Application Report

Analysis of Improved Howland Current Pump Configurations

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ABSTRACT

The Improved Howland current pump is a circuit that uses a difference amplifier to impose a voltage across a shunt resistor, creating a voltage-controlled current source capable of driving a wide range of load resistances. This design's versatility can be useful in many applications that require a current source capable of bipolar (source or sink) operation. Part of its versatility is the ability to make small alterations to the design that improves the overall performance of the circuit. This article will analyze a few Improved Howland current pump configurations and provide recommendations on how to enhance their performance.

A common goal of these designs is to create a high output impedance current source that can source or sink approximately 25mA of current while employing the Improved Howland current pump topology. Analysis will be done on four different configurations and some benefits and disadvantages of each configuration will be discussed. Depending on design requirements, one configuration might be more appropriate than another for a specific application. Precautions should be taken when driving reactive loads in an Improved Howland current pump circuit. Additionally, some loads may cause the circuit to become unstable due to insufficient phase margin. In this article only resistive loads will be discussed.

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1 Discrete Improved Howland Current Pump – Design 1

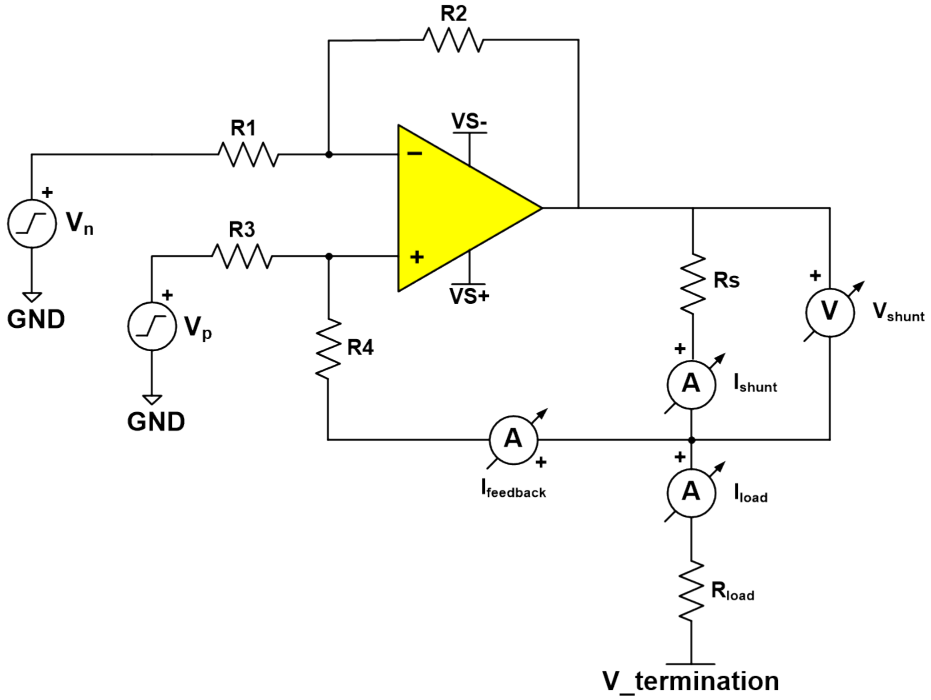

Figure 1-1. Discrete Improved Howland Current Pump

Figure 1-1 shows the basic configuration of the Improved Howland current pump that uses one operational amplifier, five discrete resistors and a resistive load, R_{load}. The current through the load (I_{load}) can be calculated using Equation 1.

$$I_{load}\,(A) = \frac{G \times (V_p - V_n)}{R_s} \tag{1}$$

$$G(V/V) = \frac{R2}{R1}, \qquad \frac{R2}{R1} = \frac{R4 + Rs}{R3} \tag{2}$$

In an ideal Improved Howland current pump; resistor R4 is sometimes set to equal R2 - Rs, which produces the expected current value by slightly altering the feedback in the positive loop. This solution has limited practicality considering the standard resistor values to choose from, as well as their tolerances. More details on the functionality of the ideal Improved Howland current pump design can be found in the link provided in the References section. Figure 1-2 shows an example of *Design 1* and the results with a modified R4 resistor. The circuit is designed for a 10mA output current with an input voltage difference of 5V using ideal components.

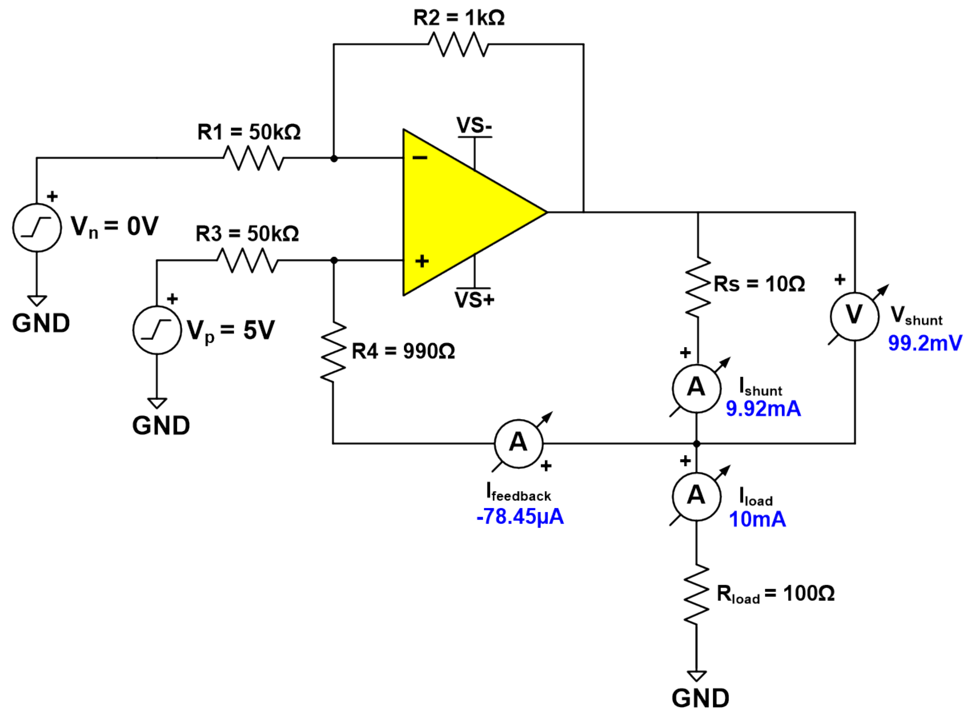

Figure 1-2. Ideal 10mA Improved Howland Current Pump

Benefits: One benefit of this configuration is the freedom to choose the gain value (G), and ultimately design for output headroom (the maximum output voltage swing or compliance range), by varying the V_{shunt} voltage. That is the case because all the resistors are discretely selected for the circuit. Another benefit is the ability to select an op amp which fits the application's specific design requirements such as size, power, and supply voltage. One last benefit for this design is that only one op amp is required.

Disadvantages: One disadvantage of this configuration is an error that is caused by the $I_{feedback}$ current affecting the I_{load} current. An ideal current source has infinite output impedance; however, this configuration's finite output impedance is determined by the two feedback resistors in series (R3+R4). This can lead to significant error in I_{load} that is more apparent when the design does not use the modified R4 resistor.

To minimize error caused by $I_{feedback}$, choosing higher value resistors for the feedback paths will increase the output impedance of the current source. This comes at the expense of more thermal noise due to larger resistor values. Possible bandwidth limitations and stability issues caused by large resistances and parasitic capacitances in the circuit also become more prevalent. To learn more about noise and stability, TI Precision Lab video links can be found in the References section.

Another disadvantage with this configuration comes from the discretely chosen resistors in the feedback network. Discrete builds with 0.1% tolerance resistors can have a worst-case CMRR value of around 60 dB, which may be too low for precision applications. More information on the importance of matching resistors can be found in the link provided in the References section. This resistor mismatch also creates gain error in the design, which contributes to the overall error. One final consideration for a discrete version of this configuration is the PC board space required considering external resistors are being used for the difference amplifier.

2 Discrete Improved Howland Current Pump with Buffer – Design 2

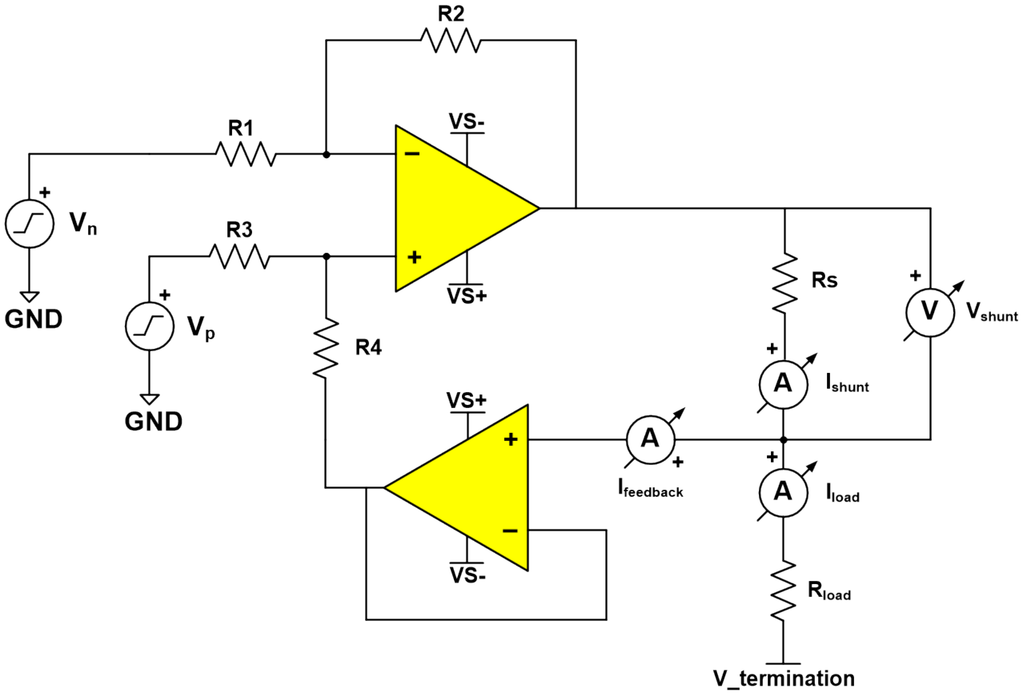

Figure 2-1. Discrete Improved Howland Current Pump with Buffer

Figure 2-1 shows a similar configuration of an Improved Howland current pump that uses two op amps. The buffer has high input impedance, which introduces high output impedance into the current source. Note when the buffer is added, the circuit designer should no longer modify R4 by the value of Rs. I_{load} can now be calculated using Equation 3 provided below:

$$I_{load}\,(A) = \frac{G \times (V_p - V_n)}{Rs} \tag{3}$$

$$G(V/V) = \frac{R2}{R1}, \qquad (R1 = R3, R2 = R4) \tag{4}$$

Benefits: This configuration has the same benefits as the non-buffered configuration shown in Discrete Improved Howland Current Pump – Design 1; however, it has the added benefit of minimizing error by practically eliminating $I_{feedback}$ current due to the added buffer. The second op amp therefore results in the ability to choose lower value resistors for the feedback network. This allows the circuit designer to minimize thermal noise attributed to high value resistors and also minimizes any stability and bandwidth concerns in the circuit.

The same 10mA current source is shown in Figure 2-2 below; the buffer practically eliminates $I_{feedback}$ current.

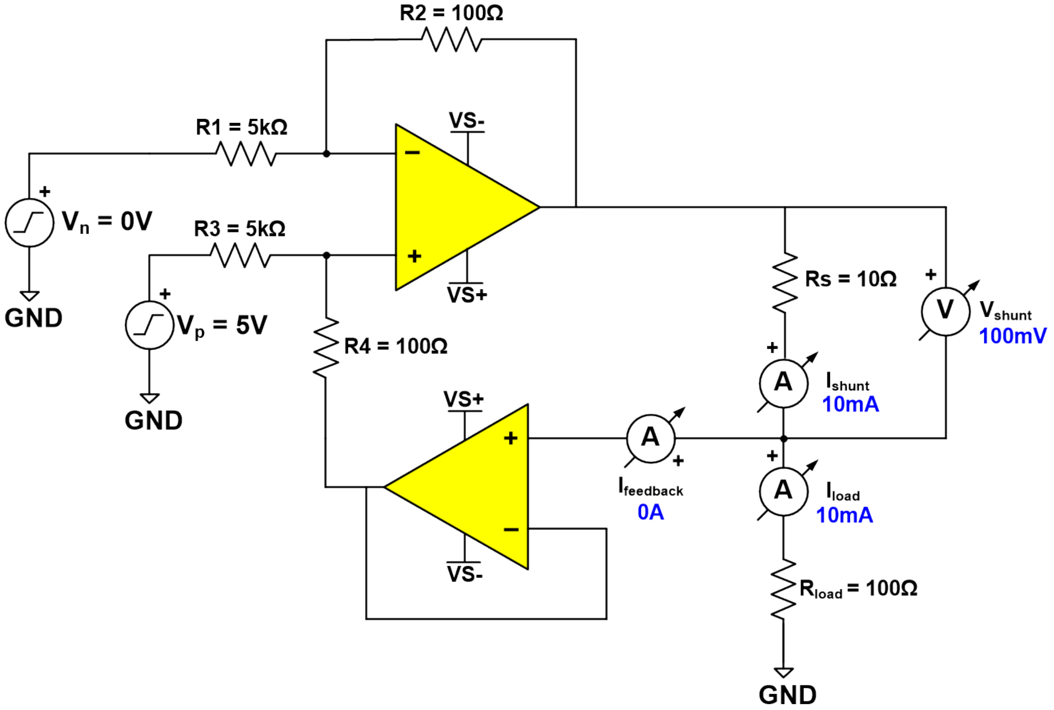

Figure 2-2. Ideal 10mA Improved Howland Current Pump with Buffer

Disadvantages: A similar disadvantage to the one op amp design comes from the mismatched discrete resistors. The overall size of the circuit increases with the addition of a second op amp which can be a disadvantage for designs that are limited in space. Fortunately, many precision op amps are available in dual configurations, which hardly add to the size or cost of the circuit.

3 Integrated Improved Howland Current Pump - INA592 and Buffer – Design 3

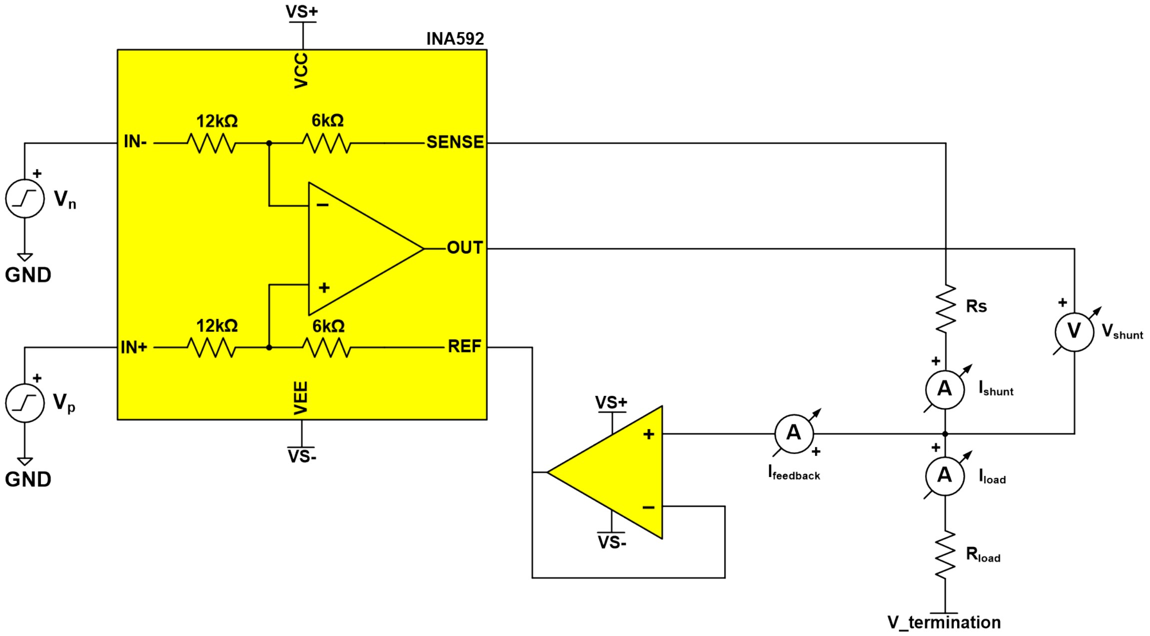

Figure 3-1. Integrated Improved Howland Current Pump with INA592 and Buffer

Figure 3-1 shows a more integrated version of the Discrete Improved Howland Current Pump with Buffer – Design 2 that integrates the difference amplifier configuration into one package. For a design target of up to ± 25mA, the INA592 can be a great selection for an integrated design. This device's performance is attributed to the core OPA192 precision op amp and precision matched thin-film resistors all integrated into one die. Load current can accurately be represented by Equation 3; however G is fixed to ½ or 2 (V/V) due to the integrated resistors. Improved Howland current pump circuits often use a voltage gain of less than 1 (V/V) so the gain of ½ (V/V) is more likely to be of use.

Benefits: The benefit of using Integrated Improved Howland Current Pump - INA592 and Buffer – Design 3 is that it minimizes many of the sources of error seen in the discrete designs. The buffer creates high output impedance practically eliminating $I_{feedback}$ current. The integrated resistors nearly eliminate the error previously caused by mismatched resistors. As a result, this device has a typical CMRR value of 100 dB as well as a typical gain error of 0.01%, sufficient for use in high precision applications. Buying discrete precision matched resistors at this performance level would be a significant expense. Considering the INA592 is priced similarly to other high performance op amps that do not include the four high precision resistors, the discrete resistors alone can easily end up costing much more than the INA592 itself.

The 12kΩ and 6kΩ integrated resistors also keep thermal noise relatively low. This also minimizes possible bandwidth limitations and stability issues. Another benefit of the integrated design is the size of the circuit. The INA592 is offered in a 3mm x 3mm VSSOP package, which is significantly smaller than most discrete op amps paired with four discrete resistors.

For precision applications it is easy to see the benefit of using an integrated configuration such as the INA592. For less precise applications or where sufficient calibration is performed, a less precise op amp and higher tolerance external resistors may fit the performance specifications required.

Disadvantages: Due to integrated resistors, the gain value is fixed for this integrated difference amplifier. In the case of the INA592, the gain value is ½ or 2 (V/V). The current through the load can be varied by changing Rs; however the fixed gains limit the range of values V_{shunt} can have for the same input voltage difference. This may result in limitations in circuits with low supply voltages or large load resistors due to limited output headroom in the design.

4 Integrated Improved Howland Current Pump - INA592 and Settable Gain – Design 4

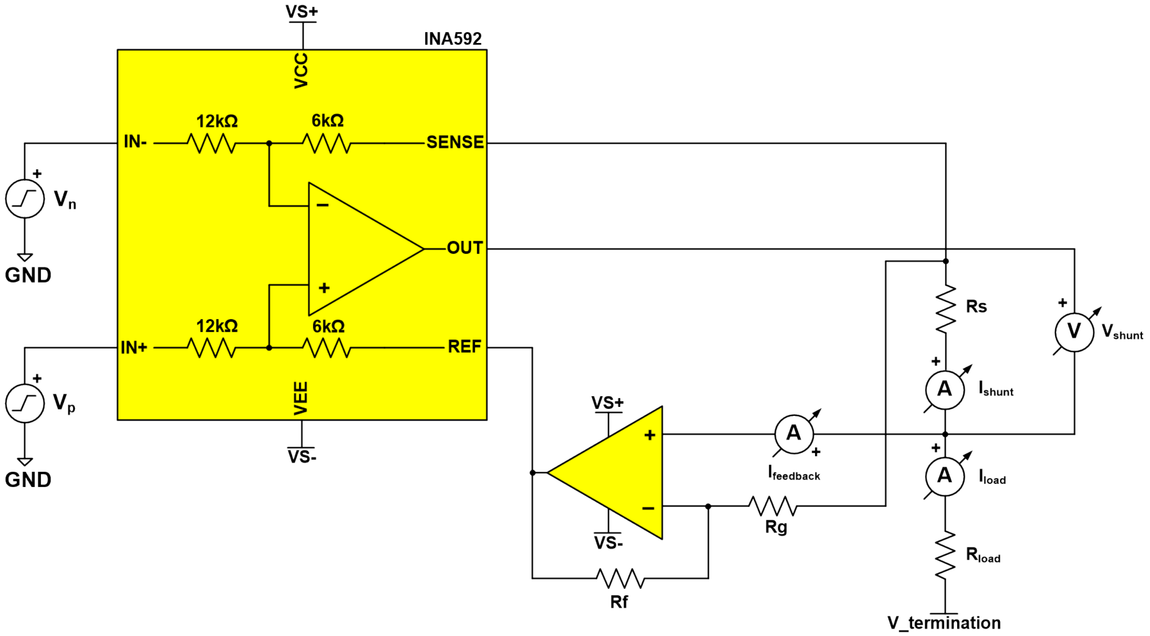

Figure 4-1. Integrated Improved Howland Current Pump with INA592 and Settable Gain

Figure 4-1 shows the same integrated design of an Improved Howland current pump as Integrated Improved Howland Current Pump - INA592 and Buffer – Design 3; the only difference being that the feedback op amp has a settable gain compared to the unity gain of the buffer configuration. This gain configuration gives the ability to design for different values of V_{shunt} for the same input voltage difference, which was limited with Integrated Improved Howland Current Pump - INA592 and Buffer – Design 3. I_{load} can now be calculated using Equation 5.

$$I_{load}\,(A) = \frac{G \times (V_p - V_n)}{Rs \times \left(1 + {}^{Rf}/_{Rg}\right)} \tag{5}$$

$$G(V/V) = \frac{1}{2} \; or \; 2 \tag{6}$$

Benefits: The benefits to this configuration are the same as in Integrated Improved Howland Current Pump - INA592 and Buffer – Design 3; with the added benefit of being able to vary the V_{shunt} voltage as discussed above. Having the ability to adjust the voltage across the shunt resistor allows the circuit designer more freedom to set the circuit's output headroom while still benefiting from the precision and high performance of the INA592.

Disadvantages: One disadvantage with this configuration could be the size of the circuit since two op amps and two external resistors are used in the design. This also leads to a slightly more complicated design than the previous three configurations. Due to non-ideal external resistors (Rf/Rg), gain error can be expected, which will affect the current accuracy of the circuit.

5 Design Needs and Considerations

The need for a simple voltage controlled current source can be readily met by implementing the Improved Howland current pump topology, and due to its versatility there are many options to choose from as discussed previously. When designing for a specific application there are many parameters to consider. With all four configurations, non-ideal characteristics of any op amp and resistor will be an inherent source of error in the design. One non-ideal characteristic of an op amp that should be considered is its offset voltage. The effect this non-ideal characteristic has on the final performance of the Improved Howland current pump circuit may be significant. Using precision op amps with very low offset voltage (<100 μV) considerably reduces the error it contributes. The offset voltage information is included in the op amp's data sheet Electrical Characteristics table.

Another non-ideal characteristic of an op amp that should be considered is output voltage swing limitations as output current changes. When considering output headroom performance, refer to the typical values given in the *Output Voltage Swing vs. Output Current* graphs in the op amp's data sheet. Doing so allows one to account for the output swing limitations. Similar considerations must be taken to ensure the common-mode input voltage range of the op amp is not violated. For designs 2 through 4, one must account for input and output swing limitations for both op amps. These input and output limitations contribute to the overall voltage compliance of the current source.

As mentioned throughout the article, each design has its disadvantages and depending on the specific design goals one design might be more suited for an application than another. Considering parameters such as output impedance, thermal noise due to resistors and the op amp(s), the amount of freedom to design for output headroom, and overall accuracy are a good start when narrowing down which design to use.

Table 5-1 can be used as a starting place when choosing which design and the level of precision of op amps to implement. In some cases implementing a general purpose op amp, such as the OPA990 / OPA2990, is enough for specific design goals compared to a more precise op amp like the OPA192 / OPA2192.

Table 5-1. Comparison Table for Designs 1-4

Design	Amplifier(s)	Output Impedance	Thermal Noise	Designing for Headroom	Accuracy
1.A	OPA990 Op Amp	R3+R4	Varies	Best	Good
1.B	OPA192 Op Amp	R3+R4	Varies	Best	Better
2.A	OPA2990 Op Amp	High	Moderate	Best	Better
2.B	OPA2192 Op Amp	High	Low	Best	Better
3.A	INA592 w/ OPA990 Buffer	High	Moderate	Good	Best
3.B	INA592 w/ OPA192 Buffer	High	Low	Good	Best
4.A	INA592 w/ OPA990 Feedback Op Amp	High	Moderate	Best	Better
4.B	INA592 w/ OPA192 Feedback Op Amp	High	Low	Best	Best

When narrowing down which configuration to use, consider the system's error, cost, and size budgets. Design specifications should also be considered, such as the current required through the load, output headroom, and voltage constraints for a specific design.

6 Operational Amplifier Considerations

Table 6-1. Operational Amplifier Considerations

Part Number	Specifications
OPA192 Precision Op Amp	RRIO, low ±5µV offset (±25µV max), low 5.5nV/ noise @1kHz
OPA191 Precision Low Power Op Amp	RRIO, low ±5µV offset (±25µV max), low 15nV/ noise @1kHz
OPA197 Precision Op Amp (for cost optimized designs)	RRIO, low ±25µV offset (±100µV max), low 5.5nV/ noise @1kHz
OPA196 Precision Low Power Op Amp (for cost optimized designs)	RRIO, low ±25µV offset (±100µV max), low 15nV/ noise @1kHz
OPA990 General Purpose Op Amp	RRIO, ±.3mV offset (±1.5mV max), low 30nV/ noise @1kHz

Table 6-2. Integrated Difference Amplifier Considerations

Part Number	Specifications
INA592 Precision Op Amp	RRIO, low ±14µV offset (±40µV max), low 18nV/ noise @1kHz (G=1/2)
INA597 Precision Op Amp (for cost optimized designs)	RRIO, low ±14µV offset (±200µV max), low 18nV/ noise @1kHz (G=1/2)
INA1620 Op Amp with integrated precision resistors	±100µV offset (±1mV max), Ultra-low 2.8nV/ noise @1kHz

7 References

- Functionality of Howland Current Pump Resource: AN-1515 A Comprehensive Study of the Howland Current Pump
- Texas Instruments, TI Precision Labs Noise Video: 8-1 TI Precision Labs - Op Amps: Noise - Spectral Density
- Texas Instruments, TI Precision Labs Stability Video: 10.1 TI Precision Labs - Op Amps: Stability - Introduction
- Texas Instruments, Importance of Matching Difference Amplifier Resistors: Difference Amplifiers – the Need for Well-Matched Resistors

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