AN1316

Using Digital Potentiometers for Programmable Amplifier Gain

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INTRODUCTION

Usually a sensor requires its output signal to be amplified before being converted to a digital representation. Many times an operational amplifier (op amp) is used to implement a signal gain circuit. The programmability of this type of circuit allows the following issues to be solved:

- Optimization of the sensor output voltage range
- Calibration of the amplifier circuit's gain
- Adapting gain to input signal variations
  - sensor characteristics change over temperature/voltage
  - multiple input sources into a single gain circuit
- Field calibration updates
- Increased reliability vs mechanical potentiometer
- BOM consolidation – one op amp and one digital potentiometer supporting the various sensor options

This Application Note will discuss implementations of programmable gain circuits using an op amp and a digital potentiometer. This discussion will include implementation details for the digital potentiometer's resistor network. It is important to understand these details to understand the effects on the application.

OVERVIEW OF AMPLIFIER GAIN CIRCUIT

Figure 1 shows two examples of amplifier circuits with programmable gain. Circuit "a" is an inverting amplifier circuit, while circuit "b" is a non-inverting amplifier circuit.

In these circuits, R_1, R_2 and Pot_1 are used to tune the gain of the amplifier. The selection of these components will determine the range and the accuracy of the gain programming.

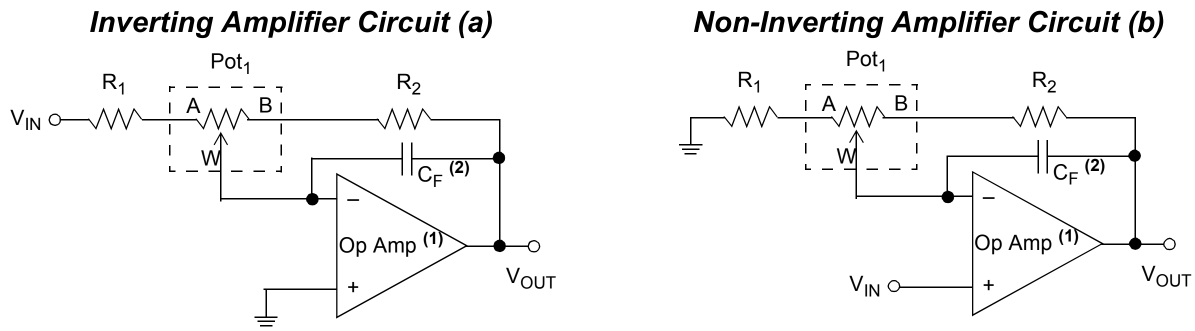
The inverting amplifier's gain is the negative ratio of $(R_2 + R_{BW})/(R_1 + R_{AW})$. The non-inverting amplifier's gain is the ratio of $((R_2 + R_{BW})/(R_1 + R_{AW}) + 1)$. The feedback capacitor (C_F) may be used if additional circuit stability is required.

These circuits can be simplified by removing resistors R_1 and R_2 ($R_1 = R_2 = 0\Omega$) and just using the digital potentiometers R_{AW} and R_{BW} ratio to control the gain.

The simplified circuit reduces the cost and board area but there are trade-offs (for the same resistance and resolution). Table 1 shows some of the trade-offs with respect to the gain range that can be achieved, where the R_{AB} resistance is the typical R_{AB} value and the R_1 and R_2 resistance values are varied. A more detailed discussion is included later in this Application Note.

Using a general implementation, the R_1 and R_2 resistors allow the range of the gain to be limited; therefore, each digital potentiometer step is a fine adjust within that range. While in the simplified circuit, the range is not limited, so each digital potentiometer step causes a larger variation in the gain.

One advantage of the simplified circuit is that the R_{BW} and R_{AW} resistors are of the same material so the circuit has a very good temperature coefficient (tempco). While in the general circuit, the tempco of the R_1 and R_2 devices may not match each other or the digital potentiometer device.



Note 1: A general purpose op amp, such as the MCP6001.

2: Optional feedback capacitor (C_F). Used to improve circuit stability.

FIGURE 1: *Amplifier with Programmable Gain Example Circuits.*

TABLE 1: OVERVIEW OF GAIN RANGES FOR EXAMPLE CIRCUITS[1,2]

Configuration			Inverting Gain (V/V) (Figure 1a)			Non-Inverting Gain (V/V) (Figure 1b)		
R_1	R_2	R_{AB}[1]	Zero Scale	Mid Scale	Full Scale	Zero Scale	Mid Scale	Full Scale
0Ω	**0Ω**	**10kΩ**	0.00	- 1.00	- 255	1.00	2.00	256
10kΩ	**10kΩ**	**10kΩ**	- 0.50	- 1.00	- 2.00	1.50	2.00	3.00
1kΩ	**10kΩ**	**10kΩ**	- 0.91	- 2.50	- 20.00	1.91	3.50	21.00
10kΩ	**1kΩ**	**10kΩ**	-0.50	-0.40	-1.10	1.05	1.40	2.10

Legend: Zero Scale: Wiper value = 0h, Wiper closest to Terminal B
Mid Scale: Wiper value is at mid-range value, Wiper halfway between Terminal A and Terminal B
Full Scale: Wiper value = maximum value, Wiper closest to Terminal A

Note 1: Gain calculations use an R_{AB} resistance of the typical 10kΩ. Gain will be effected by variation of R_{AB} resistance, except when $R_1 = R_2 = 0\Omega$, then R_{AB} variation does not effect gain.

2: The calculations assume that the resistor network is configuration A (see Figure 2). This can also be thought of as the R_{AB} string having 2^N R_S resistors (even number of resistors), there the wiper can connect to Terminal B and Terminal A. At the mid-scale tap, there is an equal number of resistors (R_S) above and below that wiper setting.

UNDERSTANDING THE DIGITAL POTENTIOMETER'S RESISTOR NETWORK

To understand how the digital potential will operate in the circuit, one needs to understand how the digital potentiometer's resistor network is implemented. Figure 2 shows the three general configurations of the resistor network. Each of these configurations has system implications.

R_{AB} is the resistance between the resistor network's terminal A and terminal B. Similarly, R_{BW} is the resistance between the resistor network's terminal B and the wiper terminal while R_{AW} is the resistance between the resistor network's terminal A and the wiper terminal. The R_S (Step) resistance is the R_{AB} resistance divided by the number of resistors in the R_{AB} string.

In Configuration A, there are 2^N step resistors (R_S) to create the resistor ladder (R_{AB}). The wiper can connect to $2^N + 1$ tap points. So for an 8-bit device with 256 R_S resistors (28), the wiper decode logic requires 257 values or 9-bit decoding.

Configuration B eliminates the top tap point, so in this configuration there are 2^N step resistors (R_S) to create the resistor ladder (R_{AB}) and 2^N wiper tap points. This only requires 8-bit decode for the wiper logic, but does not allow the wiper to directly connect to terminal A. The full-scale setting is one R_S element away from terminal A.

Configuration C eliminates that top R_S element so that there are 2^N - 1 step resistors (R_S) to create the resistor ladder (R_{AB}) and 2^N wiper tap points. Now the wiper can again directly connect to terminal A, but since there's an odd number of R_S resistors the mid-scale wiper setting does not have an equal number or R_S resistors above and below the mid-scale tap point.

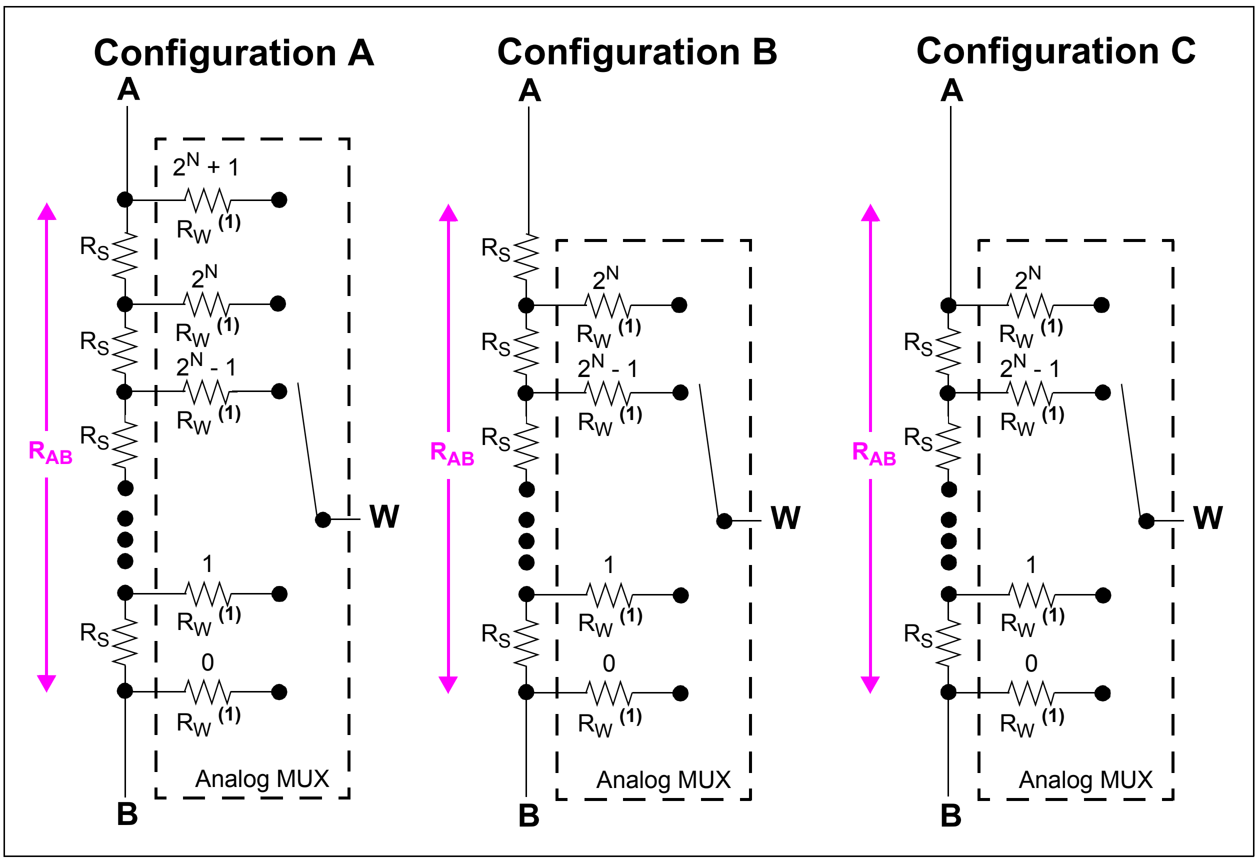


FIGURE 2: Resistor Network Configurations.

Table 2 specifies the number of taps and R_S resistors for a given resolution for each of these configurations. Table 3 shows the trade-off between the different resistor network configurations.

Table 4 shows the current Microchip digital potentiometer devices and indicates which of the resistor network configurations they implement.

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TABLE 2: MICROCHIP'S CURRENT DIGITAL POTENTIOMETER RESISTOR NETWORK CONFIGURATIONS VS. RESOLUTIONS

Resolution		Resistor Network Configuration			Comment
"Bits"	# of	A	B	C	
6-bit	Taps	65 (1)	64 (1)	64	Up/Down serial interface
	R_S Resistors	64 (1)	64 (1)	63	
7-bit	Taps	129	128 (1)	128	SPI and I^2C™ serial interface options
	R_S Resistors	128	128 (1)	127	
8-bit	Taps	257	256	256 (1)	SPI and I^2C™ serial interface options
	R_S Resistors	256	256	255 (1)	

Note 1: This resistor network configuration is not currently offered for this resolution. Future devices may be offered in this configuration for this resolution.

TABLE 3: RESISTOR NETWORK CONFIGURATION TRADE-OFFS

	Resistor Network Configuration		
	A	B	C
Number of R_S resistors	2^N	2^N	2^N -1
	even	even	odd
Supports "true" mid-scale setting (1)	Yes	Yes	No
Supports wiper connections to terminal A and terminal B (2)	Yes	No (3)	Yes
Number of wiper addressing bits	2^N + 1	2^N	2^N
	odd	even	even
Wiper addressing decode complexity	complex (4)	simple	simple

Note 1: Equal # of R_S resistors above and below mid-scale wiper tap point

2: This allows true zero-scale (wiper connected to terminal B) and full-scale (wiper connected to terminal A) operation.

3: In this configuration there is one R_S resistor between terminal A and the full-scale tap position.

4: This requires an extra bit for the wiper decode logic, so an 8-bit resistor network requires 9 bits of wiper addressing.

TABLE 4: DEVICES VS. RESISTOR NETWORK CONFIGURATIONS

Resistor Network Configuration								
A			B			C		
Device	# Taps	# R_S	Device	# Taps	# R_S	Device	# Taps	# R_S
MCP4131	129	129	MCP41010	256	256	MCP4011	64	63
MCP4132	129	129	MCP41050	256	256	MCP4012	64	63
MCP4141	129	129	MCP41100	256	256	MCP4013	64	63
MCP4142	129	129	**MCP42010**	256	256	MCP4014	64	63
MCP4151	257	257	**MCP42050**	256	256	MCP4017	128	127
MCP4152	257	257	**MCP42100**	256	256	MCP40D17	128	127
MCP4161	257	257				MCP4018	128	127
MCP4162	257	257				MCP40D18	128	127
MCP4231	129	129				MCP4019	128	127
MCP4232	129	129				MCP40D19	128	127
MCP4241	129	129				MCP4021	64	63
MCP4242	129	129				MCP4022	64	63
MCP4251	257	257				MCP4023	64	63
MCP4252	257	257				MCP4024	64	63
MCP4261	257	257						
MCP4262	257	257						
MCP4331	129	129						
MCP4332	129	129						
MCP4341	129	129						
MCP4342	129	129						
MCP4351	257	257						
MCP4352	257	257						
MCP4361	257	257						
MCP4362	257	257						
MCP4531	129	129						
MCP4532	129	129						
MCP4541	129	129						
MCP4542	129	129						
MCP4551	257	257						
MCP4552	257	257						
MCP4561	257	257						
MCP4562	257	257						
MCP4631	129	129						
MCP4632	129	129						
MCP4641	129	129						
MCP4642	129	129						
MCP4651	257	257						
MCP4652	257	257						
MCP4661	257	257						
MCP4662	257	257						

Legend: Devices in **bold blue** have multiple (2 or 4) resistor networks on the device.

Potentiometer Configuration

When the digital potentiometer is in a potentiometer configuration, the device is operating as a voltage divider. As long as there is not a load on the wiper (goes into a high-impedance input), the variation of the wiper resistance (R_W) has minimal impact on the INL and DNL characteristics.

Most operational amplifier programmable gain circuit implementations utilize the digital potentiometer in the potentiometer configuration.

Rheostat Configuration

When the digital potentiometer is in a rheostat configuration, the device is operating as a variable resistor. Any variation of the wiper resistance (R_W) effects the total resistance. This impacts the configurations INL and DNL characteristics. The rheostat configuration is discussed in the Alternate Implementation section of this Application Note.

The wiper resistance is dependent on several factors including wiper code, device V_{DD}, terminal voltages (on A, B and W), and temperature. Also for the same conditions, each tap selection resistance has a small variation. This R_W variation has greater effects on some specifications (such as INL) for the smaller resistance devices (5.0 kΩ) compared to larger resistance devices (100.0 kΩ).

AMPLIFIER CIRCUIT DETAILS

This section will discuss the two types of amplifier circuits:

- Inverting Amplifier
- Non-Inverting Amplifier

Inverting Amplifier

Figure 3 shows two implementations of an inverting amplifier with programmable gain circuit. Circuit "a" is the general circuit, while circuit "b" is the simplified circuit.

Equation 1 shows how to calculate the gain for the general circuit (Figure 3a), while Equation 2 simplifies the equation by having $R_1 = R_2 = 0$, and shows the equation to calculate the gain for the simplified circuit (Figure 3b).

So the gain is the negative ratio of the resistance from the op amp output to its negative input and the resistance from the voltage input signal source to the op amp negative input. The gain will increase in magnitude as the wiper moves towards terminal A, and will decrease in magnitude as the wiper moves towards terminal B.

The device's wiper resistance (R_W) is ignored for first order calculations. This is due to it being in series with the op amp input resistance and the op amp's very large input impedance.

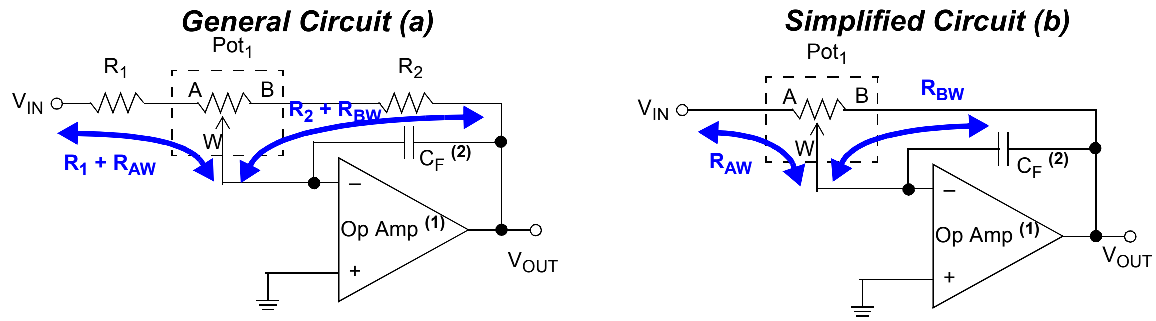
The trade-offs between the general, simplified and alternate circuit implementations are shown in Table 5.

Table 6, Table 7 and Table 8 show the theoretical gain values for the general and simplified circuit implementations for the different resistor network configurations. These calculations assume that the R_{AB} value is the typical value, and in the general circuit implementation $R_1 = R_2 = R_{AB} = 10$ kΩ.

An Excel spreadsheet is available at this application note's web page. This spreadsheet calculates the gain of the general circuit for each of the three different digital potentiometer's Configurations (A, B and C). The spreadsheet allows you to modify the R_1, R_2 and R_{AB} values and then see the calculated circuit gain (file name `AN1316 Gain Calculations.xls`). This spreadsheet was used for Table 6, Table 7 and Table 8.

TABLE 5: CIRCUIT IMPLEMENTATION TRADE-OFFS

	Advantages	Disadvantages
General Circuit (Figure 3a)	• Complete control over gain range, which determines accuracy	• Poor tempco characteristics, since R_1 and R_2 are different devices • Increases cost and board area (for R1 and R2)
Simplified Circuit (Figure 3b)	• Very good tempco characteristics, since R_{BW} and R_{AW} are on the same silicon • Minimizes area and cost	• Less control over gain range and accuracy
Alternate Circuit (Figure 4c)	• Complete control over gain range, which determines accuracy • Very good tempco characteristics, since R_{BW1A} and R_{BW1B} are on the same silicon	• More costly and increased board area (for dual digital potentiometer device) • More effected by changes in wiper characteristics (rheostat configuration vs. potentiometer configuration)



Note 1: A general purpose op amp, such as the MCP6001.

2: Optional feedback capacitor (C_F). Used to improve circuit stability.

FIGURE 3: *Inverting Amplifier with Programmable Gain Example Circuits.*

EQUATION 1: CIRCUIT GAIN EQUATION – INVERTING AMPLIFIER GENERAL CIRCUIT

$$V_{OUT} = -\left(\frac{R_2 + R_{BW}}{R_1 + R_{AW}}\right) \text{ x } V_{IN}$$

Where:

$$R_{BW} = \frac{R_{AB}}{\text{\# of Resistors}} \text{ x Wiper Code}$$

$$R_{AW} = \frac{R_{AB}}{\text{\# of Resistors}} \text{ x (\# of Resistors} - \text{Wiper Code)}$$

EQUATION 2: CIRCUIT GAIN EQUATION – INVERTING AMPLIFIER SIMPLIFIED CIRCUIT

$$V_{OUT} = -\left(\frac{R_{BW}}{R_{AW}}\right) \text{ x } V_{IN}$$

Where:

$$R_{BW} = \frac{R_{AB}}{\text{\# of Resistors}} \text{ x Wiper Code}$$

$$R_{AW} = \frac{R_{AB}}{\text{\# of Resistors}} \text{ x (\# of Resistors} - \text{Wiper Code)}$$

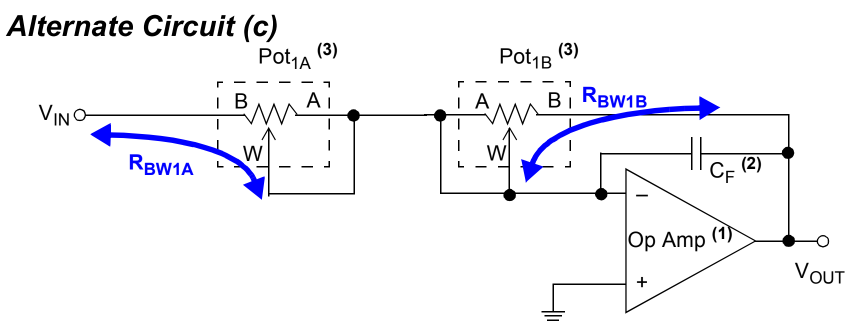
So:

$$V_{OUT} = -\left(\frac{\text{Wiper Code}}{\text{\# of Resistors} - \text{Wiper Code}}\right) \text{ x } V_{IN}$$

ALTERNATE IMPLEMENTATION

Figure 4 shows an implementation which takes the best of the general and simplified implementations. In this implementation, a digital potentiometer with two (or more) resistor networks is used. This allows each resistor for the gain to be individually controlled. Since both resistors are on the same silicon, the gain resistors have good tempco matching characteristics. With the wipers of each resistor network tied together, the wiper voltage will be the same. Therefore, the wiper resistance characteristics of the two resistor networks should be similar.

The drawback of this implementation is that a dual resistor network device is more costly than a single resistor device. Table 5 shows some trade-offs with this circuit implementation.



Note 1: A general purpose op amp, such as the MCP6001.

2: Optional feedback capacitor (C_F). Used to improve circuit stability.

3: Connecting the wiper to terminal A ensures that as the wiper register value increases, the R_{BW} resistance increases.

FIGURE 4: *Inverting Amplifier with Programmable Gain Example Circuit.*

EXAMPLE GAIN CALCULATIONS – INVERTING AMPLIFIER

Table 6 shows a comparison of the amplifier gain between the circuits (Figure 3a and Figure 3b) for digital potentiometer's resistor networks in the Configuration A (see Figure 2) implementation. Table 6 utilized a digital potentiometer with 8-bit resolution and with an R_{AB} resistance = 10 kΩ. For the general amplifier circuit, when $R_1 = R_2 = 10$ kΩ, the circuit's gain (V/V) ranged between -0.5 and -2.0. But when the simplified circuit is used (effectively having $R_1 = R_2 = 0\Omega$) the circuit's gain range is approximately between 0 and $-\infty$ (at wiper code = 255, gain = -255).

Table 7 shows a comparison of the amplifier gain between the circuits (Figure 3a and Figure 3b) for digital potentiometer's resistor networks in the Configuration B (see Figure 2) implementation. Table 7 utilized a digital potentiometer with 8-bit resolution and with an R_{AB} resistance = 10 kΩ. For the general amplifier circuit, when $R_1 = R_2 = 10$ kΩ, the circuit's gain (V/V) ranged between -0.5 and -1.99. But when the simplified circuit is used (effectively having $R_1 = R_2 = 0\Omega$) the circuit's gain range is approximately between 0 and > -255.

Table 8 shows a comparison of the amplifier gain between the circuits (Figure 3a and Figure 3b) for digital potentiometer's resistor networks in the Configuration C (see Figure 2) implementation. Table 8 utilized a digital potentiometer with 7-bit resolution and with an R_{AB} resistance = 10 kΩ. For the general amplifier circuit, when $R_1 = R_2 = 10$ kΩ, the circuit's gain (V/V) ranged between -0.5 and -2.0. But when the simplified circuit is used (effectively having $R_1 = R_2 = 0\Omega$) the circuit's gain range is approximately between 0 and $-\infty$ (at wiper code = 126, gain = -126).

Therefore, regardless of the resistor network configuration, finer calibration of the circuit is possible with the general circuit, but with a narrower range. Also, resistor network configurations that allow the full-scale setting to connect to terminal A (Configurations A and C) can have very large magnitude gains (approximately $-\infty$) since the R_{AW} resistance is almost 0.

TABLE 6: INVERTING AMPLIFIER GAIN VS. WIPER CODE AND R_W – CONFIGURATION A

# of Taps	# of Resistors	Wiper Code (7)		Gain (R_{AB} = 10 kΩ) (V/V)				Comment
		Dec	Hex	Simplified Circuit (1)	General Circuit (2, 3)			
					@ $R_{AB(MIN)}$ (5)	@ $R_{AB(TYP)}$	@ $R_{AB(MAX)}$ (6)	
257	256	0	000h	0.0000	- 0.5556	- 0.5000	- 0.4545	Zero Scale
		1	001h	- 0.0039	- 0.5583	- 0.5029	- 0.4577	
		2	002h	- 0.0079	- 0.5610	- 0.5059	- 0.4608	
		3	003h	- 0.0119	- 0.5637	- 0.5088	- 0.4639	
		4	004h	- 0.0159	- 0.5664	- 0.5118	- 0.4670	
		:	:	:	:	:	:	
		126	07Eh	- 0.9692	- 0.9911	- 0.9896	- 0.9883	
		127	07Fh	- 0.9845	- 0.9955	- 0.9948	- 0.9942	
		128	080h	- 1.0000	- 1.0000	- 1.0000	- 1.0000	Mid Scale
		129	081h	- 1.0157	- 1.0045	- 1.0052	- 1.0059	
		130	082h	- 1.0317	- 1.0090	- 1.0105	- 1.0118	
		:	:	:	:	:	:	
		252	0FCh	- 63.0000	- 1.7654	- 1.9538	- 2.1411	
		253	0FDh	- 84.3333	- 1.7740	- 1.9653	- 2.1556	
		254	0FEh	- 127.0000	- 1.7826	- 1.9767	- 2.1703	
		255	0FFh	- 255.0000	- 1.7913	- 1.98883	- 2.1851	
		256	100h	Divide Error (4)	- 1.8000	- 2.0000	- 2.2000	Full Scale

Note 1: Gain = - ((R_{AB}/# of Resistors) * Wiper Code)/ ((R_{AB}/# of Resistors) * (# of Resistors - Wiper Code)) = - (Wiper Code)/(# of Resistors - Wiper Code)

2: Gain = - (R_2 + R_S * (Wiper Code))/(R_1 + R_S * (# of Resistors - Wiper Code)

3: Uses $R_1 = R_2 = 10$ kΩ.

4: Theoretical calculations. At full scale in the simplified circuit a divide by 0 error results.

5: The $R_{AB(MIN)}$ shows the narrowest range of gain (more accuracy per wiper code step). Ensure gain range is adequate.

6: The $R_{AB(MAX)}$ shows the widest range of gain (less accuracy per wiper code step). Ensure gain resolution is adequate.

7: If the A and B terminals are swapped in the circuit, as the wiper value increases, the magnitude of the gain decreases.

TABLE 7: INVERTING AMPLIFIER GAIN VS. WIPER CODE AND R_W – CONFIGURATION B

# of Taps	# of Resistors	Wiper Code(7)		Gain (R_{AB} = 10 kΩ) (V/V)				Comment
		Dec	Hex	Simplified Circuit (1)	General Circuit (2, 3)			
					@ $R_{AB(MIN)}$ (5)	@ $R_{AB(TYP)}$	@ $R_{AB(MAX)}$ (6)	
256	256	0	00h	0.0000	- 0.5556	- 0.5000	- 0.4545	Zero Scale
		1	01h	- 0.0039	- 0.5583	- 0.5029	- 0.4577	
		2	02h	- 0.0079	- 0.5610	- 0.5059	- 0.4608	
		3	03h	- 0.0119	- 0.5637	- 0.5088	- 0.4639	
		4	04h	- 0.0159	- 0.5664	- 0.5118	- 0.4670	
		:	:	:	:	:	:	
		126	7Eh	- 0.9692	- 0.9911	- 0.9896	- 0.9883	
		127	7Fh	- 0.9845	- 0.9955	- 0.9948	- 0.9942	
		128	80h	- 1.0000	- 1.0000	- 1.0000	- 1.0000	Mid Scale
		129	81h	- 1.0157	- 1.0045	- 1.0052	- 1.0059	
		130	82h	- 1.0317	- 1.0090	- 1.0105	- 1.0118	
		:	:	:	:	:	:	
		252	FCh	- 63.0000	- 1.7654	- 1.9538	- 2.1411	
		253	FDh	- 84.3333	- 1.7740	- 1.9653	- 2.1556	
		254	FEh	- 127.0000	- 1.7826	- 1.9767	- 2.1703	
		255	FFh	- 255.0000	- 1.7913	- 1.98883	- 2.1851	Full Scale

Note 1: Gain = - ((R_{AB}/# of Resistors) * Wiper Code)/ ((R_{AB}/# of Resistors) * (# of Resistors - Wiper Code)) = - (Wiper Code)/(# of Resistors - Wiper Code)

2: Gain = - (R_2 + R_S * (Wiper Code))/(R_1 + R_S * (# of Resistors - Wiper Code)

3: Uses $R_1 = R_2 = 10k\Omega$.

4: Theoretical calculations. At full scale in the simplified circuit a divide by 0 error results.

5: The $R_{AB(MIN)}$ shows the narrowest range of gain (more accuracy per wiper code step). Ensure gain range is adequate.

6: The $R_{AB(MAX)}$ shows the widest range of gain (less accuracy per wiper code step). Ensure gain resolution is adequate.

7: If the A and B terminals are swapped in the circuit, as the wiper value increases, the magnitude of the gain decreases.

TABLE 8: INVERTING AMPLIFIER GAIN VS. WIPER CODE AND R_W – CONFIGURATION C

# of Taps	# of Resistors	Wiper Code(7)		Gain (R_{AB} = 10 kΩ) (V/V)				Comment
		Dec	Hex	Simplified Circuit (1)	General Circuit (2, 3)			
					@ $R_{AB(MIN)}$ (5)	@ $R_{AB(TYP)}$	@ $R_{AB(MAX)}$ (6)	
128	127	0	00h	0.0000	- 0.5556	- 0.5000	- 0.4545	Zero Scale
		1	01h	- 0.0079	- 0.5610	- 0.5059	- 0.4608	
		2	02h	- 0.0160	- 0.5665	- 0.5119	- 0.4671	
		3	03h	- 0.0242	- 0.5721	- 0.5179	- 0.4735	
		4	04h	- 0.0325	- 0.5776	- 0.5240	- 0.4800	
		:	:	:	:	:	:	
		62	3Eh	- 0.9538	- 0.9866	- 0.9844	- 0.9824	
		63	3Fh	- 0.9844	- 0.9955	- 0.9948	- 0.9941	Mid Scale
		64	40h	- 1.0159	- 1.0045	- 1.0053	- 1.0059	
		65	41h	- 1.0484	- 1.0136	- 1.0159	- 1.0179	
		66	42h	- 1.0820	- 1.0228	- 1.0266	- 1.0300	
		:	:	:	:	:	:	
		124	7Ch	- 41.3333	- 1.7481	- 1.9308	- 2.1118	
		125	7Dh	- 62.5000	- 1.7652	- 1.9535	- 2.1406	
		126	7Eh	- 126.0000	- 1.7825	- 1.9766	- 2.1700	
		127	7Fh	Divide Error (4)	- 1.8000	- 2.0000	- 2.2000	Full Scale

Note 1: Gain = - ((R_{AB}/# of Resistors) * Wiper Code)/ ((R_{AB}/# of Resistors) * (# of Resistors - Wiper Code)) = - (Wiper Code)/(# of Resistors - Wiper Code)

2: Gain = - (R_2 + R_S * (Wiper Code))/(R_1 + R_S * (# of Resistors - Wiper Code)

3: Uses $R_1 = R_2 = 10$ kΩ.

4: Theoretical calculations. At full scale in the simplified circuit a divide by 0 error results.

5: The $R_{AB(MIN)}$ shows the narrowest range of gain (more accuracy per wiper code step). Ensure gain range is adequate.

6: The $R_{AB(MAX)}$ shows the widest range of gain (less accuracy per wiper code step). Ensure gain resolution is adequate.

7: If the A and B terminals are swapped in the circuit, as the wiper value increases, the magnitude of the gain decreases.

Non-Inverting Amplifier

Figure 5 shows two implementations of an non-inverting amplifier with programmable gain circuit. Circuit "a" is the general circuit while circuit "b" is the simplified circuit.

Equation 3 shows how to calculate the gain for the general circuit (Figure 5a), while Equation 4 simplifies the equation by having $R_1 = R_2 = 0$, and shows the equation to calculate the gain for the simplified circuit (Figure 5b).

So the gain is the ratio of the resistance from the op amp output to its negative input and the resistance from the op amp's negative input to ground. The gain will increase in magnitude as the wiper moves towards terminal A, and will decrease in magnitude as wiper moves towards terminal B.

The device's wiper resistance (R_W) is ignored for first order calculations. This is due to it being in series with the op amp input resistance and the op amp's very large input impedance.

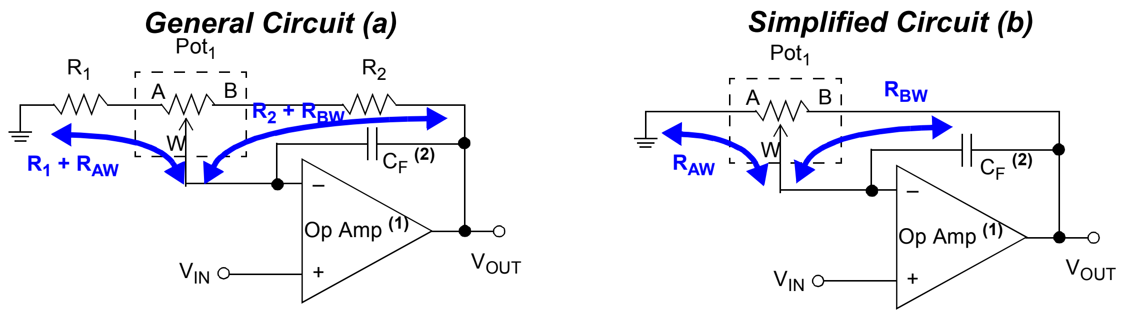
Trade-offs between the general, simplified and alternate circuit implementations are the same trade-offs as the inverting amplifier circuit. These trade-offs are shown in Table 9.

Table 10, Table 11 and Table 12 show the theoretical gain values for the general and simplified circuit implementations for the different resistor network configurations. These calculations assume that the R_{AB} value is the typical value, and in the general circuit implementation $R_1 = R_2 = R_{AB} = 10\ k\Omega$.

An Excel spreadsheet is available at this application note's web page. This spreadsheet calculates the gain of the general circuit for each of the three different digital potentiometer's Configurations (A, B and C). The spreadsheet allows you to modify the R_1, R_2 and R_{AB} values and then see the calculated circuit gain (file name `AN1316 Gain Calculations.xls`). This spreadsheet was used for Table 10, Table 11 and Table 12.

TABLE 9: CIRCUIT IMPLEMENTATION TRADE-OFFS

	Advantages	Disadvantages
General Circuit (Figure 5a)	• Complete control over gain range, which determines accuracy	• Poor tempco characteristics, since R_1 and R_2 are different devices • Increases cost and board area (for R1 and R2)
Simplified Circuit (Figure 5b)	• Very good tempco characteristics, since R_{BW} and R_{AW} are on the same silicon • Minimizes area and cost	• Less control over gain range and accuracy
Alternate Circuit (Figure 6c)	• Complete control over gain range, which determines accuracy • Very good tempco characteristics, since R_{BW1A} and R_{BW1B} are on the same silicon	• More costly and increased board area (for dual digital potentiometer device) • More effected by changes in wiper characteristics (rheostat configuration vs. potentiometer configuration)



Note 1: A general purpose op amp, such as the MCP6001.

2: Optional feedback capacitor (C_F). Used to improve circuit stability.

FIGURE 5: *Non-Inverting Amplifier with Programmable Gain Example Circuits.*

EQUATION 3: CIRCUIT GAIN EQUATION – NON-INVERTING AMPLIFIER GENERAL CIRCUIT

$$V_{OUT} = \left(\frac{R_2 + R_{BW}}{R_1 + R_{AW}} + 1\right) \text{ x } V_{IN}$$

Where:

$$R_{BW} = \frac{R_{AB}}{\text{\# of Resistors}} \text{ x Wiper Code}$$

$$R_{AW} = \frac{R_{AB}}{\text{\# of Resistors}} \text{ x (\# of Resistors — Wiper Code)}$$

EQUATION 4: CIRCUIT GAIN EQUATION – NON-INVERTING AMPLIFIER SIMPLIFIED CIRCUIT

$$V_{OUT} = \left(\frac{R_{BW}}{R_{AW}} + 1\right) \text{ x } V_{IN}$$

Where:

$$R_{BW} = \frac{R_{AB}}{\text{\# of Resistors}} \text{ x Wiper Code}$$

$$R_{AW} = \frac{R_{AB}}{\text{\# of Resistors}} \text{ x (\# of Resistors — Wiper Code)}$$

So:

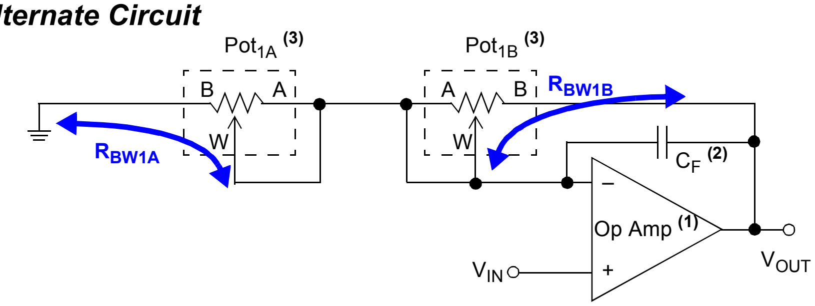
$$V_{OUT} = \left(\frac{\text{Wiper Code}}{\text{(\# of Resistors — Wiper Code)}} + 1\right) \text{ x } V_{IN}$$

ALTERNATE IMPLEMENTATION

Figure 6 shows an implementation which takes the best of the general and simplified implementations. In this implementation, a digital potentiometer with two (or more) resistor networks is used. This allows each resistor for the gain to be individually controlled. Since both resistors are on the same silicon, the gain resistors have good tempco matching characteristics. With the wipers of each resistor network tied together, the wiper voltage will be the same. Therefore, the wiper resistance characteristics of the two resistor networks should be similar.

The drawback of this implementation is that a dual resistor network device is more costly then a single resistor device. Table 9 shows the trade-offs with this circuit implementation.

Alternate Circuit



Note 1: A general purpose op amp, such as the MCP6001.

2: Optional feedback capacitor (C_F). Used to improve circuit stability.

3: Connecting the wiper to terminal A ensure that as the wiper register value increases, the R_{BW} resistance increases.

FIGURE 6: *Non-Inverting Amplifier with Programmable Gain Example Circuit.*

EXAMPLE GAIN CALCULATIONS – NON-INVERTING AMPLIFIER

Table 10 shows a comparison of the amplifier gain between the circuits (Figure 5a and Figure 5b) for digital potentiometer's resistor networks in the Configuration A (see Figure 2) implementation. Table 10 utilized digital potentiometer with 8-bit resolution and with an R_{AB} resistance = 10 kΩ. For the general amplifier circuit, when R_1 = R_2 = 10 kΩ, the circuit's gain (V/V) ranged between 1.5 and 3.0. But when the simplified circuit is used (effectively having R_1 = R_2 = 0Ω) the circuit's gain range is approximately between 1 and ∞ (at wiper code = 255, gain = 256).

Table 11 shows a comparison of the amplifier gain between the circuits (Figure 5a and Figure 5b) for digital potentiometer's resistor networks in the Configuration B (see Figure 2) implementation. Table 11 utilized a digital potentiometer with 8-bit resolution and with an R_{AB} resistance = 10 kΩ. For the general amplifier circuit, when R_1 = R_2 = 10 kΩ, the circuit's gain (V/V) ranged between 1.5 and 2.99. But when the simplified circuit is used (effectively having R_1 = R_2 = 0Ω) the circuit's gain range is between 1 and > 255.

Table 12 shows a comparison of the amplifier gain between the circuits (Figure 5a and Figure 5b) for digital potentiometer's resistor networks in the Configuration C (see Figure 2) implementation. Table 12 utilized a digital potentiometer with 7-bit resolution and with an R_{AB} resistance = 10 kΩ. For the general amplifier circuit, when R_1 = R_2 = 10 kΩ, the circuit's gain (V/V) ranged between 1.5 and 3.0. But when the simplified circuit is used (effectively having R_1 = R_2 = 0Ω) the circuit's gain range is approximately between 1 and ∞ (at wiper code = 126, gain = 127).

Therefore, regardless of the resistor network configuration, finer calibration of the circuit is possible with the general circuit, albeit with a narrower range. Also, resistor network configurations that allow the full-scale setting to connect to terminal A (Configurations A and C) can have very large magnitude gains (approximately ∞) since the R_{AW} resistance is almost 0.

TABLE 10: NON-INVERTING AMPLIFIER GAIN VS. WIPER CODE AND R_W – CONFIGURATION A

# of Taps	# of Resistors	Wiper Code[7]		Gain (R_{AB} = 10 kΩ) (V/V)				Comment
		Dec	Hex	Simplified Circuit [1]	General Circuit [2, 3]			
					@ $R_{AB(MIN)}$ [5]	@ $R_{AB(TYP)}$	@ $R_{AB(MAX)}$ [6]	
257	256	0	000h	1.0000	1.5556	1.5000	1.4545	Zero Scale
		1	001h	1.0039	1.5583	1.5029	1.4577	
		2	002h	1.0079	1.5610	1.5059	1.4608	
		3	003h	1.0119	1.5637	1.5088	1.4639	
		4	004h	1.0159	1.5664	1.5118	1.4670	
		:	:	:	:	:	:	
		126	07Eh	1.9692	1.9911	1.9896	1.9883	
		127	07Fh	1.9845	1.9955	1.9948	1.9942	
		128	080h	2.0000	2.0000	2.0000	2.0000	Mid Scale
		129	081h	2.0157	2.0045	2.0052	2.0059	
		130	082h	2.0317	2.0090	2.0105	2.0118	
		:	:	:	:	:	:	
		252	0FCh	64.0000	2.7654	2.9538	3.1411	
		253	0FDh	85.3333	2.7740	2.9653	3.1556	
		254	0FEh	128.0000	2.7826	2.9767	3.1703	
		255	0FFh	256.0000	2.7913	2.98883	3.1851	
		256	100h	Divide Error [4]	2.8000	3.0000	3.2000	Full Scale

Note 1: Gain = - ((R_{AB}/# of Resistors) * Wiper Code)/
((R_{AB}/# of Resistors) * (# of Resistors - Wiper Code)) = - (Wiper Code) /(# of Resistors - Wiper Code)

2: Gain = - (R_2 + R_S * (Wiper Code))/(R_1 + R_S * (# of Resistors - Wiper Code)

3: Uses $R_1 = R_2 = 10$ kΩ.

4: Theoretical calculations. At full scale in the simplified circuit a divide by 0 error results.

5: The $R_{AB(MIN)}$ shows the narrowest range of gain (more accuracy per wiper code step). Ensure gain range is adequate.

6: The $R_{AB(MAX)}$ shows the widest range of gain (less accuracy per wiper code step). Ensure gain resolution is adequate.

7: If the A and B terminals are swapped in the circuit, as the wiper value increases, the gain decreases.

TABLE 11: NON-INVERTING AMPLIFIER GAIN VS. WIPER CODE AND R_W – CONFIGURATION B

# of Taps	# of Resistors	Wiper Code(7)		Gain (R_{AB} = 10 kΩ) (V/V)				Comment
		Dec	Hex	Simplified Circuit (1)	General Circuit (2,3)			
					@ $R_{AB(MIN)}$ (5)	@ $R_{AB(TYP)}$	@ $R_{AB(MAX)}$ (6)	
256	256	0	00h	1.0000	1.5556	1.5000	1.4545	Zero Scale
		1	01h	1.0039	1.5583	1.5029	1.4577	
		2	02h	1.0079	1.5610	1.5059	1.4608	
		3	03h	1.0119	1.5637	1.5088	1.4639	
		4	04h	1.0159	1.5664	1.5118	1.4670	
		:	:	:	:	:	:	
		126	7Eh	1.9692	1.9911	1.9896	1.9883	
		127	7Fh	1.9845	1.9955	1.9948	1.9942	
		128	80h	2.0000	2.0000	2.0000	2.0000	Mid Scale
		129	81h	2.0157	2.0045	2.0052	2.0059	
		130	82h	2.0317	2.0090	2.0105	2.0118	
		:	:	:	:	:	:	
		252	FCh	- 63.0000	2.7654	2.9538	3.1411	
		253	FDh	- 84.3333	2.7740	2.9653	3.1556	
		254	FEh	- 127.0000	2.7826	2.9767	3.1703	
		255	FFh	- 255.0000	2.7913	2.98883	3.1851	Full Scale

Note 1: Gain = - ((R_{AB}/# of Resistors) * Wiper Code)/ ((R_{AB}/# of Resistors) * (# of Resistors - Wiper Code)) = - (Wiper Code)/(# of Resistors - Wiper Code)

2: Gain = - (R_2 + R_S * (Wiper Code))/(R_1 + R_S * (# of Resistors - Wiper Code)

3: Uses $R_1 = R_2 = 10\ k\Omega$.

4: Theoretical calculations. At full scale in the simplified circuit a divide by 0 error results.

5: The $R_{AB(MIN)}$ shows the narrowest range of gain (more accuracy per wiper code step). Ensure gain range is adequate.

6: The $R_{AB(MAX)}$ shows the widest range of gain (less accuracy per wiper code step). Ensure gain resolution is adequate.

7: If the A and B terminals are swapped in the circuit, as the wiper value increases, the gain decreases.

TABLE 12: INVERTING AMPLIFIER GAIN VS. WIPER CODE AND R_W – CONFIGURATION C

# of Taps	# of Resistors	Wiper Code(7)		Gain (R_{AB} = 10 kΩ) (V/V)				Comment
		Dec	Hex	Simplified Circuit (1)	General Circuit (2, 3)			
					@ $R_{AB(MIN)}$ (5)	@ $R_{AB(TYP)}$	@ $R_{AB(MAX)}$ (6)	
128	127	0	00h	1.0000	1.5556	1.5000	1.4545	Zero Scale
		1	01h	1.0079	1.5610	1.5059	1.4608	
		2	02h	1.0160	1.5665	1.5119	1.4671	
		3	03h	1.0242	1.5721	1.5179	1.4735	
		4	04h	1.0325	1.5776	1.5240	1.4800	
		: :	: :	: :	: :	: :	: :	
		62	3Eh	1.9538	1.9866	1.9844	1.9824	
		63	3Fh	1.9844	1.9955	1.9948	1.9941	Mid Scale
		64	40h	2.0159	2.0045	2.0053	2.0059	
		65	41h	2.0484	2.0136	2.0159	2.0179	
		66	42h	2.0820	2.0228	2.0266	2.0300	
		: :	: :	: :	: :	: :	: :	
		124	7Ch	42.3333	2.7481	2.9308	3.1118	
		125	7Dh	63.5000	2.7652	2.9535	3.1406	
		126	7Eh	127.0000	2.7825	2.9766	3.1700	
		127	7Fh	Divide Error (4)	2.8000	3.0000	3.2000	Full Scale

Note 1: Gain = - ((R_{AB}/# of Resistors) * Wiper Code)/ ((R_{AB}/# of Resistors) * (# of Resistors - Wiper Code)) = - (Wiper Code)/(# of Resistors - Wiper Code)

2: Gain = - (R_2 + R_S * (Wiper Code))/(R_1 + R_S * (# of Resistors - Wiper Code)

3: Uses R_1 = R_2 = 10 kΩ.

4: Theoretical calculations. At full scale in the simplified circuit a divide by 0 error results.

5: The $R_{AB(MIN)}$ shows the narrowest range of gain (more accuracy per wiper code step). Ensure gain range is adequate.

6: The $R_{AB(MAX)}$ shows the widest range of gain (less accuracy per wiper code step). Ensure gain resolution is adequate.

7: If the A and B terminals are swapped in the circuit, as the wiper value increases, the gain decreases.

OPTIMIZING TEMPERATURE BEHAVIOR

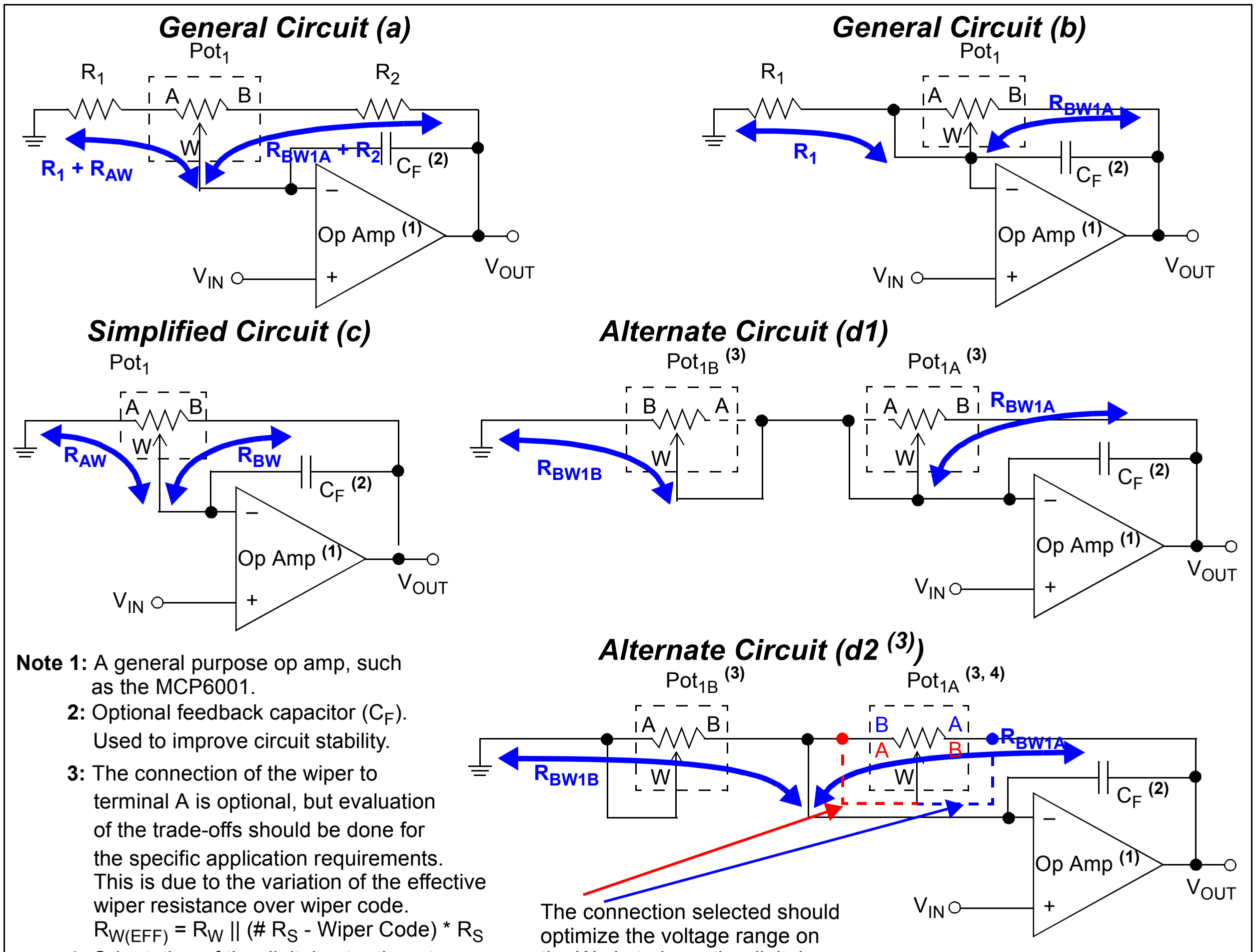
The topology of the programmable gain circuit determines how the circuit will be affected by variations in temperature as well as the manufacturing process variation of the digital potentiometer.

The gain circuit topology will effect the behavior of the circuit. Devices with multiple resistors, that are not of the same silicon, have variations due to the different temperature coefficient of the resistive devices (circuits (a) and (b)). These circuits also will have variations due to the variation of the R_{AB} resistance due to process (±20%). So one needs to understand the application's requirements to determine if the selected circuit meets those requirements.

For this discussion, Figure 7 shows the circuit options, while Table 13 compares characteristics for these circuits.

Figure 7 shows general implementations of the non-inverting amplifier with programmable gain. Two of the circuits use fixed resistors R_1 and R_2 or only R_1, while the other implementations only use digital potentiometers, either a single or dual device.

In these circuits, for our calculations we will use $R_1 = 1172\Omega$, $R_2 = 1172\Omega$. We chose this value to aid in the comparison of the implementations, since in circuit (d) it needed to be an expected R_{BW} value. So using an 8-bit device with the typical RAB value of 100 kΩ, this gives a Step Resistance (R_S) of 391Ω. Using a wiper code of 3, gives an R_{BW} resistance of 1172Ω, assuming that R_W = 0Ω. You may re-evaluate these values with assumptions based on your conditions. An Excel spreadsheet is available at this application note's web page, which allows you to modify the R_1, R_2 and R_{AB} values and then see the circuit gain and range of gain error (file name `Table 1-13 Gain Calculations.xls`).



Note 1: A general purpose op amp, such as the MCP6001.

2: Optional feedback capacitor (C_F). Used to improve circuit stability.

3: The connection of the wiper to terminal A is optional, but evaluation of the trade-offs should be done for the specific application requirements. This is due to the variation of the effective wiper resistance over wiper code. $R_{W(EFF)} = R_W$ || (# R_S - Wiper Code) * R_S

4: Orientation of the digital potentiometers for best performance is dependent on the voltage levels expected for the V_{OUT} pin and the op amps "-" input pin. The Blue lines/text vs. Red lines/text indicates the two orientations.

FIGURE 7: *Non-Inverting Amplifier with Programmable Gain Example Circuits.*

TABLE 13: NON-INVERTING AMPLIFIER WITH PROGRAMMABLE GAIN CIRCUIT COMPARISON

Circuit	Programmable Gain (V/V)								
	R_{AB} (Ω) (2)				Gain (1) (V_{OUT} / V_{IN})				
	Wiper Code	R_{BW} (Ω)	Variation (1) (%)	Tempco (ppm/°C)	Min.	Typ.	Max.	Range Error (%)	Temperature Error (ppm / °C)
(a)	3	1,172	± 20%	100	2.800	3.000	3.200	6.66	100
	128	50,000	± 20%	100	36.130	44.662	53.195	19.10	100
	255	99,609	± 20%	100	69.993	86.991	103.989	19.54	100
(b)	3	1,172	± 20%	100	1.800	2.000	2.200	10.00	100
	128	50,000	± 20%	100	35.130	43.662	52.195	19.54	100
	255	99,609	± 20%	100	68.993	85.991	102.989	19.77	100
(c) (3)	3	1,172	± 20%	100	1.012	1.012	1.012	0.00	< 1
	128	50,000	± 20%	100	2.000	2.000	2.000	0.00	< 1
	255	99,609	± 20%	100	256.000	256.000	256.000	0.00	< 1
(d) (4)	3	1,172	± 20%	100	2.000	2.000	2.000	0.00	< 1
	128	50,000	± 20%	100	43.667	43.667	43.667	0.00	< 1
	255	99,609	± 20%	100	856.000	856.000	856.000	0.00	< 1

Note 1: Assuming R_W = 0Ω. for Configuration (a): R_1 = R_2 = 1,172Ω and for Configuration (b): R_{BW1B} = 1,172Ω.

2: Typical R_{AB} resistance is 100 kΩ.

3: The gain is a ratio of the wiper tap position, so the actual R_{AB} resistance has no effect on the gain.

4: Since both R_{BW1A} and R_{BW1B} resistors are on the same process, there variations match each other. Since the matching of the one pot to the other is typically 1.00%, then the range error will have a maximum error of 1.00%.

THE FEEDBACK CAPACITOR (C_F)

The feedback capacitor (C_F) is used to stabilize the gain circuit. Initial evaluation of the feedback capacitor value can be done by applying a step input signal on the V_{IN} signal.

As the C_F value increases, the rise and fall times of the V_{OUT} signal will increase, but the overshoot and ringing of the V_{OUT} signal will decrease.

As the C_F value decreases, the rise and fall times of the V_{OUT} signal will decrease, but the overshoot and ringing of the VOUT signal will increase.

To optimize the C_F value, try the step input signal across the wiper code range for the application. So test the input step at your application's gain limits.

CONTROLLING THE DIGITAL POTENTIOMETER

Digital potentiometers are offered with different interfaces. Microchip offered devices with SPI, I^2C and Up/Down interfaces. SPI and I^2C interfaces allow the wiper to be updated with any wiper value, while the Up/Down interface requires that the wiper be sequenced through the range to get to the desired position.

Table 14 shows the available digital potentiometer development boards and if the board includes application firmware. For more information visit our web site at www.microchip.com/analogtools.

TABLE 14: DEVELOPMENT TOOL SUPPORT

Order Number	Interface	Includes Code ?
MCP402XEV	U/$\overline{D}$	Yes
MCP4XXXDM-DB	SPI	Yes
MCP42XXDM-PTPLS	SPI (1, 2)	Yes
MCP46XXDM-PTPLS	I^2C™ (1, 2)	Yes
MCP42XXEV (4)	SPI	No (2)
MCP43XXEV (3)	SPI	No (2)
MCP46XXEV (4)	I^2C™	No (2)
MCP401XEV (3)	I^2C™	No (2)

Note 1: Requires a PICDEM™ board with the PICtail™ Plus interface. Code was developed for the PIC24FJ128GA010.

2: Demos use the PICkit™ Serial Interface to control the device operation.

3: Expected Availability, April 2010.

4: Expected Availability May 2010.

SUMMARY

This application note has discussed circuit implementations and characteristics for programmable amplifier gain circuits that should be understood when using a digital potentiometer in these circuits. Digital potentiometers are a good fit for these circuits, especially with respect to gain programmability and tempco characteristics.

The topology of the programmable gain circuit determines how the circuit will be affected by variations in temperature as well as the manufacturing process variation of the digital potentiometer. It is also important to understand how the selected resistor networks configuration affects the circuits operation. Depending on your need, Microchip offers a wide range of devices. For more information contact your local sales representative or visit our web site at www.microchip.com.

Using this information and the supplied Excel spreadsheets, the programmable gain circuit can be optimized for the applications gain and temperature response requirements.

REVISION HISTORY

Rev A (April 2010)

Initial release.

Note the following details of the code protection feature on Microchip devices:

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- Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.
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