Power supply units, noise, and distortion

There are a lot of strange stories in audio engineering: sound reproduction is improved by using oxygen-free loudspeaker cable; sound reproduction is damaged by noise current flowing in a cable shield; digital recordings sound 'thinner' than analogue; and so on. TONY WALDRON believes that if a story is true then we should be able to measure what is going on as he investigates the sonic differences between linear and switch-mode power supplies.

Some 30 years' experience of high performance audio system design and production has taught me that every now and again an audio 'story' turns up an unexpected insight into the physics of electronic engineering. In a previous *Resolution* article [1], I wrote about a case where one sound engineer's exquisite hearing abilities led us to the reason why one microphone amplifier design was actually better than another. Indeed, there have been many such experiences in my working life. So, when Mike Walker — a famous and well respected theatre sound designer –- called with a strange complaint about another of my equipment designs, I decided that I had better check things out.

During a technical rehearsal at a West End theatre, one of the audio power supply units had developed a fault. CADAC mixers are normally powered by four units — separate supplies provide power for audio and logic circuitry and there is a second pair of redundant units for backup. The fault had caused one of these to 'switch off', leaving the mixer audio powered by one unit. Mike noticed that the quality of the audio reproduction had noticeably changed and went to find out why. He didn't really want to believe that one power supply unit made a difference to the audio signal compared to another, but this was his conclusion that day. After the faulty power unit had been repaired, Mike arranged a special session to see if the result could be repeated. This was when I got to hear about it.

Professional engineers who work with sound every day of their lives develop hearing acuity that the rest of us can only dream about. So, when one of us normal chaps turns up to a listening test it can take a long time to tune in to what the expert listener is hearing. This time, there was no such problem. It was perfectly clear that the audio quality changed if a particular power unit was switched off and then on again. If the other power unit was switched off and on instead, nothing changed. So what was the difference? On inspection, Mike Walker had found that the audio circuit power units were of two different models. One was a modern design, and the other was an older unit that CADAC had produced some 12 years earlier. It didn't make much sense, but there was no doubt that when the mixer was only connected to the older power unit, the reproduction was more accurate, instruments were better defined, voices more natural, there was a more accurate sense of the acoustic environment.

Now, all this sounds rather like the HiFi-Snake Oil department in full swing, but we soon found that other sound designers and recording engineers had made similar observations with power amplifiers as well as mixing consoles. So, to make absolutely sure about the phenomenon, we set up a listening test at a completely different venue and invited several extra people to give us their opinion. Once more, it was perfectly clear that the sound reproduction was better with one power unit than with the other.

Further listening tests back at the factory, using a different mixer with power units of the same type, produced identical results. We made some basic measurements, but the only conclusive difference was that one power unit was of a fundamentally different design to the other.

Let's put an historical perspective on this. There are two generic types of direct current power unit design that rely on AC mains as the initial source of energy — linear (fully analogue) and switch-mode (sort of digital). The basic block diagrams of both types are shown in Figure 1.

The linear power unit has been with us throughout the history of electronics. Its design is simple and almost anyone can build a good and reliable one. However, to design and build a high current linear power supply we need to use

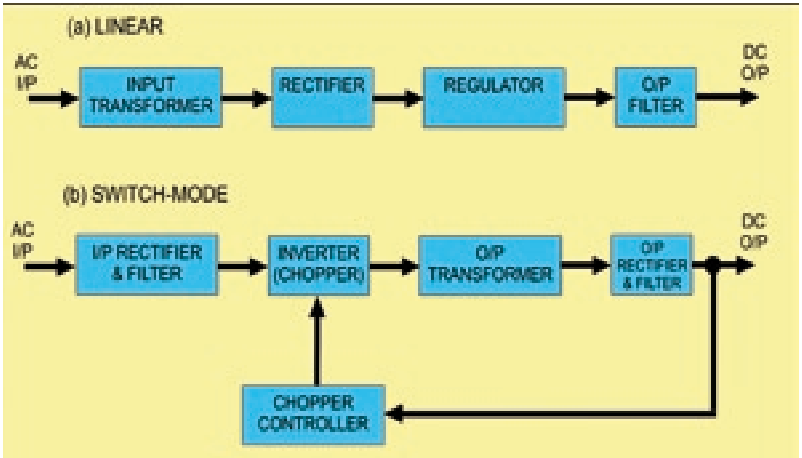

Figure 1. Basic block diagrams of linear and switch-mode supplies.

transformers so large that their low impedance windings distort the incoming AC mains waveform. This is not popular with our electricity providers, since it means that extra power generation must be provided to overcome the power lost in the waveform distortion. Linear power units are also rather inefficient — well below 50%. Regulations are now in force to encourage electronics manufacturers to design power units that minimise power-line harmonic distortion using power factor correction circuits. The only way to do this is by building switch-mode power supplies.

The switch-mode design is a relative newcomer. Initially found only in large computer systems, the switch-mode power unit is now ubiquitous despite its design complexity and the high voltage dangers posed to engineers developing and testing the circuits. Switch-mode power units can now be found inside desktop computers, with laptops as battery chargers, and in most domestic and industrial electronic equipment. Given the same output voltage and current, switch-mode power units have some very desirable characteristics over the linear variety.

CHARACTERISTIC	LINEAR	SWITCH-MODE
Construction	Large & heavy	Small & light
Input Voltage	Fixed (110V; 230V)	Variable (90 to 260V)
Efficiency	Less than 50%	Better than 80%
Cost	Relatively high	Relatively low

But there is one characteristic where the linear power unit wins hands-down and that is in terms of noise in the output current.

In a linear power unit there is some noise created by high voltage spikes in the rectifier circuit and a little bit of noise generated by the regulator electronics. But the overall noise in the output current is always quite low — somewhere below a couple of hundred V, even in a high-output power (1kW) device.

CHARACTERISTIC	LINEAR	SWITCH-MODE
Noise at O/P terminals	A few µV	Tens of mV

The switch-mode power unit is unfortunately noisy in all respects. In particular, the noise created by the chopper circuit is extremely high. The problem is made worse by the fact that the chopper circuit is switching on-and-off at several hundred thousand times per second. Due to the interaction between the chopper and its adjacent circuits, high level noise harmonics are produced either side of the switching frequency. These harmonics extend down into the audio base band, and up to several tens of MHz. Power unit designers try their very best to minimise the switching noise in the output current but a switch-mode power unit always produces some hundreds of mV of noise. This is not a problem for a computer or any device where the transmission of information stays in the digital domain and is therefore robust to noise. However, for many analogue circuits — such as a microphone amplifier or an A-D convertor — high noise levels in the power line have been shown to produce significant noise and distortion [2].

It was, of course, the linear power unit that was preferred by all of the listeners in the tests. Mike Walker writes: 'The linear supplies were able to reproduce the source sound far more accurately than the switch-mode supplies. If you routed a mono signal (a radio mic for instance) through two loudspeakers the linear supplies allowed the sound to be recreated evenly while the switch mode supplies appeared to be causing the sound to "beam" so that the result was uneven across the two speakers. This translates to a stereo image having a hole in the middle while being uneven at both extremes of the frequency spectrum. It also flattened the depth of image of the soundstage.'

When we did some basic measurements, the wide-band noise in the output current of both types of power unit was pretty typical.

	Noise on +18V line	Noise on -18V line
Linear	130µV	146µV
Switch mode	198mV	220mV

I calculated the difference in the noise levels of the two power units, based on these figures:

Noise difference (+18V) in dB = 20*log10(0.198/0.00013) = +63.65dB

Noise difference (-18V) in dB = 20* log10 (0.22/0.000146) = +63.56dB

This means that the noise in the output current of the switch-mode power unit is some 1500 times greater than that of the old linear design. Is this enough to make an audible difference in the audio output?

Thinking back to 1977, when I had been involved in the development of the first equaliser with continuously variable frequency and adjustable Q for CADAC we had to do measurements way outside the audio frequency band to figure out why the original circuit configuration was unstable. In this case, the cause of the problem was only visible at frequencies around 100kHz. If we had not done measurements outside the accepted audio bandwidth we would not have found the solution to our instability problem. I therefore decided to use our spectrum analyser to have a look at the noise waveforms way outside of the accepted audio bandwidth.

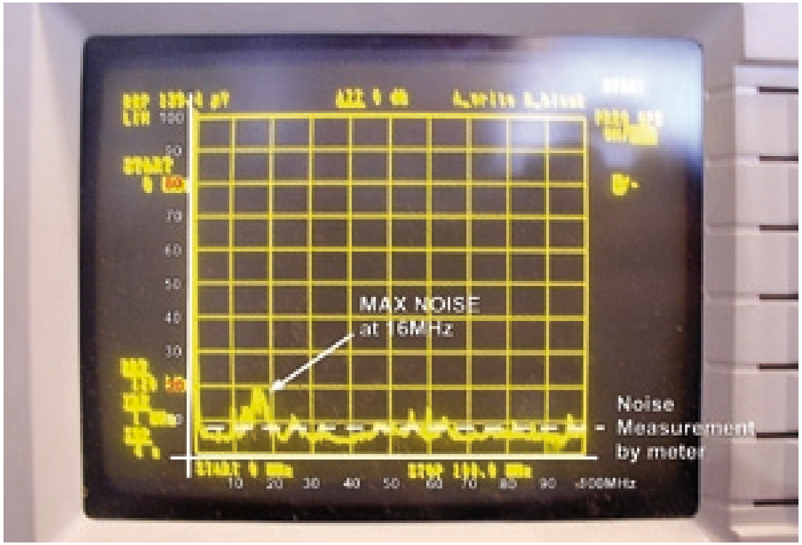

Figure 2.

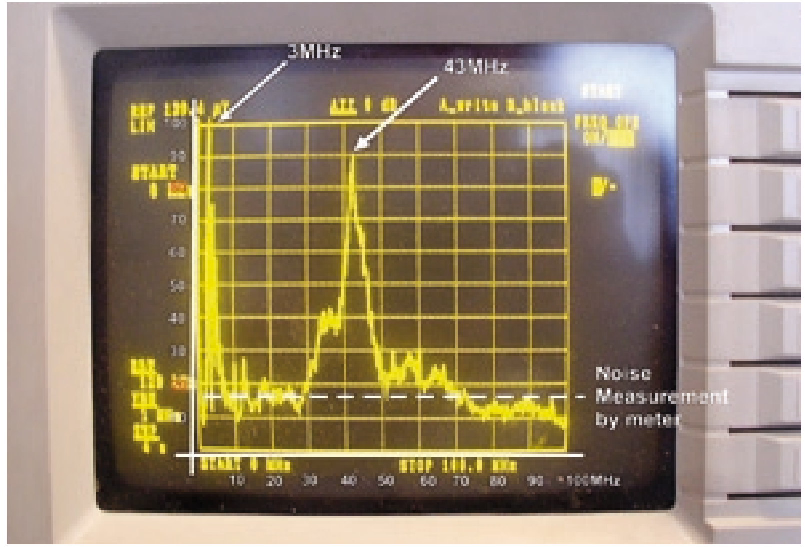

Figure 3.

WIDE BAND RESULTS

Working with the old linear design first, it took some time to find a reference level low enough to be able to display a significant noise level on the audio power lines. The bandwidth of the analyser needed to be reduced to 100MHz before it was obvious that the only relevant noise feature was the hump at 16MHz.

Some noise at 16MHz is not unexpected for a J-Type mixer, since that is the clock frequency of the Central Control Module processor chip. Now while this level of noise in the supply voltage is quite low, it has been known for many years that processor noise tends to get distributed on all power lines to all circuits in the design especially if the circuit boards are designed with multiple return conductors (referred to as earths or grounds by most people), instead of a single common plane (1). The noise can be detected and demodulated by any electronic circuit in the system, which results in noise that will be reproduced in the audio band at frequencies that can easily be heard by humans. The trick is to be able to control the level of such noise so that it is masked by the basic noise level of the analogue electronics. There is an excellent book available by Tim Williams that helps us to achieve the right results [3]. Figure 2 confirms that we did our job reasonably well.

But in the case of the switched-mode power unit, the noise in the audio power lines is dominated by interference from the power supply electronics, which is off the scale at 3MHz (Figure 3). The big noise peaks displayed are at frequencies well inside the response of the analogue and digital chips widely used by the audio industry. These chips will demodulate such frequencies and could result in audible noise.

So let's consider noise in the audio outputs. It has become the custom for manufacturers to use band-limited (weighted) measurements when publishing specifications such as noise and distortion. The more well-known weighted measurements include dBA, dBC, CCIR, and DIN (this is not the place to go into questions about why who uses what) but ever since digital processors became embedded in audio equipment designs, I have found it useful to keep an eye on wide-band audio measurements. I always have the Audio Analyser input filter set to 500kHz during development tests. When we humans listen to audio, the bandwidth limits applied by the human auditory system are certainly not any of the weighted curves mentioned above!

What I have noticed over the years is that while weighted measurements do not always change when interference becomes audible, wide-band measurements often indicate where a problem exists. Using the spectrum analyser once more, I had a look at the noise in the audio output using both power units.

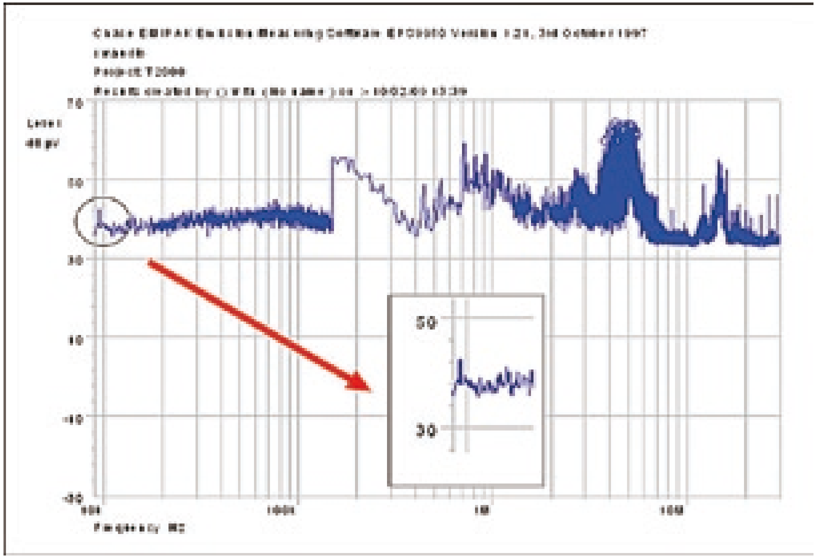

Figure 4.

In the audio outputs, the characteristic 16MHz noise stood out when the linear power unit was connected but otherwise there was nothing remarkable in the noise measured out to 30MHz. When switch-mode power was applied, there was the usual business around the switching frequency (700kHz) and another group of noise spikes around 6MHz. Apart from a small increase in the average noise level, the only real difference from the spectrum of the noise measured on the power rails was the small collection of spikes between 10kHz and 20kHz (Figure 4). These spikes are some 10dB above the background hiss.

We have not established a causal link between switch-mode power supply noise and audio distortion. Indeed, many will argue that the noise frequencies found are too high for the human auditory system to be able to respond to in any way. However, active electronic components are known to become saturated by high frequency noise, causing the device to modify the signal current. If the frequency is suitably high, this will happen regardless of published data regarding noise rejection ratios. Saturation in active circuits happens when high frequency noise on a cable shield is injected into the input of a circuit design that has the 'pin1 problem' [5], for instance. In this case, the input amplifier becomes overloaded at frequencies that are easily demodulated by the p-n junctions at the inputs of active devices, producing a wide range of audible harmonics. The resulting audio output is accompanied by twittering, and sounds as though a poorly adjusted compressor has been applied to the signal. Noise injected into the input and output ports on equipment that I have tested is certainly of the same order of magnitude as that shown in Figure 3, so there is very likely to be similar response in active circuits to noise on the DC power lines.

In part 2, we will look more closely at how active circuits become affected by noise in the power supply lines and how this may affect audio performance.

FOOTNOTE

(1) Advantage of the common plane (sometimes referred to as a ground plane) is that all return currents use a single conductive structure, enabling individual return currents to follow the signal routing traces set out on the PCB. This minimises the loop area of each signal path, minimising the generation of significant electro magnetic fields [3] and [4].

REFERENCES

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