Test Reports

QUAD 405 Current Dumping Amplifier

QUAD

for the closest approach to the original sound

QUAD 405
Power Amplifier

Gordon J. King

IN the beginning was the Class-B amplifier. Designers tended to prefer this to Class-A because of its better efficiency and hence power yield for a given size heatsink and power transistor capacity; also to satisfy the greedy demands of loudspeakers with fast diminishing electro-acoustic conversion efficiencies. Pure Class-B is totally incompatible with Hi-Fi owing to the push-pull displacement of the two halves of the output transfer characteristics, leading to serious crossover discontinuity, and hence so-called crossover distortion, particularly at low signal levels.

Class-B was brought into the Hi-Fi realm by biasing the output transistors towards Class-A so that at zero drive the transistors were not cut-off completely but passed a degree of emitter/collector current, called quiescent current. Although still often referred to as Class-B, such amplifiers are really Class-AB.

Crossover distortion is impossible from properly designed Class-A amplifiers, but it can occur in relatively small doses from Class-AB amplifiers. It tends to diminish as the biasing is adjusted towards Class-A, but then the efficiency falls and the standing temperature of the power transistors and their heat-sinks rises. A compromise between efficiency and crossover distortion is worked out, and the remaining distortion is reduced by various artifices including, in some cases, large amounts of negative feedback.

When the design has been handled correctly the net result is an amplifier of very low distortion and relatively high efficiency. indeed, crossover distortion is practically undetectable from some of the best class AB designs. However, to achieve this ideal state of affairs a large amount of design detail is essential, and components and adjustments can become critical. In spite of thermal compensation, the optimised conditions can be impaired by temperature changes and hence by the immediate past history of the programme energy and dynamics.

If intermodulation distortion is measured at very low power, around 1 mW and then measured again at the same power but this time immediately following a burst of higher power operation, some Class-AB amplifiers will give a much higher figure on the second measurement, thereby proving the thermal point.

The design team at (QUAD) the Acoustical Manufacturing Company Limited have been aware of this shortcoming for some time; also of the critical nature of adjustment required to secure the best distortion performance from Class-AB amplifiers of conventional design. the aim, then, was to design an amplifier of exceptionally low distortion and of realistic contemporary power which relies far less on critical adjustment and thermal tracking. the result is the new QUAD 405 power amplifier which I have been analysing in great detail over the last few months.

The design employs a modified version of a technique known as 'feedforward'. This is not new to amplifiers in general, having been used and experimented with for some years now in connection with carrier systems and communal aerial systems.[1,2] it has also been mooted for audio amplifiers,[3,4] but so far as I can discover QUAD are the first to use it in a commercial Hi-Fi amplifier.

The basic feedforward system uses two amplifiers, the main amplifier and an 'error' amplifier. the main amplifier performs the normal function of amplification with its inevitable addition of errors in the form of noise and distortion. By isolating the error signals from the fundamental signals it becomes possible to reinsert them back into the main signal path in such a way as to lead to their elimination. One way of isolating the errors is to sample the output and then subtract this from a sampled portion of the input, at the same time taking account of the delay time of the amplifier by delaying the sampled input by an amount equal to the amplifier delay. This secures synchronisation of the input and output samples, the two then being subtracted to leave only the errors.

Since the sampling circuits attenuate the error signals, the signals must be boosted before being reinserted into the main signal path, and this is the job of the error amplifier. Again, the delay resulting from this amplification must be taken into account to achieve complete cancellation.

Although based on this principle, the feedforward of the QUAD 405 is applied within the loop of a feedback amplifier, the circuit carrying an error component which bypasses the power transistors, thereby reducing their requirements in terms of highly critical linearity. the QUAD team has coined the term 'current dumping' for this technique.[5]

The amplifier (each channel) is arranged in the form of a feedback bridge whose active elements consist of a small but ultra-linear Class-A amplifier for providing the required swing of output voltage but at relatively small current, and the more usual large power transistors on a front heat-sink providing the higher power current demands since it is the job of these transistors to provide the majority of load current, as dictated by the programme signal, they are appropriately called 'current dumpers'.

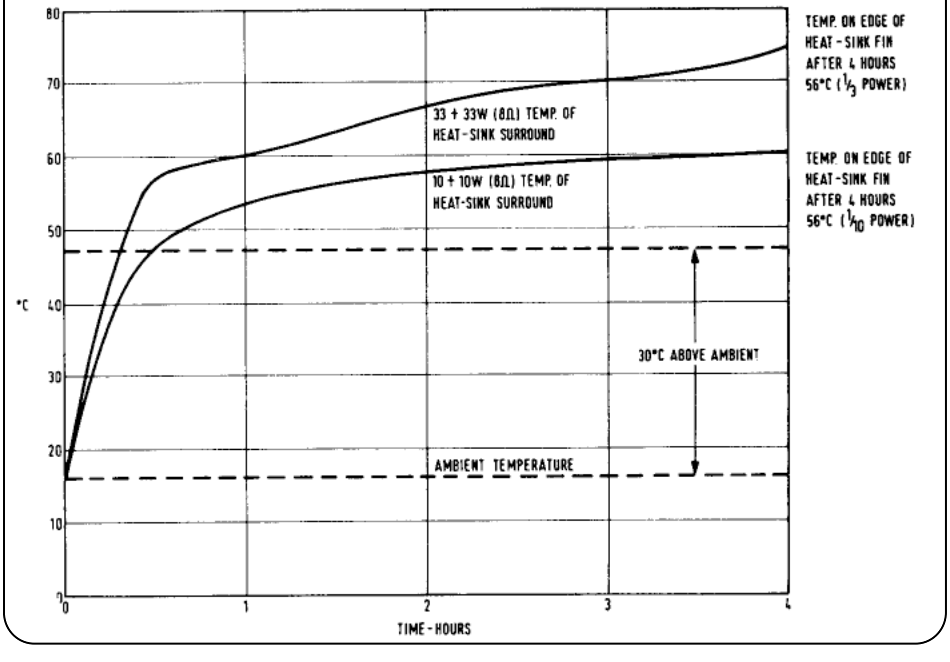
In other words, the main amplifier is of quasi-Class-B design, while the Class-A element can be regarded as a sort of 'control amplifier', which neatly deletes substantially all the distortion of the main amplifier. This clearly avoids the need to optimise the adjustments of the main amplifier critically, for whatever error there is in the output signal, the circuit cancels it out. Thus any drift or suchlike due to thermal happenings becomes insignificant !

In theory, the technique makes it possible to cut the errors essentially to zero, depending on the excellence of the Class-A amplifier. In practice there is always bound to be some residual non-linearity, albeit very small. Cancellation is also governed to some extent, though not critically so, by the balance of the bridge; but to maintain 'perfect' balance over the entire spectrum would appear to fall outside the reaches of the economy dictated by a design other than for critical laboratory purposes. Nevertheless, the 405 is an amplifier of astonishingly low distortion; it is, in fact, one of the purest which has so far passed through my laboratory, putting quite a demand on £10,000 - worth of measuring equipment. The manufacturer intimates that even with a 5% error in bridge balance-resulting from a 5% error in any component value of the design-the maximum intermodulation products will still be down to the 5 µV level at 1 kHz the maximum possible IMD being 0.01% and the maximum absolute level of these components being some 140 dB below full power.[5] the spec, puts the total of all distortions in the range 20 Hz-20 kHz at least 80 dB below the rated power, corresponding to 0.01%

The power and distortion parameters of the test sample were examined in significant detail, as brought out in the test results. The full 100 W + 100 W of power into 8 Ω resistive loads was readily available, and this power held from 10 Hz to 20 kHz without ill effect the heat-sink constitutes the front decor of the amplifier, and with steadystate drive this soon started warming up.

In accordance with our practice nowadays, the amplifier was preconditioned at one-third rated power (the power at which a Class-B amplifier is running least efficiently and hence dissipating maximum heat) at 1 kHz with both channels driven simultaneously into 8 Ω resistive loads. After an hour's operation under these conditions the top surround of

FIG.1 QUAD 405



the heatsink was far too hot to touch, it being exactly 60°C, from an ambient temperature of just over 16°C. The curves in fig.1 show how the temperature builds up over a period of four hours both at one-third rated power and 10+10 W. These measurements were made with a Comark Electronic Thermometer, Model 1601 with specially calibrated thermocouples. Although certainly high, the temperature is still well within the rating of the output transistors, whose limit is 120°C corresponding to a sink temperature of about 90°C.

The curves also show that the amplifier will safely survive and readily pass the FTC (Federal Trade Commission-American) spec. However, to get the BS 415 ticket the design would need to include a thermal cut-out to prevent the exposed temperature from rising much over 30°C above ambient under sinewave drive.

QUAD are not the only manufacturers in this quandary. I have full sympathy with latter-day designers and feel that it is about time this crazy anomaly was resolved by the standards people. It is really academic, of course, because on music signal of normal dynamic range the amplifier remains relatively cool, even when producing loud peaks. Few people listen to sine-waves, though I suppose some of the modern electronic music can resemble steadystate information. My reason for labouring the point is merely to put it into proper perspective once and for all.

Based on distortion factor, the readout was in advance of 0.01% but by calculating out the noise the spec. was adequately met, as shown by the test results. Marconi and Hewlett Packard wave and spectrum analysing equipment was employed for the IMD measurements, and Radford equipment for the distortion factor measurements. Two distortion factor residual oscillograms are given (fig. 2). The dual oscillogram shows 1 kHz signal with its residual at the top and 20 kHz distortion with its residual below, both with the amplifier operating at 10 W+10 W into 8 Ω resistive loads. In both cases the gain of

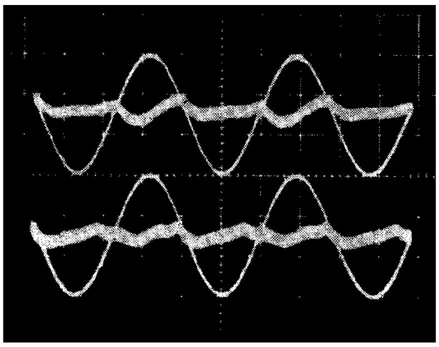


FIG.2 Distortion factor with 60 dB (1000x)gain 10 W+10 W into 8 Ω. Top: 1 kHz Bottom: 20 kHz

the distortion measuring channel was adjusted for exactly 60 dB (1000x) with respect to the sine-wave across the load. This presentation makes it possible to evaluate the peak distortion at both frequencies from the traces direct. The mean distortion (as indicated by the instrument) to the peak distortion gives an indication of the 'roughness' of the residual. A unity ratio would obtain from pure harmonic residual devoid of spikes.

Minor traces of crossover effects are indicated by the residuals, but these must be considered in the light of the extremely small mean distortion factor which, as the test results show, is little more than a mere 0.01%!

The other distortion factor oscillogram of single trace (fig. 3) was obtained at 1 kHz with the amplifier's full 28 V RMS across a load consisting of R and C (i.e. R-jx) which, at 1 kHz was adjusted for an impedance of 8 Ω the power factor being 0.75 and the phase angle 41°. Such a load is more representative of a loudspeaker than a pure resistance, though it must be noted that some loudspeakers present a much more complicated load to the amplifier, as my recent researches into amplifier/loudspeaker interface problems have dramatically indicated.

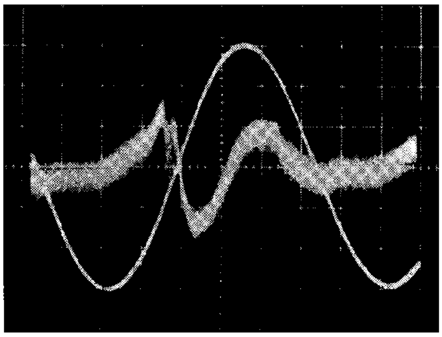


FIG.3 Distortion factor across R-jx load (8 Ω) with 70 dB (3162x) gain, 1 kHz 28 V RMS. Peak distortion =0.016%

Nevertheless, the simple impedance does put out-of-phase current through the output transistors, and when an amplifier is producing its full load voltage the current in the output transistors can precipitate the action of the voltage-operated (the voltage arising from the current through a resistor) current limiters before the full voltage output of the amplifier is reached. Bad distortion can thus be generated prior to the peak clipping of the sine-wave or programme signal.

The oscillogram shows that the QUAD limiter (on one half of the output stage) was just coming into action at full output voltage, but even then the mean distortion measured on the Radford equipment was still at a very low level.

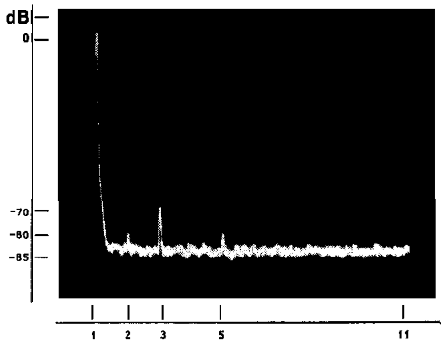


FIG.4 Frequency in kHz

Using the Hewlett Packard spectrum analyser, the spectrogram in fig.4 shows the third harmonic at -70 dB and both the second and fifth harmonics at -80 dB from a 1 kHz fundamental producing 28 V RMS across the R-jX load. The spectrogram in fig. 5 shows harmonics and intermodulation products generated from two driving signals at f_1=5 kHz f_2=9 kHz when each is

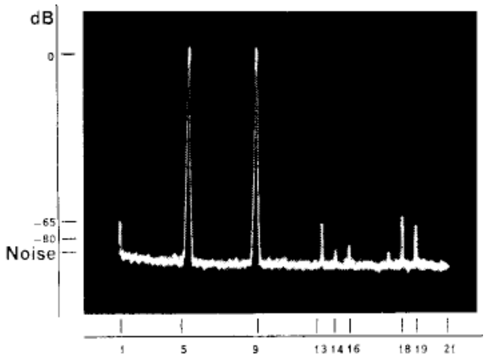


FIG.5 Frequency in kHz.

producing 14 V rms across the same load. The third-order products at 1 kHz and 13 kHz are each about 66 dB down. It is interesting to note that the second-order products are much lower, that at 4 kHz being pretty well into noise and that at 14 kHz about -80 dB. The component at 18 kHz is the second harmonic of the 9 kHz source (Sugden oscillator). The second harmonic from the 5 kHz source (Radford oscillator) is below noise.

That, then, concludes our detailed analysis of the distortion performance of the 405. Under the more general conditions of measurement the distortion is well down to -80 dB (0.01%); but slightly higher amplitude products can be evoked by the use of more stringent test procedures. However, even in the worst case the amplifier has very low distortion by anyone's standard. The analysis has also indicated why relatively simple test methods with inexpensive instruments can no longer be expected to reveal the true performance of state-of-art amplifiers.

I was pleased to discover that the QUAD team have deliberately avoided designing for a crazy RF response. The rise-time was a sensible 7.5 µs with the small-signal upper-frequency -3 dB point around 48 kHz. The small-signal response would appear to suit the speed of the 'current dumpers'. To ensure that the amplifier is fully able to 'digest' the speed of the signal fed to it (as dictated by the speed of the 'dumper' transistors used), the QUAD spec. includes an input slewing-rate limit, given as 0.1 V/µs and the distortion performance is based upon the rate of change of input signal not exceeding this limit, which corresponds to an upper-frequency of around 22 kHz.

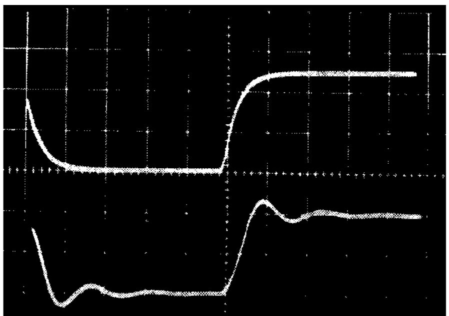


FIG.6 10 kHz Square-wave response. Top: 8 Ω Bottom: 8 Ω+1 µF

Our measurement of output slewing-rate worked out to 5 V/µs, which is virtually the same as the input spec. times the gain of the amplifier.

The step function oscillogram (fig.6) shows the rise-time across 8 Ω load at the top and the settling-time across 8 Ω in parallel with 1 µF below, both on a sweep of 10 µs/div. Although the latter produces ringing, this is swiftly damped

The 20 Hz - 20 kHz frequency response (Straight line!) is shown in Fig. 7, The high-pass filtering at the left of Fig. 8 and the HF roll-off at the right (note the difference in frequency scaling)

Both channels matched fairly closely on all parameters, and the residual offset, hum and noise, stereo separation and damping factor were well within specification.

Although quite small, the amplifier is of very 'solid' construction as already mentioned, the frony of the amplifier consists of the heatsink. The amplifier is metal - encased and finished in the conventional QUAD colouring. At the rear is a panel accommodating two pairs only of spring loaded loudspeaker connecting terminals polarity and channel identified, a mains voltage adjuster, mains fuse, three pin mains connector and 4 pin DIN socket (with plug and connecting socket supplied) for the left and right input signals.

The DIN signal cable is terminated at the far end by two "phono" - type plugs for accepting signals from a pre-amplifier, but personally I would have also liked to have seen the provision of two 'phono' type sockets actually on the amplifiers' back panel in addition to the DIN socket which correlates with the QUAD 33 pre-amplifier socketry. Perhaps QUAD had this in mind at one stage since there are two holes (covered) close to the DIN socket where they could easily be accomodated.

Electronic design is very substantial as one has come to expect from British QUAD, and the power amplifier sections are built on the 'module' basis allowing easy service and Interchange.

Unquestionably one of the very best British amplifiers on the market today, it is incredibly 'smooth' sounding and fully lives up to its specification. It packs sufficient power for the larger system but remember the heatsink will rise significantly in temperature when the amplifier is driven with sine wave signal. The mains lead supplied is 2 core with American-type two pin plug termination. However, to satisfy BS 415 a three core cable can easily be used (one conductor for direct earthing) since the three-pin mains socket has an earthed pin. When the 405 is used wrth the QUAD 33 control unit, earthing will be accommodated via the braids of the audio connecting cable. (not recommended)

The amplifier is directly coupled to the loudspeakers, and protection is by fuses and by electronic current limiters. Useful comment about loudspeaker protection is given in the instruction book, which also gives information on the connection of headphones, additional loud speakers and unbalanced and floating 600 Ω line inputs.

By the Insertion of 1.8 kΩ resistors (two supplied, one for each channel) into sockets on the printed circuit board labelled R11 (a fiddly little job) the output voltage for each channel can be limited to about 28 V peak (20 V RMS) ref. peak clipping. To avoid damage to the loudspeakers, this minor modification is necessary when the amplifier is partnered with the QUAD ESL57s. Measurements made following this modification proved that

FIG. 7 QUAD 405 FREQUENCY RESPONSE

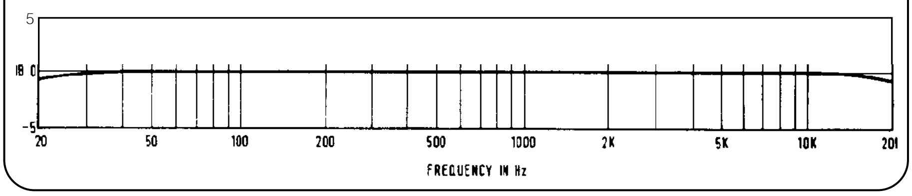
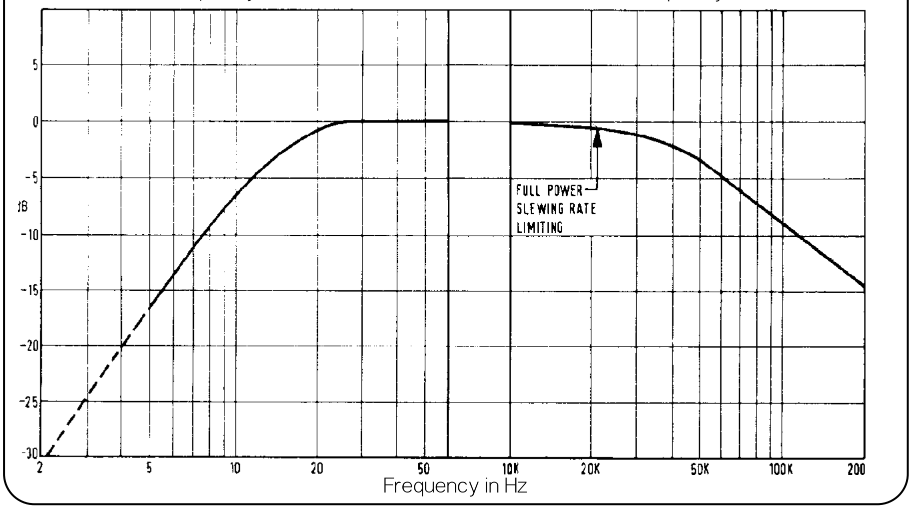


FIG. 8 QUAD 405



the clipping threshold was reduced to 28 V peak across 8 Ω resistive loads and to about 25 V peak across 4 Ω resistive loads.

Using an impedance load of 5-4 Ω and 48° phase-angle at 400 Hz, the protection transistors commenced switching and causing distortion a shade before the onset of peak clipping owing to the out of phase load and hence transistor current with respect to the voltage (see Fig. 9)

A review of a QUAD power amplifier can hardly be regarded as sufficiently exhaustive without trial in conjunction with a QUAD electrostatic loudspeaker and QUAD 33 control amplifier. The system in this form was established in a listening room of some 62m^3, receiving signal from a Shure V15/III cartridge. A range of material was assessed by a critical panel of five, including Donald Aldous and myself. There was complete agreement that the amplifier neither added to nor detracted from the disc record signal fed to the ELS model. The sound level at towards-full-power tests was monitored and no sign of overload or protection transistor switching was detected even with an RMS peak sound intensity as high as 100 dBA.

Peter Walker's design aim of 'a piece of wire with gain' has thus, in the colloquial sense, once again been met. The 405 packs more punch than the earlier 303 and tames better the higher frequency distortions; but it needs a very critical ear to say conclusively that one amplifier sounds better than the other at normal listening levels in the domestic scene. Indeed, there are still those enthusiasts who swear by the even eariler QUAD 22/II valve amplifier, and one of these at the time of writing has been removed from cold storage into my lab and listening room

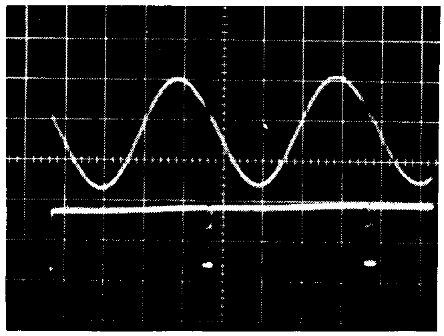


FIG. 9. *Protection transistor switching at 400 Hz when driving load of Z=5·4 Ω, ϕ=48° (voltage limiter on).*

for comparison with a contemporary transistor amplifier which scored high marks in a panel assessment test.

Desirable factors of transistor amplifiers over thermionic valve counterparts are their better power/weight ratio and efficiency, factors of significant importance when it comes to driving loudspeakers whose efficiency is a magnitude or so below that of speakers designed in the valve heyday. We certainly do need powers up to at least 100 W+100 W for realistic dynamic range in a fair sized listening room and with loudspeakers of efficiency not much better than 0.1%. A valve amplifier would be a very massive animal to cater for this sort of continous - wave power. The 405 is around the same size as just one of the early QUAD II valve power amplifiers, whose single-channel power is well below that of the 405. However, perhaps it was the more graceful overload characteristics of valve amplifiers which enabled us, partly, to get away with less continuous-wave power !

There was no trouble at all in partnering the 405 with the 33 control unit. As already noted, the amplifier uses fuse protection. Some British designers and many Japanese ones prefer relay protection, which sometimes has three modes of operation. The contacts of the relay connect the loudspeakers to the power amplifiers only when the winding is energised. Energising current is derived from a d.c. transistor amplifier and time-constant circuit which samples the power supply voltage. Thus, owing to the time constant. the loudspeakers are connected after the supply stabilises, which avoids the switch on 'thump' when direct-coupling is used to the loudspeakers, as it is in the QUAD 405.

The relay control amplifier also includes a section which monitors the current in the output transistors, so that in the event of a beyond-threshold rise in current here, resulting, say, from a short across the loudspeaker circuit when the amplifier is under high drive, the relay contacts open and remove the supply. This method of protection tends to minimise the protection transistor switching effect and hence distortion (fig. 9) which can result from lowish impedance and large phase angles of the load (i.e. loudspeaker), as already mentioned. However, a lab. study of the distortion generated by the two types of protection has revealed that the relay scheme is not always totally immune at high signal drive into a lowish impedance load of fairly large phase angle; that is, a curious type of distortion is sometimes produced before peak clipping of the sine wave test signal. In general though the protection transistor arrangement shows up worse in this respect.

The third mode of operation is that the control amplifier also detects any abnormal rise in off-set voltage across the loudspeakers, the relay contacts then opening before the loudspeakers are damaged. The 405 relies on fuses for this protection.

Frankly, I would have preferred all-round protection as can be provided by a relay in the new QUAD; but opinions can differ on this, and then, of course, there is the price to be taken into account. We cannot have it all ways. One must not get the mistaken impression that the 405 is not of rugged design. It certainly is; and of first-class competent engineering.

The amplifier is very easy to connect and use (there are no external controls), but must, of course, be operated from a good preamplifier/control unit, such as the Quad 33 It was used in the domestic scene from music signal delivered by the preamplifier section of an integrated amplifier (not QUAD) and worked without trouble or stress into IMF loudspeakers, which are noted for their insensitivity (and high quality). One of the test samples produced a mild mechanic buzz when used on a vibrant shelf; but electrically the amplifier was totally quite. Our editor also discovered a slight mechanical hum on another sample, which was reported back to Mr. Walker who immediately put several models on test in a quite room. This revealed some variation which has now been investigated and put right on the production line.

In summary, a well developed amplifier of novel conception which will go a long way to boost British audio exports.

References

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QUAD 405 POWER AMPLIFIER
Test conditions: Mains input 240V 50Hz Both channels driven simultaneously from 600Ω source

PERFORMANCE		COMMENT
Power to clipping at 1kHz	102W (L)+101W(R)	Into 8Ω Resistive loads
Bandwidth at 100W/8Ω to clipping	10Hz - 20kHz	Slewing rate limiting ` 20k Hz
Damping factor (BSI) at 40Hz and 2W	200	Includes R of connecting wires.
Frequency response (-3dB) at 1W	13Hz - 48.6kHz	Also see graphs (Figs. 7 & 8).
Rise-time	7.5µS	Also see oscillogram (Fig. 6).
Settling-time (8Ω/1µF)	20µS	Also see oscillogram (Fig. 6).
Slewing-rate (8Ω)	5V/µS	20kHz 28V RMS approximately.
Input for 28V/8Ω	515mV (L): 521mV (R)	Digital instrumentation.
Hum and Noise	0.4mv (L); 0.45mV (R)	Across 8Ω.
Stereo separation	85dB (1kHz); 82dB (10kHz)	Ref. full power with non speaking input shorted.
Offset	1.1mV (L); 0.3mV (R)	Well within spec.
Distortion factor at 10W + 10W 8Ω 20Hz (including ripple) 1kHz 20kHz	 0.235% (mean) 0.012% (mean); 0.02% (P) 0.013% (mean); 0.02% (P)	 Note that distortion factor includes noise. THD to spec. also see oscillograms (fig. 2).
Distortion factor at 100W + 100W 8Ω and 1kHz	0.0046% (mean)	Noise contribution 0.0032%
Total harmonic distortion as above	0.0033% (mean)	Noise calculated out.
Distortion factor at 28V RMS across R±jX load at 1kHz	0.0076% (mean)	Slight limiter distortion present under this condition. see oscillogram (Fig.3) and spectrogram (Fig.4).
Total harmonic distortion as above	0.0069% (mean); 0.016% (P)	Noise calculated out.
Intermodulation distortion at 100W + 100W and 1mW:	no product greater than	Measured all modes at 8Ω resistive. -80dB into 8Ω loads.

Note L=R unless otherwise stated.
Main instruments: Marconi, Hewlett Packard, Radford and Keithly