WORLD EXCLUSIVE - TACT DIGITAL AMPLIFIER

Behold the Number Cruncher

With the arrival of the TACT Millennium, the world's first digital amplifier, hi-fi has taken a massive leap forward. In this test, the first to be published anywhere in the world, our Technical Editor, **Paul Miller**, explains the concept and execution of this new technological marvel.

"Imagine, if you will, a 200-Watt amplifier that can drive any loudspeaker without clipping, but weighs just a few kilos. An amplifier that is fed directly from the digital output of your CD player or DAT recorder, yet contains no conventional, integrated digital-to-analogue converter or analogue amplification.

"Imagine an amplifier whose volume control suffers no drift or deterioration in channel balance at low levels, and maintains a constant dynamic range regardless of its setting. There would be little or no waste heat, and the unit would sound as dynamic, vivid and compelling as the highest high-end hi-fi — but without the breathtaking price tag."

So began my article, *Living By Numbers*, on the 'Digital Class D Amplifier', printed at the tail end of 1995 in *HFC* 149. In that piece I also suggested we'd have to wait only a year to see a commercial realisation of this technology. Unfortunately, thanks to the Machiavellian politics of large corporations, the end product has arrived much later than I predicted. Luckily, the Danish-based Audio Nord organisation (which has a 90 per cent stake in NAD electronics and is the parent company of DALI loudspeakers) picked up this particular digital ball and tucked it under the wing of its high-end brand, TACT. The seeds of the digital amplifier revolution, planted two-and-a-half years ago, are now sending shoots through the topsoil.

By the way, I got the price wrong, too. When it goes on sale, the TACT Millennium is expected to cost a cool £5,000!

Simplicity in itself

You might think that digital equipment is complex and hard to understand, but the Millennium couldn't be easier to use. All that's required is a digital source connected to one of the amp's signal inputs. These are both Sony/Philips Digital Interface Format (S/PDIF, phono socket) and balanced AES/EBU (XLR socket). The unit accommodates all three sampling frequencies commonly encountered: 32, 44.1 and 48kHz.

Heavy-duty binding posts clamp any choice of speaker cable in place, while on the front panel, an outrageously expensive volume wheel spins on almost frictionless, military-specification bearings.

An arbitrary volume-level readout runs from –90 to +12, the latter equating to the

full-scale digital signal level (henceforth referred to as 0dBFs). As we'll discover later, this is no volume control in the conventional sense, but rather a way of directly raising or lowering the DC voltage supplied to the output stage. In a digital amplifier, your loudspeaker is *always* directly connected to the DC power supply.

Listening to the Millennium

As befitted this very special and exclusive review, I invited critical listening comments from long-standing members of my blind listening panel. I simply plumbed the amp into the system made familiar during many years of *HFC* CD player and amplifier tests: to wit, Theta Data Basic II CD transport and Goldmund digital interconnect (used throughout the measurement régime), and a pair of Audio Note AN/BII loudspeakers with Silver Sounds 12/2 cabling.

Christy Moore's *Live At The Point* album sounded especially 'live' during this session. His 12-string guitar strode confidently into the room with explicit, percussive detailing. It was not bright or aggressive in the 'digital sense', in fact it was even a little too restrained — "never quite letting rip", one panellist suggested.

Shock TACT-ics

The Millennium amp spared no blushes when revealing the flaws in our test speakers. It was quite easy to hear Christy's voice suffer a momentary bloom or loss of focus, that was recognised by one of our listeners (a renowned speaker designer) as a coloration in the speaker's bass/mid unit.

Indeed, this amplifier is so very clean — without being 'squeaky clean' — that it is mercilessly adept at revealing otherwise hidden colorations in the partnering speakers. However, our measurements suggest it may actually 'magnify' these colorations to some degree (see page 42).

Either way, the 'sound' of the Millennium is very, very different from that of 'conventional' amps. Different does not always mean better, of course. It takes a while for the ear and brain to re-adjust from analogue to digital amplification.

The more mature among us, weaned on the snap, crackle and hiss of vinyl, will remember a similar paradigm change on first hearing the comparative silence and cleanliness of CD. The difference between analogue and digital amplification is not dissimilar.

The sound of silence

The Hyperion 'DDD' (all-digital) recording of Nikolai Demidenko, playing Bach's *Toccata* and *Fugue* in D minor, illustrated a fundamental feature of the Millennium's sound: its deathly silence. Put your ear by the tweeter of most moderately-sensitive speakers, and when they are connected to almost any amplifier — switched on, but not playing — you will hear a hiss.

By contrast with this, the Millennium is utterly silent. It permitted powerful strokes of Demidenko's Steinway to collapse into the blackest well of 'nothingness' we had ever experienced. And when the clash of hammers on strings rose a moment later, its explosive force was made all the more shocking by the lack of any warning. It's rather like being run over by an electric car that's just silently turned the corner!

The Millennium is fundamentally unique in its reproduction of silence. This contributes to a sound that is powerful, free of obvious artifice, highly emotive, yet entirely complementary to the music being played. Regular readers will be familiar with talk of 'inky blackness' or 'darkness', to describe the crucial silences between notes. But the Millennium, for all its freedom from noise, still does not sound obviously 'dark'. This adds a whole new dimension to the perceived dynamic range of a recording; and by ▶▶

TACTFUL QUESTIONS & ANSWERS

Q Is this the world's very first digital amplifier?
A To the best of our knowledge this will be the first commercial *Digital* Class D power amplifier conceived for truly 'high-end' applications. Nevertheless, there are other design teams, in the US for instance, racing to pip TACT to the post, notably pro-audio company Apogee with what it refers to as 'DDX'.

Q What makes this amp different from previous Class D designs?
A The Millennium should not be confused with existing *analogue* Class D amplifier technology, which for reasons of efficiency, finds a ready application in many high-powered car-audio systems.

Q Does an £5,000 digital amplifier sound very different to an £5,000 analogue amplifier?
A Absolutely. Then again, we already know that the more you pay for an amplifier, the more diverse become different manufacturers' 'sound philosophies'. It's this variety that keeps the 'high end' alive and well.

Q Does the Millennium sound very different to existing hi-fi amps?
A In practice it's astonishingly clean, vivid and articulate — musical notes rise and fall into utter silence. Listening to music via the Millennium is an unforgettable experience.

Q Is it any more difficult to use than an analogue amp?
A With digital sources, the Millennium is as close as you'll get to a 'plug-and-play' amplifier, though as we discovered, it does exhibit more than a little sensitivity to the choice of partnering loudspeaker.

Q Obviously this amp works seamlessly with digital equipment, but how do you use it with analogue sources such as LP, tape or tuner?
A TACT will be producing a four-input analogue-to-digital converter (ADC), which will be controllable via the Millennium's main module. This option will accommodate line-level *analogue* sources, converting them into the digital data required by the Millennium.

Q It's a groundbreaking product, but £5,000 is still a lot of money to pay. Will the technology get cheaper?
A The boffins behind the Millennium at Toccata Technology will be licensing this technology to third parties. With a trimmed-down power supply and greater economies of scale, it is feasible to imagine that sub-£1,000 digital amplifiers could be manufactured.

Q Tell us more about the company behind TACT.
A TACT is the brainchild of Peter Lyngdorf, the man who put the financial muscle into NAD, and Radomir Bozovic. It's an unashamedly high-end brand where innovation — particularly digital innovation — is prized. TACT also produces a digital preamp with comprehensive room-correction facilities.

Q When and where will the Millennium be available to buy?
A Production samples should be shipping in June this year to key NAD dealers in the UK. Please form an orderly queue behind yours truly!

Q Does this product's arrival make conventional amplifiers obsolete?
A Not in the short term. After all, the arrival of the transistor never quite killed off the valve amplifier, did it? In the longer term this exciting technology has a very bright future. The use of digital technology provides great scope for room and speaker equalisation.

Qs & As by SV and PMi

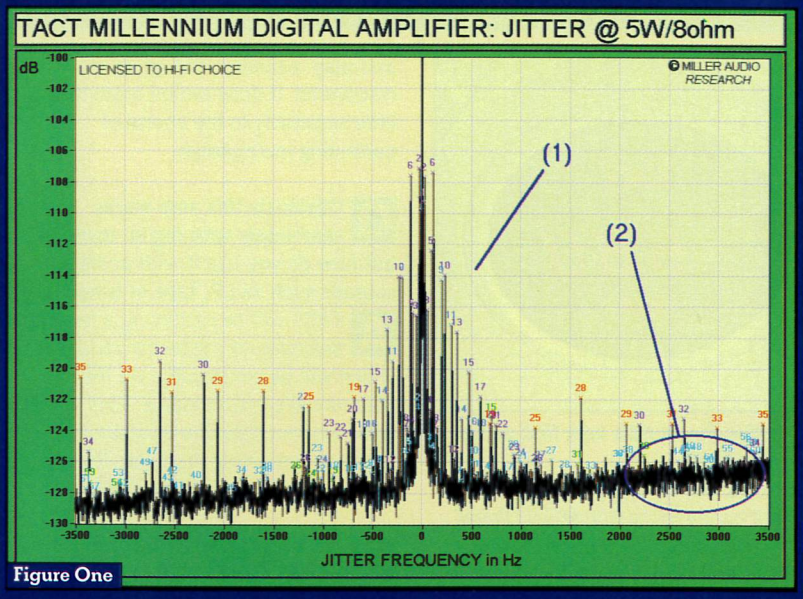


Figure One

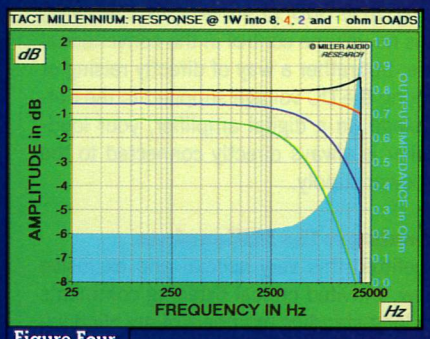


Figure Four

These Virtual Instrument plots, explained in the text, explain the workings of TACT's Millennium digital Class D amplifier, and quantify its performance. Clockwise from above: frequency response, spurious output, effect of truncation and noise-shaping, and jitter spectrum.

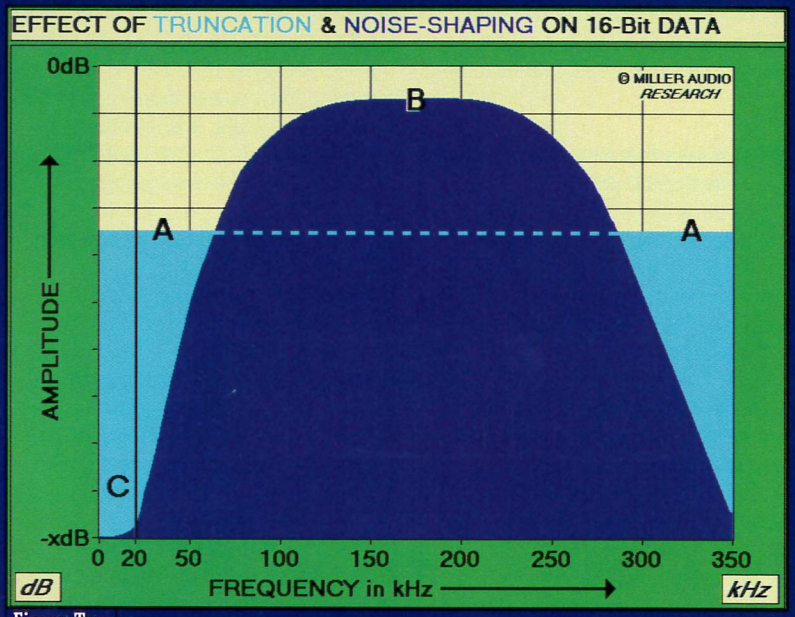


Figure Two

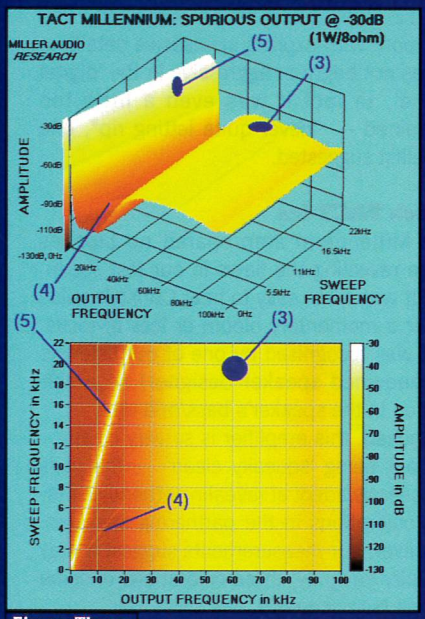


Figure Three

inference, it adds a new strand to an ongoing debate, over the relationship between amplifier power and speaker sensitivity, which has occupied my regular column (*Oasis of Sanity*) over the past few months.

The Millennium's technology

The Millennium is a digital device, and no more immune to the ravages of digital jitter than the average CD player/transport, MD recorder or DAT deck. Jitter, a form of distortion caused by errors in the *timing* of the digital data, is presently battled at the input to the Millennium by a sample-rate converter. However, on referring to Figure One (above), we can see around 500psec of low-rate jitter (1), marked-out with purple-coloured cursors, which seems to escape the process and may well lie behind the "slight loss of bass focus" reported by our listeners. TACT is addressing this issue before final production commences.

The Millennium's next step is to increase the data *rate* from 44.1kHz to 352.8kHz via an eight-times oversampling filter, which calculates seven intermediate data 'words' for each original pair, making the data stream eight times longer, but at the same time, eight times faster.

These digital 'words' (originally 16 bits wide) are reduced into smaller eight-bit chunks by a process called truncation. So far so good, but now we require each eight-bit word to describe the same information as each original 16-bit word; clearly, an impossible task. Looking at it another way, we are asking a range of 256 binary numbers (0, 1, 10, 11, 100....11111110, 11111111) to represent the same data as the previous 65,536 binary numbers (or two raised to the power of eight rather than two raised to the power of 16).

Making a 'trunc' call

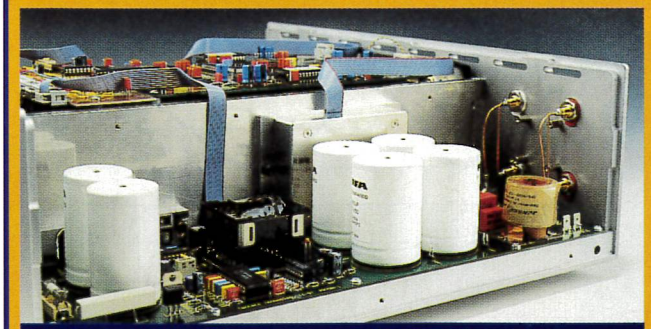
Inevitably, truncating from 16 to eight bits causes a significant error in the 'description' of the original audio waveform. Figure Two illustrates how this would be manifest as a great reduction of the available dynamic range, as noise and distortion is uniformly increased (A) across the eight-times-over-sampled frequency range. This is overcome by a technique known as noise-shaping.

Here, the eight bits shaved from the incoming 16-bit words are used to generate a corrective signal, which squeezes any extra noise and distortion within the audio range out to higher, inaudible frequencies. Importantly, noise-shaping does not reduce the total amount of noise and distortion but simply pushes it out of the way, towards the middle of the 352.8kHz spectrum.

Figure Two clearly demonstrates how the noise and distortion, produced by truncation, is concentrated at 176.4kHz (half the oversampling frequency, B).

One year after I proposed the idea (see *HFC* 77, December 1989) it was proved independently that the area under the

INSIDE THE MILLENNIUM



The 'brains' of the Millennium are on the circuit board shown top left in this photo. Pictured below right is an annotated plan view of this board. Beneath the PCB is a large toroidal transformer.

In the annotated diagram, right...

(1) Incoming data is received by a Crystal CS8412 interface chip.

(2) Data is locked to the Millennium's internal Master Clock — item **(7)** — using this sample-rate converter.

(3) Data is upsampled from 44.1kHz to 352.8kHz via this eight-times oversampling filter (could be usurped by a Pacific Microsonics PMD-100 'HDCD' filter in final production models).

(4) Motorola DSP56004 processor block produces the truncated eight-bit datastream.

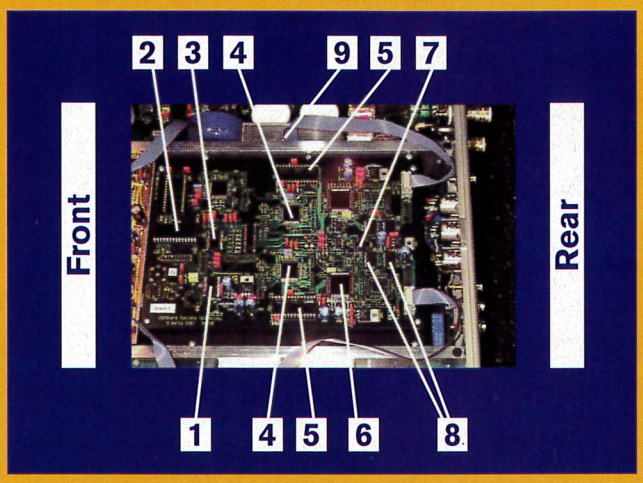
(5) Associated memory chips store the code necessary for the 16-to-eight bit truncation, fourth-order noise-shaping and distortion-correction code. (This block will be replaced by custom silicon in the production unit).

(6) High-speed logic is employed to translate the eight-bit datastream into a PWM bitstream with 256 possible pulse widths. This is locked on to the 90MHz Master Clock **(7)**.

(8) Latches are used to re-clock the final PWM signal before it modulates the DC power supply, which feeds...

(9)...this screened module, containing four high-speed n-channel HEXFET power devices, arranged in an H-bridge.

Regular readers of the magazine will know of the Radio Frequency (RF) emissions associated with bitstream CD players. Naturally, these are much more pronounced when the device in question deploys high-voltage, high-current circuits, as in the Millennium. TACT has addressed EU Electromagnetic Compliance (EMC) issues by compacting the H-bridge into a small, screened module and controlling any 'ringing' of the switched waveform at source, rather than relying on filtering at a later stage.



straight line (before noise shaping, A) and under the curve (after noise shaping, B) is equal. Ultimately, this technique realises the same signal-to-noise ratio and low distortion throughout the audioband (C), that would have been apparent *before* the truncation. It's a neat touch, but incurs the penalty of a slightly elevated HF noise floor detected during jitter analysis [Fig.2, (2)].

You might ask why it is necessary to condense those incoming 16-bit words in the first place. The reason is the incoming pulse widths could be any one of 65,536 integer (whole number) multiples of the Master Clock period. To accurately time the 'edges' of these pulses, an impracticably fast clock would be required: 8x44.1x65,536 = 23.1GHz. By truncating to eight bits, the clock accuracy is reduced to a feasible 8x44.1x256 = 90.32MHz, or right alongside Radio 3 in the FM broadcast band. Here, a binary 0 holds the Pulse Width Modulation (PWM, see box on p42) switch on for the shortest period, while the binary number 11111111 holds it on for the longest period. The widest pulse is exactly 256 times the width of the shortest pulse.

How it works in practice

The Millennium relies on an implementation of a HEXFET output stage, in which four n-channel silicon devices must switch in pairs *faster* than the 90MHz clock rate, to ensure optimum performance. These devices are configured in what is called an 'H-bridge', with one pair of devices either side of the speaker load. The incoming PWM signal effectively modulates the DC voltage of the power supply using the HEXFET devices, leaving an analogue LC (inductor-capacitor) filter to remove the high-frequency component (the 'square' in the square-wave) before it hits the speakers.

Examining the output

The set of images in Figure Three reveal the 'shaped' ultrasonic noise (3) discussed earlier, as it returns the audioband to its former 16-bit glory. A hint of third harmonic distortion (4), amounting to 0.06 per cent, is also exposed. TACT uses a second-order analogue LC filter to further suppress the ultrasonic requantisation noise from a frequency of 60kHz onwards.

This plot uses a full 0-22kHz audioband sweep (5) at the musically important –30dBFs level, and clearly shows the Millennium's freedom from any digitally-derived distortions and sampling images. This is a commendable result. Distortion with full-scale digital inputs (0dBFs) falls to 0.02 per cent, while the amplifier's low-level linearity is superior to 95 per cent of CD players, with errors of just +0.0/-0.4dB over a full 100dB dynamic range.

TACT's dual-mono, switch-mode power supplies run at 75kHz (referenced to the Millennium's Master Clock), and have been designed for minimal ripple. Clearly, as this supply effectively constitutes the output (it is always directly connected to the load) then it must be as 'clean' as possible to maintain the amplifier's wide dynamic range. This power supply also becomes the volume control, for the output level is directly governed by either increasing or reducing the supply voltage to the H-bridge.

Importantly, and regardless of whether the 0dBFs digital input is describing a continuous or momentary (ie burst) waveform, there is no dynamic headroom, just as there is no conventional 'clipping' point. A 0dBFs (full-scale) input is always referenced to a full-scale voltage supplied to the H-bridge: beyond this there is no margin for increase. (In digital systems there is no such thing as +1dBFs, for example.)

Thus I measured an output of 149 Watts from the Millennium, driving an eight Ohm load under either continuous or dynamic conditions. However, this does not mean the supply is infinitely stiff, and able to progressively *double* the output into four, two and then one Ohm loads, for example. In reality 214 Watts, rather than 298 Watts, is the limit into four Ohms, because there is a finite reserve of current available to sustain the *same* voltage into progressively lower loads. In practice current reserves work out to be about 11A, under continuous or dynamic conditions.

Speakers' corner

The output LC filter (described above) has another effect: it adds a reactive component to the amplifier's output impedance, which ▶▶

TECH TALK: QUESTIONS OF CLASS IN AMPLIFIERS

For conventional hi-fi applications, Class A amplifiers remain in vogue, despite their inherently high heat dissipation and electrical efficiency below 50 per cent.

In Class A, high levels of 'bias' current are applied to the power transistors of an amplifier's output stage. In a complementary amplifier, the positive and negative-going portions of the signal are handled by matched pairs of transistors (called n and p-channel respectively). The high bias current ensures that these complementary transistors remain conducting throughout the entire cycle of the musical waveform.

The bias, or standing current, is reduced in a Class B amplifier, so that the complementary (or push-pull) transistors conduct sequentially, in response to the positive-going and negative-going portion of the waveform respectively. Cooler running and greater efficiency (max. 78 per cent) are gained, at the expense of crossover distortion when one transistor picks up where the other has left off.

Class D, however, is a very different proposition. Here the output transistors act as switches, which are either fully on or fully off. Since a switch cannot dissipate any heat, this system will approach 100 per cent efficiency. This is distinct from the variable 'partial conduction' of Class A and B amplifiers.

Pulse Width Modulation (PWM)

As the continuous 'curve' of a musical waveform cannot be reproduced by single on/off states, a Class D amplifier represents music by varying the length of *time* that these switches are held on and off. This is known as Pulse Width Modulation, or PWM.

The whole process is rather more elegant in a *digital* Class D amplifier, because the PWM signal can be derived directly from the digital output of your CD or MD player or other, future, digital sources. It is also possible to provide advance correction of any distortions inherent in the switching stage, by manipulating the digital signal beforehand.

Class A amps, like this £690 Magnum design, are inevitably electrically inefficient, but at present remain the most cost-effective route to true high-fidelity reproduction.

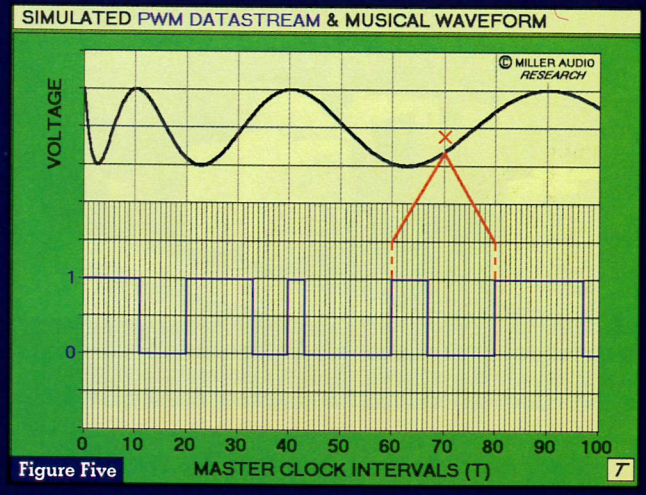


Figure Five

In the Millennium's case the PWM output stage switches at a rate which is synchronous with the 44.1kHz sample rate of your CD player's digital output, for example.

How PWM works – see Figure Five above

The PWM signal comprises a finite number of pulse widths, and each 'width' (whether in the '1' or '0' position) is an exact multiple of the amplifier's Master Clock. The simulated example (above) accommodates five digital samples across its horizontal axis, with a total of 20 Master Clock intervals lying within each sample. You might think of each sample representing a description of the musical waveform, its position or voltage, at one instant in time.

In this example, we are allowed one of 20 different pulse widths to describe the position of the musical waveform per sample (an instant in time). The ratio of time spent by the PWM signal at '1' compared to '0' defines the width of the pulse, and describes the position — or voltage — of the musical waveform, during that particular sample period. During the fourth sampling period on our simulation (between Master Clock intervals 60-80), the pulse width occupies seven Master Clock intervals, with the remaining 13 intervals occupied by a pause of digital zeros. The ratio of pulse and pause defines the position of that sample — that instant in time — on the final musical waveform (X).

As we have discovered (p41), each sample period used by the TACT Millennium lasts just 2.8 micro-seconds (2.8 millionths of a second, or eight times 44.1kHz); and within each sample period there are 256 Master Clock intervals available to accommodate any one of 256 different pulse widths.

modifies its response into different loudspeaker loads (see *Oasis of Sanity*, *HFC* 177). This output impedance is shown as the area shaded in bright blue (printers and repro permitting!) with its scale on the far right of the graph. Note how the increase in output impedance, to nearly one Ohm at 20kHz, is mirrored by changes in the treble response of the amplifier into progressively lower speaker loads, together with a net loss in dB (Volts).

The +0.7dB peak at 20kHz (black trace) has been deliberately engineered into eight Ohms. This is to ensure that, with the –0.8dB droop at the same frequency into four Ohms (red trace), the 'average' response with most speakers should even out... with a following wind. Nevertheless, this variation in response with load impedance may, indeed, cause the Millennium to act as a 'magnifying glass' to the anomalies of different loudspeakers.

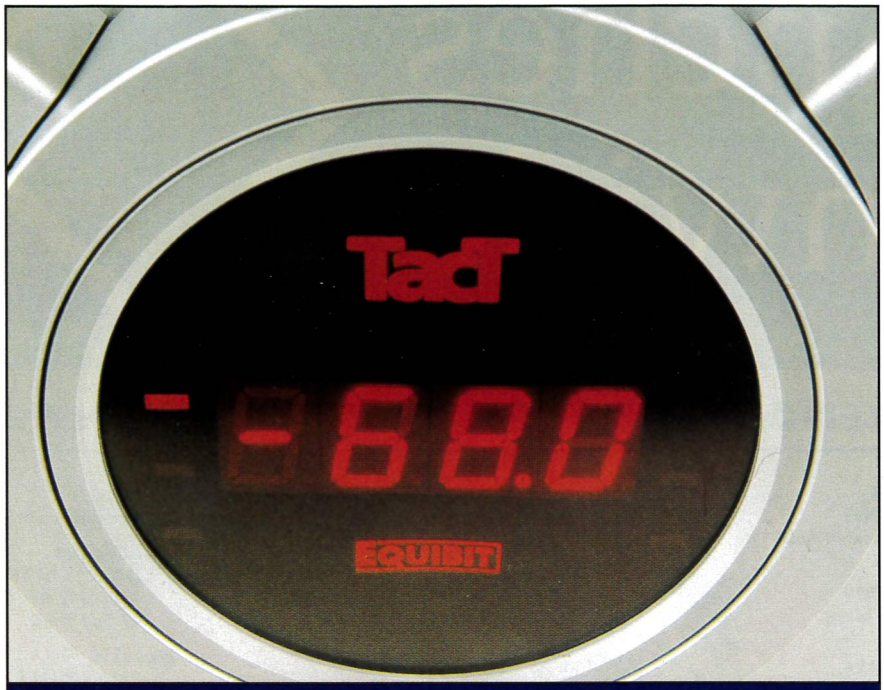
Where next?

In the effort to have this technology widely accepted, commercial reality has at least partially overridden some innate advantages of digital amplifier technology. For example, a digital Class D amplifier need not weigh half a ton, but to be taken seriously by the high-end community, following the precedents of Krell, ARC et al, expensive products need to feel as heavy as their price-tags.

Furthermore, without its inch-thick milled-alloy facia and spectacularly expensive volume dial, the Millennium would have been quite a bit cheaper. Also, as the final dynamic range of the amplifier is dependent upon the residual noise of the power supply, eliminating the final few microVolts of ripple causes an exponential increase in cost.

I feel justified in reiterating my conclusion of two years ago. The Millennium is just the beginning, a signpost towards lower-cost digital amplifiers, running from practical power supplies in lightweight cases. Analogue interconnects, crossover networks and conventional, inefficient amplification *might* become a thing of the past.

I say 'might', because the development and direction of audio is driven much more



This is the Millennium's volume control wheel, which turns on military-specification bearings. The display indicates a nominal output level, ranging from −90 to +12.

by the imperatives of marketing than by any altruistic desire to improve sound reproduction in the home.

For the fortunate few who can afford this product, the TACT Millennium amplifier offers a taste of one possible digital future. Early adopters will not be disappointed!

CONTACTS

For further information on the TACT amp in the UK, please contact Audio Club on ☎ (01296) 482017. International enquiries to TACT Audio Europe on ☎ +45 86 27 75 00.

TACT MILLENNIUM: MEASURED PERFORMANCE

	SIGNAL FREQUENCIES		
PARAMETERS	20Hz	1kHz	20kHz
Max continuous power output into 8 Ohms	147W	149W	172W
Max continuous power output into 4 Ohms		214W	
Output impedance	0.195 Ohms	0.199 Ohms	0.943 Ohms
Damping factor	40.9	40.2	8.48
Response @ 1W/8 Ohms	-0.1dB	0.0dB	+0.67dB
Channel balance	0.0dB	0.0dB	0.0dB
Channel separation	135dB	130dB	106dB
THD vs level, 0dB	-78dB	-74dB	-66dB
THD vs level, -30dB	-68dB	-65dB	-44dB
THD vs level, -60dB	-62dB	-56dB	-6dB
THD vs level,- 80dB	-28dB	-32dB	+15dB
Dithered, -90dB	-19dB	-23dB	+24dB
Dithered, -100dB		-22dB	
Dithered, -110dB		-13dB	
Resolution @ -60dB		0.0dB	0.0dB
Resolution @ -80dB		0.0dB	0.0dB
Resolution @ -90dB		-0.4dB	-0.4dB
Resolution @ -100dB		-0.2dB	-0.3dB
CCIR IMD, 0dB	-76dB		
Suppression of stop-band images	105dB		
S/N ratio (A-wtd), with emp, 0LSB	101.8dB		
S/N ratio (A-wtd), with emp, w/o emp, 0LSB	101.7dB		
S/N ratio (A-wtd), with emp, w/o emp, 1LSB	101.8dB		
De-emphasis accuracy, 1kHz	No de-emphasis		
De-emphasis accuracy, 5kHz	No de-emphasis		
De-emphasis accuracy, 16kHz	No de-emphasis		
Total Correlated Jitter	507psec		
Crystal Clock Accuracy	+4ppm		
Serial Number	N/A: prototype		
Projected Retail Price	≈£5,000		

EDITOR'S COMMENT

Digital techniques are becoming more and more a feature of modern existence. In my editorial column this month (p3), I discuss how audiophiles will soon benefit from digital radio and TV. The big electronics companies are desperate for consumers to replace existing analogue equipment with new, shiny digital versions of the same. You've played the game already with digital software like CD — why not play again with hardware?

However, this is not just a case of keeping up with the latest fashions. Digital technologies offer significant benefits by virtue of the way they work. While a cordless telephone is still only a telephone, a digital version is almost immune to noise and may be used at a considerable distance from its base unit.

TACT's Millennium still performs the hi-fi amplifier's traditional rôle, of turning electrical signals into musical sound waves. Its significance is in fulfilling, for the first time, CD's promise of low noise and large dynamic range. And it does this by using the same canvas as before (the loudspeaker), but an altogether different painting style (pulse width modulation).

Until now, CDs have been reproduced using technology harking back to the early days of radio. Input a small squiggly signal, out comes a bigger version. Analogue circuit-design techniques have been refined immensely over the years, just like the internal combustion engine — another old technology which some would say has overstayed its welcome! But nonetheless, it has been something of an anachronism to convert CD's digital code into an analogue waveform, just so that it can be amplified and reproduced.

The TACT Millennium finally opens the door on a new hi-fi paradigm, where music can be stored and transmitted completely digitally, all the way from microphone to loudspeaker.

I doubt there'll be another audio revolution so great, until we are born with phono sockets growing out of our foreheads...

ATW "Stan" Vincent, Editor-in-Chief