10.6.5 Comparison measurements

From 2012 to 2016, the university at Regensburg (Germany) offered a practical course on tube amplifiers for which a modular guitar amplifier was developed. It included a 15-W-power-stage with the possibility to directly switch between up to 10 different output transformers, and a 50-W-power-amp offering a choice between 13 OT's. The candidates are:

	Transformer	Z_{aa} / kΩ	$R_{aa=}$ / Ω	$R_{8\Omega=}$ / Ω	Core	Amplifier	€
1	Conrad ELA 10W	7,9	280	0,70	EI-48/16	Ela	6,90
2	Conrad ELA 20 W	7,0	180	0,33	EI-48/24	Ela	9,50
3	Hammond-1750E	8,8	300	0,45	EI-57/19	Deluxe Tweed	34,70
4	TAD-1839	9,1	560	0,70	EI-66/22	Deluxe Tweed	86,20
5	TAD-125A1A	6,9	330	0,44	EI-66/22	Deluxe Reverb	69,00
6	Hammond-1760H	5,9	400	0,83	EI-66/22	Deluxe 'upgrade'	54,39
7	Hammond-1750J	8,2	180	0,35	EI-75/24	Tremolux	38,65
8	TAD-MJTM18WA	9,1	670	0,60	EI-75/24	Marshall 18Watt	79,00
9	Hammond-1750Y	6,8	300	0,50	EI-75/38	VOX AC15	77,30
10	NSC 401318-T	7,1	196	0,50	EI-66/22	e.g. Fender	17,80
11	TT-SLO50	4,5	100	0,43	EI-96/40	Soldano 50W	88,90
12	Hammond-1760L	4,1	100	0,41	EI-96/31	Bassman 'upgrade'	82,30
13	Marshall JTM-50	3,5	86	0,54	EI-96/40	Marshall 50W	86,56
14	Hammond-1750N	3,5	80	0,51	EI-96/40	JCM800	77,50
15	OTH M330-50A	3,5	53	0,17	EI-96/36	university lab	--
16	Hammond-1750V	4,2	140	0,70	EI-96/40	VOX AC30	86,50
17	Hammond-1750Q	**7,9**	140	0,61	EI-96/40	JTM-45	92,25
18	Marshall JTM-45	**7,8**	155	0,42	EI-96/40	JTM-45	100,30
19	IG-Wickeltechnik	**8,2**	218	0,49	EI-96/40	JTM-45	106,20
20	Toroid mains transf.	3,5	60	0,21	∅81x35	Mains transformer	15,--
21	TAD-MJTM45A	**8,1**	360	0,49	EI-96/40	JTM-45	129,50
22	TAD-018343	4,7	100	0,20	EI-96/34	Super Reverb	110,00
23	TAD-M50A	3,7	150	0,48	EI-96/40	Marshall 50W	89,90

The 'small' transformers (upper group) are operated at either 2xEL84, or 2x6V6-GC while the 'big' ones work with either 2xEL34, or 2x6L6-GC, or 2xKT-66. Using the easily accessible datasheets as a basis, the **optimum load-impedance** (plate-to-plate, Z_{aa}) across the entire primary winding should amount to **8 kΩ** for both the 2xEL84- and the 2x6V6-GT-complement. Checking a bit more thoroughly, we find as a boundary condition e.g. for the 6V6-GC: a plate- and screen-grid-voltage of 285 V. However, the Deluxe in fact was operated already in its initial versions at 350 V, and later with as much as 420 V. This slight ☺ overload has not killed it (the datasheet allow for a maximum of U_a = 315 V) … but what about the optimum load-impedance at these voltages? The datasheets are silent about it – presumably because of the limit value mentioned above. These days, transformers produced for these amps mostly have about 8 kΩ for the early Deluxe-variants and 6.7 kΩ for the later ones. The measurements in the table indicate that these target specifications are 'generously' interpreted. For the 'big' amps there is agreement that the correct load-impedance for a JTM-45 should be exactly 8000 Ω … that does not prevent TAD to include a 3,7-kΩ-transformer with the JTM-45-kit. Well, you are free to reorder the 8-kΩ-varaint for an extra 130 Euro. Over to the 2x6L6-GC or 2xEL34: here, impedance-values of around 4 kΩ are customary, and you are in good hands with this for the AC30 (4xEL84), as well. It is recommended to take the impedance specifications with a pinch of salt – they are frequency-dependent, and the tube data that are supposed to be a match to these impedance values scatter rather strongly, too.

Fig. 10.6.25 shows the measured frequency responses of the impedance. The transformers were loaded at their 8-Ω-output with 8 Ω, and primary impedance of the *entire* winding (Z_{aa}) was measured. The Tremolux-OT (7) is actually specified for 4 kΩ / 4 Ω, and it was tested with 8 Ω at its 4-Ω-output, which approximately doubles the primary impedance. The two ELA-transformers were not actually specified for operation with a push-pull power stage but their windings allow for comparable transmission ratios. Still, it needs to be emphasized that these transformers were designed for an operation with 100 V and not for 250 V as it regularly occurs with power stages (U_a, under regular operation). Corresponding experiments therefore require adequate safeguarding. All measurements were taken with very small power such that, for the low-frequency impedance, the **initial permeability** is significant. The latter is particularly small for the ELA-transformers; but this was to be expected in the face of the very small build-size. Also, it must not be forgotten that the other transformers are about 10 times the price! The impedance increase at high frequencies is due to winding-resonances and –capacitances, and the scatter in the middle frequency-range is due to differences in the transformation ratio (turns-ratio).

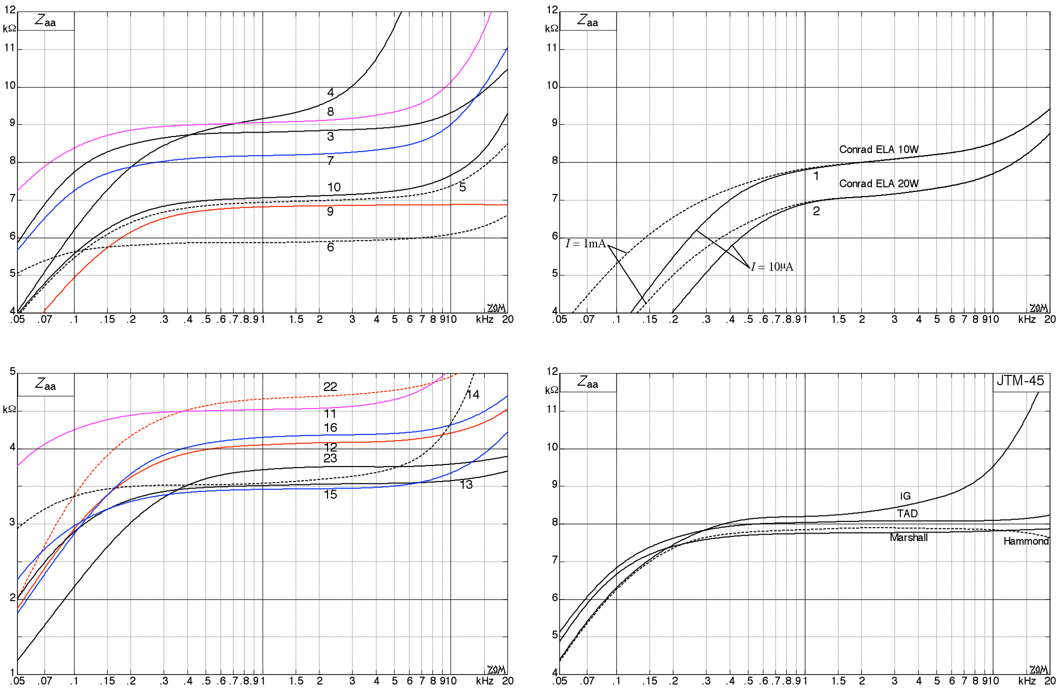


Fig. 10.6.25: Frequency response of the impedance (Z_{aa}) for drive from a stiff current-source (10 µA) and a secondary load of 8 Ω. The numbers in the figure relate to the above table.

It is not imperative to assume that the different transformation ratios result from bad manufacturing quality. The number of the turns of the wire can easily and precisely be checked; divergences are, with high probability, intentional. The suppliers indicate e.g. Z_{aa} = 8.1 kΩ, but apparently a result of 9 kΩ will not be the end of the world. What seems to be more important: *manufactured according to the original specs using authentic materials*. That's the reason for the high price. For the 5E3-Tweed-Deluxe, you will find a vast variety of output transformers; these all wait to be lovingly assembled by hand (and with authentic materials) first, and that costs. One single variant for all 18-W-amps would probably also do – but only for the very un-emotional customer.

Because a purely ohmic 8-Ω-load is required but not sufficient, the corresponding figures with loading by a loudspeaker are also included (**Fig. 10.6.26**). As already elaborated in Chapter 10.5.8, the (*straight*) load line is a first approach – reality is more complex (in the true sense of the term). The power tube does not "see" a constant resistance but a complex load the magnitude of which varies between e.g. 7 and 30 kΩ. This could as well be a range from 9 to 50 kΩ – or whatever else the transformer offers as a load. Depending on the transformer and the loudspeaker, the optimum operational range of the amplifier therefore resides within different frequency ranges, and consequently, the output transformer influences the sound. Again: this ain't no secret science: with the turns numbers, and the size of the core, you have the main ingredients already on the table.

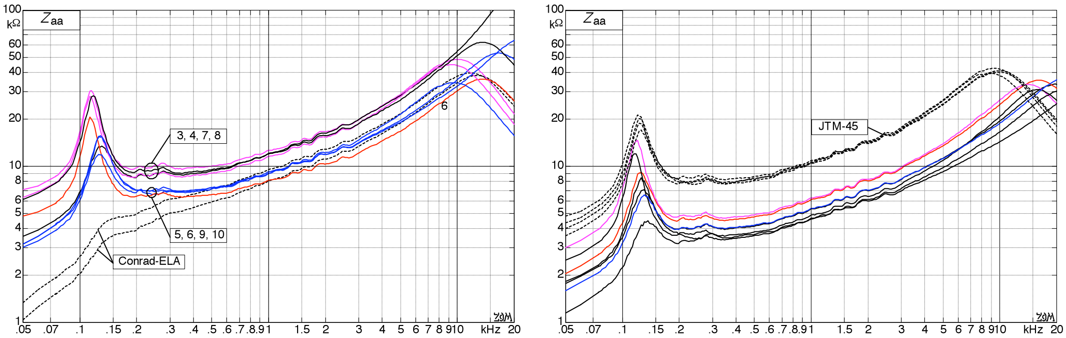


Fig. 10.6.26: Frequency responses of the impedance (Z_{aa}) with drive from a stiff current source (10 μA), load = Jensen C12N in an enclosure. Left: first-group transformers (1 – 10); dashed = Conrad-ELA-transformer. Right: 50-W-OT's of the second group; dashed = JTM-45-transformer (8 kΩ).

The impedance graphs give an impression of the strain on the tubes; more important, however, is the power transmission (**Fig. 10.6.27**). At small output power (0.2 W / 1 kHz), the variation within the transformers is not that big anymore; even the ELA-transformers provide sufficient bass-reproduction. In the range of the power-limit (right-hand section of the figure), however, differences show up, after all. No. 6 (Hammond 1760-H) has the smallest primary impedance (5.9 kΩ) and therefore delivers the highest output power in the frequency ranges where the loudspeaker is of high impedance. The opposite is represented by No. 4 (the TAD Tweed-Deluxe-transformer): its forte is in the area of low speaker impedance i.e. in the middle frequency-range. At small and medium output power, the sound can be shaped via filters almost at will. However, if the power stage is operated in the range of its power limit, we find: **for a brilliant sound, the output transformer should show low primary impedance, and for a more mid-range-y sound, it should feature higher impedance**.

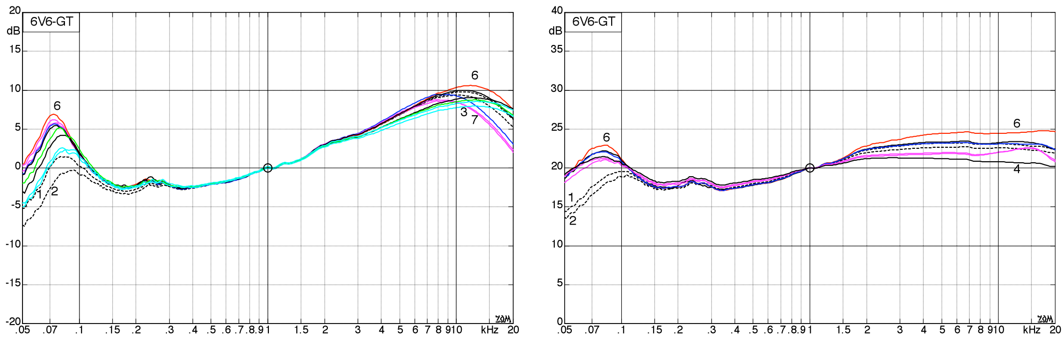


Fig. 10.6.27: Transmission from the phase-inverter input (NFB disabled) to the loudspeaker (P12N). **Normalized to 1 kHz**, small drive-level (left), high drive-level with power-stage overdrive (right).

In **Fig. 10.6.28** (not normalized), the effect of the transformer establishes itself clearly; No. 6, with small primary impedance conversely generates the largest secondary source-impedance. This is why the loudspeaker impedance maps itself relatively strongly onto the transmission frequency-response. If the internal impedance of the power stage were zero (ideal current source), the figure would show a horizontal straight line. Relative to this theoretical “ideal” situation (that for a guitar amp would generally be held as not ideal), the source impedances in the figure increase with the sequence 4-3-9-6. The compression of the curves follows almost the same sequence; it is only No. 4 that gets out of line: the TAD-transformer offered for the Tweed-Deluxe (4) has the highest DC-resistance and therefore somewhat higher copper losses. To compensate, it is the most expensive one of them all. And who knows: maybe it is the most authentic one, as well.

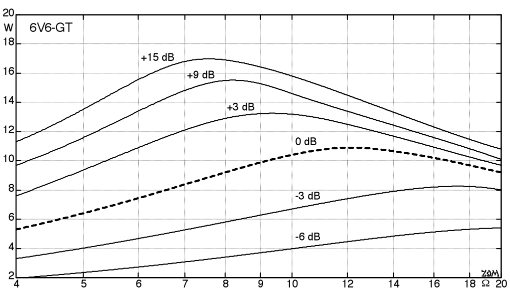
Regarding the **strain on the power tubes**, the following holds: the higher the primary impedance, the more the screen grid is likely to be overloaded (Chapter 10.5.9). Thus, if you run your 4-Ω-amp into a 16-Ω-speaker, better keep a watchful eye on your power tubes.

Diese Abbildung bleibt der Druckversion vorbehalten

Diese Abbildung bleibt der Druckversion vorbehalten

Fig. 10.6.28: Transmission from phase-inverter input (NFB disabled) to loudspeaker (P12N).
This figure is reserved for the printed version of this book.

Let us take another look at the differences between linear and non-linear operation. Between power tube and loudspeaker, there is no tone-stack – if the power tube is clipping, only the output transformer is left to have any impact on the transmission behavior. Therefore, the transformer-ratio is important to the sound. The tube power stage has a relatively high output impedance. If it were as small as it is in a transistor power stage, the output power would increase as the load-impedance decreases. Conversely, the output power increases, in a tube amp, as the load-impedance increases. This will not be the case without limit, though – at some point, the tube hits its limit and then the situation reverses. We see this in **Fig. 10.6.29** for the Tremolux-transformer (7), while Fig. 10.6.30 gives on overview over the remaining measurement results.



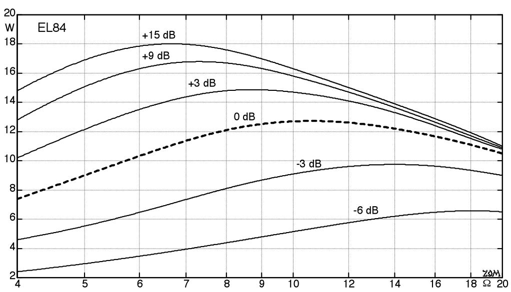


Fig. 10.6.29: Output power dependent on the load-impedance for various drive-levels. At the dashed line, the power-stage overdrive starts. Power stage without negative feedback. 1 kHz.

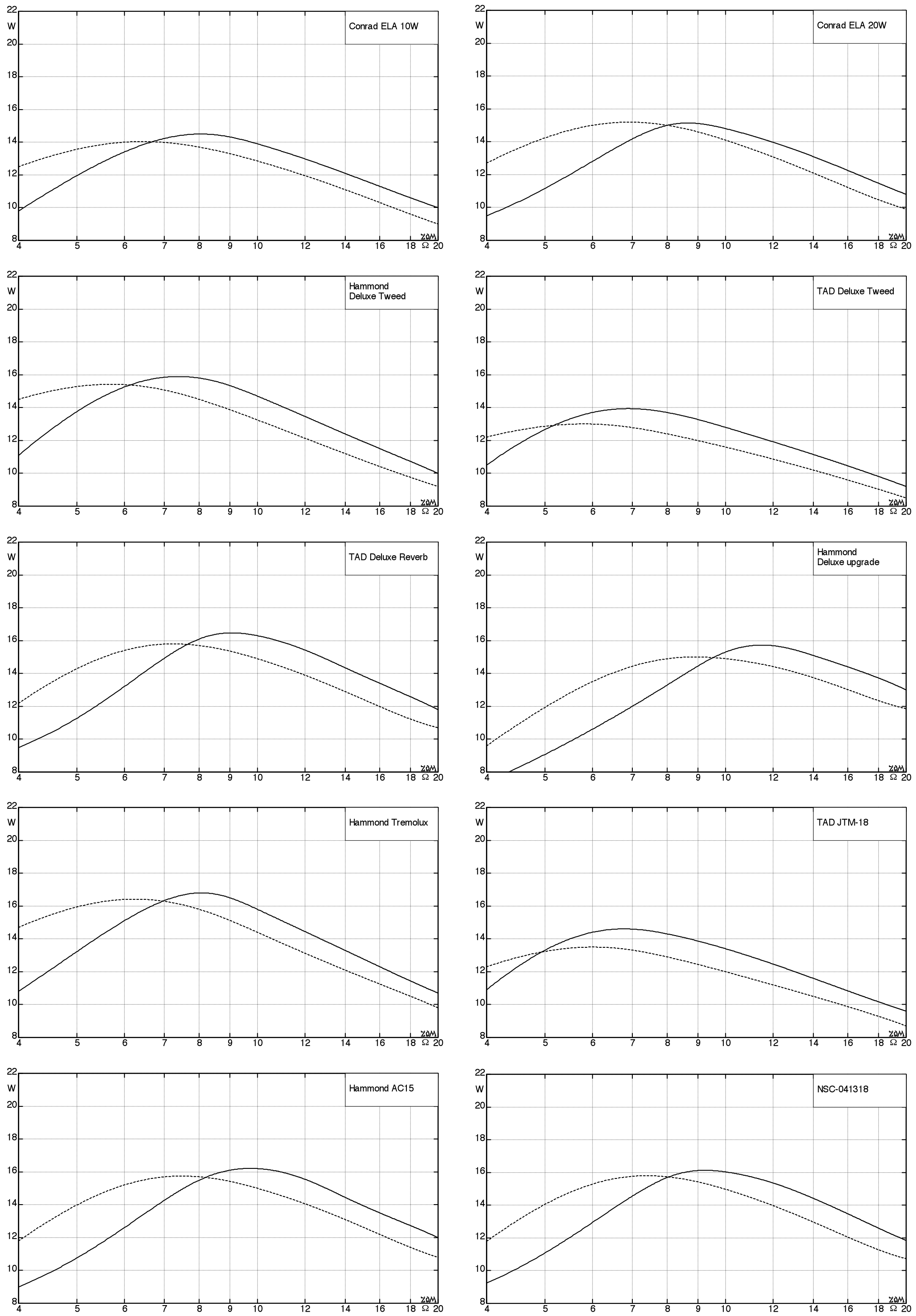


Fig. 10.6.30a: Maximum power vs. (ohmic) load-impedance; power stage overdriven by 14 dB, 1000 Hz. Two different 6V6-GC pairs: Ultron (——), TAD (-----); R_K = 270 Ω // 250 µF.

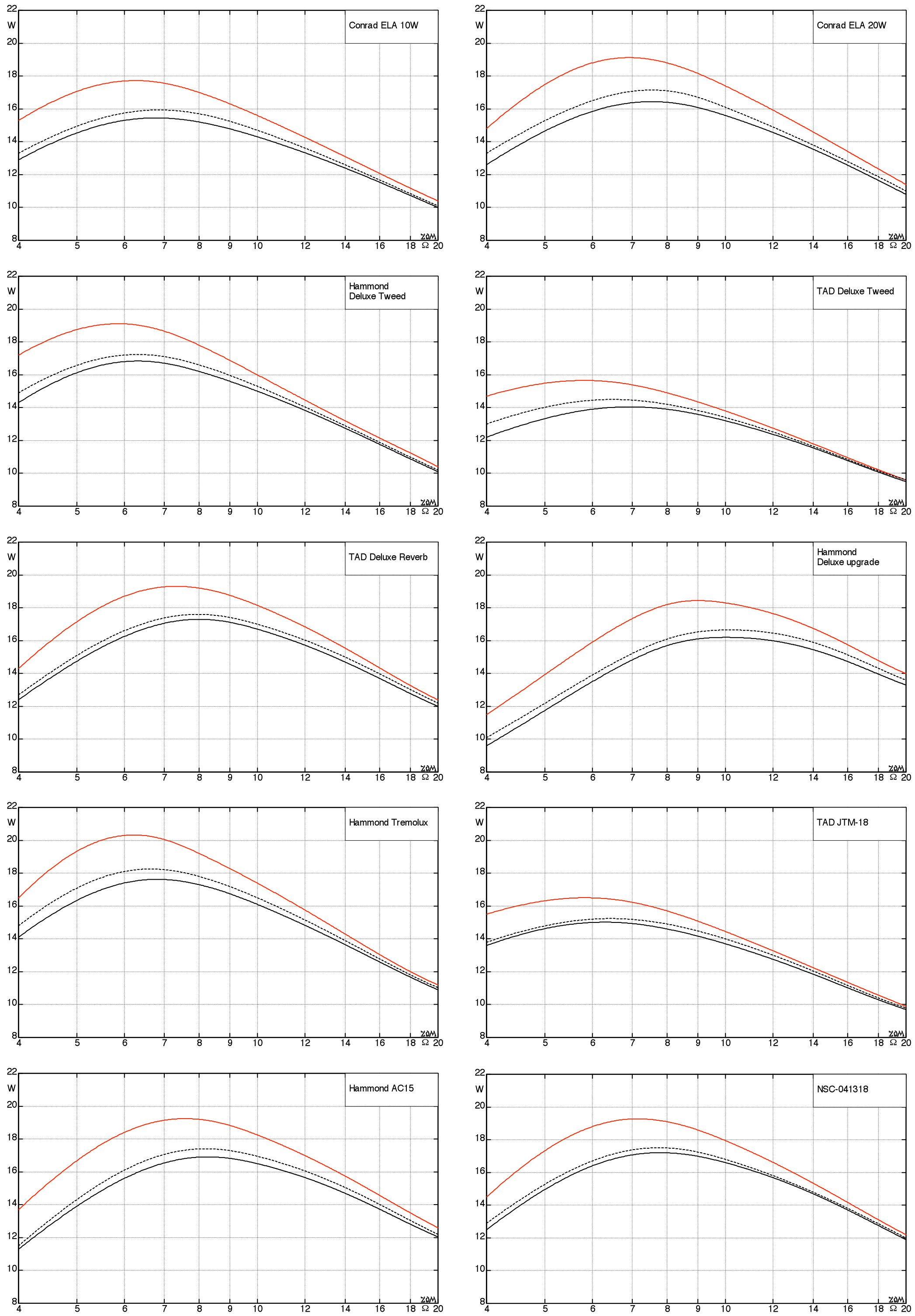


Fig. 10.6.30b: Maximum power vs. (ohmic) load-impedance; power stage overdriven by 14 dB, 1000 Hz. Three different EL-84 pairs: JJ (upper curve), Ultron (------), TAD (lower curve); R_K = 120 Ω // 250 µF.

The preceding diagrams indicated that output transformers may result in different operational behavior – even if offered for the same amplifier model. One parameter in this context is the frequency response under full load (Fig. 10.6.28), another is the maximum power (Fig. 10.6.30), and a third is the **harmonic distortion**. The Hammond transformer investigated in these measurements works (in conjunction with Ultron 6V6-G) most efficiently at a load of 12 Ω. This result is documented in **Fig. 10.6.31**, as well. However, using other tubes, different values were obtained which again shows that the cooperation of several components determines the transmission behavior of the power stage.

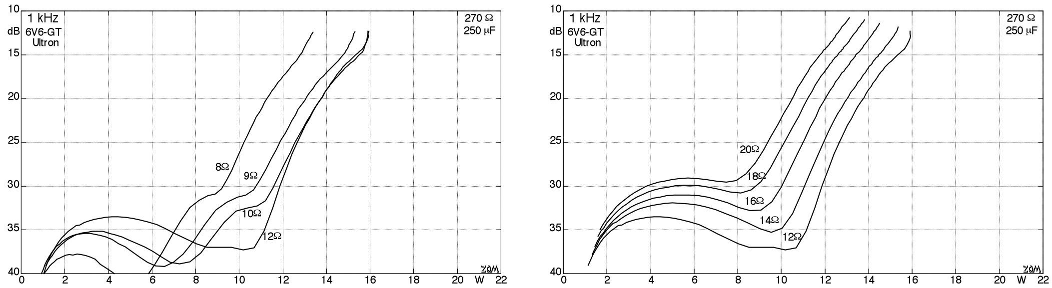


Fig. 10.6.31: Power stage: distortion-suppression for different load-impedances: Hammond Deluxe upgrade. A distortion-suppression of 20 dB corresponds to a harmonic distortion of k = 10%.

Fig. 10.6.32 shows the measurement results for two different tubes (6V6-GT, EL-84) and two different cathode circuits. **EL-84** with R_K is typical for the VOX AC-15 and the 18-W-Marshall (Model 1958). **EL-84** without R_K reflects the Mesa/Boogie Studio-22, and **6V6-GT** with R_K corresponds to e.g. the Tweed Deluxe. **6V6-GT** without R_K is exemplified in the Deluxe Reverb. Because of their differing turns-ratios, the transformers exert a different load onto the power tubes and generate different distortion-suppression that way. This is for 1 kHz, though! Here, another parameter enters the scene: **the frequency**. This now is the point where the depictions start to become confusing. It shall be mentioned only in passing that on top of everything, the plate-voltage, the screen-grid resistor, and the phase-inverter may also vary.

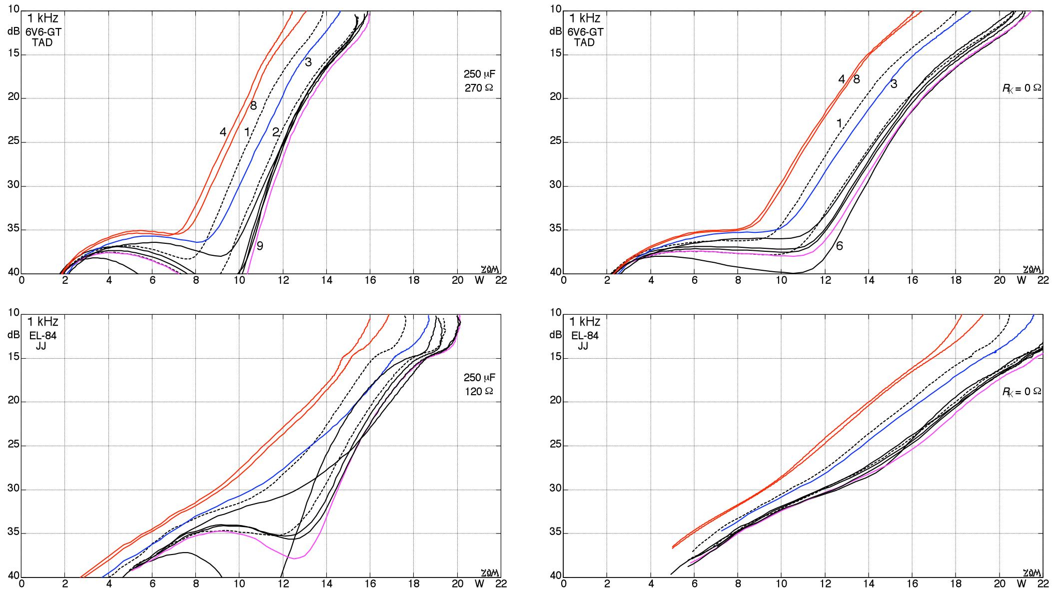


Fig. 10.6.32: Distortion-suppression: power stage with different output transformers. On the respective upper right the cathode circuit is indicated (common R_K bridged by 250-µF-capacitor, and fixed bias, respectively). 8 Ω.

In all these transformer-measurements, only the turns-ratio has shown itself as relevant so far. However, distortion measurements in the **low-frequency** range redirect the attention to the **main inductance,** or the core-material and –size. If the turns-number is too small, the bass-reproduction becomes weak and distorted. An increase in the turns-number, however, can only be achieved (due to the limited space for the winding) by reducing the diameter of the wire, in turn increasing the copper-resistance. If the secondary copper-resistance amounts to 0.83 Ω (as it is the case in the Hammond 1760H), 10% of the generated power remains in the secondary winding. Approximately the same percentage will again be dissipated in the primary winding. If both high efficiency *and* good bass-response are the objective, only changing to a better core will help, resulting in higher weight and/or price. No magic here: the small Conrad-ELA-transformer (1) features merely a cross-section of the iron of 2.4 cm^2 in its small core, and no attention was given to achieving a minimum air gap, either. The result can be seen in **Fig. 10.6.33**: very strong distortion in the bass. With its proud 8.7 cm^2, the AC-15-transformer of course has a much easier life here. It is no contradiction that the 20-W-transformer (2) is even worse than transformer (1): (2) is of particularly low impedance and therefore has an even smaller *L*. Again: these are ELA-transformers!

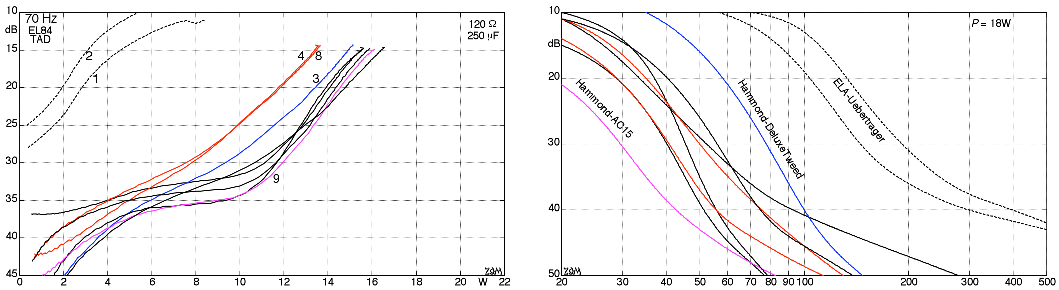


Fig. 10.6.33: Left: distortion-suppression in the power stage for different OT's. 8-Ω-load at the 8-Ω-output. Right: distortion-suppression of the OT (without power stage) as a function of frequency.

The distortion shown in the left-hand section of Fig. 10.6.33 is generated in part by the output transformer and in part by the power tubes, while the distortion shown in the right-hand section stems from the output transformer only. The ELA-transformers experience strong overdrive at low frequencies and are good for distortion sounds, if anything at all. Their primary impedance in the mid-frequency range is a good match for the tubes but their inductance is too small. However, all other transformers are suitable for guitar amplifiers, whether they cost 18 or 86 Euro. Unless blatant errors are made, the following theorem holds: **in the frequency range important for the electric guitar, the turns-ratio (i.e. the primary impedance Z_{aa}) is the decisive parameter; everything else is of minor importance**. Indeed, the manufacturers do use different core sheets, and, yes, they do invest much time in "authentic" replicas. They procure old (i.e. outdated) insulation paper, search for wire insulated in an antiquated fashion, copy scary nesting for the winding, and of course they need to be royally remunerated for the whole hoopla – it is, after all, almost one-off production. **Mindless reproduction of outdated technology on the basis of misunderstood context?** Yes, for the odd transformer this impression does force itself. However, let's not take such a narrow view. Maybe we should consider the approach of the placebo-pharmacologist: where there's a will, there's a market. So: at the latest as we have outgrown our 18-W-shoes and have dragged our 30-W-whopper to the stage despite the slipped disc, we sigh contently: two really fat transformers, thus really fat sound.

We have given the 'small' 18-W-transformers a lot of space – almost too much since more diagrams do not necessarily mean more clarity. Therefore, a short description shall suffice for the 'big' **50-W-transformers**. The frequency responses have already been shown – maximum power and distortion have similar characteristics as with the 18-W-OT's, just with a higher power level. Overall, the quality is somewhat higher, because for the larger transformers the inductance-determining relationship iron-surface-to-iron-length is more favorable. All 50-W-transformers investigated here perform well, whether they have 3.5 kΩ or 4.7 kΩ (R_{aa} each). Supplementing Fig. 10.6.26, **Fig. 10.6.34** depicts the transmission frequency responses of the complete power stage employing EL34's. It is clear that, in the frequency range important for the electric guitar, all transformers work almost equally well♣.

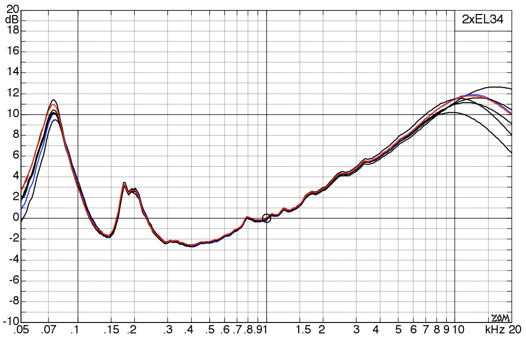


Fig. 10.6.34: Transmission from the phase-inverter input to the loudspeaker (Vintage-30 in enclosure). Right: transformers No. 11 – 16; left: transformers No. 17 – 19.

We see larger differences for the non-linear distortion (**Fig. 10.6.35**). As will be elaborated later, the 8-kΩ-transformer is unsuitable for a power stage deploying EL34's. All other transformers show a similar behavior at and above 90 Hz; it takes a backseat compared to the effect of the tubes. The self-wound M330-50A (compare to Fig. 10.6.23) was a first foray into building an OT – it is suitable, as well. With the addition of 10% more turns, this transformer could have been brought into the range of the other transformers (there would be enough space even with the same wire diameter) – however, this step was not deemed necessary. The red curve refers to a very special "output transformer": a **mains transformer**. Indeed, this works, as well! Not with just any mains transformer – we needed to look around a bit, but this one fits the bill. It's a toroidal transformer costing all of **15 Euro** – is smaller, more efficient, lighter by 1.5 kg, and much less expensive (due to large-scale manufacture). Why do we then still need an EI96? Maybe because it has been done like that for more than 60 years? And because micro-entrepreneurs do like to make the odd 100 – 300 Euro …

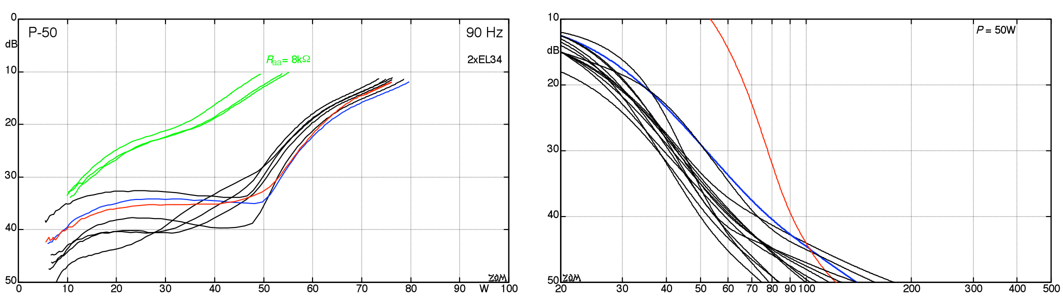


Fig. 10.6.35: Distortion-suppression. Left: whole power stage with 10 different OT's; right: OT's only; *blue*: M30-50A; *red*: mains transformer as OT.

♣ The difference 3.5 kΩ vs. 8 kΩ will be discussed later.

Mains transformers are optimized to achieve optimum efficiency – exotic issues such as “harmonic distortion” are of zero interest in this area. You just wind thick wire and decently drive the core in order to find a good compromise between power-losses and cost. The copper-resistance of the 9-V-winding – which we abused as 8-Ω-winding – reads only 0.2 Ω, compared to 0.4 to 0.7 Ω for the real OT’s. Given a few more turns, the main inductance could be increased without significant deterioration (and especially with next to no additional cost), and the harmonic distortion could correspondingly be lowered. This is not intended as a general call: “guys ‘n’ gals, just load your power stage with a low-cost mains transformer”, but it means to say that, given the correct calculation, and fabricated in industry-correct quantities, a toroidal transformer can be a small, light-weight and inexpensive alternative. And what about the frequency response? It’s fully in the green, as shown by Fig. 10.6.34. For the sake of completeness, the measurements with an ohmic load are shown in **Fig. 10.6.36**. All OT’s are perfect – including the mains transformer..

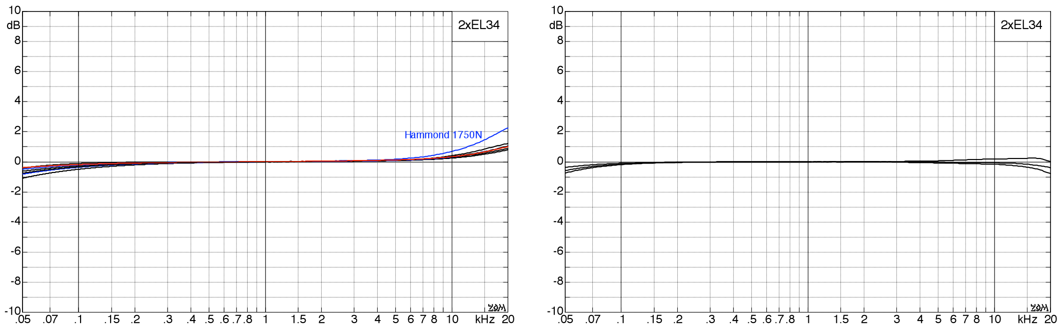
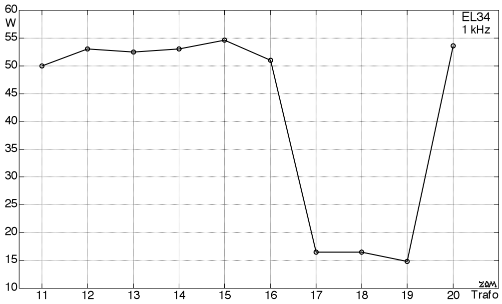


Fig. 10.6.36: Frequency response at an ohmic load (8 Ω); right: 8-kΩ-transformers. On the left, the frequency response of the mains transformer (abused as output transformer) is of course also included.

In order **to preempt misunderstandings**, here a short afterthought: guitar amplifiers are no HiFi-systems. The latter require a significantly wider frequency range and a significantly lower distortion. The message here is not that generally a mains transformer will do as output transformer, but rather that the high prices of output transformers result from their small production numbers, and from the more or less authentic replication of out-of-date historic examples. If authenticity is not the main objective, a mains transformer in the output stage of a guitar amplifier may be a low-cost alternative to the dedicated special output transformer. Each of us has to find out (**!**) on his/her own what is deemed suitable – the expectations vary too much.

A peculiarity: the special **JTM-45**-transformers wound – very authentically – to an R_{aa} = 8 kΩ specification. This certainly is inappropriate for an EL34-power-stage, but in the original JTM-45 we do not find EL34’s but two KT-66’s. Do these then require an 8-kΩ-transformer? Yes. Or no – it depends on the source. According to Doyle’s Marshall-book, **Radiospares** was the first purveyor to the court with their "De Luxe Output Transformer". Radiospares, however, was not a manufacturer but a distributor (they became RS-Components later). Who actually manufactured these early transformers is the object of escalating discussions (allegedly up to five manufacturers may be in the running). The RS-transformer was a typical universal transformer featuring a choice of several primary impedances: 6.6 kΩ (with ultra-linear tap) for EL34 and KT66, and 8 kΩ or 9 kΩ for 6L6, 6V6 and EL84. The power stage of the JTM-45 does not operate in ultra-linear mode; the experts consider 2xKT-66 / R_{aa} = 8 kΩ to be the nominal complement. The Drake-transformer used after the RS-transformers operates with this primary impedance, too. And the GEC-datasheet of the KT-66 (1956), as well, specifies 8 kΩ, but does this for "cathode-bias" which is not used for the JTM-45.



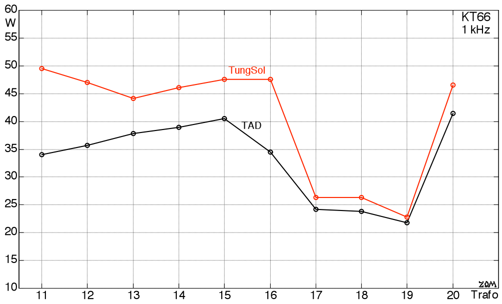


Fig. 10.6.37: Output power at 8 Ω, for a distortion-suppression of 30 dB; transformer-numbers acc. to the table.

Fig. 10.6.37 shows the measurement results for a supply-voltage of 400 V. Two EL34 will yield well over 50 W, given a primary impedance of about 3.5 kΩ. At 8 kΩ, the power output drops to a meager 15 – 16 W – for sure, this is not optimal. Using two KT-66's, about 25 W are achieved with 8 kΩ impedance, which is about in agreement with the datasheet. We obtained more power operating our JTM-45 with two KT-66's and a 3.5-kΩ-transformer: just under 50 W with a Russian TungSol-KT-66, significantly less with a TAD-KT-66 (measurement results in Fig. 10.11.3).

Besides the maximum output power, the source impedance shows differences, as well. Pentodes are of high impedance, and therefore the source impedance of the power stage (the internal impedance) is relatively high, too. It will be around 100 – 200 Ω with two KT-66 cooperating with a 3.5-kΩ-transformer, but only 40 – 80 Ω with an 8-kΩ-transformer (each at the 8-Ω-output with the negative feedback disabled). The effects have already been discussed several times; they show up e.g. in Fig. 10.6.34.

Well then, it's getting to be after hours – time to go home for dinner. It's been quite a while. You want a recommendation? Because, according to an OECD-study, many readers have difficulty to hang in there when confronted with longer texts? Ok, here we go:

Loud = 2xEL34 with 3.5-kΩ output transformer;
Authentic = 2xKT66 with 8-kΩ output transformer;
Prepared to take a risk = 2xEL34 with (special) mains transformer as output transformer;
Moronic = expensive replacement transformer from faraway lands.

Is that short enough, and intelligible despite three multiplication signs?
You are welcome – happy to comply.

> It is not the things that delight us,
> but the opinion we have about the things♣

♣ loosely based on Epiktet

