Operational Amplifiers

6.0 The Ideal Amplifier

What you'll learn in Module 6.

The Ideal Amplifier

In amplifier modules 1 to 5 voltage and power amplifiers are described in some detail so that the circuit elements that go into making an amplifier can be understood. Each of these circuit elements, such as negative and positive feedback, impedance, linearity, gain and efficiency are used with the aim of improving the amplifier's performance towards the goal of making the ideal amplifier. The bad news is that the ideal amplifier does not exist, but the good news is that the op amp does!

The ideal amplifier should:

- Have an infinitely wide bandwidth.

- Have an infinitely high gain available that can be easily controlled.

- Be ideally linear, with no distortion.

- Generate no noise (have an infinitely high signal to noise ratio).

- Be easily convertible to perform different amplifier functions.

- Be cheap.

All of the above is what the op-amp does, or at least comes pretty close to.

Early Op amps

Amplifiers with gain controlled by negative feedback were first thought of in the 1930s as a way of creating amplifiers for the telephone system that could have a controllable and reliable gain, but became operational amplifiers when they were adopted by designers of analogue computers, because of their ability to perform accurate mathematical operations, such as adding, subtracting, integration and differentiation.

Op amp ICs

Operational amplifiers can still built from discrete components but with the introduction of silicon planar technologies and integrated circuits their performance improved and both size and cost reduced dramatically, and although computing has practically all moved from analogue circuitry to digital, the op amp had become so useful in so many circuits that deal with real (analogue) quantities such as sound, light, heat and motion, that the op amp is now a widely varied and indispensable part of electronics equipment.

This module will discuss the basic properties of op amps and comparators, and how their integrated circuit versions can be manipulated to make simple circuits that provide so many vital functions in electronics.

Module 6.1

Op Amp Inputs

What you'll learn in Module 6.1

After studying this section, you should be able to:

Recognise typical forms of op amp circuit symbols.

Understand the need for single & dual power supplies.

Understand typical operating requirements.

• High gain & negative Feedback.

• Differential inputs.

• Constant current sourcing.

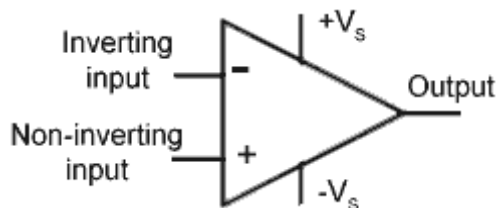• Common Mode Rejection, CMRR.

• Offset null.

Fig. 6.1.1 Op Amp Circuit Symbol

Op Amp Circuit Symbol

The circuit symbol for an op amp is basically the standard triangle symbol for an amplifier. Main connections such as the inverting ($-$) and non-inverting inputs and the output are shown, but often, other connections are not. A typical op amp symbol is shown in Fig. 6.1.1. Note however, that many circuit diagrams do not show the DC supply connections.

Dual Power Supplies

An op amp needs a minimum of five connections as shown in Fig 6.1.1; as well as the two inputs and one output there are two power supply connections. These may be labelled +Vs and -Vs indicating that the IC needs both positive and negative supplies. These will often be in the range of +5V to +15V for the positive supply and -5V to -15V for the negative supply. This dual supply arrangement allows for the output voltage to swing both above and below zero volts, and also gives an output of 0V when there is no voltage difference between the two inputs.

Single Supply Op Amps

A growing number of op amps are available however, that use a single supply, labelled +V and Gnd or 0V. This is a useful arrangement for many portable and mobile applications where dual positive and negative supplies are not readily available, for example in automobile applications.

High Gain Negative Feedback DC Amplifier

Op amps are basically negative feedback (NFB) DC amplifiers. The op amp has a very large gain, the output can be hundreds of thousands times larger than the input. This huge gain however, is reduced using negative feedback to produce a circuit whose gain is stable and independent of the semiconductor characteristics.

Op amps are also always DC coupled, unlike an amplifier using discrete components where it is possible to include AC components such as capacitors and inductors, in a tiny integrated circuit it is not possible to fabricate AC components large enough to be useful at audio frequencies, therefore an op amp MUST be a DC amplifier.

One advantage of using DC (directly coupled or direct current) amplifiers is that their bandwidth extends right down to 0Hz, making them suitable for many control and measurement applications where the op amp's ability to produce a DC output, relative to the difference between two DC input quantities is extremely valuable. The problem with directly coupled amplifiers however, is their tendency to drift. That is for the DC voltages present in the circuit to change, especially with changes in temperature. Because the op amp has a very high gain, it only takes a tiny change in voltage at the input to produce a large voltage change at the output. Because of this, op amp input circuits are designed around a differential amplifier, also called an emitter-coupled amplifier or a long tailed pair, which provides the op amps two (inverting and non-inverting) inputs and also has the ability to cancel out voltage drift.

Difference Amplifier

The Op amp's basic operation is that of a difference amplifier, producing a voltage output that is proportional to the voltage difference at its two inputs. These inputs, labelled - (the inverting input) and + (the non-inverting input) form the inputs of an emitter coupled amplifier, a basic example of which is shown in Fig. 6.1.2, it consists of a pair of matched transistors Tr1 and Tr2, which share the same emitter resistor R_E. Suppose that one of the inputs (b) is held at a fixed voltage, provides a suitable bias for Tr2 base. If a signal is now applied to input (a), each time the signal voltage rises Tr1 conduction increases, its collector voltage falls and its emitter voltage (the voltage across the shared R_E) rises. This rise also

Fig.6.1.2 Emitter Coupled Amplifier

causes a rise in the emitter voltage of Tr2. As the base of Tr2 is fixed, the base-emitter voltage (V_{BE}) of Tr2 decreases and reduces the current through Tr2. This causes a fall in voltage at Tr2 collector making the signal at output C in anti-phase to the output at D.
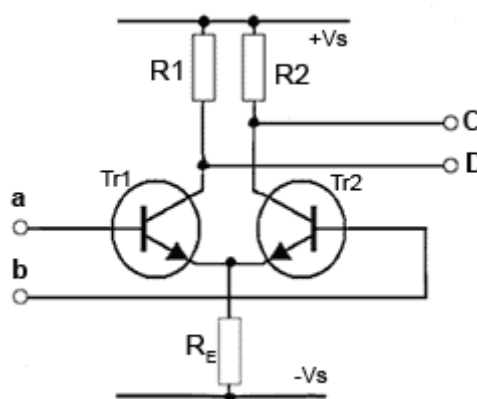
Provided that the transistors are ideally matched, and there are no other factors to cause differences between the conduction in each half of the circuit, the rise in current due to Tr1 conducting is cancelled out by the fall in current through Tr2, and the voltage across R_E should not change. In practice the change would only be a few millivolts.

Common Mode Signals

If two identical signals are applied to each input, two possibilities may be considered:

1. The signals at each input are identical and in anti-phase with each other.

2. The signals at each input are identical and in phase with each other.

Condition 1 is called a differential input as there is a difference produced by the anti7#45;phase signals. In this case the two amplified signals produced at the two outputs will be an amplified difference between the two signals, but as the output signals are in anti-phase with each other, as on signal voltage rises the other signal voltage falls and the resulting signal between outputs C and D will be twice the amplitude of either single output.

Condition 2 has both input signals in phase and so is called a common mode input. The outputs C and D are also in phase, both rising and falling together. Therefore the difference between outputs C and D is zero. The differential amplifier therefore can be said to amplify a differential input, but to reject, or to be immune to, a common mode input. This ideal rejection of common mode signals does not quite occur in practice as there are bound to be some slight differences between the gains

between each of the two inputs and their respective outputs, even when, in an integrated circuit they are fabricated on the same piece of silicon. However, common mode signals that cause both Tr1 and Tr2 emitter currents to rise and fall in unison, this will set up changing voltage across the shared emitter resistor R_E and because there is no decoupling across R_E negative feedback will occur, causing the common mode gain of the amplifier to be reduced. This common mode feedback can be used to improve common mode rejection if a large value for R_E is used.

Constant Current Source

Rather than relying solely on the negative feedback produced by R_E to improve common mode rejection in integrated circuits, most op amp ICs replace R_E in the emitter coupled amplifier with a constant current source as shown in Fig. 6.1.3. This circuit is much more efficient at preventing variations in the shared emitter current of Tr1 and Tr2 that are due to common mode signals. The base of Tr3 is biased at relatively fixed voltage, in this case by a potential divider formed by R4 and the three forward biased diodes D1, D2 and D3, but other arrangements, usually consisting of some combination of diodes or zener diodes and resistors can be used.

In the presence of a common mode signal, the collector-emitter current through Tr3 will try to vary; any increase in this current would increase the voltage across R3, and any decrease would reduce it. However because the base voltage of Tr3 is held at a steady voltage, an increase in

Fig.6.1.3 Constant Current Source

collector-emitter current will increase the emitter voltage and therefore reduce V_{BE}. This will reduce the conduction of Tr3 and reduce the collector-emitter current, back to its original value. A decrease in Tr3 collector-emitter current would similarly increase V_{BE} and increase conduction of Tr3 until the current returned to normal once again. Including a constant current source in the emitter circuit of the differential amplifier makes the rejection of common mode signals very efficient.

Notice that in the circuit shown in Fig. 6.1.3 only a single output from Tr2 collector is used to produce a single amplified voltage that is proportional to the difference between inputs a and b, and is almost entirely unaffected by changes common to a and b. There are op amps available that use two outputs, but single output op amps are far more numerous.

Common Mode Rejection Ratio (CMRR)

Ideally the op amp output responds only to differential signals, but in practice, even when the inputs are at exactly the same potential, and the output should be at zero volts, some small output potential will be present. This is caused by inevitable small differences in gain between the inverting and the non-inverting inputs. The op amp therefore has some gain to common mode signals, which is indicated by the parameter Common Mode Voltage Gain (A_{VCM}) and the ratio between this and the Differential Voltage Gain (A_{VD}) is indicated in the main op amp parameters by the Common Mode Rejection Ratio CMRR. Because this ratio is normally a very large number it is often quoted in deciBels.

A reason that the CMRR is an important parameter is that when an op amp is used, as they often are, in circuits involving measurement, some error will be present, for example when measuring the
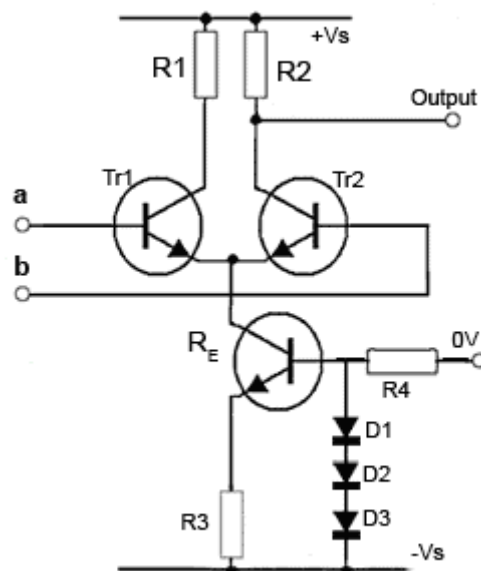
difference between two very small voltages, this error is amplified along with the true differential voltage, so making any measurement inaccurate.

In some modes of operation common mode signals are not produced, such as when the op amp is used as an inverting amplifier, and the non-inverting input is grounded. Then the only time the inputs are the same is when they are both zero.

Offset Null

If common mode signals are to be avoided, the gain from each of the inputs must match as closely as possible. To produce op amps with minimal common mode gain, manufacturers use various techniques such fabricating extra resistors to control the gain form each input within the chip, these may then be removed as required, by selectively blowing fuses to remove individual resistors from one or other channel to balance the input gains. Another, more accurate technique with tiny resistors embedded in the silicon chip, is to use lasers to trim the width of the resistors to alter their resistance during manufacture and testing process.
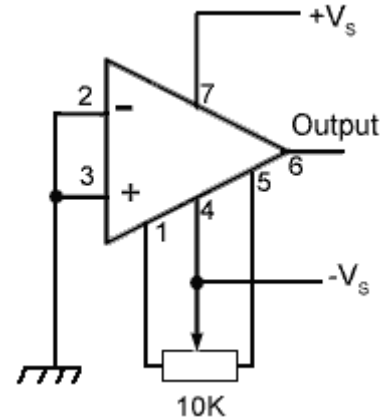
Fig.6.1.4 Offset Null Adjustment

Although modern op amps can be made to have very low offset voltages many op amps provide two extra pins for additional external offset nulling. A typical offset null arrangement is shown in Fig. 6.1.4. A potentiometer is connected between the two offset null pins with the potentiometer wiper connected to the negative power supply. The inputs are both connected to ground and with power on and the IC running at ambient temperature the pot is adjusted to make the output voltage = 0V. Note that it is quite common for the offset null potentiometer, although present in the actual circuit, to be omitted from the circuit schematic diagram, as once adjusted during manufacture it is not considered to play any further part in the circuit's basic operation.

Because such small voltages are involved, the adjustment can be quite sensitive and where necessary the 10K potentiometer could be replaced by a 1K with 4K7 resistors fitted between each end of the potentiometer track and the offset null pins of the IC.

Module 6.2

Comparators

Using the Op Amp's Open Loop Gain

The output of an op amp can swing positive and negative to a maximum voltage close to the supply rail potentials. For example, the maximum output voltage for the popular 741 op amp, when connected to a ±18V supply is ±15V Because the open loop gain of an op amp is extremely high however, typically 10,000 to one million, means that without negative feedback, any input that creates a difference in voltage between the two input pins greater than ±150µV will amplified 100,000 or more times and drive the output into saturation; the output appears to be 'stuck' either its maximum or minimum value. Using the maximum open loop gain in this way can be useful when either dealing with extremely small (and low frequency or DC) inputs in instrumentation or medical applications, or for comparing two voltages, using the op amp as a comparator. In this mode the output will go to either a maximum high or minimum low level depending on whether one input is just a few micro volts higher or lower than a reference voltage applied to the other input.

The Op Amp as a Comparator

Basic op amp types such as the 741 will perform adequately as comparators in simple circuits, such as a temperature controlled switch that is required to switch on or off a circuit when the input voltage from a temperature sensor is higher or lower than a preset reference value. In Fig. 6.6.1 a reference voltage is applied to the non-inverting input, whilst a variable voltage is applied to the inverting input. Whenever the voltage applied to pin 2 is higher than the reference voltage on pin 3 the output will be at a low voltage, only slightly higher than −Vs and if pin 2 is at a lower voltage than pin 3, the output voltage will be high, slightly less than +Vs.
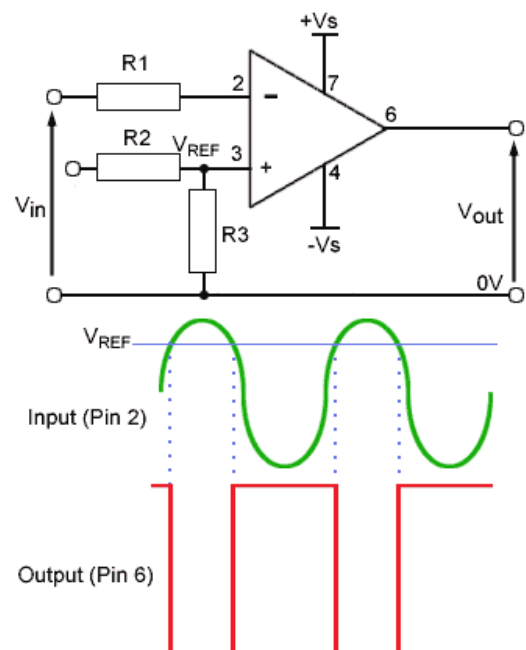

Fig. 6.6.1 Using an Op Amp as a Comparator

However standard op amps are designed for low power amplification purposes and if they are driven into, then out of saturation, it takes some time for the output voltage to recover and for the op amp to begin operating in a linear manner once more.

Op amps designed as amplifiers are not particularly suited to use as comparators especially where the input signals are changing rapidly in such applications as audio level sensors or analogue to digital converters. Another problem with the basic comparator arrangement illustrated in Fig 6.6.1 that is addressed by op amps specially designed as comparators rather than amplifiers, is that of noise. If there is a significant amount of noise on the input signal, especially when the input signal voltage is close to the reference voltage level, the high frequency voltage variations caused by the random nature of the noise will make the input signal voltage higher and lower than the reference voltage in rapid succession, causing the output to momentarily oscillate between its maximum and minimum voltage levels. However this problem is overcome in many dedicated comparators by applying hysteresis.

Hysteresis

This refers, in comparators and switching circuits, to the property of the output in switching to its high or low states at different input values. If a comparator switched its output at a single input voltage level as explained in the previous paragraph, or if the difference in the two levels provided by the comparator's hysteresis is not wide enough, the switching from one of the two output conditions to the other could be very uncertain. Hysteresis can be applied to the op amp comparator and adjusted for a suitable hysteresis gap by using positive feedback in a circuit arrangement called the Schmitt Trigger.

The Schmitt Trigger

The Schmitt Trigger circuit shown in Fig. 6.6.2 is an inverting comparator based on the LM339 quad comparator IC from Texas Instruments with its reference value applied to the non-inverting input by the potential divider R1 and R2. This sets the reference voltage at half of the 5V single supply. R3 is a pull-up resistor, which is used on the LM339 as this comparator has an open collector output, that is an output stage whose collector does not have an internal load resistor connected to supply. The reason for this is that it allows the output to have a wider range of DC voltages, rather than just being able to vary between supply and ground.
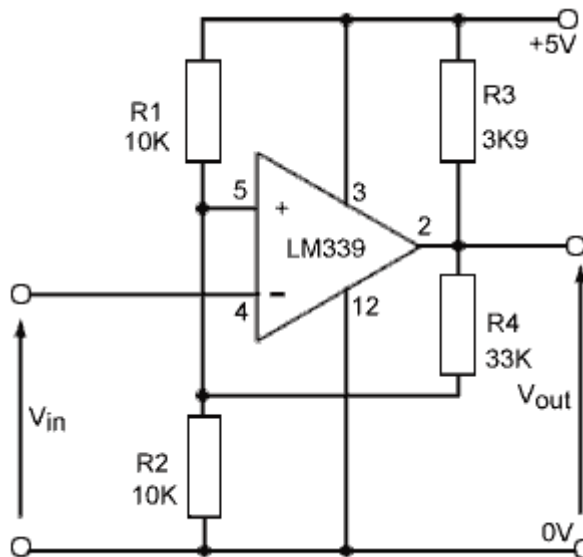

Fig. 6.6.2 The Op Amp Schmitt Trigger

Positive Feedback

The resistor R4, connected between output and pin 5 (the non-inverting input) provides positive feedback to speed up output switching as follows. Suppose the voltage V_{in} on pin 4 is rising towards the reference voltage V_{ref} on pin 5 and the output on pin 2 is high. Once V_{in} is slightly higher than V_{ref} the output will start to fall towards 0V. A proportion of this fall in voltage is fed via R4 to pin 5 and so begins to reduce V_{ref} increasing the difference between V_{ref} and V_{in}. This causes the output to fall faster and because this fall is continually fed back to V_{ref} the fall in the output voltage accelerates, causing a very rapid fall to zero volts.

A similar action occurs when a high voltage on pin 4 falls to a lower value than pin 5, ensuring very fast output switching. There is however, another action taking place; it was mentioned in the previous paragraph that a fall in the output voltage is fed back via R4 and causes a fall in V_{ref} and likewise a rising output voltage will cause a rise in V_{ref}. Therefore V_{ref} changes depending on whether the output voltage is high or low. Some hysteresis has been introduced into the circuit operation.

Controlling the Hysteresis

The centre point between the hysteresis on and off levels is V_{ref} controlled by the choice of values of R1 and R2. The amount of hysteresis (the difference between the switch on and switch off points) is controlled by the value R4. The reason for this can be seen from Fig. 6.6.3, which shows that because the output end of R4 is effectively connected to either +5V (when the output is high, or to 0V when the output is low, it is either in parallel with R1 (high output) or with R2 (low output), and so changes the voltage at the centre of the R1/R2 potential divider accordingly. Therefore by appropriately choosing the value of R4, the amount of hysteresis can be chosen to accommodate various anticipated levels of noise.
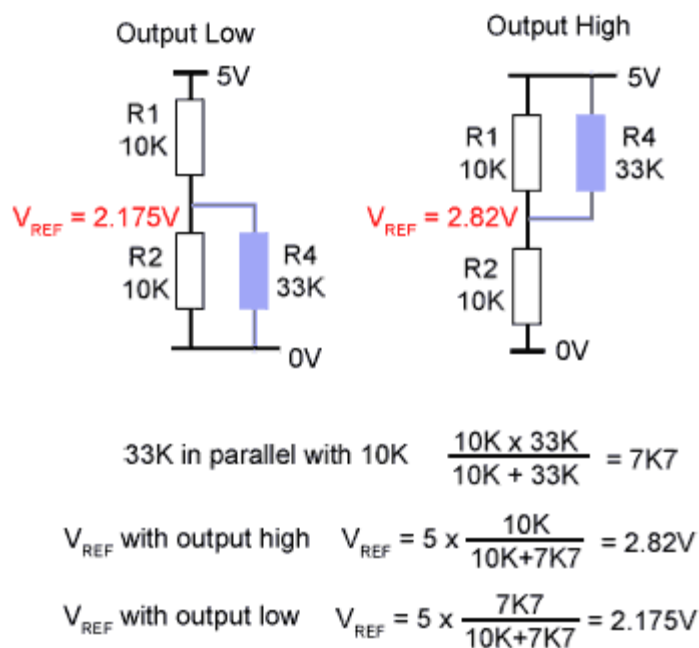
33K in parallel with 10K $\dfrac{10K \times 33K}{10K + 33K} = 7K7$

V_{REF} with output high $V_{REF} = 5 \times \dfrac{10K}{10K+7K7} = 2.82V$

V_{REF} with output low $V_{REF} = 5 \times \dfrac{7K7}{10K+7K7} = 2.175V$

Fig. 6.6.3 The Effect of R4 on Hysteresis

Dedicated Comparator ICs

For high speed comparisons many dedicated comparator op amps are also available that will change their output state in less than 1μs. However, as is general with most electronic circuits, the faster the outputs change, the more power is consumed. Comparators of various speeds and different power consumption figures are available so that the ideal IC for a given application can be used whether power consumption or speed is more important.

Using methods similar in effect to those described above, high speed comparator integrated circuits with built in hysteresis are available such as the LTC1541 from Linear Technology, which has a built in hysteresis property of ±2.25mV to allow for noise on the input signal.

Comparator ICs are also available that have variable hysteresis to cope with different amounts of noise, and a built in precision reference voltage. Some comparators, such as the LMP7300 from Texas Instruments can also operate from very low single supply voltages and at extremely low currents. This makes them ideal for such applications as low battery voltage detectors in portable equipment.

Module 6.3

Op Amp Voltage Amplifiers

What you'll learn in Module 6.3

After studying this section, you should be able to:

Compare ideal and practical op amps.

Understand the operation op amps

• The use of negative feedback.

• Current rule for op amps.

• Voltage rule for op amps.

• The inverting voltage amplifier.
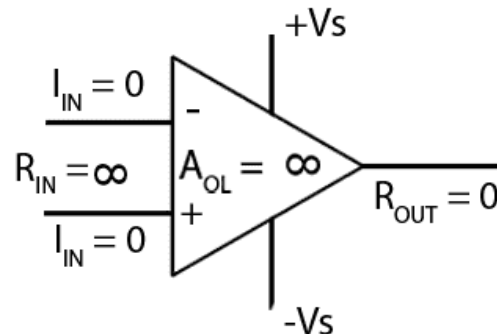
• The non-inverting voltage amplifier.

Fig. 6.7.1 The Ideal Op Amp

The Ideal Op Amp

Although the ideal op amp does not exist in reality, a real (practical) op amp comes reasonably close to achieving the ideal. An ideal amplifier should, in addition to other desirable parameters, have at least an infinitely high input impedance, an output impedance of zero ohms, an infinitely high gain and an infinitely wide bandwidth. Table 1 compares some basic parameters of some typical real (practical) op amps with the 'ideal' model:

Table 1: The Ideal Amplifier v The Practical Op Amp				
Parameter	**The Ideal Amplifier**	**741**	**TLC271**	**LMC660**
Input Impedance (Z_{IN})	Infinity.	$2M\Omega$	$1T\Omega$	$>1T\Omega$
Input Bias Current (I_{IN})	Zero.	80nA	60pA	0.002pA
Large Signal Voltage Gain (A_V)	Infinity	316 to 200,000 (50dB to 106dB)	5,000 to 46,000 (74dB to 93dB) minimum	40,000 to 990,000 (92dB to 126dB)
Output Impedance (Z_{OUT})	0Ω	Depends on gain and feedback but typically less than 100Ω to more than $1K\Omega$		

Negative Feedback

There are two basic methods of connection for op amp voltage amplifiers, making the op amp into an inverting or a non-inverting voltage amplifier. In each case, the voltage gain of the amplifier is set simply by the ratio of two resistors. Using a very high gain amplifier and applying negative feedback produces a very stable amplifier whose gain is virtually independent of changes in temperature or variations in semiconductor characteristics. Just as in the discrete component amplifiers described in Module 3, the negative feedback also reduces distortion and noise in addition to increasing the bandwidth of the amplifier.

Op Amp Rules

Ideal op amps, when used with feedback, operate in a way that can be predicted by a couple of basic rules, often called "Golden Rules"

Rule 1. The Voltage Rule.

The op amp output will change as necessary to keep the two input voltages identical. If any input signal or voltage tries to make the inputs different potentials, the op amp output will change in the opposite polarity to the input and, via the feedback loop, keep the difference between the two inputs at 0V.

Rule 2. The Current Rule.

Because the input impedance is infinitely high, no current can flow into either input.

These rules used in relation to the ideal op amp can be used to make the operation of the two main voltage amplifier circuits easier to understand. The small differences between ideal and practical op amps can be temporarily ignored.

The Inverting Amplifier

Fig. 6.7.3 shows the inverting amplifier, in this configuration the signal input is applied to the inverting (−) input to produce an anti-phase output signal whose amplitude is V_{in} x A_{vcl} where A_{vcl} is the closed loop gain of the op amp.

Negative feedback is used to reduce the op amp's very high maximum gain to the required level. The closed loop gain (A_{vcl}) is set simply by the ratio of R_f to R_{in}

How the Inverting Amplifier Works

By applying the two rules to the ideal op amp shown in Fig. 6.7.3a it can be assumed that:

Pin 3 is at 0V, as it is connected to ground, so pin 2 will also be at 0V (Rule 1)

Therefore R_{in} and R_f are effectively connected in series between V_{in} and V_{out} with pin 2 between the two resistors held at 0V

No current can flow into pin 2 (Rule 2) so the current flowing into V_{in} cannot be flowing into the op amp, therefore it must be flowing through R_f

The diagram in Fig. 6.7.3b shows that in effect R_{in} and R_f are two resistors connected in series between V_{in} and V_{in} with Pin 2 at 0V.

Although pin 2 is not actually connected to ground, pin 3 is connected to ground and rule 1 is making pin 2 0V, this effect of making a point that is not actually connected to ground maintain a zero voltage is called 'virtual earth' (or virtual ground).
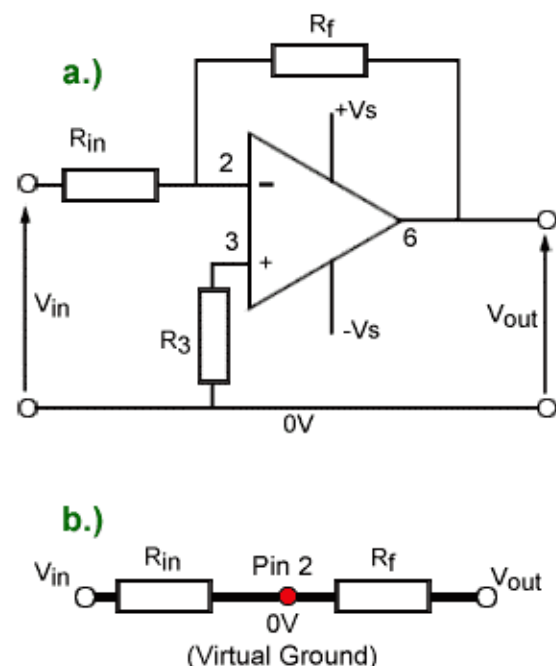

Fig.6.7.3 The Inverting

Any input current (I_{in}) therefore flows directly from the input, via R_{in} and R_f to the output, with R_{in} and R_f forming a potential divider between the opposite polarity voltages V_{in} and V_{out} with pin 2 at 0V.

The current through a series resistor circuit is the same for each resistor, so the input voltage V_{in} will be proportional to the resistance of R_{in}, and the voltage across R_f will be proportional the resistance of R_f

Notice that because R_f is effectively connected between the output terminal and virtual earth (0V) the voltage across R_f is also equal to V_{out}. This makes R_f / R_{in} equal to V_{out} / V_{in} (the gain of the amplifier) and therefore the closed loop gain of the inverting op amp voltage amplifier (A_{vcl}) is given by the equation:

$$\text{Inverting Amplifier Closed Loop Gain } A_{vcl} = \frac{R_f}{R_{in}}$$

Notice that the formula only tells you the ratio of the resistor and not their actual values. Fortunately in audio amplifiers the values are not too critical, usually keeping the resistor values between about 10K and 100K is OK. However it is good to try and keep R_{in} as high a resistance as possible, and also in a practical amplifier, rather that grounding the non-inverting input directly it should be grounded by a resistor with the same value as R_{in} to keep the (tiny) input currents equal. This gives a better chance of the output voltage being zero volts (or close to it) when the input is zero volts.

The Non-inverting Amplifier

In the non-inverting amplifier illustrated in Fig. 6.7.4a the input is applied to the non-inverting input (pin 3) while the negative feedback resistor (R_f) together with R1 set the closed loop gain of the amplifier.

The input and output signals are now in phase, which changes the circuit operation. As shown in Fig. 6.7.4b, the circuit does not have a virtual earth point, but the bottom end of R1 is connected to ground, which means that pin 2 will follow the varying input voltage V_{in} on pin 3 (Rule 1).

R_f and R1 now form a potential divider between V_{out} and 0V and just like the inverting amplifier, no current will flow into pin 2 (Rule 2) so the voltages across R1 and R_f will be proportional to the individual resistances. The ratio of the resistances, and the ratio of V_{out} to V_{in} i.e. the closed loop gain is given by the standard potential divider formula (R_f + R1) / R1.
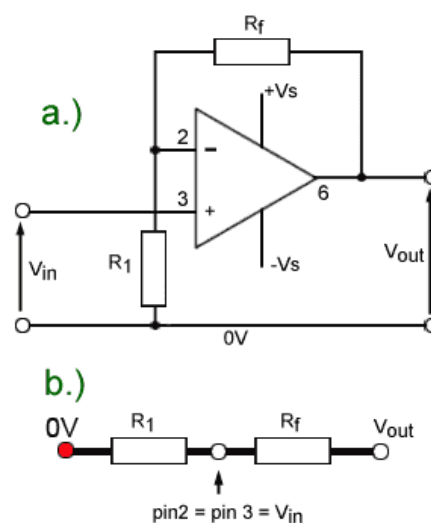

Fig.6.7.4 The Non-Inverting Amplifier

$$\text{Non-Inverting Amplifier Closed Loop Gain } A_{vcl} = \frac{R_f + R1}{R1}$$

Module 6.4

Op Amp Characteristics

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What you'll learn in Module 6.4

After studying this section, you should be able to:

Understand commonly published op amp characteristics.

• Power suppliy requirements.

• Open loop voltage gain.

• Large signal voltage gain.

• Gain bandwidth product.

• Input offset current.

• Maximum differential input.

• Input resistance, Temperature coefficient.

• Slew rate, Power bandwidth.

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Supply Voltage

Two types of supply are used for op amps, the dual and single supply. Many op amps, especially older types use a dual supply (+V_S and -V_S often in the 12 to 18V range. This allows a zero diffence between the input terminals to produce a 0V output and an output signal to swing both positive and negative with respect to ground.

Single voltage supplies have grown in popularity with the increase in portable (battery operated and/or automotive) devices where dual supplies, using multiple batteries are more expensive to implement. A zero diffence between the input terminals on these devices will produce an output at half supply, allowing an output signal to swing between supply and ground.

Frequency Response

An important characteristic of any amplifier is its frequency response, in the ideal amplifier its frequency response should be infinite; it will amplify any and all frequencies equally. In practical amplifiers this is difficult/impossible to achieve, and not always desirable, but op amps have extremely wide, and easily variable bandwidths.

Open Loop Voltage Gain

Fig. 6.4.1 shows the frequency response of a typical op amp (LMC660), which confirms that the open loop gain (with no feedback) at very low frequencies is huge. When Open loop Gain is quoted it refers to the maximum AC gain at very low frequencies. It can be seen from Fig. 6.4.1 that the LMC660 for example has an open loop voltage gain of about 126dB (a voltage gain of nearly 2 million), but at frequencies above a few Hz, gain begins to fall rapidly at 20dB/decade until, at 1.4MHz the gain has reduced to 0dB, a voltage gain of x1.
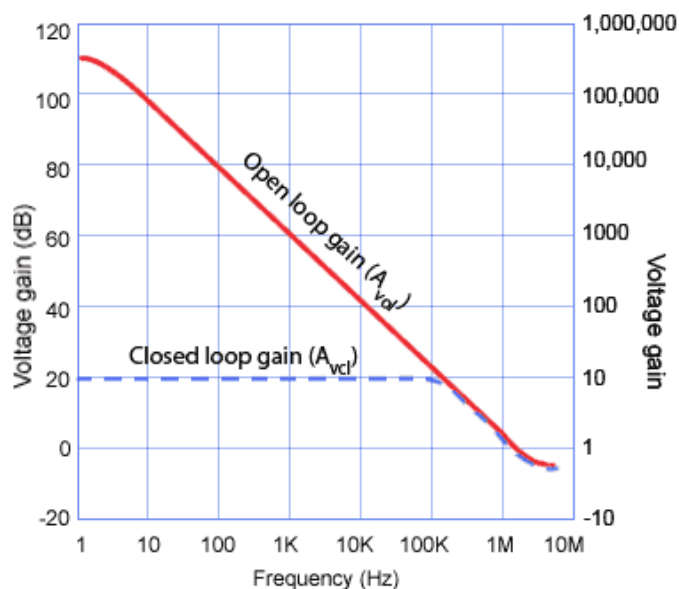
Fig.6.4.1 Typical Op Amp Frequency Response

Large Signal Voltage Gain

The large signal voltage gain is usually quoted in preference to the open loop voltage gain. This is the open loop voltage gain measured at DC with the amplifier producing a large (just less than maximum) voltage output, usually quoted in V/mV. Figures for large signal voltage gain can cover a wide range for a given op amp, depending on design variant and factors such as minimum or maximum operating temperature.

Closed Loop Voltage Gain

In practise the huge gain of an op amp is greatly reduced by applying an appropriate amount of negative feedback. In this way an impressively level response can be achieved, extending from DC (0Hz) to any frequency up to about 1MHz or more, as well as the added benefits of reduced noise and distortion. The blue dotted line shows the response of the op amp with negative feedback. The gain has been reduced to 20dB, a closed loop voltage gain (A_{cl}) of x10, which has produced a flat response from 0Hz to about 140kHz.

Gain Bandwidth Product

As the closed loop gain and the small signal bandwidth of an op amp are closely related, the parameter **'Gain Bandwidth Product'** is often used to better describe the possible combinations of gain and bandwidth. The graph of the open loop frequency response in Fig. 6.4.1 therefore plots all those points where voltage gain x bandwidth = 1.4 million(Hz). For example, 140kHz bandwidth multiplied by a voltage gain of 10 also gives a Gain Bandwidth Product of:

10 x 140kHz = 1.4MHz

Note that bandwidth indicated by the Gain Bandwidth Product applies to small signals, but when large AC signals are involved, especially signals with fast rising and falling edges, the bandwidth may be further reduced by the Slew Rate. Then the Power Bandwidth becomes more relevant.

Maximum Differential Input

The maximum voltage that can be applied between the two inputs, on some devices this can be equal to the supply voltage, but on others it can be considerably less.

Input Resistance

The resistance looking into the input terminals with the amplifier operating without feedback (open loop). Typical resistances for bipolar devices are in the range of 1MΩ to 10MΩ. For FET and CMOS types, resistances are much higher, and range up to $10^{12}\Omega$ or more.

Input Offset Current

The currents flowing into the two inputs should ideally both be zero, but for practical op amps, although the input currents are still extremely small, they do exist and also may be different. Unequal currents cause different voltages at the inputs, and when this small difference in voltage is amplified, it causes the output to be other than zero. To overcome this effect an **Input Offset Voltage** can be applied between the inputs to correct the output voltage to zero. Typical values for bipolar op amps would be ±1mV ranging up to 15mV for FET types.

Temperature Coefficients

Both the input offset current and input offset voltage are affected by changes in temperature, and tend to drift higher as temperature increases. The temperature coefficient of input offset current is measured in nA or pA / °C while the temperature coefficient of input offset voltage is usually measure in μV/°C.

Slew Rate

The Slew Rate of an op amp describes how fast the output voltage can change in response to an immediate change in voltage at the input. The higher the value (in V/μs) of slew rate, the faster the output can change and the more easily it can reproduce high frequency signals.

If a square wave is applied to the input of the op amp, the output should also be a square wave. However the fast rising and falling edges of the square wave can tend to cause the amplifier to oscillate for a short time after the rise or fall. To prevent this effect, the op amp's internal circuitry contains a small amount of compensation capacitance that slows down the rate of change by acting as a CR time constant so that very fast transient voltages do not trigger oscillation, but this compensation also limits the slew rate of the op amp, as shown in Fig. 6.4.2.
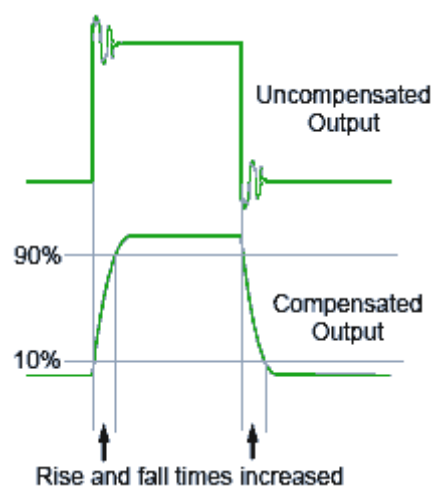

Fig.6.4.2 Output Compensation

In some op amps, because this compensation is internal, there is no way of altering the slew rate, but others use an external compensation capacitor, and therefore provide the means to control slew rate to some degree.

The slew rate also affects sine wave (and audio) signals as well as square waves. The rate of change of voltages in a sine wave is continually varying, it is changing at its fastest rate as the signal voltage crosses zero, and falls momentarily to zero (no change) at both the positive and negative peaks of the wave. If the slew rate of the amplifier cannot keep up with the fastest rate of change of

the signal, some distortion will be produced. Therefore, to be sure of amplifying large amplitude signals that are most likely to produce large (and fast) rates of voltage change, an op amp needs to have a sufficiently high value of slew rate to cope with the greatest possible rate of voltage change. If the largest possible voltage swing and the highest frequency of the signal are known, the minimum required slew rate for the op amp can be calculated using the formula:

$$\text{Slew Rate (V/\mu s)} = 2\pi f\, V\text{pk}$$

Where f = the highest signal frequency (Hz) and V_{pk} = the maximum peak voltage of the signal.

For example if an op amp is to amplify a signal with a peak amplitude of 6 volts at a frequency of 40kHz, an op amp with a slew rate of at least 2π x 40 exp3 x 6 = 1.5V/μs would be required.

Power Bandwidth

Once the slew rate calculated as above for the large signal becomes equal or greater than the amplifier's slew rate, 'Slew Rate Limiting' starts to occur, causing reduced gain and distortion of the signal. The highest frequency than can be used to amplify a full amplitude signal before Slew Rate Limiting is the highest frequency limit of the **Power Bandwidth,** which, for example in an op amp operating from a ±15V supply would be specified as the frequency range in which a ±10V swing can be measured at the output with a total harmonic distortion of less than 5%. The Power Bandwidth is usually less than the small signal bandwidth indicated by the graph of the closed loop gain, and in many cases the major factor in specifying the amplifier bandwidth

Module 6.5

Op amp Packages

What you'll learn in Module 6.5

After studying this section, you should be able to:

Recognise typical op amp packages.

• 4 pin & 8 pin DIL

• Metal can.

• Pentawatt

• Power amplifier packages.

Recognise typical pin functions on op amps.

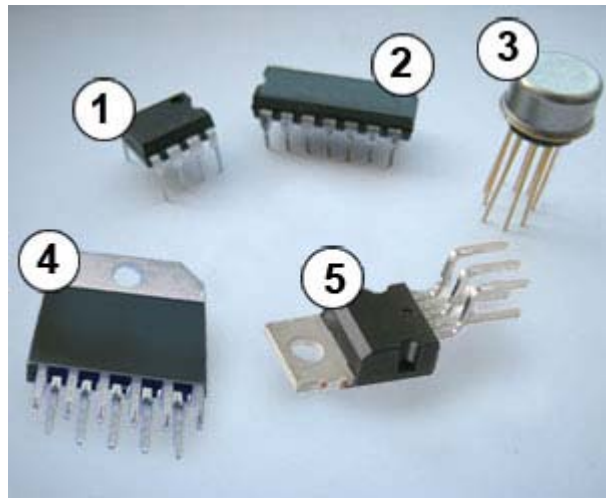• Offset null.

• Power inputs.

• Programmable inputs.

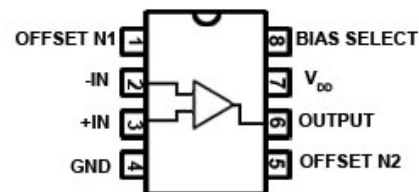**Fig 6.5.1 Typical Op amp packages**

Op Amp Packages

Op amps, like any amplifier circuit, can be built from discrete components, i.e. resistors, capacitors and transistors, or even using valves (tubes). However, op amp integrated circuits are available in many different types and packages, some examples of which are shown in Fig. 6.1.1. Manufacturers offer ranges of both BJT and CMOS amplifiers, as well as comparators, that can be incorporated into many electronics systems using a minimum of external components, greatly reducing design complexity and cost. Further integration has produced Application Specific Integrated Circuits (ASICS) where op amp technology has been combined with other circuit elements within a single IC designed to carry out a specific circuit function within a particular dedicated application such as a TV receiver or a cell phone.
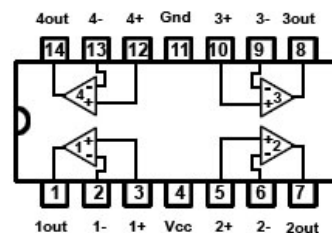
Op Amp Pinout Examples

1. TLC271 Programmable Op Amp

The TLC271 from Texas Instruments is a programmable op amp in an 8pin DIL (Dual In Line) package, (other package types available) which offers a range of programmable power consumption modes, selected by the level of voltage applied to the bias select pin.
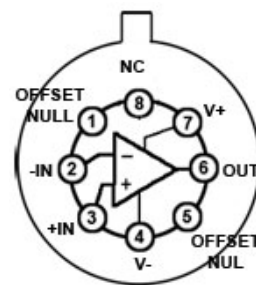
2. LMC660CN Quad CMOS Operational Amplifier

National Semiconductor LMC660CN CMOS quad operational amplifier offers 4 op amps in a single package that uses a single voltage power supply of between 5V and 15V. See the LMC660 datasheet from Texas Instruments for additional features.
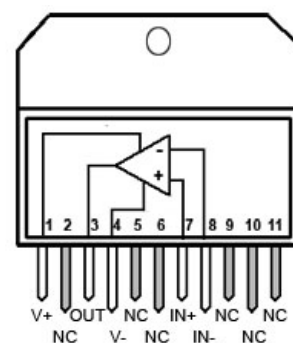
3. 741 General Purpose Op Amp

The 741 op amp has been a very popular design since its introduction by Signetics (now part of Philips NXP Semiconductors) in the 1960s. Today, it is available from a number of manufacturers (including Texas Instruments) in several different versions and in a variety of package designs including the 8 pin DIL package. The illustration shows it in an eight lead TO5-8 package, and although the 741 has been superseded in many respects by more modern designs, it remains a good general purpose op amp.
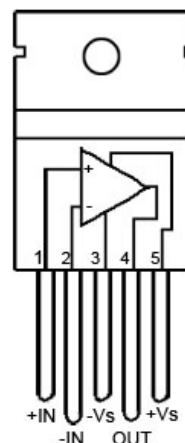
4. LM3875 56Watt Power Amplifier

The LM3875 from National Semiconductor is a high-performance audio power amplifier in a single integrated circuit, capable of delivering 56W of continuous average power to an 8O load with 0.1% total harmonic distortion and noise within the 20Hz to 20kHz audio range. All this in a TA11B 11 pin package less than 1 inch square.

5. TDA2003A 10Watt Car Audio Power Amplifier

The TDA2003A from ST Microelectronics is a high performance audio amplifier designed for car radios. This 10watt amplifier will deliver an output current of 3.5V and uses a power supply of up to 18V DC. The 5 pin Pentawatt package offers savings in space and cost, requiring only a few external components.

Module 6.6

Op amp Circuits

<table>
<tr><td>

What you'll learn in Module 6.6

After studying this section, you should be able to:

Understand the operation of typical op amp circuits.

• Voltage follower.

• Differential amplifier.

• Instrumentation amplifier.

• Summing Amplifier:(DC level control, weighted resistor DAC, audio mixer).

• Differentiator.

• Integrator.

• Active filters: (low pass, high pass, band pass).

</td></tr>
</table>

Op Amp Circuits

Op amps are extremely versatile and have become the amplifier of choice for very many applications. The advantages of integration also allow op amps to be included in many application specific integrated circuits (ASICs) where, combined with other circuit elements, a chip can be designed to carry out a specific function, which for example, can vary from a dedicated tone control or a programmable filter network to a complete audio or communications system.

This section introduces some basic variations on the voltage amplifiers described in Module 6.3 that are commonly used in many circuits.

Voltage Follower

The voltage follower shown in Fig. 6.6.1 looks rather like a non-inverting voltage amplifier, but without its feedback and input resistors. The gain of a non-inverting voltage amplifier would normally be described using the values of R_f and R_{in} by the formula:

$$A_{vcl} = \frac{R_f + R_{in}}{R_{in}}$$

In the voltage follower circuit however, both R_{in} and R_f are replace by simple conductors, and so both these values in the above formula will be infinitesimally small, therefore the gain is 1. The voltage follower does not therefore, act as an amplifier, the output voltage 'follows' the input voltage, but the circuit does have some very useful properties.
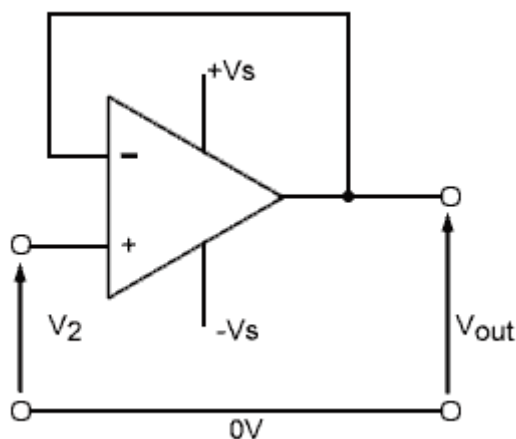

Fig.6.6.1 The Voltage Follower

Module 3.2 described how negative feedback can be used to increase the input impedance, and reduce the output impedance of an amplifier. The voltage follower uses 100% negative feedback that is effectively voltage derived and series fed, so the effect of the feedback on impedance is dramatic. The input impedance of the circuit is increased to typically many megohms (10^6 Ω) or even teraohms (10^{12} Ω) while the output impedance of the op amp remains very low, in the range of ohms to hundreds of ohms. As with any other NFB amplifier noise and distortion are also reduced.

The voltage follower is therefore very useful as a buffer amplifier, that will reduce the loading effect on previous circuits and, because of its low output impedance to deliver more current to any following circuit.

Differential Amplifier

Fig. 6.6.2 shows a differential amplifier with a single output. This operating mode is a combination of both the inverting and the non-inverting amplifier. In this mode the output will be the difference between the two inputs, multiplied by the closed loop gain.

Setting the value of closed loop gain is normally achieved by choosing the ratio of the feedback and input resistors. In both the inverting and non-inverting amplifiers only one input was used; the other input being connected to ground. In the differential amplifier however, both inputs are in use so two pairs of resistors are needed control the gain, one pair for each input. It is important that the gains from both inputs are equal, otherwise the output would be equal to the voltage difference and the difference in gain. Therefore in Fig. 6.6.2 for equal gain at each input R1 should equal R2 and R3 Should equal R4.
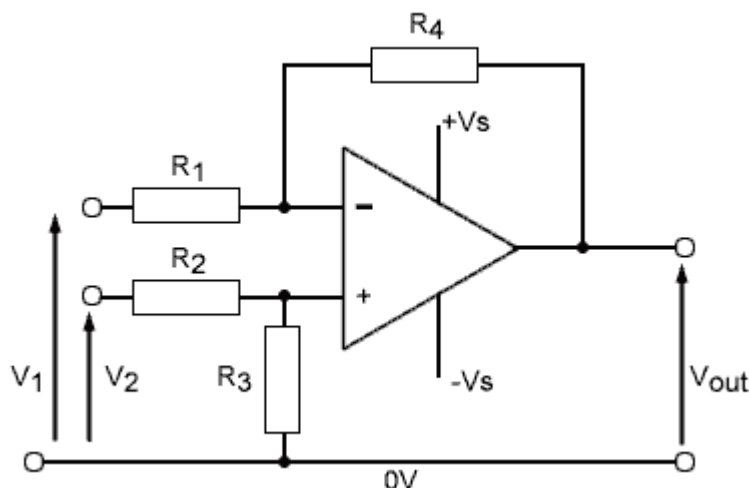

Fig.6.6.2 The Differential Amplifier

One problem with the circuit in Fig. 6.6.2 is that, compared with the single input op amp mode, the input impedance is quite low. Another problem, especially where a gain greater than 1 is required, is that it becomes difficult to match the two gains accurately enough, even with close tolerance resistors because of unequal input currents and the very small differences in input voltages that may be amplified to produce larger errors at the output.

Instrumentation Amplifier

Both of these problems can be remedied by using a slightly more complex design, the Instrumentation Amplifier, shown in Fig. 6.6.3. This circuit addresses the problem of low input impedance by using two non-inverting buffer amplifiers at the inputs to increase input impedance.

Unlike the basic voltage follower buffer amplifier illustrated in Fig. 6.6.1 and to solve the problem of uneven gain, these single input non-inverting buffer amplifiers are designed with feedback resistors to give a closed loop gain of more than 1.
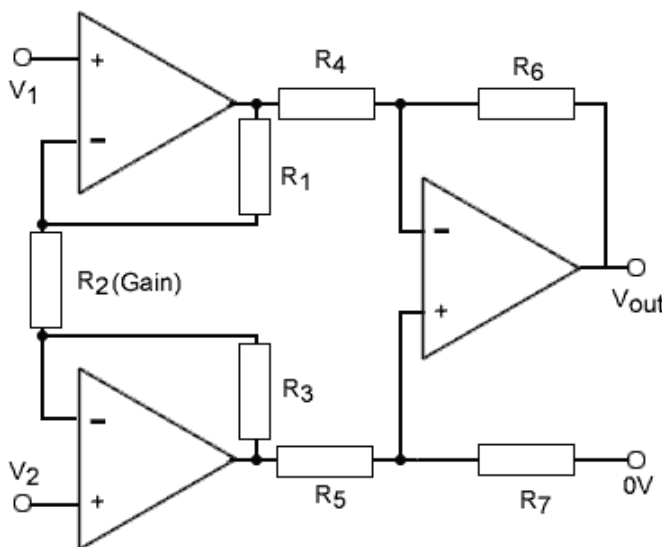

Fig.6.6.3 The Instrumentation Amplifier

The two buffer amplifiers use a shared input resistor (R2) so that the gain of both input amplifiers is set by just a single resistor and the output amplifier can have a gain of 1 where R4, R5, R6 and R7 can be all the same value. The problem of producing amplifiers and resistors with close tolerances and identical temperature coefficients is made easier if they are produced on a singe wafer of silicon within an integrated circuit, therefore integrated circuit instrumentation amplifiers such as the INA114 from Texas Instruments are produced, looking very much like a single op amp but using a single resistor to set its gain.

Summing Amplifier

A summing amplifier is an extension of (usually) the inverting amplifier, which performs an addition of a number of analogue signals (AC or DC) at its inputs. It can have a number of uses:

1. DC Level Control

By applying an AC signal to one of the summing amplifier inputs, and a DC voltage to the other, the DC voltage is added to the AC signal, changing the DC level of the AC wave. An example application of this could be the Y shift control on an analogue oscilloscope changing the vertical position of the waveform.
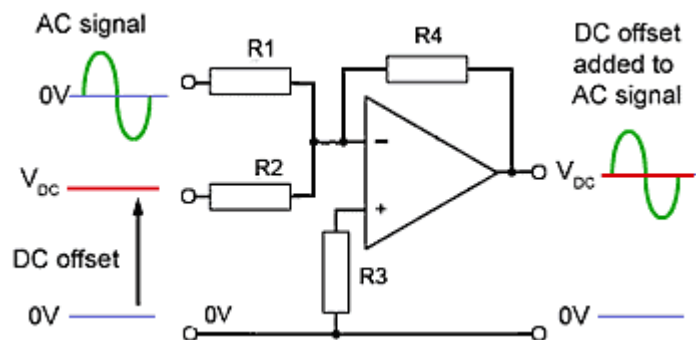

Fig.6.6.4 Adding a DC offset to an AC wave

2. Digital to Analogue Conversion

The simplest type of Digital to Analogue Converter (DAC) uses a Summing Amplifier and a weighted resistor network as shown in Fig. 6.6.5 where resistors having values in the ratio 1, 2, 4 and 8 are fed from a stable reference voltage and can be individually switched into the input circuit of the summing op amp. The amplifier output will have 16 different voltage levels, depending on the 4 bit digital code applied to the inputs D_O to D_3. Supposing that V_{ref} is 5volts, the output voltages for any possible input code would be as shown in the table in Fig 6.6.5.

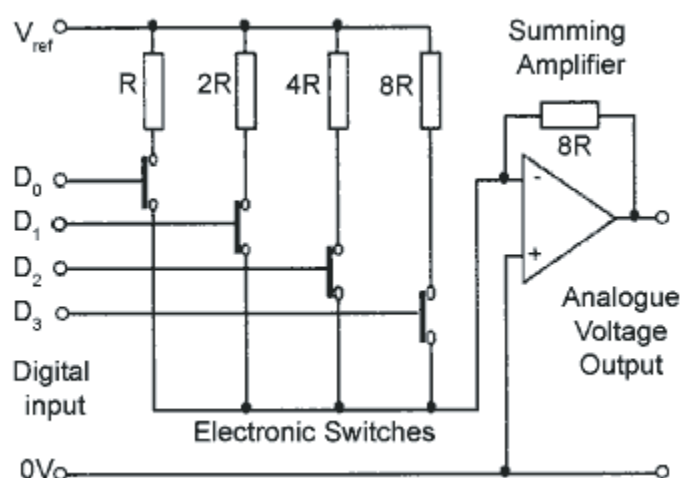| D_3	D_2	D_1	D_0	V_{out}
0	0	0	0	0V
0	0	0	1	333mV
0	0	1	0	666mV
0	0	1	1	999mV
0	1	0	0	1.333V
0	1	0	1	1.666V
0	1	1	0	1.999V
0	1	1	1	2.333V
1	0	0	0	2.666V
1	0	0	1	2.999V
1	0	1	0	3.333V
1	0	1	1	3.666V
1	1	0	0	3.999V
1	1	0	1	4.333V
1	1	1	0	4.666V
1	1	1	1	4.999V

Fig.6.6.5 Digital to Analogue Conversion (DAC) using a Summing Amplifier

3. Audio Mixer

The audio mixer shown in Fig. 6.6.6 uses a Summing Amplifier made from an inverting op amp with multiple input resistors (R1, R2 and R3), which together with the feedback resistor R5, add the individual signal input voltages voltages at the inverting input of the op amp. In audio mixers R1 R2 and R3 will usually be the same value.
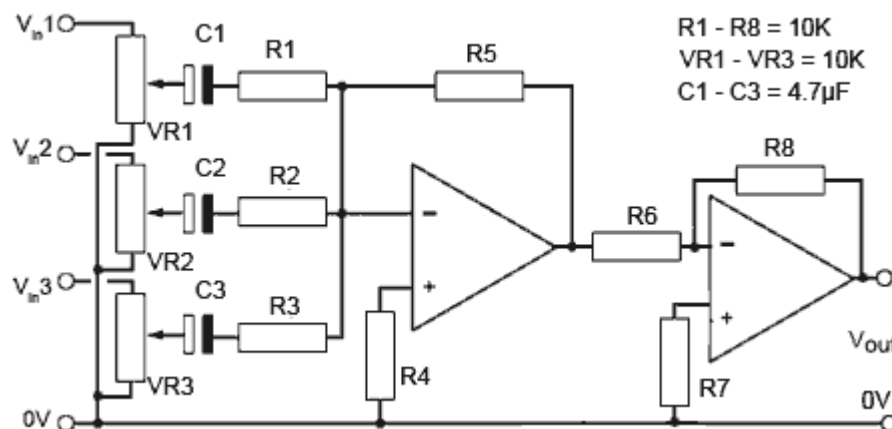

Fig.6.6.6 Audio Mixer Using a Summing Amplifier

Because the summing amplifier used in stage one is based on an inverting amplifier, the signal at the output of stage one will be in anti-phase to the input signal, so to restore the signal to its original phase a second inverting amplifier is used. With R1 to R8 all of equal value, the gain of each stage, and therefore the overall gain, will be 1.

Active Filters & Wave Shaping

Adding an op amp to the passive wave shaping and filter circuits described in AC Theory Module 8 overcomes the problem that the gain of passive circuits is always less than 1, the output is always less than the input. This may be acceptable where only first order circuits (having only a single wave shaping or filter element) are used, but as the efficiency of the circuit is generally improved by using multiple circuit elements, for example using a low pass filter and a high pass filter in combination to make a band pass filter. In such cases the attenuation caused by the extra passive filter can cause an unacceptable reduction in signal amplitude.

With active filters and wave shaping circuits, op amps are used to overcome the losses due to passive components, making multiple (2nd, 3rd, 4th...etc. order) filters possible that have superior performance such as sharper cut off and a higher Q factor.

Op Amp Differentiator

When op amps are used in wave shaping circuits, the operation of the circuit uses the characteristics of the amplifier together with the properties of resistors and capacitors to obtain changes to the wave shape.

The circuit in Fig. 6.6.7 uses a CR time constant of C1 x R2 (10exp-9 x 470exp3) = 470µs to convert a square wave with a periodic time of 1/100Hz = 10ms, to positive and negative pulses. **The time constant of a differentiator is shorter than the periodic time of the wave.**
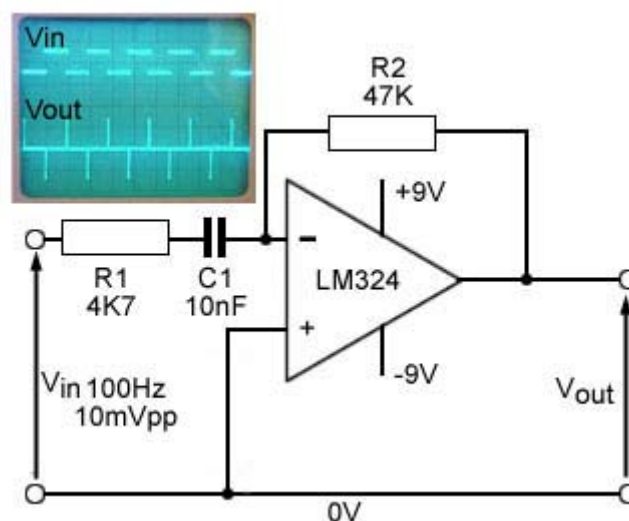
Temporarily ignoring R1, the operation is as follows:

Fig.6.6.7 Op Amp Differentiator/High Pass Active Filter

The circuit illustrated in Fig. 6.6.7 is basically that of an inverting amplifier, but with the addition of a capacitor at the inverting input. If a steady voltage is applied to the left hand plate of C1 there will a voltage across C1 as the right hand plate is held at 0V (virtual ground) by the action of the op amp keeping the inverting input at the same voltage as the non-inverting input, which is connected to 0V. While the input voltage (a square wave) remains at a constant level, there will be no current flowing through C1 and therefore no current through R2. The output voltage will also be constant.

When the input voltage suddenly changes, there will be a sudden pulse of current into the capacitor as it quickly charges (due to the short CR time constant) to the new level. Supposing the input voltage has gone more positive, the op amp output will go negative to keep the inverting input at 0V. Notice that the active circuit produces a pulse in the opposite phase to that expected from a passive differentiator circuit due to the action of the inverting amplifier.

The op amp differentiator has produced good (though inverted) differentiation at low frequency, and the amplitude of the pulses depends on the rate of change of the input wave and also on the gain of the op amp. The gain will in turn depend on the ratio of R2 to the capacitive reactance (X_C) of C1. However reactance reduces as frequency increases and so the gain of the op amp will increase with frequency. At some high frequency the reactance of C1 will have reduced to practically 0Ω and the gain of the op amp will be almost infinitely high. This will cause serious problems of high levels of noise together with instability. The circuit will start to oscillate uncontrollably. The purpose of R1 is to help prevent this instability, as the reactance of C1 reduces it will at some frequency fall below the resistance value of R1, and as C1 and R1 are in series the low value of X_C becomes irrelevant and the ratio controlling the maximum gain is R2/R1.

Active High Pass Filter

With both passive and active circuits the differentiator wave shaping circuit shown in Fig. 6.6.7 also acts as a high pass filter when the input is a sine wave. However with active versions of the circuit there is a significant difference to the passive circuit. Because the gain of the op amp falls off at some frequency due to its power bandwidth and slew rate limitations. This can affect its high frequency operation so that an active high pass filter will also behave to some extent as a band pass filter, with attenuation both below and above a central pass band as shown in Fig. 6.6.8. This can be a problem, but also an advantage if the frequencies at which the low and high corner frequencies are managed by the choice of appropriate component values.
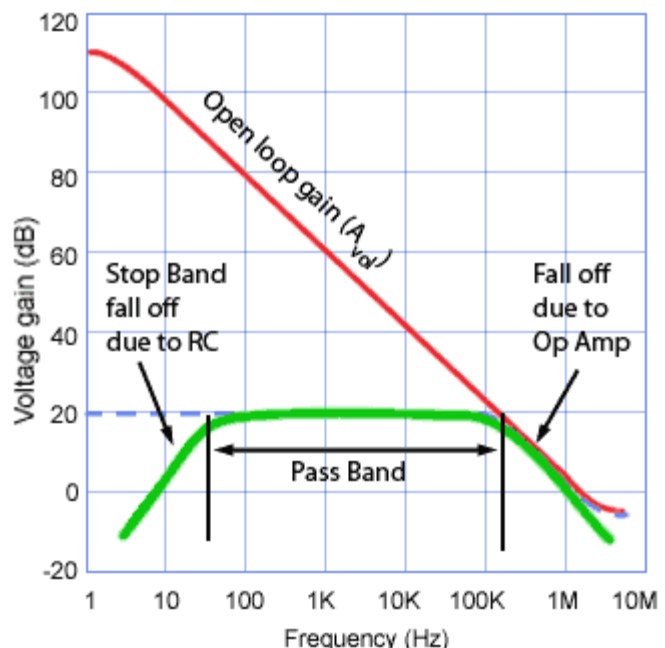

Fig.6.6.8 High Pass/Band Pass Active Filter Response

Integrator/Low Pass Filter

In the op amp integrator circuit the capacitor is inserted in the feedback loop and creates a CR time constant with R1 at the inverting input. This point is held at virtual ground by the action of the op amp. As long as the input is at 0V there will be no current through the resistor R as its right hand end is at virtual ground and C will be in a discharged state because of the presence of R2, which prevents C1 holding some charge from a previous state; if this were to happen the output (connected to the right hand plate of C1) could easily be driven to either $+V_S$ or $-V_S$ causing the op amp to 'lock up' and not be able to restore a normal output voltage.
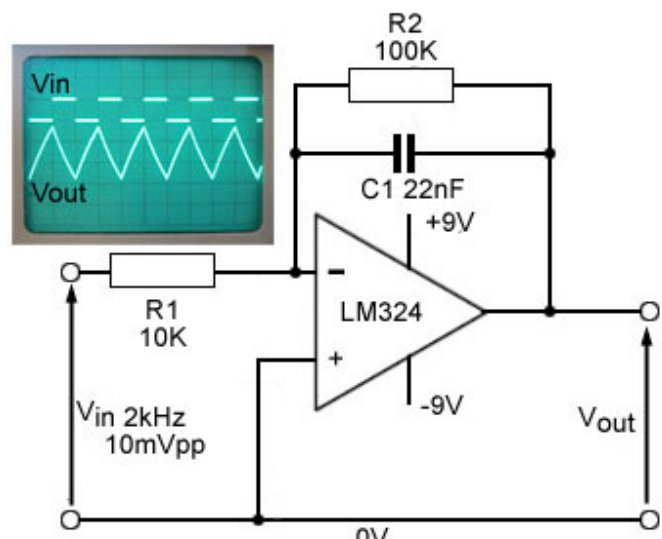

Fig.6.6.9 Op Amp Integrator/Low Pass Active Filter

If a square wave applied to V_{in} now enters its positive half cycle and produces a steady positive DC voltage at V_{in} a current will flow through R and begin to charge C causing its right hand plate, after a rate controlled by the CR time constant, to try and reach a negative voltage, equal and opposite to V_{in} as the op amps action keeps the inverting input at 0V. This action causes a relatively linear negative going ramp at the output until (well before the end of one time constant) the input square wave suddenly changes polarity.

Changing the voltage at V_{in} back to its lower level at the start of the negative going half cycle of the square wave will make capacitor begin to discharge and, to keep the inverting input at 0, the voltage

at the op amp output will increase in a linear manner. This continues until the input suddenly goes positive once again at the start of the next cycle.

To produce a linear ramp on the output triangular waveform, the CR time constant of the integrator circuit should be similar to, or longer than half the periodic time of the input wave. In the case illustrated in Fig. 6.6.9, a time constant R1 x C1 (10exp3 x 22exp-9) = 220μs converts a 1kHz square wave with a periodic time of 1/2exp3Hz = 500μs/2 = 250μs into a reasonably linear triangular wave.

Fig. 6.6.10 shows a 2nd order Sallen-Key low pass filter with a double CR low pass filter network. Such filters are normally designed using graphs and tables of component values for particular frequencies, as the design of multi order filter networks using mathematics is extremely complex and time consuming. An alternative is to use multi stage programmable filters, which contain several active filters in a single integrated circuit. These are of two main designs, either switched capacitor or analogue filters. Fig 6.6.11 illustrates a typical analogue example, the UAF42 by Texas Instruments. It contains four separate analogue active filters that can be digitally programmed to create any combination of the four main filter types.
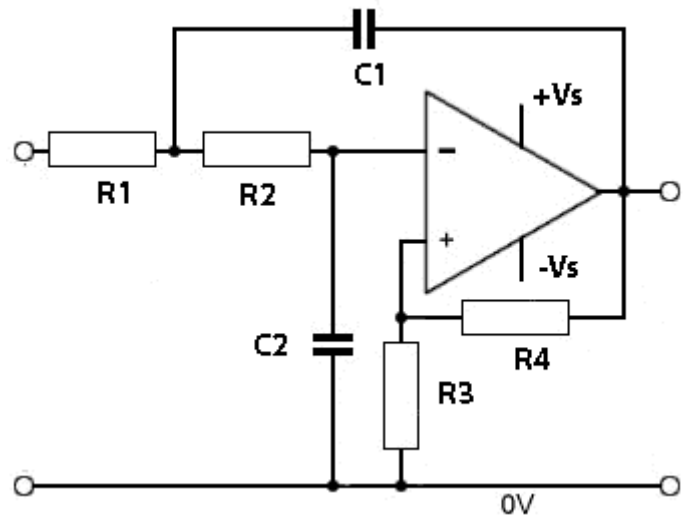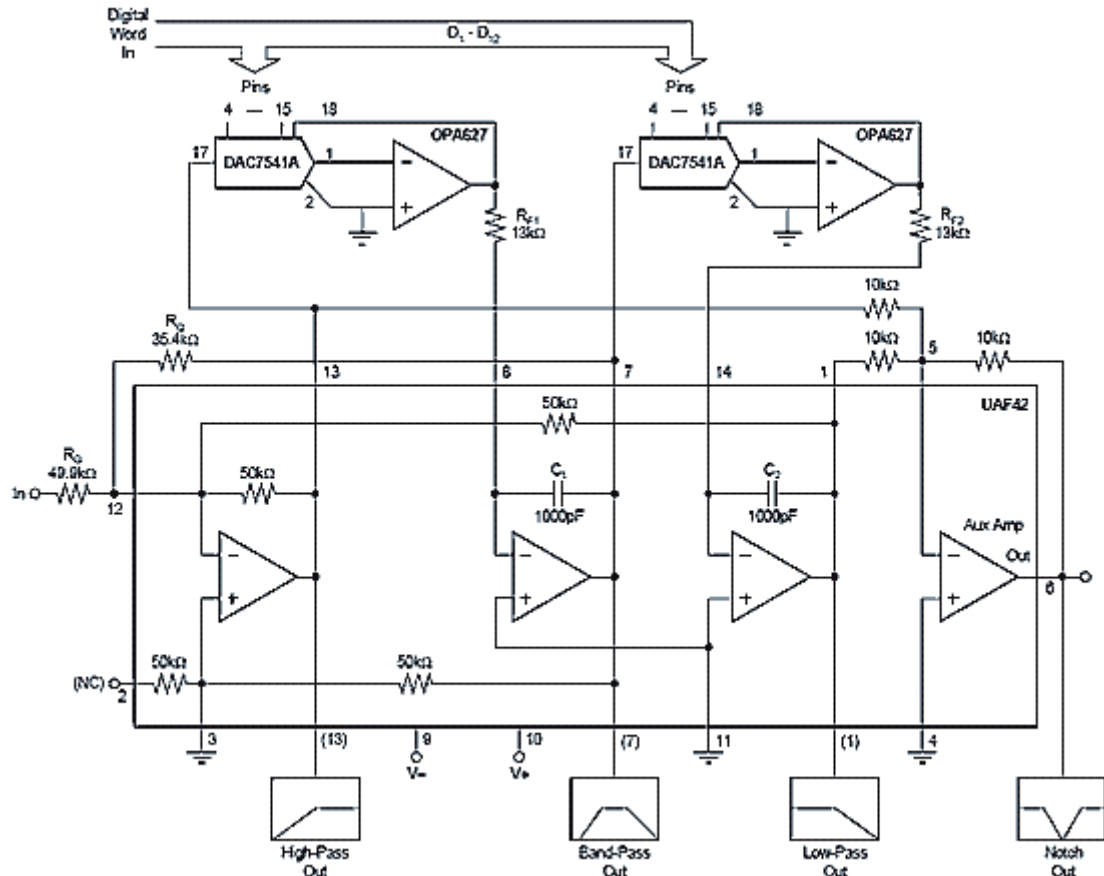

Fig.6.6.10 2nd Order Low Pass Active Filter

Fig.6.6.11 UAF42 Digitally programmable Analogue Filter IC by Texas Instruments

Amplifiers Module 6.7

Amplifiers Quiz 6

Try our quiz, based on the information you can find in Amplifiers Module 6. You can check your answers by going to:

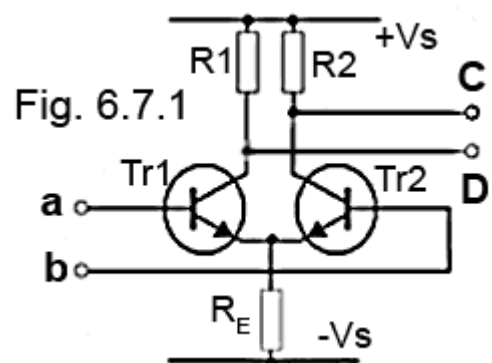http://www.learnabout-electronics.org/Amplifiers/amplifiers67.php

1.

Which of the following properties should an ideal op amp have?

a) Infinitely wide bandwidth, infinitely high output impedance and perfect linearity.

b) High DC gain, low input reactance and perfect linearity.

c) Infinitely high input impedance, perfect linearity and zero noise.

d) Infinitely high gain, perfect linearity and zero input impedance.

2.

Refer to Fig. 6.7.1: If the voltage at input 'b' is fixed, biasing Tr2 so it is conducting and the voltage at input 'a' then rises to a more positive level than input 'b', what will be

a) The voltage at output C will fall and output D will rise by an equal amount.

b) The voltage at output C will rise and output D will fall by an equal amount.

c) The voltage at output C will rise and output D will be unaltered.

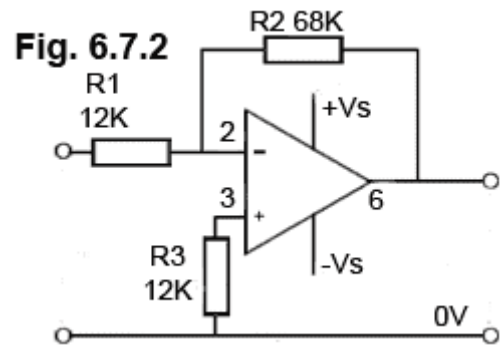d) The voltage at output C will fall and output D will be unaltered.

3.

On op amps that use an offset null control, this is adjusted to give which of the following conditions:

a) To make both inputs equal zero volts.

b) To make both inputs the same voltage.

c) To balance the positive and negative supplies.

d) To make the output voltage equal zero volts.

4.

Calculate the approximate voltage gain of the amplifier in Fig. 6.7.2

Fig. 6.7.2

a) 5.7   b) 14.3   c) 6.7   d) 17.6

5.

Refer to Fig. 6.7.2 : If R2 is changed to 82K and +0.7 V DC (w.r.t. 0V) is applied to the circuit input, what will be the approximate output voltage and its polarity w.r.t 0V?

a) +3.99V   b) −3.99V   c) −4.8V   d) +5.5V

6.

What does the "Large Signal Voltage Gain" of an op amp refer to?

a) The open loop gain at DC (0Hz), measured in dB

b) The Gain that produces a peak to peak signal output equal to the difference between the positive and negative supply voltages measured in dB.

c) The voltage ratio of the peak to peak output signal to a 1 volt peak to peak input signal, measured in mV/V

d) The open loop gain that produces the largest undistorted output signal measured in V/mV
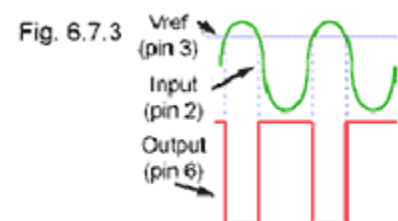
7.

What characteristic of an op amp is the formula $2\pi f V_{pk}$ used to calculate?

a) The gain bandwidth product.

b) The slew rate.

c) The power bandwidth.

d) The open loop voltage gain.

8.

Refer to Fig 6.7.3, which shows the DC input to pin 3, the low frequency signal to pin 2 and the output signal at pin 6 of a 741 op amp. What purpose is the op amp being used for?

a) A buffer amplifier.

b) A differentiator.

c) A comparator.

d) An integrator.

9.

Fig. 6.7.4 shows the package outline of a TLC271 programmable op amp. If the two ends of a preset potentiometer are connected across pins 1 and 5, to which pin should the potentiometer wiper be connected to?

Fig. 6.7.4

OFFSET N1 [1   8] BIAS SELECT
IN − [2   7] V$_{DD}$
IN + [3   6] OUT
GND [4   5] OFFSET N2

      a) 2   b) 3   c) 4   d) 8

10.

Simple D to A conversion can be achieved using a weighted series of resistors and a single op amp configured in which of the following modes?

      a) Voltage follower.

      b) Integrator

      c) Summing amplifier.

      d) Differential amplifier