Gain Error
TI Precision Labs – Current Sense Amplifiers

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Hello, and welcome to the TI Precision Labs series on current sense amplifiers. My name is Peter Iliya, and I’m an applications engineer in the Current & Position Sensing product line. In this video, we will introduce gain error in current sense amplifier circuits.
Total gain error

Components of total gain error:

\[ e_{\text{Gain}}(\%) \approx e_{\text{Gain\_error}} + e_{\text{gain\_error\_temperature\_drift}} + e_{\text{Linearity}} \]

Worst-case total error – more conservative

\[ \varsigma_{\text{Worst}}(\%) \approx e_{\text{Vos}} + e_{\text{CMRR}} + e_{\text{PSRR}} + e_{\text{Gain\_error}} + e_{\text{Linearity}} + e_{\text{Shunt\_tolerance}} + e_{\text{Bias\_current}} + e_{\text{Other}} \]

Root-sum-square (RSS) total error – more realistic

\[ \varsigma_{\text{RSS}}(\%) \approx \sqrt{e_{\text{Vos}}^2 + e_{\text{CMRR}}^2 + e_{\text{PSRR}}^2 + e_{\text{Gain\_error}}^2 + e_{\text{Linearity}}^2 + e_{\text{Shunt\_tolerance}}^2 + e_{\text{Bias\_current}}^2 + e_{\text{Other}}^2} \]
Total gain error includes the device’s internal gain error, the device’s gain drift with temperature, and device linearity. Technically, the shunt resistor tolerance also contributes to the system gain error, but this video will only focus on the device’s gain error.

Gain error differs from offset error in that it contributes the same amount of percentage error to total system error over the linear dynamic range.

In general, gain error is the dominant error type at high input signal levels.
Current sense amplifier (CSA) gain error

\[ V_{OUT} = V_{IN} + V_{IN-} - V_{IN+} \]

\[ G_{IDEAL} = G = \frac{R_F}{R_{INT}} \]

\[ G_{MIN} \]

\[ G_{MAX} \]

Slope = Gain

\[ V_{IN} = V_{IN+} - V_{IN-} \]
For the typical current sense amplifier (or abbreviated as CSA), device gain is set by the ratio of the internal network resistors $RF$ and $RINT$. These resistors are not trimmed to an exact resistance, rather they are manufactured to have a precise ratio, as the ratio is what sets the device gain. How much the ratio varies is what dictates device gain error.

Gain curves can be visualized with the plot on the right. Gain is simply the slope of the output vs. the input. The worst-case maximum and minimum gain curves set the bounds of possible linear gain error in a current sense amplifier. Note that this plot assumes perfect linearity.
CSA linearity error

\[ e_{\text{Linearity\_max}} = \text{Max}\left(\frac{|V_{\text{OUT\_Measured}} - V_{\text{OUT\_CALIBRATED}}|}{V_{\text{OUT\_FULL\_SCALE}}} \right) \times 100 \]

\[ V_{\text{OUT\_LINEAR}} = V_{\text{OUT\_CALIBRATED}} = \frac{(y_n - y_1)}{(x_n - x_1)} \times (V_{\text{SENSE}}) + b \]

Non-linear gain

\[ V_{\text{SENSE}} = V_{\text{IN+}} - V_{\text{IN-}} \]
Linearity error is a specification of how linear the gain curve is. To characterize linearity, the device’s input is swept with \(N\) number of points. A calibrated gain curve is calculated by linear approximation using two data points at 10% and 90% of the full-scale output range. For example, if the supply is 5-V, then the two points considered are 0.5V and 4.5V. Determining the calibrated gain requires calculating linear slope and offset. Linearity error specified in the datasheet is set by the data point that is the furthest from the calibrated gain curve. The percentage linearity error is calculated as 

\[
\frac{V_{\text{out measured}} - V_{\text{out calibrated}}}{\text{full-scale Vout range}}
\]

Usually, linearity error is much smaller than the maximum gain error and can be ignored. However, linearity error becomes more important if a system is to execute this two-point gain calibration. If the exact gain is determined for a CSA in a real system by measuring two data points and calculating linear gain, then the only remaining error left is the linearity error and gain drift.
Gain error vs. temperature

7.5 Electrical Characteristics

At $T_A = 25 \degree C$, $V_{S} = 5 \, V$, $V_{\text{SENSE}} = V_{\text{IN+}} - V_{\text{IN-}}$, $V_{CM} = 12 \, V$, and $V_{REF1} = V_{REF2} = V_{S} / 2$ (unless otherwise noted).

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>TEST CONDITIONS</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
<th>UNIT</th>
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<tbody>
<tr>
<td>OUTPUT</td>
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<tr>
<td>G</td>
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<td></td>
<td>INA240A1</td>
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<td>INA240A3</td>
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<td></td>
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<td></td>
<td>INA240A4</td>
<td>200</td>
<td></td>
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<tr>
<td>Gain error</td>
<td>$\text{GND} + 50 , \text{mV} \leq V_{\text{OUT}} \leq V_{S} - 200 , \text{mV}$</td>
<td>$\pm 0.05%$</td>
<td>$\pm 0.20%$</td>
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<td>$T_A = -40\degree\text{C} \text{ to } 125\degree\text{C}$</td>
<td>$\pm 0.5$</td>
<td>$\pm 2.5$</td>
<td>ppm/$\degree\text{C}$</td>
<td></td>
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<tr>
<td>Non-linearity error</td>
<td>$\text{GND} + 10 , \text{mV} \leq V_{\text{OUT}} \leq V_{S} - 200 , \text{mV}$</td>
<td>$\pm 0.01%$</td>
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What is the maximum gain error when $T_A = -10\degree\text{C}$ to $+100\degree\text{C}$? Ignore non-linearity error.

$$\text{Error}_{\text{max}} = E_G + \frac{\Delta E_G}{\Delta T_C} \cdot |\Delta T_A|$$

$$\text{Error}_{\text{max}} = 0.2\% + 2.5 \frac{\text{ppm}}{\degree\text{C}} \cdot 10^{-4} \cdot (100\degree\text{C} - 25\degree\text{C})$$

$$\text{Error}_{\text{max}} = 0.2\% + 0.0275\% = \pm 0.2275\%$$
It is important to understand that the gain error specification of a CSA only applies when the device is operating within the testing conditions of the datasheet. Once the ambient temperature deviates from the gain error testing condition, the engineer must account for gain drift.

For example, what is the maximum gain error if the system ambient temperature could vary from negative 10 degrees to positive 100 degrees Celsius? Well the total gain error sums the initial gain error and the gain drift error. Initial gain error, which is tested at 25 degrees Celsius, is 0.2% max. When determining the drift component, the engineer needs to locate the drift specification and then multiply by the temperature change with respect to the initial gain error’s testing temperature condition. The temperature change of importance is 100 degrees – 25° Celsius. Only the largest absolute change from 25 degrees Celsius should be considered because the gain error specification can almost always can be positive or negative. Note that an easy way to convert parts per million into percentage is to multiply by ten to the negative fourth power.

So if we continue the calculation in terms of percent, the maximum gain error is + or - 0.2275%.
CSA total gain error ($E_G$)

$$e_{\text{Gain}} (%) \approx e_{\text{Gain\_error}} + e_{\text{gain\_error\_temperature\_drift}} + e_{\text{Linearity}}$$

$$G_{\text{MAX}} = G \left(1 + \frac{E_G + \frac{\Delta E_G}{\Delta \theta} * \Delta T_A + E_{\text{Linearity}}}{100}\right)$$

$$G_{\text{MIN}} = G \left(1 - \frac{E_G + \frac{\Delta E_G}{\Delta \theta} * \Delta T_A + E_{\text{Linearity}}}{100}\right)$$

$V_{\text{OUT}} = V_{\text{IN+}} - V_{\text{IN-}}$

$G_{\text{IDEAL}} = G = \frac{R_F}{R_{\text{INT}}}$

Slope = Gain
The worst-case gains of a CSA are the maximum and minimum possible gains. To calculate these worst-case gains, simply add all of the gain errors percentages together, and divide by 100 to yield a gain error factor. Finally, add or subtract this gain error factor from one. Since most all gain error specifications are symmetrical about 0, the maximum and minimum gains are symmetrical about the nominal device gain.
CSA output limitations

\[ V_{\text{OUT}} = V_{\text{REF}} + V_{\text{IN}} \times G \]

Gain error testing condition

\[ V_{\text{SENSE}} = -5 \text{ mV to } 5 \text{ mV} \]
\[ T_x = -40^\circ \text{C to } +125^\circ \text{C} \]

(Versions A and B)

Gain error vs temperature

\[ T_x = -40^\circ \text{C to } +125^\circ \text{C} \]

3 ppm^\circ \text{C}

Nonlinearity error

\[ V_{\text{SENSE}} = -5 \text{ mV to } 5 \text{ mV} \]

±0.01%

Maximum capacitive load

No sustained oscillation

1 nF

Swing to V+ power-supply rail

\[ R_x = 10 \text{ k} \Omega \text{ to GND} \]
\[ T_x = -40^\circ \text{C to } +125^\circ \text{C} \]

(V+ - 0.05 V)

Swing to GND

\[ R_x = 10 \text{ k} \Omega \text{ to GND} \]
\[ T_x = -40^\circ \text{C to } +125^\circ \text{C} \]

(V_{\text{GND}} - 0.005 V)

(V_{\text{GND}} + 0.05 V)

Linear operating region

\[ V_{\text{IN}} = \text{Load} \times R_{\text{SHUNT}} \]

(V)

(11.25 mV, 4.75 V)
It is important to know when gain error is reliable. Like most amplifiers, the output of CSAs are limited by their voltage supplies, in that they can only swing so close to the supply rails. How close the output can swing is set by the specifications called swing-to-negative (VSN, otherwise known as swing-to-ground) and swing-to-positive rail (VSP).

While the swing-to-rail specifications set the bounds of the output, they do not set the linear region of the amplifier. For proper amplifier gain, the output must be within the linear region. The range of the linear region depends upon several factors, but the best practice is to not violate the VOUT vs. IOUT curve(s) of datasheet and apportion the linear output range to be tens to hundreds of millivolts within the swing-to-rail specifications.

Gain error is always tested in a region smaller than the entire possible linear region, so it is helpful to understand how to set an appropriate output linear region and maximize an accurate dynamic range of the amplifier.

Let’s examine the INA210 as an example for determining linear output region. We will assume a 5-V supply and 2.5-V reference voltage. If we examine the datasheet’s Electrical Characteristics Table we can fill in the chart. For the swing-to-rail specifications, we see 50 mV for the swing-to-ground and Vs minus 200 mV for the swing to positive rail, which translates to a 4.8 V VOUT limit for the 5-V supply rail.

Next we see that gain error is specified from an input range of -5 mV to +5 mV over temperature. Since the INA210 has a gain of 200 V/V and is offset with 2.5-V reference, this means gain error is tested from 1.5V to 3.5V. Remember that VOUT always equals VREF + VIN*G.

Next its time to set an appropriate linear region. As long as we do not violate any output current conditions we can conservatively set the linear region to 50mV below VSP and 50mV above VSN. This equates to 100mV to 4.75V of VOUT range, which when referred to the input is -12mV to 11.25mV of sense voltage.
Example 1 – INA210

Conditions

- Gain $G = 200 \text{ V/V}$
- Gain error $E_G = \pm 1\%$ (-40°C ≤ $T_A$ ≤ +125°C)
- Input offset $V_{OS_{\text{MAX}}} = \pm 35 \text{ µV}$
- Input voltage $V_{IN} = 0.5 \text{ mV}$ to 22.5 mV

Calculations

\[
V_{out_{\text{ideal}}} = V_{in} \times G = 100 \text{ mV}$ to 4.5 V
\]

\[
V_{out_{\text{MAX}}} = (V_{in} + V_{OS}) \times G \times \left(1 + \frac{E_G}{100}\right)
\]

\[
V_{out_{\text{MIN}}} = (V_{in} - V_{OS}) \times G \times \left(1 - \frac{E_G}{100}\right)
\]

Note: $R_{SHUNT}$ has perfect 0% tolerance in this example
Let’s now consider an example using the INA210, which is set to a gain of 200 V/V with a ±1% maximum gain error. The available power supply is a 5-V rail.

The input voltage range of consideration, which is set by the load current and the shunt resistor, will range from 500 uV to 22.5 mV.

To calculate $V_{out\_ideal}$, we simply multiply the input voltage by the gain. This results in a range of 100 mV to 4.5 V, which is well within the normal output operating region.

The maximum and minimum possible output voltage equations are shown. When determining worst case error it is best to pair a positive gain with a positive offset and vice versa, a negative gain with a negative offset.
Example 1 – worst-case error analysis

![Graph showing positive and negative errors as a function of input voltage (V_IN).]

- **Positive Error**
- **Negative Error**

![Graph showing maximum total error and maximum gain error as a function of input voltage (V_IN).]

- **Maximum Total Error**
- **Maximum Gain Error**
The plot on the left shows the output error in volts between the actual and ideal outputs. In this case you can see that the error voltage changes linearly with input voltage.

The relative errors are plotted on the right. As stated earlier, relative gain error is constant over the input range. The total error curve includes the offset error, so error increases with a $1/x$ relationship.

We recommend selecting an amplifier with a gain error specification that meets or exceeds your total error requirement.
Example 2 – INA226 (digital output)

Conditions

- **LSB_shunt_voltage** = 2.5 µV
- Shunt voltage gain error \( E_G = 0.1\% \) (\( T_A = 25^\circ C \))
- Input offset \( V_{OS\_MAX} = \pm 10 \) µV (4 LSB)
- Input voltage \( V_{IN} = 0.5 \) mV to 80 mV
- \( T_A = 25^\circ C \) stable

Calculations

\[
G_{ideal} = \frac{1}{2.5\mu V} = 40000
\]

\[
Codes_{IDEAL} = V_{in} \times G_{IDEAL}
\]

\[
Codes_{MAX-MIN} = (V_{in} \pm V_{OS}) \times G \times \left(1 \pm \frac{E_G}{100}\right)
\]
Let’s now consider an example using the INA226, which is digital current sense monitor that converts the shunt voltage into digital codes. Determining gain error for digital CSAs uses the same theory, but the math changes since the input voltage is not amplified, but rather converted into the digital realm.

For the calculations, the gain is simply the inverse of the shunt voltage least significant bit. Since gain error is same over the entire range, we can multiply the ideal shunt voltage by the gain and the gain error factor to determine the maximum and minimum worst case codes.
Example 2 – worst-case error analysis

Graph 1: Error (codes) vs. $V_{IN}$ (mV)

Graph 2: Error (%) vs. $V_{IN}$ (mV)

- Blue line: Positive Error
- Red line: Negative error
- Blue line: Max Total Error
- Red line: Max Gain Error

<table>
<thead>
<tr>
<th>$V_{IN}$ (mV)</th>
<th>Error (codes)</th>
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<tbody>
<tr>
<td>0</td>
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<tr>
<td>10</td>
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<td>80</td>
<td>-16</td>
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<tr>
<td>90</td>
<td>-18</td>
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<table>
<thead>
<tr>
<th>$V_{IN}$ (mV)</th>
<th>Error (%)</th>
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<tbody>
<tr>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>10</td>
<td>0.5%</td>
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<tr>
<td>20</td>
<td>1.0%</td>
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<td>30</td>
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<td>0.0%</td>
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As we can see, the error response for the digital device is the same as the analog. Absolute error on the left increases linearly, relative gain error is constant, and total relative error, which includes offset, has an inverse relationship where the curve approaches gain error at higher shunt voltages.
To find more current sense amplifier technical resources and search products, visit ti.com/currentsense
That concludes this video - thank you for watching! Please try the quiz to check your understanding of the content.

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