Understanding Op-amp Specifications

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Introduction

This article explains the various parameters of an operational amplifier and how to interpret the data sheet. Be aware that different manufacturers use slightly different terminology. The data sheet generally has three columns for minimum, typical, and maximum values. It does not make sense to list values in all three columns so data is only listed for the appropriate columns for a given item. This is either minimum and typical or typical and maximum. For some parameters that are not controlled there may only be a typical value given. The data sheet may have multiple repeated sections for different operating conditions so be sure to use the appropriate section – don't just use the first section you see. Often there will be some information as to how a parameter is measured – that can sometimes be helpful when determining if a particular op-amp is appropriate for your application. Always read all the information and seek application information such as application notes to be sure you understand the part well. Although all op-amps work fundamentally the same way, there is a wide variety of optimizations for the different parameters of interest.

Op-amps can be generally grouped as follows:

General purpose These are the most common type of op-amp used. They have decent specifications and are low cost. They generally have gain-bandwidth products in the 1 to 10 MHz range and are very often unity gain stable. These op-amps would be used where critical specifications are not important.

Wideband These op-amps have gain-bandwidth products in the 10 MHz to over 1 GHz range. The DC specifications are often very inferior to other types – high offset voltage, high bias current, etc. Many of these op-amps are not unity gain stable and must operate with a minimum closed loop gain or they will oscillate. There are some advanced circuit methods to trick the part into being stable with a low closed loop gain. You must study the application notes for these parts very carefully as they are very prone to oscillate if the physical circuit is not constructed in a particular way. There is a special version of wideband op-amps that uses current feedback instead of voltage feedback – study the application information carefully.

Precision These op-amps feature premium DC specifications such as very low offset voltage and drift as well as very low bias current and drift. These tend to be expensive but are well worth it for the intended applications. The gain-bandwidth product is typically in the low 100 kHz range which is really not important since the primary application is very low frequencies. These amplifiers are practically always unity gain stable. Some premium versions of these are rated for electrometer use and feature ultra low bias current. These amplifiers also tend to have very low voltage and current noise.

Special feature These op-amps have some special characteristic that makes them particularly suited for special applications. The special characteristic generally comes by a compromise of other characteristics. A short list of op-amps of this type would include micro-power, audio applications, high output drive current, etc. Some other special features include zero offset voltage using a commutation technique, ultra high common-mode voltage range that may exceed the power supply voltage by a significant factor, and high power supply voltage amplifiers. The list here can continue to most anything imaginable.

Data Sheet Parameters

The following is a list of common data sheet parameters for op-amps.

Open-loop gain, Av The open-loop gain, Av, of an op-amp is typically very large and may range from around 10,000 to over 1,000,000. Av typically varies over about a five to one range from unit to unit. Av varies with temperature and power supply voltage. Av for large signals is generally less than Av for small signals.

Offset voltage This is the voltage difference between the non-inverting input and the inverting input when the op-amp is in a stable (i.e. no dynamics) condition with negative feedback and the output voltage is not saturated at either the upper or lower power supply rail. This voltage is typically in the single digit millivolts but can be over ten millivolts for very high speed op-amps. Some op-amps are factory trimmed so that the net offset voltage is well under 100 microvolts. The data sheet will show a guaranteed maximum and a typical value. These values represent a magnitude as the offset voltage can be of either polarity. A minimum value is never shown as that would be meaningless. The offset voltage is not purely static. It varies with power supply voltage, temperature, common-mode voltage, and other parameters. The maximum value shown on the data sheet often represents the worst case taking all parameters into account.

Offset voltage drift This specification is usually given as it relates to drift with temperature and has typical units of microvolts per degree C. The specification is usually given as a magnitude as the drift can be of either polarity.

Input bias current All op-amps must have some input bias current however small. This value is typically in the nanoampere region but is can be in the picoampere region for premium parts and even the femtoampere region for op-amps made for what is known as electrometer applications. Positive bias current is current into the part. Bias current can be either positive or negative and we are usually only concerned with the magnitude. Each input has its own bias current within the specified maximum magnitude on the data sheet. The data sheet shows a typical and maximum value. Bias current is not purely static. It varies with power supply voltage, temperature, common-mode voltage, and other parameters. The maximum value shown on the data sheet often represents the worst case taking all parameters into account. For bipolar op-amps, the temperature variation of IB is not too great. For FET op-amps, IB approximately doubles for each 10 degree C rise in temperature. Thus, at high temperatures, it is possible for a bipolar op-amp to have lower IB than a FET op-amp.

Input offset bias current The difference between the bias current for the non-inverting input and the bias current for the inverting input is known as the offset bias current (often referred to as the offset current). The data sheet indicates a maximum value that is typically in the range of ten to thirty percent of the magnitude of the maximum bias current. Input offset bias current is not purely static. It varies with power supply voltage, temperature, common-mode voltage, and other parameters.

Input bias current drift This specification is usually given as it relates to drift with temperature and has typical units of picoamperes per degree C. The specification is usually given as a magnitude as the drift can be of either polarity.

Common-mode input voltage range The common-mode input voltage must be between the specified limits in order for the op-amp to work. If the voltage is outside this range then the output of the amplifier is undefined – it may go to either the positive or negative rail and may even be inverted based on the differential input voltage. If the voltage is exceeded by only a small amount then no damage will occur and the amplifier will just not work. A very common mistake is inadvertently exceeding the common-mode input voltage range and observing erroneous behavior often attributed to a “bad part” when the real problem is “operator error.” The typical input common mode range is from a few volts above the lower power supply voltage to a few volts below the upper power supply voltage. Some op-amps are known as rail-rail input and the common mode input voltage includes the entire power supply range. For some op-amps the common-mode input range extends a few volts past one or both power supply voltages.

Maximum input differential voltage In normal usage with negative feedback, the input differential voltage is zero. However, when the op-amp is driven such that the output voltage can not drive the inverting input to match the non-inverting input then a differential input voltage exists.

Maximum output voltage This specification is a measure of how close the output voltage can be to the upper power supply. Typically, this is roughly 2.5 volts which means that for a +15 volt VCC, the maximum output voltage of a common op-amp is about 12.5 volts. Some op-amps have what is known as rail-rail output stages and those can put out a voltage that is within millivolts of VCC.

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Minimum output voltage This specification is a measure of how close the output voltage can be to the lower power supply. Typically, this is roughly 2.5 volts which means that for a -15 volt VEE, the minimum output voltage of a common op-amp is about -12.5 volts. Some op-amps have what is known as rail-rail output stages and those can put out a voltage that is within millivolts of VEE.

Maximum output current There is a limit to how much current the output stage of an op-amp can source or sink. Generally, this is around 5 mA but can be higher.

Maximum power supply differential voltage This is the maximum voltage that can exist between the VCC and VEE terminals. For many op-amps this is typically around 36 volts but can be higher or lower. A common power supply voltage for op-amps is +-15 volts for a total differential of 30 volts. A VCC of 100 volts and a VEE of 75 volts would also be fine for example – provided the input terminal voltages do not exceed the common-mode limits.

Gain-bandwidth product This is the extrapolated unity gain frequency which by definition is the frequency at which the gain of the op-amp has dropped to 1.0. This is often at least several hundred kilohertz and could be over 1 GHz for some op-amps. We normally do not use an op-amp past around one hundredth of its unity gain frequency but certainly no more than one tenth. The term, gain-bandwidth product comes from multiplying the gain of the amplifier at DC by the frequency at which the gain has dropped by 3 dB (this is often around 10 Hz).

Slew rate The slew rate is the maximum rate of change in the output voltage and has typical units of volts per microsecond. Low-bandwidth amplifiers may have a limit of less than a volt per microsecond. Wide bandwidth amplifiers may have a limit of over 50 volts per microsecond. The slew rate limit is usually different for positive going signals than for negative going signals.

Large signal bandwidth or Full power bandwidth This is the bandwidth over which the output of the amplifier can produce an undistorted full amplitude signal. This bandwidth is typically much less than the gain-bandwidth product. The reason for this is slew rate limiting. Sometimes the specification is provided as a specific peak-peak amplitude of several volts (for common applications) instead of the absolute full output (rarely used) so that the specification relates better to real applications and is not overly pessimistic.

Minimum stable gain This term is described in different ways depending on whose data sheet you are reading but it refers to the fact that many op-amps, especially wideband op-amps, will oscillate if the closed loop gain is less than a specified amount. Other op-amps are advertised as “unity gain stable” which means they will remain stable even for a closed loop gain of one. Unity gain stable parts typically have compromised high frequency characteristics to achieve unity gain stability.

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Input resistance This is the input resistance with respect to circuit ground and is often many megohms, especially if the input stage is based on field-effect transistors. Except for wideband amplifiers the input resistance is often treated as infinite. The specification is provided for the situations where a finite value will have a definite effect on circuit operation.

Differential input resistance This is the resistance between the non-inverting and inverting inputs. It is typically many megohms and in many cases can be treated as infinite. The specification is provided for the situations where a finite value will have a definite effect on circuit operation.

Output resistance This is the open loop output resistance and is often in the 50 to 200 ohm range at low frequencies and typically increases with frequency. The effective closed loop output resistance is the open loop value divided by the loop gain. For DC the closed loop output resistance typically works out to be in the milliohm or less range. The closed loop output resistance rises with frequency as the loop gain falls.

Common-mode rejection CMR is a measure of how well the amplifier rejects common-mode signals at the inputs. An ideal amplifier would have infinite rejection. CMR is given at DC and has typical specs in the 60 to 100 dB range and degrades as frequency is increased. At GBW, CMR may only be between 0 and 20 dB. Often there is a plot of CMR versus frequency.

Power supply rejection PSR is a measure of how well the amplifier rejects variations on the power supply voltages. An ideal amplifier would have infinite rejection. PSR is generally provided at some low frequency has typical specs in the 60 to 100 dB range and degrades as frequency is increased. At high frequencies PSR may be only between -6 and 10 dB. Note that switching power supplies put out considerable switching transients (0.5 to 1 volt peak-to-peak) in the 100 kHz to 5 MHz range. These transients will appear on the output of the op-amp unless proper power supply de-coupling techniques are used. Note that PSR for the negative supply is often worse than PSR for the positive supply.

Input voltage noise This specification is very important in determining how small a signal can be processed by the amplifier. Because the manufacturer can not know what bandwidth you will be using they provide the noise specification normalized to a one Hertz bandwidth. Thus, the units are typically nanovolts per root Hz. You multiply this value by the square root of the bandwidth you are using to obtain the rms noise voltage referred to the input of the op-amp. The noise at the output is input noise multiplied by the closed loop gain. At very low frequencies there are different noise effects and the manufacturer provides rms or even peak-peak noise over specific bandwidths.

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Input current noise This specification is very important in determining how small a signal can be processed by the amplifier. Because the manufacturer can not know what bandwidth you will be using they provide the noise specification normalized to a one Hertz bandwidth. Thus, the units are typically picoamperes per root Hz. You multiply this value by the square root of the bandwidth you are using to obtain the rms input noise current. Each input has its own (mostly uncorrelated) current noise. The current noise becomes a voltage noise when passing through external resistances at each amplifier input. The noise at the output is input noise voltage multiplied by the closed loop gain. At very low frequencies there are different noise effects and the manufacturer provides rms or even peak-peak noise over specific bandwidths.

Other notes

Many of the newer op-amps feature a common mode input range that extends from the lower power supply to the upper power supply. These are known as rail-rail input op-amps. Rail-rail input amplifiers are so easy to use that it is tempting to specify them for all circuits. Be aware that these parts tend to cost more and not work as well as non rail-rail amplifiers. The circuit methods to achieve this feat often lead to compromised DC specifications and the worst effect may be a shift in input offset voltage and current at different input voltage levels. This shift may be of no consequence in some circuits and may be a serious defect in others. The designer must understand the application and choose the appropriate op-amp. The general advice is to avoid these unless the rail-rail feature is essential. Always consult application information before using the part. That an op-amp has rail-rail inputs does not infer that it also has a rail-rail output.

Another feature of some of the newer op-amps is an output voltage range that extends from the lower power supply to the upper power supply. These are known as rail-rail output op-amps. Be sure to study the application information for the part as some unexpected effects may be present. These effects may be of no concern for some applications or a serious defect in others. The designer must understand the application and choose the appropriate op-amp. Rail-rail output is very convenient and is often essential for very low voltage applications. That an op-amp has a rail-rail output does not infer that it also has rail-rail inputs.

Some op-amps feature rail-rail inputs and rail-rail output. These are sold at a premium price. They are very convenient to use and generally work well but be aware of possible limitations or compromises in specifications. The general advice is to avoid these unless the rail-rail features are essential. At low power supply voltages of 5 volts or less, rail-rail input and output is typically a must have feature.