coupling capacitors.

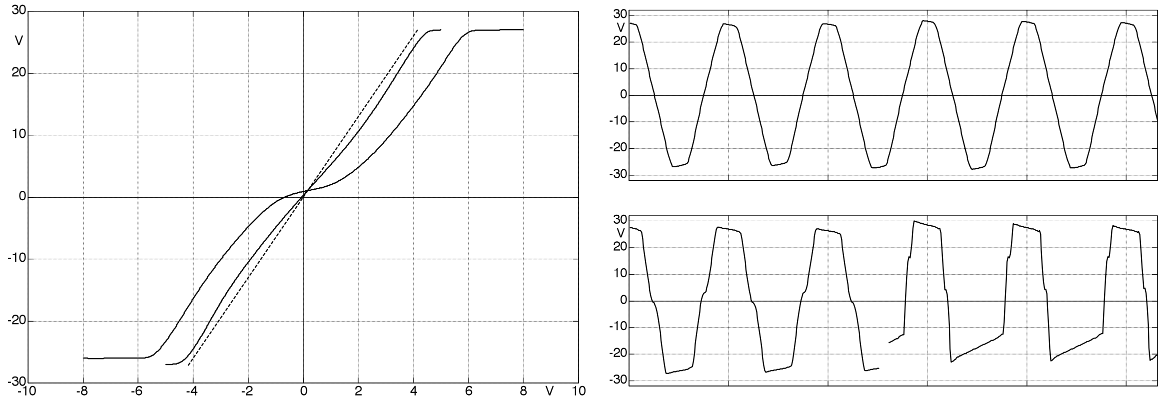

Fig. 10.5.61: Idealized characteristic (left), output time-function with ohmic nominal load (right).

We can see from **Fig. 10.5.62** that the output power of 40 W (as specified e.g. in the 1968 catalog) is actually achieved. This is in sharp contrast to the JTM-45, the replica of which is advertised by TAD (in 2008) with "about 45 Watt" but reaches merely 30 W. The minimum of the harmonic distortion is due to the progressively curved characteristic that changes the direction at the onset of distortion. The strain on the power tubes is similar to the JTM-45: the screen grid is overloaded for overdrive operation with a high-impedance load (**Fig. 10.5.63**). One significant difference is found in the input capacitor: if it is only 1 nF (AB763), the plate is overloaded less (compare to Fig. 10.5.55). There are, however, also Fender amplifiers with a larger input capacitor (e.g. 10 nF).

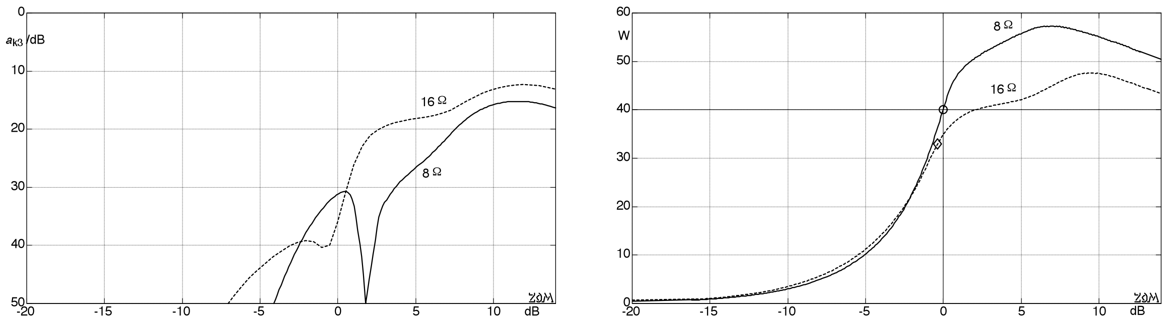

Abb. 10.5.62: Super-Reverb: harmonic distortion, output power at the 8-Ω- output with 8-Ω- and. 16-Ω-load.

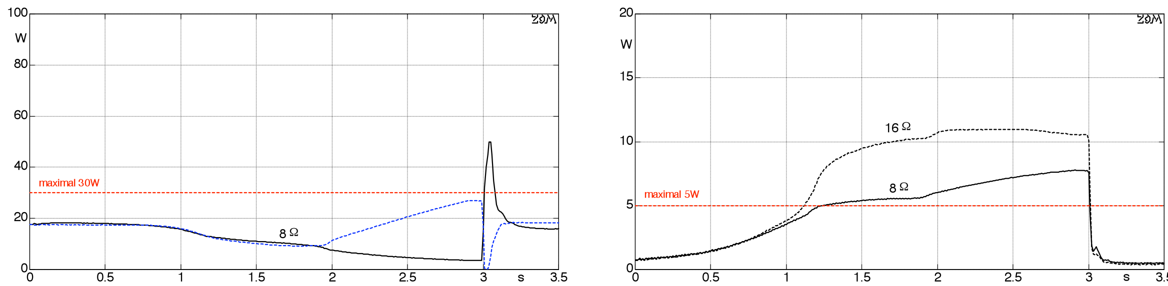

Fig. 10.5.63: Power dissipation at the plate for both output tubes (left); power dissipation at the screen grid for two different load impedances (right). The level of the input signal (500 Hz) rises linearly from 0 – 3 s, switch-off occurs at t = 3 s. From t = 1.3 s, the power stage is overdriven.

 Translated by Tilmann Zwicker

Comparison of power stages

The 1960's holy trinity: VOX, Marshall, Fender. Of course there are also Gibson, Ampeg, Hiwatt and many more, but the 'big three' stand out. So, what makes for the difference between these amplifiers or, rather, between the respective power stages (to do this chapter adequate justice)? This question cannot be answered generally because there is not *the one* Marshall- or Fender-amp. Even at VOX, the AC-30 ran through several production variants. For Fender, Dave Funk lists 250 pages of schematics – and still has not captured all Fender amps. Practically every amplifier model (e.g. the Bassman) was, over the years, built in many variants, and there are many models to begin with. It is therefore impossible to speak of one Fender-typical circuit, or of one Fender-typical sound. The situation is similar for Marshall – only the AC-30 remains reasonably true to itself, although even here there are modifications, e.g. the models developed for the US that only seemingly were similar to the UK-standard.

Even when concentrating on only three special power stages, a comparison turns out to be difficult due to many small differences in detail. Most important are category of output-power, negative feedback (and correspondingly the internal impedance), and balancing processes during overdrive conditions. Even the loudspeaker needs to be considered although it is not part of the power stage: its impedance determines the load on the power stage and thus the frequency response of the latter. The circuitry preceding the power stage plays a considerable role, as well: is it of high or low impedance, and what voltage can it offer without distorting? If the power stage were a linear and time-invariant system, we could record its frequency response and have a good starting point for comparisons. However, guitar amps are subject to overdrive (i.e. they are operating as non-linear systems), and therefore a small-signal analysis allows for only very limited conclusions on their behavior.

To illustrate the problems appearing when comparing amplifiers, let us look at the VOX AC-30 and the Fender Super-Reverb. The VOX offers 30 W, the Fender 45 W. In the VOX-cabinet we find two 12"-**loudspeakers** while four 10"-speakers are deployed in the Super-Reverb. If we allow for each power stage to work with its original speakers, we not only compare the power stages but also the loudspeakers. Should we consider connecting the VOX-speakers to the Fender, we risk blowing them because Celestion specifies only a 15-W-load for each speaker. Moreover, the nominal impedance the Super-Reverb is specified for is 2 Ω, while it is 16 Ω for the VOX. One could re-solder the VOX-speakers to a 4-Ω-configuration, but that would result in yet another different scenario. How about the other way round: operating the VOX with the Fender speakers? That would work in terms of power capacity, but the issue with the different output power remains: it could result in differing loudspeaker distortion (with the sub-harmonics being level-dependent).

Therefore, the chosen approach would have to be to use only one and the same loudspeaker for all amps to be compared. What would remain now as power-stage specific differences? First, the **internal impedance**: it is high in the VOX, medium in the Fender and low in the Marshall. The speaker impedance will therefore more or less shape the frequency response. At resonance, the loudspeaker impedance can rise to 40 Ω or even 150 Ω, implying a voltage-level difference of almost 12 dB for a high-impedance source and an almost unchanged level or a low-impedance source. This is an enormous difference that is neither due to the power stage by itself nor caused by the loudspeaker by itself (**Fig. 10.5.64**). Even though the power stages are neither pure voltage sources nor pure current sources, the corresponding difference between an AC-30 ($R_i \approx 80$ Ω) and a JTM-45 ($R_i \approx 2$ Ω) is considerable.

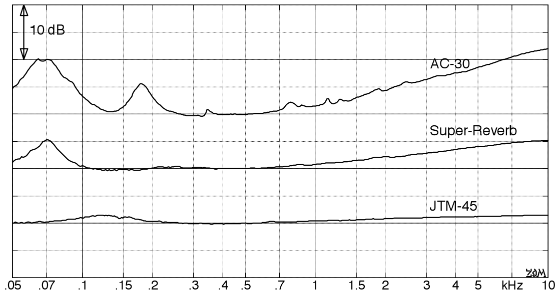

Fig. 10.5.64: Frequency responses from phase-inverter input to loudspeaker output.

AC-30 with 2x12"-Celestion in combo-enclosure,
Super-Reverb with 4x10"-Jensen in combo-enclosure,
JTM-45 with 4x12"-Celestion in separate 1960AX enclosure.

The reason for the different internal impedances is the **negative feedback** (NFB) **in the power stages**: it is strong in the JTM-45, somewhat less strong in the Super-Reverb, and non-existent in the AC-30. Besides influencing the internal impedance, the NFB also has an effect on the non-linear distortion of the power stage: this distortion is stronger in the AC-30 and smaller in the Super-Reverb and, in particular, the JTM-45. The type of distortion varies, as well: with increasing overdrive, the duty cycles in the JTM-45 and the Super-Reverb change, and correspondingly 2nd-order **distortion** mounts. Conversely, the output signal remains largely half-wave anti-symmetric in the AC-30, with k_3 remaining dominant.

The **output transformer** influences the output signal, too – though less than first expected (see Chapter 10.6.5). In the low-frequency range, harmonic distortion caused by the transformer can become audible – but only for really low-quality transformers. All transformers investigated here gave no cause for complaint. Because not all transformers have the same turns-ratio, the frequency responses differ a little; this, however, is no secret science – in essence this is a matter of the number of turns in the windings.

The ratio of **impulse power** to **continuous power**, and the **hum-interference-modulation** is not alone a characteristic of the power stage but the power supply is involved, as well. The Super-Amp 5F4 had a capacitor of 16 µF connected after the rectifier tube, and another 16 µF after the choke. That was indeed rather modest, so the successor receives 40 µF / 20 µF. With Marshall, the JTM-45 first included 32 µF / 32 µF, but the model 1987 filtered with an ample 100 µF / 50 µF. Started out with 16 µF / 16 µF, the AC-30 was upgraded to 32 µF / 32 µF later. It is a well-known fact that all these electrolytic capacitors often had considerable tolerances.

The plate resistors in the **phase inverter** are a science in themselves: we have 82k/100k with the 7025 in the 6G4, 100k/100k with the 12AT7 in the AA763, 47k/47k with the 12AT7 in the AB568. In the Marshall, an ECC83 with 82k/100k is at work, and in the VOX an ECC83 with 100k/100k. The anti-symmetry of the phase-inverter outputs influences the even-order distortions in the power stage. The scatter of component values can have an extremely strong effect, and, of course, the equality of the **power tubes** plays a role, as well ("matching").

The power tubes: EL84, 6V6GT, 6L6GT, KT66, EL34, KT88, and relations. This is a difficult topic because there is not "the" 6L6GT – the scatter can be very wide. The acquisition of a large number of 6L6GT (say 12 pieces) does not help here, either: if all twelve tubes are from the same production batch, they might have similar parameters, but if we later buy another pair, the parameters might well be entirely different. It has already been elaborated that "selecting" and "matching" are no cure-alls, either (Chapter 10.5.11). The measurement results listed in the following are therefore to be taken merely as a snapshot to provide orientation values of limited general validity.

 Translated by Tilmann Zwicker