V_{CM} vs. V_{OUT} plots for instrumentation amplifiers with two op amps

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Background

The most common issue found in the TI E2E™ Community for instrumentation amplifiers involves interpreting the datasheet plot for common-mode voltage versus output voltage (V_{CM} vs. V_{OUT}). Misinterpretation or misunderstanding this plot results in forum posts that describe distorted output waveforms, incorrect device gain, or 'stuck' outputs. Verifying that the device is operating within the limits of the V_{CM} vs. V_{OUT} plot is always the first thing I check when responding to an application issue.

This article introduces the V_{CM} vs. V_{OUT} plot for an instrumentation amplifier with two operational amplifiers (op amps) and delivers a thorough treatment of this amplifier topology. Additionally, the internal node equations are derived and used to plot each internal amplifier's input common-mode and output-swing limits as a function of the instrumentation amplifier's common-mode voltage. Finally, a software tool that simulates the V_{CM} vs. V_{OUT} plot is introduced.

The V_{CM} vs. V_{OUT} plot

The input common-mode and output-swing limitations of all internal amplifiers of an instrumentation amplifier are represented in the V_{CM} vs. V_{OUT} plot.

A typical V_{CM} vs. V_{OUT} plot for a two-op-amp instrumentation amplifier is shown in Figure 1. The interior of the plot defines the linear operating region of the instrumentation amplifier because each line in the plot corresponds to either an input or output limitation of one of the two internal amplifiers. The V_{CM} vs. V_{OUT} plot is specified for a particular supply voltage, reference voltage, and gain as shown in Figure 1.

Operating outside the boundaries of a V_{CM} vs. V_{OUT} plot causes the device to operate in a non-linear mode as shown in Figure 2.

A three-part series article and blog post discuss the V_{CM} vs. V_{OUT} plot for the ubiquitous three-op-amp instrumentation amplifier.[1, 2] Two-op-amp instrumentation amplifiers are popular because of their low-cost and relatively large V_{CM} vs. V_{OUT} plots.

Figure 1. V_{CM} vs. V_{OUT} plot for two-op-amp instrumentation amplifier

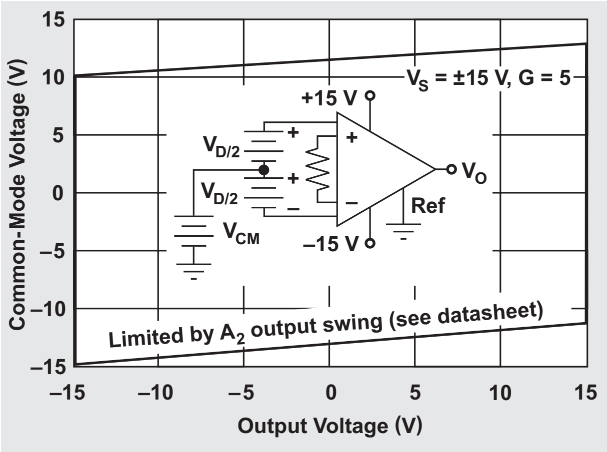
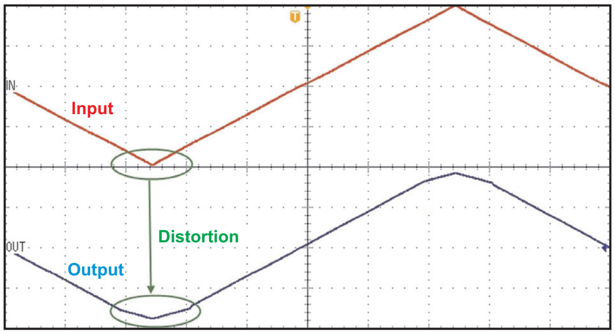


Figure 2. Instrumentation amplifier output distortion due to V_{CM} vs. V_{OUT} violation[1]



Analysis of a two-op-amp instrumentation amplifier

Figure 3 depicts a typical two-op-amp instrumentation amplifier connected to an input signal. This topology has high input impedance and requires only one resistor, R_G, to set the gain, which is the same as the three-op-amp topology.

Figure 3 also depicts the definition of common-mode (V_{CM}) and differential-mode (V_D) voltages. A differential amplifier (for example, op amp, difference amplifier, instrumentation amplifier) ideally rejects the common-mode voltage, V_{CM}.

However, the signal-path imbalance from V_{+IN} and $V_{–IN}$ to the output degrades the device's common-mode rejection ratio (CMRR), especially over frequency (Figure 4). This degradation in CMRR is one of the primary reasons why two-op-amp instrumentation amplifiers typically cost less than their three-op-amp counterparts.

The transfer function for the circuit in Figure 3 is given by Equation 1. Notice that the common-mode voltage does not appear in the equation because ideally it is rejected by the instrumentation amplifier.

$$V_O = \left(V_{+IN} - V_{-IN}\right) \times G + V_{REF} = V_D \times G + V_{REF} \tag{1}$$

Deriving the transfer function of this topology aids in understanding the V_{CM} vs. V_{OUT} plot.

Figure 5 depicts a more traditional drawing of the schematic in Figure 3. In order to determine the contribution of the reference voltage at the output, $V_{O(VREF)}$, apply superposition by shorting the input sources to ground.

Amplifier A_2 applies an inverting gain to V_{REF} based on the ratio of R_{FA2} and R_R. Similarly, A_1 applies an inverting gain to the output voltage of A_2 based on the ratio of R_{FA1} and R_{OA2}. Equation 2 depicts the transfer function for V_{REF}.

$$\begin{aligned} V_{O\_VREF} &= V_{REF}\left(\frac{-R_{FA2}}{R_R}\right)\left(\frac{-R_{FA1}}{R_{OA2}}\right) \\ &= V_{REF}\left(\frac{R_{FA1} \times R_{FA2}}{R_R \times R_{OA2}}\right) \end{aligned} \tag{2}$$

Figure 3. Topology of a two-op-amp instrumentation amplifier

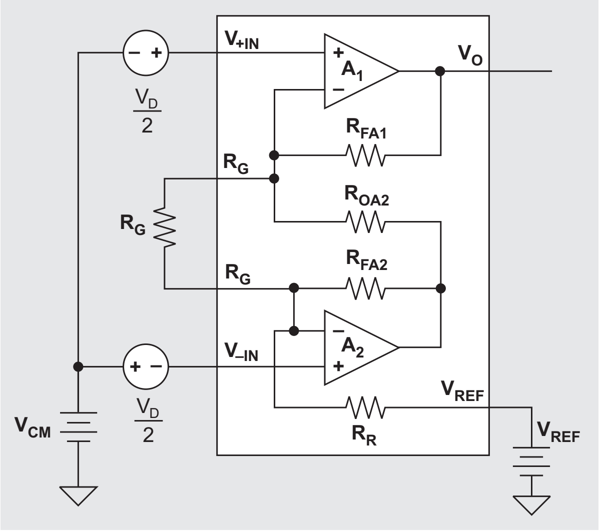


Figure 4. CMRR of two-op-amp vs. three-op-amp topologies

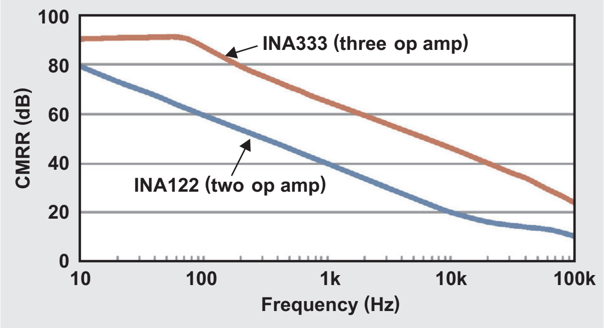
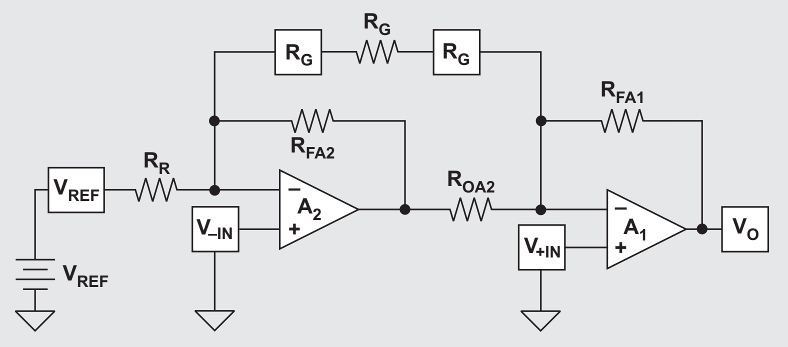


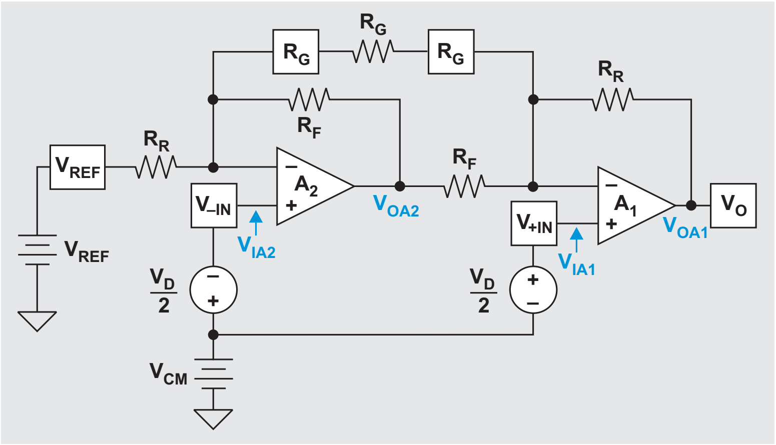
Figure 5. Alternate drawing for Figure 3



The gain applied to the instrumentation amplifier's reference voltage should be 1 V/V. To fulfill this requirement, set $R_{FA1} = R_R$ and $R_{FA2} = R_{OA2} = R_F$. Figure 6 depicts the updated two-op-amp topology that results in unity gain for the reference voltage. Furthermore, the internal nodes are labeled for future analysis.

Despite just two amplifiers and five resistors, the circuit in Figure 6 has six gain terms. This is because each amplifier applies gain to three input signals. While it may be obvious that A_2 applies gain to V_{-IN} and V_{REF}, A_2 also applies gain to V_{+IN} via the virtual short across the inputs of A_1 and R_G. Similarly, A_1 applies gain to V_{OA2}, V_{+IN}, and V_{-IN}. Equations 3 through 8 depict the six gain terms associated with a two-op-amp instrumentation amplifier.

Figure 6. Two-op-amp topology with internal nodes labeled



$$G_{A2VR} = \frac{-R_F}{R_R} \tag{3}$$

$$G_{A2V-IN} = 1 + \frac{R_F}{R_G \parallel R_R} \tag{4}$$

$$G_{A2V+IN} = \frac{-R_F}{R_G} \tag{5}$$

$$G_{A1VOA2} = \frac{-R_R}{R_F} \tag{6}$$

$$G_{A1V+IN} = 1 + \frac{R_R}{R_G \parallel R_F} \tag{7}$$

$$G_{A1V-IN} = \frac{-R_R}{R_G} \tag{8}$$

Equations 9 and 10 depict the output voltages of amplifiers A_1 and A_2.

$$V_{OA1} = V_O = V_{+IN}\left(G_{A1V+IN}\right) + V_{-IN}\left(G_{A1V-IN}\right) + V_{OA2}\left(G_{A1VOA2}\right) \tag{9}$$

$$V_{OA2} = V_{+IN}\left(G_{A2V+IN}\right) + V_{-IN}\left(G_{A2V-IN}\right) + V_{REF}\left(G_{A2VR}\right) \tag{10}$$

Substituting Equation 10 for V_{OA2} in Equation 9 and simplifying yields Equation 11.

$$V_O = V_{+IN}\left(G_{A1V+IN} + G_{A2V+IN}G_{A1VOA2}\right) + V_{-IN}\left(G_{A1V-IN} + G_{A2V-IN}G_{A1VOA2}\right) + V_{REF} \tag{11}$$

The relationship between the gain terms in Equation 11 is shown in Equation 12.

$$\begin{aligned} G_{A1V+IN} + G_{A2V+IN}G_{A1VOA2} &= -\left(G_{A1V-IN} + G_{A2V-IN}G_{A1VOA2}\right) \\ &= G_{A1V+IN} - G_{A1V-IN} = 1 + \frac{R_R}{R_F} + \frac{2R_R}{R_G} \end{aligned} \tag{12}$$

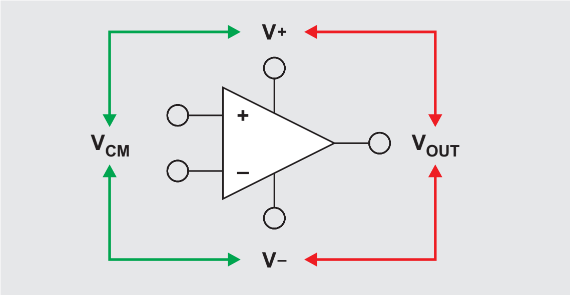
Finally, using Equations 11 and 12, the transfer function for a two-op-amp instrumentation amplifier is shown by Equation 13, which is consistent with Equation 1.

$$\begin{aligned} V_O = V_{OA1} &= \left(V_{+IN} - V_{-IN}\right) \times G + V_{REF} \\ &= V_D \times \left(1 + \frac{R_R}{R_F} + \frac{2R_R}{R_G}\right) + V_{REF} \end{aligned} \tag{13}$$

Op amp limitations

Linear operation of an instrumentation amplifier is contingent upon the linear operation of its primary building block; op amps. An op amp operates linearly when the input and output signals are within the device's input common-mode and output-swing ranges, respectively. The supply voltages used to power the op amp (V+ and V–) define these ranges (Figure 7).

Figure 7: Op amp input common-mode and output-swing ranges depend on supplies[1]



A real-world example of common-mode and output-swing limits is shown in Figure 8. Notice that the common-mode range and output-swing ranges are not necessarily the same.

Two-op-amp node equations

With a solid understanding of the two-op-amp instrumentation amplifier and op-amp limitations, the next step is to examine the node equations as indicated in Figure 6. The equations for V_{OA2} and V_{OA1} are already given by Equations 10 and 13, respectively. Equations for V_{IA1} and V_{IA2} from Figure 6 are given as:

$$V_{IA1} = V_{+IN} = V_{CM} + \frac{V_D}{2} \tag{14}$$

$$V_{IA2} = V_{-IN} = V_{CM} - \frac{V_D}{2} \tag{15}$$

The V_{CM} vs. V_{OUT} plot can vary based on gain and reference voltage. Therefore, Equations 10 and 13 through 15 must be solved for V_O as a function of the gain terms, V_{CM}, and V_{REF}. One important relationship that allows for this is obtained by solving Equation 13 for V_D, as shown in Equation 16.

$$V_O = V_D \times G + V_{REF} \rightarrow V_D = \frac{V_O - V_{REF}}{G} \tag{16}$$

After making all of the proper substitutions and solving for V_O, Equations 17 through 20 capture the linear operating region of a two-op-amp instrumentation amplifier at its output as a function of the gain terms, V_{CM}, V_{REF}, and the common-mode and output limitations of each amplifier (V_{IA1}, V_{IA2}, V_{OA1}, V_{OA2}).

$$V_{O\_IA1} = 2 \times G \times (V_{IA1} - V_{CM}) + V_{REF} \tag{17}$$

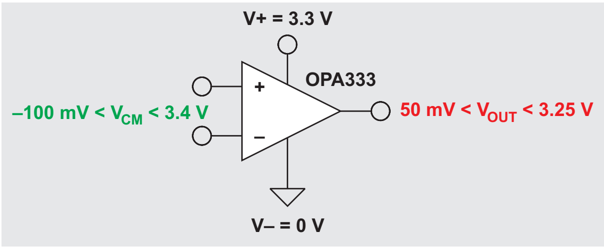
$$V_{O\_IA2} = -2 \times G \times (V_{IA2} - V_{CM}) + V_{REF} \tag{18}$$

$$V_{O\_OA1} = V_{OA1} \tag{19}$$

$$V_{O\_OA2} = 2V_{CM} - V_R + 2G_{A1VOA2}(V_{OA2} - V_{CM}) \tag{20}$$

In order to operate in a linear region, the voltage at V_{IA1} must not violate the input common-mode range of A_1. Similarly, the voltage at node V_{OA1} must not violate the output swing limitation of A_1. The same holds true for V_{IA2} and V_{OA2} for op amp A_2. The values of the internal op amp limitations are not usually explicitly stated in an instrumentation amplifier's data sheet. In lieu of such information, a combination of examining the device's limitations and measuring the linear operating region can be used to determine the values.

Figure 8. Op amp V_{CM} and V_{OUT} ranges for 3.3-V supply[1]



To move the input common-mode range closer to the negative supply voltage, some instrumentation amplifiers (for example, INA122) level-shift the inputs using precision transistor buffers.[1] This is particularly useful when operating with a single supply.

Figure 9 depicts a TINA-TI™ simulation that plots Equations 17 through 20 for both the maximum and minimum common-mode and output-swing limits for the internal amplifiers of the INA122. The linear operating region is the interior of all lines.

Figure 9. V_{CM} vs. V_{OUT} plot

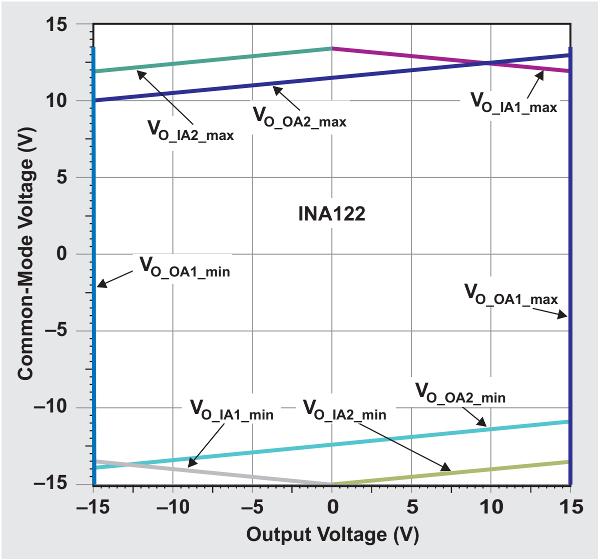
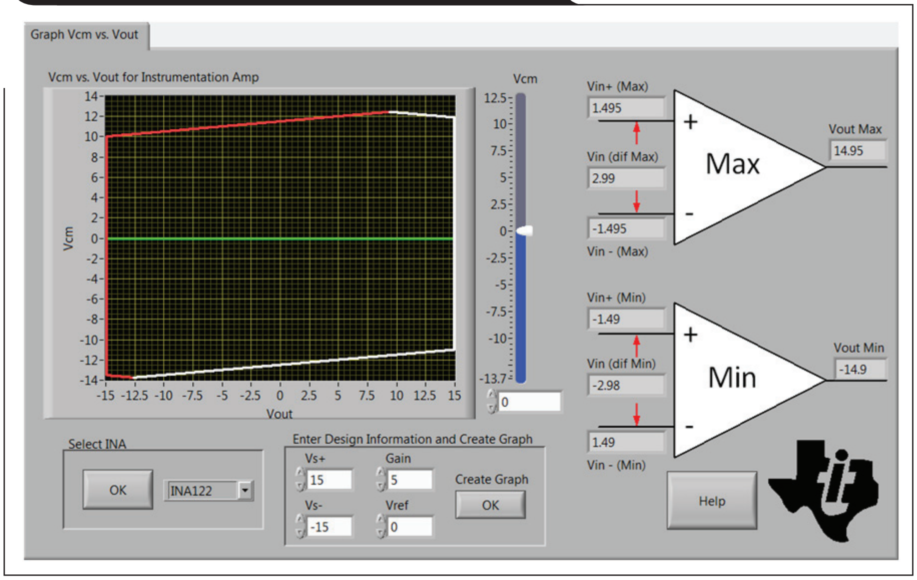


Figure 10. V_{CM} vs. V_{OUT} software tool



Vcm: 0

Vin+ (Max): 1.495

Vin (dif Max): 2.99

Vin - (Max): -1.495

Vout Max: 14.95

Vin+ (Min): -1.49

Vin (dif Min): -2.98

Vin - (Min): 1.49

Vout Min: -14.9

Select INA: INA122

Vs+: 15

Gain: 5

Vs-: -15

Vref: 0

A software tool was developed to simplify the creation of V_{CM} vs. V_{OUT} plots for varying gains, reference voltages, and supply voltages. See Related Web sites an the end of this article for download links. Figure 10 depicts the V_{CM} vs. V_{OUT} plot for the INA122 given standard datasheet conditions. Notice that it compares well with Figure 1 and Figure 9. The datasheet plot in Figure 1, however, only depicts the output limitations of A_1 and A_2, whereas the software tool includes the common-mode limitations. Finally, note that the software tool can be downloaded to generate V_{CM} vs. V_{OUT} plots for both two- and three-op-amp instrumentation amplifiers.

Summary

This article addressed the most misunderstood concept of two-op-amp instrumentation amplifiers: the V_{CM} vs. V_{OUT} datasheet plot. A thorough analysis of the two-op-amp topology was delivered along with the derivation of the internal node equations. These equations were used to create the V_{CM} vs. V_{OUT} plots. The output from the downloadable software tool was found to correlate well with the plot in the INA122 datasheet. This tool gives designers a simple method for ensuring linear operation of the instrumentation amplifier in their design.

Acknowledgements

The author would like to thank Art Kay at Texas Instruments for developing the V_{CM} vs. V_{OUT} software tool and Collin Wells for his technical contributions to this article.

References

1. Peter Semig and Collin Wells, "Instrumentation amplifier V_{CM} vs. V_{OUT} plots," Part 1, Part 2 and Part 3, EDN Network, December 2014
2. Peter Semig, "How Instrumentation Amplifier V_{CM} vs. V_{OUT} plots change with supply and reference voltage," TI Precision Hub, January 30, 2015.

Related Web sites

Software tool:
V_{CM} vs. V_{OUT} plot generator

Product information:
INA122
INA333
OPA333

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