Fully differential amplifiers

By Jim Karki

Systems Specialist, High-Speed Amplifiers

Introduction

Professional audio engineers usually use the term “balanced” to refer to differential signal transmission. This imparts the idea of symmetry, which is very important in differential systems. The driver has balanced outputs, the line has balanced characteristics, and the receiver has balanced inputs.

There are two methods commonly used to manipulate differential signals: electronic and transformer.

1. Electronic methods have advantages such as low cost, small size and weight, and superior frequency response at low frequency and dc.
2. The advantages that transformers offer are excellent common-mode rejection ratio (CMRR), galvanic isolation, no power consumption (efficiencies near 100%), and immunity to very hostile EMC environments.

This article focuses on integrated, fully differential amplifiers for signal conditioning differential signals. Basic operations, such as how to transform single-ended signals into differential signals and how to construct active anti-alias filters, are discussed.

What is an integrated, fully differential amplifier?

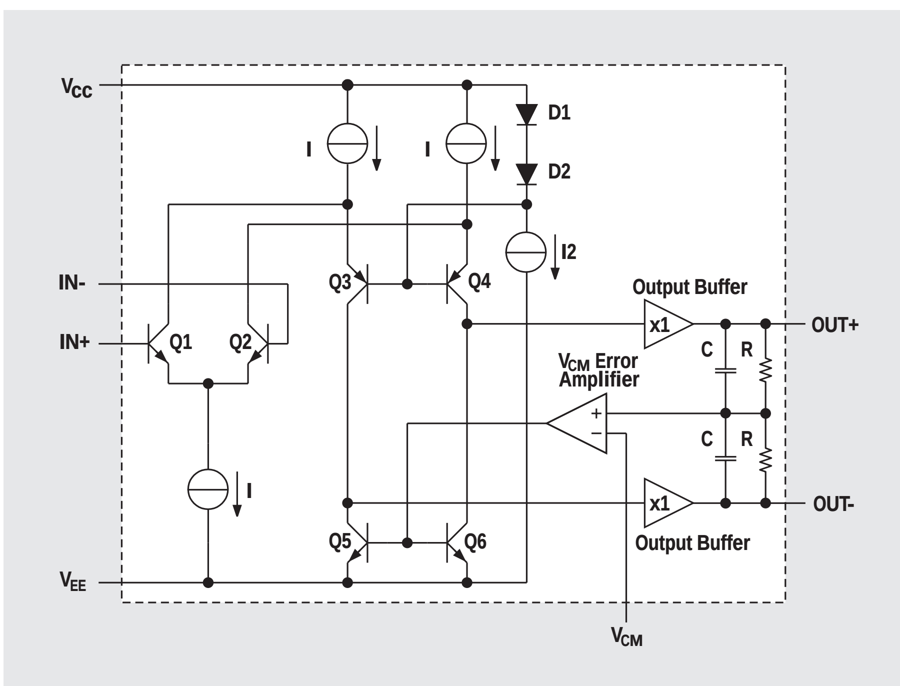
An integrated, fully differential amplifier is very similar in architecture to a standard operational amplifier.

Figure 1 shows a simplified version of an integrated, fully differential amplifier. Q1 and Q2 are the input differential pair. In a standard op amp, output current is taken from only one side of the input differential pair and is used to develop a single-ended output voltage. In a fully differential amplifier, currents from both sides are used to develop voltages at the high-impedance nodes formed at the collectors of Q3/Q5 and Q4/Q6. These voltages are then buffered to the differential outputs OUT+ and OUT–.

For a first-order approximation, voltage common to IN+ and IN– does not produce a change in the current flow through Q1 or Q2 and thus produces no output voltage; it is rejected. The output common-mode voltage is not controlled by the input. The V_{CM} error amplifier controls the output common-mode voltage by sampling it, comparing it to the voltage at V_{CM}, and adjusting the internal feedback.

The two complementary amplifier paths share the same input differential pair, their characteristics are very well

Figure 1. Simplified, fully differential amplifier



matched, and the architecture keeps their operating points very close to each other. Therefore, distortion in the amplifiers is also matched, resulting in symmetrical distortion of the differential signal. Symmetrical distortions tend to cancel even-order harmonics. Lab testing shows that the second harmonic levels in a differential output are reduced by approximately 5 dB in the THS4141 at 1 MHz when measured differentially as compared to measuring either single-ended output. The measured level of the third harmonic is unchanged.

Voltage definitions

To understand how a fully differential amplifier behaves, it is important to understand the voltage definitions that are used to describe the amplifier. Figure 2 shows a block diagram that represents a fully differential amplifier and its input and output voltage definitions.

The voltage difference between the plus and minus inputs is the input differential voltage, V_{ID}. The average of the two input voltages is the input common-mode voltage, V_{IC}.

The difference between the voltages at the plus and minus outputs is the output differential voltage, V_{OD}. The output common-mode voltage, V_{OC}, is the average of the two output voltages and is controlled by the voltage at V_{CM}.

A_f is the frequency-dependent differential gain of the amplifier, so that $V_{OD} = V_{ID} \times A_f$.

Increased noise immunity

Invariably, when signals are routed from one place to another, noise is coupled into the wiring. In a differential system, keeping the transport wires as close as possible to one another makes the noise coupled into the conductors appear as a common-mode voltage. Noise that is common to the power supplies will also appear as a common-mode voltage. Since the differential amplifier rejects common-mode voltages, the system is more immune to external noise. Figure 3 shows the noise immunity of a fully differential amplifier.

Increased dynamic range

Due to the change in phase between the differential outputs, the dynamic range increases by 2x over a single-ended output with the same voltage swing (see Figure 4).

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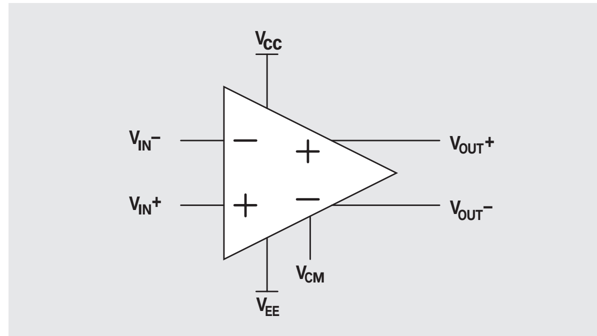
Figure 2. Fully differential amplifier voltage definitions



Input voltage definition

$$V_{ID} = (V_{IN}+) - (V_{IN}-) \qquad V_{IC} = \frac{(V_{IN}+) + (V_{IN}-)}{2}$$

Output voltage definition

$$V_{OD} = (V_{OUT}+) - (V_{OUT}-) \qquad V_{OC} = \frac{(V_{OUT}+) + (V_{OUT}-)}{2}$$

Transfer function

$$V_{OD} = V_{ID} \times A_f$$

Output common-mode voltage

$$V_{OC} = V_{CM}$$

Figure 3. Fully differential amplifier noise immunity

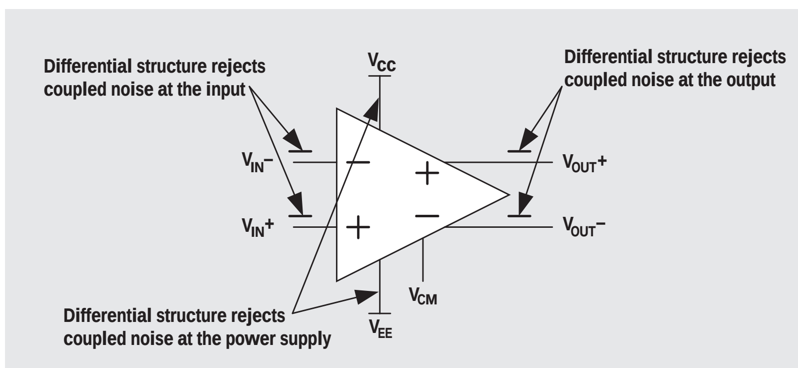
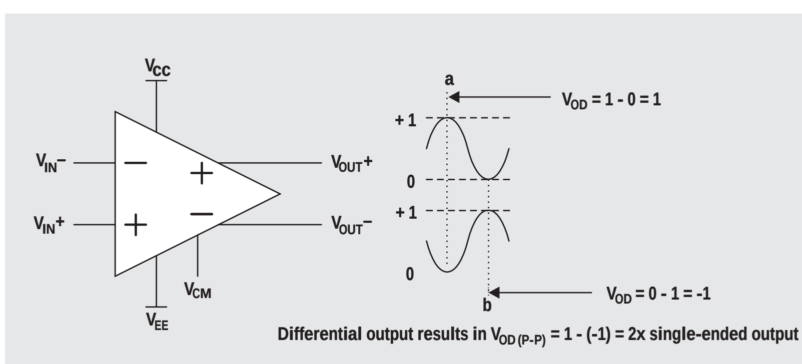


Figure 4. Differential output voltage swing



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Basic circuits

To maintain balance in a fully differential amplifier, symmetrical feedback must be taken from both outputs and applied to both inputs. The two sides form symmetrical inverting amplifiers, and inverting op amp topologies are easily adapted to fully differential amplifiers. Figure 5 shows how to maintain a balanced amplifier by using symmetrical feedback, where the feedback resistors, R_F, and the input resistors, R_G, are equal.

It is important to maintain symmetry in the two feedback paths to maintain good CMRR performance. CMRR is directly proportional to the resistor matching error. For example, a 0.1% error results in 60 dB of CMRR. For small variations in feedback due to mismatched resistors, the differential gain of the amplifier is approximately the average gain of the two sides. Output balance is maintained by the V_{CM} error amplifier.

In the past, generation of differential signals has been cumbersome. Different means have been used, requiring as many as three amplifiers and dc blocking capacitors to set the output common-mode voltage. The integrated, fully differential amplifier provides a more elegant solution. Figure 6 shows an example of converting single-ended signals to differential signals.

Active anti-alias filtering

A major application for fully differential amplifiers is signal conditioning ADC inputs. Low-pass filters are needed to keep high-frequency noise from aliasing into the frequency band of interest. Multiple feedback (MFB) is a good topology that is adapted easily to a fully differential amplifier. An MFB circuit is used to realize one complex pole pair in the transfer function of a second-order low-pass filter. An example is shown in Figure 7.

Figure 5. Amplifying differential signals

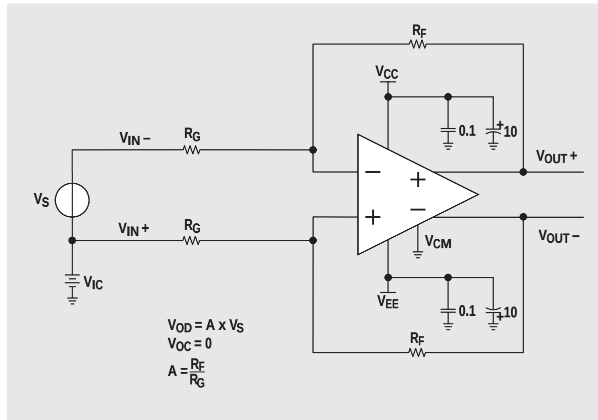


Figure 6. Converting single-ended signals to differential signals

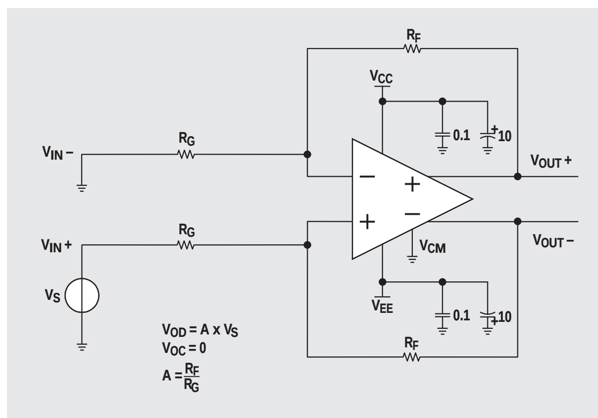
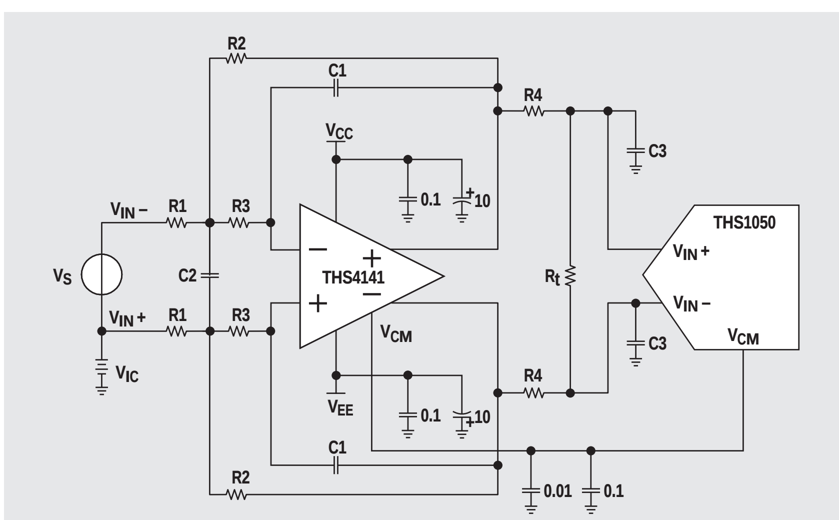


Figure 7. Low-pass, fully differential filter driving an ADC



The transfer function for this filter circuit is:

$$H_d(f) = \left[\frac{K}{-\left(\frac{f}{FSF \times f_C}\right)^2 + \frac{1}{Q}\frac{jf}{FSF \times f_C} + 1}\right] \times \left(\frac{\frac{R_t}{2R4 + R_t}}{1 + \frac{j2\pi f R4 R_t C3}{2R4 + R_t}}\right),$$

where $K = \frac{R2}{R1}$, $FSF \times f_C = \frac{1}{2\pi\sqrt{2 \times R2R3C1C2}}$, and

$$Q = \frac{\sqrt{2 \times R2R3C1C2}}{R3C1 + R2C1 + KR3C1}.$$

K sets the pass-band gain, f_C is the cut-off frequency for the filter, FSF is a frequency scaling factor, and Q is the quality factor.

$$FSF = \sqrt{Re^2 + |Im|^2}, \quad \text{and } Q = \frac{\sqrt{Re^2 + |Im|^2}}{2Re},$$

where Re is the real part, and Im is the imaginary part of the complex pole pair. Setting R2=R, R3=mR, C1=C, and C2=nC results in:

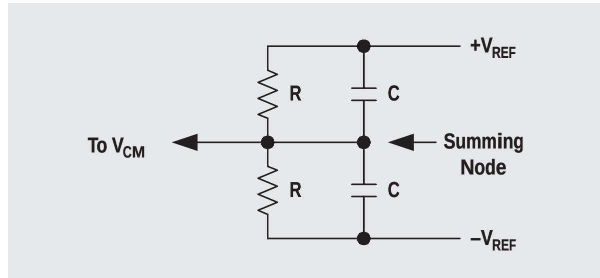
$$FSF \times f_C = \frac{1}{2\pi RC\sqrt{2 \times mn}}, \quad \text{and } Q = \frac{\sqrt{2 \times mn}}{1 + m(1 - K)}.$$

Start by determining the ratios, m and n, required for the gain and Q of the filter type being designed, then select C, and calculate R for the desired f_C.

The combination of R4, R_t, and C3 has multiple effects. R4 isolates the amplifier output from the input of the ADC. R4 and Rt provide for double termination of the transmission line between the amplifier and the ADC, and form a voltage divider. C3 helps absorb charge injection from the ADC's input. R4 and C3 form a real pole that can be used to make a third-order filter, in conjunction with the complex pole pair from the MFB stage, or it can simply be placed above the frequencies of interest.

The proper V_{CM} is provided as an output by some ADCs with differential inputs. Typically, all that needs to be done is to provide bypass capacitors—0.1 µF and/or 0.01 µF. If not provided, V_{CM} can be generated from the ADC's reference voltages as shown in Figure 8. The voltage at the summing node will be the midpoint between the reference voltage and will center V_{OC} in the middle of the ADC's input range.

Figure 8. Typical V_{CM} error source



Each power pin should have a 6.8-µF to 10-µF tantalum capacitor in parallel with a 0.01-µF to 0.1-µF ceramic capacitor located very close by. Figure 7 shows 10-µF and 0.1-µF power-supply bypass capacitors.

Conclusion

Integrated, fully differential amplifiers are very similar to standard single-ended op amps except that output is taken from both sides of the input differential pair to produce a differential output.

Differential systems provide increased immunity to external noise, reduced even-order harmonics, and twice the dynamic range when compared to single-ended systems.

Inverting amplifier topologies are adapted easily to fully differential amplifiers by implementing two symmetric feedback paths.

Integrated, fully differential amplifiers are well-suited for driving differential ADC inputs. They provide an easy means for anti-alias filtering, and the required common-mode voltage is set easily via the V_{CM} input.

Related Web sites

www.ti.com/sc/amplifiers
www.ti.com/sc/docs/products/analog/ths4141.html
www.ti.com/sc/docs/products/analog/ths1050.html