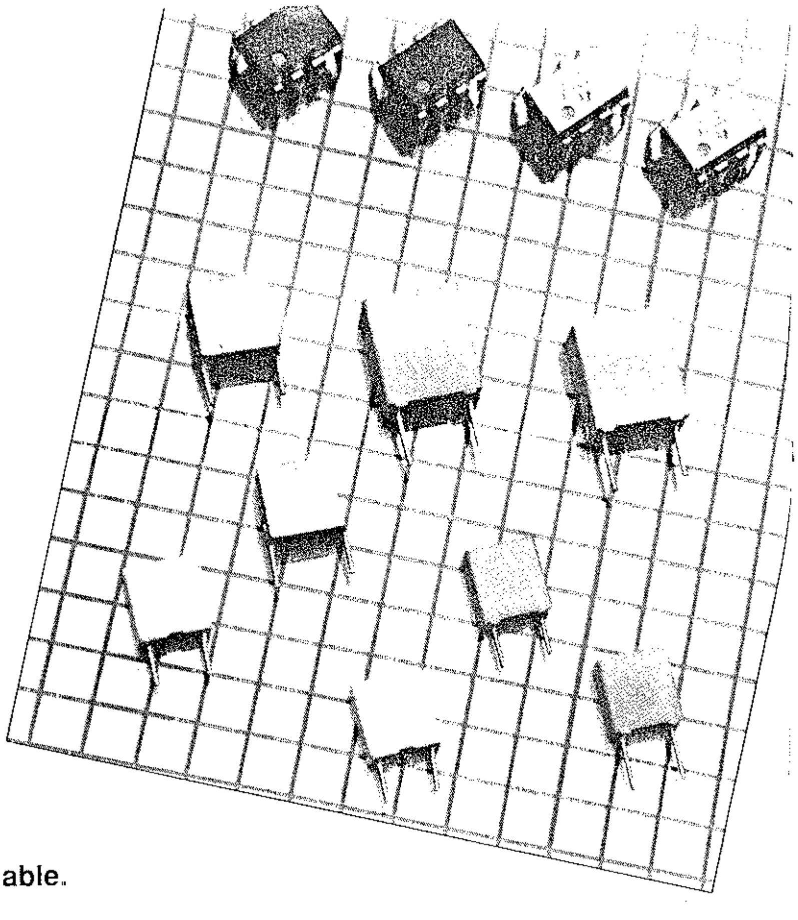
CHOPPER-STABILIZED OPERATIONAL AMPLIFIERS

Chopper-stabilized opamps are in many cases the only feasible alternative when we want to amplify very small direct voltages. In this article we will explore why chopper opamps have such excellent d.c. characteristics. A theoretical background to the operation of interesting new devices is given, followed by a discussion of some inherent problems (and, of course, proposed solutions). The article is closed off with an overview of the most popular chopper opamps currently available.



by J. Ruffell, with contributions from B. Marshall (Texas Instruments) and G.J. van Os (Acal Auriema)

FOR a long time to come instrumentation amplifiers will be required to operate at the highest possible accuracy. This expectation is based on the trend towards ever higher resolution of DACs (digital-to-analogue converters) and ADCs (analogue-to-digital converters). It will be clear that high resolution in a measurement is not achieved just by the use of converters with a high resolution. After all, it makes little sense to perform a measurement at an accuracy of 18 bits when the analogue amplifier used has a maximum resolution of, say, 16 bits. In practice, the accuracy of the hardware for analogue signal conditioning must be doubled for every additional bit to be measured.

Analogue signals are preferably conditioned and/or amplified by a.c.-coupled circuits, mainly because these can be built by relatively simple means and at low cost. There are, however, many applications where the wanted signal is applied in the form of a direct voltage or a direct current. Devices used in such applications include thermocouples, photodiodes and, on a larger scale, the digital multimeter, which is an example of a data acquisition system. Since these devices and circuits can only be d.c. coupled, the designer is faced with off-set voltages and drift of the linear amplifier he intends to use. The origins of input off-set voltages and their stability is discussed in an earlier article on new opamps, see Ref. 1.

Although conventional operational amplifiers such as the OP07 and the OP77 are good choices for d.c. signal conditioning, there are devices whose extremely low drift and off-set voltage make them far better suited to the application. The type of operational amplifier we have in mind is generally referred to as a chopper opamp or, more accurately, a chopper-stabilized opamp.

Chopping: the classic approach

During the valve era, the terms chopper amplifier and indirect d.c. amplifier were familiar to almost anybody in the field of electronics. At that time, chopping was taken very literally. A kind of electronic guillotine was used to convert the low-frequency alternating voltage (or the direct voltage) to be amplified, into a signal with a higher frequency. Next, this 'high-frequency' signal was raised in an a.c. coupled amplifier, and subsequently restored to its original frequency by a synchronous detector. In practice, the chopping element used to be a relay or, a little later, a bipolar transistor or a FET.

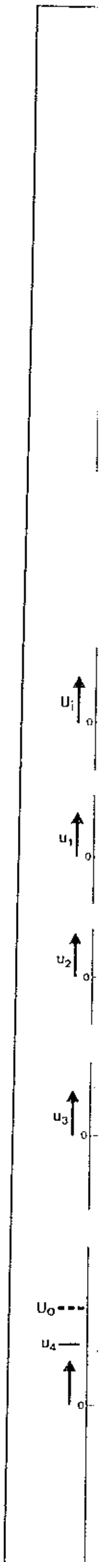
Figures 1a and 1b show the basic schematic of a classic chopper amplifier and the associated waveforms. The input voltage, U_i, is converted to a pulsating waveform, u_1, by switch S_1. The d.c. component is removed before u_2 is amplified by a.c. coupled amplifier A_1. It will be clear that the original waveform (with a higher amplitude) must be recovered from u_3. The recovering, or demodulation, of u_3 is effected by switch S_2. This electronically operated switch connects the right-hand side of capacitor C_2 to ground on every second half-cycle of the oscillator signal. The waveform of u_4 indicates that the switching results in a shift of the direct voltage level. Finally, an integrating filter recovers the amplified voltage, U_o, from u_4.

Although this type of amplifier allows good drift specifications to be achieved, it suffers from a number of inherent shortcomings. The chopper, for instance, often introduces glitches at the output. Also, the amplifier lacks a differential output, while its bandwidth is limited to a few hundred hertz.

Integrated

Modern chopper opamps no longer work as described above. These days, the signal to be amplified is no longer chopped to pieces and then rebuilt. Instead, use is made of a control loop which compensates the input off-set voltage of a normal differential amplifier. As a result, these new circuits look quite similar to the standard opamps you have grown accustomed to in many circuits in this magazine.

Chopper opamps, like standard opamps, have a differential input circuit. Because of this likeness, and because their principle of operation is based on the old chopper model, the new devices are generally called chop



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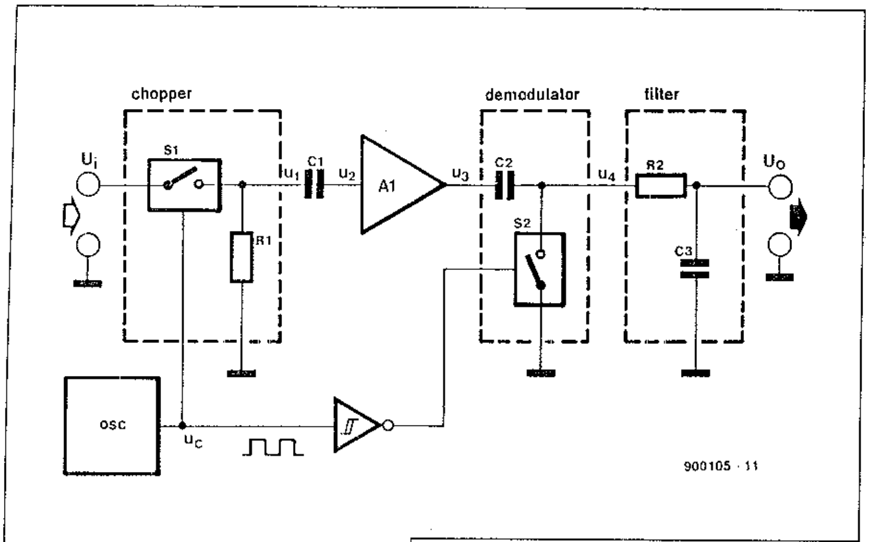


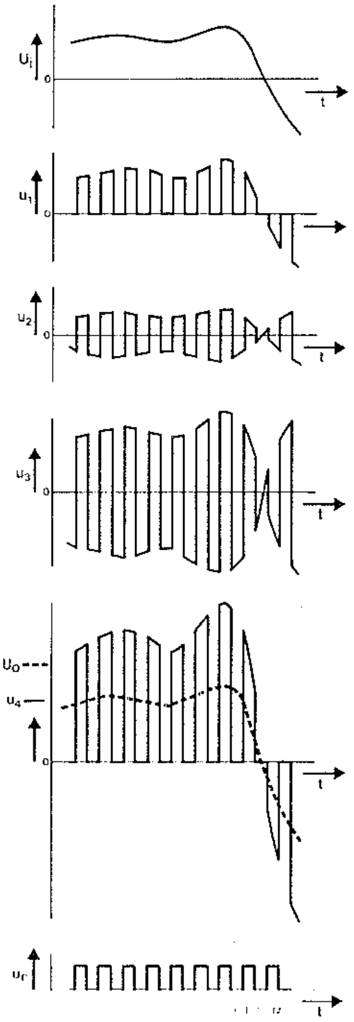


Fig 1 Schematic diagram of a classic chopper amplifier (1a), and the waveforms pertaining to this type of circuit (1b)

per-stabilized operational amplifiers, or chopper opamps. A typical application circuit of a chopper opamp is shown in Fig 2

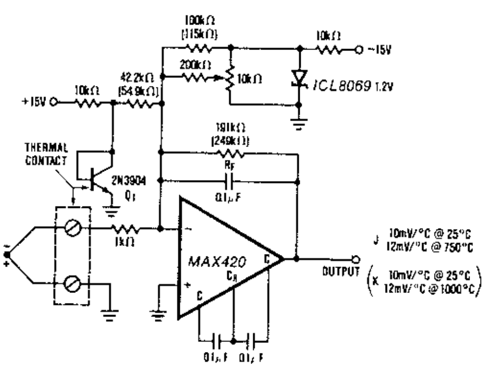
Automatic off-set compensation

The off-set compensation control applied with chopper opamps is in many ways similar to a technique used to compensate the input off-set voltage U_{OS} of a standard opamp This technique entails off-set compensation by fitting a voltage source that supplies $-U_{OS}$ in series with the non-inverting input of the opamp (see Figs 3 and 4). Automatic input off-set voltage compensation thus requires a circuit capable of measuring U_{OS}, and supplying an accurate 'negative copy' $-U_{OS}$, at the non-inverting input

You may start wondering at this point how U_{OS} can be measured when the opamp is already part of an existing circuit Assuming that a simple electronic circuit is used it can be shown that the input off-set voltage is best measured between the input terminals of the opamp in question Figure 5 shows how this is done in an inverting amplifier set up around the ideal opamp model Equation 1 describes the voltage between the non-inverting and the inverting input of the opamp True, the equation looks fairly complex However assuming for the moment that U_i does not contain an alternating voltage component, you will easily discover that the expression in equation 1 is virtually equal to $-U_{OS}$ This is because the open-loop gain A_{OL} is high (say 100 000) so that E (see equation 2) approaches 1 The upshot is that equation 1 can be simplified to give equation 3 The output voltage is approximated as described by equation 4

The schematic in Fig 6 shows a circuit designed on the basis of the above discussion. An auxiliary amplifier is used to measure and compensate the input off-set voltage of the main opamp Equation 5 which describes the output voltage indicates that the effect of the input off-set voltage is reduced by a factor of $1-E$. Assuming an open-loop gain of 100,000, and $R_1 = R_2$, the reduction amounts to no less than 50,000 times Compared to the off-set error of about $2U_{OS}$ in the output signal of the circuit in Fig. 5, a specification of the order of $1/25{,}000U_{OS}$ is quite impressive for the circuit in Fig 6 Thus equation 6 may be applied with confidence for d c applications

It should be noted that the off-set of the opamp can only be compensated successfully if the auxiliary amplifier is sufficiently compensated This is why we have shown the auxiliary amplifier as an ideal device, i.e an opamp without input off-set It will be clear that such a device does not exist And yet the circuit can be extended in a way that does allow automatic off-set compensation to be achieved Basically the auxiliary am-



Note 1: Q_1 and connection terminals must be at the same temperature
Note 2: Values in parentheses are for type K thermocouple
Note 3: Connections to inverting input of op-amp should be kept as short as possible to reduce noise pickup
Note 4: All circuit power is ±15V

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Fig 2 Typical application of a chopper-stabilized opamp in a thermocouple amplifier with cold-junction compensation (illustration courtesy Maxim)

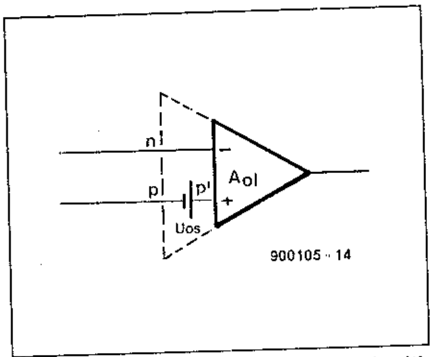

Fig 3 Operational amplifier model with input off-set voltage U_{os}

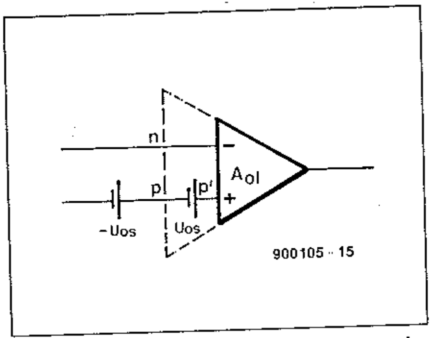

Fig 4 The input off-set voltage may be compensated by placing a voltage source $-U_{os}$ in series with the non-inverting input.

$$(u_p - u_n) = -\frac{(1-E)\,R_2}{R_1 + R_2}\,u_i + E\,U_{os} \qquad \text{Eq [1]}$$

$$E = \frac{1}{1 + \frac{R_1 + R_2}{A_{ol}\,R_1}} \qquad \text{Eq [2]}$$

$$(u_p - u_n) \approx -U_{os} \qquad [A_{ol} \to \infty] \qquad \text{Eq [3]}$$

$$u_o = E\left\{\left(1 + \frac{R_2}{R_1}\right)U_{os} - \frac{R_2}{R_1}\,u_i\right\} \qquad \text{Eq [4]}$$

$$u_o = E\left\{\left(1 + \frac{R_2}{R_1}\right)(1-E)\,U_{os} - \frac{R_2}{R_1}\,(2-E)\,u_i\right\} \qquad \text{Eq [5]}$$

$$u_o \approx -\frac{R_2}{R_1}\,u_i \qquad [A_{ol} \to \infty] \qquad \text{Eq [6]}$$

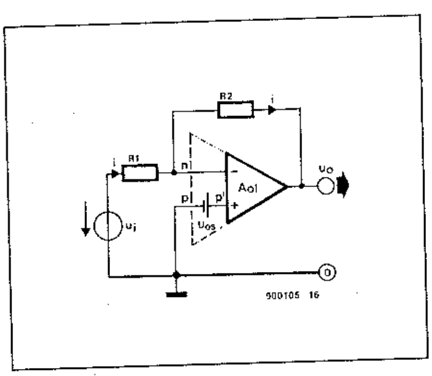

Fig. 5. This basic circuit allows us to prove, by calculation, that the voltage difference between the inverting and the non-inverting input of the opamp is practically equal to $-U_{os}$ if u_i does not contain an alternating voltage component.

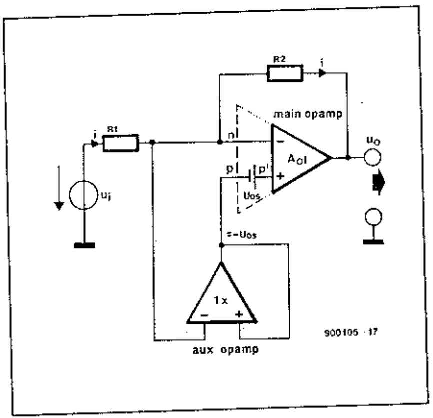

Fig 6 First design of a control circuit for automatic compensation of the off-set voltage

plifier must measure and compensate its own input off-set voltage before handling the off-set of the main opamp The necessary extensions are shown schematically in Fig. 7.

Off-set compensation thus consists of two successive phases During the first phase. the electronic switch S_1 is set to position A This causes the inputs of the auxiliary opamp to be short-circuited so that the output voltage of this amplifier is virtually equal to its own input off-set voltage. U_{os1} Just before S_1 switches to position B a sample-and-hold circuit S&H-1. connects U_{os1} in series with the inverting input of the auxiliary amplifier This results in compensation of the off-set error of this amplifier at the start of the second phase During the second phase. S_1 connects the positive input of the auxiliary amplifier to the positive input of the main opamp. This. in fact. creates the circuit in Fig 6 The sample-and-hold circuit still compensates the off-set of the auxiliary amplifier whose output is at a potential of practically $-U_{os2}$ To retain this voltage a second sample-and-hold. S&H-2. is introduced As shown in Fig 7 this causes $-U_{os2}$ to be connected in series with the non-inverting input of the main opamp At least in theory the result is as may be expected: the input off-set voltage is automatically compensated

The off-set compensation of the two amplifiers may be optimized by repeating the two phases Depending on the repeat rate input off-set drift as a result of temperature changes or supply voltage fluctuations may be eliminated. preventing these factors from affecting the stability of the instrumentation amplifier

Main amps and null amps

The above information will no doubt. enable you to take a well-prepared look at the block schematic diagram of a chopper-stabilized opamp The functional diagram used by most manufacturers is shown in Fig 8 The term main amp refers to the main operational amplifier. while the term null amp is meant to identify the auxiliary amplifier The switches and the oscillator should not surprise you by now The two sample-and-hold circuits are not so easily discovered because they appear in the form of two capacitors. C_A and C_B The only new blocks are a clamping circuit and a circuit to suppress intermodulation These two sub-circuits are of vital importance to a good chopper opamp and their function will therefore be reverted to a little further on in this article

During the first phase also called the clock phase the null amp compensates itself Switch S_1 is closed and short-circuits the amplifier inputs The output voltage is stored in external capacitor C_A via switch S_{1a}. Since there is no input signal, the voltage on C_A is equal to the input off-set voltage of the null amp Furthermore. the capacitor voltage is fed back to an additional inverting input. so that the off-set error of the null amp is eliminated During the second period of the clock signal. switch S_2 is closed. and S_1 is open The null amp then measures the input off-set voltage of the main opamp and stores it in capacitor C_B At the same time. the measured voltage is applied to the non-inverting input of the main amp so that the input off-set voltage is compensated Thus the system compensates U_{os} of both amplifiers at the rate of the clock- or chopper-frequency. f_c

It will be noted that the chopping operation is effected only by the main opamp The glitches mentioned at the close of the section on the classic chopping amplifier are virtually absent with chopper opamps because the amplified signal is always passed via the continuously operating main opamp.

Recovery time

The decision to use chopper opamps in a practical circuit instead of standard opamps may lead to some surprising problems First chopper opamps typically require a much longer time to recover from an overdrive condition. which may occur for instance when the output circuit is driven into saturation. Saturation occurs readily and is perfectly normal in, for instance, a comparator circuit.

After an overdrive condition, the main amp no longer works as a linear amplifier. As a result, the voltage difference between the inverting and the non-inverting input is large relative to U_{OS}. The auxiliary opamp responds to this condition by charging the two capacitors C_A and C_B to the maximum level, i.e., the supply voltage. Inevitably, the main opamp requires some time to remove these capacitor charges when the overdrive condition is passed. In the datasheets, the discharge time is referred to as the overload recovery time. For a conventional opamp this time is about 10 µs. A chopper opamp, however, may need up to 4 s to recover

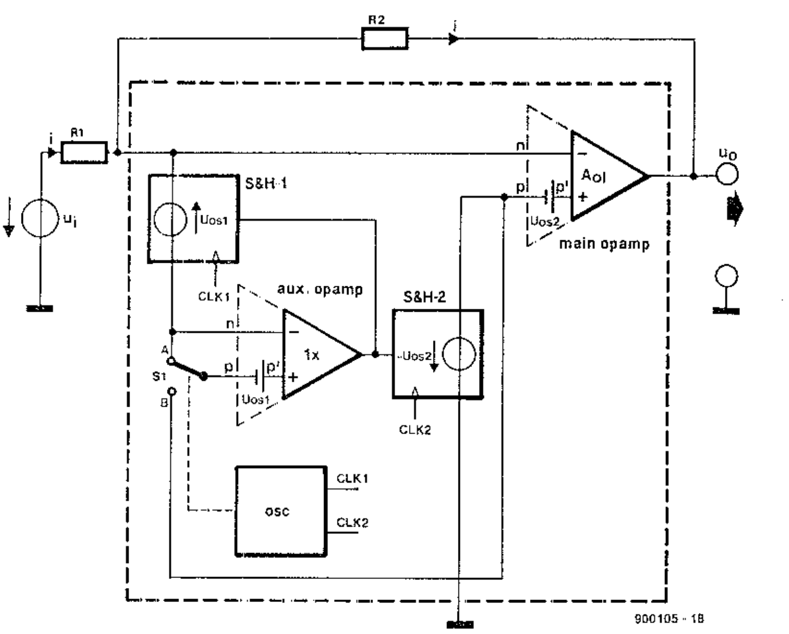

Fig. 7 In this circuit, the input off-set of the main opamp is automatically compensated during two phases of the clock signal

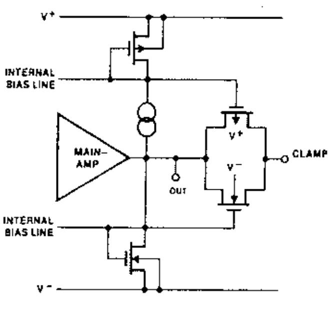

Fig. 9 This clamp circuit reduces the overload recovery time of the ICL7650.

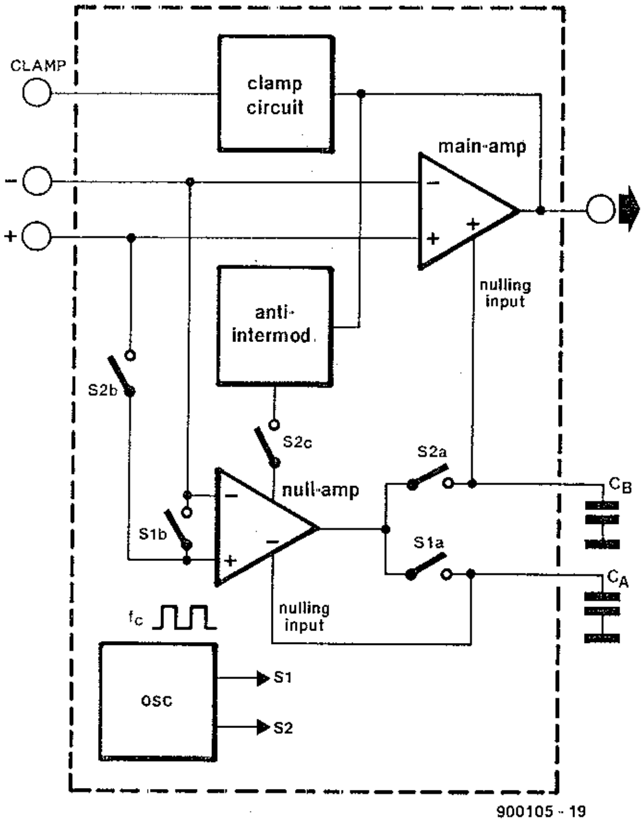

Fig. 8 Typical block diagram of a chopper-stabilized operational amplifier

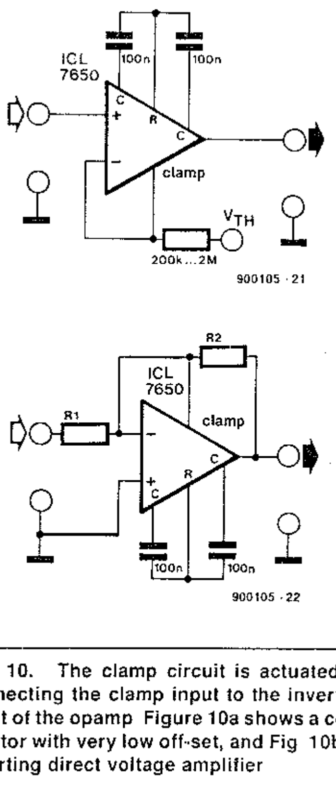

Fig. 10. The clamp circuit is actuated by connecting the clamp input to the inverting input of the opamp. Figure 10a shows a comparator with very low off-set, and Fig. 10b an inverting direct voltage amplifier

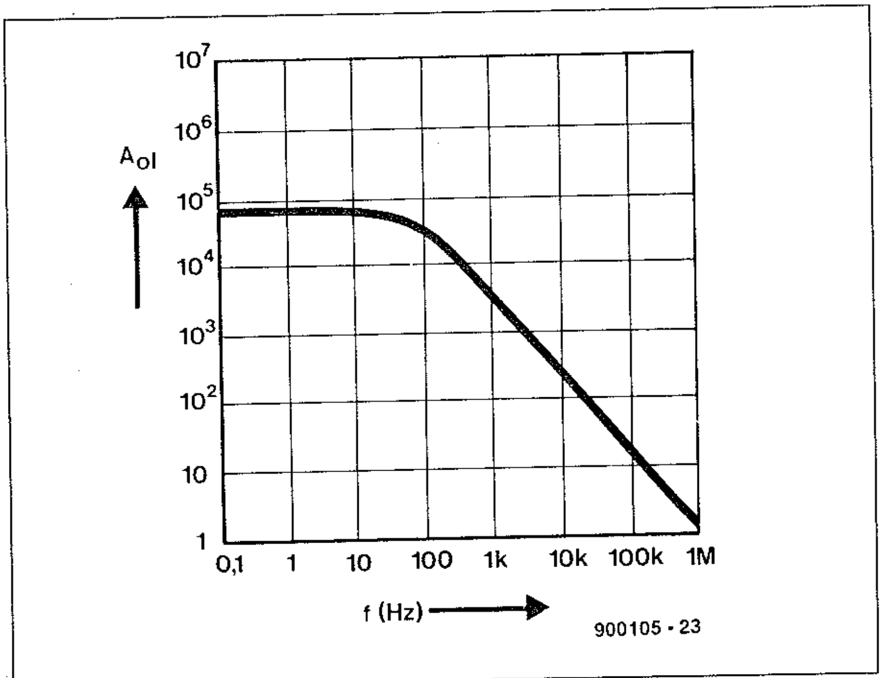

Fig. 11. Open-loop gain, A_{ol}, as a function of frequency.

The clamp circuit provided in the latest chopper opamps serves to reduce the recovery time The ICL7650 manufactured by Maxim and Teledyne for instance has a recovery time of only 300 ms The clamp circuit used in this chip is shown in Fig. 9. The circuit is actuated by connecting the clamp terminal to the inverting input of the amplifier Figure 10 shows two circuits that make use of this option

The clamp circuit is really quite simple, and consists of a mere switch that closes automatically when the output voltage is too close to the supply voltage When that happens the switch shunts the externally connected feedback resistor so that the amplification is reduced. The clamp thus effectively prevents the amplifier being driven into saturation. The very latest chopper opamps have an additional circuit that limits the voltage across the sample-and-hold capacitors. The result is an even shorter recovery time—Texas Instruments' TLC2652 for instance, has a recovery time of only 40 ms

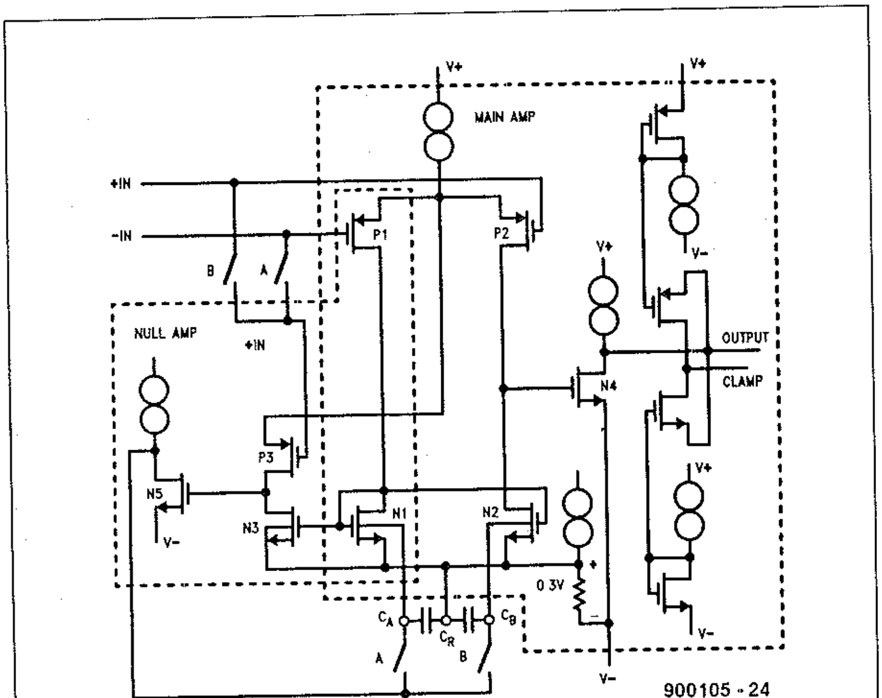

Fig 12 Simplified internal diagram of the LMC688.

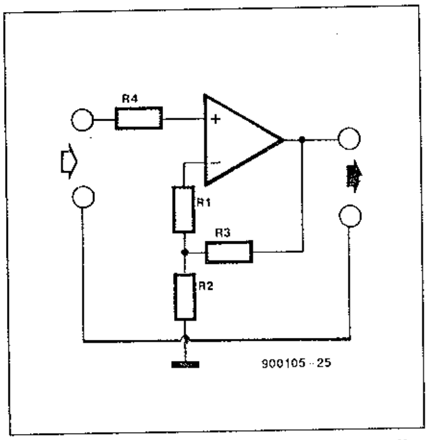

Fig. 13. Resistor R4 is normally superfluous, but it is fitted here to ensure a thermal balance at the input of the circuit.

Next problem: intermodulation

A further problem with chopper opamps may not be noticed until you are dealing with alternating voltages Unfortunately, an alternating input voltage may cause unwanted sum and difference frequencies because it is mixed with the clock signal The cause of this annoying effect called intermodulation, can be traced back to the fact that the voltage between the inverting and the non-inverting inputs of the opamp corresponds closely to the off-set voltage It should be noted, however that this is valid for direct voltages only when the main opamp has a very high open loop gain and equation 1 may be replaced by equation 3. As soon as an alternating voltage is applied to the opamp, the open-loop gain drops rapidly, as shown by the graph in Fig 11

Equation 1 allows us to deduce that the limited value of A_{ol} in (u_p–u_n) also includes a part of the input signal:

$$\frac{(1-L)\,R_2}{R_1+R_2}\,u_i$$

Furthermore this part increases with frequency since variable L deviates more and

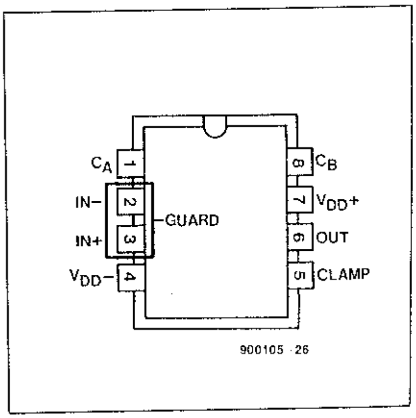

Fig 14. Leakage currents may be kept to a minimum by providing a guard area around the opamp inputs.

Table 1. Electrical specifications at T = 25 °C

TYPE	U_{os} (µV) max.	dU_{os}/dT (nV/K) typ	INPUT BIAS (pA) typ	NOISE(1) (mV_{pp}) typ.	SUPPLY CURRENT (mA) typ	SUPPLY VOLTAGE(3) (V) max.
ICL7650	5	100	1.5	2.0	2.0	18
TLC2652C	3	3	4	2.8	1.5	16
TLC2654C	20	4	50	1.5	1.5	16
LMC668	10	50	20	2.0	2.5	18
MAX420C	10	20	10	1.1	1.3	36
TSC900BC	15	100	80	4.0	0.2	18
LTC1049C	10	20	15	3.0	0.2	18
LM741C	6000	5000	80 000	—	1.7	36
OP177B	55	100	2400	0.33(2)	2.0	44

Notes: (1) 0 – 10 Hz (2) 1 – 100 Hz (3) V+ to V−

Table 1. Overview of the most popular chopper opamps, and their main technical characteristics. The 741 and the OP177B are not choppers — they are included here for reference.

more from the ideal value of 1 when the open-loop gain becomes smaller (see equation 2). Hence, this alternating voltage component appears also at the output of the auxiliary amplifier and at the input of S&H-2 (see Fig. 7). These components are generated as a result of the sampling operation, which causes sum and difference frequencies. To prevent these frequencies rising to an unacceptably high level in the output signal, the chip contains a special suppressor circuit. As shown in Fig. 8, the anti-intermodulation circuit injects a compensation signal into the null amp. This also results in additional suppression of harmonics of the chopper frequency.

Unfortunately, the suppressor circuit is not capable of resolving all problems. When the input frequency approaches the chopper frequency, a low-frequency beat signal is generated. This component is inevitably treated as off-set during the nulling of the main amp, and thus causes a complete disruption of the chopper amplifier. This annoying problem may be solved to a large extent by using a chopper frequency which is at least twice as high as the highest anticipated frequency in the amplified signal.

In many applications that rely on high d.c. accuracy (e.g. thermocouples) the bandwidth of the input signal is no more than a few hertz. It will be clear that such low frequencies prevent interference problems with the chopper frequency beforehand. In a number of cases, however, the signal bandwidth will have to be limited by a low-pass filter. When it is not possible, for whatever reason, to limit the bandwidth, the designer still has the possibility to apply another chopper amplifier rated for a higher clock frequency. The ICL7650, for instance, 'chops' at 200 Hz, the LMC688 (National Semiconductor) at 400 Hz, the TLC2652 at 450 Hz, and the TLC2654 at 10 kHz. In some cases, it is possible to apply an externally generated clock signal to the chip.

Practical notes

Chopper-stabilized opamps usually have the same pinning as standard types. This allows them to be used as upgrades in existing circuits, replacing opamps with worse d.c. specifications. The only components to be added are the two external capacitors, C_A and C_B. This is not required, however, with some amplifiers. The LTC1049 and LTC1050 from Linear Technology, for instance, have on-chip capacitors. Unfortunately, production techniques limit the maximum capacitance of such integrated capacitors to about 450 pF, which gives these opamps a low performance in regard to noise. The usual values of the external capacitors lie between 0.1 µF and 1.0 µF. In al cases, high-grade capacitors are required to bring out the specific qualities of a chopper opamp. Film capacitors like polystyrene and polypropylene types are well worth using.

Unfortunately, the use of high-grade capacitors is no guarantee that a d.c. amplifier is obtained with a small off-set and a low drift. There is another factor, which has not been mentioned so far: thermovoltages. Thermovoltages occur where two different metals are in contact. As indicated by the name of the phenomenon, the voltage is temperature-dependent. In practice, a thermovoltage readily amounts to a few microvolt per kelvin. The average drift of a good chopper-stabilized opamp is of the order of 10 nV/K. However, this value is not usually achievable in a practical amplifier without paying attention to thermoelectric effects in and around the circuit. Components which form connections without soldering, such as switches, relays and connectors, must not be used in the input circuit. Where parts are soldered, it is best to use solder tin with a low thermoelectric specification, such as a tin-cadmium alloy. Errors brought about by thermoelectric effects may also be kept to a minimum by arranging a symmetrical circuit at the opamp inputs. The most sensitive part of the amplifier is thermally balanced by using the same components in the two branches (even if they are really superfluous for the function of the circuit, see Fig. 13), and by forcing an equal number of solder joints. Furthermore, temperature differences as a result of, say, ventilation or power dissipation, must be kept as small as possible.

Guard !

An additional advantage of chopper-stabilized opamps is the extremely low input currents. The TLC2652, for instance, has an average input bias current of 4 pA at an ambient temperature of 25 °C. In practice, however, little use is made of this characteristic because the external leakage currents are much higher. Nonetheless, these leakage currents are fairly easily kept in check. The necessary measures may already be taken during the printed-circuit board design phase. For instance, the solder spots near the inverting and the non-inverting inputs of the opamp can be surrounded by a screening copper area, called a guard. The principle is illustrated in Fig. 14. It is desirable that the guard be held at about the same potential as the inputs of the opamp. Thus, the guard is connected to ground in an inverting circuit, and connected to the −input of the opamp in a non-inverting circuit. It will be clear that guards must be provided at both sides of the PCB. Finally, the PCB is cleaned with alcohol before fitting the components.

The differences

From the above discussion you will have gathered that there are many types of chopper opamps available. A selection of the most popular types, along with their main specifications, may be found in Table 1. The good old 741 opamp, which is *not* a chopper, is also included for your amusement. The OP177B at the end of the list represents the latest in bipolar technology, and is a competitive alternative to chopper opamps, according to the manufacturer, PMI.

Finally, a word of warning to those of you who want to start immediately replacing standard opamps by chopper types: as yet, these devices are quite expensive (expect to pay around £10 per amplifier) and difficult to obtain as one-offs. ■

Reference:

1. "Introducing OP-series opamps", *Elektor Electronics* February 1990.