
Operational Amplifier Applications Using 8-Bit PIC[®] Microcontrollers

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INTRODUCTION

An operational amplifier (op amp) is a high-gain direct-coupled differential amplifier. It is an analog data processing element used in various applications. Knowing the characteristics of the op amp is vital when choosing it for a specific purpose, which in turn calls for knowing the application requirements well. There are an overwhelming number of end applications that an op amp can be used in, and this document discusses a few of them, while not attempting to cover all of them.

The transfer function of the amplifier with feedback can be effectively controlled by some of the passive elements in the network. For any application, during the initial design, it would be safe to assume that the op amp is ideal. But, applications demanding a more precise requirement would need the designer to look at some non-ideal parameters and characteristics of the op amp. While certain routine requirements can be accomplished using some popular rules of thumb, a more thorough analysis of the characteristics would be needed when the performance requirements of the application are severe.

This document aims at uncovering some of the more important parameters of the op amp and the significance in certain applications. Specific examples and case studies of applications using the on-chip op amp of the PIC16F families of microcontrollers will be discussed. A comparison of the characteristics of the op amp on PIC16F will be done with the stand-alone op amps like MCP602 and TL082.

Note: For information on the fundamentals and operating principles of op amps, refer to application notes AN682, AN722, AN723 and AN1177. These are available on the Microchip web site.

CHARACTERISTICS OF OP AMP

Before going into the characteristics of the op amps on PIC[®] microcontrollers, taking a look at some of the important parameters of a generic op amp will illustrate their significance. For some of the parameters, comparison of the internal op amp on PIC16F is done with other stand-alone op amps like MCP602 and TL082. These are standard op amps available in the market that are commonly used for the applications discussed in this application note.

HIGH FREQUENCY ROLL-OFF AND COMPENSATION IN OP AMP

If the input of an op amp with negative feedback receives a -180° out of phase replica of the output through the feedback network, then this will result in oscillations. Op amps mostly have a 'high frequency roll-off' which means that eventually it will hit -180° phase, but this is at higher frequencies compared to the normal operating frequencies and is determined by many poles.

However, it has to be ensured that the roll-off happens when the gain has fallen well below '1'. One way to accomplish this is by forcing a roll off using a compensation capacitor. Since the gain of an op amp is generally high, it is very important to have a high-frequency roll-off, without which they are prone to high-frequency oscillations. A high-frequency roll-off can also be perceived as an inherent low-pass filter built into the op amp.

STABILITY IN OP AMP

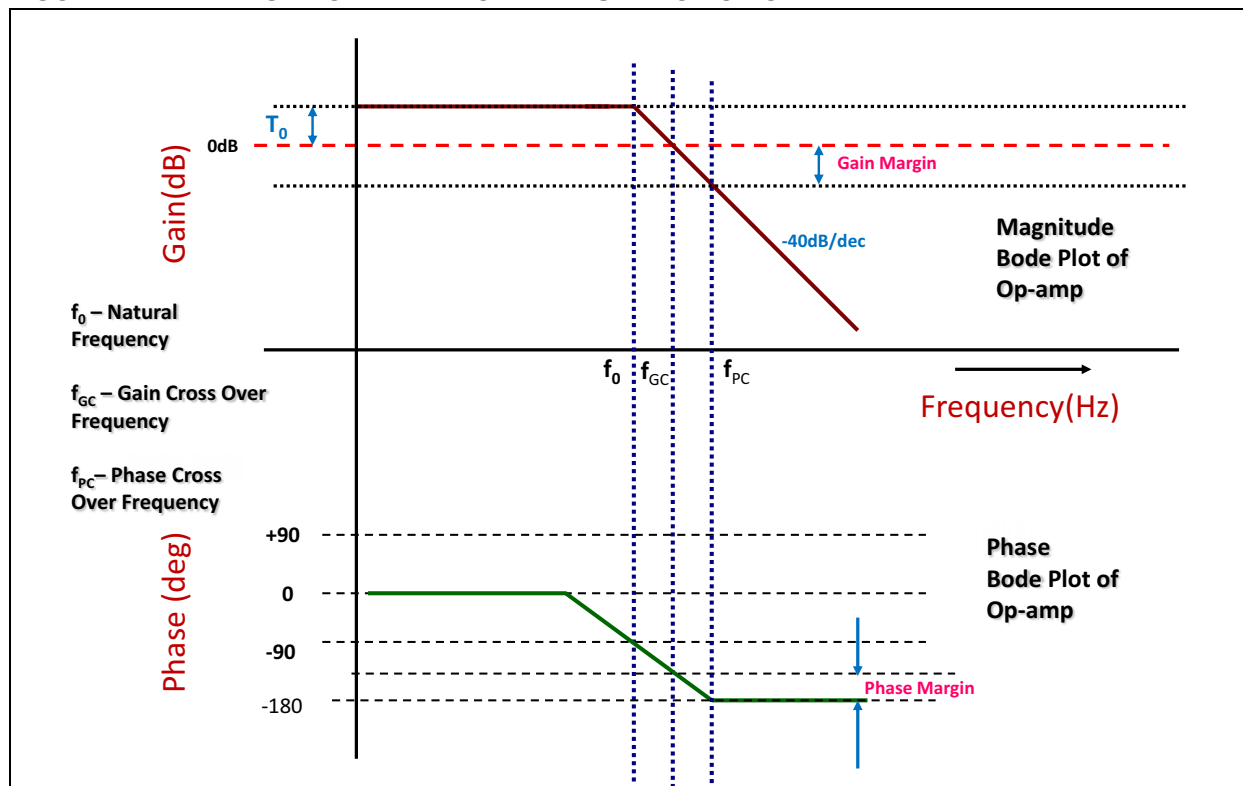
For an op amp based system to be stable, the closed-loop response must resemble a single pole response. If the closed-loop gain intersects the open-loop gain at a rate of 20 dB/decade, then the system is stable. When a point is reached where the closed-loop response falls at a rate of 40 dB/decade, the op amp will oscillate. One pole adds a 90° phase and hence two poles add 180° of phase. Once 180° of phase is added into the feedback path, the negative feedback system transforms itself into a positive feedback system; hence, will start producing oscillations.

PHASE MARGIN

As shown in the Bode phase plot of a generic op amp in Figure 1, phase margin signifies the phase shift at unity gain that is left to approach the 180° point. Phase margin is one of the figures of merit for analyzing the stability of an op amp. As can be seen from the same figure, the change in the phase does not necessarily happen at the corner frequency. Instead, the phase starts changing a decade back from the corner frequency itself. A phase margin of about 40° under standard operating conditions is typical of an on-chip op amp on a PIC16F microcontroller.

Note: For detailed information on the Frequency Domain Analysis of an op amp refer to the application note AN723, which is available on Microchip's web site.

FIGURE 1: MAGNITUDE AND BODE PHASE PLOT OF OP AMP



GAIN-BANDWIDTH PRODUCT

The selection of an op amp and its feasibility in a given application often stands on a few important parameters, of which the Gain-Bandwidth Product is one. As the name suggests, the product of the open-loop gain and the bandwidth is termed the Gain-Bandwidth Product. On a PIC16F microcontroller, the op amp has a Gain-Bandwidth Product of about 2 MHz with an open-loop gain of 90 dB, under standard operating conditions. Gain-Bandwidth Product on a standard op amp like MCP602 is 2.8 MHz and on a TL082 is 4 MHz. Higher Gain-Bandwidth Product is desirable in order to handle signals of higher frequencies.

Consider an application such as measuring the inductor current in a power converter which demands a bandwidth of about 100 kHz and a gain of 10, the Gain-Bandwidth Product requirement on a cursory glance appears to be about 1 MHz. However, when looking at the Bode plot, it is evident that the point where the closed-loop gain intersects the open-loop gain, the response is 3 dB lower. Hence, a Gain-Bandwidth Product of 1 MHz would not suffice and a factor of 5 to 10 should be accommodated when choosing the op amp.

SLEW RATE

There is always a limit over the rate of change of the output in any op amp, and this limit is termed as slew rate. This means that the output of the op amp can swing without deviating from the desired response only if the rate of change of the output is within the slew rate of the op amp. Due to the circuit design, op amps can have different slew rates during the positive and negative swings. However, slew rates in most of the fast op amps are reasonably symmetrical. Slew rate is often expressed in V/us, and in the case of PIC16F microcontrollers, it is about 3V/us as compared to 2.3V/us on a MCP602 and 13V/us on a TL082. If the slew rate is higher, it means that the response to changes in the op amp input are faster.

INPUT BIAS CURRENT AND OFFSET VOLTAGE

To an op amp user, the input bias current is an issue because this current flows through external impedances and creates offset voltages, thereby adding to the errors in the design. The input structure of an op amp often uses a current-controlled device like a BJT (Bipolar Junction Transistor). Hence, there is always some current needed to keep the device operating, and there will be some offset voltage as well. In the PIC16F, the typical value of the offset voltage is about ± 3 mV when compared to ± 0.7 mV on a MCP602 and ± 5 mV on a TL082. The Input Offset Voltage should be very less relative to the operating voltage range of the op amp. Since there are two inputs

in the op amp, there are two bias currents as well and in most cases, these can be assumed to be equal. If there is a considerable difference in the two input bias currents, then this will result in input offset current.

INPUT COMMON-MODE VOLTAGE

The allowable voltage on the input pins is called the input common-mode voltage. Since the PIC16F family of controllers have rail-to-rail op amps, the input common-mode voltage is often the full supply range, which is '0' to VDD. However, referring to the specific device data sheet would provide the exact numbers.

COMMON-MODE REJECTION RATIO

A small output will result from a change in the input common-mode voltage. The reason for this is that there will always be a slight mismatch between the resistors and transistors at the two input terminals in an input stage of the op amp. This small error also gets amplified along with any other signal that appears at the input. Hence, the rejection of such a signal is important. The ability of the op amp to reject such common-mode signals seen at the input terminals is termed as Common-Mode Rejection Ratio (CMRR). The CMRR is one important measure of op amp efficiency. Typically, a CMRR of 70 dB is achievable using the op amps on PIC16F family devices. On a MCP602, the CMRR is 90 dB and on a TL082, it is about 100 dB. Higher CMRR indicates that the rejection of common mode noise is better in the op amp.

POWER SUPPLY REJECTION RATIO

The influence that the power supply voltage ripple has on the output voltage of the op amp is measured using the Power Supply Rejection Ratio (PSRR) of the op amp. It is usually of the order of 80 dB in a typical op amp. The best and only way to improve the ripple rejection in an op amp is to have a good filtering of the power supply output voltage itself. PSRR on a MCP602 is about 88 dB and on a TL082 is about 100 dB. If we use a PIC16F, which has a PSRR of 80 dB, in a circuit designed to give 20 dB closed-loop gain, this would allow about 0.1 mV of power supply ripple to be superimposed on the output for every 100 mV of ripple in the supply.

Covered so far are some key parameters necessary for choosing an op amp or while designing an op amp based circuit. The table below shows all the parameters and their normal range.

For further details about a specific op amp, please refer to the respective device data sheets on the Microchip web site.

Comparison Between PIC16(L)F1782, MCP602 and TL082

DC and AC Characteristics		Standard Operating Conditions (unless otherwise stated) of Device V _{DD} , Temperature 25°C, High-Power Mode									
		PIC16(L)F1782/3 (V _{DD} = 3V)			MCP602 (V _{DD} = 5.5V)			TL082 (V _{DD} = 15V)			
Symbol	Parameters	Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.	Units
GBWP	Gain-Bandwidth Product	—	2	—	—	2.8	—	—	4	—	MHz
PM	Phase Margin	—	40	—	—	50	—	—	45	—	degrees
SR	Slew Rate	—	3	—	—	2.3	—	8	13	—	V/μs
OFF	Offset	—	±3	±9	-2	±0.7	+2	—	±5	±15	mV
CMRR	Common Mode Rejection Ratio	55	70	—	75	90	—	70	100	—	dB
AOL	Open Loop Gain	—	90	—	100	115	—	—	—	—	dB
V _{ICM}	Input Common Mode Voltage	0	—	V _{DD}	V _{SS} - 0.3	—	V _{DD} - 1.2	±11	+15 -12	—	V
PSRR	Power Supply Rejection Ratio	—	80	—	80	88	—	70	100	—	dB
—	Op Amp Pin Output Current	—	—	±100*	—	—	±22	—	—	±20	mA

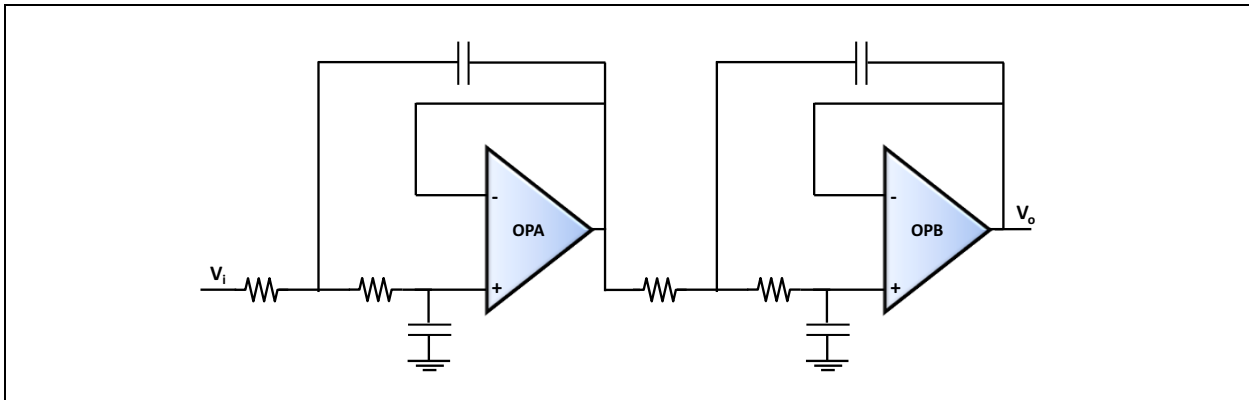
* Care should be taken not to exceed the Max current, since no on-chip short circuit protection is provided.

(Information in this table is taken from
 PIC16(L)F1782/3 Data Sheet (DS41579),
 MCP601/1R/2/3/4 Data Sheet (DS21314),
 TL082 Texas Instrument Data Sheet and ST Data
 Sheet).

OP AMP IN SIGNAL PROCESSING

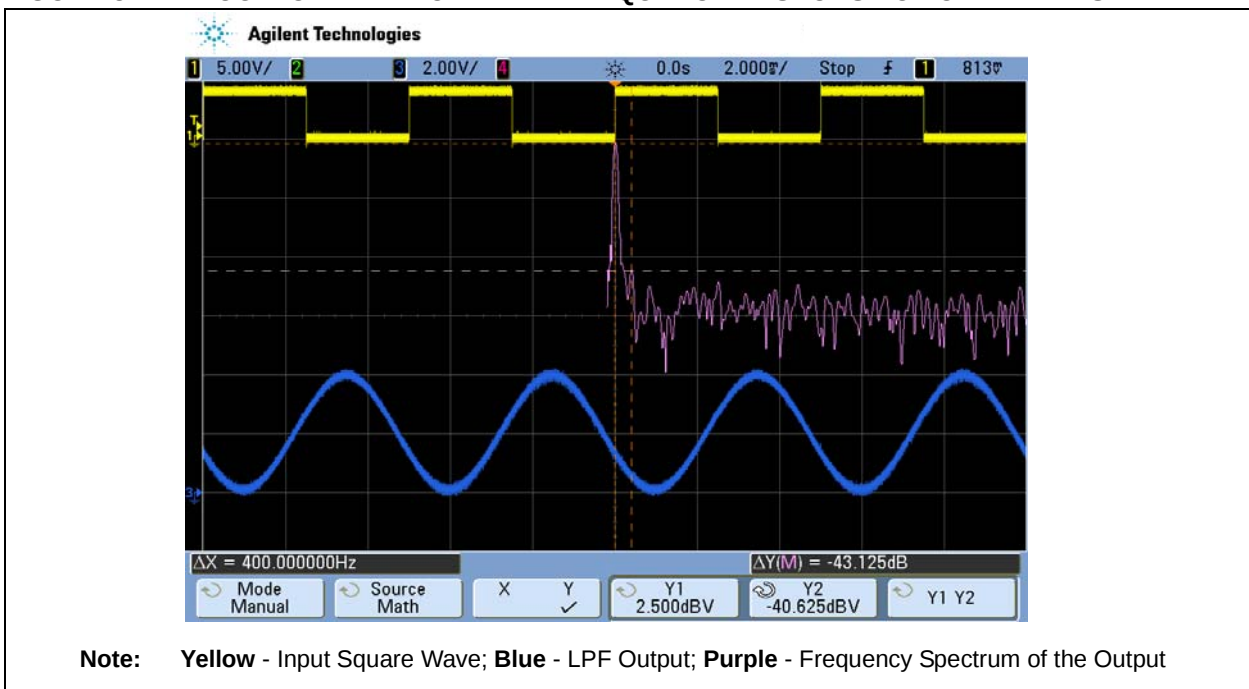
Consider the design of a system which yields a sine wave output with a square wave given at its input. If the fundamental frequency of the square wave is about 200 Hz, our aim would be to generate a sine wave of the same frequency. Looking at the frequency spectrum of the square wave, it can be observed that there are signals of many odd frequencies other than the signal at the fundamental frequency itself. So, consider designing a low-pass filter in Sallen Key configuration, as shown in the [Figure 2](#).

FIGURE 2: OP AMP IN A LOW-PASS FILTER APPLICATION



The cut-off frequency for the filter can be chosen to be about 250 Hz, such that all the signals at higher order frequencies are attenuated to a large extent and their effect on the output is almost nullified, as shown in [Figure 3](#).

FIGURE 3: OUTPUT WAVEFORM AND FREQUENCY RESPONSE OF OP-AMP BASED LPF



Usually low-frequency signal generation becomes important when designing low-frequency sensors. The sensors normally adopt a technique called correlation to detect any presence of low-frequency signals. This is described in detail in the Application Note AN1523 on “Sine Wave Generation Using Numerically Controlled Oscillator Module” in a case study. The signal to be tested or detected is correlated with a reference low-frequency signal. This reference low-frequency signal can be generated using the technique just described.

Applications that may require low-frequency generation or detection are:

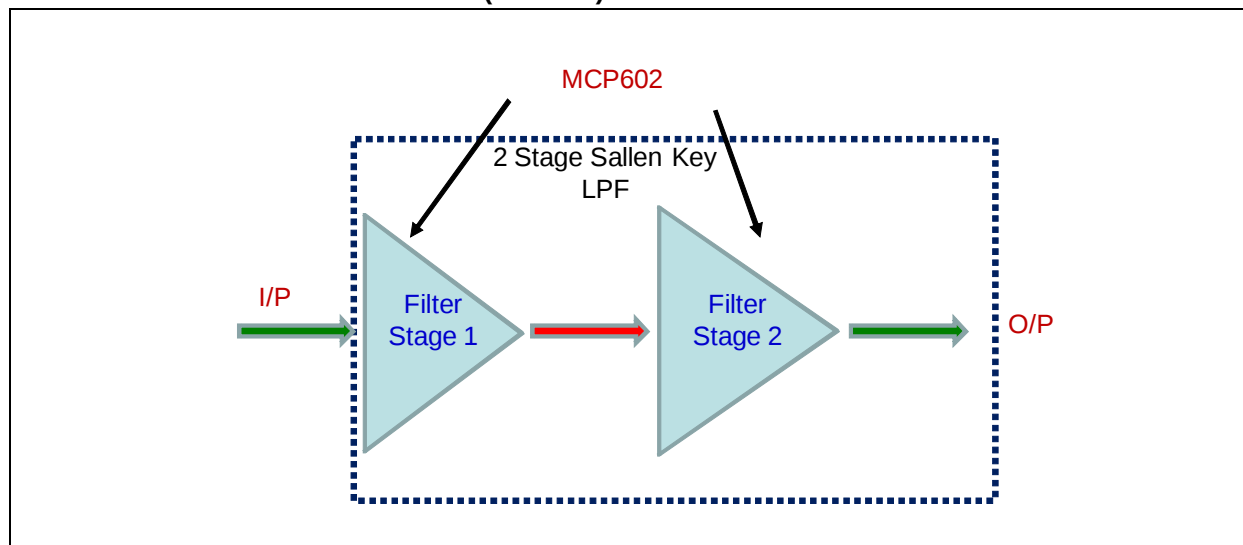
- Low-frequency sensors in geotechnical and pipeline leak detection systems
- Extremely low-frequency detection for locating hot spots, low-frequency radiation from electrical appliances
- Seismic wave detection – These are normally in the range of 1 Hz to few 10s of Hz
- Notification Appliance Circuits (NAC) to awaken individuals in case of fire or other hazards – Here, low-frequency tones are preferred in the case of individuals with low to severe hearing loss
- Low-frequency and low-impedance pressure sensors for engine combustion and turbulence detection applications

PERFORMANCE COMPARISON OF INTERNAL OP AMPS WITH RESPECT TO EXTERNAL OP AMPS

For a signal processing application like the one described, attempt to compare the performance of the low-pass filter using internal op amps of a PIC16F1783 microcontroller against a stand-alone Microchip op amp like MCP602.

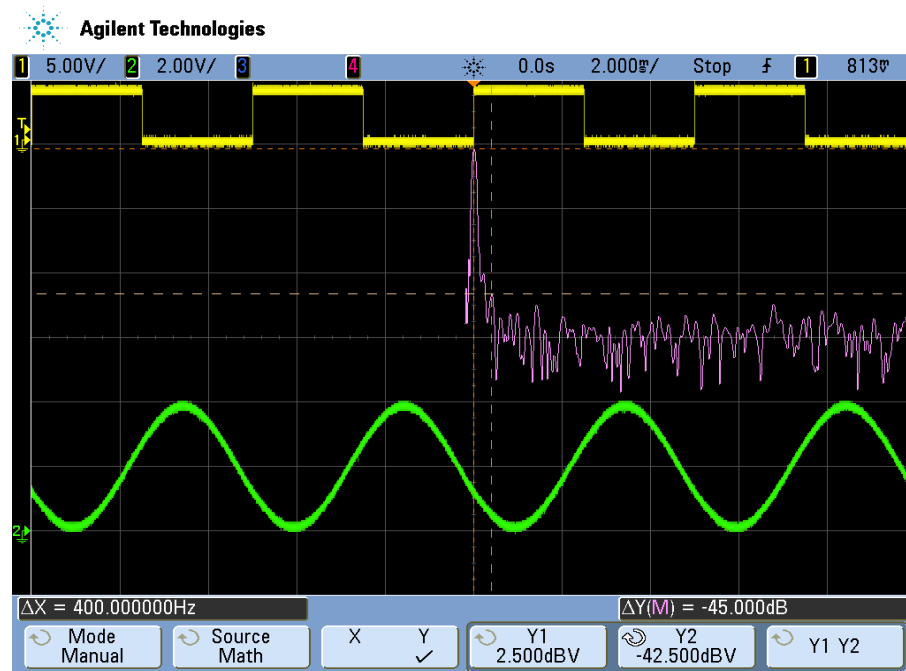
First, consider the two-stage Sallen Key Low-Pass Filter, designed using two MCP602 op amps. The simplified diagram of the Two Stage Sallen Key Filter described previously is shown in [Figure 4](#).

FIGURE 4: EXTERNAL OP AMP (MCP602) IN A LOW-PASS FILTER APPLICATION



The Frequency Response of the output of this filter is shown below (see Figure 5).

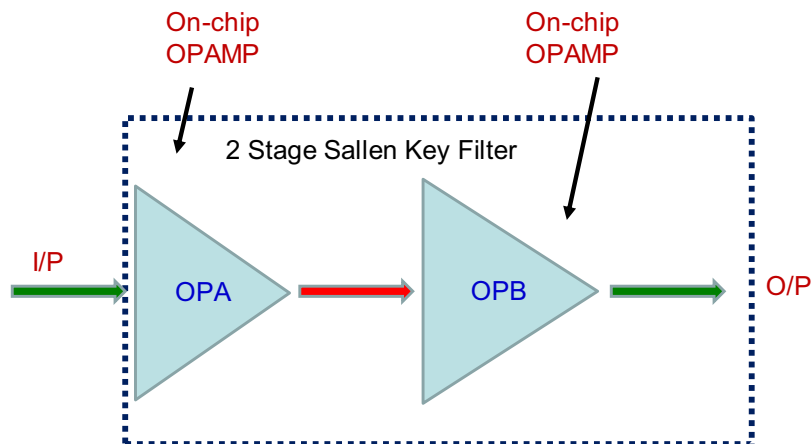
FIGURE 5: SCOPE PLOTS OF MCP602 BASED LPF



Note: Yellow – Input Square Wave; Blue – LPF using two MCP602 op amps; Purple – FFT of the sine wave (green waveform).

Now, consider designing a similar filter using the two op amps on a PIC16F1783 controller.

FIGURE 6: INTERNAL OP AMP (PIC16F1783) IN A LOW-PASS FILTER APPLICATION



The Frequency Response of the output of this filter is shown below (see Figure 7).

FIGURE 7: SCOPE PLOTS OF PIC16F1783 BASED LPF

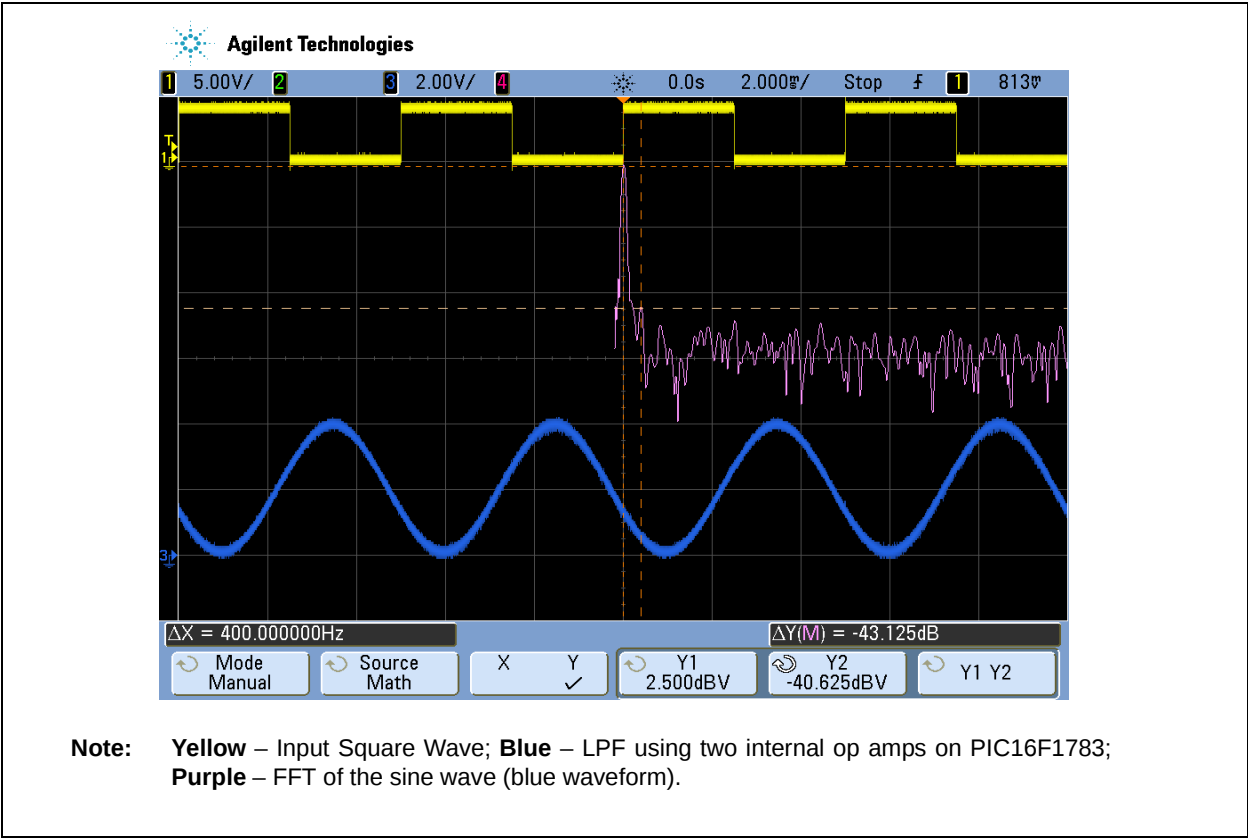


TABLE 1: COMPARISON OF PERFORMANCE OF LOW-PASS FILTERS

	Input Square Wave	Sallen Key Filter with two MCP602 Op Amps	Sallen Key Filter with OPA and OPB Op Amps
Frequency (Hz)	200	200	200
1 st harmonic (200 Hz) gain (dBV)	5	2.5	2.5
2 nd harmonic (400 Hz) gain (dBV)	-35	n/a	n/a
3 rd harmonic (600 Hz) gain (dBV)	-9.375	-42.5	-40.625

The results obtained based on Frequency Analysis of the two filter methods are as shown in the [Table 1](#).

The outputs from the MCP602 based analog filter and PIC16F178X based analog filter are similar and contain very low harmonics. Devices with two internal op amps like PIC16F1783, PIC16F170X, and PIC16F171X can be used for such implementations.

This demonstrates that the performance of the internal op amp is very similar and comparable to the standard stand-alone op amps available in the market. Using the internal op amp on a PIC16F device has the advantage of reduction in the overall Bill of Material (BOM) cost in addition to reduction in form factor of the board. There will be improvement in the immunity to external noise since additional traces required for op amp connections will be eliminated. For all characteristic graphs of the op amp, please refer to the respective device data sheets.

APPLICATIONS OF OP AMP

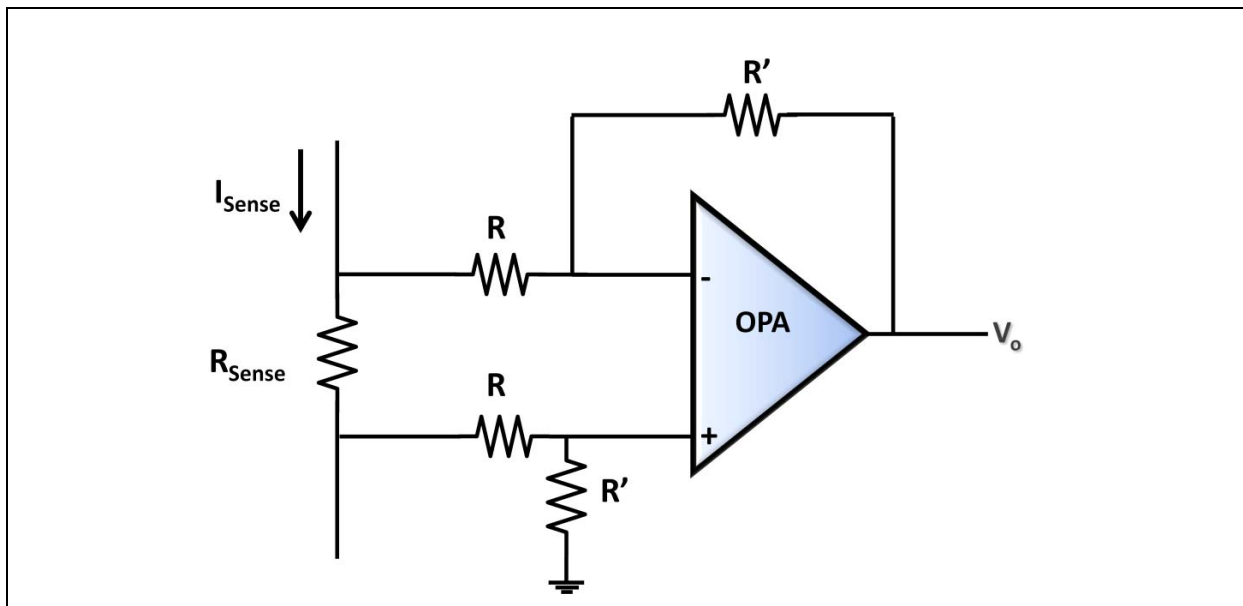
Now that certain important parameters and characteristics of the op amp have been covered and compared, taking a look at some applications will give a better understanding of their use in various areas.

OP AMP IN MEASURING CIRCUITS

Op amps form a key component when designing any analog or mixed-signal power supply. They find use in both signal measurements and compensation networks. Consider one example of each of these to show how op amps can play an important role in power supply design.

A very common use of op amp in Digital Power Converters is in the measurement of current flowing through the inductor. Similarly, in the case of motor control and energy metering applications, it is used in the measurement of current flowing through the phases of the inverter. Most commonly, a sense resistor is used in series in the path of current flow of the phase as shown in [Figure 8](#). The voltage drop across the sense resistor is then amplified and fed back to the Analog-to-Digital Converter (ADC) of the microcontroller.

FIGURE 8: OP AMP AS DIFFERENCE AMPLIFIER FOR CURRENT SENSING APPLICATION



Since the value of the sense resistor used will usually be very small, of the order of a few milliohms to a few ohms, amplification of the measured voltage becomes necessary. An op amp hence is used in a difference amplifier configuration here so that, irrespective of the direction of current flow, the voltage difference is faithfully amplified.

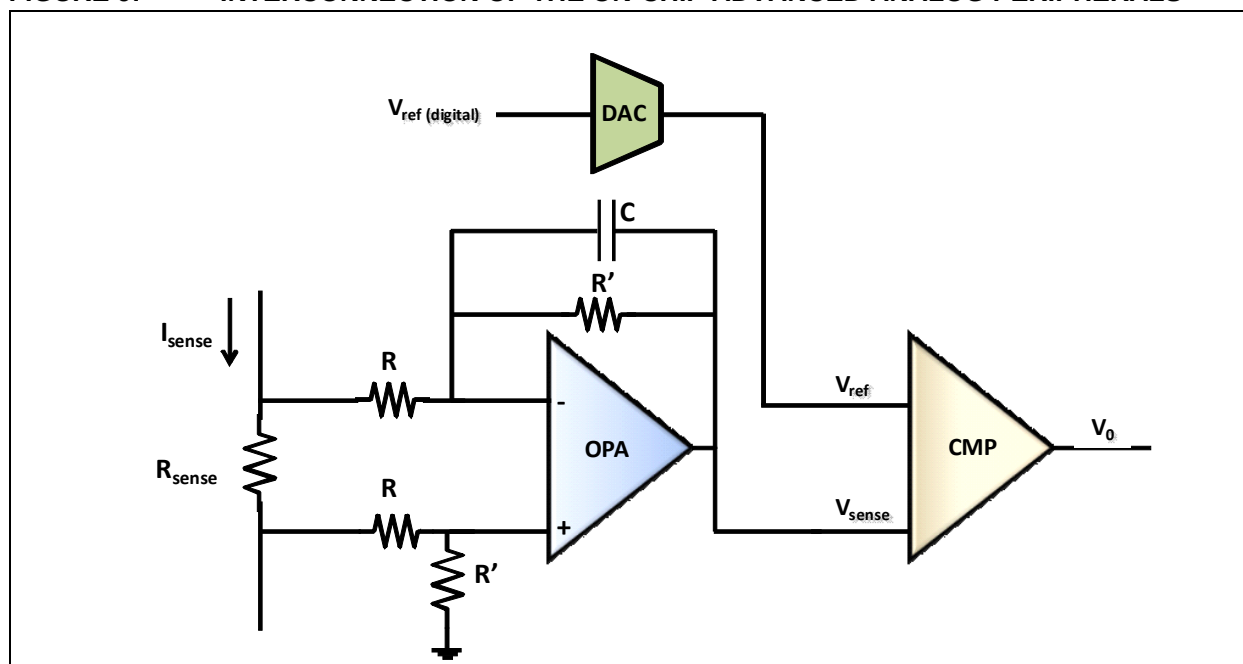
A microcontroller like PIC16F753, having a single op amp on-chip, would be a right candidate for such applications. The op amp being internal to the controller would reduce the overall cost of the design and even save board space. Immunity to noise will improve since there will not be as many traces on the board as would be required when using an external op amp.

Note: When the same analog signal is connected to the inputs of both ADC and op amp, there can be a change in output of op amp without an actual change in the input signal applied, when the GO bit is set in ADC. This is because of the disconnection of the sample and hold capacitor of ADC from the analog channel. To minimize the change of op amp output voltage due to setting of GO bit in ADC, a capacitor with a capacitance more than the sample and hold capacitance should be connected to the input of the op amp

INTERCONNECTION OF THE ON-CHIP ANALOG PERIPHERALS

The advanced analog peripherals on the PIC16F1783 and the PIC16F753 devices can be interconnected together to cater to more complex applications. Consider the typical case where a designer needs to amplify a small signal from a sensor and compare this to a controllable reference level. The amplification of the signal from the sensor can be done using the on-chip op amp. The reference level can be programmed and controlled in software using the on-chip Digital-to-Analog Converter (DAC) and an internal comparator can be used to monitor the condition where the signal traverses the reference level. Figure 9 shows such an arrangement. Using the internal connections in the PIC16F753, it is possible to construct such a system using only three device pins.

FIGURE 9: INTERCONNECTION OF THE ON-CHIP ADVANCED ANALOG PERIPHERALS



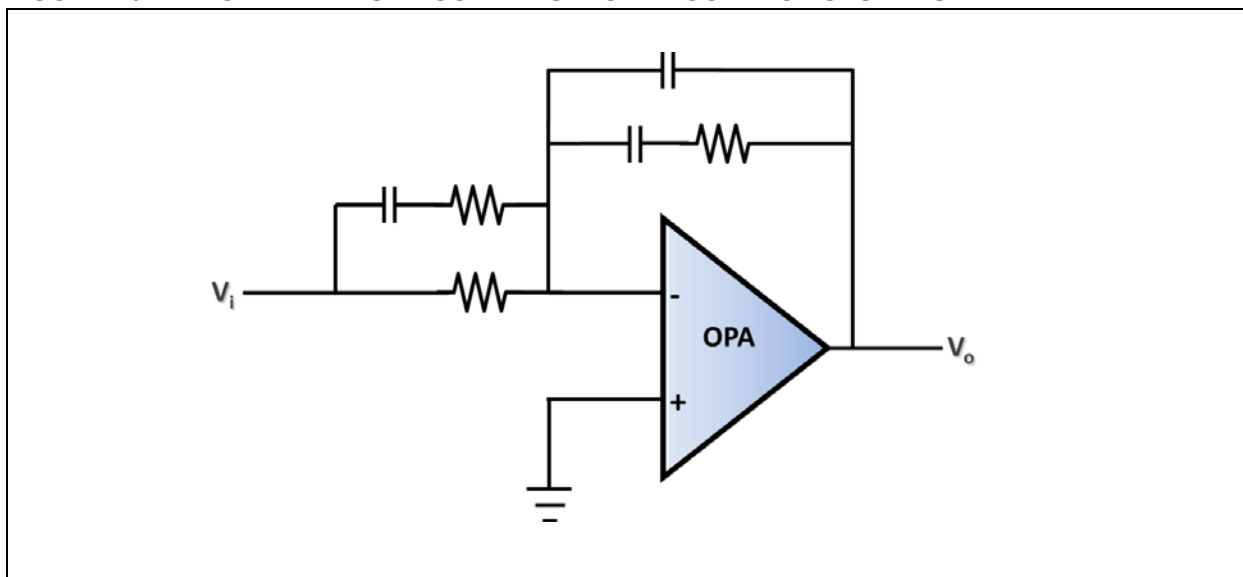
OP AMP IN CONTROL SYSTEMS

If an analog control approach is taken when designing a power converter operating in a buck or a boost topology to regulate the output voltage, the control system invariably requires a compensator using an op amp.

A compensator which has three poles (one at the origin) and two zeros is normally required if the control method uses only the output voltage for control. Such a control method is referred to as Voltage Mode Control (VMC) and such a compensator is commonly called a Type-III compensator. The Type-III compensator is a small variation of the inverting amplifier in terms of changes in the feedback network. The feedback network is suitably designed to provide a transfer function which has three poles and two zeros.

A loop crossover somewhere between the zeros and the poles can be achieved if the two zeros coincide at one frequency and the two poles coincide at one frequency. A reasonable phase margin can be met using such compensators since a good amount of boost in the phase is possible.

FIGURE 10: OP AMP BASED COMPENSATOR IN CONTROL SYSTEMS

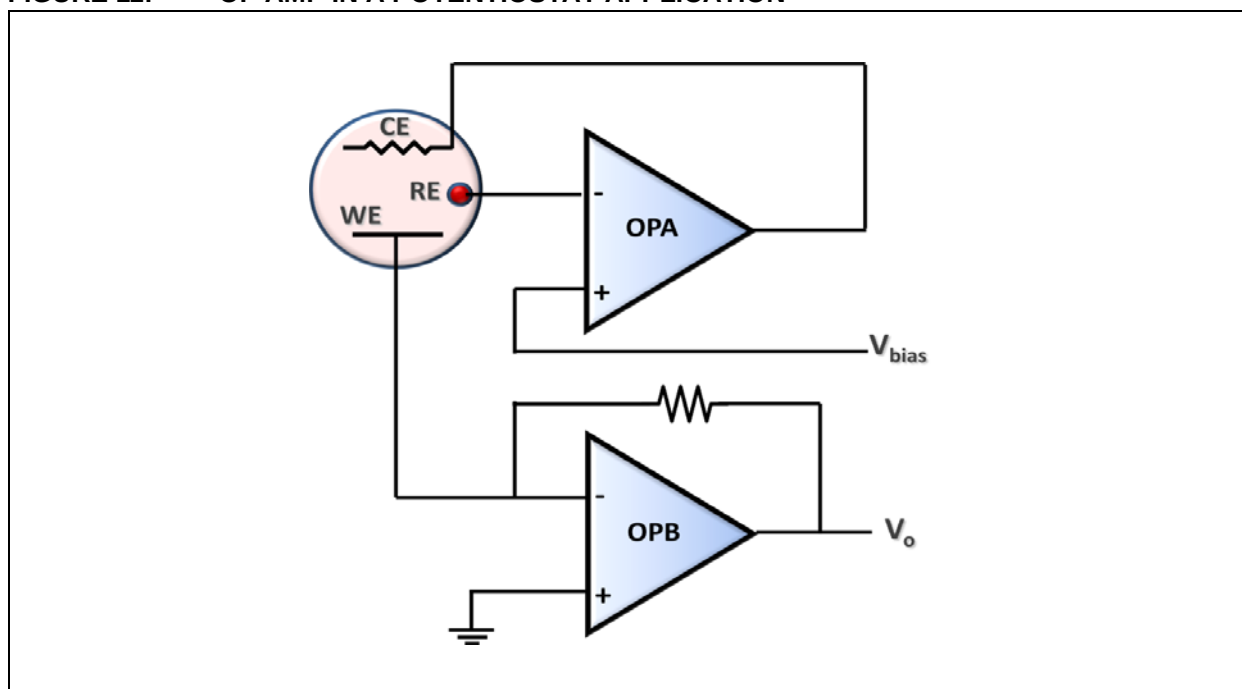


OP AMP IN MEDICAL ELECTRONICS

Bioelectrochemical sensors are an essential piece in most of the medical equipment used for monitoring various vital parameters of the human body. The biosensors often involve certain electrochemical activity taking place in microbes, enzymes or chemical compounds. Such activities need to be tested, measured and, in some cases, controlled as well. One common electronic circuit used in such applications is the potentiostat or galvanostat. This device is needed for proper operation of a bioelectrochemical sensor. In certain applications like odor and taste detection sensors, a bank of multiple potentiostats may also be needed.

A simple arrangement of a potentiostat is shown in [Figure 11](#). As can be seen, there are two op amps used for such a configuration. A PIC16F1783 or PIC16F1786 would perfectly suit such a realization because these devices have two internal op amps in them.

FIGURE 11: OP AMP IN A POTENTIOSTAT APPLICATION



A potentiostat is a three-electrode cell consisting of the working electrode, the reference electrode and the counter electrode. The counter electrode conducts current into or out of the cell, and this current has to balance the current generated at the working electrode. The reference electrode provides a reference with which the electrolyte's potential can be measured on the working electrode.

The amplifier is responsible in maintaining the voltage between the reference electrode and the working electrode as closely as possible to the voltage V_{BIAS} connected to the non-inverting terminal. Its output is controlled to maintain the cell current so that a condition of equilibrium is achieved. In summary, the potentiostat has to measure the current from the working electrode and deliver a useful signal at the output terminal. This current can be bipolar and is measured irrespective of whether the current flows in or out of the working electrode.

CONCLUSION

It is seen that the ubiquitous presence and influence of the op amps exist across the length and breadth of the electronic world. Discussed in this application note are certain key parameters and characteristics of op amps in general and, in particular, Microchip's PIC16F based op amps. We also attempted to dwell a little inside the application areas where op amps play a significant role, be it medical electronics or power supplies or even some generic signal processing and measurement applications. Lastly, it was shown that the on-chip op amps perform quite well against the conventional stand-alone op amps, yielding very similar results.

ADDITIONAL MICROCHIP RESOURCES

1. AN682 – *Using Single Supply Operational Amplifiers in Embedded Systems*
2. AN1332 – *Current Sensing Circuit Concepts and Fundamentals*
3. AN951 – *Amplifying High-Impedance Sensors Photodiode Example*
4. AN1258 – *Op Amp Precision Design: PCB Layout Techniques*
5. AN722 – *Operational Amplifier Topologies and DC Specifications*
6. AN990 – *Analog Sensor Conditioning Circuits – An Overview*
7. AN684 – *Single Supply Temperature Sensing with Thermocouples*
8. AN844 – *Simplified Thermocouple Interfaces and PICmicro[®] MCUs*

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