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Digital Potentiometers vs. Mechanical Potentiometers: Important Design Considerations to Maximize System Performance

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Abstract

This article will provide design details on how to use digital potentiometers with other components highlighting the important considerations and specifications for each use case to ensure the designer gets the best possible system performance. Important design considerations and specifications that should be taken into account when combining digital potentiometers with other components, such as op amps to create flexible multiuse systems will be addressed. Digital potentiometers' advantages and disadvantages vs. traditional potentiometer designs will be explored as well. The article will also use numerous real-world examples to demonstrate how digital potentiometers can provide a marked improvement over more traditional alternative solutions. For example, using a digital potentiometer as a feedback resistor in an op amp allows the gain of the op amp to alternate according to amplitude of the input signal.

Digital potentiometers are digitally controlled variable resistors that can be used in place of their functionally equivalent mechanical counterparts. While digital potentiometers offer comparable functionality to mechanical potentiometers, the specifications, reliability, and repeatability associated with digital potentiometers for many designs are superior. Potentiometers can be used to adjust voltages or currents by varying the resistance of the device. The adjustment can then be used to set a varying level or gain when used in conjunction with other components such as op amps. Using a variable component such as a digital potentiometer allows designers to design systems that are flexible and multifunctional. For example, using a digital potentiometer as a feedback resistor in an op amp allows the gain of the op amp to alternate according to amplitude of the input signal. This gives the designer the benefit of reducing the components (such as multiple op amps) while maximizing the type of input signals the system can work with a reduced PCB footprint. A digital potentiometer provides a lot of functionality in a small footprint.

Digital vs. Mechanical Potentiometers

Digital and mechanical potentiometers share similarities that allow them to be interchangeable in many applications. Both are adjustable, offer wide arrays of end to end resistances, and solve the requirement for a user adjustable resistance. Some advantages that mechanical potentiometers have over their digital counterparts include the ability to withstand larger voltages, larger current carrying capability, and larger power dissipation. However, due to the design of mechanical potentiometers they are prone to performance changes and reliability concerns over time. They are more sensitive to shocks and vibrations, and the mechanical wiper contact resistance can change due to oxidation, aging, and wear. This reduces the usable lifetime of a mechanical potentiometer. A digital potentiometer consists of a number of CMOS transmission gates (see Figure 1). As there are no mechanical elements, the digital potentiometer is resilient against shocks, wear, aging, and contact.



Figure 1. Digital potentiometer-internal structure.

What to Consider When Using a Digital Potentiometer

As with all components, there are some factors to consider when choosing the correct component for your application. The ranking of how important each specification is will depend on the final use and other system considerations.

Table 1. Important Considerations When Choosing a Digital Potentiometer

Voltage of Input Signal	Maximum Current and Power	End to End Resistance	Tolerance and Temperature Coefficients	Resolution/ Channel Density
Linearity	Power Up	Memory	Interface	Size

The best way to understand these considerations is to take a look at how they affect the choice of digital potentiometer in a specific application. So, we will now look at two important use cases for digital potentiometers in more detail.



Some applications that digital potentiometers are commonly used in are as follows:

- Attenuators for dc and ac signals
- Varying the gain of an op amp

How to Use Digital Potentiometers as Attenuators

A digital potentiometer can be used to emulate a simple low resolution digital-to-analog converter (DAC). Figure 2 shows this setup, as well as some terminology that is frequently seen. The end to end resistance is defined as R_{AB} , the resistance between terminals A and B. R_{AW} and R_{WB} refer to the resistance between the wiper and the terminal. The transfer function is also noted in Figure 2.



Figure 2. Digital potentiometer as a low resolution DAC.

For this setup, there are three key parameters to note while choosing a digital potentiometer. The voltage supply range, the digital potentiometer resolution, and linearity.

Voltage supply¹ and resolution² are important considerations as these specifications cover the range of inputs the digital potentiometer can pass and number of distinct resistance levels that can be achieved. The linearity of a digital potentiometer is specified in a similar manner to DACs using INL (integral nonlinearity) and DNL (digital nonlinearity). INL refers to the maximum deviation of a real digital potentiometer from an ideal straight line drawn from zero scale to full scale. DNL refers to the difference between the output and ideal transfer function for successive codes.

For ac applications, the same parameters as dc power supplies apply also (voltage supply range, resolution, and linearity). Total harmonic distortion (THD) and bandwidth are key factors that should also be considered.

How to Use Digital Potentiometers in Creating Variable Gain Op Amps

Digital potentiometers are very useful in varying the gain of an op amp. The gain ratio of Rb/Ra can be set and varied precisely using the digital potentiometer. Applications that utilize gain control include volume control, sensor calibration, and contrast/brightness in LCD screens. However, there are a number of digital potentiometer characteristics that must be considered during configuration.

When a digital potentiometer is used in potentiometer mode, one must be aware of the transfer function of the digital potentiometer as the resistance increases from zero scale to full scale. As the resistance between R_{AW} increases, R_{BW} decreases, this creates a logarithmic transfer function. Logarithmic transfer functions are more suited to the human ear and eye response (Figure 3(a)).

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If the application requires a linear response, the digital potentiometer can be linearized either by using the digital potentiometer in rheostat mode (Figure 3(b)), a Vernier DAC configuration (Figure 3(c)), or through the linear gain setting mode, a feature exclusive to members of the ADI digiPOT+ family such as the AD5144 (Figure 3(d)).



Figure 3. Potentiometer configurations.

Rheostat Mode with a Discrete Resistor

Using the digital potentiometer in rheostat mode and placing it in series with a discrete resistor, the output can be linearized (Figure 3(b)). This is a simple design, however, there are design considerations that need to be taken into account to maintain system accuracy.

Both mechanical and digital potentiometers have a tolerance on the resistance for different reasons. For mechanical potentiometers, the tolerance can vary due to the difficulty of achieving repeatable values. For digital potentiometers, there is tolerance due to the manufacturing process but it has values that are far more repeatable compared to a mechanical potentiometer.

A discrete surface mount resistor may have an offset as small as 1%, but some digital potentiometers can have an end to end resistance tolerance of up to 20%. It is this mismatch that can lead to loss in resolution and can be a significant problem, particularly in open loop applications where monitoring is not practical to compensate for the error. Where monitoring is possible, the built-in flexibility of digital potentiometers allows a simple calibration routine to adjust the wiper position of the digital potentiometer and adjust for any offsets.

Analog Devices portfolio of digital potentiometers are specified with varying tolerances of 20% down to 1% to match the most stringent precision and accuracy needs. Some digital potentiometers, such as the AD5258/AD5259, factory test the error tolerance and store the results in user accessible memory to allow resistor matching at production.

¹ The signals that are sent through a digital potentiometer's terminals are limited to the maximum and minimum supply voltages. If the signal exceeds the supply, the internal ESD protection diodes will clamp the signal. For ac signals, the signal can be biased to maintain within the single-supply range or consider a dual-supply digital potentiometer.

² Like a DAC, resolution refers to the number of wiper positions. Some common numbers include 128, 256, and can go as high as 1024.

Linear Gain Setting Mode

The final method is the linear gain setting mode exclusive to ADI's digiPOT+ portfolio. Figure 3(d) shows how the patented architecture implemented allows for independent programming of the value for each string R_{AW} and R_{WB} . Using this mode allows for a linear output by fixing the output of one string (R_{WB}) and setting the other string (R_{AW}) . This operation is similar to using the rheostat mode digital potentiometer with a discrete resistor. However, the overall tolerance error is less than 1% without any extra parallel or series resistance combination.

This is due to the error in the resistances, as it is common in both resistor string arrays and can be disregarded. Figure 4 shows the mismatch error between the two resistances is small at higher codes. The mismatching does increase above $\pm 1\%$ at codes lower than quarter scale, but this is due to the error added by the effect of the internal CMOS switches resistance which cannot be ignored.



Figure 4. 10k resistance match error.

Why Memory Is Important to Your Application

When using digital potentiometers to set levels in circuits or calibrate sensors and gain settings, the power-up state of the digital potentiometer is important to ensure accurate and speedy configuration. Digital potentiometers are available in many options to ensure the device powers up in the user's preferred state. There are two categories of digital potentiometer:

- Nonvolatile—Parts have an on-chip memory element which stores the user chosen wiper position to be configured on power-up.
- Volatile—Parts do not have a programmable memory, instead the part powers up the wiper position at zero scale, midscale, or full scale depending on the part configuration. See each product's data sheet for full details.

Within the nonvolatile digital potentiometer classification there are further options:

- EEPROM
- One time programmable (OTP)
- Multiple time programmable (MTP)

The wide variety of memory options allow the digital potentiometer choice to be tailored to the particular system. For example, for systems that require constant adjustment volatile digital potentiometers can be used. For systems that only require a calibration on factory testing, an OTP potentiometer can be used. EEPROM digital potentiometers can be used to retain the last wiper position so that on power-up the digital potentiometer will return to the last state and can continue to be adjusted as needed after power-up.

Summary

As previously shown, digital potentiometers can be used to create easy to use, adjustable signal chains, replacing mechanical potentiometers, thus improving specifications, reliability, and PCB area. These improvements can be achieved and system design considerations can be reduced by taking the above considerations into account.

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