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.

Contents

List of Figures

Related Literature

For a full list of related documents, visit our website:

- 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.

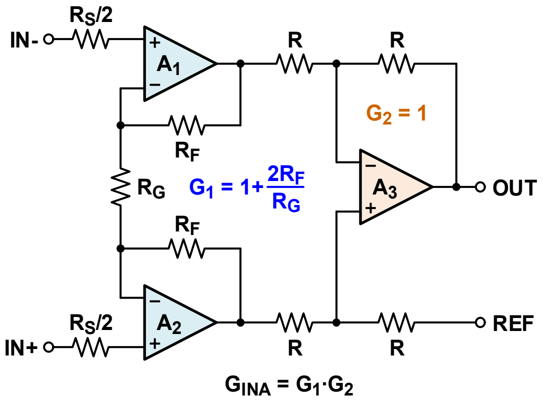

Figure 1. Driver with Drive Logic and H-Bridge Output

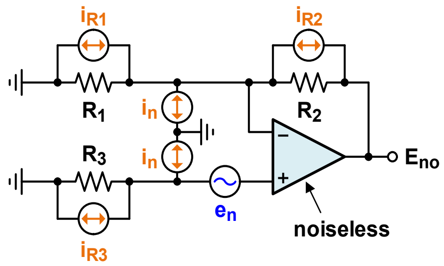

Figure 2. Driver Differential and Common-Mode Output Voltages

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.

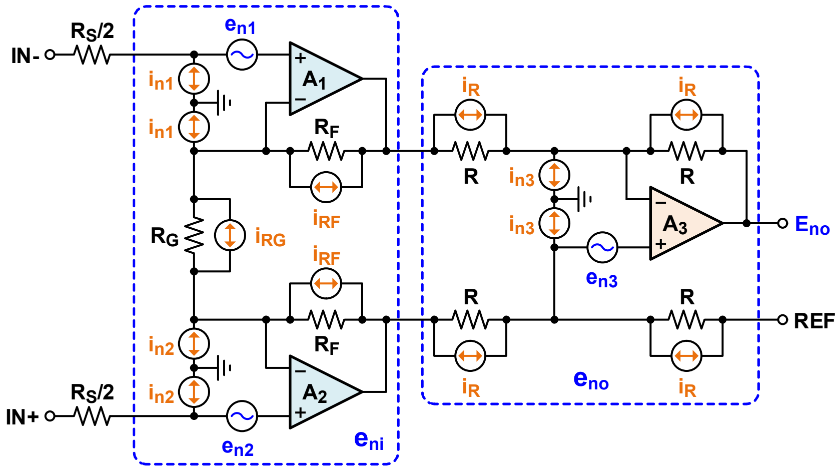

Figure 3. Detailed Noise Model of a Discrete 3-Amp INA

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}.

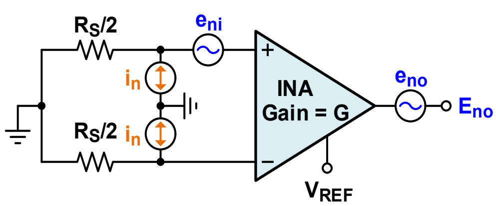

Figure 4. INA Noise Model with Separate Input and Output Voltage Noise Sources, e_{ni} and e_{no}

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

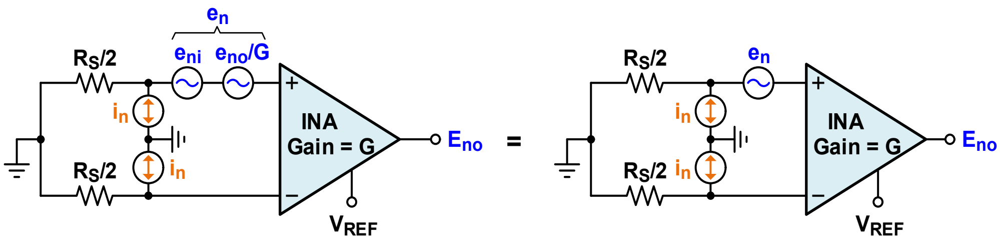

Figure 5. INA Noise Model with Total Input-referred (RTI) Voltage Noise, e_n

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 $R_P = R_F = R_1 \| R_2$ = 50kΩ.

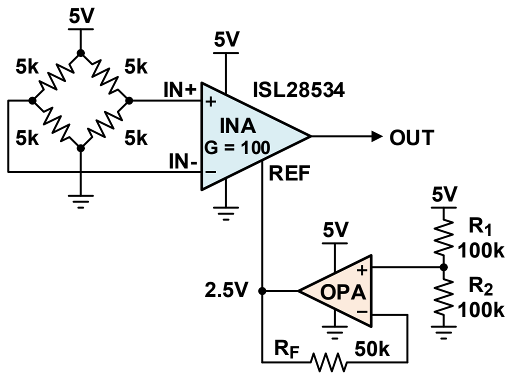

Figure 6. Signal Conditioner with INA ISL28534 at G = 100

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

IMPORTANT NOTICE AND DISCLAIMER

RENESAS ELECTRONICS CORPORATION AND ITS SUBSIDIARIES (“RENESAS”) PROVIDES TECHNICAL SPECIFICATIONS AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for developers skilled in the art designing with Renesas products. You are solely responsible for (1) selecting the appropriate products for your application, (2) designing, validating, and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. Renesas grants you permission to use these resources only for development of an application that uses Renesas products. Other reproduction or use of these resources is strictly prohibited. No license is granted to any other Renesas intellectual property or to any third party intellectual property. Renesas disclaims responsibility for, and you will fully indemnify Renesas and its representatives against, any claims, damages, costs, losses, or liabilities arising out of your use of these resources. Renesas' products are provided only subject to Renesas' Terms and Conditions of Sale or other applicable terms agreed to in writing. No use of any Renesas resources expands or otherwise alters any applicable warranties or warranty disclaimers for these products.

(Rev.1.0 Mar 2020)

Corporate Headquarters

TOYOSU FORESIA, 3-2-24 Toyosu,
Koto-ku, Tokyo 135-0061, Japan
www.renesas.com

Contact Information

For further information on a product, technology, the most up-to-date version of a document, or your nearest sales office, please visit:
www.renesas.com/contact/

Trademarks

Renesas and the Renesas logo are trademarks of Renesas Electronics Corporation. All trademarks and registered trademarks are the property of their respective owners.

© 2020 Renesas Electronics Corporation. All rights reserved.