An operational amplifier

Introduction:

Anoperational amplifier, which is often called anop-amp, is aDC-coupledhigh-gainelectronic voltageamplifierwith a differential input and, usually, a single-ended output. An op-amp produces an output voltage that is typically millions of times larger than the voltagedifferencebetween its input terminals. Typically uses of the operational amplifier are to provide voltage amplitude changes (amplitude and polarity), oscillators, filter circuits, and many types of instrumentation circuits. An op-amp contains a number of differential amplifier stages to achieve a very high voltage gain.

Typically the op-amp’s very large gain is controlled bynegative feedback, which largely determines the magnitude of its output voltage gain in amplifier applications, or thetransfer functionrequired. Without negative feedback, and possibly withpositive feedbackforregeneration, an op-amp essentially acts as acomparator. High inputimpedanceat the input terminals and low output impedance at the output terminals (ideally zero) are important typical characteristics.

Op-amps are among the most widely used electronic devices today, being used in a vast array of consumer, industrial, and scientific devices. Many standard IC op-amps cost only a few cents in moderate production volume; however some integrated or hybrid operational amplifiers with special performance specifications may cost over $100 US in small quantities. Op-amps sometimes come in the form of macroscopic components, or asintegrated circuitcells; patterns that can be reprinted several times on one chip as part of a more complex device.

The op-amp is one type ofdifferential amplifier. Other types of differential amplifier include thefully differential amplifier(similar to the op-amp, but with two outputs), theinstrumentation amplifier(usually built from three op-amps), theisolation amplifier(similar to the instrumentation amplifier, but with tolerance to common-mode voltages that would destroy an ordinary op-amp), andnegative feedback amplifier(usually built from one or more op-amps and a resistive feedback network).

An Amplifier is made of:

1. A Gain " Block" (ideally possessing infinite gain)
2. Feedback
3. A Network that sets the amount of feedback (e. g. resistors)

The circuit symbol for an op-amp is shown to the right, where:

The power supply pins (V_{text{S}!+}andV_{text{S}!-}) can be labelled in different ways). Despite different labelling, the function remains the same – to provide additional power for amplification of signal. Often these pins are left out of the diagram for clarity, and the power configuration is described or assumed from the circuit.

Op amps are versatile ICs that can perform a variety of mathematical functions. For this reason, they are the building blocks of many signal processing circuits. They have almost infinite gain, high input impedance, and low output impedance. Because of this, there is no current drawn at either input, and the voltage at both inputs must be equal (they are often drawn with a short connecting them)

Op amps have two inputs, an inverting (-) and non inverting (+). A positive voltage source and negative voltage source or ground are connected directly to the op amp, although these are rarely shown on circuit diagrams. There is a single output, which is almost always connected to the inverting input with a feedback loop.

Ideal Op Amps:

There are three rules for analyzing op amp circuits. In addition to KVL and KCL, any op amp circuit should be solvable with these rules.

Infinite input impedance. No current is drawn so:

Infinite gain. This means that the input voltages must be equal.

Zero output impedance. This means that output voltage does not depend on the output current.

Real Op Amps:

Ideal op amps are modelled with infinite gain and infinite impedance. While real op amps have high gain and low impedance, they are not infinite. This limiting factor can affect the performance of the circuit, so it should be considered. Another limitation of real op amps is voltage gain. Instead of being infinite, the maximum output voltage is about 1. 4 V lower than the supply voltage (this is due to diode drops in the op amp).

Ideal behaviour is not an accurate modelling technique when square waves are used. For this type of input, the voltage changes infinitely fast as it jumps from the high to the low parts of the wave. Op amps can’t change instantaneously, there is a slight slope produced in the output. This can be measured by the slew rate (with is the change in voltage over the change in time). Rise time is another parameter used to calculate how quickly an op amp can adjust. The amount of time it takes the voltage to change from 10% to 90% of the desired value is the rise time. For application with square wave input, these two factors can affect the response of your circuit.

Connecting an Op Amp:

Op amps with Dual in Line Packages should be connected to a breadboard as shown here. The notch is at the top of the op-amp, with pins counted counter clockwise from the upper left corner.

Operation:

The amplifier’s differential inputs consist of V_{!+}input and aV_{!-}input, and ideally the op-amp amplifies only the difference in voltage between the two, which is called thedifferential input voltage. The output voltage of the op-amp is given by the equation,

WhereV_{!+}the voltage at the non-inverting terminal is, V_{!-}is the voltage at the inverting terminal andGopen-loopis theopen-loopgain of the amplifier. (The term open-loop refers to the absence of a feedback loop from the output to the input.)

Op-amp with inverting input grounded through a resistor; input at the non-inverting input, and no feedback

With no negative feedback, the op-amp acts as a switch. The inverting input is held at ground (0 V) by the resistor, so if the Vinapplied to the non-inverting input is positive, the output will be maximum positive, and if Vinis negative, the output will be maximum negative. Since there is no feedback from the output to either input, this is anopen loopcircuit. The circuit's gain is just the Gopen-loopof the op-amp.

Standard two-resistor non-inverting amplifier circuit

The magnitude ofGopen-loopis typically very large-seldom less than a million-and therefore even a quite small difference betweenV_{!+}andV_{!-} (a few microvolts or less) will result in amplifier saturation, where the output voltage goes to either the extreme maximum or minimum end of its range, which is set approximately by the power supply voltages. Finley's lawstates that " When the inverting and non-inverting inputs of an op-amp are not equal, its output is in saturation." Additionally, the precise magnitude ofGopen-loopis not well controlled by the manufacturing process, and so it is impractical to use an operational amplifier as a stand-alonedifferential amplifier. If linear operation is desired, negative feedbackmust be used, usually achieved by applying a portion of the output voltage to the inverting input. The feedback enables the output of the amplifier to keep the inputs at or near the same voltage so that saturation does not occur. Another benefit is that if much negative feedback is used, the circuit's overall gain and other parameters become determined more by the feedback network than by the op-amp itself. If the feedback network is made of components with relatively constant, predictable, values such as resistors, capacitors and inductors, the unpredictability and inconstancy of the op-amp's parameters (typical of semiconductor devices) do not seriously affect the circuit's performance.

If no negative feedback is used, the op-amp functions as a switch or comparator.

Positive feedback may be used to introducehysteresisor oscillation.

Returning to a consideration of linear (negative feedback) operation, the high open-loop gain and low input leakage current of the op-amp imply two “ golden rules” that are highly useful in analysing linear op-amp circuits.

Golden rules of op-amp negative feedback

Ifthere is negative feedback andifthe output is not saturated,

1. both inputs are at the same voltage;
2. no current flows in or out of either input.

These rules are true of the ideal op-amp and for practical purposes are true of real op-amps unless very high-speed or high-precision performance is being contemplated (in which case account must be taken of things such as input capacitance, input bias currents and voltages, finite speed, and otherop-amp imperfections, discussed in a later section.)

As a consequence of the first rule, theinput impedanceof the two inputs will be nearly infinite. That is, even if the open-loop impedance between the two inputs is low, the closed-loop input impedance will be high because the inputs will be held at nearly the same voltage. This impedance is considered as infinite for an ideal opamp and is about onemegaohmin practice.

Ideal and real op-amps:

An equivalent circuit of an operational amplifier that models some resistive non-ideal parameters.

An ideal op-amp is usually considered to have the following properties, and they are considered to hold for all input voltages:

- Infiniteopen-loop gain(when doing theoretical analysis, alimitmay be taken as open loop gainGgoes to infinity)
- Infinite voltage range available at the output (vout) (in practice the voltages available from the output are limited by the supply voltagesV_{text{S}!+}andV_{text{S}!-})
- Infinitebandwidth(i. e., the frequency magnitude response is considered to be flat everywhere with zerophase shift).
- Infiniteinput impedance(so, in the diagram, R_{text{in}} = infty, and zero current flows fromv_{!+}tov_{!-})
- Zero input current (i. e., there is assumed to be noleakageorbiascurrent into the device)
- Zeroinput offset voltage(i. e., when the input terminals are shorted so thatv_{!+}= v_{!-}, the output is avirtual groundor vout= 0).
- Infiniteslew rate(i. e., the rate of change of the output voltage is unbounded) and power bandwidth (full output voltage and current available at all frequencies).
- Zerooutput impedance(i. e., Rout= 0, so that output voltage does not vary with output current)
- Zeronoise
- InfiniteCommon-mode rejection ratio(CMRR)
- InfinitePower supply rejection ratiofor both power supply rails.

In practice, none of these ideals can be realized, and various shortcomings and compromises have to be accepted. Depending on the parameters of interest, a real op-amp may be modelled to take account of some of the non-infinite or non-zero parameters using equivalent resistors and capacitors in the op-amp model. The designer can then include the effects of these undesirable, but real, effects into the overall performance of the final circuit. Some parameters may turn out to havenegligibleeffect on the final design while others represent actual limitations of the final performance that must be evaluated.

History:

1941: First (vacuum tube) op-amp

An op-amp, defined as a general-purpose, DC-coupled, high gain, inverting feedbackamplifier, is first found in US Patent 2, 401, 779 " Summing Amplifier" filed by Karl D. Swartzel Jr. of Bell labs in 1941. This design used threevacuum tubesto achieve a gain of 90dB and operated on voltage rails of ±350V. It had a single inverting input rather than differential inverting and non-inverting inputs, as are common in today's op-amps. ThroughoutWorld War II, Swartzel's design proved its value by being liberally used in the M9artillery directordesigned at Bell Labs. This artillery director worked with the SCR584radarsystem to achieve extraordinary hit rates (near 90%) that would not have been possible otherwise.

1947: First op-amp with an explicit non-inverting input

In 1947, the operational amplifier was first formally defined and named in a paper by Professor John R. Ragazzini of Columbia University. In this same paper a footnote mentioned an op-amp design by a student that would turn out to be quite significant. This op-amp, designed by Loebe Julie, was superior in a variety of ways. It had two major innovations. Its input stage used a long-tailedtriode pair with loads matched to reducedriftin the output and, far more importantly, it was the first op-amp design to have two inputs (one inverting, the other non-inverting). The differential input made a whole range of new functionality possible, but it would not be used for a long time due to the rise of the chopper-stabilized amplifier.

1949: First chopper-stabilized op-amp

In 1949, Edwin A. Goldberg designed achopper-stabilized op-amp. This set-up uses a normal op-amp with an additionalACamplifier that goes alongside the op-amp. The chopper gets an AC signal fromDCby switching between the DC voltage and ground at a fast rate (60Hz or 400Hz). This signal is then amplified, rectified, filtered and fed into the op-amp’s non-inverting input. This vastly improved the gain of the op-amp while significantly reducing the output drift and DC offset. Unfortunately, any design that used a chopper couldn’t use their non-inverting input for any other purpose. Nevertheless, the much improved characteristics of the chopper-stabilized op-amp made it the dominant way to use op-amps. Techniques that used the non-inverting input regularly would not be very popular until the 1960s when op-ampICsstarted to show up in the field.

In 1953, vacuum tube op-amps became commercially available with the release of the model K2-W from George A. Philbrick Researches, Incorporated. The designation on the devices shown, GAP/R, is a contraction for the complete company name. Two nine-pin 12AX7 vacuum tubes were mounted in an octal package and had a model K2-P chopper add-on available that would effectively “ use up” the non-inverting input. This op-amp was based on a descendant of Loebe Julie’s 1947 design and, along with its successors, would start the widespread use of op-amps in industry.

1961: First discrete IC op-amps

With the birth of thetransistorin 1947, and the silicon transistor in 1954, the concept of ICs became a reality. The introduction of theplanar processin 1959 made transistors and ICs stable enough to be commercially useful. By 1961, solid-state, discrete op-amps were being produced. These op-amps were effectively small circuit boards with packages such as edge-connectors. They usually had hand-selected resistors in order to improve things such as voltage offset and drift. The P45 (1961) had a gain of 94dB and ran on ±15V rails. It was intended to deal with signals in the range of ±10V.

1962: First op-amps in potted modules

By 1962, several companies were producing modular potted packages that could be plugged intoprinted circuit boards. These packages were crucially important as they made the operational amplifier into a singleblack boxwhich could be easily treated as a component in a larger circuit.

1963: First monolithic IC op-amp

In 1963, the first monolithic IC op-amp, the μA702 designed byBob Widlarat Fairchild Semiconductor, was released. MonolithicICsconsist of a single chip as opposed to a chip and discrete parts (a discrete IC) or multiple chips bonded and connected on a circuit board (a hybrid IC). Almost all modern op-amps are monolithic ICs; however, this first IC did not meet with much success. Issues such as an uneven supply voltage, low gain and a small dynamic range held off the dominance of monolithic op-amps until 1965 when the μA709 was released.

1966: First varactor bridge op-amps

Since the 741, there have been many different directions taken in op-amp design. Varactorbridge op-amps started to be produced in the late 1960s; they were designed to have extremely small input current and are still amongst the best op-amps available in terms of common-mode rejection with the ability to correctly deal with hundreds of volts at their inputs.

1968: Release of the µA741

The popularity of monolithic op-amps was further improved upon the release of the LM101 in 1967, which solved a variety of issues, and the subsequent release of the µA741 in 1968. The µA741 was extremely similar to the LM101 except that Fairchild’s facilities allowed them to include a 30pF compensation capacitor inside the chip instead of requiring external compensation. This simple difference has made the 741thecanonical op-amp and many modern amps base their pin out on the 741s. The µA741 is still in production, and has become ubiquitous in electronics-many manufacturers produce a version of this classic chip, recognizable by part numbers containing741.

1970: First high-speed, low-input current FET design

In the 1970s high speed, low-input current designs started to be made by usingFETs. These would be largely replaced by op-amps made withMOSFETsin the 1980s. During the 1970s single sided supply op-amps also became available.

1972: Single sided supply op-amps being produced

A single sided supply op-amp is one where the input and output voltages can be as low as the negative power supply voltage instead of needing to be at least two volts above it. The result is that it can operate in many applications with the negative supply pin on the op-amp being connected to the signal ground, thus eliminating the need for a separate negative power supply.

The LM324 (released in 1972) was one such op-amp that came in a quad package (four separate op-amps in one package) and became an industry standard. In addition to packaging multiple op-amps in a single package, the 1970s also saw the birth of op-amps in hybrid packages. These op-amps were generally improved versions of existing monolithic op-amps. As the properties of monolithic op-amps improved, the more complex hybrid ICs were quickly relegated to systems that are required to have extremely long service lives or other specialty systems.

Recent trends

Recently supply voltages in analog circuits have decreased (as they have in digital logic) and low-voltage op-amps have been introduced reflecting this. Supplies of ±5V and increasingly 5V are common. To maximize the signal range modern op-amps commonly have rail-to-rail inputs (the input signals can range from the lowest supply voltage to the highest) and sometimes rail-to-rail outputs.

A very typical commercial IC op amp circuit is the 741. This IC has been available for many years, and a number of variations have been developed to help minimize the errors inherent in its construction and operation. Nevertheless, the analysis we will perform here using the 741 will apply to any other IC op amp, if you take into account the actual parameters of the device you are actually using. Therefore, we will use the 741 as our example IC op amp.

A differential amplifier connected as an op amp.

To the right is a circuit using the 741 op amp IC, with the input and feedback resistors that are required for this circuit to operate properly in an analog computer. Note that there are actually two inputs to the amplifier, designated “+” and “-” in the figure. This is because the 741, like all IC op amps of this type, is in fact a differential amplifier. Thus, the output voltage is determined by thedifferencebetween the two input voltages. The “+,” or non-inverting input, is grounded through a resistor as shown. Thus, its input voltage is always zero. The “-,” or inverting input, is the one that is actively used. Thus, we establish that the inverting input, which is also the junction of the input and feedback resistors, must operate as a virtual ground in order to keep the output voltage within bounds.

So far, so good, but what about the actual voltage gain? It can’t possibly be infinite, and if it isn’t infinite, there must be some non-zero input voltage to produce a non-zero output voltage. In fact, the typical open-loop voltage gain for the 741 is 200, 000. This does not mean that every such device has a gain of 200, 000, however. What is guaranteed is that the commercial version (the 741C) will have a minimum gain of 20, 000. The military version is more stringently selected, and will have a minimum voltage gain of 50, 000.

For the 741C, then, with a maximum output voltage of ±10 volts, the maximum input voltage required at the inverting input can never be more than ±10/20, 000 = ±0. 0005 volt, or 0. 5 milli volts. Typical measurement accuracy uses three significant digits, so we would measure voltages from 0. 00 volts to ±10. 00 volts. The maximum input voltage is more than an order of magnitude smaller than this, and hence is insignificant in a typical analog computer.

But what about input bias current? Surely the IC requires at leastsomesmall amount of input current? Well, yes, it does. The 741C requires a typical input bias current of 80 nA (that's nano Amperes, where 1nA= 10-9A). The maximum input bias current for the 741C is 500nA, or 0. 5μA.

So how do we use this information to minimize the errors it could cause into insignificance? Well, let's consider the resistance that would be required for this current to cause a significant voltage drop. If we keep the voltage error small enough, we can ignore it as immeasurable. This means we must keep the values of Rinand Rfas small as possible, consistent with proper operation of the circuit. At the same time, we cannot make them too small, or the op amp itself will be overloaded. For proper operation, the total load resistance at the 741 output should not be smaller than 2000 ohms, or 2k. This amounts to a maximum output current of 5 mA at 10 volts output.

This means that the output resistance of the op amp is not the desired zero ohms. However, as long as you don't draw too much current from the output, the use of heavy negative feedback has an added benefit: It makes the op amp behaveas ifit had zero output resistance. That is, any internal resistance will simply mean that the op amp must produce an internal voltage enough higher than the calculated value so that the final output voltage will be the calculated value.

So what if we make our input and feedback resistors about 10k each? Then the current demand on the output is only 1 mA at 10 volts, leaving plenty of capacity for additional inputs. And the voltage caused by the input bias current won't exceed 10, 000-0. 5-10-6= 0. 005volt. This is half of the least significant digit of our measurement capability, which is not as good as we would like, but will do. Also, this is the absolute worst-case situation; most practical applications won't see an error this big.

In addition, the input bias current applies equally to both inputs. This is the reason for the resistor connecting the "+" input to ground. If this resistor is close in value to the parallel combination of Rin and Rf, the same voltage error will be generated at the two inputs, and will therefore be cancelled out, or very nearly. Thus, we can relegate this problem to true insignificance by means of correct circuit design and careful choice of component values.

The 741 does also have two error characteristics, calledinput offset voltageandinput offset current, which define the inherent errors which may exist between the two inputs to the IC. However, the 741 also has the means for balancing these variations out, so the actual errors are minimized or eliminated, thus once again removing them from significance.

A problem with any op amp is a limited frequency response. The higher the gain of the complete circuit, the lower the working frequency response. This is one reason an overall gain of 20 is a practical limit. (Another reason is that the input and feedback resistors become too different from each other.) Also, the standard 741 has aslew rateof 0. 5v/µs. This means that the output voltage cannot change any faster than this. The newer generation of op amps, such as the 741S, have a slew rate more like 5v/µs, and hence can operate over the entire audio range of frequencies without serious problems.

Classification of Operational Amplifier:

Op-amps may be classified by their construction:

- discrete (built from individualtransistorsortubes/valves)
- IC (fabricated in anIntegrated circuit) – most common
- hybrid

IC op-amps may be classified in many ways, including:

- Military, Industrial, or Commercial grade (for example: the LM301 is the commercial grade version of the LM101, the LM201 is the industrial version). This may defineoperating temperatureranges and other environmental or quality factors.
- Classification by package type may also affect environmental hardiness, as well as manufacturing options; DIP, and other through-hole packages are tending to be replaced bySurface-mount devices.
- Classification by internal compensation: op-amps may suffer from high frequencyinstabilityin somenegative feedbackcircuits unless a small compensation capacitor modifies the phase- and frequency- responses; op-amps with capacitor built in are termedcompensated, or perhaps compensated forclosed-loopgains down to (say) 5, others: uncompensated.

- Single, dual and quad versions of many commercial op-amp IC are available, meaning 1, 2 or 4 operational amplifiers are included in the same package.
- Rail-to-rail input (and/or output) op-amps can work with input (and/or output) signals very close to the power supply rails.
- CMOSop-amps (such as the CA3140E) provide extremely high input resistances, higher thanJFET-input op-amps, which are normally higher thanbipolar-input op-amps.
- Other varieties of op-amp include programmable op-amps (simply meaning the quiescent current, gain, and bandwidth and so on can be adjusted slightly by an external resistor).
- Manufacturers often tabulate their op-amps according to purpose, such as low-noise pre-amplifiers, wide bandwidth amplifiers, and so on.

Single-Ended Inputs

With single-ended inputs you connect one wire from each signal source to the data acquisition interface – the Micro link. The measurement is the difference between the signal and the ground or earth at the Micro link. This method relies on

1. the signal source being grounded (earthed), and
2. the signal source’s ground and the Micro link’s ground having the same value.

Differences in Ground Levels

We think of the ground as a constant 0V, but in reality the ground, or earth, is at a different level in different places. The closer together the places, the more likely the ground level will be the same. Make a connection between two grounds and the difference in levels can drive large currents, known as earth or ground loops. This can lead to errors when using single-ended inputs.

Noise Errors

Single-ended inputs are sensitive to noise errors. Noise (unwanted signal contamination) is added because signal wires act as aerials, picking up environmental electrical activity. With single-ended inputs you have no way of distinguishing between the signal and the noise.

The ground and noise problems can be solved by differential inputs.

Differential Inputs

With differential inputs, two signal wires run from each signal source to the Microlink. One goes to a + input and one to a – input. Two high-impedance amplifiers monitor the voltage between the input and the interface ground. The outputs of the two amplifiers are then subtracted by a third amplifier to give the difference between the + and – inputs, meaning that any voltage common to both wires is removed.

This can solve both of the problems caused by single-ended connections. It means that differences in grounds are irrelevant (as long as they aren't too large for the amplifier to handle). It also reduces noise – twisting wires together will ensure that any noise picked up will be the same for each wire.

Floating Signals

A common problem when using differential inputs is neglecting any connection to ground. For example, battery-powered instruments and thermocouples have no connection to a building's ground. You could connect a battery, for instance, between the Micro link’s + and – inputs. The 2 input amplifiers will try to monitor the voltages + to earth and – to ground. However, as there is no connection between the battery and ground, these voltages to ground could be any value and may be too large for the amplifier to handle.

For these “ floating” signal sources you should provide a reference. The Micro link has a socket labelled 0V. Run a wire from, say, the – wire to this OV socket, either directly or via a resistor. (If your signal source is itself grounded don’t make a connection to the Micro link’s 0V socket.)

Amplifier Ability and Operating Range

The three amplifiers used for differential inputs are collectively known as an “ instrumentation amplifier”. Ideally, as previously described, any voltage common to both wires (common mode voltage) is cancelled. In practice the two input amplifiers are not perfectly matched so a fraction of the common mode voltage may appear. How closely the instrumentation amplifier approaches the ideal is expressed as the common mode rejection ratio (CMRR). This is the reciprocal of the fraction let through and is usually given in decibels. The higher the rejection ratio the better.

Another specification to look for is the common mode range. This is the maximum contamination voltage with which the amplifier can cope. If the difference in ground levels between your interface and signal source exceeds this value, your measurement will be inaccurate.

Less Signals with Differential Inputs?

An obvious disadvantage of differential inputs is that you need twice as many wires, so you can connect only half the number of signals, compared to single-ended inputs. Should you decide that single-ended inputs are OK for you – if you have short signal wires, close together signal sources, and signals larger than around 100 mV for e. g. – you can use differential inputs in single-ended mode. To do this short one of the signal wires (usually the – input) to the Micro link V input. Differential inputs, therefore, give you the option of either mode.

Op-Amp Characteristics:

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