THIRD-GENERATION OP-AMPS

RCA CA3140 and TI TL071/2

John Linsley continues his series of articles on i.c. design with a look at the operational amplifiers which succeeded the versatile 741. The TL072 is the type used in the modular preamplifier, to be described in the next three issues.

by J. L. Linsley Hood

I made the comment in the first article of this series, last October, that I felt the advent of the 741 integrated-circuit operational amplifier was the turning point in the conversion of many linear circuit engineers to the use of i.cs. However, useful though the 741 and other similar contemporary i.c. op-amps were, they were relatively slow and their input impedance was low enough to make it necessary to consider the likely effects of the flow of the input bias current in the input circuitry.

CA3140

It is understandable, therefore, that the advent of the RCA 'mosfet-input' op-amp, the CA3140, with an input impedance of more than $10^{12}\Omega$ and a slew-rate of some 9V/μs in comparison with that of the 0.5V/μs typical of the 741 in the mid-1970s, should have been greeted with great enthusiasm by the industrial electronic-engineering fraternity, for whom a lot of rather awkward jobs now became very much easier to accomplish. Examination of the circuit, drawn in simplified form in Fig. 1, shows a very great similarity in general structure to that of the 741, except that the complementary-pair output stage emitter followers have been replaced by a single emitter-follower Darlington pair ($Tr_{17,18}$) with an active emitter load built up from $Tr_{15,16}$ and Tr_{21}.

The input stage is conventional, consisting of an input long-tailed pair of p-channel mosfets driving a current mirror ($Tr_{11,12}$) and a single class-A amplifier (Tr_{13}) with a constant-current source as its collector load. High-frequency compensation is again conventional in form, with a collector-base capacitor (C_c) connected across Tr_{13} to impose a dominant-lag type reduction in h.f. gain.

The major advantage of this circuit arrangement stems from the replacement of the relatively poor 'lateral' p-n-p transistors which would have to be used in a conventional, bipolar only type of i.c., with p.m.o.s. devices, which have an exceedingly high input impedance and very good h.f. characteristics. Unfortunately, in this circuit, there is an inevitable load mismatch so that, in spite of the current-mirror load, the gain of this input stage is only about 10×. Also, the need to protect the input gates from inadvertent breakdown due to electrostatic charges forces the use of internal Zener diodes, whose leakage currents effectively limit the input impedance to some 1.5×10^{12} ohms at 25°C.

In order, therefore, to get the gain up to the 100,000 mark expected from his type of device, some ingenuity has been applied to the design of the second class-A gain stage and the output circuitry, shown in full in Fig. 2. In this, the most obvious feature, apart from the four p.m.o.s. devices ($Tr_{8,9,10,21}$), is the most elaborate biassing circuitry, with its ladder of current-mirrors built up from D_1, Tr_1, Tr_6 and Tr_7, all fed from Tr_8, whose geometry is organized to make it act as a current source. This ladder of current-mirrors is used to control the cascade-connected current sources (Tr_2 and Tr_5) in the 'tail' of

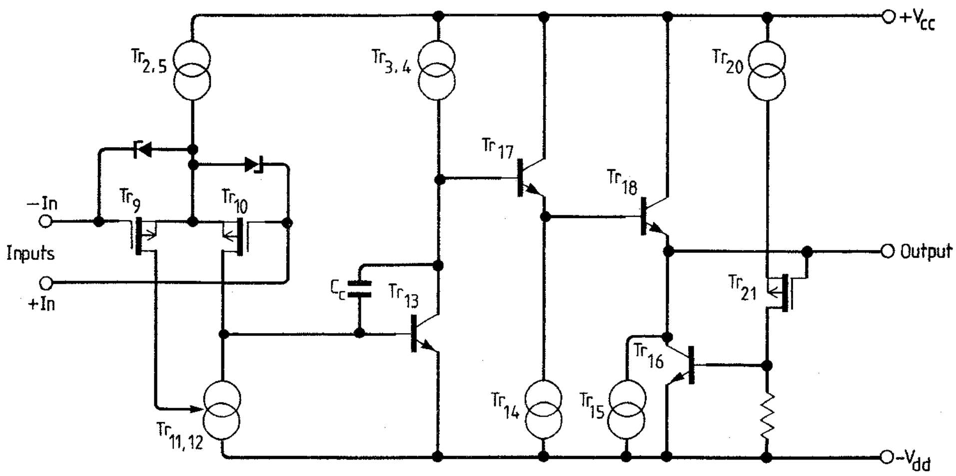


Fig. 1. Simplified CA3140 circuit, showing general similarity to 741 structure.

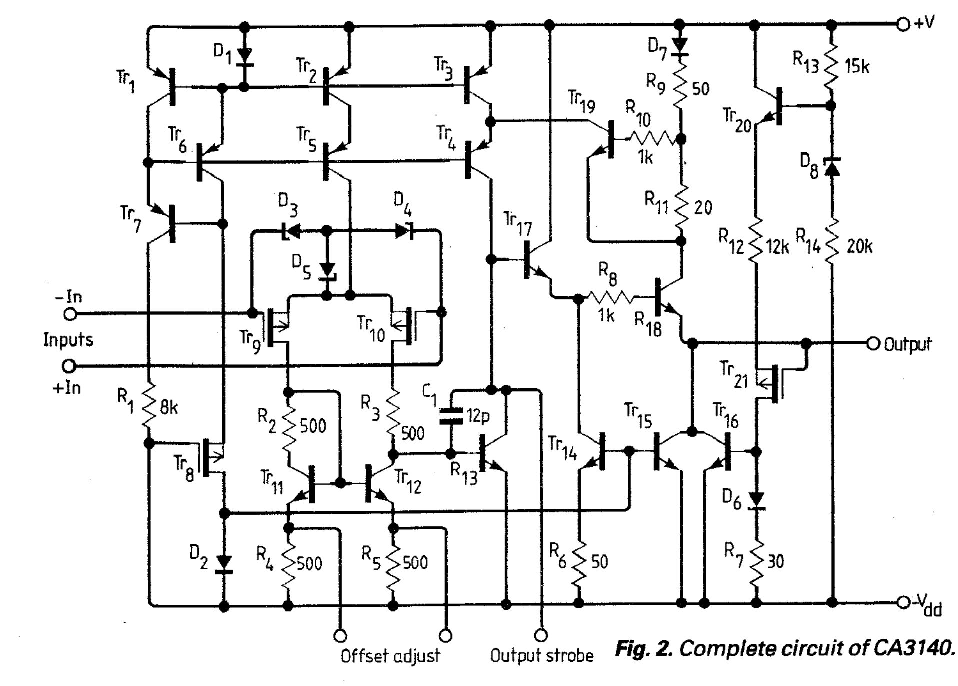


Fig. 2. Complete circuit of CA3140.

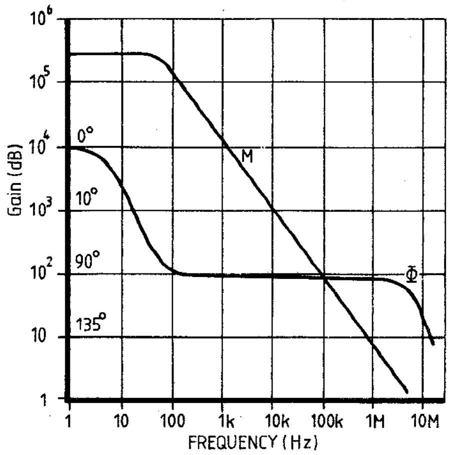


Fig. 3. Gain/frequency plot for CA3140.

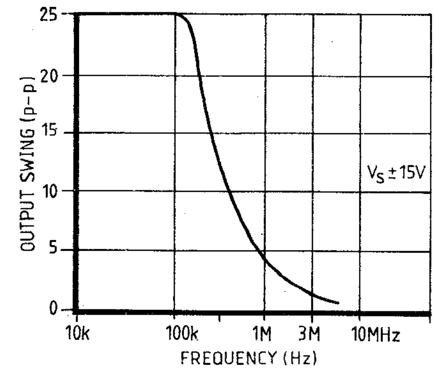


Fig. 4. Output swing plotted against frequency for CA3140.

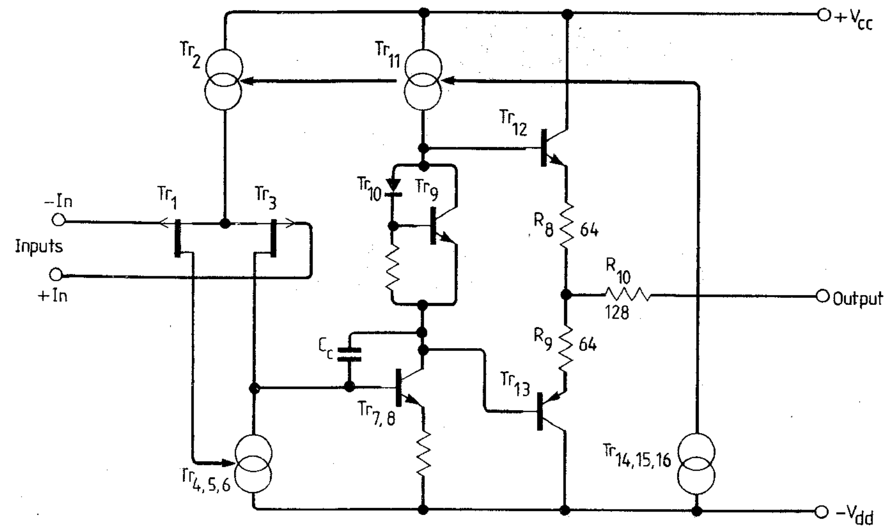


Fig. 5. TL071 in simplified form, showing return to complementary-pair output and apparently rudimentary short-circuit protection.

the input long-tailed pair (Tr_9 and Tr_{10}) and in the load circuit (Tr_3 and Tr_4) of the class-A amplifier transistor (Tr_{13}). This second pair of cascade-connected current sources is used as an ingenious output overload protection device, in that if the current through the output transistor (Tr_{18}) exceeds some 30mA at 25°C (or less at higher temperatures), Tr_{19} will be turned on, and will steal the current from the driver stage.

The maximum current available from the lower half of the output stage ($Tr_{16,15}$) is already limited by the current fed into the two output current-mirrors ($Tr_{15}+D_2$, $Tr_{16}+D_6$ and R_7) from Tr_8 and R_{12}, which is itself fed from a semi-fixed voltage source arranged around the zener diode D_8 and Tr_{20}.

All in all, it is a rather elaborate circuit arrangement, which has always been somewhat expensive to produce and has demanded a relatively large chip size. Nevertheless, the performance of the i.c. is very satisfactory, and it has retained its place in instrumentation use, where its good high-frequency performance, its high input impedance, and its ability to operate over the supply voltage range $\pm 2V$ – $\pm 18V$ has made it a useful circuit component. Characteristic gain/frequency and output swing/frequency graphs are shown in Figs. 3 and 4.

TL071

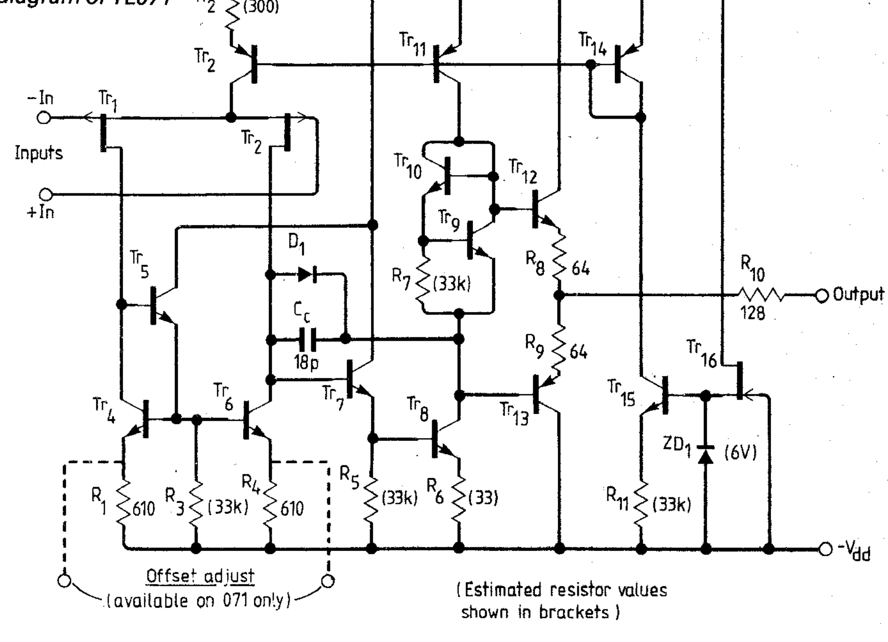
From the point of view of the audio circuit engineer, the remaining requirements which remained to be satisfied in the field of i.c. operational amplifiers were guaranteed low noise and low distortion parameters. These residual requirements were amply met in mid-1977 when Texas Instruments introduced their TL0** series of 'BiFET' devices, based on a combination of bipolar and junction fet technologies, which were now capable of fabrication on the same chip.

Of these, for reasons of personal interests, the one which was most immediately attractive was the TL071, 072, 074 series of single, dual and quad op-amps which are characterized for use in audio circuitry, with a noise specification of $18nV/\sqrt{Hz}$ and a total harmonic distortion, just below clipping, of typically less than 0.01%. In addition, the typical input impedance was still of the order of 10^{12} ohms, and the unity-gain slew rate was typically 13V/μs. The use of junction fet input devices has also allowed a somewhat simpler circuit configuration, shown in its basic form in Fig. 5.

Once again, the circuit architecture is of familiar form, with an input long-tailed pair of p-channel junction fets driving a current mirror to add the signal components of both halves, a single class A amplifier stage (actually a Darlington-pair connected stage), and a complementary pair of n-p-n and p-n-p output transistors biased into class AB1 operation. The only curious feature to the professional op-amp watcher is the apparently complete absence of any formal positive-excursion output short-circuit protection, other than the use of an output resistor, R_{10}, and the adoption of relatively high-value emitter resistors for the output emitter-follower pair. However, the makers claim that such an output short-circuit can be sustained indefinitely.

I have shown the full circuit of the TL071 in Fig. 6, in which there are a few further details not apparent from the simplified diagram. It will be seen that the input circuit load is formed from a more highly developed form of current-mirror $Tr_{4,5,6}$ and $R_{1,3,4}$) than the simple, two-

Fig. 6. Full circuit diagram of TL071



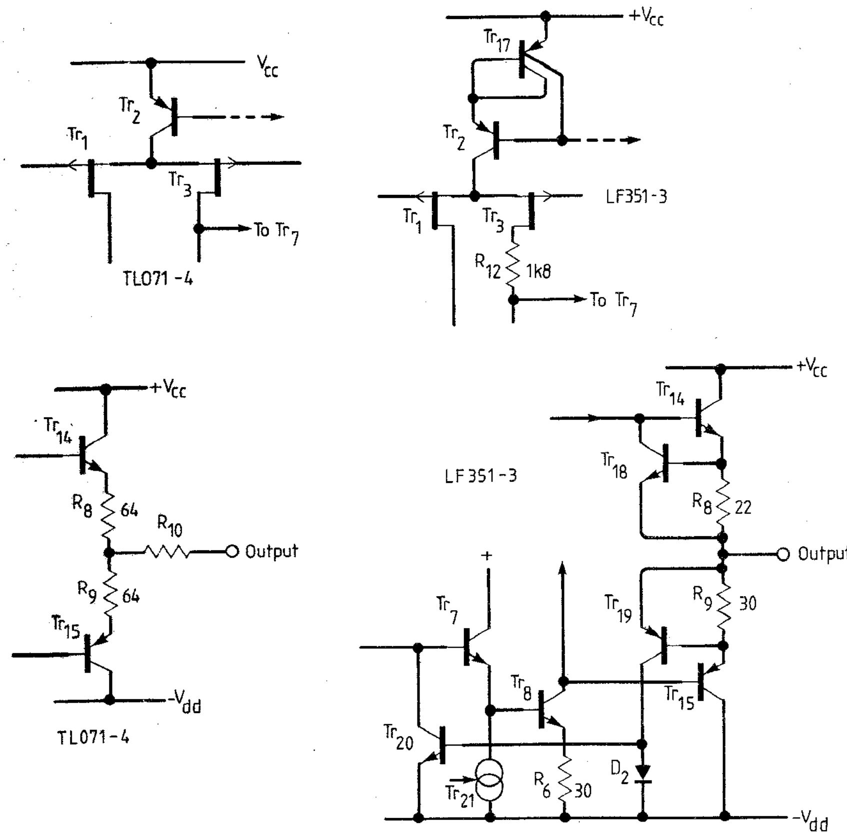


Fig. 7. *Comparison between TL071 and LF351 from National Semiconductor, showing variations in input stage and overload protection.*

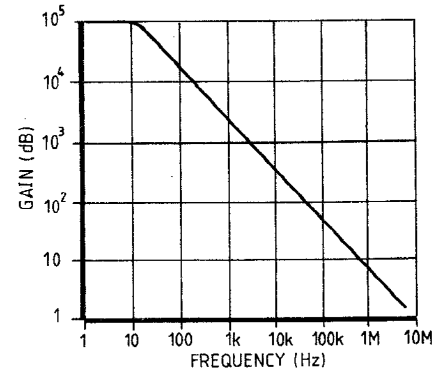


Fig. 8. *Open-loop gain and phase characteristics of TL071-4.*

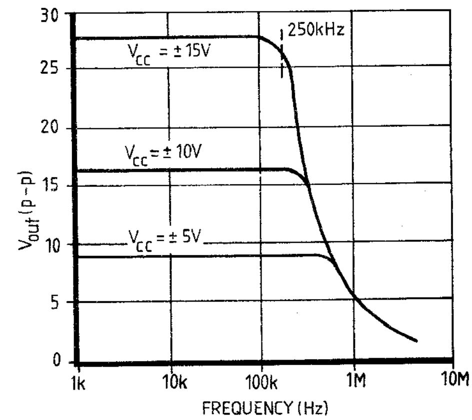


Fig. 9. *Output voltage swing as function of supply voltage and frequency in TL071.*

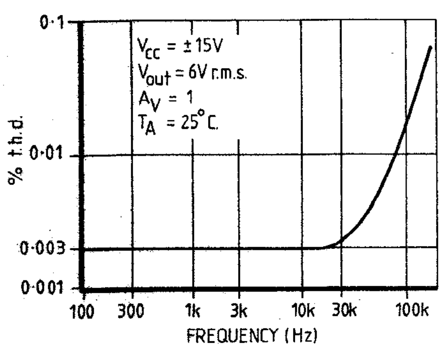


Fig. 10. *Harmonic distortion plotted against frequency.*

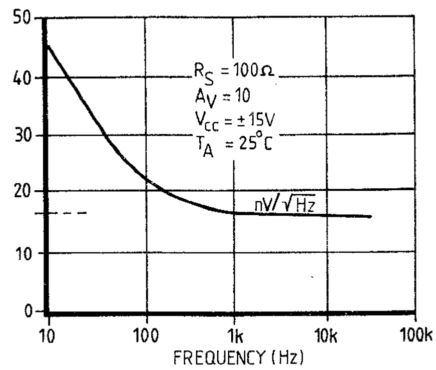


Fig. 11. *Equivalent input noise voltage.*

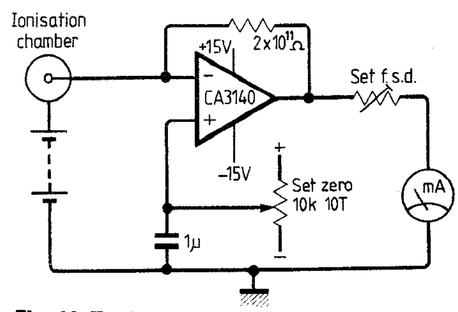
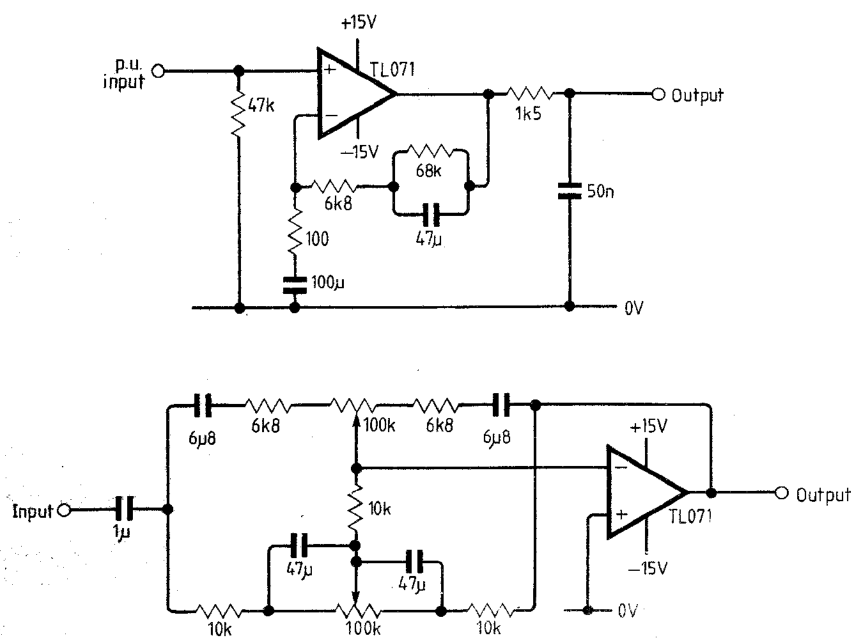


Fig. 12. *Typical application of CA3140 is as ionization chamber amplifier at high impedance.*



transistor circuit employed in the 3140, and a catch-diode is connected across the compensation capacitor (D_1) to bypass the amplifier stages Tr_7 and Tr_8 if Tr_{13} is driven into saturation. This assists in output overload protection, and also speeds up recovery from any swing which drives the circuit into negative line clipping.

Transistors $Tr_{2,11,14}$ form a current-mirror group fed from the constant current source $Tr_{16,15}$,R_{11}, with transistors 2 and 11 acting as the input 'tail' and the class 'A' stage load, respectively. The transistor pair Tr_{10} and Tr_9, are merely a passive biassing network for the output emitter followers, in which Tr_{10} acts simply as a forward-biassed diode. Because of the relatively large proportion of the total (1.5-2mA) quiescent current consumption

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◄ ***Fig. 13.*** *Low noise and low distortion of TL071 make it very useful in small-signal audio circuitry.*

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the vertical signal from the Y amplifier and triggers the sawtooth oscillator if the switch on pin 2 of the 4070 is in the 'Trig' position (closed). In the 'Free Run' position, the sawtooth oscillator runs continuously.

Two exclusive-Or gates form the clipper circuit, the 2.2 MΩ feedback resistor across the two gates preventing the trigger waveform having multiple edges due to noise on the vertical signal. The polarity of the trigger waveform may be inverted by the following ex-Or gate when the switch is in the negative position. The first of the two Nand gates in the feedback path of the sawtooth oscillator is used to inhibit the oscillator when $\overline{Q}$ of the 4013 is logic 0.

With the circuit waiting for a trigger edge, and the switch in the 'Trig' position, logic levels are:
4011 pin 8 – logic 1
4011 pin 9 – logic 0
4011 pin 1 and 2 – logic 1
4011 pin 12 and 13 – logic 1
4070 pin 3 – logic 1
4013 pin 4 – logic 0 (reset is off)
4013 pin 8 – logic 0 (set if off)

When a positive-going trigger edge clocks pin 11 of the 4013, the Q output pin goes to logic 0, the 4011 pin 3 goes to logic 1 and resets the 4013, $\overline{Q}$ pin 2 to a logic 1; this allows the sawtooth oscillator to run. Further trigger waveform edges cannot now inhibit the oscillator until it has reset and the positive-going edge following flyback clocks the 4013 at pin 3. The circuit is then ready to accept a further trigger pulse.

Note that when the sawtooth generator is waiting for a trigger edge, the CA3130, pin 6, is at +12 V (the fet is therefore off) and the 4011 pin 4 is logic 0, so that the current transistor is off. The timing capacitor therefore floats from a starting voltage of +4 V and, depending on the leakage, would gradually drift over a period of tens of seconds. However, this drift has no effect when the circuit is operating normally.

Flyback suppression

This is a.c. coupled to simplify the coupling to the tube grid, which is at about −200V. The pulse amplitude is about 35V negative-going at the collector of the 2N2369. A.c. coupling results in a spot at the left-hand side of the trace when the circuit is waiting to trigger.

Calibration oscillator

The squarewave oscillator generates an accurate 1 kHz squarewave at 1 volt p-p.

Cathode-ray tubes for this design can be obtained from: Colomor (Electronics) Ltd, 170 Goldhawk Road, London W12; Langrex Supplies Ltd, Climax House, Fallsbrook Road, Streatham, London SW16 6ED.

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which is routed through the last class 'A' stage (Tr_8-Tr_{11}), a very high slewing rate (13V/μs) is attained in spite of the relatively large value of C_c. An offset nulling adjustment, for the output d.c. level, is provided on the TL071 only, by which an adjustment may be made with a centre-tapped trimmer potentiometer between the 'offset adjust' pins and the $-V_{dd}$ line.

In spite of the relatively simple circuit layout (for an i.c.) the performance of this device is excellent, and is becoming adopted as the industry standard for low-noise, low-distortion, high-input-impedance amplifiers of this type.

As is fairly typical, the National Semiconductors design engineers have 'second-sourced' this device with their own version (known as the LF351 and LF353 for the single and dual units) incorporating a few design improvements, which I have shown in side-by-side comparison in Fig. 7. Although these design changes allow a somewhat improved published specification, my own tests suggest that the performance differences between the TI and NS units are less than the small random variations between one device and the next, so the performance characteristics for the TL07* devices shown in Figs. 8-11 can be taken as representative of the LF351-353 as well. The basic differences in the circuitry concern the 'tail' of the input stage, and in the output stage overload protection, which is done much more formally in the NS design by the addition of the protection transistors Tr_{18} and Tr_{19}. Because Tr_{19} is a low gain 'lateral' type of device, it is used to rob base current from Tr_7 by way of an additional amplifier transistor Tr_{20}. Other circuit differences between these two types of i.c. are trivial.

As examples of the types of circuit which can be built very satisfactorily using these types of op-amp i.c., I have shown two typical applications in Figs. 12 and 13. In particular, the low noise and very low distortion of the TL07* family makes its use in high quality audio preamplifier systems a very natural development. It is unlikely that developments of such i.cs., in this type of TO99 or DIL package, will rest at this level of performance, and straws in the wind are the Mullard/Signetics NE5532-5534 series and the Precision Monolithics OP-27, which have noise figures in the range 3-5nV/√Hz, though as yet, only with relatively low input impedance characteristics. WW

Next month

Modular preamplifier. John Linsley Hood begins his description of a new, modular preamplifier, designed for use with the 100W power amplifier recently featured. Among its features are a noise-blanker stage to minimize scratch 'clicks', a push-button, eight-octave tone-control, a four-input mixer, a rumble filter with a 22dB/octave cut and a signal-strength meter.

Electronic compass. This is a 'no-moving part' design, by Neil Pollock which uses a flux-gate sensor, the construction of which is described. The output of the sensor can be processed by a microprocessor to provide a numerical display, or the hard-wired circuit shown in the article can be used.

Low-frequency oscillator. A sine-plus-square oscillator, working in the 10-Hz to 250KHz range, which provides a tone-burst output for loudspeaker testing. There is octave switching and a RIAA pre-emphasis network, and the instrument is built in the modular manner.

On sale Sept 15.