AN737

Using Digital Potentiometers to Design Low-Pass Adjustable Filters

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INTRODUCTION

The most common filter found in a data acquisition system signal path is a low-pass filter. This type of filter is usually used to reduce A/D Converter (ADC) aliasing errors. If there is more than one signal that is applied to the A/D converter through a multiplexer, each signal source may have its own set of filter requirements (i.e., settling time, fast transition region, etc.). Consequently, a variety of filters may be required in the circuit prior to the multiplexer. Usually these filters are implemented with operational amplifiers (op amps) in combination with fixed resistors and capacitors.

An alternative filter design solution is to have one filter following the multiplexer. In this circuit, the low-pass filter would need to be programmable. The obvious advantage of having the filter serve many analog inputs is that there is a reduction in chip count. An example of this type of approach is shown in Figure 1.

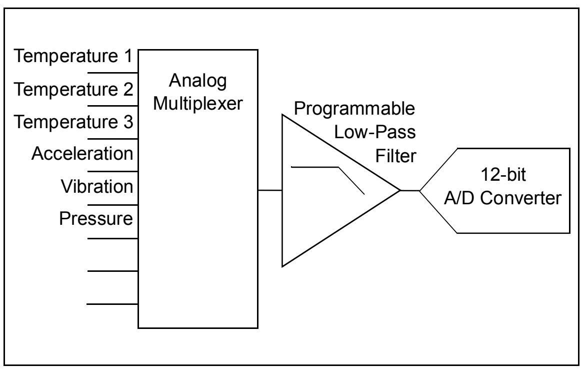

FIGURE 1: If a programmable low-pass filter is used in the application circuit, it can be placed after the analog multiplexer. The programmability of the filter allows for a wide variety of input signals.

Programmable Low-Pass Filters

In this application note, a programmable, second-order, low-pass filter will be presented in four different scenarios. The first three scenarios will illustrate how a dual digital potentiometer and a single amplifier can be configured for low-pass second-order Butterworth, Bessel and Chebyshev responses with a programmable corner frequency range of 1:100. An example of the digital potentiometer setting for these designs is summarized in Tables 1, 2 and 3. The fourth scenario will show the same circuit design, where all three approximation methods (Butterworth, Bessel and Chebyshev) can coexist with a programmable corner frequency range of 1:10. An example of the digital potentiometer settings for this combination of approximation methods is summarized in Table 4.

Figure 2 shows the details of a single-supply, unity gain, second-order, programmable low-pass Sallen Key filter. This filter is implemented with two resistors and two capacitors. The two resistors in this circuit are replaced with the dual MCP42100, 100 kΩ, 8-bit, digital potentiometer.

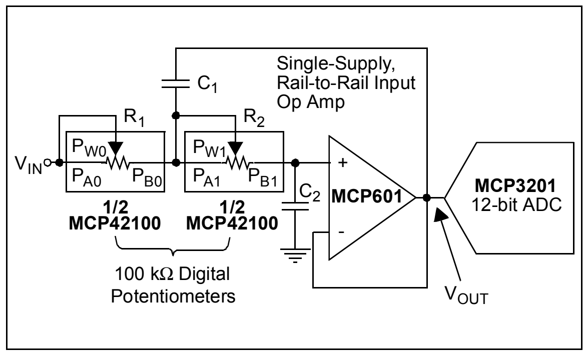

FIGURE 2: The combination of a dual digital potentiometer and a single-supply, rail-to-rail amplifier can be used to construct a programmable, second-order, Sallen-Key, low-pass filter.

Digital potentiometers can be used to adjust system reference levels, gain errors and offset errors, while offering the added capability of digital adjustment control. Devices such as Microchip's MCP41XXX and MCP42XXX digital potentiometer families have three resistive terminals for the single versions (MCP41010, MCP41050 and MCP41100) and six resistive terminals for the dual versions (MCP42010, MCP42050 and MCP42100) and are illustrated in Figure 3. The MCP41010 and MCP42010 are both 10 kΩ potentiometers. The MCP41050 and MCP42050 are both 50 kΩ potentiometers, while the MCP41100 and 42100 are both 100 kΩ potentiometers.

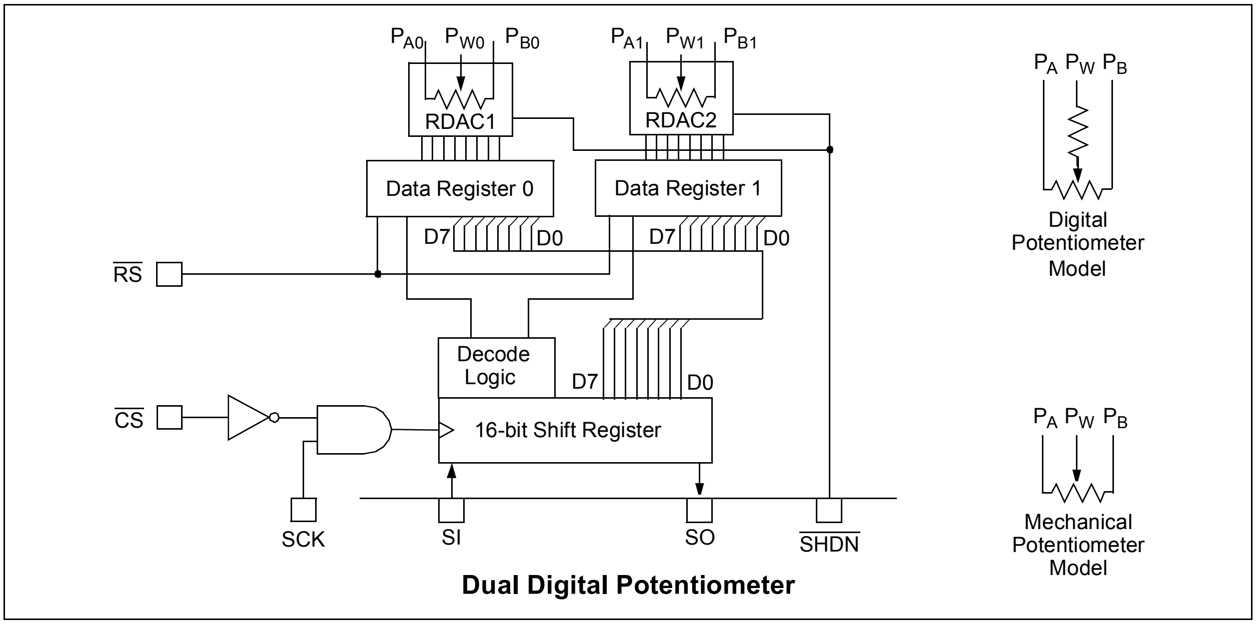

FIGURE 3: *The operation of the digital potentiometer as compared to the mechanical potentiometer is functionally the same. The adjustment of the digital potentiometer is done with a serial code to the device. Although the mechanical potentiometer provides simplicity, the digital potentiometer provides flexibility and reliability.*

The potentiometer can be configured for two modes: the Rheostat mode and Voltage Divider mode. In the Rheostat mode, the wiper (terminal P_W) is shorted to either the P_A or P_B terminal of the device. This configuration is shown in Figure 4. When used in the Voltage Divider mode (Figure 4.b), all three terminals are connected to differing nodes in the circuit. For the analog filter example in this application note, the digital potentiometer will be configured in the Rheostat mode.

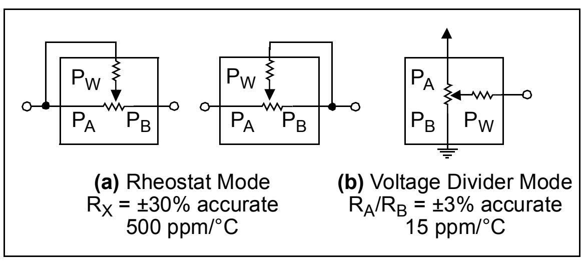

FIGURE 4: *A digital potentiometer can be configured in the (a) Rheostat mode or (b) Voltage Divider mode.*

The operational amplifier used in this application circuit is a single-supply, rail-to-rail out device. The MCP601 is a single amplifier that belongs to the MCP601/2/3/4 family of operational amplifiers. The MCP603 is also a single amplifier with a Chip Select feature. The dual version is the MCP602, while the quad version is the MCP604. These amplifiers are optimized for high speed, low offset voltage and single-supply operation.

By adjusting the two digital potentiometers in Figure 2, the frequency cutoff and the filter approximation method of this second-order low-pass filter can be changed.

The design equation for this low-pass filter configuration is:

$$\frac{V_{OUT}}{V_{IN}} = \frac{K/(R_1R_2C_1C_2)}{s^2 + s(1/R_1C_1 + 1/R_2/C_1 + 1/R_2C_2 - K/R_2C_2) + 1/R_1R_2C_1C_2}$$

Where: K = 1

With this formula, the appropriate resistance and capacitance can be calculated. An alternative to this tedious design exercise is to determine the capacitor and resistor values using the FilterLab® software, a filter design program that can be downloaded from Microchip's web site at www.microchip.com.

The Circuit screen in this program allows the user to adjust the capacitors to desired values (C_1 and C_2 per Figure 2). When these capacitors are set, the software changes the resistors in the circuit to appropriate values for the circuit implementation. There may be a corner frequency and stability error with low-pass filters that are designed at frequencies higher than 100 kHz. This error is introduced by the parasitic capacitance of the digital potentiometer. As a general guideline, C_1 and C_2 should be larger than 10 nF.

For more detailed information concerning anti-aliasing filters, please refer to Microchip's Application Note 699, entitled *"Anti-Aliasing, Analog Filters for Data Acquisition Systems"* (DS00699).

TABLE 1: A BUTTERWORTH FILTER DESIGN ADJUSTING THE RESISTORS THROUGH A DIGITAL POTENTIOMETER

Specifications: Programmable cutoff frequency range of 100 Hz to 10 kHz by using capacitors of C_1 = 0.047 µF, C_2 = 0.018 µF and adjusting the resistors through a digital potentiometer.

Cutoff Frequency, Hz	FilterLab Calculated 1% R_1 Value, kΩ	Closest Nominal Digital Pot. R_1 Value, kΩ	Digital Pot. R_1 Code, decimal	FilterLab Calculated 1% R_2 Value, kΩ	Closest Digital Pot. R_2 Value, kΩ	Digital Pot. R_2 Code, decimal
100	32.2	32.031	82	92.8	92.969	238
200	16.1	16.016	41	46.4	46.484	119
300	10.7	10.156	26	30.9	30.859	79
1000	3.22	3.125	8	9.28	9.375	24
2000	1.61	1.563	4	4.64	4.688	12
3000	1.07	1.172	3	3.09	3.125	8
10000	322	0.391	1	928	0.781	2

Butterworth Second-Order Low-Pass Filters

When a Butterworth filter is required, the Sallen Key configuration shown in Figure 2 can have an adjustable frequency range of 1:100. The frequency behavior of the Butterworth filter is maximally flat in the magnitude response in pass band. The rate of attenuation in transition band is better than the Bessel filter, though not as good as the Chebyshev filter. There is no ringing in the stop band. The step response of the Butterworth filter has some overshoot and ringing in the time domain, though this is less than the Chebyshev filter.

The capacitor values in this circuit are kept constant while the resistive elements are adjusted. The two capacitors should be carefully selected to be constants in the FilterLab software so that the digital potentiometer resistances are the only values that are changing. These capacitive values can easily be found in the FilterLab software through experimentation.

As an example, a programmable second-order, low-pass Butterworth filter with a corner frequency that ranges from 100 Hz to 10 kHz can be designed by setting C_1 = 0.047 µF and C_2 = 0.018 µF. The values calculated by the FilterLab software for this filter design are summarized in Table 1. Table 1 also includes the closest values for R_1 and R_2 from the digital potentiometer, along with the digital program code for the MCP42100.

Verification of the performance of the Butterworth filters that use 1% discrete resistors can be performed with the SPICE listing that is provided as an output from the FilterLab software. The SPICE simulations for the 100 Hz, 200 Hz, 300 Hz and 1,000 Hz filters using the values calculated by the FilterLab software are shown in Figure 5.

To validate the digital potentiometer design, SPICE simulations can be performed on the Butterworth filters using the digital potentiometer values. The 100 Hz, 200 Hz, 300 Hz and 1,000 Hz filters using the calculated nominal resistance values of the digital potentiometers, per Table 2, are shown in Figure 6.

From these two SPICE simulations, it is easy to see that the filters from Figure 5 behave fundamentally the same over frequency as compared to Figure 6.

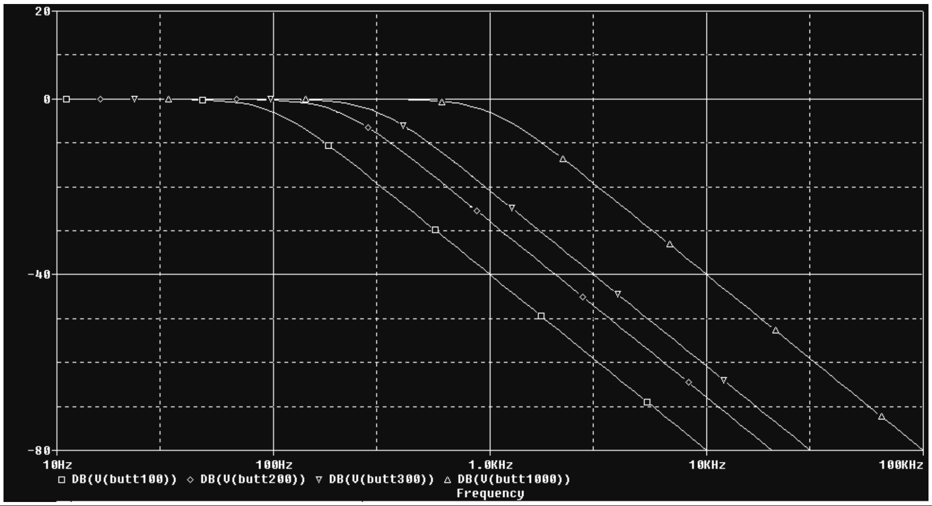

FIGURE 5: *SPICE simulation of four Butterworth, second-order low-pass filters with corner frequencies of 100 Hz, 200 Hz, 300 Hz and 1,000 Hz. In this simulation, 1% resistor values were used.*

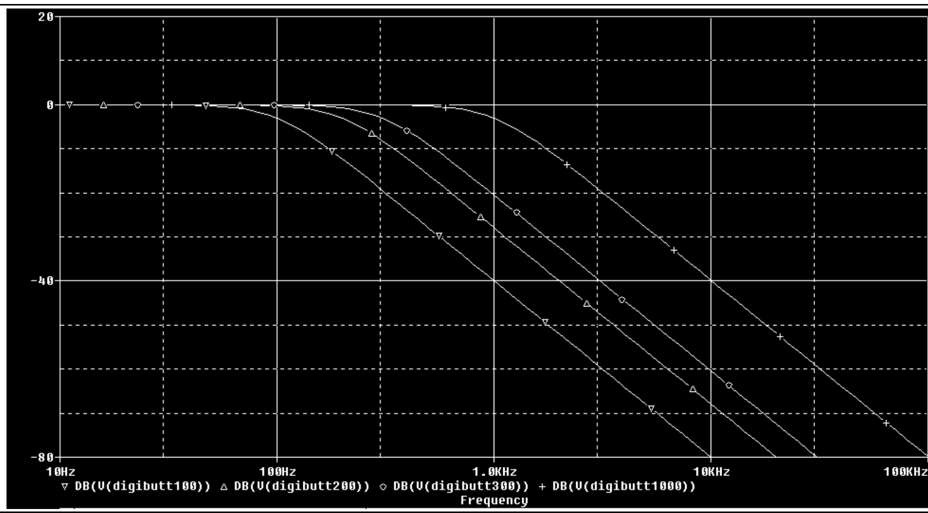

FIGURE 6: *SPICE simulation of four Butterworth, second-order low-pass filters with corner frequencies of 100 Hz, 200 Hz, 300 Hz and 1,000 Hz. In this simulation, nominal digital potentiometer resistor values, per Table 1, were used.*

TABLE 2: A PROGRAMMABLE BESSEL FILTER DESIGN USING A DUAL 100 KΩ DIGITAL POTENTIOMETER.

Specifications: A programmable Bessel filter with a cutoff frequency range of 100 Hz to 10 kHz can be implemented with C_1 = 0.033 µF, C_2 = 0.018 µF and a dual 100 kΩ digital potentiometer.

Cutoff Frequency, Hz	FilterLab Calculated 1% R_1 Value, kΩ	Closest Nominal Digital Pot. R_1 Value, kΩ	Digital Pot. R_1 Code, decimal	FilterLab Calculated 1% R_2 Value, kΩ	Closest Digital Pot. R_2 Value, kΩ	Digital Pot. R_2 Code, decimal
100	28.7	28.516	73	91.5	91.406	234
200	14.3	14.453	37	45.7	43.75	117
300	9.57	9.375	24	30.5	30.469	78
1000	2.87	2.734	7	9.15	8.984	23
2000	1.43	1.563	4	4.57	4.688	12
3000	0.957	0.781	2	3.05	3.125	8
10000	0.287	0.391	1	0.915	0.781	2

Bessel Second-Order Low-Pass Filters

When a Bessel filter is desired, the Sallen Key configuration, shown in Figure 2, can have an adjustable frequency range of 1:100. As with the Butterworth filter, the frequency response of the Bessel filter has a flat magnitude response in the pass band. Following the pass band, the rate of attenuation in the transition band is slower than the Butterworth or Chebyshev. Finally, there is no ringing in the stop band. This filter has the best step response of all of the filters mentioned in this application note, with very little overshoot or ringing.

In Table 3, a programmable Bessel filter is designed with a corner frequency range of 100 Hz to 10 kHz, by setting C_1 = 0.033 µF and C_2 = 0.018 µF. Once again, in the FilterLab software, the capacitor values are kept constant, while the resistive elements are adjusted.

Chebyshev 2nd Order Low-Pass Filters

The filter in Figure 2 can also be designed in the Chebyshev approximation for an adjustable range of 1:100. With the Chebyshev filter, the frequency behavior exhibits a ripple in the pass-band that is determined by the specific placement of the poles in the circuit design. With the design discussed in this application note, the ripple is 3 dB. In general, an increase in ripple magnitude will lessen the width of the transition band. The rate of attenuation in the transition band is steeper than Butterworth and Bessel filters. Although there is ringing in the pass-band region with this filter, the stop band is devoid of ringing. The step response has a fair degree of overshoot and ringing.

An example of the digital potentiometer settings for a 2nd order, low-pass Chebyshev filter is given in Table 3.

TABLE 3: CHEBYSHEV FILTER DESIGN

Specification: Chebyshev, 3 dB Ripple, 100 to 10 kHz cutoff, C_1 = 0.15 µF, C_2 = 0.015 µF						
Cutoff Frequency, Hz	**FilterLab Calculated 1% R_1 Value, kΩ**	**Closest Nominal Digital Pot. R_1 Value, kΩ**	**Digital Pot. R_1 Code, decimal**	**FilterLab Calculated 1% R_2 Value, kΩ**	**Closest Digital Pot. R_2 Value, kΩ**	**Digital Pot. R_2 Code, decimal**
100	21.0	21.094	54	75.6	75.781	194
200	10.5	10.547	27	37.8	37.891	97
300	7.01	7.031	18	25.2	25.391	65
1000	2.10	1.953	5	7.56	16.016	41
2000	1.05	1.563	4	3.78	3.9063	10
3000	0.701	0.781	2	2.52	2.344	6
10000	0.210	0.391	1	0.756	0.781	2

TABLE 4: THE BUTTERWORTH, BESSEL AND CHEBYSHEV APPROXIMATION METHODS

Specifications: The Butterworth, Bessel and Chebyshev approximation methods can be designed into the circuit in Figure 2 by using a dual potentiometer and capacitive values of C_1 = 0.015 µF, C_2 = 0.0022 µF. The adjustable cutoff frequency range of these filters is 1,000 Hz to 10 kHz.					
Cutoff Frequency, Hz	**Filter Approximation Method**	**Closest Digital Pot. R_1 Value, Ω**	**Digital Pot. R_1 Code, decimal**	**Closest Digital Pot. R_2 Value, Ω**	**Digital Pot. R_2 Code, decimal**
1,000	Butterworth	8.203	21	94.141	241
	Bessel	5.078	13	93.359	239
	Chebyshev (3 dB Ripple)	3.516	9	33.984	87
2,000	Butterworth	3.906	10	47.266	121
	Bessel	2.344	6	46.484	119
	Chebyshev (3 dB Ripple)	15.625	40	17.188	44
3,000	Butterworth	2.734	7	31.250	80
	Bessel	1.563	4	31.250	80
	Chebyshev (3 dB Ripple)	10.547	27	11.328	29
10,000	Butterworth	0.781	2	9.375	24
	Bessel	0.391	1	9.375	24
	Chebyshev (3 dB Ripple)	3.125	8	3.516	9

Combining Butterworth, Bessel and Chebyshev Second-Order Low-Pass Filters

All three approximation methods can be combined, with some limitations, in this circuit. Since there is a large variety of pole locations, the cutoff frequency range is 1:10. An example of a programmable filter with a cutoff frequency range of 1,000 Hz to 10 kHz is shown in Table 4.

ERROR ANALYSIS OF PROGRAMMABLE FILTERS

Absolute Accuracy of Circuit Elements

The nominal resistance of a 100 kΩ digital potentiometer (MCP42100), per data sheet specifications, varies approximately ±30%. If the 10 kΩ digital potentiometer (MCP42010) is substituted for the MCP42100, the nominal resistance variance from part-to-part is specified at ±20% for the MCP42010. When the 10 kΩ potentiometer is substituted, the capacitive values should be increased by 10X. For instance, in the Butterworth example of Table 1, C_1 should be changed to 0.47 µF and C_2 changed to 0.18 µF. When this is done, the codes to the potentiometer that can stay the same, remain unchanged. The change of the potentiometer from the MPC42100 (100 kΩ) to the MCP42010 (10 kΩ) will, in fact, decrease the values, as stated in Table 1, by 10X.

In this application circuit, it is suggested that the dual version of the digital potentiometer be used because there can be part-to-part variation of the nominal resistance (±30% for the MCP42100 and ±20% for the MCP42010). With the dual potentiometer, resistor-to-resistor variation on chip is specified to a typical value of 0.2%. The resistance variation of these digital potentiometers is primarily dependent on the process variation of the sheet-rho of a diffused p-silicon layer and the on-resistance of the internal switches.

If 20% accurate capacitors are used, the variability of this filter in a manufacturing environment is dominated by the capacitors.

Wiper resistance

The wiper resistance of the MCP42100 digital potentiometer is approximately 125Ω (typ) when V_{DD} = 5.5V. This wiper resistance appears as an error in the resistance value of the digital potentiometer only at lower programmed settings. For instance, with the MCP42100, the nominal resistance step for each code is equal to 100 kΩ/256, or 390.625Ω. With a digital code setting of ‘1’, the ideal nominal resistance is 390.625Ω. However, with the added wiper resistance, this resistance is nominally 515.625Ω.

CONCLUSION

It is possible to design second-order, low-pass, programmable filters with one dual digital potentiometer, one amplifier and two capacitors.

REFERENCES

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AN691, “Optimizing Digital Potentiometer Circuits to Reduce Absolute and Temperature Variations”, Bonnie C. Baker, Microchip Technology Inc., DS00691, 2001.

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