Amplifier Design
Text: Rob Squire

Any job worth doing is one worth procrastinating over and I've hedged around the topic of amplifiers for a good while now. But let's face it, unless you're recording onto wax cylinders, at some point you're using amplifiers, and lots of them. Take a medium-sized studio with a console and a bunch of outboard, for example. Hiding behind the front panels of all these devices are as many as several hundred amplifiers in some cases. A perfect example of this is sitting on the bench in front of me right now – a modern 24-channel console that's having most of its integrated circuit amplifiers replaced in the pursuit of a sonic improvement, and there won't be many left over from the tube of 200 that I ordered. Crudely put, there's bugger all that can be done in the audio world without employing amplifiers of one type or another – they're in virtually every electronic circuit you've ever used.

Implied in this intro is the idea that an amplifier is so much more than a power amp that's hooked up to speakers. Amplifiers are quite simply a device with an input and an output, between which some form of gain occurs. Our experience with amplification leads us to expect that an increase in gain will cause the voltage level to increase. In the case of an amplifier, however, this is only one aspect of the type of gain they can produce. The other form is current gain, where the output of an amplifier can deliver more current from its output than its input receives. An example of this type of amplifier is a DI running at unity gain (and thus no voltage gain). With a typical input impedance of 1MΩ and a low output impedance, capable of say driving a 600Ω load, it could be outputting 1000 times the current drawn at the input. Many practical amplifiers have both types of gain: voltage and current.

At this point it's also worth reminding ourselves of the fact that amplifiers are also found outside the audio world – shocking, I know. The mobile phone, for example, besides having an amplifier to drive the speaker and an amplifier to boost the level from the microphone, has an amplifier to drive radio frequencies out of the antenna and another to recover radio frequencies received by the antenna. So even in your run-of-the-mill phone there are four amplifiers, all performing very different tasks. And as you might have already surmised, these four different tasks demand four very different amplifier designs. Coming back down the frequency spectrum to the amplifiers we use in audio, it's fruitful to examine the fundamental design types or 'classes' that we use to pigeonhole amplifiers.

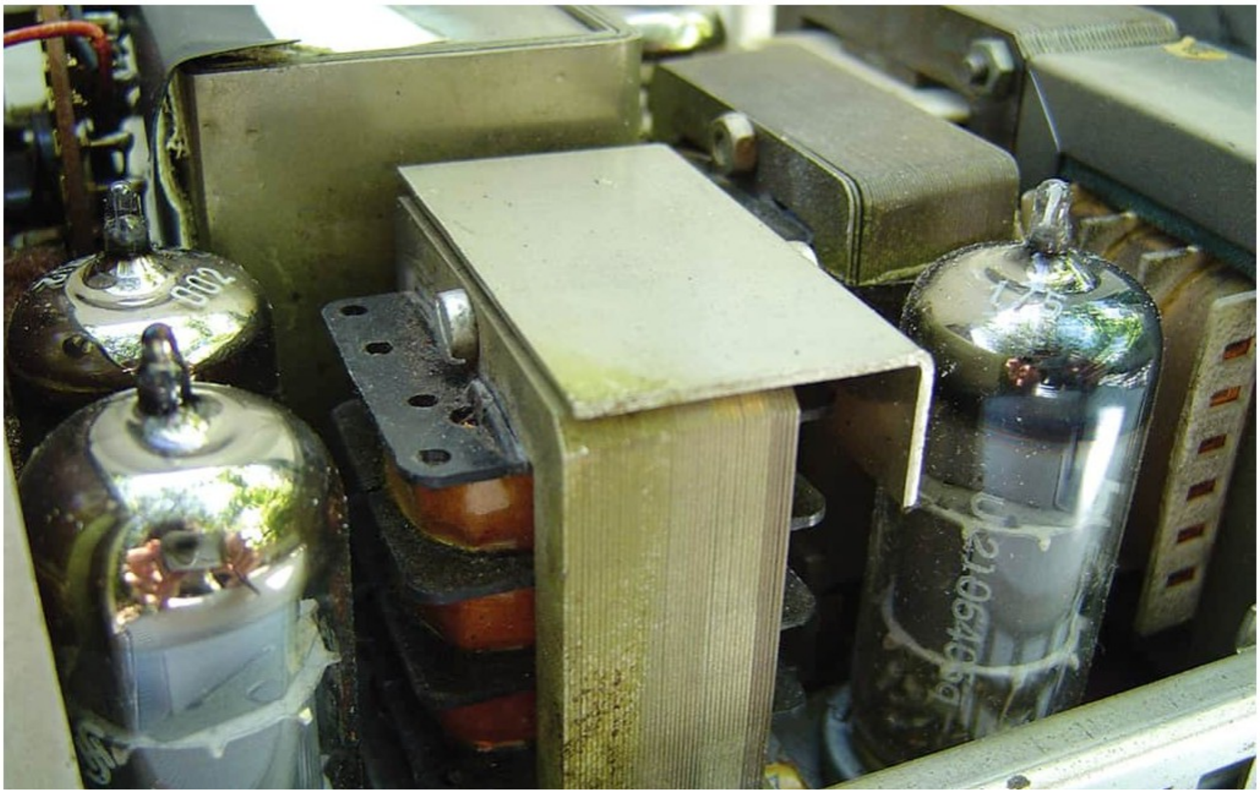
CLASS-A

Probably no term gets bandied about more than 'Class-A'. It's an amplifier design that seems to require no description beyond the name itself, as if to infer that any product featuring this type of amplifier will automatically be great sounding. Valves are easily implemented as Class-A amplifiers and it follows that historically this was one of the first amplifier designs. Just last week I was doing some repairs to my 1938 Healing valve AM radio and, as it turns out, the audio amplifiers in that are all Class-A! [It must sound great – Ed.] Between you and me, the radio sounds okay in a fun sort of way but high fidelity… certainly not! [Bugger – Ed.] Class-A is no guarantee of quality.

A Class-A amplifier is one where an amplifying device – whether it be tube, transistor or FET – is operated such that it's conducting (drawing current) all the time regardless of the input signal. This operating point is achieved through the bias voltage applied to the amplifying device. The setting of the idle or 'no signal' condition – called the biasing – is the key to differentiating the first three classes of amplifier design. Class-A amplifiers are biased such that regardless of the input signal they never turn off, and a well-biased Class-A amplifier is biased into the most linear region of the device's operation. The penalty for Class-A operation is inefficiency, as the amplifying device is operating regardless of the amplitude or even presence of the input signal, meaning that current is always drawn from the power supply. Efficiency, as a measure of the power supply current wasted as heat compared to the energy of the signal emerging from the amplifier is, at best, 50 percent and can be as low as 25 percent.

If we plough these statistics back into a real world example: a stereo 100W per-channel Class-A power amp that's designed to drive loudspeakers could be emitting 500 to 1000W of heat. Getting rid of that much waste heat before the electronics are cooked in their own juices is no trivial matter. This is why Class-A power amps are rare and expensive beasts, and why, when they do exist, often have 25 to 50W output ratings to avoid dealing with considerable heat they'd otherwise generate at higher output powers – 1000W of wasted heat is like running a twin bar radiator inside a box! The upside to a Class-A design is the freedom from any sort of crossover distortion or discontinuity in reproducing the input signal at the output. Crossover distortion is particularly nasty with higher-order harmonics present at high levels and with the percentage of distortion increasing as the signal level decreases. So whilst Class-A is not necessarily free of distortion, the distortion products are always a simple progression of odd and even harmonics that decrease in amplitude with the increasing harmonic order and the percentage of distortion decreases as the signal level decreases. Class-A is a good design approach for low-level, and low-power signals, where considerations of efficiency are not as important.

Amplification, tube style: internals of a TAB V76.



CLASS-B

Class-B amplifiers require two active devices to operate, with each device amplifying only one half of the input signal. With no input signal present the bias applied to both devices is such that they're just turned off and thus consume no current from the power supply. When an input signal is applied, the first device will switch on and conduct on only the positive waveform excursions, while the other device remains off. On negative excursions the first device will turn off and the other will begin to conduct. Keeping the devices just turned off, hovering ready for one or the other to conduct when the smallest input signal appears is exceedingly difficult to set up, and in the real world, essentially impossible. This gives rise to crossover distortion, a kind of dead zone where every time the signal swings from positive to negative both devices are off, the output is no longer following the input signal and gross distortion occurs. The upside of this amplifier design is that Class-B amplifiers are pretty efficient at converting power from the power supply to the signal output.

CLASS-AB

Class-AB amplifiers are a marriage of the efficiency of Class-B with the crossover distortion-free benefits of Class-A. Here the amplifier is biased such that both output devices are just barely turned on, as opposed to just turned off. Operating as a Class-A amplifier for small signals, these output devices are conducting all the time and neither device is turned fully off. As the signal level gets larger, the amplifier will reach a point where one device will turn off and the amplifier now operates in Class-B mode. Since this transition happens at a higher signal level the crossover distortion (as a percentage of the signal) will be much lower. Class-AB can be operated or 'biased on' to various degrees, increasing the range of signal levels at which the amplifier remains operating in Class-A. These are sometimes referred to as AB1 or AB2 etc. The vast majority of amplifiers are Class-AB: most hi-fi stereo amps, all integrated circuit op-amps, self-powered monitor speakers, the output section of tube guitar amps, etc. Despite still suffering to some extent from crossover distortion we'll soon see how that can be further minimised.

CLASS-C

In the pursuit of efficiency, Class-C amplifiers are biased such that they only conduct for 50% or less of the input signal. In essence, half or more of the input signal just isn't reproduced at all. This equates to severe distortion and is well and truly into total fuzz territory and therefore pretty useless for audio purposes. For AM radio transmitters, however, it's just the ticket – the 90% efficiency is handy when you're pumping out 10,000W! Since AM radio transmitters are amplifying just one single frequency, a highly tuned, high-Q filter can be placed on the amplifier's output, effectively removing all the distortion products and restoring the waveform to its original pure single frequency.

A stereo 100W per-channel Class-A power amp that's designed to drive loudspeakers could be emitting 500 to 1000W of heat. Getting rid of that much waste heat before the electronics are cooked in their own juices is no trivial matter.

CLASS-D

'D' doesn't stand for 'digital' – let's get that out of the way first up. Most Class-D amplifiers convert the audio to a stream of very high-frequency pulses where the pulse width is representative of the original audio waveform. This is known as pulse width modulation. The output amplifier device in this situation simply has to turn fully on or fully off in response to each pulse, resulting in very high efficiency. Mosfets are the device of choice for Class-D amplifiers as they can have very low resistance, resulting in very low heat dissipation when turned on hard and thus minimal power is wasted as heat. The switching or pulse frequency must be at least twice that of the highest audio frequency you wish to reproduce. In practice, Class-D amplifiers often run at 10 times the highest audio frequency of interest – namely, 20kHz. Mosfets are also well suited to this very high speed of operation. Class-D is one of the increasingly popular choices for today's extraordinarily high-powered PA amps and goes some way to explaining how you can get an 8000W amplifier into a two-unit rack case without the unit melting its way through to the centre of the earth. The MC2 E90 power amp reviewed in Issue 70 is an example of a massive Class-D amplifier, achieving 84% efficiency in converting the incoming mains 230Vac to 16,000W of audio power. All Class-D amplifiers require extensive passive filtering on their outputs to remove the high-frequency information from the width modulated pulses and effectively reconstitute the original audio waveform.

CLASS-G & H

Lets jump right past Class-E and F; they're of no interest for audio circuits and are mind-bendingly difficult to understand without some hardcore understanding of inductor and capacitor resonant circuits. Class-G, however, has been exploited in a number of high-power audio amps. In essence, a Class-G amplifier is really a standard Class-AB amplifier but with an additional set of higher voltage power supply rails. The lower voltage rails supply power to the output circuit for signal levels below a particular threshold and thus keep the heat wastage to a minimum. Whenever the audio signal exceeds this threshold the higher supply voltage is electronically switched on to supply the output devices, enabling an even greater output level to be achieved. This technique improves the thermal efficiency when the amplifier is reproducing real-world audio, as the amp, whilst capable of reproducing peak powers of, say, 500W, can automatically throttle back to, say, 50W whenever the peak power isn't required. Class-H is a variation on Class-G, whereby the higher supply voltage is continuously variable and able to track the shape of the audio peaks by supplying just enough voltage as and when it's required.

GETTING REAL

A real-world amplifier – whether it's a mic preamp, a monster PA power amp or part of an equaliser – consists of a number of individual stages or sections that, when combined, represent the complete amplifier design. Earlier I mentioned that all integrated circuit op-amps are Class-AB – this really only expresses the topology of the output stage of the full amplifier circuit. Typically, the complete design will include a Class-A input stage, a Class-A voltage gain stage and a Class-AB output stage. An op-amp is certainly the most ubiquitous amplifier topology, whether packaged into an integrated circuit or built up out of discrete transistors. Most preamps employ an op-amp design and many power amps are also really just a big op-amp. An op-amp is a particular amplifier design that has two inputs and one output plus connections for the power supply. The inputs are referred to as 'inverting' and 'non-inverting'. The inverting, as its name suggests, causes a signal applied to this input to be inverted or phase reversed at the output, whereas the non-inverting input maintains the input-to-output phase relationship. Op-amps have very high gain; typically in the order of 100dB, which in any practical application, is way more than you'd ever require. This enormous gain is reined in through the use of negative feedback – taking a percentage of the output signal and sending it back to the inverting input. This negative feedback reduces the overall gain of the op-amp and indeed can reduce the gain to unity or beyond, even to a gain of zero!

Negative feedback is the great leveller when it comes to amplifier design and is used to reduce a multitude of sins. Whenever negative feedback is employed (and it almost always is) the positive benefits are significant. Output impedance and distortion are lowered while bandwidth is increased. It's the distortion reduction in particular that enables an amplifier with a Class-AB output stage to achieve very low distortion levels – in the case of some modern integrated op-amps, figures as low as 0.00008% can be achieved with careful implementation.

Ultimately, amplifier performance hinges on the overall design, whether Class-A, Class-AB, valve, transistor or FET, the synergy of the combination of the individual parts and how feedback is employed determines an amplifier's sonic stamp.