

Ncore Technology White Paper

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Ncore® is the trade name for the first significant step in power amplifier performance in a decade. Building on the strong heritage of UcD, Ncore takes the things UcD does well and does them ten times better. Literally. Following nearly two years of sporadic unofficial demonstrations Hypex is ready to announce this ground-breaking technology to the world.

Of course, this being audio, people will not only want to know how well it performs, but how it works. Here's the story.

1 Synopsis

Ncore technology combines the stability of UcD with improved load-independence, lower distortion and lower output impedance. The approach is multi-pronged:

- A mathematically exact understanding of self-oscillation. This allows optimization of large-signal performance.
- Improved comparator circuitry insures that actual behaviour matches the theoretical model as closely as possible.
- New gate drive circuitry improves open-loop distortion at moderate signal levels while significantly reducing idle losses.
- A new control loop ups loop gain by 20dB across the full audio range without sacrificing stability.

Amplifiers using all four of the above will be marketed under the name Ncore. Amplifiers using only the first three will still be sold under the UcD brand even though their internals no longer resemble that of the well-known 2001 circuit and their performance is already a clear step up.

2 The back story

When the UcD circuit was developed in 2001 the aim was to build, in a minimum of time, a simple circuit addressing the shortcomings of contemporary class D solutions sufficiently to make it a drop-in replacement for linear amplifiers in cheap consumer goods. It's fair to say that the result quite overshoot the target. 10 years on there are still no competing technologies able to match its combined output impedance, high-frequency THD performance and sheer sound quality. However, some competing products have now come round the corner that approach regular UcD amplifiers' midrange

THD and their manufacturers are making much of that fact. High time to move onwards and upwards.

3 From practice...

UcD's technical success is particularly remarkable considering the crude theoretical tools available at the time. The original AES paper made greatly simplified assumptions about how self-oscillating circuits work. No apologies are made for this: even today, most literature artificially divides self-oscillating modulators into hysteretic and phase-shift types depending on which approximate analysis works best, where the same method of the UcD paper is still used to deal with phase-shift controlled modulators. The limitations are well known but get downplayed as practical or secondary matters. Most importantly, self-oscillating control loops have a non-linear DC transfer function that was largely unpredictable other than through trial and error. A thoughtlessly designed controller could easily cause more distortion than the power stage, at least near the clipping point.

Louis Pasteur once quipped "serendipity favours only the prepared mind". Well, when the time came to give UcD an overhaul, we were going to get very prepared indeed.

4 ...to theory...

Self-oscillating controllers combine two functions: to provide loop gain and to turn the error signal into a pulse-width modulated signal. Also called sliding mode control, they are usually credited with three benefits:

- Simplicity. There's no oscillator and yet no extra parts are needed in compensation. What changes is how the poles and zeros are placed.

- Loop bandwidth. Self-oscillating loops are said to have a wider usable bandwidth/switching frequency ratio.
- Robustness. Loop dynamics remain largely unaffected by significant changes in operating conditions such as load changes and component tolerances.

The first and last are very real, the middle one is only true for standard triangle wave based implementations. Ripple-compensated modulators¹ do not suffer from this limitation but they are significantly more complicated.

The main drawbacks are:

- Potential demodulation of one amplifier's carrier by a neighboring one.
- Significantly non-linear DC transfer.

The former is of a practical nature. It has been successfully mitigated in the circuit layout of Hypex UcD modules ever since their commercial release. Gratifyingly, other manufacturers of self-oscillating circuits are still struggling.

The latter is the more fundamental one. The classical analysis of phase-shift controllers has been extremely unhelpful in this regard. It predicts small-signal behaviour with passable accuracy but makes no meaningful predictions of large-signal behaviour. It consists of first determining the frequency where the loop phase transitions 360°:

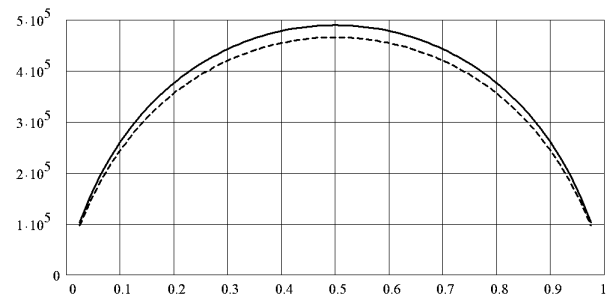
$$\arg(H(2i \cdot \pi \cdot f)) = 0$$

Next, the nearly sinusoidal waveform at the comparator is treated as an external carrier and small-signal DC gain derived on the basis of the slope. It took a while to realise that the classical analysis was wrong in every way: firstly, only pure sine wave oscillators run at the 360° phase point. A class D amplifier is a square wave oscillator. Secondly the resulting "carrier" waveform at the comparator input responds immediately to the signal so it can't be treated as though it were independent.

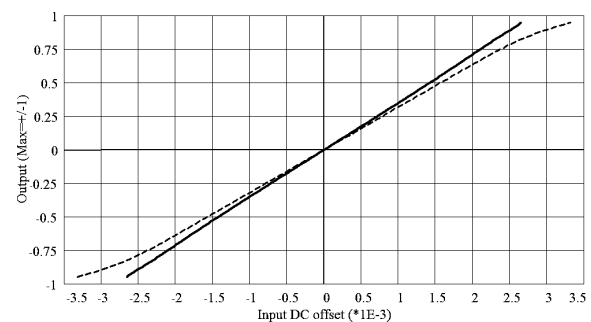
Remarkably, an exact oscillation criterium for square wave oscillators can be derived² on the back of an envelope³. By adding in extra terms for the harmonics of the square wave it predicts not only the exact idling frequency, but also the switching frequency at arbitrary duty cycles.

$$\arg\left(\lim_{t \rightarrow 0^+} \sum_{n=1}^{\infty} \frac{(1 - e^{-2i\pi n h}) \cdot (1 - e^{2i\pi n h})}{2 \cdot n} \cdot H(2i \cdot \pi \cdot f \cdot n) \cdot e^{i f t}\right) = 0$$

A graph of the solutions with H being the loop function of a UcD style amplifier shows that the switching frequency follows a roughly elliptical trajectory:



Of course, once you've got the precise switching frequency corresponding with all values of duty cycle, it's trivial to work out what the DC component of the comparator voltage is. Having found DC input as a function of duty cycle, the DC transfer function of the self-oscillating loop is the inverse of that. Here's the graph for two different sets of component values:



This is a very significant result. Switching frequency may be all over the place but *linearity can be optimized to near perfection*. It certainly can be

¹ WO2009131440, "Method and control circuit for controlling pulse width modulation"

² "Globally Modulated Self-Oscillating Amplifier with Improved Linearity", presented at the 37th AES conference, 2009.

³ One of those large brown ones that tend to contain mail-order catalogues.

made better than the open-loop linearity of the power stage. That wasn't obvious from either past theory or practice. Being able to optimize linearity removes the single biggest obstacle posed by self-oscillating control.

5 ...and back

5.1 Making practice match theory

The original UcD circuit has a remarkably simple comparator circuit consisting of six transistors and two diodes. This is fine until one wants to design optimized modulators and expects the circuit to behave accordingly. At that point a much more "ideal" comparator is in order. The final design contains ten transistors, which is nothing compared to the benefit. The new comparator circuit is a lot faster and handles much smaller signals. The match between predicted and actual distortion performance is now almost exact, resulting in low distortion right until the onset of clipping.

5.2 A more muscular control loop.

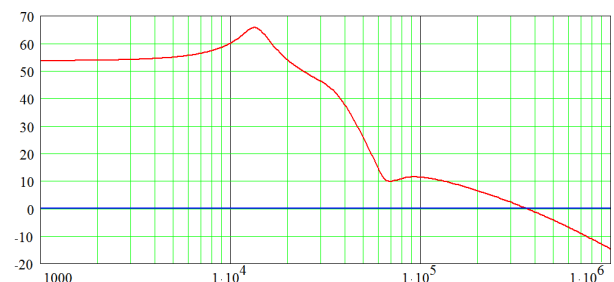
Early class D prophets foresaw that future amplifier generations would be running at much higher switching frequencies and switch very fast. They were *good* prophets because as such people always do, they got it totally wrong. Power FET performance improves only gradually and any speed benefits offered by new devices is immediately turned into increasing output power and efficiency but never raising switching frequency if it can be helped. Switching exceedingly fast is never a good idea from a reliability and EMI point of view so that isn't happening either. We may expect gain bandwidth and open-loop distortion to remain relatively constant for the foreseeable future. Any substantial performance improvement will have to come from higher order control loops.

Now I know that error control ("negative feedback") gets bad rap in some circles. Why this is so is explained elsewhere⁴ and I won't repeat the arguments, suffice to say that contrary to myth, a truly large amount of feedback vastly improves perceived sound quality as well as measured performance. If it doesn't there's something wrong with the implementation, not with error control itself. Feedback has been so badly executed in some amplifiers

in the past that it's understandable how this myth arose in the first place.

UcD amplifiers are designed to have essentially frequency-independent distortion for psychoacoustic reasons. They typically have a loop gain of 32dB from DC to 20kHz and open loop THD in the order of 1% (or much lower at low power levels) resulting in in-band distortion products hovering around the 0.03% mark for all audio frequencies. Given UcD's success on the audiophile front a successor would have to follow the same spirit. Simply shifting one of UcD's two real poles to DC would have made the numbers look nicer, but would not have yielded a better amp. Instead, another pole was added to obtain a total of 5 poles: one real and two complex pairs (one pair being the output filter).

The loop gain plot bears closer resemblance to that of a sigma-delta modulator than to that of an amplifier:



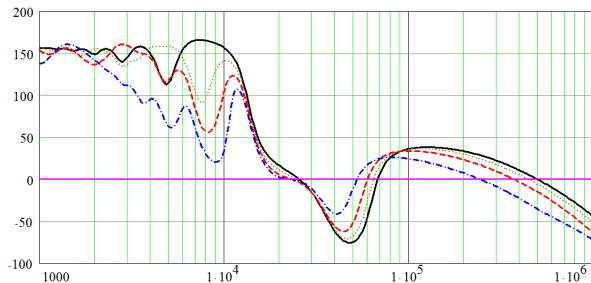
Across the audio band, loop gain never drops below 53dB. Compare this to linear amplifiers that may have much more at 10Hz, but rarely better than 25dB at the end of the audio range. In fact, most likely you have indeed *never* heard an amplifier with "a lot of feedback", although you may have certain ideas about feedback based on hearing amplifiers that you *thought* had a lot of feedback. Time to try and to be very surprised what it sounds like.

5.3 Active stabilization

The exact oscillation criterium has a second function: to point out whether there are any unwanted solutions i.e. if the amplifier isn't liable to "go unstable" that is, operate at another frequency. This happens when the amplifier clips. If near clipping more than one solution exists, the amp may restart at the wrong solution. This may be the right moment to insert a plot of the exact oscillation criterium of such an amplifier (an NC1200 prototype). Different curves belong to different duty cycles, and

⁴ "The F-Word", Linear Audio, vol. 1, April 2011

solutions appear as downward zero crossings. There are two, one at 500kHz and one at 26kHz.



We have three lines of attack. Firstly no unwanted solutions might exist. This is how UcD works. Even with no load, there was only one viable switching frequency.

Secondly the unwanted solution(s) may be unreachable. This is the case in the example above. As the duty cycle approaches 100%, the graph dips below zero less and less until it no longer crosses zero at all right before clip. The unwanted solution doesn't exist near clipping so there's no way for the amp to hop from 500kHz to 26kHz.

Thirdly, if nothing else helps, some arrangement in the modulator may detect clipping and simply remove a few poles from the loop until the coast is clear.

I must admit that making any unwanted solutions unreachable is very geeky but in the end the active stabilizer won the plot.

Keeping higher order loops stable is a perennial issue in industrial control. In the case of amplifiers, previous attempts centered either on detecting clip and holding all integrators in reset, or on letting the integrators clip intentionally near maximum modulation. The former has the advantage of being very clean and responding only when needed. The latter is very simple, but recovers quite noisily and is liable to be triggered by fast-slewing signals without being anywhere near clipping.

It's unnecessary to go too deeply into the method used to control Ncore as savvy readers will undoubtedly know where to find the patent. Basically, it is a half-way house between the two where the onset of clipping is detected not at the output but inside the loop itself, and the response is to knock out two poles while the remaining three keep the amplifier running normally. Recovery from clip is fast and the noise-shaping action of the loop (which is rein-

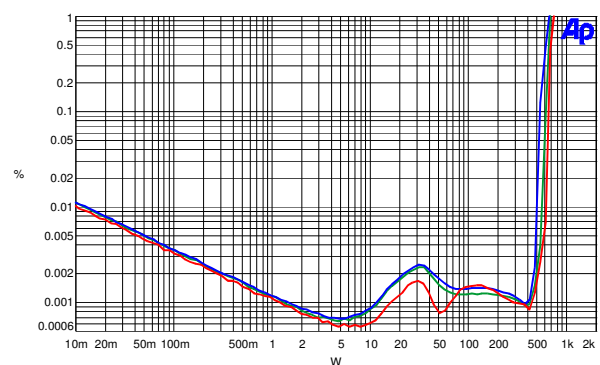
stated immediately after clip) insures that no noises other than regular clipping distortion remain inside the audio band.

5.4 Improved MOSFET gate drive

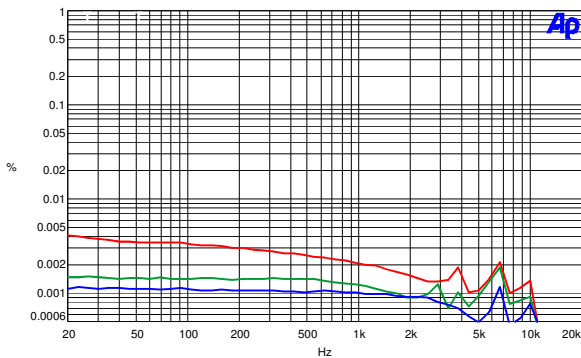
The power stage has to fulfil conflicting requirements. Best open-loop distortion is obtained by minimizing dead time and switching very fast. Best EMI is obtained by switching slowly. Diode recovery takes time and turning on the opposing FET gently helps reduce the recovery spike but increases conduction losses after recovery. Lowest idling losses are to be had with a longish dead time which gives the inductor the time to recycle energy stored in parasitic capacitances. A rule of thumb is that idling losses of an amplifier optimized for efficiency are about 1% of maximum output power while 2% is the more realistic figure for amplifiers optimized for audio performance. UcD falls into the second category. Along with the new comparator circuit a new driver circuit was designed that significantly reduces idling losses while actually improving crossover distortion. Idling losses of amplifiers using the new gate drive circuit are below 1%.

6 Technical Results

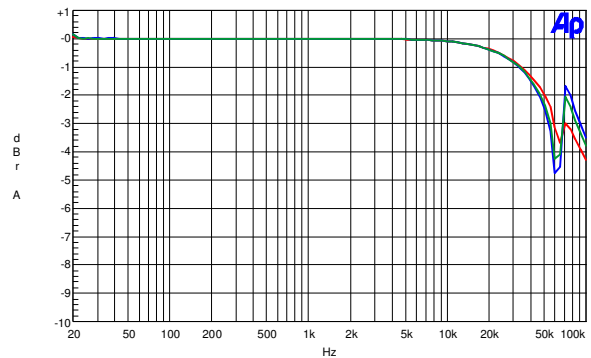
Although a full data sheet is available elsewhere, a few graphs from a typical Ncore amplifier are shown here. It is the NC1200 module, named after the fact that it puts out 1.2kW into 2 ohms.



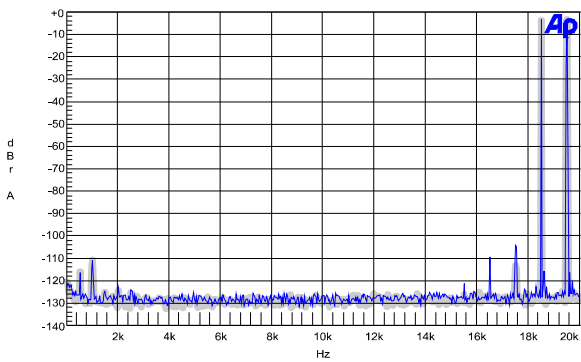
THD into 4 ohms at 100Hz (blue), 1kHz (green) and 6kHz (red).



THD into 4 ohms at 500W (blue), 100W (green), 10W (red).

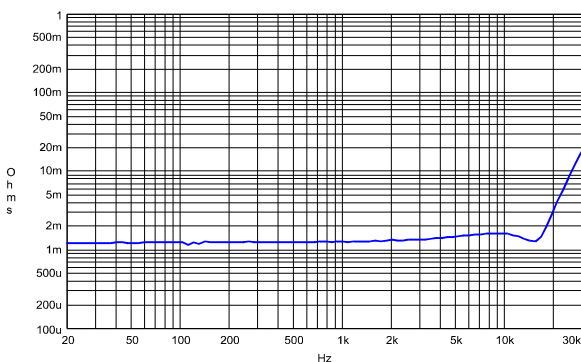


Frequency response at 8, 4 and 2 ohms.



HF IMD at 200W, 4 ohms. The IMD of the instrument alone is shown in grey.

The IMD graph shows that the feedback loop is equally capable of handling IMD products. If I didn't include this graph people would say that "feedback is only good for harmonic distortion but not for IMD and stuff with high slew rates". Of course, including this graph won't stop them but at least it makes them look silly.



Output impedance.

This measurement was quite hard to make. Output impedance is lower than the resistance of three feet of 4 gauge loudspeaker cable. At high frequencies the inductance of even a few inches will dominate.

7 Sound

Not so long ago a reviewer, having to test "yet another Hypex UcD based amplifier", yammered that it really was no fun writing about these things as "they just sound clean and neutral and do what they're asked to do".

Shouldn't that be the *point* of high fidelity? I understand that one of the joys of audio writing is generating baroque prose to describe the sonic vagaries (or pleasantries) of products designed expressly so that reviewers can have something interesting to write about them, but as an engineer I can't help preferring doing a good job.

Reviewers, prepare yourselves: Ncore continues along the path set out by UcD and the step forward is quite big. If you want to wax lyrically about all the different sonic colours and textures amplifiers can add to the listening experience, there's not much to say. If you want to forget completely that you're listening to an amplifier, how it's made and how it works and instead you just want to get sucked into the *music*, this amp is for you.

8 Conclusion

A new class D amplifier was presented that delivers audio performance and sound quality well exceeding that of the best linear designs without trading in any of the classical benefits of switching amplification.

Bruno Putzeys & The Hypex Crew