Cambridge Audio White paper

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Cambridge Audio 840A Class XD™ integrated amplifier

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Cambridge Audio made a significant leap forward with the introduction of the Azur range in 2003 by pushing the boundaries of what was possible in the budget audiophile segment of the market. However, we were also keen to produce a high-end product range which allowed us to flex our engineering muscles and show what we can do with fewer constraints. A number of development programmes burgeoned while working on the original and V2 Azur ranges of which the 840A Class XD™ integrated amplifier was one, part of our new 8-Series.

A number of ideas came to the fore, including the implementation of full microprocessor control for all functions, nameable inputs and AV mode, custom install features such as RS232 and outputs for our own Incognito multi-room system. But above all, the unit had to be a true audiophile product in that sound quality was paramount.

We decided the 840A should in fact be a pre-amplifier and dual-mono power amplifier all in one chassis. It should also have a balanced input for the matching CD player (of which more in a separate white paper), two pairs of very high current output transistors per channel so it could drive any speaker, a new acoustically damped casework and relay switching for input selection. A relay/resistor ladder volume control scheme for excellent channel balance and low distortion was also designed.

Cambridge Audio prides itself on employing the finest staff and we are lucky enough to have Douglas Self, the renowned writer, designer and amplifier researcher working in our engineering team. When Doug joined us he already had the seed of an idea to develop a new amplifier topology and it wasn't long before he'd pitched us his 'brave new idea' and what was to become the Class XD™ development programme began. The 840A is the first ever Class XD product and the result of over two years development work.

This new patent-pending technology is only a part of the 840A but is significant enough to warrant separate treatment here, this white paper aims to outline Class XD technology in simple terms. Please bear in mind this paper is by its nature technical in style and does not cover the many other small circuits and tweaks developed as part of the 840A's extensive measurement and listening test programme.

For a more in depth technical description of Class XD, please refer to our UK Patent application number GB 0505024.0.

Background: The state-of-the-art

The great divide in solid-state amplifier technology has always been between the efficient but ultimately compromised Class B approach and the beautifully linear but dishearteningly inefficient Class A.

The basic difference between the two methods being that in Class A the output transistors are modulated by the audio signal to turn more or less 'on' but never actually turn off, in Class B the output transistors actually at some point turn off as the output is passed from one transistor to another. It is at the point at which the output moving from one transistor to another (the crossover point) that a small amount of distortion is created. This 'crossover distortion' is inevitable and although it can be minimized, it can be shown that it cannot be completely eliminated. Class A of course avoids this small pitfall (because the transistors are always on) but at the expense of a lot of heat generation. Managing this heat and power dissipation inevitably means that Class A designs are much more expensive to implement and often of lower power output so as to minimise the heat as much as possible.

It is indisputable that Class A power amplifiers have the potential to give the best linearity when well designed, but they are usually impracticable, in reasonably priced equipment at least. Alternatively, optimal Class B linearity can of course be very good when well designed and is the preferred method we and most other amplifier designers use in our core products.

We won't cover these two design methodologies in more detail here as they are generally well understood and covered in other sources. It is important that it should not be assumed that in doing this work we intended to replace the Class B or A approaches, both have very real advantages at different ends of the market and both can be made to sound wonderful when well implemented. What we were seeking with the development of Class XD was a way of incorporating a lot of the advantages and sound quality of Class A at a far lower price level than normal and without the inefficiency inherent in that method.

Well designed Class B amplifiers can in fact achieve extremely low distortion levels of <0.001%-at 1 kHz [Ref 2]. The Class B approach however, does have its ultimate limitations, as we have said Class B inherently generates crossover distortion, and inconveniently displays this non-linearity at the zero-crossing, where it is always in evidence no matter how low the signal amplitude. At one unique value of quiescent current the distortion produced is a minimum, and this is what characterises optimal Class B; however at no value can it be made to disappear. It is in fact inherent in the classical Class B operation of a pair of output transistors.

Fig 1 shows a simulation of an output stage that illustrates the heart of the 'problem'. The diagram plots the incremental gain of the output stage against output voltage; in other words the gain for a very small signal. A complementary-feedback pair (CFP) output stage was used. Both 8 and 4 Ohm loads are shown. You can see from the Y-axis that in the 8 Ohm case in particular, the gain variations are very small, with an inoffensive-looking gain ripple around the zero-crossing at 0V output. This gain ripple however does generate high-order harmonics that can be poorly linearised as the negative-feedback factor in any linear amplifier falls with increasing frequency.

The 4 Ohm case shows lower overall gain due to the increased loading, and a drop-off of gain at each side due to falling transistor beta (current gain); this latter distortion mechanism is however relatively easy to deal with by the use of negative feedback and other methods, and is not considered further. The awkward gain perturbations at the crossover point are similar to the 8 Ohm case, but can be seen to be larger in size.

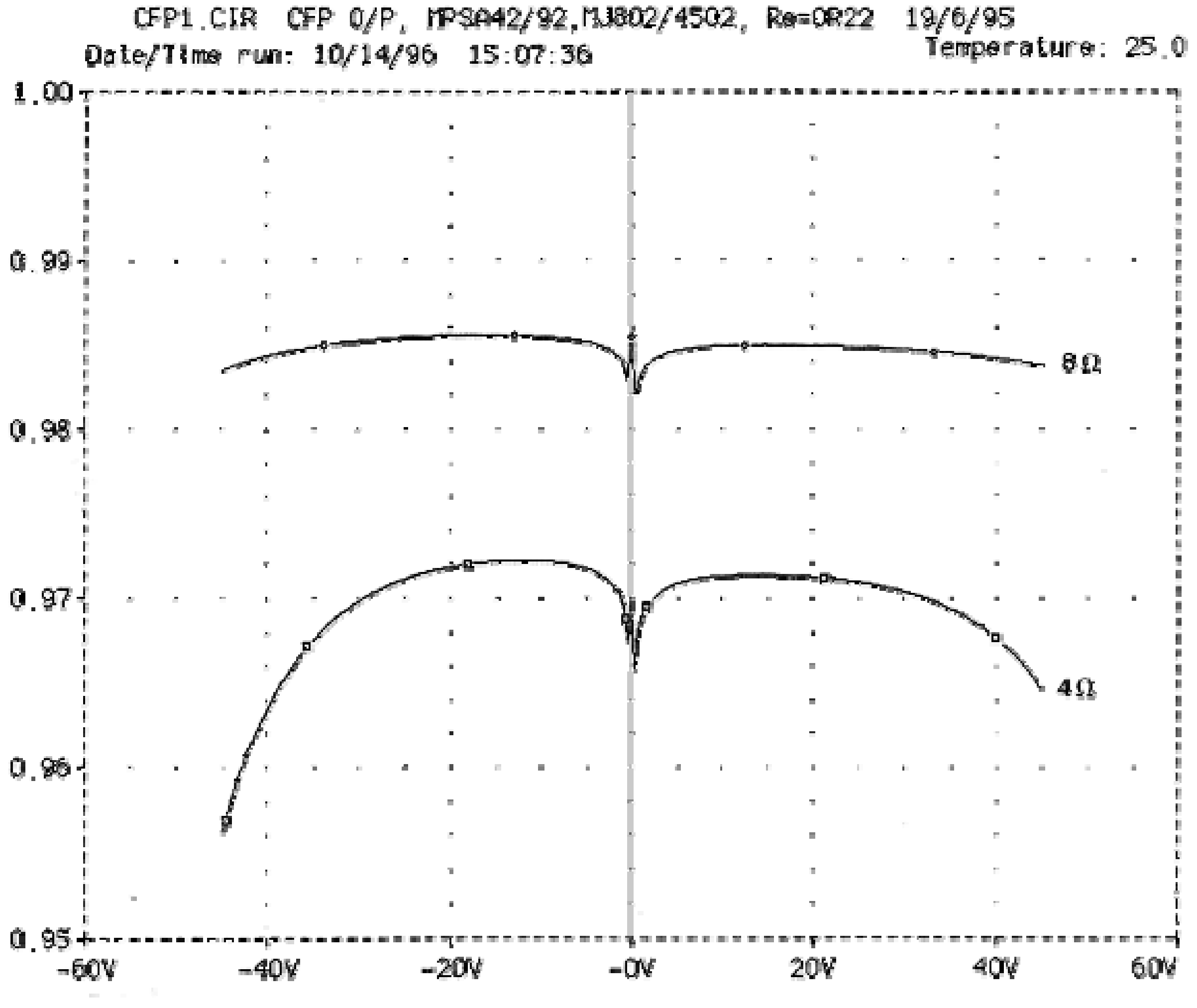

Fig 1: The incremental gain of a CFP output stage as output voltage changes. SPICE (Simulation Program with Integrated Circuit Emphasis) for 8 and 4 Ohm loads.

There has always been a desire for a compromise between the efficiency of Class B and the linearity of Class A and the most obvious way to make one is to turn up the quiescent current of a Class B stage giving what is called Class AB operation. As this is done, an area of Class A operation, with both output transistors conducting, is created around the zero-crossing.

In fact as this area widens as the quiescent current increases, until ultimately it encompasses the entire voltage output range of the amplifier, there is thus an infinite range of positions between the two extremes of Class B and Class A, and this range of modes of operation is referred to as Class AB.

Unfortunately, while Class AB would seem to be a perfect compromise between Class A and Class B operation, it does have some hidden issues.

It can be shown [Ref 1] that if Class AB is used to trade-off between efficiency and linearity, its performance is certainly superior to B below the AB transition level, operating as it does in this region in pure Class A. This can have very low THD indeed, at less than 0.0006% up to 10 kHz [Ref 3].

However, once the signal exceeds the limits of the Class A region, the THD worsens and does so somewhat abruptly due to the gain-changes when the output transistors turn on and off. Linearity is in fact inferior not only to Class A but also to optimally-biased Class B. This is not always fully appreciated. The effect is sometimes called "gm-doubling".

Class AB distortion can be made very low by good design, but remains at least twice as high as for the equivalent Class B situation. The bias control of a Class B amplifier actually does not give a straightforward trade-off between power dissipation and linearity at all levels; this is often not well understood and often catches out the unwary. To demonstrate this, Fig 2 shows THD plotted against output level for Classes AB and B.

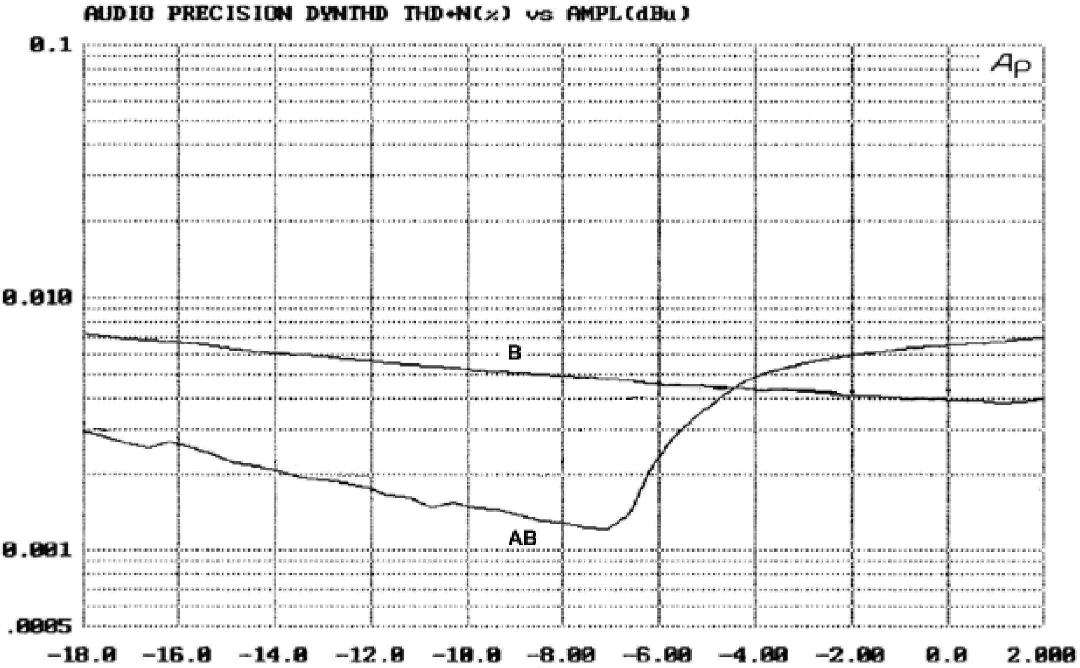

Fig 2: THD vs. level for Class B and Class AB. (0 dB is 30W into 8 Ohms)

So actually it would be much more desirable to have an amplifier that would give Class A performance up to the transition level, with Class B after that, rather than AB. This would abolish the AB gain changes that cause the extra distortion. This was the purpose of our Class XD development program, could it be done?

The Class XD crossover displacement principle

We can see that in Class B it would be better if the crossover region were anywhere else rather than where it is. If the crossover were displaced away from its zero-crossing position, then the amplifier output would not traverse it until the output reaches a certain voltage level. Also below this transition point the performance could be pure Class A; above it the performance normal Class B.

This is the basic Class XD principle, and it's a very simple one, develop a topology that displaces the crossover point to one side of zero crossing.

The essence of the Crossover Displacement principle is the injection of an extra current, into the output point of a conventional Class B amplifier. This is shown in Fig 3.

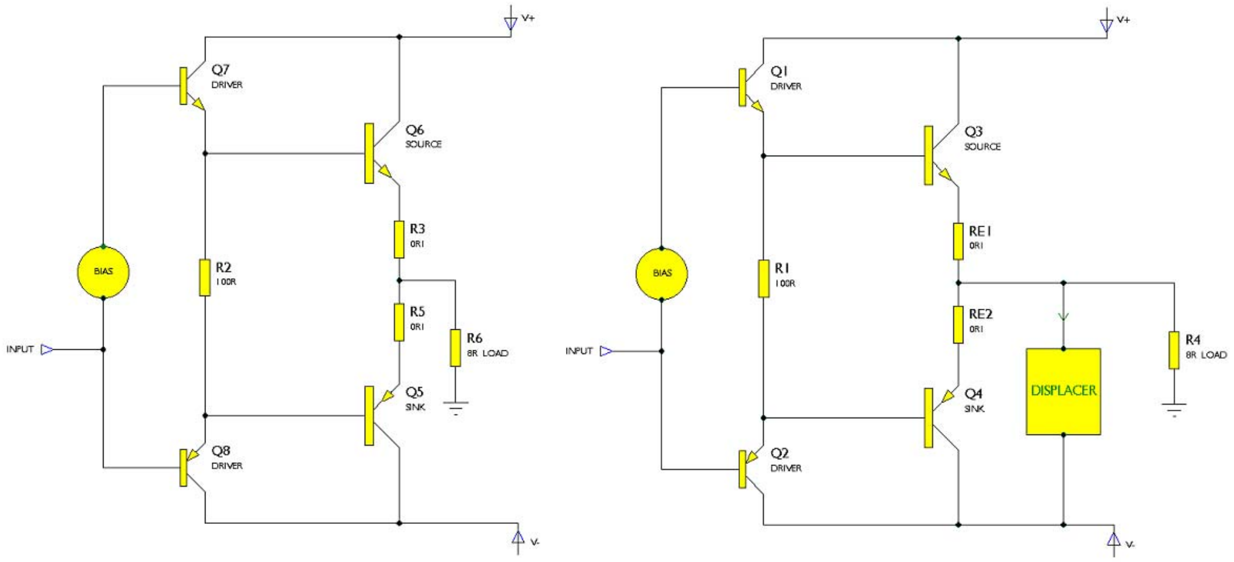

Fig 3: On the left is a conventional Class B output stage, showing drivers and bias voltage source. At the right the stage has been modified by adding a displacer system that draws current from the output and sinks it into the negative rail.

For convenience we have called the current-injection subsystem The Displacer. Similarly the upper transistor is The Source, while the lower is The Sink. The displacement current does not directly alter the voltage at the output - the output stage inherently has low output impedance, and this is further lowered by the use of global negative feedback. What it does do is alter the pattern of current flowing in the output devices. The displacement current in the version shown here is sunk to V- from the output, rather than sourced from V+, so the crossover region is displaced downward rather than being pulled upwards. This is arbitrary as the direction of displacement makes no difference, either could be used.

The extra current therefore flows through Re1, and the extra voltage drop across it means the output voltage must go negative before the current through Re1 stops and that in Re2 starts. In other words, the crossover point when Q3 hands over to Q4 has been moved to a point negative of the 0V rail; for the rest of this article we refer to this as the “transition point”. For output levels below transition no crossover distortion is generated. The resulting change in the incremental gain of the output stage is shown in Fig 4.

The displacer current could of course be constant, or, as we then developed in more sophisticated implementations could even vary with the signal…

We now have before us the intriguing prospect of a power amplifier with three output devices, which if nothing else is novel. The operation of the output stage is inherently asymmetrical, and in fact that is its raison d’être, but this should not cause undue alarm. Circuit symmetry is often touted as being a pre-requisite for either low distortion or healthy operation in general, but this has no real basis in fact. A perfectly symmetrical circuit may have no even-order distortion, but it may still have any amount of odd-order non-linearity, such as a cubic characteristic. Odd-order harmonics are normally considered more dissonant and often more noticeable and deleterious to perceived sound quality in listening tests, so circuit symmetry in itself is not a useful goal.

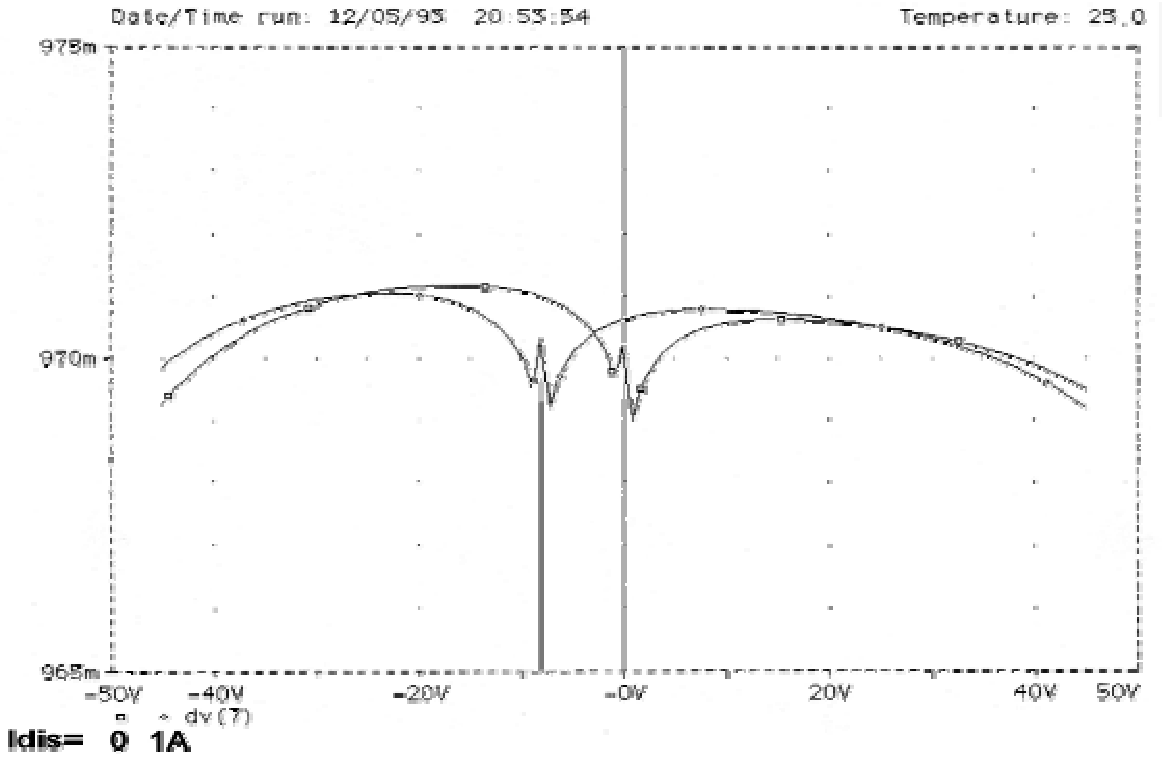

Fig 4: SPICE simulation of the output stage gain variation with and without a constant 1Amp of displacement current. The central peak is moved left from 0V to -8V.

Realisation

There are several ways in which a suitable displacement current can be drawn from the main amplifier output node.

Resistive crossover displacement

The most straightforward way to implement crossover displacement would be to simply connect a suitable power resistor between the output rail and a supply rail, as shown in Fig 5.

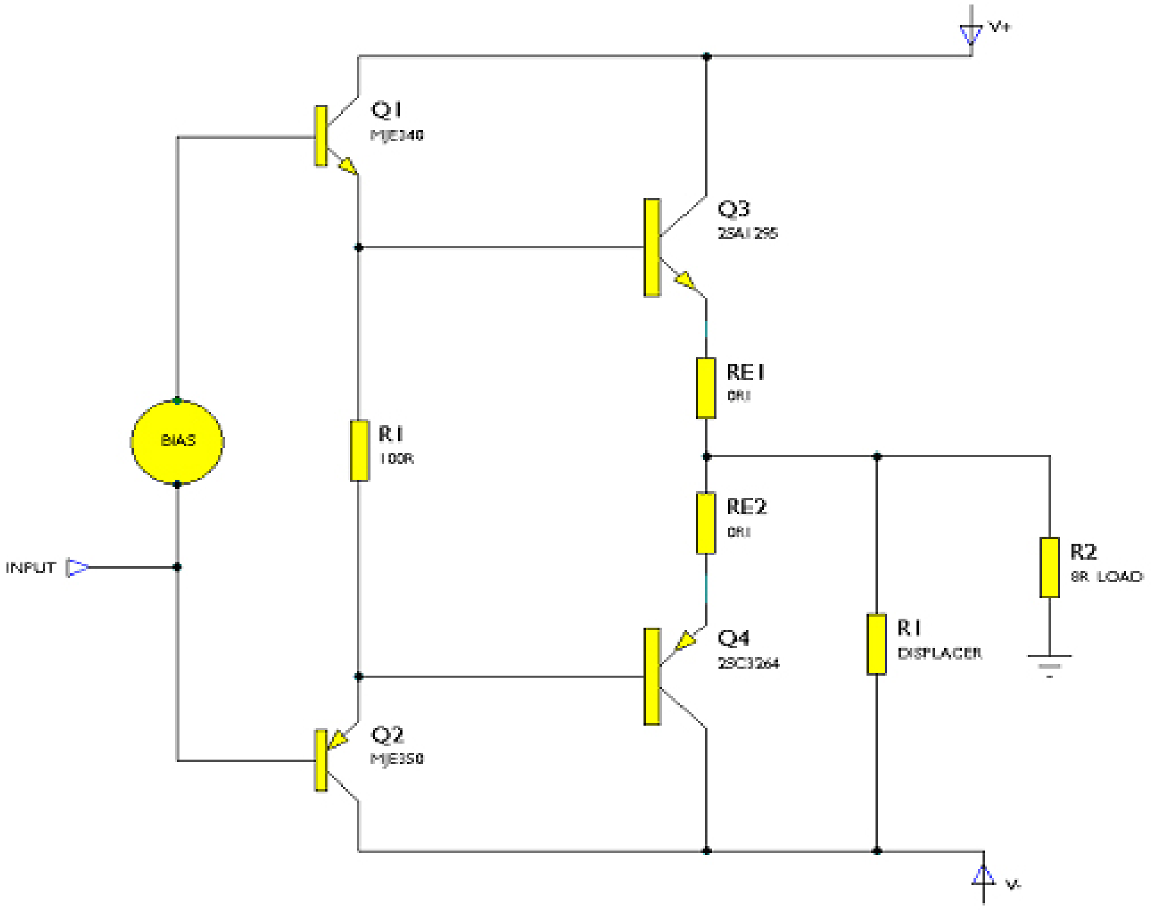

Fig 5: The concept of resistive crossover displacement. In and the following cases, the crossover point is displaced positively by sinking a current into the negative rail.

This method suffers from poor efficiency, as the resistance acts as another load on the amplifier output, effectively in parallel with the normal load. It also threatens ripple-rejection problems as R is connected directly to a supply rail, which in most cases is unregulated and carrying substantial 100 Hz ripple. A regulated supply to the resistor could be used, but this would be very uneconomic and even less efficient due to the voltage drop in the regulator. The resistive system is inefficient because the displacement of the crossover region occurs when the output is negative of ground, but when the output is positive the resistor is still connected and greater current is drawn from it as the voltage across it increases. This increasing current is of no use in the displacement process and simply results in increased power dissipation in the positive output half-cycles.

This method has the other drawback that the distortion performance of the basic amplifier will be worsened because of the heavier loading it sees, the resistor being connected to ground as far as AC signals are concerned.

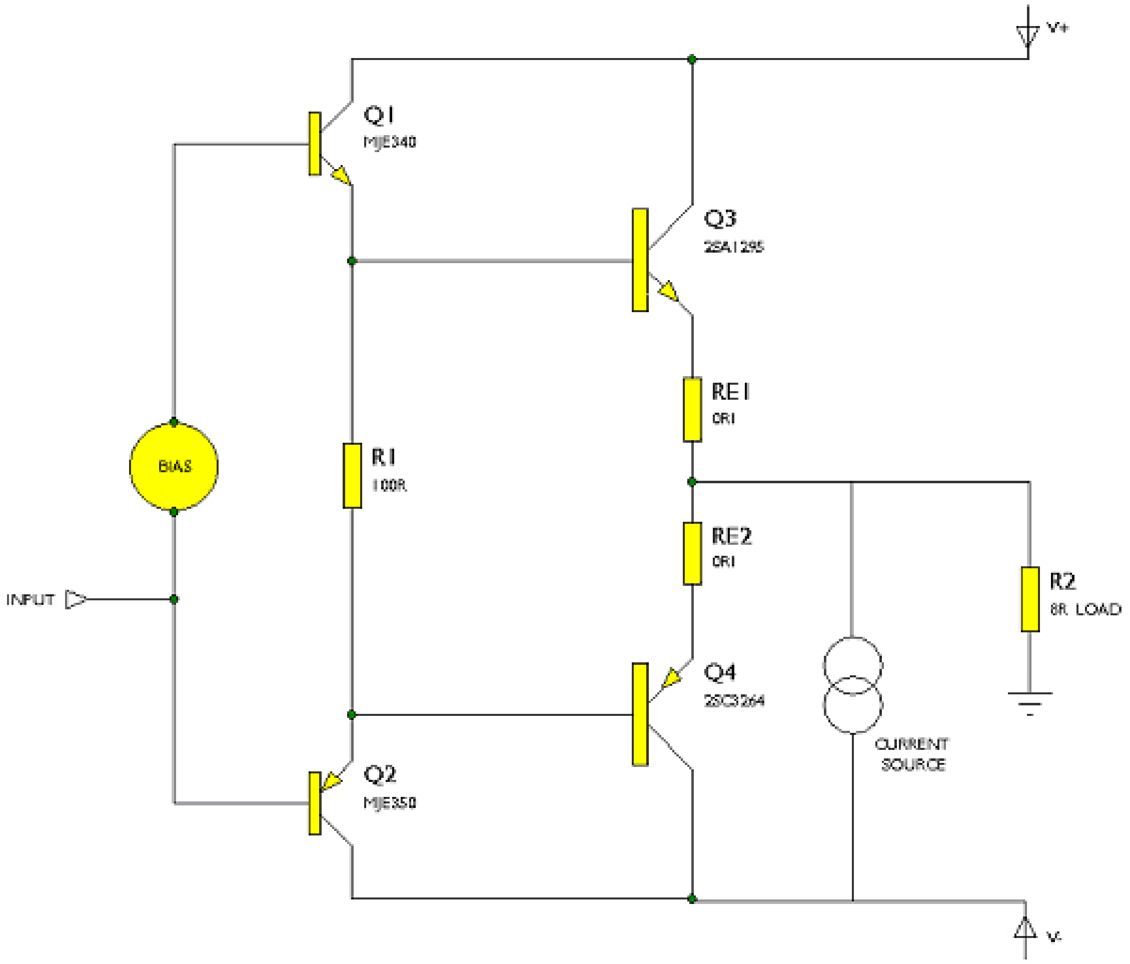

Fig 6: The concept of constant-current crossover displacement

Constant-current displacement

A much better solution is to use constant-current displacement, and this is where we started as in Fig 6. A constant-current source is connected between the output and negative rail. Efficiency is better as no output power is wasted in the displacer due to the high dynamic impedance of the current source. The output of the current source does not need to be controlled to very fine limits. Long-term variations in the current only affect the degree to which the crossover region is displaced, and this is not a critical parameter. Noise or ripple on the displacement current is greatly attenuated by the very low impedance of the basic power amplifier and its global negative feedback, so complex control circuitry is not required. The efficiency of this configuration is greater, because the output current of the displacer does not increase as the output moves more positive. The voltage across the current source increases and so its dissipation is still increased - but by a smaller amount. Likewise, the source transistor is passing less current on positive excursions so its power dissipation is less.

Push-pull displacement

Having moved from a simple resistor displacer idea to a constant-current source implementation, we then considered whether we could even modulate the current source. Our next step was to move from a constant current to a voltage-controlled current source (VCIS) whose output is modulated by the signal to further improve efficiency. The most straightforward way to do this is to make the displacement current proportional to the output voltage. Thus, if the displacement current is 1 Amp with the output at quiescent at 0V, it is set to increase to 2 Amps with the output fully negative, and to reduce to zero with the output fully positive. The displacer current is set by the equation:

$$Id = Iq\ (1 - Vout/Vrail)$$

where Iq is the quiescent displacement current (i.e. with the output at 0V) and Vrail is the bottom rail voltage, a constant which must be inserted as a positive number to make the arithmetic work.

Depending on the design of the VCIS, a scaling factor is required to drive it correctly; see Fig 7. Since an inversion is also necessary to get the correct mode of operation, active controlling circuitry is necessary.

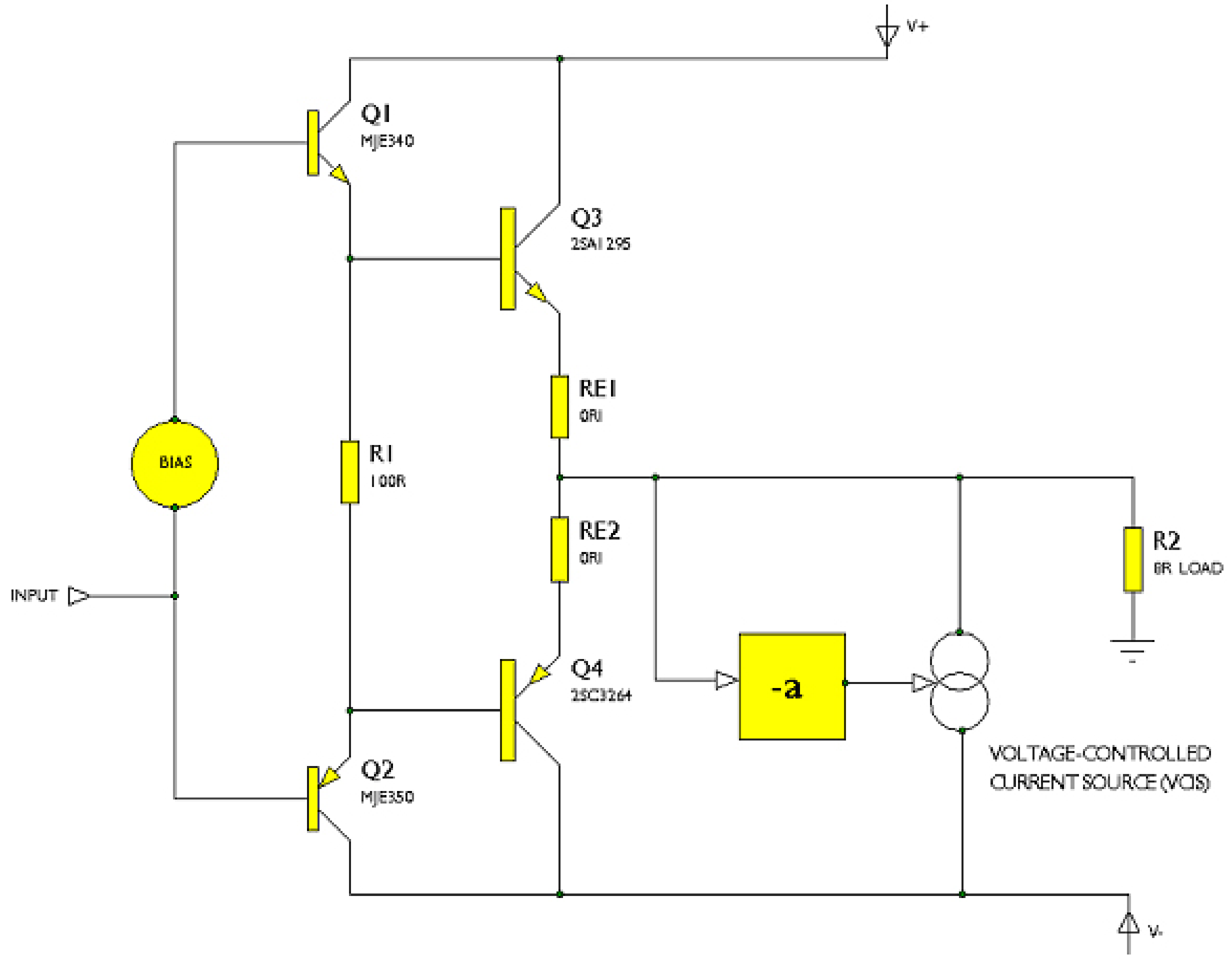

Fig 7: The concept of push-pull crossover displacement. The control circuitry implements a scaling factor of -a.

The use of push-pull displacement is analogous to the use of push-pull current sources in Class A amplifiers, where there is a well-known canonical sequence of increasing efficiency, illustrated in Fig 8. [Ref 5] This begins with a real resistance giving 12.5% efficiency at full power, moves to a constant-current source with effective infinite impedance giving 25%, and finally to a push-pull controlled current-source, giving 50%. In the last case the sink transistor acts in a sense as a negative resistance, though it is more usefully regarded as a driven source (VCIS) than a pure negative resistance, as the current does not depend on rail voltage. In each move the efficiency doubles. Note that these efficiency figures are ideal, ignoring circuit losses, and that efficiency is also reduced at output powers less than the maximum. Similarly, there is a canonical sequence of efficiency in Crossover Displacers, though the differences are smaller.

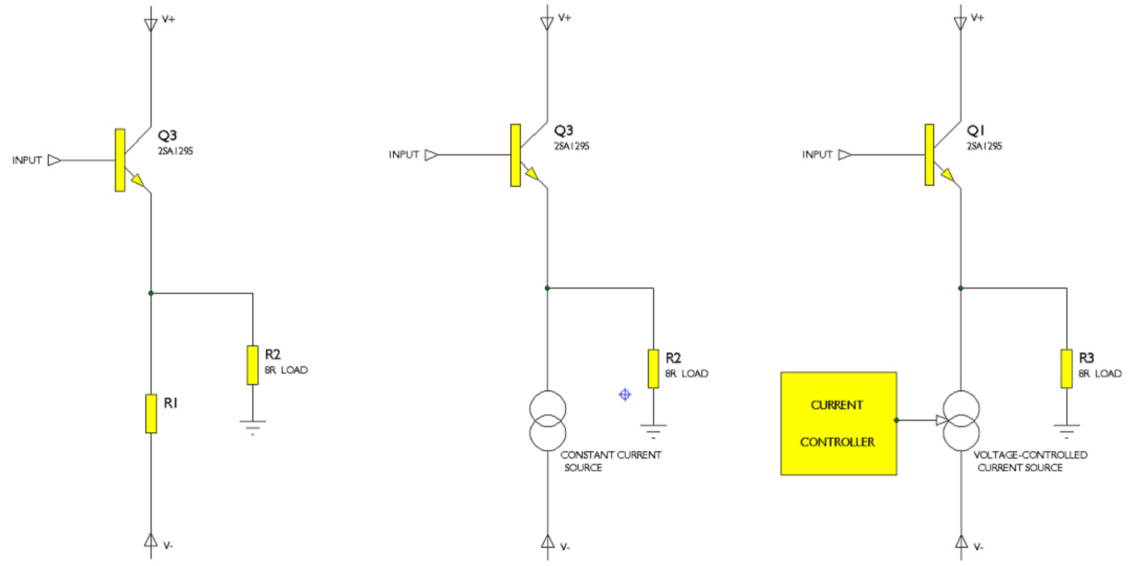

Fig 8: Left is a resistive Class A amplifier giving 12.5% efficiency, while centre shows constant-current Class A giving 25%. On the right is push-pull Class A, which achieves 50%; the current source may be controlled by either voltage or current conditions in the output stage.

The push-pull displacement approach even has another benefit; it reduces distortion when operating above transition in the Class B mode. This is because the push-pull system acts to reduce the current swings in the output devices, as the displacement current varies in the correct sense for this. This is equivalent to a decrease in output stage loading; this is the exact inverse of what occurs with resistive displacement, which increases output loading. Lighter loading is known to make the current crossover between the output devices more gradual, and so reduces the size of the gain-wobble that causes crossover distortion. [Ref 2] In addition the crossover region is spread over more of the output voltage range, so the distortion harmonics generated are lower-order and receive more linearization from a negative feedback factor that falls with frequency. In push-pull displacement operation, the accuracy of the current variation does not have to be high to get the full reduction of the distortion, because of the low output impedance of the main amplifier, which maintains control of the output voltage. The global feedback around this amplifier is effective in reducing the inherently low output impedance of the output stage in the usual way, being unaffected by the addition of the displacer.

So while the constant-current displacement method is simple and effective, the push-pull version of crossover displacement has many advantageous and was preferred for the best linearity and efficiency; the extra control circuitry developed was relatively simple and works at low power so adding relatively minimally to total amplifier cost.

Performance

Measurements are presented here to demonstrate how the crossover displacement principle reduces distortion in reality.

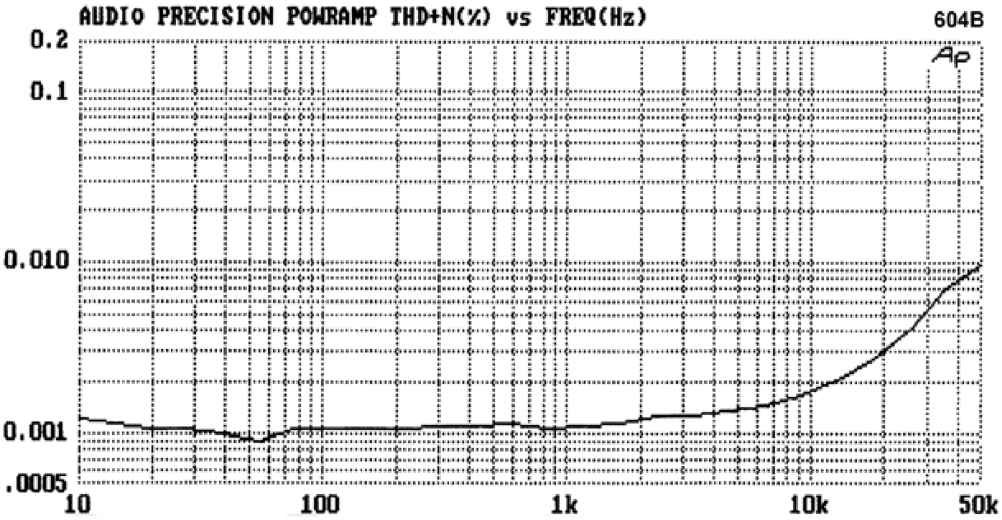

Fig 9: THD vs. frequency for a Class B amplifier at 30W/8 Ohm. (604b)

Firstly, as a reference, the results obtainable from well-implemented Class B amplifier, Fig 9 shows THD vs. frequency for a Class B amplifier giving 30W into 8 Ohms. The distortion shown only emerges from the noise floor at 2 kHz, and is wholly due to the inherent crossover artefacts; the bias is optimal, so this is essentially as good as Class B gets. The distortion only gets really clear of the noise at 10 kHz, so this frequency has been chosen for the THD/amplitude tests below. This frequency provides a demanding test for an audio power amplifier. In all these tests the measurement bandwidth was 80 kHz. This filters out ultrasonic harmonics, but is essential to reduce the noise bandwidth; it is also a standard setting on many distortion analysers.

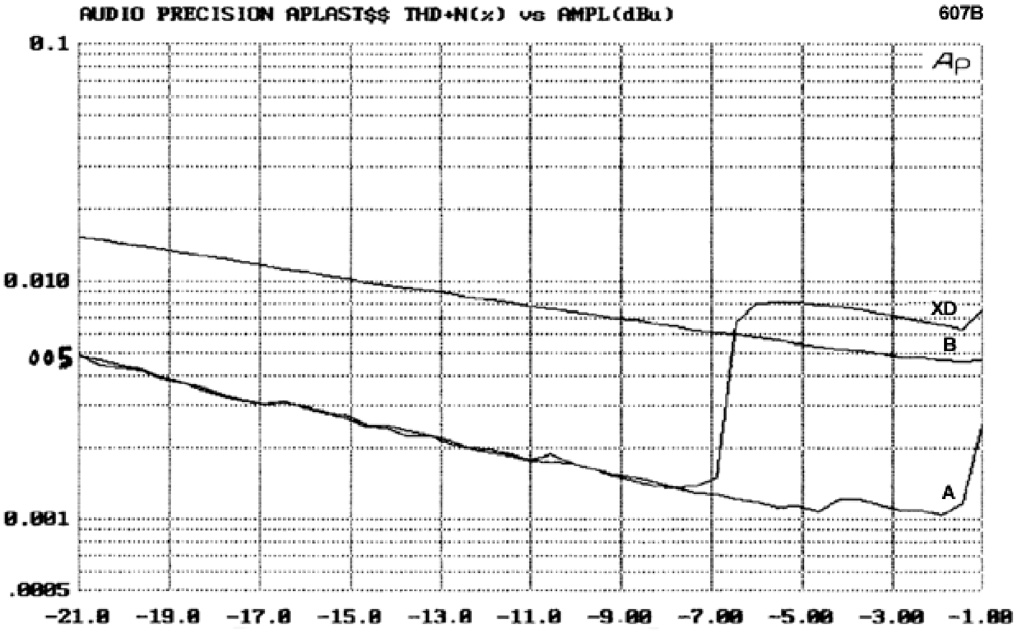

Fig 10: THD vs. power out for Class A, Class B, and Class XD with constant-current crossover displacement. Tested at 10 kHz to get enough distortion to measure; 0 dB is 30W into 8 Ohms.

Looking at the same amplifier operating in three different Classes of operation in fig 10, this shows distortion against amplitude at 10 kHz, over the range 200mW - 20W is plotted in this covers the power levels at which most listening is done. (0 dB is 30W into 8 Ohms) Trace B is the result for the Class B operation; the THD percentage increases as the power is reduced, partly because of the nature of crossover distortion, and partly because the constant noise level becomes proportionally greater as level is reduced. Trace A shows the result for Class A operation which is essentially distortion-free at 10 kHz, and simply shows the increasing relative noise level as power reduces. Trace XD demonstrates how a constant-current crossover displacement amplifier has the same superb linearity as Class A up to an output of -7 dB, but distortion then rises to the Class B level as the output begins to traverse the displaced crossover region. (In fact it slightly exceeds Class B in this case; this set of data was acquired before the prototype was fully optimised).

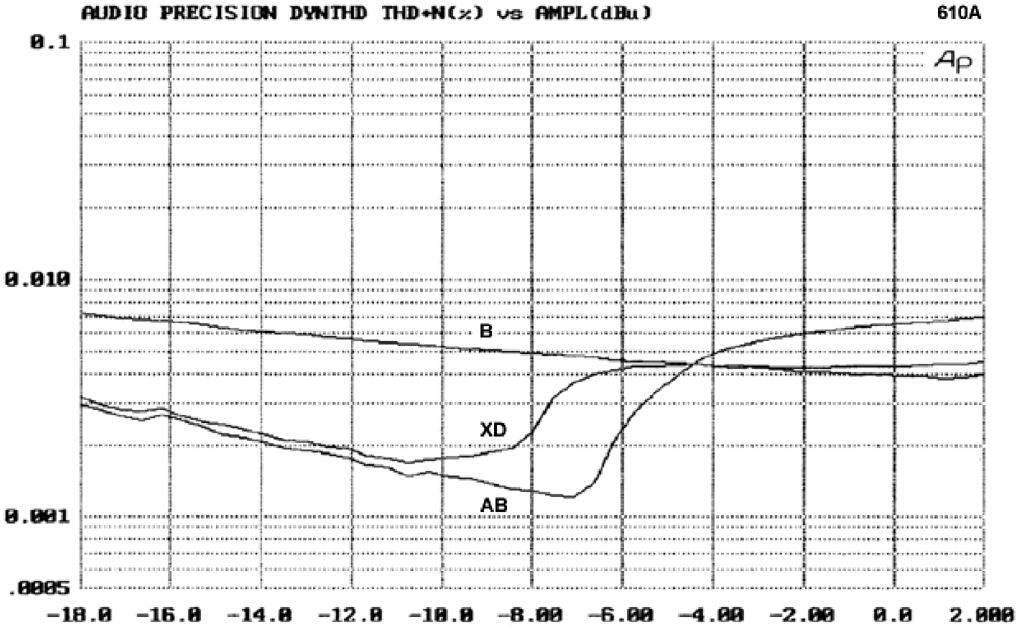

Fig 11 THD vs. power out for Class B, Class AB, and Class XD with constant-current crossover displacement. Tested at 10 kHz, power as before.

A similar THD/amplitude plot in Fig 11 now compares Class B with Class AB (as most amplifier designers use) and constant-current XD. Here the transition point from Class A to Class B is at -8 dB and gm-doubling begins in Class AB at -7 dB.

Note now the XD distortion is actually always slightly below that from Class B and better than AB at high levels but worse than AB at low levels. So this kind of Class XD makes an interesting compromise between Class B and AB having some of the advantages of both but cannot be said to actually better either.

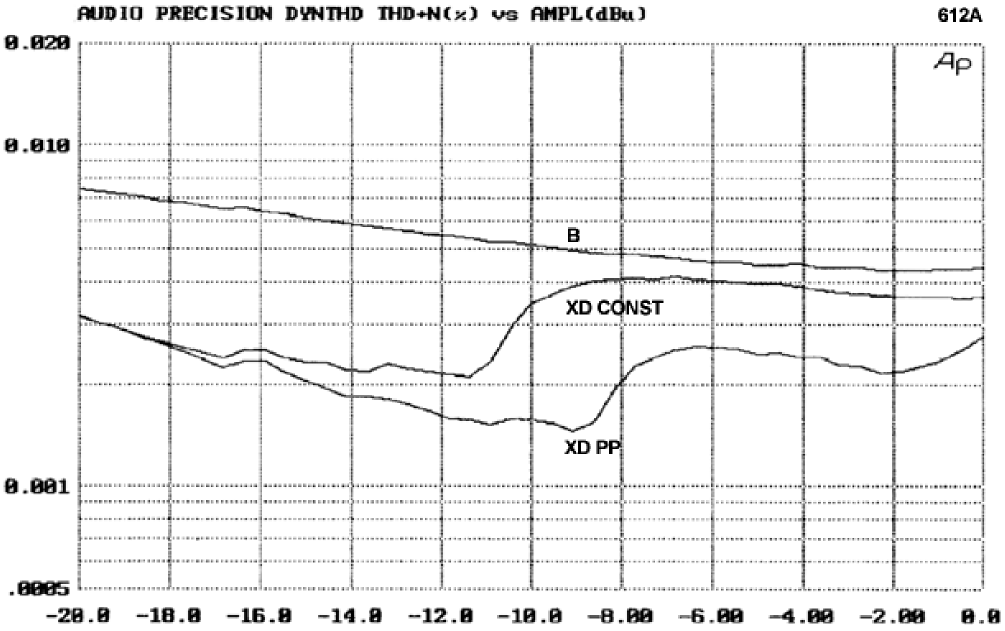

Fig 12 showing crossover displacement against class B.

Looking at push-pull crossover displacement, Fig 12 shows that push-pull crossover displacement (XD PP) gives much lower distortion than constant-current crossover displacement. (XD CONST) tested at 10 kHz, power as before. The transition points can also be seen to be not quite the same (-8 dB for push-pull versus -11 dB for constant-current). The salient point is that at -2 dB, THD is very significantly lowered from 0.0036% to 0.0022% by the use of the push-pull method, which reduces the magnitude of the current changes in the output transistors of the main amplifier. In fact THD is lower at all points than both Class B and Constant Current Class XD.

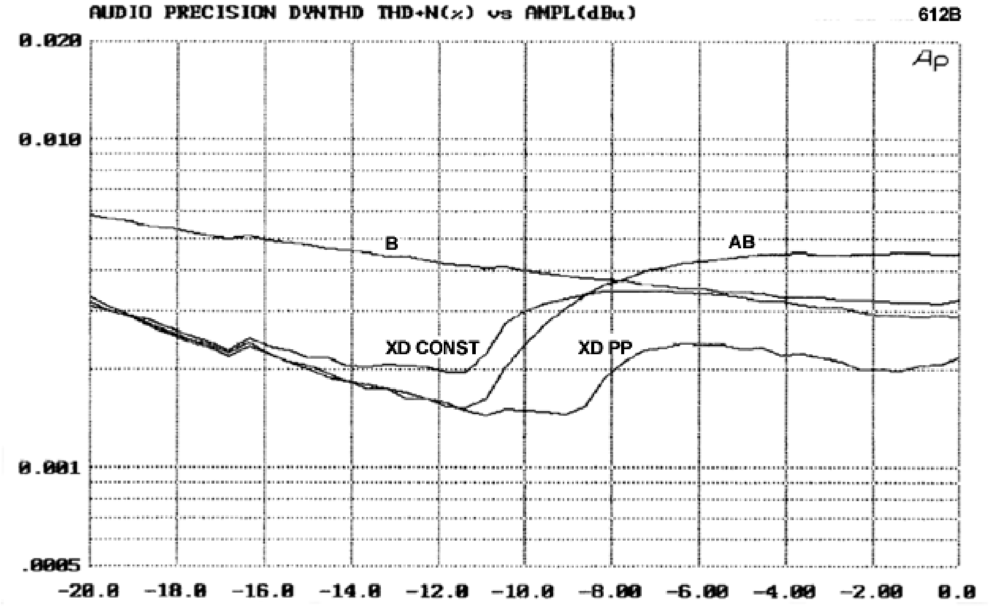

Fig 13 adds a THD vs. level plot for Class AB to the Fig 15 diagram, making it very clear that Class AB gives significantly greater THD above its transition point (say at -4 dB) than Class B, constant-current Class XD gives slightly less, and push-pull Class XD gives markedly less.

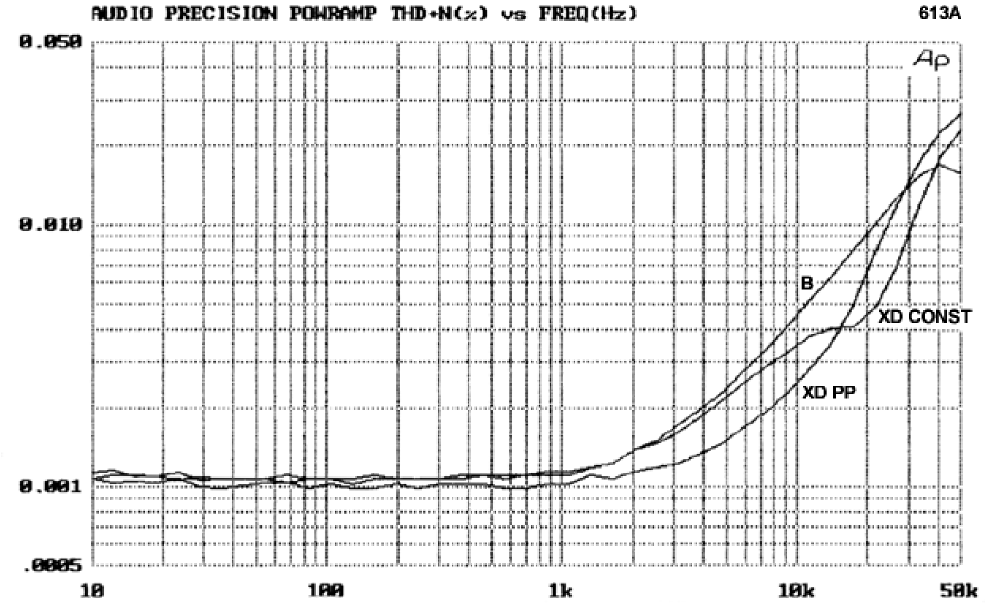

Fig 14 returns to the THD/frequency format, and shows that XD push-pull gives lower THD over the range 1kHz - 30kHz than optimal Class B and is in fact better at all points.

Efficiency

The Crossover Displacement technique is highly effective but does increase the total power dissipated in the output stage. The dissipation in the Source transistor is increased by the displacement current flowing through it, while in the sink transistor it is unchanged. There is also the additional dissipation in the Displacer itself, which is mounted on the same heat sink as the main output devices.

Table 1 shows the calculated efficiency for the various classes/types of amplifier. The calculations were not the usual simple theoretical ones that ignore voltage drops in emitter resistors – transistor saturation voltages and so on – but a lengthy series of SPICE simulations of complete output stage circuits. The effects of transistor non-linearity and so on are taken into account. The results are therefore as real as extensive calculations can make them.

For comparison, the ‘classical’ calculations for Class B give a full power efficiency of 78%, but more detailed simulations show that it is only 73% when typical losses are included. The output stages were simulated using +/-50V rails, giving a maximum power of about 135W into 8 Ohms. XD displacement currents were set to give a transition from Class A to B at 5W. All emitter resistors were 0.1 Ohm.

	Full output	Half power	1/10 power
Class B	74%	54%	23%
Class XD push-pull	66%	46%	14%
Class XD constant	57%	39%	11%
Class A	43%	23%	4%

Table 1. Efficiency of amplifier types

Here we have demonstrated that there is some penalty in efficiency when crossover displacement is used but when compared to Class A a notable improvement is evident.

Summary

Crossover displacement aims to provide a genuine way to affect an elegant compromise between the superior linearity of Class A and the efficiency of Class B giving the lowest distortion possible without implementing pure Class A operation. This compromise gives genuine measureable and above all perceivable improvements in sound quality, and can give better sound quality than conventional Class AB. Class XD is patent pending Cambridge Audio technology and is unique to us.

The advantages:

- Class XD pushes crossover distortion away from the central point where the amplifier output spends most of its time
- Below the transition point the amplifier actually runs in pure Class A with no crossover artifacts at all
- Above the transition point the amplifier moves into an optimized Class B with still lower distortion than is possible with Class AB
- Much lower heat than Class A, although more than conventional Class AB

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6] Self, D "Audio Power Amplifier Design Handbook" as above, p267. (Class A distortion data)

7] Moore, B J “An Introduction to The Psychology of Hearing” Academic Press 1982, pp48-50.

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