Abstract
Adding to the understanding of noise calculations from Application Note: Noise Calculations of Op-Amp Circuits, this application note describes calculating the output noise of an Instrumentation Amplifier (INA). As in the case of op-amps, the noise parameters from the device datasheet help determine the output noise of the classic three op-amp INA.

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- Operational Amplifiers
1. Introduction

Instrumentation amplifiers amplify small input signals accurately. Because noise has a detrimental effect on small signals, it is important to understand the contributions of all noise sources involved. Figure 1 shows the schematic of the classic three op-amp INA with its input source resistances. Because of the symmetry of the INA input stage, it is common to assign one half of the source resistance, $R_S/2$, to each INA input.

![Figure 1. Driver with Drive Logic and H-Bridge Output](image1)

Figure 2. Driver Differential and Common-Mode Output Voltages

2. INA Noise Models

For a discrete INA design, it is possible to develop a detailed noise model by applying the standard op-amp noise model in Figure 2 to each of the three amplifiers (Figure 3). The op-amp noise model uses noise currents of equal magnitude ($i_{n+} = i_{n-} = i_n$) to accommodate the single noise current specifications in op-amp datasheets.

The resulting noise model is complex and its computation tedious.

![Figure 3. Detailed Noise Model of a Discrete 3-Amp INA](image2)

The noise models of integrated INAs are simpler. Some INA manufacturers model the noise of the input and output stages separately, which are indicated in Figure 4 with the spectral densities, $e_{ni}$ and $e_{no}$.

![Figure 4. INA Noise Model with Separate Input and Output Voltage Noise Sources, $e_{ni}$ and $e_{no}$](image3)
Others model INA noise with a single input referred voltage noise, \( e_n \), by dividing \( e_{no} \) by the INA gain and placing it in series with \( e_{ni} \). The total input-referred voltage noise, \( e_n \), then is the rms sum of \( e_{ni} \) and \( e_{no} \) (Figure 5):

\[
(\text{EQ. 1}) \quad e_n = \sqrt{e_{ni}^2 + \left(\frac{e_{no}}{G}\right)^2}
\]

![Figure 5. INA Noise Model with Total Input-referred (RTI) Voltage Noise, \( e_n \)](image)

In this model, the voltage source of the differential input stage, \( e_{ni} \), and the voltage noise due to noise current, \( i_n \cdot \frac{R_S}{2} \), are amplified by the INA gain. Both noise sources are uncorrelated and must be add quadratically to yield the total rms input noise of the INA:

\[
(\text{EQ. 2}) \quad E_{ni(INA)} = \sqrt{\text{NEB} \cdot \left(e_{n(RTI)}\right)^2 + 2 \cdot i_n^2 \left(\frac{R_S}{2}\right)^2}
\]

where NEB is the noise equivalent bandwidth, calculated with \( \text{NEB} = 1.57 \times \text{INA Bandwidth (f_{-3dB}) at Gain = G.} \)

To determine the rms output noise of the INA, \( E_{no(INA)} \) is multiplied by the INA gain:

\[
(\text{EQ. 3}) \quad E_{no(INA)} = G \cdot E_{ni(INA)} = G \cdot \sqrt{\text{NEB} \cdot \left(e_{n(RTI)}\right)^2 + 2 \cdot i_n^2 \left(\frac{R_S}{2}\right)^2}
\]

\( \text{Equation 2 and Equation 3 only provide the rms input and output noise of the INA. Neither the thermal noise from the source resistance, } E_{no(RS)}, \text{ nor the output noise of a reference buffer, } E_{no(REF)}, \text{ are included. These noise sources add to the INA output noise, } E_{no(INA)}, \text{ to yield the total rms noise of the INA circuit:} \)

\[
(\text{EQ. 4}) \quad E_{no} = \sqrt{E_{no(INA)}^2 + E_{no(RS)}^2 + E_{no(REF)}^2}
\]

### 3. Calculation Example

This example shows how to calculate the total output noise of the bridge-sensor signal-conditioner in Figure 6, using the instrumentation amplifier, ISL28534, at a gain of \( G = 100 \). The circuit is powered by a 5V single-supply and uses a 2.5V reference buffer to bias the INA output at mid-rail, when the bridge is in a balanced condition.

Figure 7 lists the parametric values of the circuit design for clarity. The values for the gain bandwidth products and the noise spectral densities are taken from the datasets.

The closed-loop bandwidths of the INA and the OPA are calculated with \( f_{BW} = \text{GBWP/Gain} \), which results in \( f_{BW(INA)} = 2.3\text{MHz/100} = 23\text{kHz} \) and \( f_{BW(OPA)} = 3\text{MHz/1} = 3\text{MHz} \).

Because both closed-loop gains represent a 1st order low-pass, their noise equivalent bandwidths are calculated with \( \text{NEB} = 1.57 \cdot f_{BW} \), therefore resulting in \( \text{NEB(INA)} = 1.57 \cdot 23\text{kHz} = 36.1\text{kHz} \) and \( \text{NEB(OPA)} = 1.57 \cdot 3\text{MHz} = 4.71\text{MHz} \).

The source resistance, \( R_S/2 \), for each INA is 2.5k\( \Omega \), because each input sees the parallel circuit of two bridge resistors.

The parallel resistance, \( R_P \), of the reference buffer, contributing to thermal noise and voltage noise because noise current, is given with \( R_P = R_F = R_1 \parallel R_2 = 50k\Omega \).
3.1 INA Output Noise

Applying Equation 3 gives the rms output noise of only the INA:

\[
E_{\text{rms(INA)}} = G_{\text{INA}} \cdot \sqrt{\text{NEB}_{\text{INA}}} \cdot \left(e_{\text{n(INA)}}^2 + 2 \cdot e_{\text{n(INA)}} \cdot R_s \cdot 2 \right) = 342 \mu V_{\text{rms}}
\]

3.2 Thermal Noise due to Source Resistance

The thermal noise of each resistor is calculated with the following:

\[
E_{\text{Rs}/2} = \sqrt{4kT \cdot \text{NEB}_{\text{INA}} \cdot R_s/2}
\]

where \( k = 1.38 \cdot 10^{-23} \text{ J/K} \) is Boltzmann's constant, \( T \) is the absolute temperature in Kelvin, and \( R \) is the resistance in ohms. Since the input noise sources are uncorrelated, their total rms noise at the INA input is:

\[
E_{\text{n(Rs)}} = \sqrt{E_{\text{Rs}/2}^2 + E_{\text{Rs}/2}^2} = \sqrt{2 \cdot E_{\text{Rs}/2}^2} = \sqrt{8kT R_s/2 \cdot \text{NEB}_{\text{INA}}}
\]

This noise is amplified by the INA gain to produce an output noise of:

\[
E_{\text{no(Rs)}} = G_{\text{INA}} \cdot E_{\text{n(Rs)}} = G_{\text{INA}} \cdot \sqrt{8kT R_s/2 \cdot \text{NEB}_{\text{INA}}} = 161 \mu V_{\text{rms}}
\]

3.3 Output Noise of the Reference Buffer

The output noise of the voltage reference buffer is calculated, using Equation 9. This equation is derived in Application Note: Noise Calculations of Op-AMP Circuits. Since the reference buffer operates at a gain of one, its output noise equals its input noise:

\[
E_{\text{no(REF)}} = E_{\text{n(REF)}} = \sqrt{\text{NEB}_{\text{OPA}}} \cdot \sqrt{8kT R_p \cdot R_{\text{OPA}}^2 + 2R_{\text{OPA}}^2 e_{\text{n(REF)}}^2} = 96 \mu V_{\text{rms}}
\]

3.4 Total Circuit Output Noise

Now we can apply Equation 4, which adds all three output noise components in rms fashion to yield the total rms output noise of the circuit:

\[
E_{\text{no}} = \sqrt{E_{\text{no(INA)}}^2 + E_{\text{no(Rs)}}^2 + E_{\text{no(REF)}}^2} = \sqrt{(342 \mu V)^2 + (161 \mu V)^2 + (96 \mu V)^2} = 390 \mu V
\]
4. **Conclusion**

The dominant noise component is that of the INA. This noise can be reduced by drastically reducing the signal bandwidth through a low-pass filter at the INA output.

Further noise reduction is achieved by reducing the bandwidth of the bridge sensor. In this case, each INA input receives a low-pass filter.

Lastly, the noise of the reference buffer can be reduced by connecting a large input capacitor (10μF to 100μF) in parallel to R₂ and a small feedback capacitor (10nF) in parallel to Rₚ. Using lower resistor values is also possible but comes at the cost of higher current consumption.

5. **Revision History**

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<td>1.00</td>
<td>Aug.20.20</td>
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