Comprehensive Error Calculation for Instrumentation Amplifiers

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Instrumentation amplifiers (IAs) are widely used as versatile building blocks in analog electronic circuits, whenever high input impedance, robustness against common-mode voltage perturbations, as well as programmable gain are needed. The higher level of integration in an IA (compared to a standalone operational amplifier) also enables the user to reduce overall system errors; for example, by leveraging the improved resistor matching of on-chip, thin-film resistors in state-of the art process technologies. Most modern signal-conditioning systems calibrate errors at room temperature. However, calibration of errors that result from a change in temperature is normally difficult and costly. Therefore, minimizing these drift errors is important. Make sure to choose high-precision components, such as the INA821, that have improved specifications over a wide temperature range. Figure 1 along with Table 1 show an example application.

Resistor-adjustable devices (such as the INA821) show the lowest gain error in G = 1 because of the inherently well-matched drift of the internal resistors of the differential amplifier.

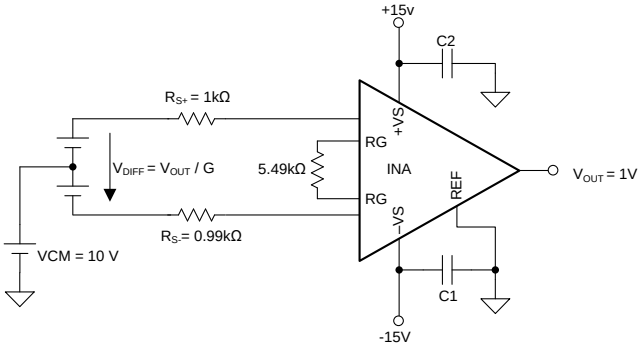

Figure 1. Example Application With G = 10 V/V

At gains greater than 1, (for instance, G = 10 V/V or G = 100 V/V), the gain error becomes a significant error source because of the contribution of the resistor drift of the 24.7-kΩ feedback resistors in conjunction with the external gain resistor. Except for very high gain applications, the gain drift is by far the largest error contributor compared to other drift errors, such as offset drift.

The INA821 offers excellent gain error over temperature for both G > 1 and G = 1 (no external gain resistor). Table 2 summarizes the major error sources in common IA applications, and compares the three cases of G = 1 (no external resistor), G = 10 (5.49-kΩ external resistor), and G = 100 (499-Ω external resistor). All calculations assume an output voltage of V_{OUT} = 1 V. Thus, input signal V_{DIFF}, given by $V_{DIFF} = V_{OUT} / G$, exhibits smaller and smaller amplitudes with increasing gain G (that is, V_{DIFF} = 1 mV at G = 1000 in this example). All calculations refer the error to the input for easy comparison and system evaluation. As listed in Table 2, errors generated by the input stage (such as input offset voltage) are more dominant at higher gains, while the effects of output stage are suppressed because they are divided by the gain when referring them back to the input. Note that the gain error and gain drift error are much more significant for gains greater than 1 because of the contribution of the resistor drift of the 24.7-kΩ feedback resistors in conjunction with the external gain resistor. In most applications, static (absolute) errors can readily be removed during calibration in production, whereas the drift errors will be the key factors limiting overall system performance.

Table 1. System Specifications for Error Calculation

Parameter	Value	Units
V_{OUT}	1	V
VCM	10	V
VS	1	V
R_{S+}	1000	Ω
$R_{S–}$	999	Ω
RG tolerance	0.01	%
RG drift	10	ppm/°C
Temperature range upper limit	105	°C

Table 2. Error Calculation

Error Source (Units)	Error Calculation	INA821 Values				
		Specification	Units	G = 1 Error (ppm)	G = 100 Error (ppm)	G = 1000 Error (ppm)
Absolute Accuracy at 25°C						
Input offset voltage	V_{OSI} / V_{DIFF}	35	µV	35	350	3500
Output offset voltage	V_{OSO} / (G × V_{DIFF})	350	µV	350	350	350
Input offset current	I_{OS} × maximum (R_{S+}, $R_{S–}$) / V_{DIFF}	0.5	nA	1	5	50
CMRR (min)	V_{CM} / ($10^{CMRR/20}$ × V_{DIFF})	92 (G = 1), 112 (G = 10), 132 (G = 100)	dB	251	251	251
PSRR (min)	(V_{CC} – V_S)/ ($10^{PSRR/20}$ × V_{DIFF})	110 (G = 1), 114 (G = 10), 130 (G = 100)	dB	3	20	32
Gain error from IN (max)	GE(%) × 10^4	0.02 (G = 1), 0.15 (G = 10, 100)	%	200	1500	1500
Gain error from external resistor RG (max)	GE(%) × 10^4	0.01	%	100	100	100
Total absolute accuracy error at 25°C (ppm), worst case	sum of all errors	—	—	940	2576	5738
Total absolute accuracy error at 25°C (ppm), average	rms sum of all errors	—	—	487	1603	3834
Drift to 105°C						
Gain drift from INA (max)	GTC × (T_A – 25) / V_{DIFF}	5 (G = 1), 35 (G = 10, 100)	ppm/°C	400	2800	2800
Gain drift from external resistor RG (max)	GTC × (T_A – 25) / V_{DIFF}	10	ppm/°C	800	800	800
Input offset voltage drift (max)	(V_{OSI_TC} / V_{DIFF}) × (T_A – 25)	0.4	µV/°C	32	320	3200
Output offset voltage drift	[V_{OSO_TC} / (G × V_{DIFF})] × (T_A – 25)	5	µV/°C	400	400	400
Offset current drift	I_{OS_TC} × maximum (R_{S+}, $R_{S–}$) × (T_A – 25) / V_{DIFF}	20	pA/°C	2	16	160
Total drift error to 105°C (ppm), worst case	sum of all errors	—	—	1634	4336	7360
Total drift error to 105°C (ppm), typical	rms sum of all errors	—	—	980	2957	4348
Resolution						
Gain nonlinearity		10 (G = 1, 10), 15 (G = 100)	ppm of FS	10	10	15
Voltage noise (at 1 kHz)	$\sqrt{BW} \times \sqrt{(e_{NI}^2 + \left[\frac{e_{NO}}{G}\right]^2 \times \frac{6}{V_{DIFF}}}$	e_{NI} = 7, e_{NO} = 65	μV_{PP}	1335	886	3566
Current noise (at 1 kHz)	I_N × maximum (R_{S+}, $R_{S–}$) × $\sqrt{BW}$ × (1 / V_{DIFF})	0.13	pA/$\sqrt{Hz}$	0.4	2	11
Total resolution error (ppm), worst case	sum of all errors	—	—	1345	896	3581
Total resolution error (ppm), typical	rms sum of all errors	—	—	1335	886	3566
Total Error						
Total error (ppm), worst case	sum of all errors	—	—	3919	7808	16724
Total error (ppm), typical	rms sum of all errors	—	—	1726	3478	6806

Table 3. Alternative Device Recommendations

Device	Description	Gain Equation	RG Pins
INA821	35-µV offset, 0.4 µV/°C V_{OS} drift, 7-nV/$\sqrt{Hz}$ noise, high-bandwidth	G = 1 + 49.4 kΩ / RG	2, 3
INA819	35-µV offset, 0.4 µV/°C V_{OS} drift, 8-nV/$\sqrt{Hz}$ noise, low-power	G = 1 + 50 kΩ / RG	2, 3
INA828	50-µV offset, 0.5 µV/°C V_{OS} drift, 7-nV/$\sqrt{Hz}$ noise, low-power	G = 1 + 50 kΩ / RG	1, 8
INA333	25-µV V_{OS}, 0.1 µV/°C V_{OS} drift, 1.8-V to 5-V, RRO, 50-µA I_Q, chopper-stabilized	G = 1 + 100 kΩ / RG	1, 8

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