Measurements of Amplifier Peak Output Voltages Under Dynamic Conditions and Into a Real Loudspeaker Load - Part I.

by Peter van Willenswaard

Click here for Part II

(An earlier version of this story was published in Stereophile, Sept. 2000. I now expanded the score from three to five amplifiers, redid all the measurements using the same vertical scale in order to make comparisons easier and added an analysis of the effect of feedback)

Most people who listen to valve amplifiers once started with a transistor amp. They know from experience that a valve amp of a given measured output power sounds louder than its nominally identical transistorized equivalent. The unofficial consensus is that you need two to four times the power with transistors to achieve the same loudness as you would using valves. In other words, given the (subjectively) undistorted sound level a 25 Watt valve amp can provide, if you want the same loudness from solid state technology you would have to replace it with at least a 50 Watt transistor job. This comparison assumes similar circuit topologies: both class-A, both push-pull; otherwise the differences will be greater. At the same measured power, Class-A will sound louder than Class-B, Single-Ended will sound louder that push-pull, etc.

As an aside, 25 Watt may be just a fraction the filament power-consumption figure alone of many big American valve amps, but here in Europe it is quite a normal figure for the output power of a valve amp. We just have more efficient speakers; which are faster and livelier to boot. I do my normal listening on a homebred 300B SE (using the largest AudioNote 300B output transformer as well as an AudioNote interstage transformer) outputting some 9 Watts, the exact figure depending on where you put your tolerance of THD. I also have a nice-sounding pair of 40 years old Philips power amps (modified) delivering about 4 measured Watts per channel, EL84 push-pull in triode mode, class-A, no overall feedback. And I'm not ashamed to confess that it's sometimes replaced by its baby brother of two times 1.6 W...

There have been many speculations about the reasons for these differences between measured performance and perceived loudness. The oldest is probably the one that points out that valve amps tend to clip rather softly whereas most transistor amps clip hard. So you can drive your valve amp into clipping, the occasional peaks will in fact be compressed and rounded off, but not chopped off like would happen in a transistor amp which is subjectively far more objectionable.

Of more recent date are the theories that say that it is the different harmonic distortion spectral contents of the two technologies which accounts for the perceived difference in loudness.

THE FIRST STROKE

There is probably some truth in the above observations, but during the last weeks of the past century I reserved a couple of days to examine an idea which had been triggered by the CD 'Touch' recorded by my friend and colleague Eelco Grimm for cable manufacturer Siltech. And it turned out that there is also a directly measurable explanation for the discrepancy!

On 'Touch' you hear percussion music, performed by one single player. Edwin van der Klei of Siltech and Eelco are both purists, which is why they worked together on this project. Siltech wanted to celebrate their new G-3 cable (gold-doted silver) and G-3 was used for all cables in the recording. Valve mics and mic-amps were used, it just had to be top. During the mastering process, Eelco found that whatever processing he tried on the recorded material (even though it was done in the digital domain) had a detrimental effect on the sound quality. He tried slight limiting and clipping to lift the average loudness to a more acceptable level but the (digital) amplification itself appeared to degrade the sound. He tried level shifting using Sonic Solutions, Meridian 518, Wave renaissance EQ, he even tried 1-bit level shifting using a specially written program, everything degraded the sound. Many kinds of noise shaped dither were tried, also leading to the conclusion that 'simplest is best'. In the end Edwin and Eelco decided to use no processing and leave the recording as it was, and apply flat dither when truncating from 20 to CD's 16 bit. (Contact a Siltech dealer or distributor for this CD).

Now, percussion is extremely dynamic. On practically all commercial Cds compression is used to render it suitable for playback in a home environment (let alone in a car!). Play 'Touch' with your volume control at its normal setting and you'll hear almost nothing. But some peaks are within 0.5 dB from clipping!

Listening to this CD renewed my curiosity about the puzzling perceived dynamic performance of valve amplifiers. I finally did what I should have done a long time ago: I hooked up my oscilloscope to one of the 'speaker outputs of my 300B amp and observed the screen while the disk was playing. Holy Moses, I saw something like 30 Volts peaks from an amp that on the testbench driven with sinewaves and loaded with an 8 ohms resistor never showed more than 14 Volts peak! More than twice the voltage technically supposed possible! You'd need a 50 Watt transistor amp to realize the same peaks my 9 Watt 300B launched without wincing at my 'speakers!

HOW TO UNEARTH WHAT WAS HAPPENING HERE?

I did not know how to shoot a picture of such a moving target and a digital scope I do not own. So to record this behaviour for history, I carried the amps to my car and drove to where Eelco works as a technical editor: they have an Audio Precision System Two there. We loaded the amps with 8 ohms, fired a variety of pulse-like signals at it but never arrived at more than 1.4 times the peak voltage observed with a steady state sinewave near clipping. I was disappointed and puzzled: what was happening here?

Back home I decided not to give up yet. I had to have a digital oscilloscope with a memory and a printer output to be able to do further research. So I called Hewlett-Packard, now called Agilent Technolgies (the HP name is reserved for computer peripherals) and they kindly lent me a HP54615B oscilloscope plus a HP33120A function generator. When I repeated my earlier measurements and added some more for further analysis half a year later again no problem: they lent me a 54622A this time. These scopes are roughly similar and it didn't take to long to become familiar with all the buttons and menus. Both then and now I soon had the floor littered with printouts. I'll share the most revealing with you.

THE MEASUREMENTS

First, I took a 25 W transistor amp. Loaded with 8 ohms it clipped at almost 21 Vpeak on a continuous sinewave, fig.1 (the amp was a bit low on output power during the measurements for Stereophile but has been brought to spec since). The vertical scale used here and throughout this article is 10 V/div. Next, I connected the amp to my main speakers (AudioNote Es) and took the CD. 5 seconds into the first track the player hits a tambourine real hard (in fact, he broke two tambourines during the recordings....). The oscilloscope was triggered to capture the first 8 ms of this strike, which sets off a train of pulses at basically 600 Hz (so I also chose 600 Hz as the frequency for the sinewave measurements). The result is in figure 2 and is about 22 Vp. This (slight) increase can be explained as this amp was not fully class-A implicating that under pulse conditions the power supply voltage will be slightly higher than when driven with a continuous sinewave.

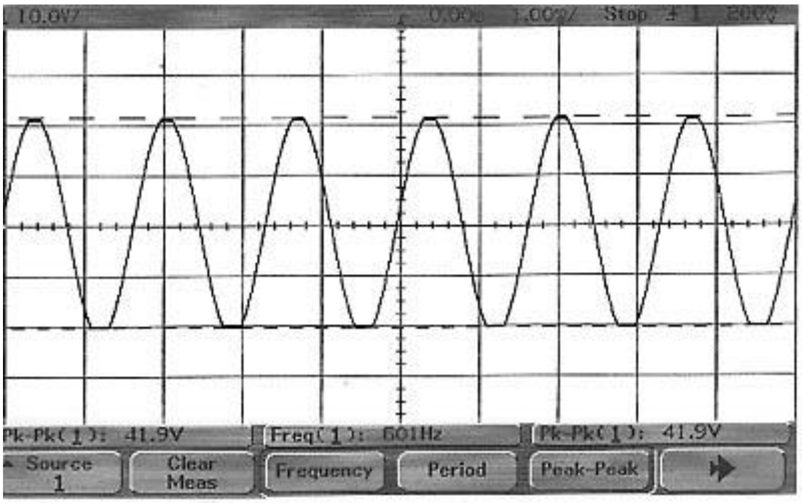

Fig 1: 25 W transistor amp loaded with 8 ohms,
sinewave just into clipping, 21 Vpeak (positive).

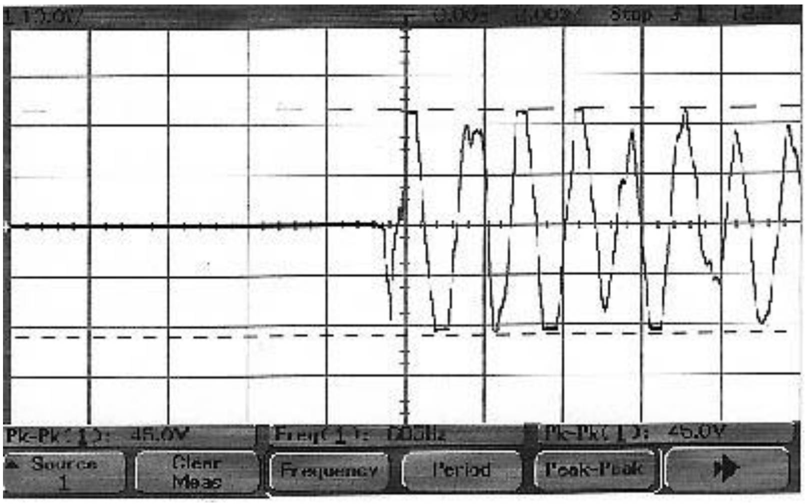

Fig 2: 25 W transistor amp loaded with AudioNote-E loudspeaker,
signal from 'Touch' CD at 0:05 into first track,
driven to maximum produced 22 Vp.

I then simulated the tambourine strike by an 8 ms train of 600 Hz sines, I tried a single-period 600 Hz burst, I tried a different speaker as a load, I tried 8 ohms and bursts, I tried to push the amp harder (to see if there was anything 'beyond clipping'), but in all cases I ended up with the same 22 Vp max.

Then I connected my 300B amp and repeated the tests. Figure 3 shows where this amp went well into clipping (THD measured 25%) into 8 ohms, reaching 15 Vp at the positive, least clipping side and 12 Vp negative, suggesting 11 Watt RMS. Doubling the amps input voltage produced heavy clipping at no more than 17 Vp positive. I switched to the speaker and the CD at 0:05, tried how far I could crank up the volume control until no further increase in output occurred and got fig 4: certainly distorted in comparison to fig 2 (although my ears couldn't pick up anything problematic at all), but look at that 37 Vp in the negative half of the picture! It would take an 80 W class-A transistor amp to allow such a voltage excursion! Figure 4 also seems to suggests that if the 300B output stage were dimensioned differently and optimized for these TRANSIENT conditions in stead of the usual steady-state sinewave one, the heavy positive clipping might be avoided. This deserves investigation, and will be treated in a future article.

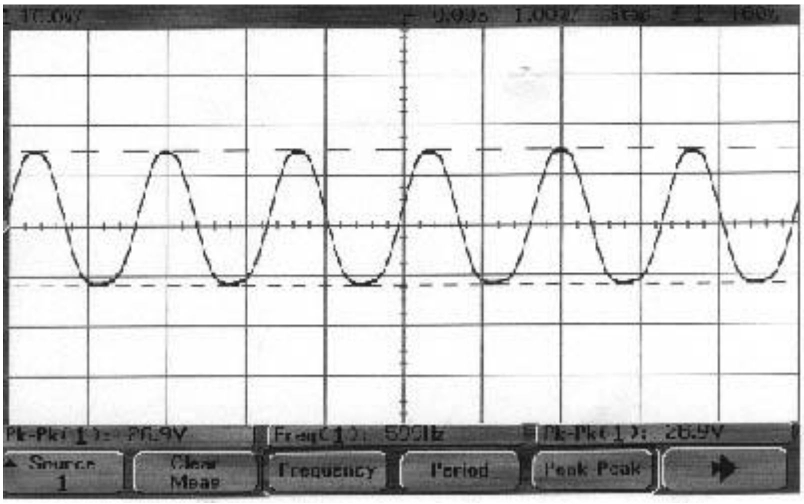

Fig 3: 11 W 300B SE valve amp loaded with 8 ohms,
sinewave just into clipping, 15 Vp (positive).

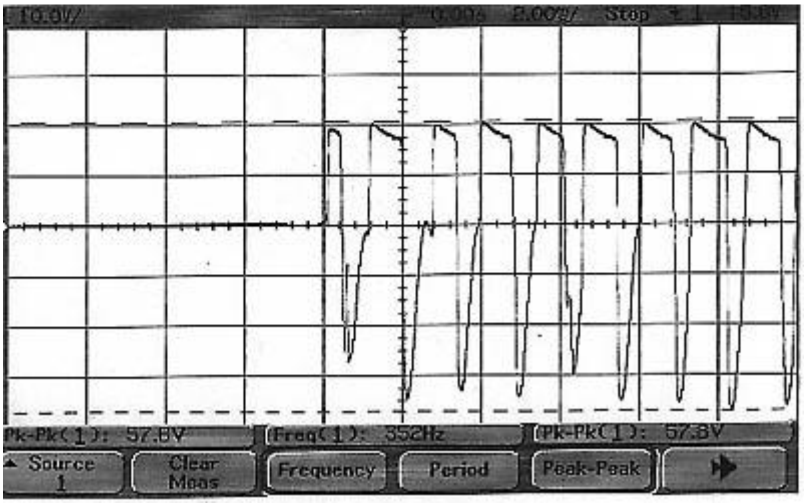

Fig 4: 11 W 300B SE valve amp loaded with AN-E loudspeaker,
signal from 'Touch' CD at 0:05 into first track,
driven to maximum produced 37 Vp (negative).

Next, I tried to simulate the tambourine strike with 600 Hz single-sine and 8 ms bursts. Into the speaker load, the results were roughly similar, but into an 8 ohms resistor the amp bottomed out at 19 Vp. I tried the CD 0:05 signal and the 8 ohms load: same 19 Vp. So it had to be an interaction between valve amp and speaker! I connected a different speaker, an old Wharfedale Denton 2XP: an astonishing 39 Vp. So here lies a key to another mystery: it is well known that valve amps and especially the SE-variants are choosy with respect to the speaker they have to drive. High sensitivity (preferably >90 dB/W/m) is a necessary condition of course, but not a sufficient one. Pick a speaker that impedance-wise looks like an 8 ohms resistor (the theoretical ideal!) and your valve amp will sound restrained.

By now I had become pretty curious how my 4 W push-pull triode would fare. Figure 5 gives the 8 ohms situation, Vp is about 8.5 Volts and accepting the 3% THD the 'scope indicates a 4.2 Watt RMS power rating. Pushing further leads to hard clipping at 10.5 Vp. CD at 0:05 and speaker load managed to produce figure 6, with a positive Vp of 15 Volts.

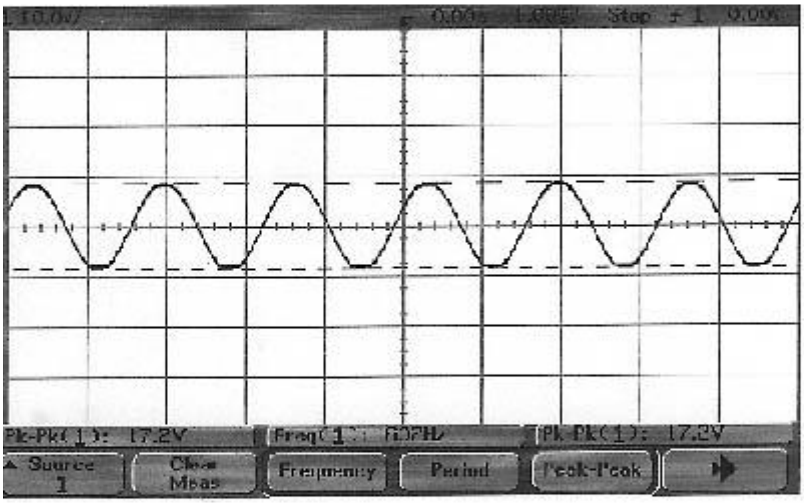

Fig 5: 4 W EL84/triode-mode PP valve amp loaded with 8 ohms, sinewave just into clipping, 8.5 Vp.

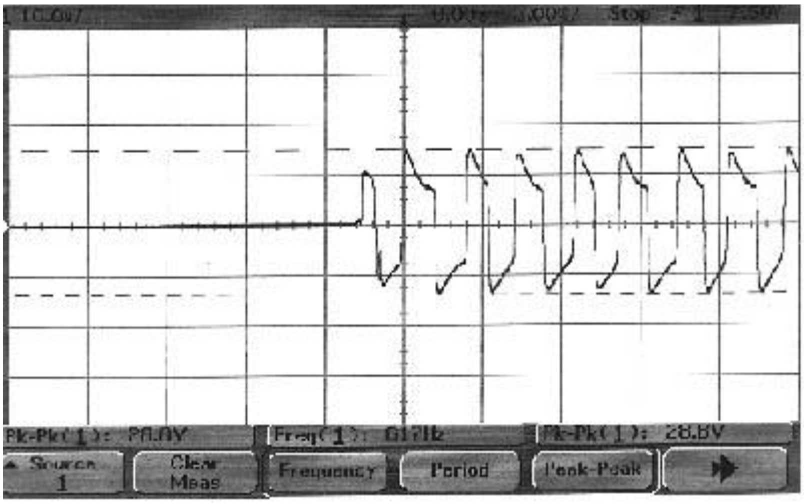

Fig 6: 4 W EL84/triode-mode PP valve amp loaded with AN-E loudspeaker, signal from 'Touch' CD at 0:05 into first track, driven to maximum produced 15 Vp.

Not as shocking as with the 300B but this still implies almost a doubling of the Vp under steady-state conditions, representing a quadrupled transient power output. With the Denton 2XP a Vp of 15.5 could be observed (only a few Volts away from what the 25 W transistor amp put out. Not bad for a 4 W triode, eh?). I repeated the simulation tests, nothing new submerged.

Similar behaviour could be observed in other valve amps. I measured 15 Vp on sinewave into 8 ohm on a Dynaco SCA-35 (fig. 7), while loading it with the AudioNote E loudspeaker and fed the tambourine stroke it produced 27 Vp at the positive (fig 8). The SCA-35 is an EL84 push-pull pentode class-AB design, and uses overall feedback.

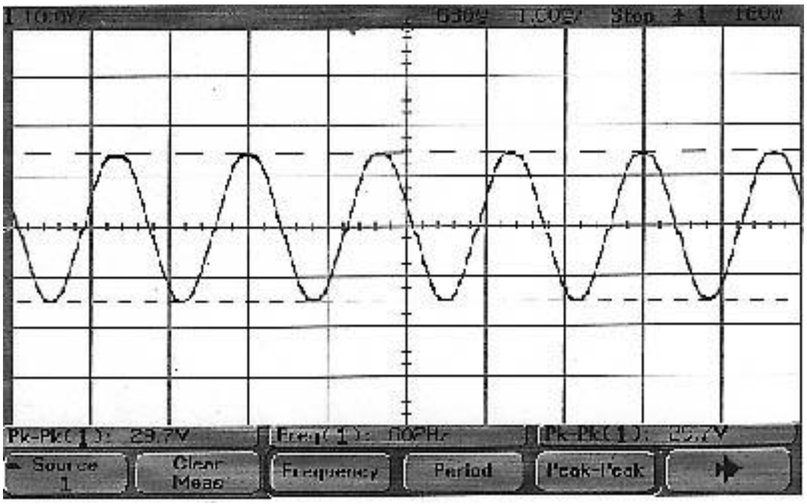

Fig 7: Dynaco SCA-35 EL84 PP Pentode loaded with 8 ohms, sinewave just into clipping, 15 Vp.

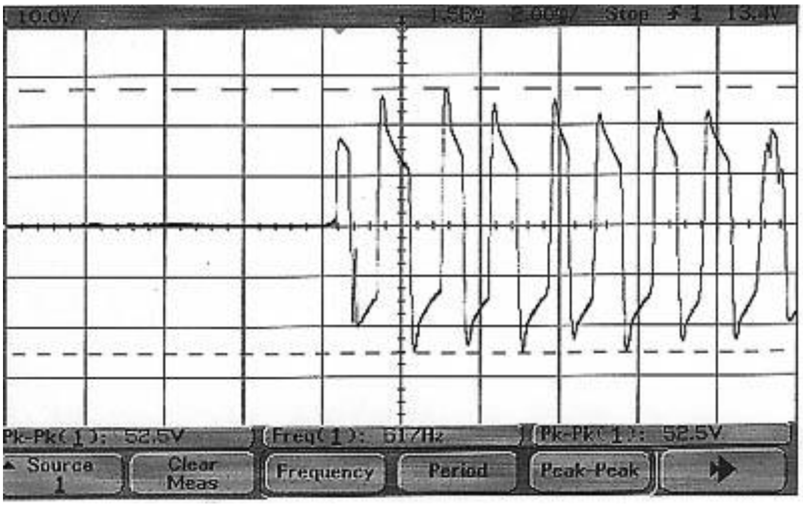

Fig 8: Dynaco SCA-35 EL84 PP Pentode loaded with AN-E loudspeaker, signal from 'Touch' CD at 0:05 into first track, driven to maximum produced 27 Vp.

(By the way, if the original Dynaco 7199 driver is worn out and you replace it with a Sovtek 7199, the amp will oscillate at 500 Hz. This is because the feedback set-up in the SCA-35 is a bit quirky and only just stable with the original 7199, but not with the Sovtek which provides more gain. Detach the 1 uF C18 from pin 6, the pentode section's cathode, and connect it to ground instead. This will vastly lower the loop-gain and stabilize the amp once and for all. Plus, it will sound a lot better because of the much lower feedback. Plus, the Sovtek 7199 sounds better than the original Dynaco).

An old Saba Telewatt from Germany, ECL82 push-pull, put out some 12 Vp on sinewaves and 17.5 Vp under the 'speaker/tambourine condition. The least spectacular of all valve amps measured here, but still.

ROLE OF THE OUTPUT IMPEDANCE

The interaction between speaker and valve amp haunted me. Both valve amp operated without overall feedback, so their internal output (source-)impedance was about 3.5 ohms, against 0 ohms for the transistor amp. What if I added an external 3.5 ohms resistor to the latter? The output under steady-state conditions would fall, of course: see figure 9, Vp now being 16 Volts against the 21 Vp measured earlier directly at the output. With a speaker hooked up and the CD signal Vp now arrived at 21 Volts positive, fig 10.

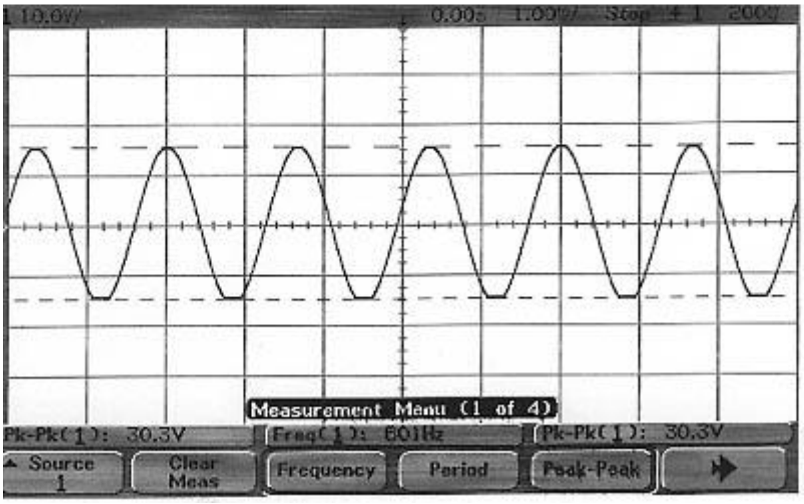

Fig 9: 25 W transistor amp with 3.5 ohms in series with output, system loaded with 8 ohms, sinewave just into clipping, 16 Vp.

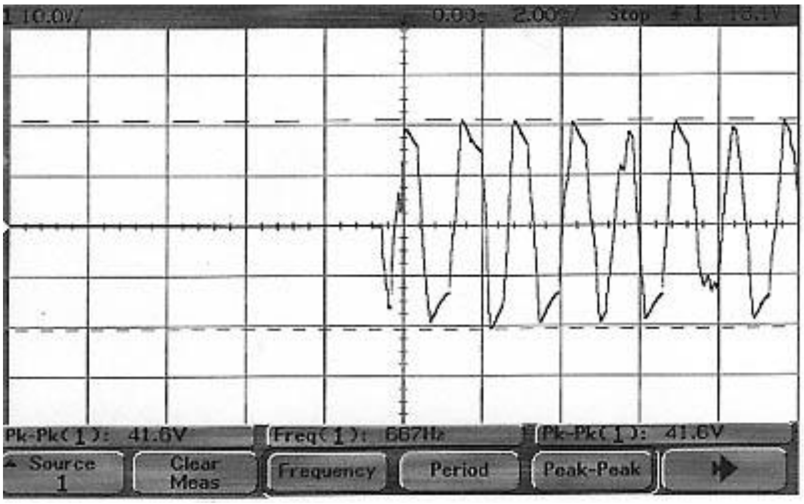

Fig 10: 25 W transistor amp with 3.5 ohms in series with output,
system loaded with AN-E loudspeaker, signal from
'Touch' CD at 0:05 into first track, driven to maximum produced 21 Vp.

Compare this to fig 2 and note that the transient output level into a speaker load in both cases is almost the same regardless the presence of the external 3.5 ohms resistor. So nothing is gained and nothing is lost. Or IS something gained and would this externally modified transistor amp now suddenly sound valvelike? Try, anyone?

Without the 3.5 ohms resistor, the transistor amp performed the same statically and dynamically. With the 3.5 ohm the dynamic-to-static Vp-ratio improved to almost 1.5, equalling that of the Saba. But the tiny Philips push-pull triode outclasses it at 1.8x, as does the Dynaco. Triumphantly, the 300B SE reigns at a supreme 2.6x (these figures mean a 2.2, 3.2 and 6.7 fold increase respectively in power).

THE ROLE OF FEEDBACK

So there's more at work than just the output impedance. Magnetic energy stored in the output transformer? Unlikely, I would have seen it at work with an 8 ohms resistive load also, and I didn't.

Feedback might be a factor. As the 4 W Philips used to be a feedback design (until I discovered how very much better it sounded without any!) and still had an undecoupled 56 ohm resistor in its driver's cathode circuit, I decided to use this amp for the experiment. Adding a 1k1 resistor between this cathode and the output I transformed 8.5 dB of the amp's 30 dB open-loop gain into feedback. However, music peak output was unchanged at 15 Vp, the oscilloscope's image was totally equal to the non-feedback case of fig. 6. I would have expected Vp to be lower now, as feedback decreases the output impedance but this proved not the be the case. HOWEVER, IT DID SOUND ABOUT 6 dB LESS LOUD!!!

In despair I lowered the feedback resistor value to 470 ohm, sacrifying another 4.5 dB (i.e. 13 dB total) of open-loop gain to feedback. Same 15 Vp out, with only microscopic differences in the signal waveform (see fig. 11). And it sounded still softer than with only 8.5 dB thrown at the feedback! Why this is, is beyond me. I do not have even a beginning of an explanation.

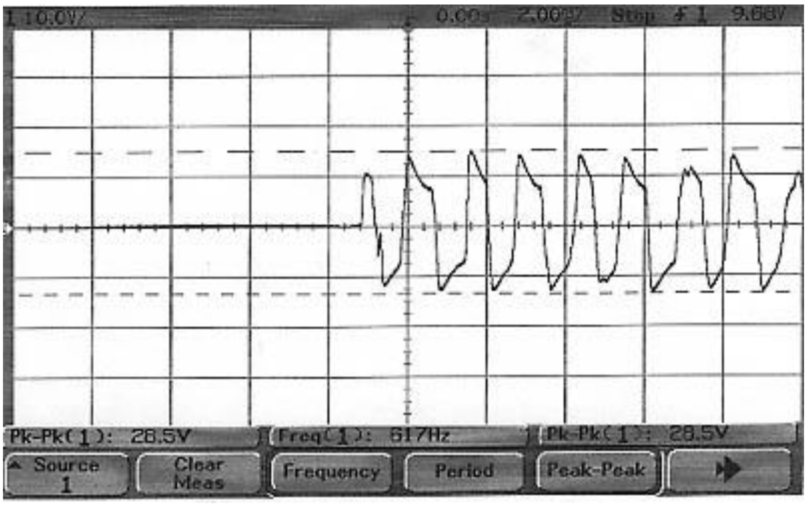

Fig 11: 4 W EL84/triode-mode PP valve amp now with 13 dB of its 30 dB open-loop gain applied to overall feedback, loaded with AN-E loudspeaker, signal from 'Touch' CD at 0:05 into first track, driven to maximum produced the same 15 Vp.

CONCLUSIONS

A transistor amplifier performs similarly into either a resistive or a real loudspeaker load. Externally augmenting its traditionally very low output impedance (high 'damping factor') to a value of 3.5 ohm as commonly found in non-feedback valve amps helps mimicking valve amp behaviour. Apparently, amplifiers that have 'ideal' near-zero output impedance waist energy that the loudspeaker has in store and is ready to use for building up extra sound pressure, by short-circuiting this energy out.

The feedback issue as yet leads to further confusion. But feedback or non-feedback, most valve amps laugh in the face of the poor solid-state amp, even with the external 3.5 ohm applied.

So valves do something special transistors can't. But we already knew that, didn't we.