Operational Amplifiers

Noise Calculations of Instrumentation Amplifier Circuits

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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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.

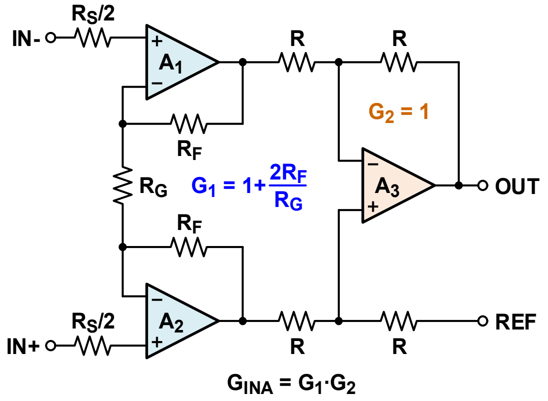

Figure 1. Driver with Drive Logic and H-Bridge Output

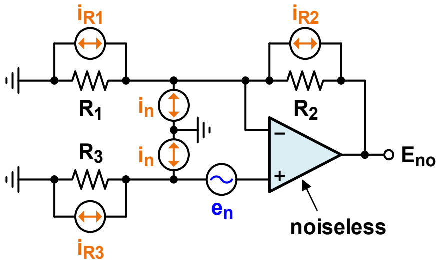

Figure 2. Driver Differential and Common-Mode Output Voltages

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.

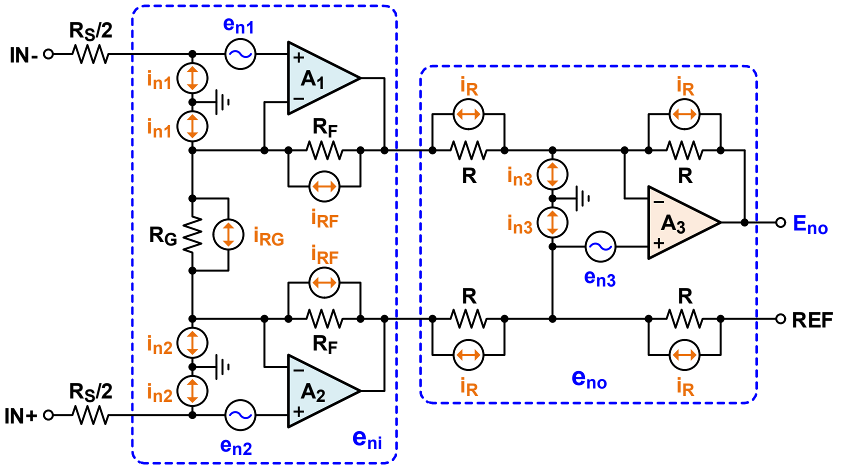

Figure 3. Detailed Noise Model of a Discrete 3-Amp INA

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}.

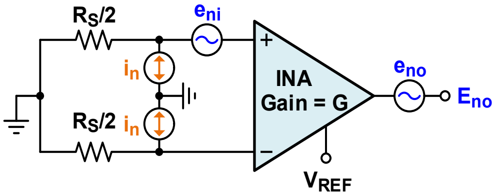

Figure 4. INA Noise Model with Separate Input and Output Voltage Noise Sources, e_{ni} and e_{no}

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):

(EQ. 1) $$e_n = \sqrt{e_{ni}^2 + (e_{no}/G)^2}$$

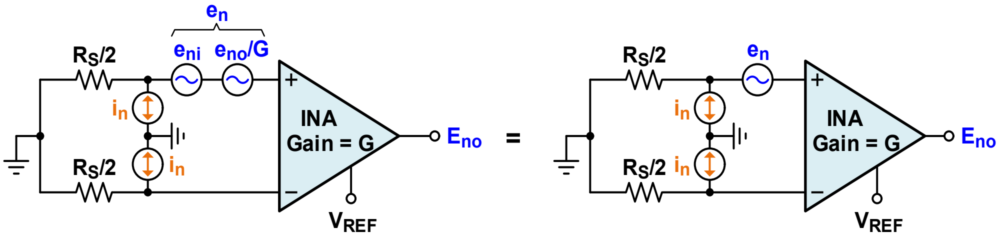

Figure 5. INA Noise Model with Total Input-referred (RTI) Voltage Noise, e_n

In this model, the voltage source of the differential input stage, e_{ni}, and the voltage noise due to noise current, $i_n \cdot R_S/2$, 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:

(EQ. 2) $$E_{ni(INA)} = \sqrt{NEB} \cdot \sqrt{e_{n(RTI)}^2 + 2\,i_n^2 (R_S/2)^2}$$

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

To determine the rms output noise of the INA, E_{ni}(INA) is multiplied by the INA gain:

(EQ. 3) $$E_{no(INA)} = G \cdot E_{ni(INA)} = G \cdot \sqrt{NEB} \cdot \sqrt{e_{n(RTI)}^2 + 2\,i_n^2 (R_S/2)^2}$$

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

(EQ. 4) $$E_{no} = \sqrt{E_{no(INA)}^2 + E_{no(Rs)}^2 + E_{no(REF)}^2}$$

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 datasheet.

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

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

The source resistance, $R_S/2$, for each INA is 2.5kΩ, 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 $R_P = R_F = R_1 \parallel R_2$ = 50kΩ.

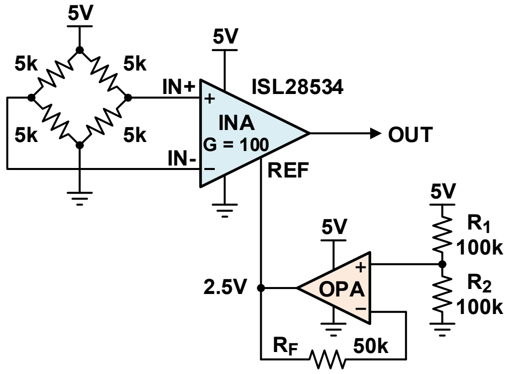

Figure 6. Signal Conditioner with INA ISL28534 at G = 100

INA		OPA	
G_{INA}	100	G_{OPA}	1
$e_{n(INA)}$	18 nV/√Hz	$e_{n(OPA)}$	10 nV/√Hz
$i_{n(INA)}$	50 fA/√Hz	$i_{n(OPA)}$	200 fA/√Hz
GBWP	2.3 MHz	GBWP	3.0 MHz
$f_{BW(INA)}$	23 kHz	$f_{BW(OPA)}$	3.0 MHz
NEB_{INA}	36.1 kHz	NEB_{OPA}	4.71 MHz
$R_S/2$	2.5 kΩ	$R_P = R_F = R_1 \| R_2$	50 kΩ

Figure 7. Parametric Values of Signal Conditioner

3.1 INA Output Noise

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

(EQ. 5)
$$E_{no(INA)} = G_{INA} \cdot \sqrt{NEB_{INA}} \cdot \sqrt{e_{n(INA)}^2 + 2\, i_{n(INA)}^2 (R_S/2)^2} = 342\mu V_{rms}$$

3.2 Thermal Noise due to Source Resistance

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

(EQ. 6)
$$E_{Rs/2} = \sqrt{4kT \cdot NEB_{INA} \cdot R_S/2}$$

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

(EQ. 7)
$$E_{ni(Rs)} = \sqrt{E_{Rs/2}^2 + E_{Rs/2}^2} = \sqrt{2 \cdot E_{Rs/2}^2} = \sqrt{8kTR_S/2 \cdot NEB_{INA}}$$

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

(EQ. 8)
$$E_{no(Rs)} = G_{INA} \cdot E_{ni(Rs)} = G_{INA} \cdot \sqrt{8kTR_S/2 \cdot NEB_{INA}} = 161\mu V_{rms}$$

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:

(EQ. 9)
$$E_{no(REF)} = E_{ni(REF)} = \sqrt{NEB_{OPA}} \cdot \sqrt{8kTR_P + 2R_P^2 i_{n(OPA)}^2 + e_{n(OPA)}^2} = 96\mu V_{rms}$$

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:

(EQ. 10)
$$E_{no} = \sqrt{E_{no(INA)}^2 + E_{no(Rs)}^2 + E_{no(REF)}^2} = \sqrt{(342\mu V)^2 + (161\mu V)^2 + (96\mu V)^2} = 390\mu V$$

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 R_2 and a small feedback capacitor (10nF) in parallel to R_F. Using lower resistor values is also possible but comes at the cost of higher current consumption.

5. Revision History

Rev.	Date	Description
1.00	Aug.20.20	Initial release

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