Maximizing the Signal: How to Use and Understand Embedded Operational Amplifiers

Introduction

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Operational Amplifiers are an extremely common analog building block used in a wide array of signal processing applications. However, when designing a signal chain, it is crucial to understand how to use an embedded operational amplifier and what the performance characteristics of the device mean in the application. This document covers some of the common analog characterizations and circuit configurations of the embedded operational amplifier.

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1. Basics of Operational Amplifiers

Operational amplifiers are a common building block in analog designs due to their low cost and high performance. The goal of the operational amplifier circuit is to match the voltage on the inverting (negative) input with the voltage on the non-inverting (positive) input. If the voltage on the inverting input is less than the non-inverting input, then the operational amplifier increases the output voltage to try and compensate for the error through the feedback in circuit.

This behavior is useful for circuit analysis, as the voltage applied to one input normally is matched on the other input. Another useful behavior of operational amplifiers is their extremely high input impedance. (Some specialized types of operational amplifiers may break this rule, but these are outside of the scope of this document.) The high input impedance keeps the input bias current of the operational amplifier inputs to a minimum, making it negligible in many general-purpose applications.

There are many different types and architectures of operational amplifiers, which vary in performance and characteristics. For example, a zero-drift operational amplifier is designed such that the voltage offset is very small and extremely stable across temperature. (See Voltage Offset for more information.) Unless otherwise stated, this document will focus on general-purpose operational amplifiers that are embedded in a microcontroller.

1.1 Discrete and Integrated Operational Amplifiers

One of the most important design decisions is whether to go with a discrete operational amplifier or an integrated (embedded) operational amplifier peripheral. Each of these solutions have specific strengths that can be used to evaluate whether they are the right approach for a design.

1.1.1 Discrete Operational Amplifiers

A major benefit to using discrete operational amplifiers is the high analog performance. Discrete operational amplifiers do not need to share I/O pins with the microcontroller and can use the full die area to enhance their analog performance. In addition, discrete operational amplifiers are available in specialty configurations and architectures such as zero-drift, instrumentation and current sense. Plus, a discrete operational amplifier can utilize a bipolar power supply.

Notes:

1. The integrated operational amplifiers can be set up into a similar configuration, at reduced analog performance. See 3.3. Instrumentation Amplifier for more information.
2. The integrated operational amplifiers can perform current sensing in certain circuit configurations.

1.1.2 Integrated Operational Amplifiers

The biggest advantage of integrated operational amplifiers is the reduction in design area and part count. Since the operational amplifier is on the die of the microcontroller, only one package is needed on the PCB. Another benefit of the integrated solution is the integration with the microcontroller. Unlike a discrete solution, the operational amplifier on the microcontroller can be configured and controlled digitally like other peripherals. Depending on the device family, this integration can be used to control features such as:

- Power on/off
- Signal gain control (available on devices with an integrated resistor ladder)
- Output state (varies by device; this may include tri-stated outputs, forced GND or V_{DD} output levels)

1.2 Signal Gain and Noise Gain

When working with operational amplifiers, a common term used is A_V, also known as gain. Specifically, A_V refers to Signal Gain, which is equal to the ratio of the output signal over the input signal:

$$A_v = \frac{V_{OUT}}{V_{IN}}$$

Another term sometimes used with operational amplifiers is called Noise Gain (NG). NG is the gain seen by the small, parasitic voltage sources in series with the device inputs. By analyzing the NG response with frequency, the stability of the operational amplifier's circuit can be determined.

Another use of NG is to predict the change in the Signal-to-Noise Ratio (SNR) with frequency. Some configurations of the operational amplifier have a flat response between Av and NG, such as in unity gain or non-inverting amplifier.

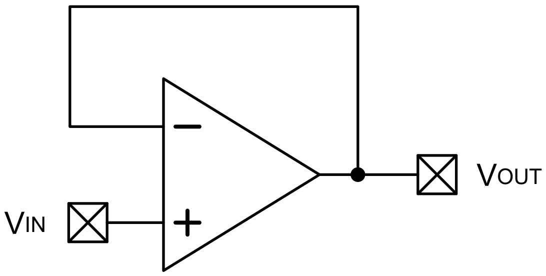
However, in other cases, the NG may increase faster than A_V, which implies a reduction of the SNR at higher gains.

2. Single Operational Amplifier Configurations

2.1 Unity Gain / Voltage Follower

One of the simplest configurations for an operational amplifier is unity gain, also sometimes known as a voltage follower. A unity gain operational amplifier has an output that is equal to the signal applied to the non-inverting input. The inverting input is connected directly to the output of the operational amplifier. This configuration is ideal for full-scale, high-impedance signals that are difficult to directly acquire with an Analog-to-Digital Converter (ADC).

Figure 2-1. Unity Gain Schematic



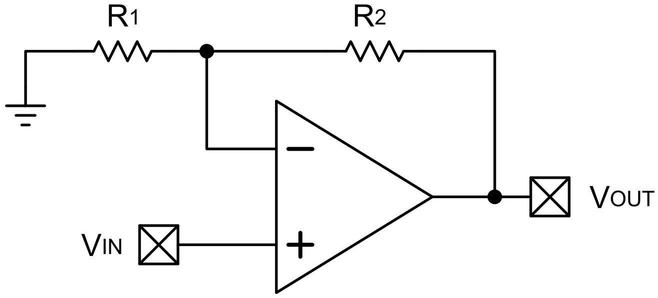
The output of this circuit can be calculated using the following formula:

$$V_{OUT} = V_{IN}$$

2.2 Non-Inverting Amplifier

Another very common configuration is as a non-inverting amplifier. A non-inverting amplifier has an output that is greater than the input signal. The schematic for the non-inverting amplifier is shown below.

Figure 2-2. Non-Inverting Amplifier Schematic



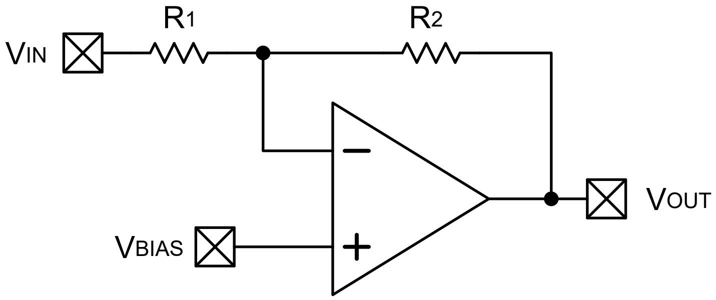
The output of this circuit can be calculated using the following formula:

$$V_{OUT} = \left(1 + \frac{R_2}{R_1}\right) * V_{IN}$$

2.3 Inverting Amplifier

An inverting amplifier is a configuration of the operational amplifier that inverts and scales the output.

Figure 2-3. Inverting Amplifier Schematic



However, due to the resistor feedback used with this configuration, the impedance of the input signal will affect the gain of this circuit; this can be seen by adding the signal impedance to R_2 in the output formula. Additionally, since the embedded operational amplifiers are single supply, the non-inverting input of the operational amplifier must be biased to ensure the signal remains within the output range of the operational amplifier.

The output of this circuit can be calculated using the following formula:

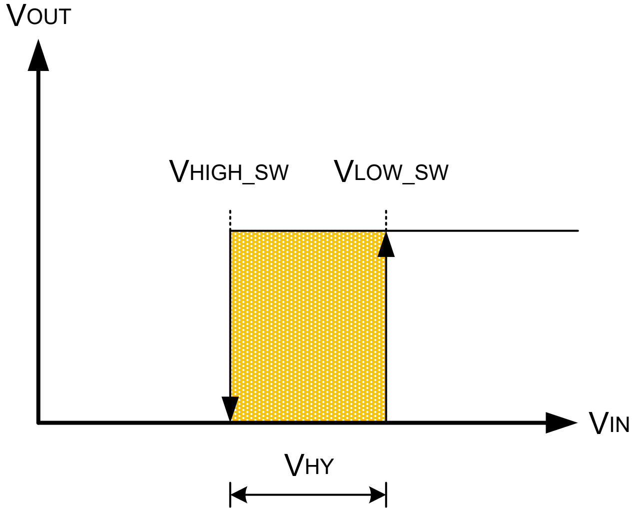
$$V_{OUT} = \left(1 + \frac{R_2}{R_1}\right) * V_{BIAS} - \left(\frac{R_2}{R_1}\right) * V_{IN}$$

⚠**WARNING** Never apply an input signal that exceeds the absolute maximum ratings of the device. Output signals with a predicted output above or below the absolute maximum ratings are self-limiting to the maximum or minimum values of the output range.

2.4 Schmitt Trigger

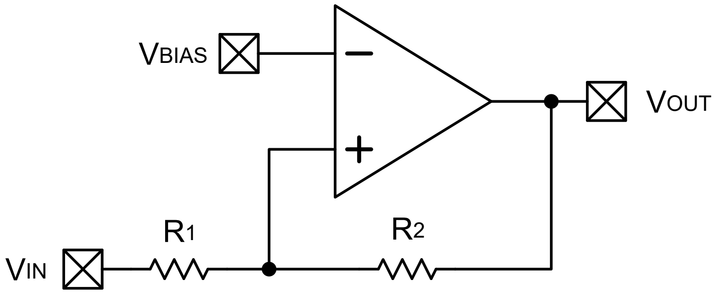
The Schmitt trigger is an analog comparator with *hysteresis*, a dead-zone where the output remains in the same state until the input exits the zone. This prevents a marginal signal from causing output oscillations. The output function for the Schmitt trigger is shown in the figure below.

Figure 2-4. Schmitt Trigger - Output Function Example



Unlike other configurations, the feedback network is connected to the non-inverting input. This creates positive feedback, which helps the output latch to either V_{DD} or GND.

Figure 2-5. Schmitt Trigger Schematic



The switching points of the Schmitt trigger are set by a combination of bias voltage and feedback resistors. In the state where the output is 0V, the feedback resistors act as a voltage divider. When the divided signal is greater than the bias voltage the output flips.

$$V_{LOW\_SW} = \frac{R_2 + R_1}{R_2} * V_{BIAS}$$

In the case where the output is V_{DD}, the feedback resistors also act as a voltage divider (with the resistors flipped).

$$V_{HIGH\_SW} = V_{DD} - \left(\left(\frac{R_2 + R_1}{R_1}\right) * V_{BIAS}\right)$$

From these two expressions, the amount of hysteresis can be calculated:

$$V_{HY} = \left|V_{DD} - \left(R_1 + R_2\right) * \left(\frac{1}{R_1} + \frac{1}{R_2}\right) * V_{BIAS}\right|$$

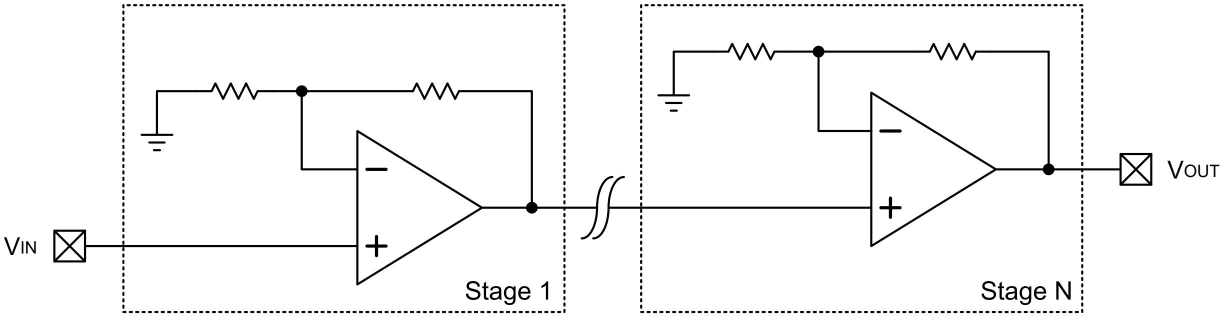
If the microcontroller contains an integrated resistor ladder, rather than entering absolute values into the above expression, the values of the resistors relative to a fixed (or arbitrary) value (for example, R_1 = 4R and R_2 = 6R, where R is an unknown or arbitrary number) can be entered since the resistance units cancel out.

3. Multi Operational Amplifier Configurations

3.1 Cascaded Amplifier

A cascaded amplifier is a configuration of the operational amplifier composed of two or more smaller configurations in series. An example of a cascaded amplifier could be two non-inverting amplifiers where the output of the first stage is the input of the next. In this scenario, the gain of the circuit is equal to the product of the gain in each stage. For example, in a two-stage cascaded amplifier with each stage having a gain of 9 and 5 respectively, the total gain is equal to 45. Figure 3-1 shows an example of this type of configuration.

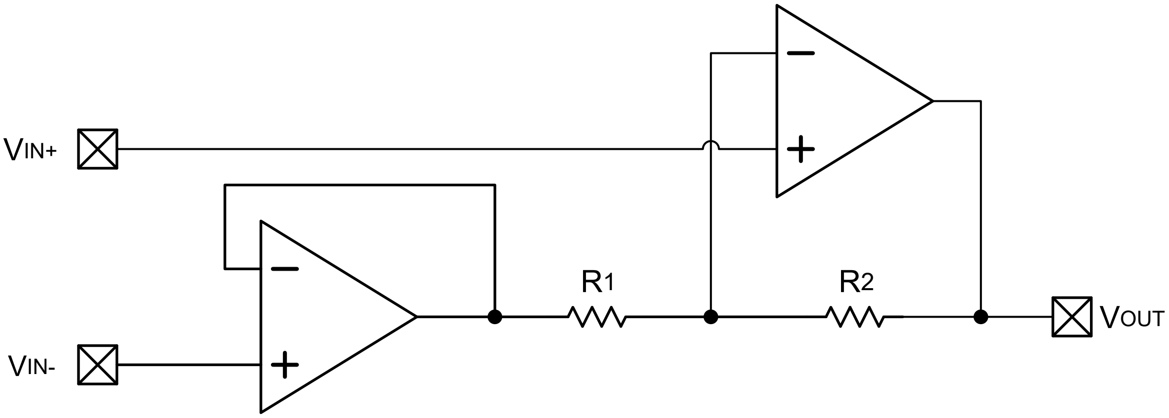
Figure 3-1. One Possible Cascaded Amplifier Configuration



3.2 Differential Amplifier

Differential amplifiers are designed to take two input signals and subtract them to get only the difference between the input signals. Differential amplifiers are related to, but distinct from the Instrumentation Amplifier. Figure 3-2 shows a differential amplifier implementation.

Figure 3-2. Differential Amplifier Configuration



One of the most important differences compared to the instrumentation amplifier is that the differential amplifier adds a bias voltage to the output. This is beneficial in that the output may remain valid if the inputs are flipped. However, the gain of each input is not matched, which may lead to unexpected outputs if both inputs change at the same time.

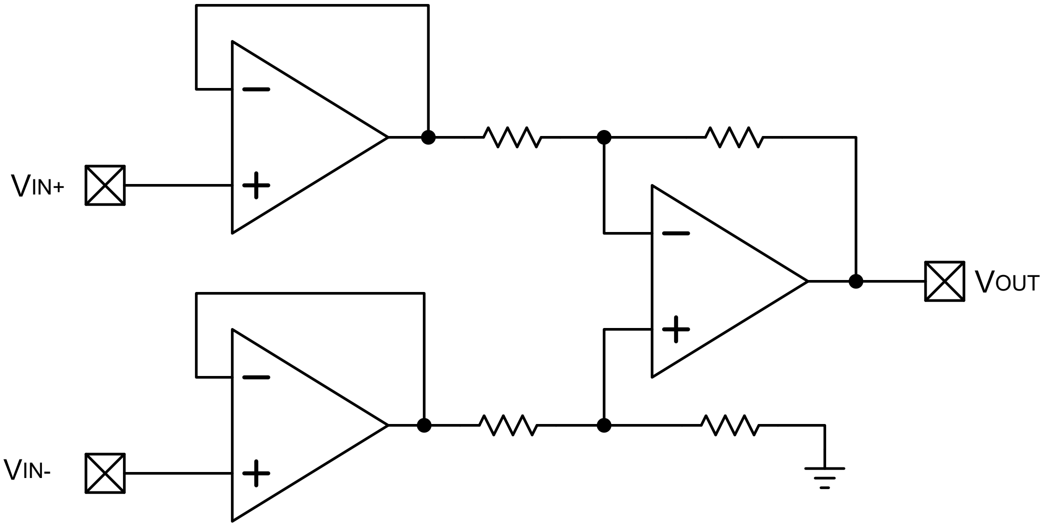
For the most predictability, either fix one of the inputs at a known constant, or measure one of the inputs before solving for the other. The output formula is shown below:

$$V_{OUT} = \left(1 + \frac{R_2}{R_1}\right) * V_{(IN+)} - \frac{R_2}{R_1} * V_{(IN-)}$$

3.3 Instrumentation Amplifier

Like the Differential Amplifier, instrumentation amplifiers are designed to amplify the difference between two input signals. An instrumentation amplifier uses three operational amplifiers while a differential amplifier uses only two. The configuration implemented in the microcontroller is shown below in Figure 3-3.

Figure 3-3. Instrumentation Amplifier Configuration



Note: Discrete instrumentation amplifiers may use a different circuit implementation that the one in the microcontroller.

Unlike the differential amplifier, the instrumentation amplifier inputs have a matched gain, which makes it easier to calculate the differential voltage when both inputs vary at the same time. However, the instrumentation amplifier configuration is unidirectional - if the inputs are flipped, the output will become ground (see 5.4. Output Swing for more information). The output formula is shown below:

$$V_{OUT} = (V_{IN+} - V_{IN-}) * GAIN$$

Consult the device data sheet for possible gain configurations for this circuit.

4. General Implementation Information

4.1 Resistor Selection

Resistors are almost always used as part of the feedback network for operational amplifier circuits. In most cases, the resistors in the feedback network are critical elements that determine the behavior of the circuit. Because of this, resistor tolerance can cause errors in the expected behavior of the circuit. Each resistor has a specified accuracy tolerance - the better the tolerance, the more expensive the resistor is. However, in most cases, the absolute accuracy of the resistor is not crucial: only the ratiometric accuracy with respect to the other resistor(s) in the circuit determines the circuit's accuracy.

On devices with an internal resistor ladder, the absolute accuracy of the resistor network is not tightly controlled, however the ratiometric accuracy on the ladder is more stable, as both resistors were fabricated on the same die in the same wafer lot. The internal resistor ladder is recommended for use in area-constrained applications and in applications where gain accuracy is not very strict (or can be calibrated out). The gain of the resistor ladders can be measured using the method discussed in Microchip Application Note AN3633, *"Gain and Offset Calibration of the Analog Signal Conditioning (OPAMP) Peripheral"* (DS00003633A) to calibrate out some of the errors in the ladder.

4.1.1 Thermal Drift

Another source of resistor error is thermal drift - if one resistor's temperature drift is different from the other, the error will increase as the temperature changes from the calibrated point. To avoid this effect, especially in applications at varying temperatures, the resistors must have the same temperature drift coefficient and be located as close as possible to each other to avoid temperature differentials.

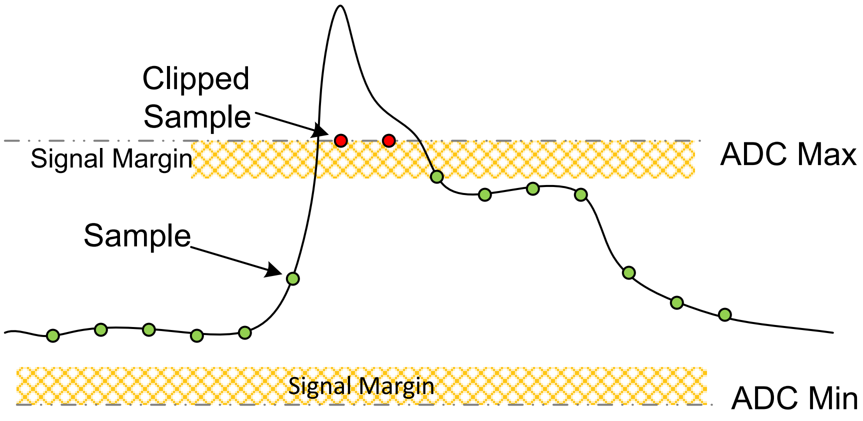
Another way to handle thermal drift is to use resistor networks (or arrays). These resistors are assembled in the same package, which keeps the network closely matched in temperature. Similarly, the internal resistor ladder is built on the die of the microcontroller, which keeps it tightly matched in temperature and in terms of temperature coefficient.

4.2 Signal Margin and Analog-to-Digital Converters (ADCs)

Analog-to-Digital Converters (ADCs) measure an analog signal and generate a digital value proportional to the input. To maximize the input signal range of the ADC, a larger voltage reference can be used, but this comes at the cost of signal resolution.

One solution for this is to use the operational amplifier to dynamically scale the input signal for more resolution from the ADC. However, when using the operational amplifier for signal gain, it is important to leave a small amount of margin to account for any errors in the signal chain. If the output of the operational amplifier exceeds the measurement range, then the digital value will be clipped at the largest value possible in the ADC. This is described in more detail in Microchip Application Note AN4225, *"Maximizing the Signal: Tips and Tricks to Properly Acquiring Analog Signals"* (DS00004225A).

Figure 4-1. Signal Clipping Example



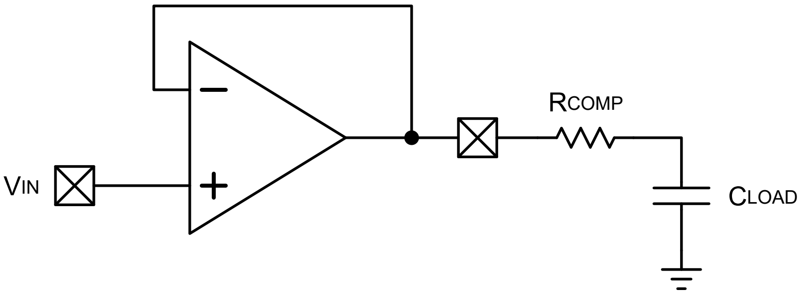
4.3 Capacitive Loads and Stability

One of the key parameters to keep in mind when using the operational amplifier is the load on the output. For heavy resistive loads, the Output Swing may reduce, but the amplifier will remain stable. However, heavy capacitive loads introduce a phase shift of the output in relation to the input (note that there may be a slight phase shift even in resistive operating conditions). If this phase shift causes the output to be too far out-of-phase, then the operational amplifier will begin to oscillate.

Note: This phase shift parameter is related to Phase Margin, which is discussed in more detail in Microchip Application Note AN723, *"Operational Amplifier AC Specifications and Applications"* (DS00723A).

The simplest way to stabilize the phase shift is to put a resistor between the output and the capacitive load, as shown below. The exact value of the resistor will vary depending on the load capacitance and the specific characteristics of the operational amplifier, such as maximum output current and slew rate.

Figure 4-2. Compensating for a Capacitive Load



4.4 Effects from Mixed Signal I/O

When using mixed signal I/O in the microcontroller with analog inputs, there are parasitic effects created by the I/O pads. The two biggest parasitics to consider are input capacitance and Electro-Static Discharge (ESD) diode leakage. The leakage through the ESD diodes is not Input Bias Current, which is the current entering or exiting the operational amplifier, but from a high-level view, the effect is similar. In some cases, the leakage through the ESD diodes may exceed the leakage from the input bias current. Higher operating temperatures will cause significantly higher current leakage than cooler temperatures.

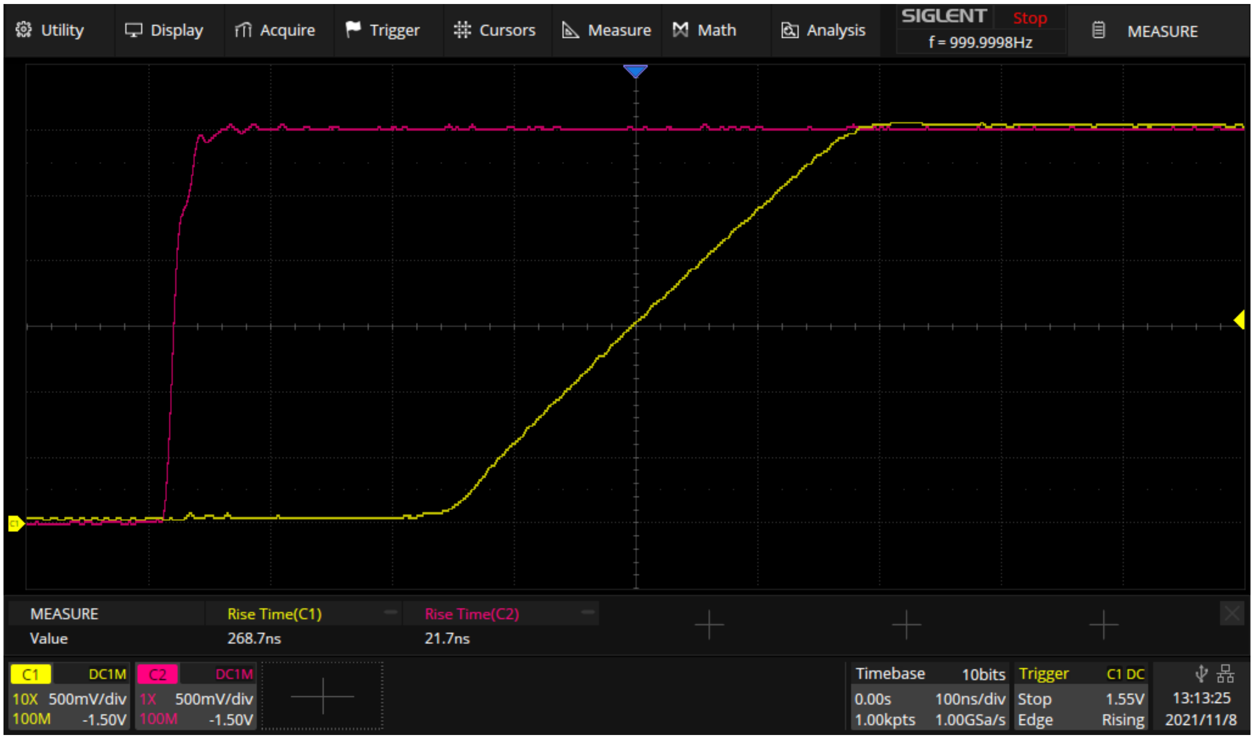
5. Performance Characteristics

Operational amplifiers, like all electronic components, have finite performance characteristics that differ from the ideal. This section of the document delves into the most common performance characteristics and how they can impact a design.

5.1 Slew Rate

The slew rate of an operational amplifier determines how fast the output signal can rise and fall. With an ideal square wave input, the output edges of the waveform should be near vertical, however a real waveform will have sloped edges, as shown in Figure 5-1.

Figure 5-1. Example of a slew rate limit



Stop
f = 999.9998Hz

MEASURE	Rise Time(C1)	Rise Time(C2)
Value	268.7ns	21.7ns

C1 DC1M 10X 500mV/div 100M -1.50V
C2 DC1M 1X 500mV/div 100M -1.50V
Timebase 0.00s 1.00kpts 10bits 100ns/div 1.00GSa/s
Trigger C1 DC Stop 1.55V Edge Rising
13:13:25 2021/11/8

Another consequence of slew rate is a reduction in bandwidth with high amplitude signals. This can be shown by calculating the derivative of the input signal. If the rate of change exceeds the slew rate, it will be limited to the maximum slew rate of the device, even if the signal is within the available bandwidth.

5.2 Open Loop Gain

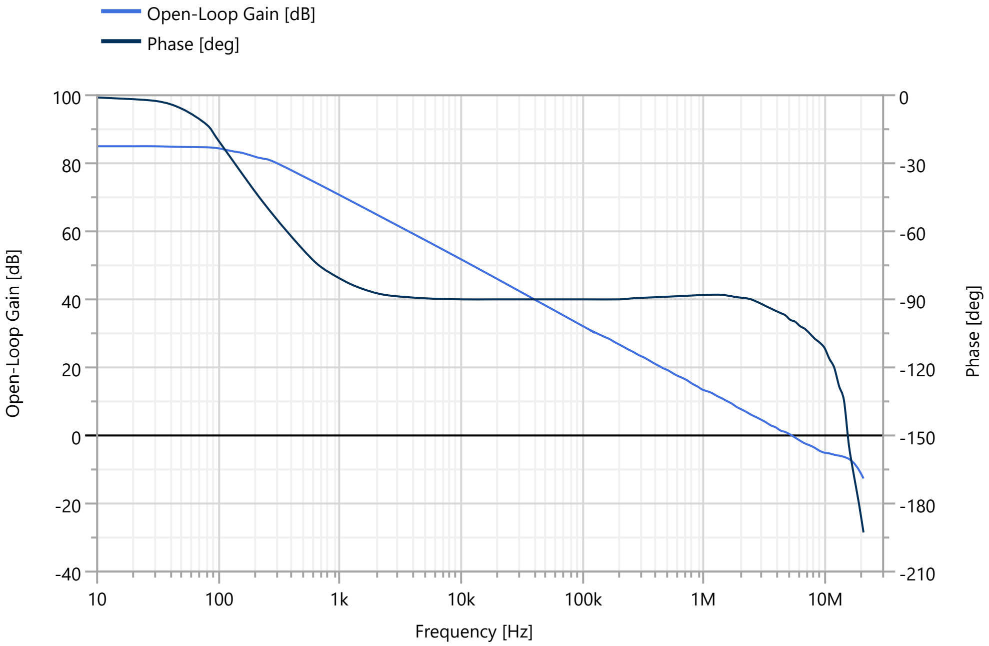
Recall from earlier in the 1. Basics of Operational Amplifiers - the operational amplifier is designed to try and null the difference in voltage between its inputs. Open loop gain is the change in output voltage due to a small change in input differential voltage, in the absence of negative or positive feedback.

Note: For stability and performance, the operational amplifier must always be used with some form of feedback.

5.3 Gain Bandwidth Product (GBWP)

The GBWP is an estimation of the maximum amount of gain possible at a given circuit bandwidth. At DC, the starting value is Open Loop Gain. For low frequencies, the gain will remain relatively stable–but not necessarily equal to Open Loop Gain–until a critical frequency, at which point the gain will start to fall by -20 dB per decade. The GBWP is the point at which the gain of the operational amplifier reaches 0 dB (unity gain). Figure 5-2 shows the open loop gain plotted by frequency for the operational amplifier on an AVR® DB microcontroller, with a GBWP of 5 MHz.

Figure 5-2. Open loop gain versus frequency for AVR® DB



The GBWP can be used to estimate the maximum gain of an operational amplifier at a given bandwidth. If an operational amplifier has a GBWP of 5 MHz, then at a gain of five, the maximum bandwidth is 1 MHz.

Note: It is strongly recommended to leave a margin for tolerances and non-ideal characteristics.

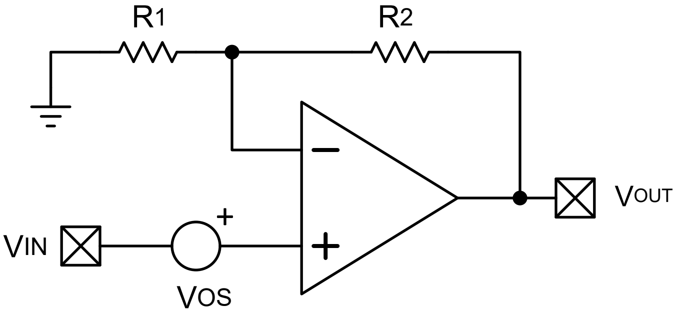
5.4 Output Swing

The output swing of an operational amplifier specifies how close to the power and ground rails the output can reach at a given output load. Some operational amplifiers are referred to as “Rail-to-Rail”, which indicates that the output can get very close to the power supplies compared to a standard operational amplifier. Heavier loads on the output of the operational amplifier will reduce the output swing range.

5.5 Voltage Offset

As mentioned earlier: the objective of the operational amplifier is to null the difference between its inputs to zero. However, due to the non-ideal properties in the operational amplifier, there is a slight voltage offset that is effectively added in series with the non-inverting input, as shown in Figure 5-3.

Figure 5-3. Non-Inverting Amplifier Configuration with Offset Voltage Shown



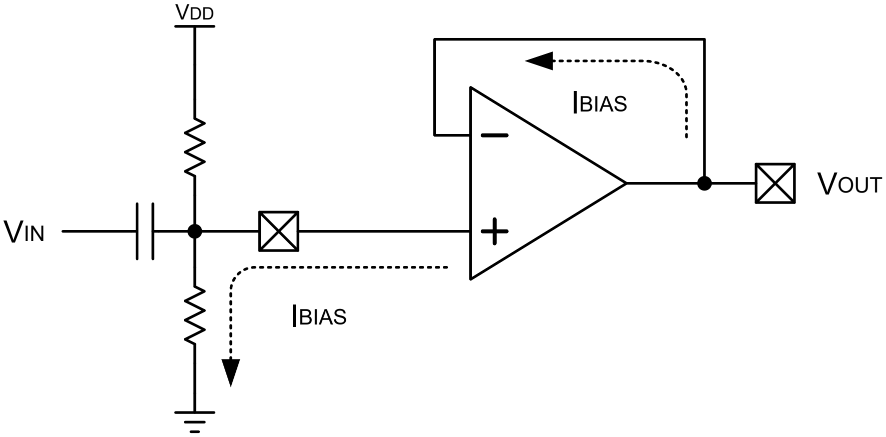
In many cases, this small input offset voltage is negligible or can be calibrated out. However, the gain of the operational amplifier will magnify the input offset as an unwanted component of the output. The gain as seen by the input offset voltage is referred to as the Noise Gain (NG), see 1.2. Signal Gain and Noise Gain for more information.

5.6 Input Bias Current

In the ideal operational amplifier, no current flows into the inputs of the operational amplifier. However, due to internal leakage currents, a small amount of current flows into (or out of) the inputs. Expect this current to be in the nA to µA range, with the current increasing significantly as temperature goes up.

It is important that there is always a path for this current to flow. If the input is AC coupled or the signal source is not referenced to the ground of the microcontroller, this charge can build up and cause erroneous behavior. A method of diverting this current is shown below in Figure 5-4.

Figure 5-4. Possible Return Paths for Bias Current



5.7 Input Common-Mode Voltage

Another limitation of operational amplifiers is the input common-mode voltage. This range is defined as the voltage that is common to both inputs of the operational amplifier. If the common-mode voltage is outside of the limits specified, the operational amplifier may malfunction, perform outside of electrical specifications, or become damaged.

5.8 Noise

Noise is one of the most complex topics to consider. There are many possible sources of noise, ranging from intrinsic noise within the operational amplifier to switching noise from changing I/O. This section will cover some of the most common sources of noise.

5.8.1 Crosstalk

Crosstalk is noise caused by fast rising or falling signals that couple into the inputs or outputs of the operational amplifier. Frequently, crosstalk occurs from digital signals that are near analog signals. Analog signals with a high input impedance are the most vulnerable to this type of interference.

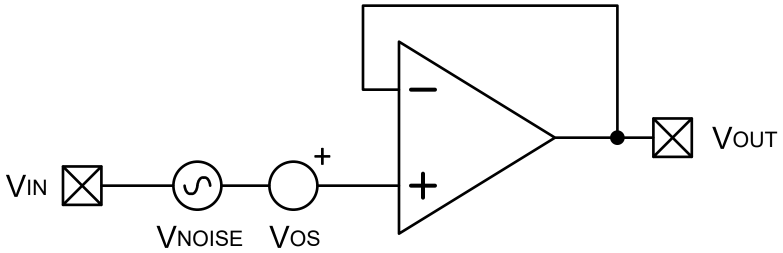
To minimize crosstalk, keep digital signals as far away from analog inputs and outputs as possible. For high noise signals, such as those from oscillators or clocks, these traces must be kept as short as possible. To minimize noise from the microcontroller, the device must be in sleep and the I/O must not be switched when sensitive operations are on-going. Another way to reduce crosstalk is to reduce the slew rate of the I/O, which reduces the high-frequency components created when switching.

For more information about reducing noise when using the Analog-to-Digital Converter (ADC), consult Microchip Application Note AN4225, *“Maximizing the Signal: Tips and Tricks to Properly Acquiring Analog Signals”* (DS00004225A).

5.8.2 Voltage Noise

Voltage noise is an estimation of the amount of noise internally added by the amplifier in series with the non-inverting input signal, as shown below.

Figure 5-5. Unity Gain Operational Amplifier with Voltage Offset and Noise Shown



This noise source is characterized in two frequency ranges - a low frequency range and a high frequency range. Input noise voltage is the equivalent voltage noise within the low-frequency range (commonly 0.1 to 10 Hz). Outside of this range, the noise can be calculated using the bandwidth of the circuit and the input noise voltage density.

For example, if a unity-gain operational amplifier had an input noise voltage of 100µV (pk-pk), input noise voltage density of 100 nV/rt(Hz) and a circuit bandwidth of 1 MHz, then the noise from the operational amplifier can be approximated (pk-pk):

$$V_{NOISE} = 100\mu V + 6.6 * 100\frac{nV}{\sqrt{Hz}} * \sqrt{1MHz - 10Hz}$$

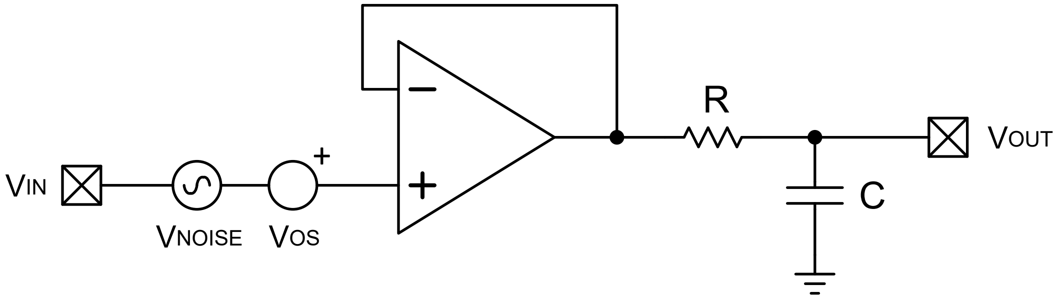
$$V_{NOISE} = 760\mu V$$

Notes:

1. For non-unity gain circuits, take the computed value and multiply by the noise gain of the circuit.
2. Input voltage noise density is usually specified in Root Mean Square (RMS) values, not peak-to-peak.
3. Circuit bandwidth must not be confused with the GBWP. Circuit bandwidth is specific to the maximum bandwidth the operational amplifier has in circuit.

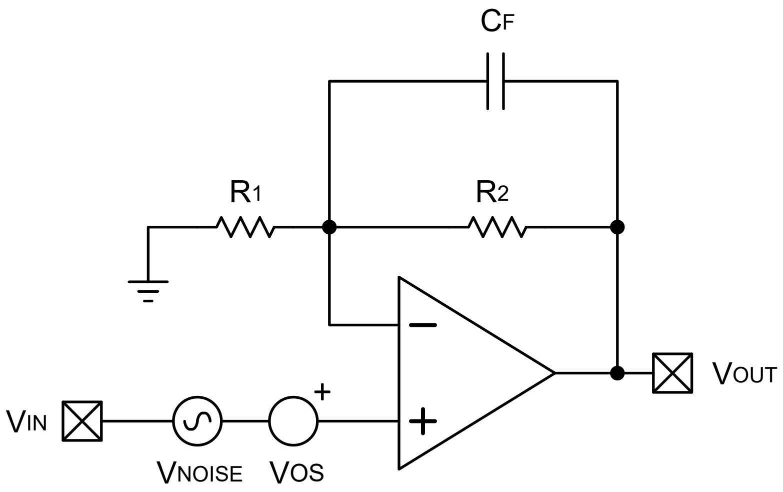
One way to reduce the amount of noise is to lower the bandwidth of the operational amplifier. This can be done in multiple ways. The first way is to put a low-pass filter on the output of the operational amplifier. This method increases the output impedance and may cause stability issues depending on the R and C used in the filter. The figure below shows this implementation:

Figure 5-6. RC Low-Pass Filter on the Output of the Operational Amplifier



The second way is to add a capacitor across the operational amplifier's feedback. This will cause the impedance of the feedback resistor to drop at high frequencies, thus reducing the amount of gain at higher frequencies, as shown in the figure below.

Figure 5-7. Reducing Noise Gain at High Frequencies



5.8.3 Removing Noise Digitally

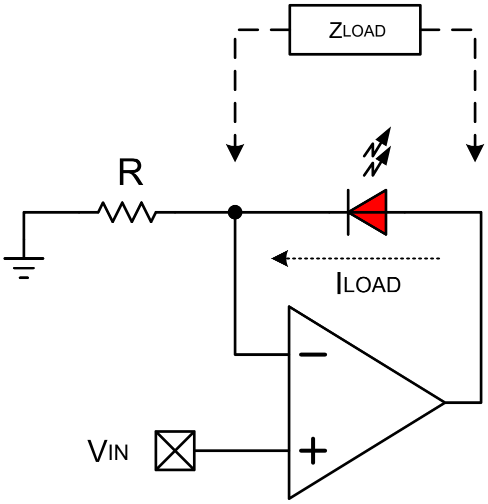
If the operational amplifier is being used with an Analog-to-Digital Converter (ADC), digital averaging of the data can remove or reduce the amount of noise present in a sample. All microcontrollers can perform this action in software; but some microcontrollers feature advanced ADC peripherals that can perform this operation in hardware for reduced CPU utilization. This method of noise reduction is further discussed in Microchip Application Note AN4225, *“Maximizing the Signal: Tips and Tricks to Properly Acquiring Analog Signals”* (DS00004225A).

6. Advanced Operational Amplifiers Applications

6.1 Voltage-Controlled Current Source

A voltage-controlled current source is a type of circuit where the current passing through a load is set by an input voltage. This type of circuit is especially useful for non-linear loads, such as LEDs (which have an exponential current-voltage relationship). An example circuit is shown below:

Figure 6-1. Voltage-Controlled Current Source Schematic



In this circuit, the LED from the output to the inverting input acts as the constant-current load. The resistor from the inverting input to ground sets the current response of the circuit, according to this formula.

$$I_{LOAD} = \frac{V_{IN+}}{R}$$

The ideal output response comes with a few caveats. This assumes the voltage at the inverting input is equal to the voltage at the non-inverting input, V_{IN+}, which is only true if the maximum output of the operational amplifier minus the voltage drop across the load is equal to V_{IN+}. If this condition is not met, the output will be current limited to:

$$\frac{V_{OH} - V_{LOAD}}{R} = I_{MAX}$$

Where V_{OH} is the max output voltage of the operational amplifier and V_{LOAD} is the drop across the load at I_{MAX}.

This example is shown in Microchip Application Note AN3632, *"Constant-Current Driver Using the Analog Signal Conditioning (OPAMP) Peripheral"* (DS00003632A).

7. More Information

For more information about the integrated operational amplifier, please refer to the following documents, available from the Microchip web site (www.microchip.com).

- AN682 – Using Single Supply Operational Amplifiers in Embedded Systems (DS00682D)
- AN723 - Operational Amplifier AC Specifications and Applications (DS00723A)
- AN1747 – Operational Amplifier Applications Using 8-bit PIC® Microcontrollers (DS00001747A)
- AN3521 – Analog Sensor Measurement and Acquisition (DS00003521A)
- AN3633 – Gain and Offset Calibration of the Analog Signal Conditioning (OPAMP) Peripheral (DS00003633A)
- AN4225 - Maximizing the Signal: Tips and Tricks to Properly Acquiring Analog Signals (DS00004225A)
- TB3279 – Optimizing Internal Operational Amplifiers for Analog Signal Conditioning (DS90003279A)
- TB3280 – Using the Operational Amplifier on PIC16 and PIC18 (DS90003280A)

8. Revision History

Document Revision	Date	Comments
A	02/2022	Initial document release

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