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Getting The Most From The Improved Howland Current Pump: Output Impedance

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The improved Howland current pump depicted in Fig. 1 has been the subject of many papers and articles, with the majority of them discussing stability and the circuit techniques for providing stability. That's because this circuit combines high levels of both negative and positive feedback, and is therefore subject to stability problems.

However, few articles discuss how to get the best accuracy and performance and usually recommend careful matching of the gain-setting resistors with little further elaboration. Most often these recommendations are intended to provide the best gain accuracy, but in high-performance applications the improved Howland has another important performance parameter: output impedance.

Analyzing and optimizing for maximum output impedance is rarely covered in any detail or calculation with any accuracy (see the references). Somewhat better documented are methods for providing specific values of output impedance as part of the general subject of "back termination" to reduce the losses of passive back-termination in high-speed transmission line requirements. Less has been published regarding achieving maximum possible output impedance for performance improvement as a pure current source. That objective will be the focus of this article.

Some articles have documented the effects of resistor values on output impedance in an attempt to maximize performance while neglecting the open-loop gain of the op amp (AOL). This is significant because the finite nature of AOL has a dramatic effect on the output impedance. Additionally, there is a region of operation which offers negative impedance that should always be avoided except by those who are brave or adventurous, since this is the point where the positive feedback begins to dominate. In this discussion, we'll present an equation for output impedance that includes AOL and describe a technique for trimming one of the resistor values to compensate for the finite AOL and thereby maximize output impedance while avoiding the region of negative resistance.

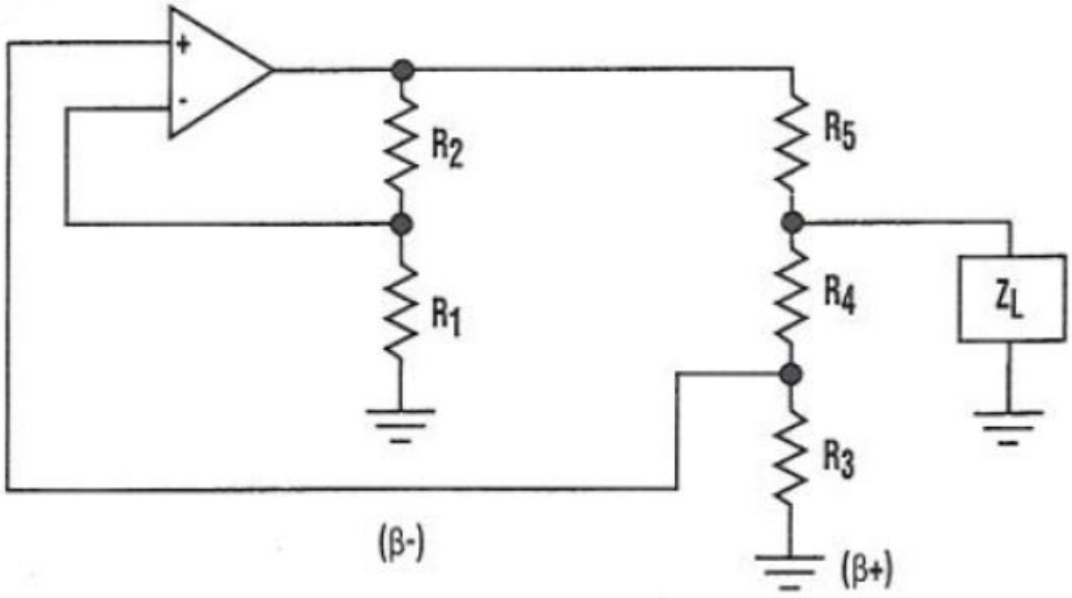

Fig. 1. The basic configuration of the improved Howland with positive and negative feedback paths. R5 is the current-sensing shunt.

How The Improved Howland Works

To understand how the improved Howland functions, let us first imagine that we have a perfect op amp, including an open-loop gain of infinity. Referring back to Fig. 1, imagine that R4 and R3 are a voltage divider that divides down any voltage that appears at the output of the circuit, and deliver that signal to the non-inverting input as shown in Fig. 2.

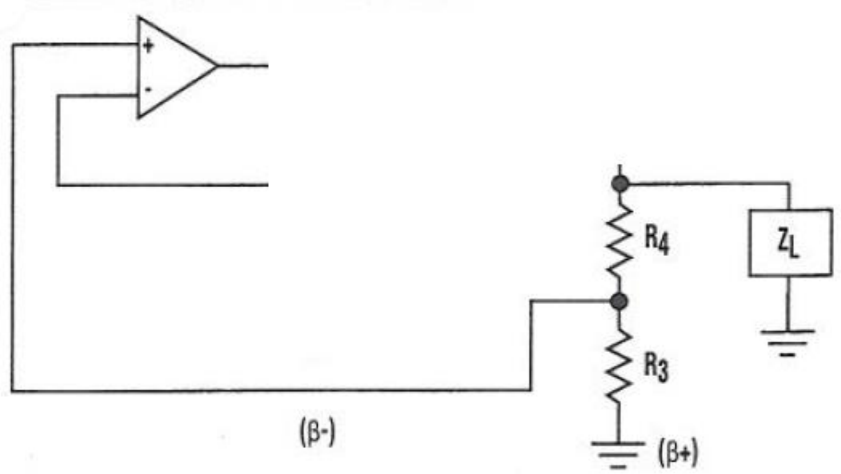

Fig. 2. This portion of the improved Howland looks like a simple attenuator providing input to an amplifier. Ultimately it becomes a positive feedback loop.

Now imagine that R1 and R2 provide a gain network as shown in Fig. 3, with the objective to set the gain exactly equal to the attenuation of R4 and R3.

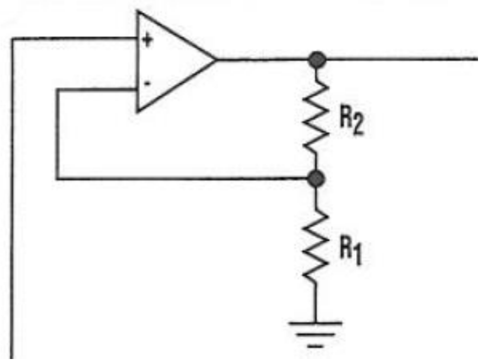

Fig. 3. The simplified circuit of the op amp and resistors R1 and R2 comprise a simple non-inverting op amp circuit. An accurate gain calculation should consider the finite open-loop gain of the op amp. While there are several ways in the entire Howland circuit to compensate for this, the obvious way is to increase R2 slightly to provide the desired closed-loop gain. By doing this you perfectly match (or ratio) all but R2 and then trim or otherwise optimize R2. A perfectly matched R2 will prove to be low in value.

With this condition satisfied it will be noted that any voltage impressed upon the output will be sensed and amplified to appear at the amplifier output with an identical value such that the voltage across R5 is zero. There will be no current flow and therefore infinite impedance. Applying input voltage to either R1, R3, or both differentially will command the amplifier circuit to enforce this behavior at a desired current level.

Aside from the requirement to account for AOL at dc and low frequencies to arrive at an R2 value to provide best performance, another tradeoff occurs due to op amp AOL roll-off with frequency. Some wideband op amps can support a flat AOL curve up to fairly high frequencies as one possible solution. Furthermore, this AOL reduction and accompanying phase shift will cause the output impedance to appear capacitive.

Equations have been published elsewhere to calculate the output impedance that omit the effect of finite open loop gain. The following formula for improved Howland output impedance does account for finite open loop gain:

$$Z_O = \frac{R5}{1-\left(\frac{R3}{R3+R4}\right)\left(\frac{A_{OL}}{1+A_{OL}\left(R1+\frac{R1}{R2}\right)}\right)}$$

Meanwhile the equivalent output capacitance for the improved Howland can be calculated as

$$C_{eq} = \frac{R_1+R_2}{2\pi f_O R_3 R_5}$$

where f_O = gain-bandwidth product of the op amp.

R2 Trim Considerations

Plotting the output impedance equation reveals that as R2 is increased the output impedance reaches a peak. As R2 continues to increase the output impedance reaches infinity, then flips to negative infinity and comes back as a negative output impedance.

Negative impedances can occasionally be useful (such as cancelling the effect of undesired positive impedance in the load) however the dominance of positive feedback in this region makes achieving stability difficult or impossible. It might be achieved when loads are fixed and well-defined. Fig. 4 depicts a plot of the effects on output impedance of increasing R2 through this region.

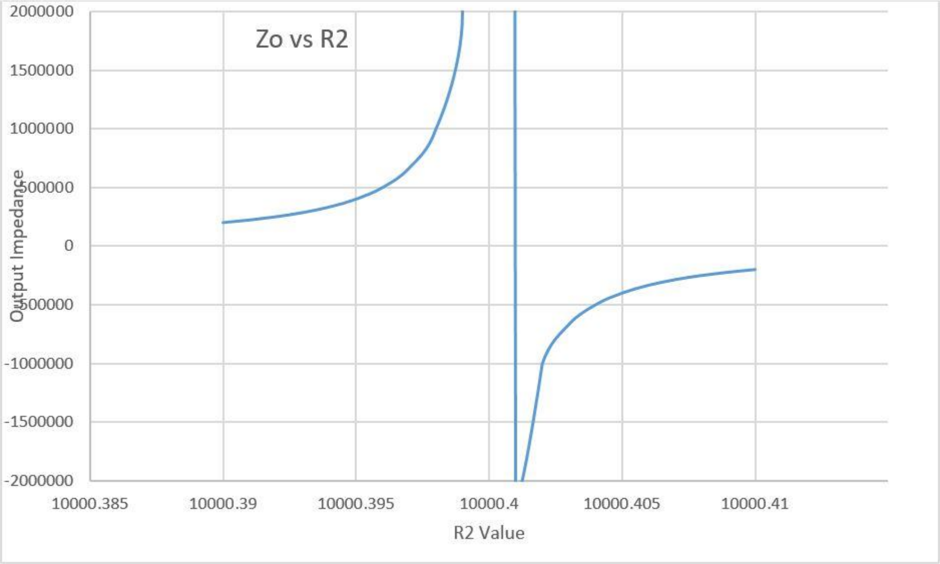

Fig. 4. Plot of improved Howland output impedance per the above equation for Z_O based on the use of 10-kΩ resistors in all locations (R1 – R4) with trimming of the R2 value. An AOL of 79,000 (i.e. 98 dB) is assumed. At 10000.400 to 10000.401 Ω the impedance turns negative.

Plotting the output impedance vs. R2 drives home the significance of the output impedance of the improved Howland. This plot depicts the transition as R2 is trimmed up from its value that is matched perfectly to the remaining resistors. The point where the resistance is equal to R2+0.4 indicates what is likely a practical value of trimmed resistor performance to achieve maximum output impedance.

The graph continues to depict the transition into the negative resistance region. The plot also depicts how you can trim the circuit to a specific output resistance such as 50 Ω in order to avoid the attenuation of passive back termination in transmission line applications. However, for those more concerned with the design of accurate and predictable current sources for test instruments or related applications, the trimming technique described here also offers a method for achieving that goal.

While the above description of trimming illustrates the concept—which can be viewed as a form of "bootstrapping" where impedance is raised due to small amounts of positive feedback—real world trimming consists of applying a signal to the output of the circuit and trimming for maximum amplitude but not beyond that point. And of course all discussions have assumed adequately low impedance from the source driving R1, R3 or both. Or that the sources are properly buffered to meet this requirement.

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About The Author

Jerry Steele, who recently joined Microchip Technology as a staff engineer, has a long association with power management products from his early days at Burr-Brown, Apex Microtechnology, National Semiconductor and Maxim, and at Texas Instruments as a senior member of technical staff. His experience has covered a variety of products including precision analog and mixed-signal devices dedicated to temperature, current, and power measurement to system management and protection devices including devices such as eFuses and hot swap controllers. Jerry has authored a considerable number of analog and mixed-signal articles over the years, and co-authored five patents.

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