Matched Resistors Maximize Amplifier Performance

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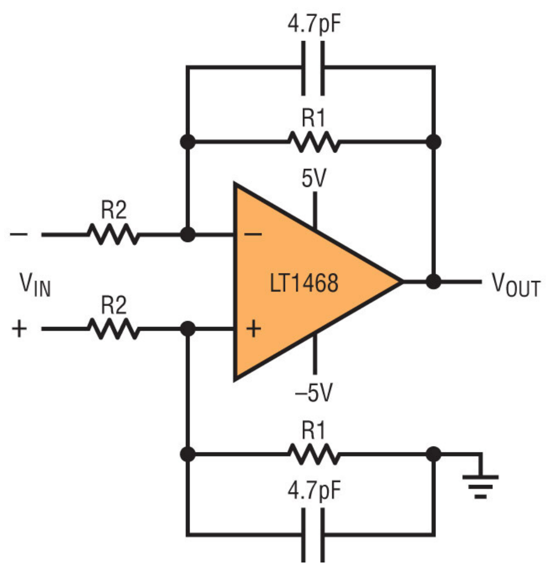
Operational amplifiers are the analog designer's workhorse – they are used to extract, scale, shift, buffer, combine, filter and condition the real world signals. For applications requiring high precision and stability, designers carefully consider specifications such as input offset voltage, noise and bandwidth, and choose op amps that achieve the necessary performance. Errors tend to stack up, so careful attention is also paid to the selection of other components which follow the amplifier such as data converters and voltage references. While this is important, one must be careful not to ignore the accuracy effects of the components, which come before and surround the amplifier, especially resistors.

Resistor Matching Effects on System Accuracy

The example circuit shown below uses 4 resistors and an operational amplifier to form a traditional difference amplifier.

DIFFERENCE AMPLIFIER



The output voltage is determined by the ratio of the resistors:

$$Vout = \frac{R1}{R2} Vin$$

From the above formula, we see that this is a case where resistor matching is more critical than absolute accuracy in determining the performance of the amplifier circuit. If R1 and R2 vary proportionally, the gain will not change. If one resistor changes relative to the other, then the ratio of R1 to R2 and therefore the gain does change. This is also true in other commonly used ratiometric circuits such as precision dividers, precision gain stages, and bridge circuits. In the discussion that follows, the performance effects of resistor mismatch will be explored for three types of resistors: precision discrete resistors, traditional matched resistor arrays, and the LT5400 a new family of precision matched thin film resistors.

In precision applications such as the difference amplifier shown above, something better than standard 1% resistors will be needed. Let's begin by considering ten times higher accuracy 0.1% resistors. Since each resistor can vary -0.1% to +0.1% from its nominal value, the worst case matching for two resistors would be ±0.2% ((1+0.001)/(1-0.001) = 1.002) or 2000ppm, or 9 bits of accuracy at room temperature. Over temperature, matching is an even bigger issue. Most resistor manufacturers specify a temperature coefficient that is separate from the tolerance specification. The 0.1% resistors used in this example might have a tempco of 25ppm/°C. Over a 0°C to 70°C range, the result is greater than 3000ppm error. This error translates to amplifier circuit gain error and does not include non-idealities in the op amp itself or other error sources in the signal chain.

For better accuracy, more precise 0.01% tolerance resistors may be chosen, but for the best performance a precision matched resistor array should be used. A resistor array, where multiple resistors are included in a single package, will have resistors that tend to track each other over temperature. For example, a 0.01% tolerance array might have a ±2ppm/°C ratio tempco, resulting in 190ppm error from 0°C to 70°C. This is a significant improvement over the discrete 0.1% resistor case.

When even higher precision is needed, a new family of precision matched resistors from Linear Technology, the LT5400 can be used. It employs careful layout techniques so that each of its 4 thin film resistors is balanced geometrically and shares the same center point. The LT5400 is available in a small, surface mount package and has a ±75V operating voltage. Each package includes four resistors and different nominal resistance values are available with R1/R2 ratios of 1, 5 and 10 with more options to come (see Table 1). A large exposed pad on the bottom of the package provides consistent thermal conditions for each of the four resistors, and the pad also minimizes internal temperature rise for large dissipated power. This design ensures that all four resistors are subject to the same operating environment. The LT5400 offers resistor-to-resistor matching better than 0.01% over temperature, matching temperature drift of 1ppm/°C, and long term stability error of less than 2ppm after 2000hrs. As a result, it achieves 100ppm matching error over the 0°C to 70°C range (Table 2). It maintains excellent performance over even wider temperature ranges, up to -50°C to 150°C. The LT5400 is also very stable over time. It exhibits less than 2ppm variation at 2000 hours.

Common Mode Voltage Effects

In many applications, the signal being conditioned by the amplifier is superimposed on a larger (and sometimes varying) common mode signal. Ideally the amplifier ignores the common mode signal and amplifies, buffers, or otherwise conditions the differential signal. If the common mode signal is not effectively cancelled by the amplifier, offset voltages and distortion can result at the output. An amplifier's common mode rejection ratio (CMRR) is a measure of how well an op amp blocks the common mode component of the incoming signal. Once again, resistor mismatch in these applications can easily be the greatest contributor to common mode error. CMRR due to resistor mismatch is usually expressed in dB and can be calculated using the following formula:

$$CMRR_{RESISTORS} = 20\log\left[\frac{\frac{1}{2}\bullet(1+G)}{(\Delta R/R)}\right]$$

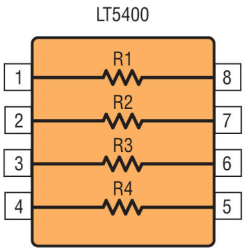
where G is the nominal value of R1/R2 and ΔR/R is the resistor ratio matching error.

Following our examples above we see that the resistors once again can play a dominant role in setting the overall system performance. Using the above equation, we can calculate the common mode rejection ability of the example resistors previously discussed. A pair of 0.1% resistors will exhibit 54dB CMRR, and a 0.01% array will exhibit 74dB CMRR. The LT5400 resistor array is different from the other resistors considered in terms of its CMRR performance. This is because it is designed, tested, and guaranteed specifically for a tight tolerance for CMRR. It provides a guaranteed specification for matching for CMRR of 0.005%, achieving 86dB over temperature for the highest grade version. This is 2x better performance than would be achieved by using the formula alone.

Conclusion

Op amps combined with discrete components make up a broad array of useful circuits. Equal care should be taken in selecting these external components as in choosing the amplifier itself. Resistor matching, and especially matching over temperature and common-mode voltage range are important specifications that will determine the accuracy of the system and how much factory or field calibration is needed to achieve the desired system accuracy. Resistor arrays are best suited for these applications, and new products such as the LT5400 quad resistor array achieve excellent precision.

TABLE 1



FAMILY OF 6 PARTS

PART NUMBER	R2 = R3 (Ω)	R1 = R4 (Ω)	RESISTOR RATIO
LT5400-1	10k	10k	1: 1
LT5400-2	100k	100k	1: 1
LT5400-3	10k	100k	1:10
LT5400-4	1k	1k	1: 1
LT5400-5	1M	1M	1: 1
LT5400-6	1k	5k	1: 5

TABLE 2

RESISTOR TYPE	MATCHING ERROR (0°C TO 70°C
0.1% Discrete	3800ppm
0.01% Array	190ppm
LT5400 Array	100ppm