Dear Editor,

I thank you for the opportunity to comment on scopeboy's question that appeared on DIYaudio forum on the 6th of October 2014 post post #24. Scopeboy, a.k.a. Steve Conner, asked some other questions about cube-law and square-law amps and I think that it may help to combine several queries into a letter for your Linear Audio site. The questions were asked in the section "Ian Hegglun's ClassA^3 Cube-Law Amp" starting from post #17. Thank you Steve for your thoughtful and probing questions.

Here's part of post #19, referring to cube-law Class-A, Steve asks,
"*But the sum of the device currents is no longer constant, and there must be more distortion than a "true" Class-A output stage, because the transfer function is now a curve, not a straight line. What does it achieve that a high biased Class-AB output stage doesn't?*"

I'm glad you asked that because I discovered something interesting about cube-law push-pull that, hopefully, can be seen using **Figure 1**. I mentioned it in 'Closing thoughts' in my article [1] and explained it in the Supplement [2].

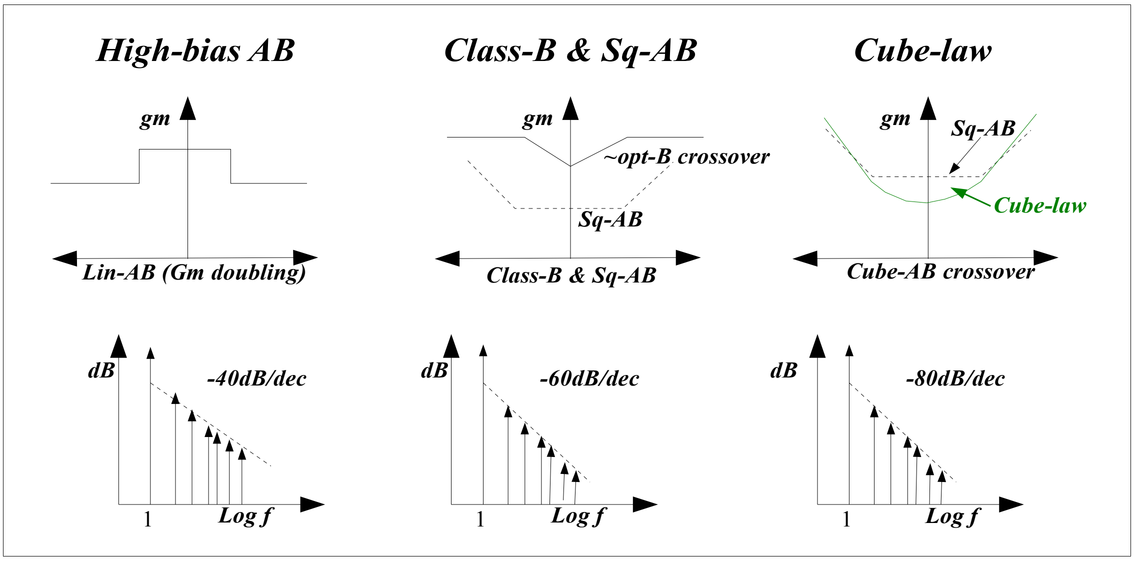

Figure 1. Harmonic spectra for various output stage types

Figure 1 shows the gain plots for different push-pull output stages; high biased Class-AB is on the left with a gain step at the -A boundary, so called "g_m doubling". Cube-law-AB is shown on the right; a very different approach, the gain still doubles at the -A boundary like high biased Class-AB except with cube-law's the gain change is smooth throughout including the -A boundary. To appreciate the effect on what we hear we need to compare the harmonic profiles. These plots have been developed from simulations [2].

Harmonics produced by cube-law-AB roll-off at *twice the slope* of high-bias Class-AB. A much faster roll-off in harmonics with cube-law's makes a huge difference to the distortion level that we need to make crossover distortion inaudible. My listening tests suggest we can get away with 0.1% THD's using cube-law-AB. This may run contrary to what most of us have been told we need but when you use valves/tubes this level of distortion is low enough and it is because there is no high-order distortion.

Compared to the more common optimum bias Class-B these plots suggest we needs around ten times lower distortion levels or <0.01% because the roll-off slope is ten times higher. For high bias Class-AB we need around 100 times lower distortion. Douglas Self has said all along that high bias Class-AB is worse than optimum bias Class-B because of more high-order harmonics and these plots suggest he is right.

With cube-law-AB_{50} [2,3] we can lower the idle dissipation and get the heatsink down to the same size as Class-B without the pesky high-order crossover distortion. We now have *a practicable compromise between Class-A and Class-B* – the efficiency of Class-B with negligible crossover distortion by using cube-law-AB.

This might also clarify query in post #19
"*You have not got rid of the crossover distortion, just lowered the order of it.*"

Yes, but is that a problem? With cube-law-AB we don't need to get the distortion down to minuscule levels like a few ppm. Now we only need to aim for 0.1% distortion. It becomes much easier to design and build power amps that sound great. The downside at present is the exotic lateral MOSFET's are not cheap.

I think we will still need some expensive super sensitive distortion test gear for digital converters we now use in audio because they generate a similar type of distortion to high-order crossover distortion.

Also post #19
"*Douglas Self discovered that an emitter follower output stage with lots of parallel devices and low-value emitter resistors did the same thing: flatten and widen the gain hump in the crossover region.*"

I am aware of this but it bring the cost closer to using lateral MOSFET's? I have been looking at using RET bipolar's to achieve similar low crossover distortion to cube-law-AB with some advantages over MOSFET's:
1) BJT's they are around 1/10th the cost of lateral MOSFET's for a similar SOA, and
2) the idle current with parallel devices is similar to cube-law-AB_{50}, and
3) the idle current becomes less critical, and
4) the -A boundary crossover distortion is like cube-law-AB – better than square-law-AB and better than optimum biased Class-B.

BTW my Supplement [2] also mentions a bipolar transistor output topology that uses them in their beta current mode to achieve a very good open loop linearity and a low idle current that is hardly affected by temperature changes.

Finally, a question in post #24 on HF IMD in cube-law amps:
"*Another question for me would be, how does the HF IMD performance of this amp compare to more traditional designs? I expect the IMD at high power and frequency (maybe 19+20kHz) would be pretty bad, as the output stage will be generating lots of 3rd or 5th order products and relying on global feedback to get rid of them. If there are IMD test results in the issue of Linear Audio I promise to buy it :)*"

Sorry, I didn't include any HF IMD plots in my article. But I have generated some plots from simulations if that is any help.

Before getting into those simulations I'd like to mention if a may a few interesting things about my design in Linear Audio Volume 8. It is quite unusual for a solid-state amp because from about 25 watts, which is half the full output swing, soft clipping starts to ramp down the incremental gain to zero when reaching about 130 watts into 8 ohms. Below 25 watts the distortion is mainly 3rd harmonic from cube-law class-A and my measured spectrum plot in open loop at 8W/8R is provided in the article to show this.

Also, for the first 2/3rd of the output range it operates in cube-law class-A up to 66W. So from 25 watts to 66 watts the soft clipping rounds over the cube-law's increasing parabolic gain so the 'bad' high current nonlinearity is not that bad. An error correction circuit is used to straighten the gain below 25 watts. BTW it is called "100W/8R" because that's where the soft clipping has ramped the gain to about half and the distortion (from clipping) is audible at 1.3% mostly 3rd harmonic.

Only 20dB of global feedback is used. This is sufficient to make the distortion, which is low order distortion, inaudible over most of the output swing. With only 20dB of feedback some will question whether re-entrant (or spectral growth distortion) is a problem, because it generates high order distortion out of low order distortion. My simulations did not show this to be a problem. I did not posted these simulations after publication of my article but if someone want to see them them then contact me for them (use the Contact area on my download site [2]).

On HF IMD testing, Bob Cordell uses the CCIF IM test with 19kHz and 20kHz and provides a good coverage of various tests in his book in Chapter 22 [4]. The CCIF IM test has the advantage of not needing high purity oscillators but you need a spectrum analyser to 30kHz (which unfortunately is just outside the range of common PC sound cards).

Willy Sansen's IEEE tutorial [5] on p317says, “Under low-distortion conditions, there is a one-to-one correspondence between harmonic and intermodulation distortion. It is thus sufficient to specify only one of them.” He derived shows from first principles the first two harmonics the relationship as $IM_2=2\times HD_2$ (or 6dB higher) and $IM_3=3\times HD_3$ (or 10dB higher). But his analysis applies to wideband amplifiers and most power amplifiers use a feedback factor that varies with frequency including within the audio frequency range. The cube-law amp in Linear Audio has an open loop bandwidth slightly above the audio band so the HD and IM levels should be fairly close to those given above from first principles.

Figure 3 compares simulated HD (left) and the HF IMD harmonic readings (right) at the same power level of 8W/8R to see if there is any correlation between HD and IM for this cube-law amp at a moderate power (before the soft clipping starts) [6]. The HD readings are at 1kHz and the IM reading use 19kHz plus 20kHz 1:1. **Figure 4** shows the enlarged part of the IM products.

Comparing harmonics, the 2nd harmonic HD readings are -83dB and IM is -89dB – so IM is *6dB lower*. The 3rd harmonic readings are -73dB and -65dB – so IM is *8dB higher*. The 5th harmonic readings are -92dB and -73dB – so IM is *19dB higher*.

From simple analysis the IM 2nd should be *6dB higher* and the 3rd IM *10dB higher*. In these simulations the 3rd harmonic is, as expected, 10dB higher. The 2nd is lower (not higher). But they are in the right ball park. Using Cube-law's, at least in this amp, does not throw up much higher than expected HF IMD readings.

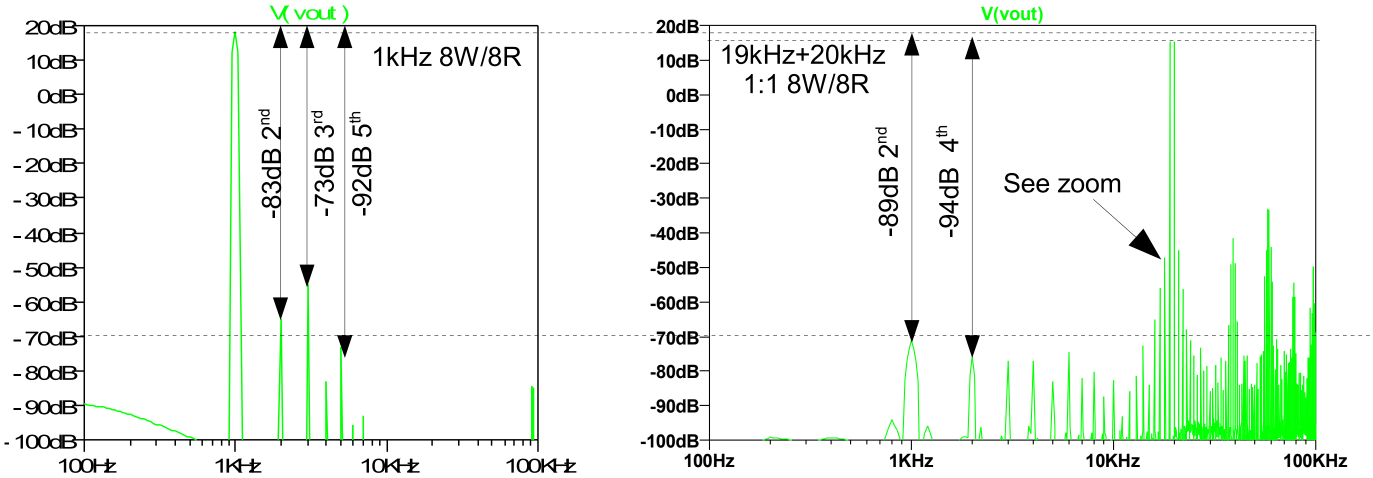

Figure 3. Simulated HD at 1kHz and IM at 19/20kHz, both are 8W into 8R

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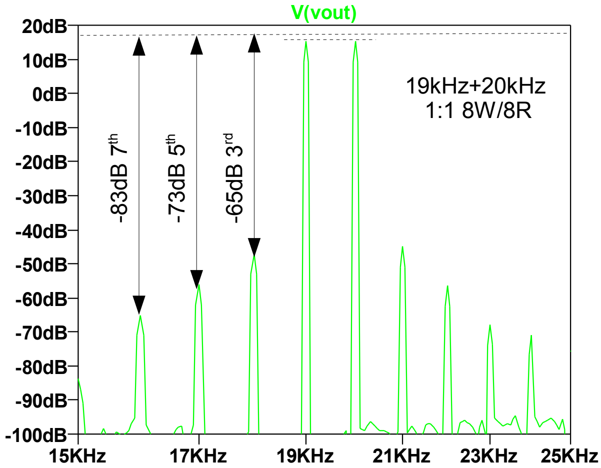

Figure 4. Zoomed IM products around 20kHz.

Unfortunately, I can't comment on how this amps HF IMD tests compare to other amplifiers at this stage. I am hoping that those who build and test my amp will make their findings public or contact me.

For those thinking of purchasing Linear Audio Volume 8 I would like to mention that my article includes my thoughts on how amplifier clipping has distorted our understanding of what we need to make a good amplifier. I now thinking that we need to design our amplifiers for soft clipping, either by including it in the amplifier itself (like my cube-law amp) or by adding a soft limiter before the power amplifier. I provide references to others who have come to the same conclusion (BTW there's a further one in the supplement [2]).

This and the need for weighting of harmonics [7], mainly as a check on how much high-order distortion is present, means we can design and build better amplifiers even though some of our sensitive tests suggest otherwise, and, hopefully help us to stay out of the audio asylum :) .

References:

1. Linear Audio, A Cube-law audio power amplifier, Vol.8 p149-174 www.linearaudio.net
2. Free supplement PDF follow the links at www.greenchild.us, kindly provided by Mason Green since my download site is temporary.
3. Cube-law-AB_{50} means 50% of cube-law-A idle current or 1/16th the peak current for 8 ohms.
4. Bob Cordell, Designing Audio Power Amplifiers, McGraw Hill, 2011 www.cordellaudio.com
5. Willy Sansen, Download available via www.greenchild.us
6. Simulation files for IM and HD for the above plots will be posted for download via www.greenchild.us in a zip "LTE-09-Oct-2014 circuits"
7. Linear Audio, Towards a reconciliation of measurements with listening test, Vol.4 p31-60 www.linearaudio.net