

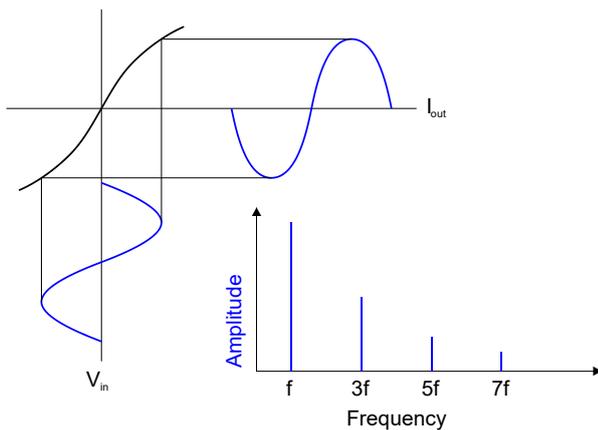
UcD and IMD, DIM, Slew Rate

“Dear Hypex, Why don’t your data sheets state IMD and DIM performance figures?”

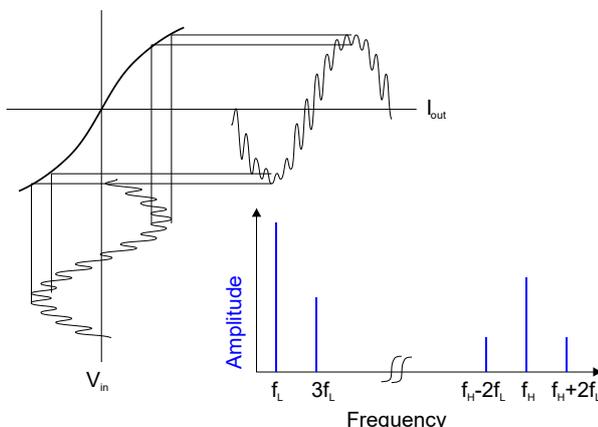
Fair question. Will these tests tell us anything a simple THD measurement doesn’t? It’s often proposed that IMD and especially DIM tests produce objective corroboration for certain sonic mysteries surrounding different amplifier topologies. The idea is that more complicated signals will suddenly bring out the beast in an amplifier that measures like an angel THD wise. I’m not that convinced.

1.1 Genesis

IMD and THD products are generated in exactly the same way. Subjecting one sine-wave to a non-linear transfer function will produce new sinusoidal components at integer multiples (harmonics) of the test frequency. If the non-linear transfer is written as a polynomial series expansion, the whole picture can be worked out using basic trig. The picture below shows a symmetrical non-linearity. It can be written as a polynomial with only odd orders. As a result, only odd harmonics appear.



If one wishes, the transfer function can be reconstructed based on the amplitude and phase of the distortion components. A single THD spectrum will do to characterise fully the distortion mechanism. Next, the same non-linearity is confronted with two sinusoidal inputs.



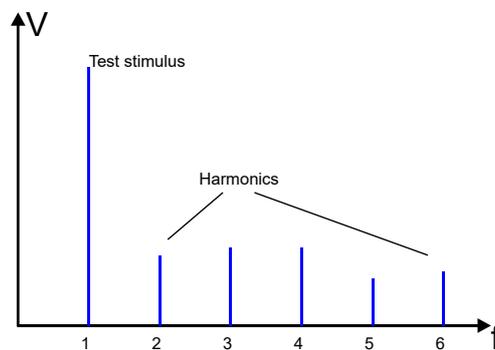
This too can be completely written out algebraically using standard trig no more complicated than the single-tone case. It’s just more maths, but in no way more complicated.

1.2 Hide and Seek

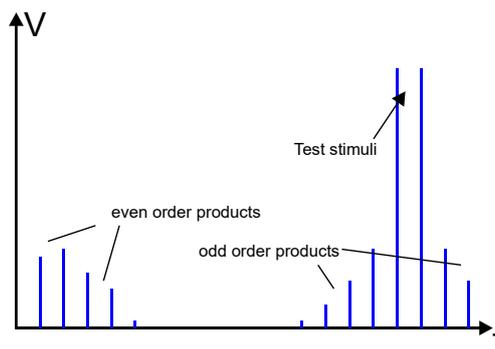
As far as the actual distortion mechanism is concerned, a single sinewave gives us all the information we need and the extra spectral components produced by more complicated test stimuli will only make intuitive readout harder. In principle there are no IMD tests that will magically bring out things that a simple THD test won't. What we do find is that when frequency-dependent effects are added to the system, the frequency at which the distortion products appear can make a difference to whether a problem is obvious or not.

1.2.1 Analyzer Bandwidth

The main problem with THD tests is that distortion products are at multiples of the input frequency. At higher test frequencies, less and less harmonics will actually fit inside the analyser bandwidth.



This renders THD measurement impractical at higher frequencies. For example, if we want to do a THD test at 20kHz, one needs a 60kHz measurement bandwidth just to capture the second and third harmonic, let alone any higher-order nonlinearities. The great advantage of IMD tests then is that it allows better characterisation of high frequency problems by insuring that a more of the distortion products land inside the measurement (audio) band. Testing with 18.5kHz+19.5kHz (CCIF IMD) will place a spray of odd order components at 1kHz intervals around the two test tones and even order components start from DC.

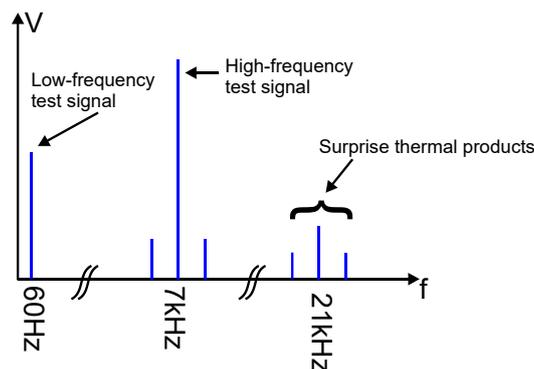


Suddenly the 20kHz audio band is wide enough to hold in all 38 distortion components (not counting the two stimuli). In a "memory-free" non-linearity, the individual components that we find in the IMD test are the same as the ones found in a simple single-tone test (with the same peak amplitude).

1.2.2 Memory and Feedback

In a nonlinearity with memory (e.g. a feedback system) the picture is less obvious, though no less consistent. The distortion components that appear in a 18.5k+19.5k test correspond with the harmonics of a 19kHz tone with the same peak amplitude, but with the loop attenuation superimposed. This is why an amplifier with significant second order distortion might still look surprisingly good in a CCIF test. Since the loop gain is usually rather high at 1kHz, the second order mix product gets attenuated rather well. This is one case where certain distortion components fly under the radar when tested using an IMD test while another test method (here a simple THD measurement) makes it all too obvious.

Things can equally work out the other way round. Take thermal distortion. In some circles there is considerable skepticism around the existence of this effect in linear (class B) power stages. Good low-frequency distortion performance is brought in to support this view. Again, the cause of the confusion lies in the amplifier's loop gain, which is usually very high at a few 100Hz. If loop gain were taken into account, distortion would be clearly seen to rise toward lower frequencies. Increasing the test frequency doesn't quite help because the thermal modulation effect is reduced at precisely the same rate as loop gain decreases. Here, an IMD test with 60Hz+7kHz is used to move the distortion products *upward* to where they are easier to measure i.e. 7kHz and (rather more importantly) 21kHz.



In both cases, the large difference in loop gain between high and low frequencies accounts for the discrepancies between THD and IMD figures. When doing tests on amplifiers with large DC loop gains the most directly useful distortion measurements are always the ones that put the relevant distortion products at higher (but still sub-20kHz) frequencies to keep them from being suppressed beyond measurement by the control loop. Sometimes, the best test is a THD measurement, sometimes it's IMD.

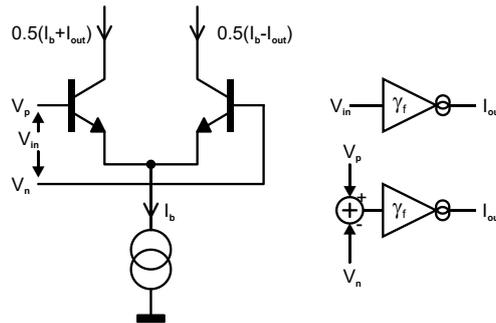
1.2.3 UcD and Loop Gain

UcD is a bit of an oddity in the field of power amps, in that the very simple passive control loop results in a rather moderate loop gain (around 35dB) that is constant over the full audio range. The result is that the discrepancy between IMD and THD results described above simply doesn't appear in the UcD circuit. Distortion at 100Hz equals distortion at 1kHz equals distortion at 5kHz. Inside the audio band, the amplifier is highly frequency-independent. As a result single-tone distortion products directly correspond to IMD results and vice versa. This is why we're happy doing just THD sweeps for frequencies up to 6kHz and a CCIF test for higher frequencies.

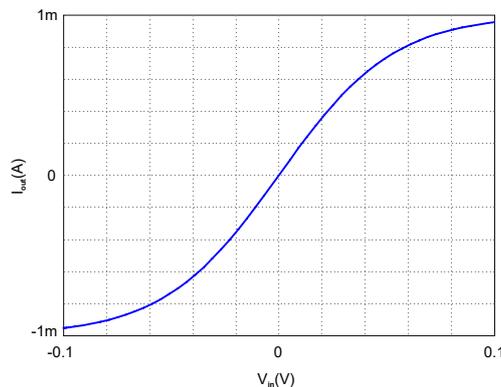
1.3 Slew Rate Matters (sometimes)

1.3.1 Slew Rate in Linear Amplifiers

Slew-rate distortion in linear amplifiers is a cause for a further rise in THD against frequency beyond (but linked to) the decreasing loop gain. It has been identified as an important cause of bad sound in amplifiers. In linear amplifiers, slew rate distortion is almost exclusively caused by the input pair. One is reminded that the input pair forms a differential transconductance amplifier.



The transfer function shows differential output current vs differential input voltage. The transconductance is the slope of the transfer function.

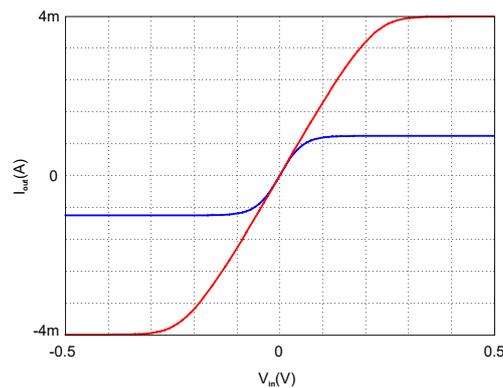
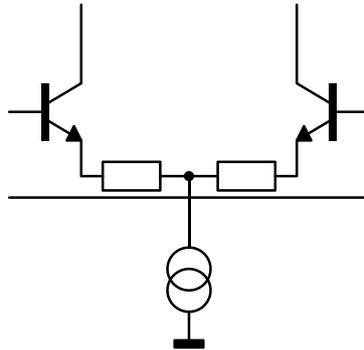


The amplifier slew-rate limits when the differential output current equals bias current i.e. when one of the two transistors is completely cut off.

Since this distortion is an odd-order effect (chiefly 3rd), it increases proportionally to the square of the input amplitude. With a 1st order loop that's also the square of frequency. The same 1st order loop has a loop gain that drops inversely proportional to frequency, the net effect of which is a rise proportional to the cube of frequency. This notion jives quite well with my subjective test experience, namely that if an amp has frequency-independent (but sufficiently low) THD behaviour, it sounds great. If THD rises 20dB/dec with frequency, it may still sound OK. If THD rises faster than that, it's useless for anything more demanding than a megaphone.

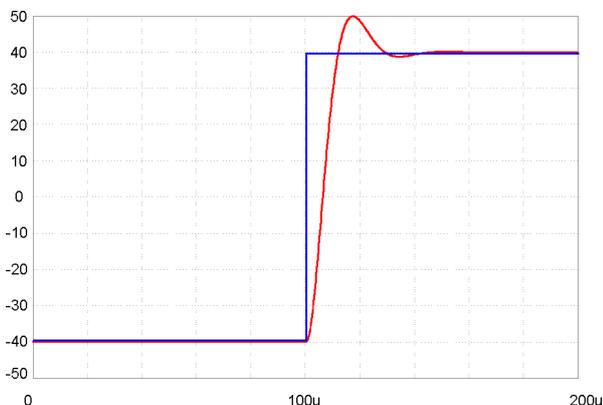
What makes slew rate induced distortion in linear amplifiers so insidious is that it doesn't just add distortion products, it also affects loop gain. As the amplifier is driven nearer to its slew rate limit, transconductance approaches zero and so does loop gain. The loop becomes increasingly powerless against any other distortion products. Unlike power stage distortion, slew-rate induced distortion products are attenuated much less than what the small signal loop gain would have predicted. The knee-jerk reaction would be just to try increasing slew rate. This has led to some kind of slew rate machismo on the audio market. But that's really barking up the wrong tree. An amplifier with moderate slew rate that remains perfectly linear until it actually slew limits is a much better amplifier than

one with a huge slew rate that starts distorting much earlier. Whether slew-rate distortion is significant depends on the exact transfer function of the input pair. A pair with the emitters tied directly together is fairly non-linear as the above graph shows. Slew-rate distortion in such amplifiers appears long before the amplifier comes anywhere near its slew rate limit. A more intelligent approach (popularised by Douglas Self but undoubtedly known long before) is to insure that the input stage remains linear longer. Slightly degenerating the input pair and increasing tail current to make up for the g_m loss does precisely that, in addition to increasing slew rate.



1.3.2 Slew Rate in Class D Amplifiers

But I'm digressing. Slew rate in class D amplifiers is completely unrelated to that found in linear amplifiers. The input stage is a comparator with the 400kHz carrier at its input. The "slew rate" is limited by the output filter. Apply a voltage step from $-V_{cc}$ to $+V_{cc}$ to the output filter and look at the output.

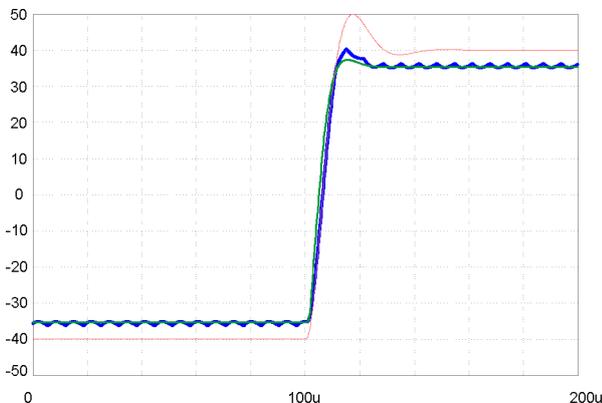


The bandwidth limiting action of the filter necessarily limits the dV/dt found there. That doesn't mean that the filter or anything else has gone non-linear. It's just that the bandwidth is limited, nothing

more, nothing less. Slew rate in a class D amplifier is a completely linear effect. Here, power bandwidth equals small signal bandwidth by definition, because there is no non-linear effect involved.

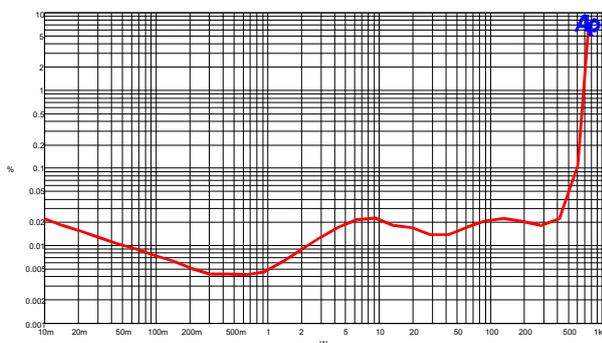
Well, sort of. It's not just that simple. UcD takes its feedback after the output filter. The only controlled variable is output voltage, and the small signal bandwidth is now set by the control loop, not by the output filter. In fact, the frequency response of UcD is completely independent of the output filter's. If the small signal bandwidth exceeds the power bandwidth the amplifier can definitely try to force a faster slew rate. Then it's not the input but the modulator that saturates when this happens.

Like with any amplifier, the effect is easiest to elicit if the small signal bandwidth is made much larger than the power bandwidth, and can be prevented completely by setting the small signal bandwidth lower than the power bandwidth. Based on reasonable expectations, we didn't take it that far. Power bandwidth is 35kHz while small signal bandwidth is 50kHz.



One could say that the output stage "clips". In green is the theoretical closed loop response. In red the filter response to a rail-to-rail step. Blue shows the actual amplifier closed-loop response. The green curve shows the amp would like to be just a bit faster than what the filter will allow. This is an example of actual slew rate limiting in a class D amplifier. The most important realisation is that the non-linearity (the overloading modulator) is fully enclosed by the control loop which in turn is not at all affected by slew rate. Slew rate induced distortion is therefore attenuated just as much as any error product.

To get an idea of how near we can come to the slew rate limit without any discernable performance degradation, we can turn to the THD versus level plot which gives an indication of the non-linearity involved. We find that distortion starts rising after $P_r/2$ or 70% modulation index.



Slew rate distortion will become noticeable only when the slew rate is 70% of the limiting value. This happens at $(70\% * 35\text{kHz}) = 20\text{kHz}$ and even then only at full power (when "normal" distortion is already higher). So, slew rate distortion is completely swamped by level-dependent distortion up to a full scale 20kHz input. I think that's reasonable.

1.3.3 DIM

All of this implies that in the case of UcD a DIM-100 test will provide no further information beyond the fact that the small signal bandwidth slightly extends beyond power bandwidth, and will show slew rate limiting just before the amplifier clips. A DIM-30 test will hardly produce any information at all.

In the case of linear amplifiers, DIM is a valid test protocol to assess slew rate using an analyser bandwidth of only 20kHz. Nevertheless, if a linear amplifier has low and constant (or increasing at worst 20dB/decade), THD up to 20kHz at high powers, a DIM test will not correlate with perceived sonic performance because normal audio will be unable to produce the effects tested for.

1.4 In Conclusion

The reason why we characterise the performance of our amplifiers using only THD and CCIF IMD is because UcD has:

- Constant loop gain
- No input distortion
- Negligible slew rate artifacts up to 20kHz full power (even though its power bandwidth is “only” 35kHz)

and is therefore fully characterised using only these two simple tests. Life is complicated enough.

Bruno Putzeys