TB3280

Using the Operational Amplifier on PIC16 and PIC18

Introduction

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The Operational Amplifier (OPA) module for the PIC18-Q41 device family includes a variety of new features that enhance analog performance, while minimizing design time and cost. This peripheral has an integrated internal resistor ladder, which allows the OPA module to be used as a Programmable Gain Amplifier (PGA), without the need for external components. This peripheral also features hardware controlled override of the OPA modes of operation, and an input offset voltage calibration register. The OPA module, alongside the other advanced analog peripherals found on many PIC® microcontrollers, can be used for analog signal conditioning in sensor and real-time control applications. This technical brief will provide a detailed overview of the OPA module, discussing the peripheral features in detail and explaining the setup for each mode of operation. For more information about the analog performance and characteristics of this module, refer to TB3279 "*Optimizing Internal Operational Amplifiers for Analog Signal Conditioning*" (DS400003279A).

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1. Operational Amplifier

The Operational Amplifier (OPA) module is a general purpose operational amplifier that is integrated with the microcontroller, making control and configuration simple. Standard operational amplifiers have only a single connection per input to the operational amplifier (op amp), while this module contains a multiplexer that enables four external inputs for each of the inputs. In addition, this module also contains a secondary multiplexer, which enables inputs from the Digital-to-Analog Converter (DAC) modules, an internal programmable resistor ladder, or select reference signals (such as $V_{DD}/2$ or V_{SS}).

The OPA module also integrates a software output control that can be used to force the output of the op amp to V_{SS} or V_{DD}, ignoring the inputs to the op amp. In addition, the OPA module has a hardware controlled override, which enables another peripheral to change the output configuration between modes, such as Rail Drive, Forced Unity Gain or Software Configuration, without software intervention.

For ease of use, the OPA module has been integrated with the ADC to enable sampling of the output or the non-inverting input. This feature can be used to create a self-calibration routine. Refer to Input Offset Voltage Calibration Example for more information. When the op amp is not needed, the OPA module can be disabled to save both power and to free the I/O pins that the module controls.

2. Operational Amplifier Limits

For all operational amplifiers, the output is limited by the power rails. For the OPA module, it is single-supply, meaning that it can only utilize V_{DD} and V_{SS} for power. If a non-inverting amplifier has a predicted output in excess of V_{DD}, then the output will be limited to the upper output range. The same situation holds from an output less than V_{SS}, with the output clamped at the lower output range.

This assumes that both inputs are within the power rails of V_{DD} to V_{SS}. For example, if a negative voltage (V_{IN}-) was applied in an inverting configuration such that the output was within the valid area, the device would be damaged since V_{IN}- is not within the specified I/O pin limits or within the power rails of the amplifier.

The electrical specifications section of the device data sheet for the operational amplifier states how close to V_{DD} or V_{SS} the output can reach.

Important: The OPA module inputs have the same limitations as general purpose I/O. Inputs must be kept within the absolute maximum ratings, both for expected performance and part operation. Refer to the **"Electrical Specifications"** chapter in the device data sheet for details.

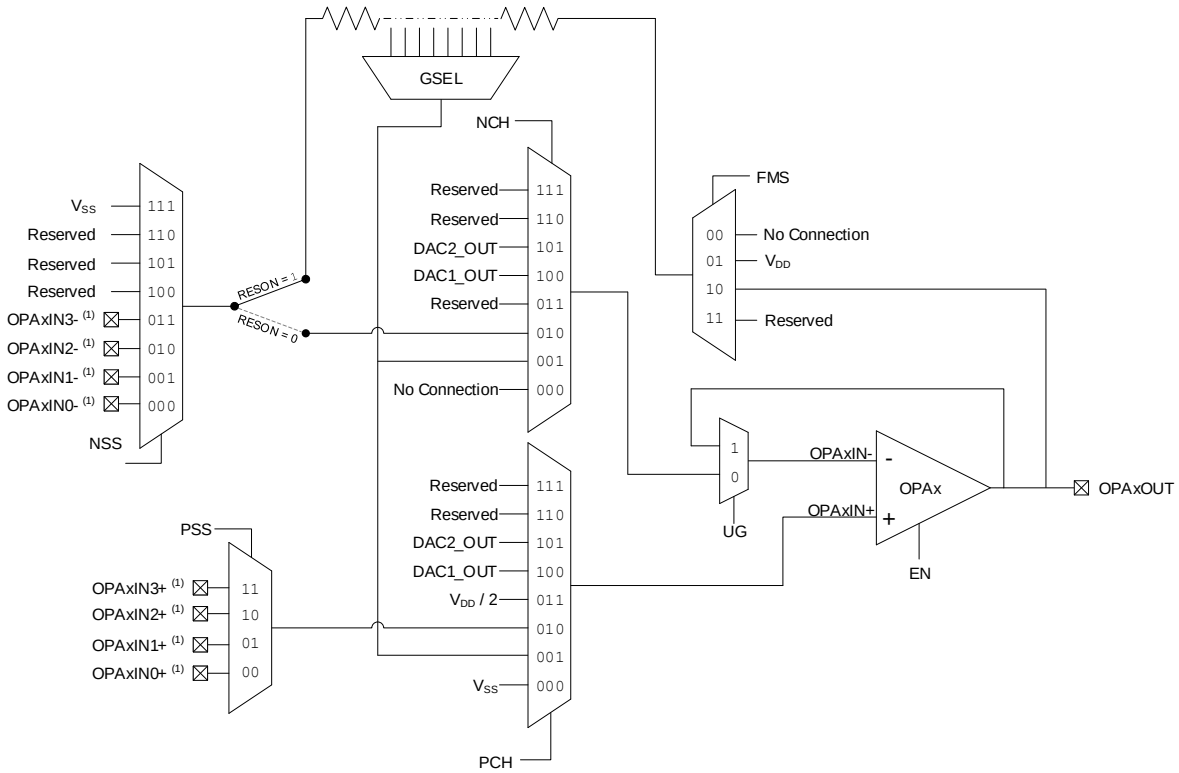
3. Module Overview

Unlike a discrete operational amplifier, the latest OPA module has unique features and integrations that reduce board space, the number of external components required, and allows for easy configuration. The module is configurable in software, which allows the designer to change gain settings, amplifier configurations, or to disable the module without using any external components.

Figure 3-1 shows the block diagram of the OPA module. The key components of this module are:

- Operational amplifier, which uses OPAxIN+ and OPAxIN- as inputs.
- Feedback control multiplexer (FMS), which selects the internal feedback path from the options of V_{DD}, OPAxOUT or No Connection.
- Unity gain multiplexer (UG), which is used to enable unity gain on the device.
- Channel input multiplexers (NCH and PCH), which selects which signal is connected to the operational amplifier's inputs.
- Resistor ladder (GSEL and RESON), which provides the programmable gain options for the operational amplifier.
- Input source multiplexers (NSS and PSS), which select the I/O pins that are inputs to the module.

Figure 3-1. PIC18-Q41 OPA Module Block Diagram



Note:

1. Refer to the "**Pin Allocation Table**" section of the device data sheet for details about OPAxIN- and OPAxIN+ availability per port.

4. Software Controls

4.1 Enabling the OPA Module

The OPA module can be enabled or disabled by writing to the EN bit of the OPAxCON0 register. Disabling the OPA module when not in use, saves power and allows OPA specific pins to be reused as general purpose I/O.

4.2 Software Output Control (SOC)

There are three software defined output modes that are selected using the SOC bits of the OPAxCON0 register:

- Basic operation in user-defined configuration or unity gain
- Rail drive to V_{DD}
- Rail drive to V_{SS}

In Rail Drive modes, the OPA module output is forced to V_{DD} or V_{SS}, depending on the configuration of the SOC bits. In these modes, feedback configuration and the OPA inputs do not affect the output. When the OPA module is configured in basic operation, the OPA module output will respond to the OPA inputs and the user-defined feedback configuration.

4.3 Internal Resistor Ladder

The OPA module includes an internal resistor ladder, which can be configured to control the gain of the operational amplifier.

The internal resistor ladder can be used to provide feedback to the OPA module using the following configurations:

- Set the RESON bit (RESON = `0b1`).
- Set the internal resistor ladder to the required value using the GSEL bits.
- The NSS channel must be configured to connect the OPA inverting input source to the internal resistor ladder.
  - In non-inverting configurations, NSS is usually grounded to V_{SS} (NSS = `0b111`).
  - In inverting configurations, NSS is connected to a user selectable input (NSS = `0b0xx`).
- Set one of the input channels (NCH or PCH) to use the Internal Resistor Ladder (GSS), (NCH or PCH = `0b001`).

4.4 Feedback Mode Selection

The Feedback Mode Select (FMS) bits of OPAxCON3 are used to select how the internal feedback is connected to the internal resistor network. There are three configurations for FMS:

- Connected to OPAxOUT
  - Internally, feedback goes from the output of the operational amplifier (OPAxOUT) to the resistor ladder. This is often used in conjunction with the internal resistor ladder for setting the OPA module's gain.
- Connected to V_{DD}
  - There is no feedback through the multiplexer. However, the top of the resistor ladder is connected to V_{DD}, which can be used to create a programmable resistor divider.
- No Connection
  - There is no feedback through the multiplexer, and the top of the resistor ladder is floating. This mode is recommended when external components are connected to the feedback network of the amplifier[(1)].

Important:
1. Leaving FMS enabled may introduce a resistor in parallel with external feedback elements.

4.5 Unity Gain

The OPA module can be configured to force the module into a unity gain configuration. Unity gain can be enabled in software by setting the UG bit of the OPAxCON0 register. While in Unity Gain mode, the inverting input to the operational amplifier becomes connected to the output (OPAxOUT). The inverting input is not used in this mode, and the corresponding pins can be used as general purpose I/O. Refer to Common Configurations for more information.

Note: The NCH multiplexer must not be set to Resistor mode (`0b001`) when using Unity Gain mode. In this case, the I/O pin affects the output of the OPA module.

4.6 Charge Pump

The CPON bit of the OPAxCON0 register can be used to control the OPA module's internal charge pump. When the charge pump is enabled, the OPA module functions as a rail-to-rail(1) operational amplifier. The main tradeoff of the OPA charge pump is a significant increase in the quiescent current of the module.

Important:
1. Rail-to-rail operation refers to the output range approaching the power rail limits.

4.7 Input Offset Voltage Correction

The input offset voltage on devices with this OPA module are factory calibrated to within the specified limits listed in the **"Electrical Specifications"** chapter of the data sheet. For additional error correction, the OPAxOFFSET register can be used to correct for changes in operational amplifier performance over time or temperature. On a Power-on Reset, the OPA module defaults to the factory calibration, erasing any value that was previously written to OPAxOFFSET.

4.7.1 Input Offset Voltage Calibration Example

In this example, the OPA module is configured as an inverting amplifier. For improved precision, the module will periodically enter a calibration state where the OPA module must be set such that the input voltage, output voltage and gain are known exactly. To remove gain errors, the OPA module is put into Unity Gain. By measuring the difference between the input and the output with the ADC, the OPAxOFFSET register is stepped in increments, until the difference in value is within a user-set tolerance.

Figure 4-1. Normal Operation Mode

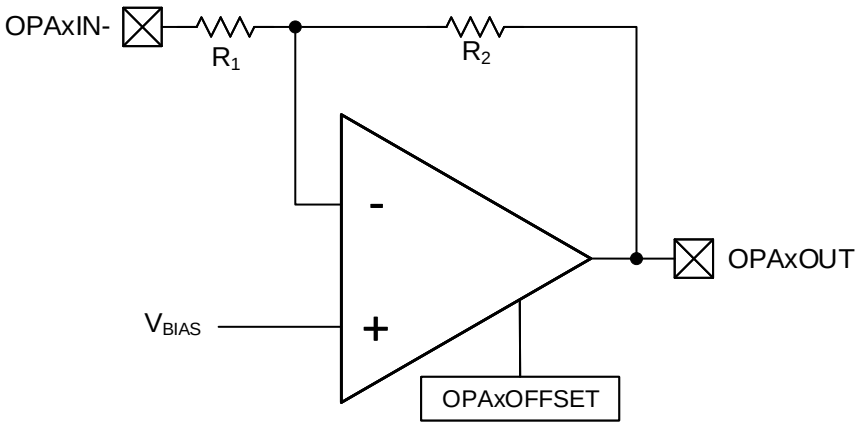
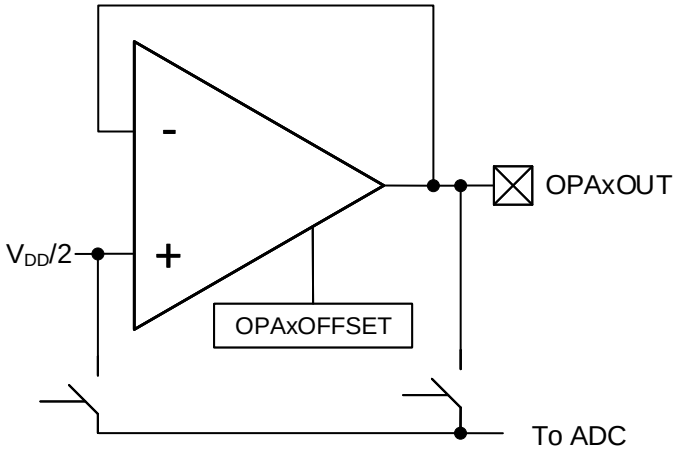
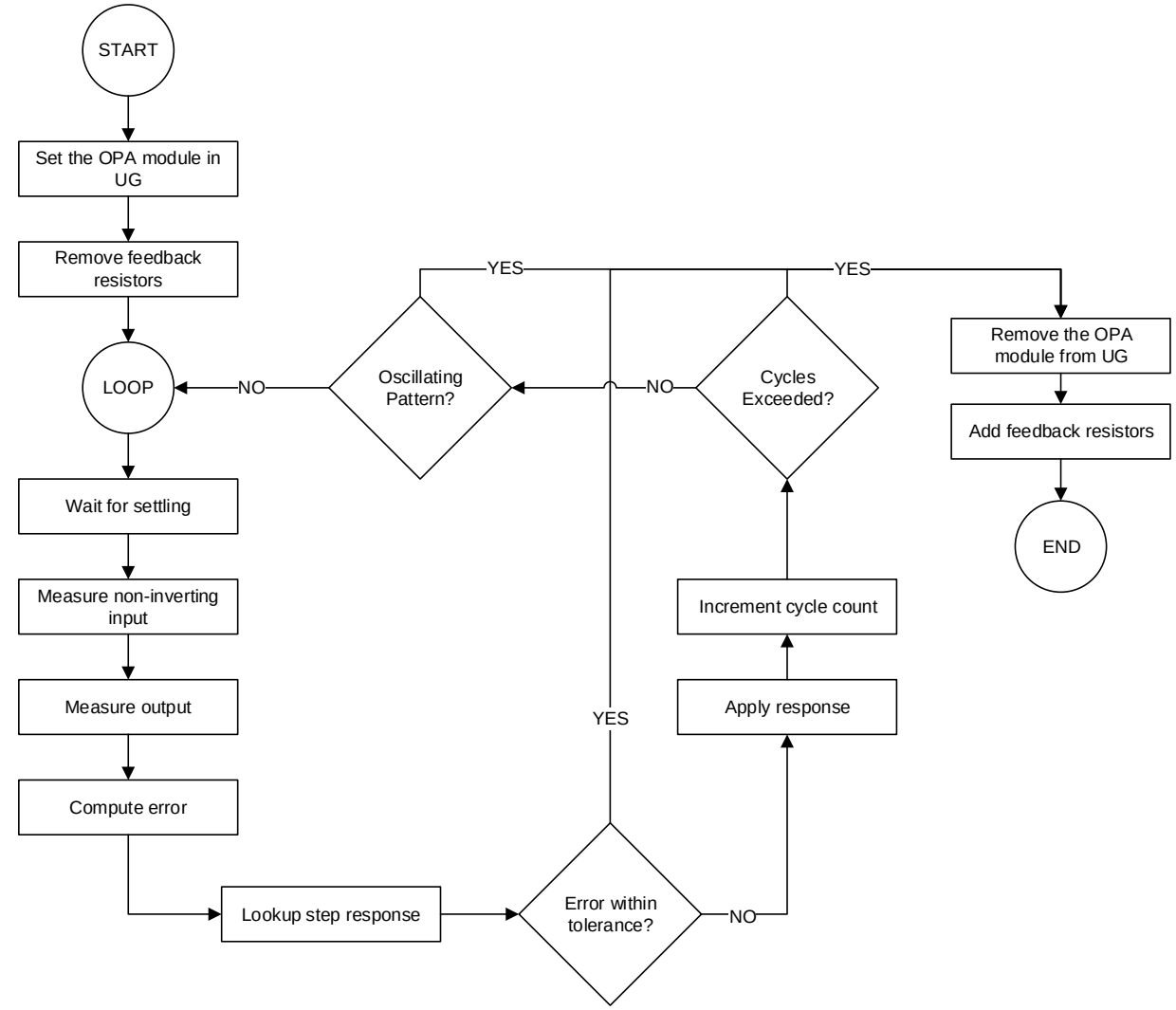


Figure 4-2. Calibration Mode



Important: The specific performance of calibration in-field is dependent on the environment and what the part is doing in the background at the time. It is unlikely to be as accurate or stable as a calibration in a controlled lab.

Figure 4-3. Calibration Flowchart



View Code Examples on GitHub
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4.8 Pin Selections

When the OPA module is enabled, the module takes control of the specified output pin (OPAxOUT), overriding any TRIS[1] or PPS[2] settings. Any pin selected as an OPA input, such as OPAxIN-, will also be forced to become an input, regardless of TRIS or PPS settings. If the OPA module is configured in Unity Gain mode, then the OPAxIN- pins will be free to use as general purpose I/O.

Notes:

1. Setting the TRIS bit allows a pin to be an input, and clearing the TRIS bit allows a pin to be an output.
2. PPS allows the developer to map certain inputs and outputs to different pins.

4.9 Hardware Controlled Overrides

Another way to use the OPA module is to enable hardware overrides. The hardware controlled override allows for automatic switching between the following modes of operation:

- Basic operation with user-defined configuration
- Rail drive mode (V_{SS} or V_{DD})
- Unity Gain mode

The hardware controlled override allows the device to switch between the above modes, core independently. There are two bit fields associated with the hardware controlled override feature: the HWCH and HWCL bits. HWCH controls the hardware controlled override behavior when the override signal is active high while HWCL controls the override when it is active low. This could be used as a way of auto-ranging an input signal. In this example, one of the comparators would act as a trigger for the hardware controlled override, with HWCH and HWCL set to Unity Gain mode and basic operation.

The hardware controlled override features a polarity bit (ORPOL), which can be used to invert the override signal. This enables an active-high signal to trigger the active-low configuration, and vice versa. This can be used in the case where a V_{DD} output is desired when the source is low, since only HWCH can access the V_{DD} rail drive, and HWCL can only access the V_{SS} rail drive.

Hardware controlled overrides can be enabled using the following steps:

- Set OPAxORS to the trigger source.
- Setup OPAxHWC
  - Configure HWCH and HWCL.
  - Set ORPOL, if desired.
  - If software control is used, configure the OPA module appropriately.
  - Enable OREN.

Table 4-1. Override Polarity (ORPOL) Example

ORPOL Bit	Override Source is High	Override Source is Low
0	V_{DD}	Unity Gain
1	Unity Gain	V_{DD}

Note: HWCH is set to V_{DD}, and HWCL is set to Unity Gain.

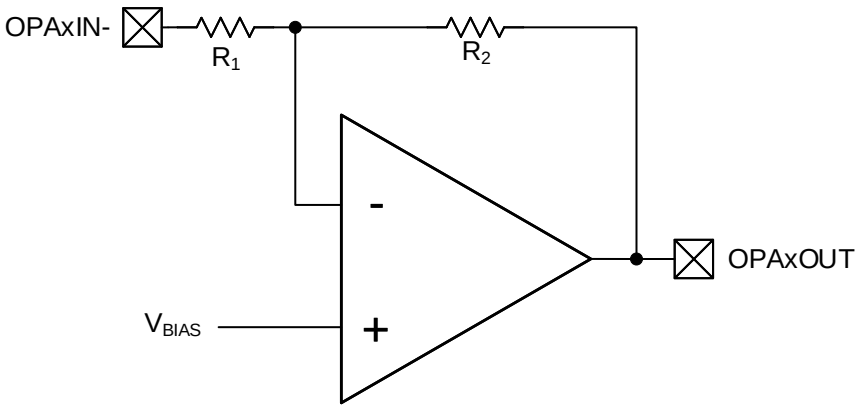
5. Common Configurations

The most common configurations of the OPA module are easily configurable in MPLAB® Code Configurator (MCC). MCC provides a visual interface generating initialization code and APIs to setup and use each peripheral on the part.

5.1 Inverting Amplifier

The inverting amplifier configuration requires a biasing source (Vbias) that comes from an internal analog signal or from an external reference. Vbias level shifts the output of the OPA module and subtracts the scaled signal from the level-shift. Inverting amplifiers are commonly used to invert signals or for signals that need to be scaled up or down. The internal resistor ladder of the OPA module can be used to implement the OPA module (see Figure 5-1). The code snippet in 5.1.1 utilizes the internal resistor ladder and the Vdd/2 internal signal for a gain of -3 after shifting.

Figure 5-1. Inverting Amplifier



5.1.1 Inverting Amplifier Setup

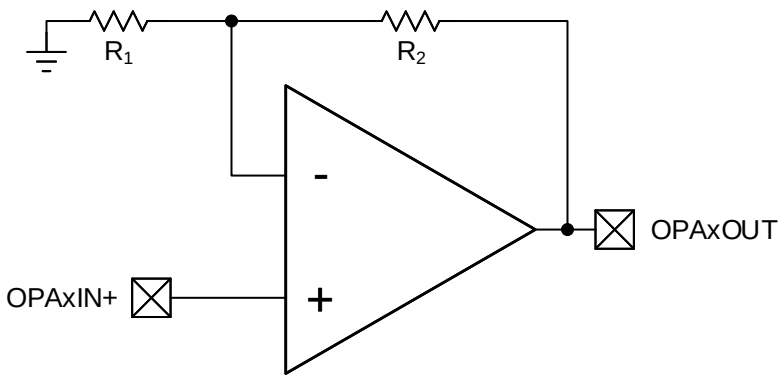
Example 5-1. Inverting Amplifier Setup

```
void InvertingSetup(void)
{
    OPA1CON0 = 0x00;
    OPA1CON1 = 0x00;

    OPA1CON1bits.RESON = 1;
    OPA1CON1bits.GSEL = 0b101;  //Gain of 3

    //Select OPA1IN0- as the input
    OPA1CON1bits.NSS = 0b000;

    OPA1CON2 = 0x00;

    //Connect the inverting input to the resistor ladder
    OPA1CON2bits.NCH = 0b001;

    //Connect the non-inverting input to Vdd/2
    OPA1CON2bits.PCH = 0b011;

    OPA1CON3 = 0x00;

    //Enable internal feedback
    OPA1CON3bits.FMS = 0b10;

    //Enable the Module
    OPA1CON0bits.EN = 1;
}
```

5.2 Non-Inverting Amplifier

A non-inverting amplifier is a configuration of the operational amplifier where the input signal is scaled by a gain (A_V) greater than 1. Non-inverting amplifiers are commonly used with small or sensitive signals, such as those from a current-sense line. The circuit shown in Figure 5-2 can be implemented using the internal resistor ladder rather than external components. The code snippet in 5.2.1 shows an example implementation with a gain of 2.

Figure 5-2. Non-Inverting Amplifier



5.2.1 Non-Inverting Amplifier Setup

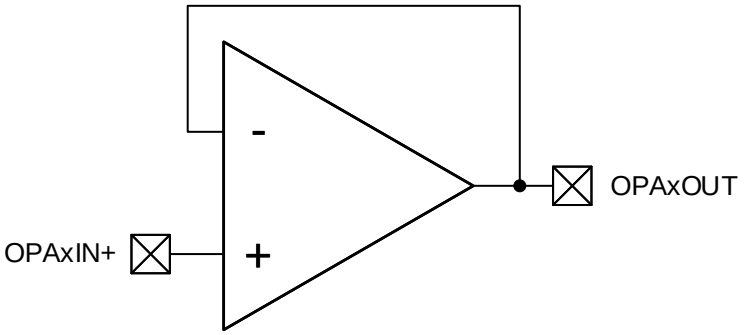
Example 5-2. Non-Inverting Amplifier Setup

```
void NonInvertingSetup(void)
{
    OPA1CON0 = 0x00;
    OPA1CON1 = 0x00;
    OPA1CON1bits.RESON = 1;
    OPA1CON1bits.GSEL = 0b011;  //Gain of 2

    //Ground the resistor ladder
    OPA1CON1bits.NSS = 0b111;

    OPA1CON2 = 0x00;

    //Connect the inverting input to the resistor ladder
    OPA1CON2bits.NCH = 0b001;

    //Connect the Non-inverting input to OPA1IN+
    OPA1CON2bits.PCH = 0b010;

    OPA1CON3 = 0x00;

    //Select OPA1IN0+ as the input
    OPA1CON3bits.PSS = 0b00;

    //Use internal feedback
    OPA1CON3bits.FMS = 0b10;

    //Enable the Module
    OPA1CON0bits.EN = 1;
}
```

5.3 Unity Gain

Unity gain, also known as a voltage-follower or buffer, is a configuration of the operational amplifier that causes the voltage applied to the non-inverting input to be matched by the output. Unity gain is commonly used to buffer high-impedance sources, such as resistor dividers. The OPA module has an internal switch to enable unity gain operation without the need for an external wire, as shown in Example 5-3. See section 4.5 Unity Gain for more information about this feature.

Figure 5-3. Unity Gain Buffer



5.3.1 Unity Gain Setup

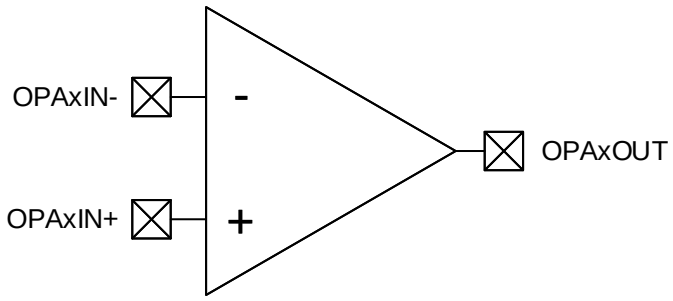
Example 5-3. Unity Gain Setup

```
void UnityGainSetup(void)
{
    OPA1CON0 = 0x00;
    OPA1CON0bits.UG = 1;

    OPA1CON1 = 0x00;
    OPA1CON2 = 0x00;

    //Connect the Non-inverting input to OPA1IN0+
    OPA1CON2bits.PCH = 0b010;

    OPA1CON3 = 0x00;

    //Enable the Module
    OPA1CON0bits.EN = 1;
}
```

5.4 Custom

In this configuration, the internal resistor ladder and the internal feedback system is disabled. The inputs to the operational amplifier are routed to the I/O pins (OPA1IN+ and OPA1IN-). The code snippet in 5.4.1 shows an example setup for this mode of operation, with OPA1IN0+ and OPA1IN0- selected as the pins.

Figure 5-4. Custom Configuration



5.4.1 Custom Setup

Example 5-4. Custom Setup

```
void ExternalSetup(void)
{
    OPA1CON0 = 0x00;
    OPA1CON1 = 0x00;

    //Select OPA1IN0-
    OPA1CON1bits.NSS = 0b000;

    OPA1CON2 = 0x00;

    //Connect the Inverting Input to OPA1IN-
    OPA1CON2bits.NCH = 0b010;

    //Connect the Non-inverting input to OPA1IN+
    OPA1CON2bits.PCH = 0b010;

    OPA1CON3 = 0x00;

    //Select OPA1IN0+
    OPA1CON3bits.PSS = 0b00;

    //Enable the Module
    OPA1CON0bits.EN = 1;
}
```

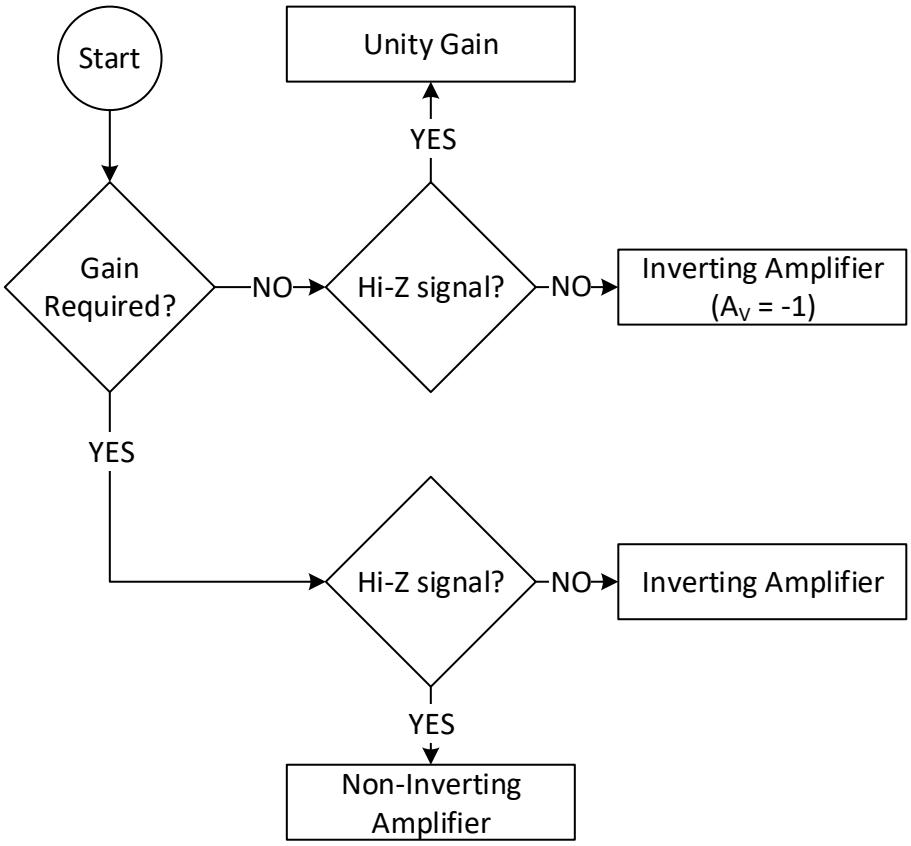
6. Configuration Selection

Choosing a gain configuration is a design decision that is dependent on a few key parameters:

- Maximum input level
- Frequency of the signal
- Signal sensitivity
- Source impedance
- Gain accuracy

A full circuit analysis is required to find the best configuration, but Figure 6-1 shows a simplified example decision tree for DC signals. AC signals are more complex to analyze and require AC parameters specific to the device.

Figure 6-1. DC Gain Configuration Flowchart



7. Conclusion

Operational amplifiers serve a key role in analog design. Microchip's OPA module provides an easy path to integrate and design a simple analog signal chain, using minimal external components. The operational amplifier is software configurable, which allows designers to switch between different amplifier configurations with ease.

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