AN-1515 A Comprehensive Study of the Howland Current Pump

ABSTRACT

It is well known to analog experts that you can use the positive and negative inputs of an operational amplifier to make a high-impedance current source (current pump) using a conventional operational amplifier (op amp). This basic circuit can put out both + and - output current (or zero current) into various loads. The theory is simple. But the practical problems involved are not so simple or obvious. This application note provides an indepth study of the Howland Current Pump.

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1 A Comprehensive Study

There are two basic circuits -- the Basic Howland Current Pump, Figure 1, and the "Improved" Howland Current Pump. The Basic circuit does good service for simple applications, but if its weaknesses are unacceptable, the "Improved" circuit may do much better for critical tasks. See Figure 5.

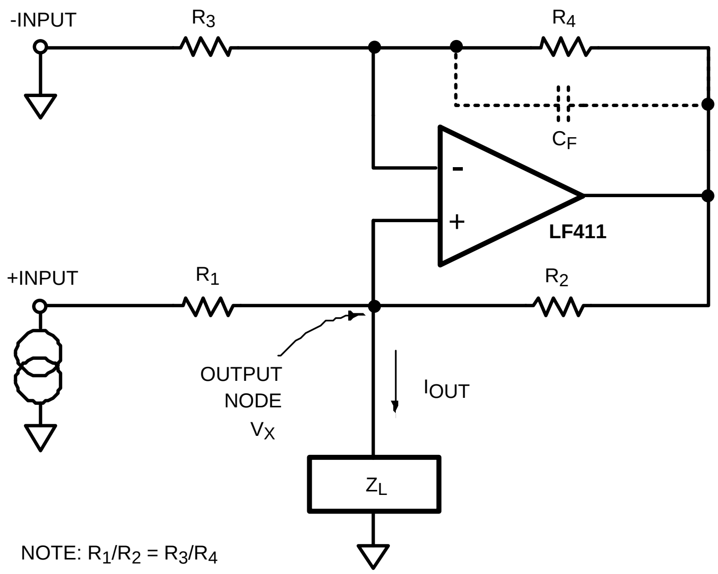


Figure 1. The Basic Howland Current Pump

2 Applications for the Howland Current Pump

Sometimes a unidirectional current source (or sink) is just right. It is easy to make them with high output impedance and wide range, using an op-amp and some Darlington-connected transistors. But sometimes you need a current pump that can put out a current in either direction – or even AC currents. The Howland current pump is usually excellent for that. Current sources are often used for testing other devices. They can be used to force currents into sensors or other materials. They can be used in experiments, or in production test. They can bias up diodes or transistors, or set test conditions. When you need them, they are useful — even if you only need them once or twice a year.

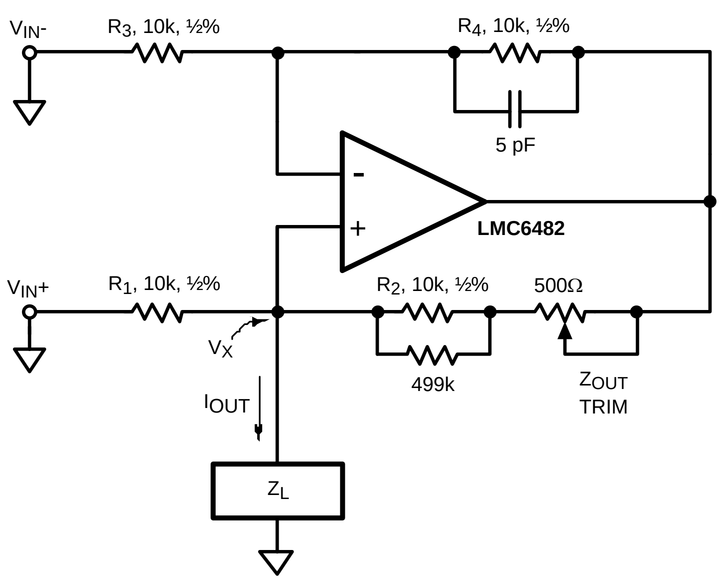


Figure 2. Basic Howland Current Pump with Trim of Z_{OUT}

The "Basic Howland Current Pump" was invented by Prof. Bradford Howland of MIT, about 1962, and the invention was disclosed to his colleague George A. Philbrick (the analog computer pioneer who was head of Philbrick Researches, Boston MA at that time). This circuit was not patented. The Howland Current Pump was first published in the January 1964 "Lightning Empiricist", Volume 12, Number 1. It is Figure 5A on page 7 of an article by D. H. Sheingold, "Impedance & Admittance Transformations using Operational Amplifiers". This can be found at www.philbrickarchive.org/1964-1_v12_no1_the_lightning_empiricist.htm. It was also included in the Philbrick Researches Applications Manual, in 1965. Its elegance arises because the feedback from the output to both the + and - inputs is at equal strength -- the ratios of R1/R2 and R3/R4 are the same. While it is possible to analyze this circuit mathematically, it is easiest to just analyze it by inspection:

If the "output" node Vx -- which is the + input of the op amp -- is grounded, it is easy to see that the "gain" is 1/R1, that is, the output current per change of the input voltage is equal to 1/R1. So you don't need a fancy set of equations for that. The resistors R2, R3, and R4 have no effect when the output is grounded, and only the + input voltage is active.

When you move the - input upward, the gain to the grounded output node is – R4/R3 x 1/R2. Since the ratio of the resistors is defined to be R1/R2 = R3/R4, then that gain is also equal to - 1/R1. That is easy to remember! Note that the gain is reversed for the - input.

Thus it is easy to see that if both Vin+ and Vin- are moved together, then there is no change of Iout. When Vin + rises, the "gain" to the output node is "1/R1". Then it follows that the gain for the - input is also "1/R1" but with a negative sign. So this current pump can accept positive or negative inputs. It has true differential inputs. Now all that we need to show, is that the output impedance is high, so that the gain is correct for all output voltages and impedances, and for all inputs.

It is easy to see that the output impedance is very high, using this analysis: If both signal inputs are grounded, and if the "output" node Vx is lifted up, somebody has to drive the resistance "R1". But as the op-amp's + input is lifted, the - input must also rise up, and the output also rises, providing just enough current through R2 to cancel the current flowing through R1, thus making the output impedance very high indeed. The principle of linear superposition says that no matter what is Vin+ or Vin-, and no matter what is Zload, and no matter what is Vout (within the limitations that you shouldn't ask the op-amp output to put out more than it can do, in voltage or current), the Iout will be (Vin+ - Vin-) x 1/R1. If you like to see a lot of fancy equations, see Appendix A.

Most applications notes just indicate the circuit and the ratio, that R1/R2 must be equal to R3/R4. However they do not indicate how important it is to have precise matched or trimmed resistors. If all 4 resistors were 10 k ohms with a 1% tolerance, the worst-case output impedance might be as bad as 250 k ohms -- and it might be plus 250k, or it might be minus 250k! For some applications, this might be acceptable, but for full precision, you might want to use precision resistors such as 0.1% or even 0.01%. These are not inexpensive! But it may be preferable to use precision resistors rather than to use a trim pot, which has to be trimmed (and which may get mis-trimmed).

Note that if you use adjacent resistors from a tape of 1% resistors, the odds are that they will match better than 1/2%. But that is not ensured!

Figure 2, Figure 3, and Figure 4 show ways to use a trim-pot to make the output impedance very high. Typically, using 1/2% resistors and one trim pot, you can trim the output impedance to be 5 ppm of I (full scale) per volt.

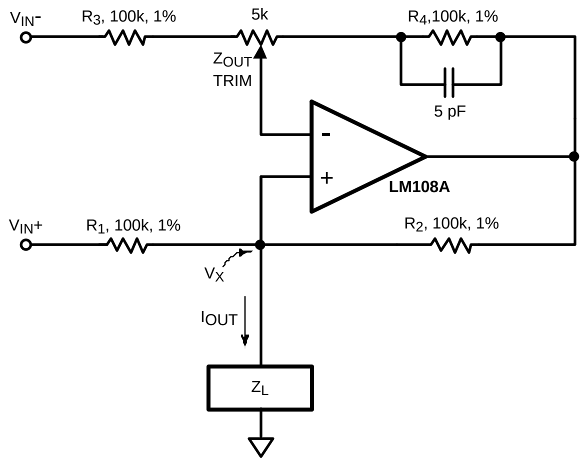


Figure 3. Basic Howland Current Pump with Trim of Z_{OUT}

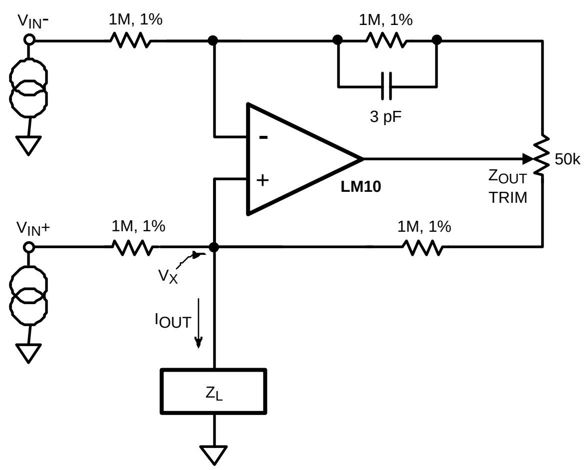


Figure 4. Basic Howland Current Pump with Trim of Z_{OUT}

However the resistor tolerance is not the only thing that needs to be trimmed out. The CMRR of the amplifier needs to be accommodated. Fortunately, an amplifier CMRR of 60 dB would cause the output impedance to degrade only to 10 megohms, not even as bad as 0.1% resistors would cause, in the example above. And many amplifiers have CMRR better than 80 dB. However, the CMRR of an op-amp is not always linear -- it may be curvy or it may be otherwise nonlinear. Some amplifiers that have the advantage of rail-to-rail inputs may have a nonlinear Vos which may jump a millivolt or more as the CM signal gets within a couple volts of the + rail. Amplifiers with bipolar inputs often do have this kind of nonlinearity. Amplifiers such as LM6142 and LM6152 have nonlinearities of this type (see Appendix B). Some CMOS amplifiers such as the LMC6482, LMC6462, etc. (see Appendix C) have a fairly linear curve of Vos, with no jumps, due to proprietary input process and circuit design.

One of the weaknesses of the Basic Howland Current Pump is its output capability. Its output node does not normally swing very close to the rail. For example, the basic 10k/10k/10k/10k scheme can only swing its output node to + or - 5 or 6 volts , with ± 15-volt supplies. If the output node rises a lot, the op-amp's output would have to rise about twice as high. When that is no longer possible, the "Improved Howland" should be considered.

If you kept the gain resistor R1 as 10k, and change R2 and R4 to 1k, you could make a 10k/1k, 10k/1k circuit, that would let the output node rise to 10 volts with a good amplifier. However, this is a little less accurate, with more offset and noise.

Another weakness of the Basic circuit is the inefficiency. If you want to have a gain of (1/100 ohms), with R1 at 100 ohms, the amplifier has to put out a lot of drive, if the load voltage swings a lot. If the load is a low voltage, such as a diode, that may not be so bad. If the load only rises a half volt, only a few mA will be wasted. But if it had to rise 5 volts, that is a lot of power wasted!

If you had to drive a heavy load, you do not have to have equal resistances at R1 and R3. You could have 100 ohms, 100 ohms for R1/R2, and 10k/10k for R3/R4. Then if you want to drive the - input, the input impedance will not be very heavy. However, when you have this imbalance, you must be careful that the amplifier's Ib does not cause a big error, which may be significant if a bipolar input op amp is used.

To avoid these weaknesses of the Basic Howland, the "Improved" Howland generally does solve many of these problems, very well. See Figure 5.

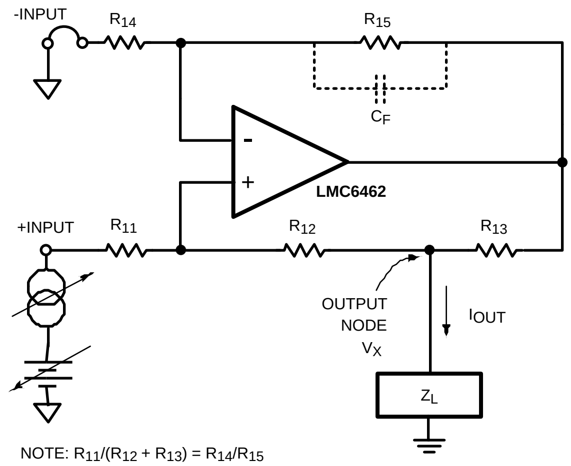


Figure 5. The "Improved Howland" Current Pump

3 The "Improved Howland" Current Pump

In this case, you still have to trim the R's to get good CMRR and high output impedance. But the gain is set by R13, modified by the ratio of R14/R15 (which is typically 1/1). Consequently you can use low values for R13, and keep all the other resistors high in value, such as 100k or 1 Megohm.

In the "Improved" Howland, note that it is not just the ratio of R11/R12 that must match R14/R15; it is the ratio R11 / (R12 + R13) that must be equal to R14/R15. If you do the intuitive analysis as mentioned above, you can see that if R14 = R15, R12 will normally be (R11 - R13). Conversely, you could make R11 a little higher, to get the gain to balance out. You could put a 2k pot in series with R11. This "improved" circuit can now force many milliamperes (or as low as microamperes, if you want) into voltages as large as 10 volts, with good efficiency. See Figure 6.

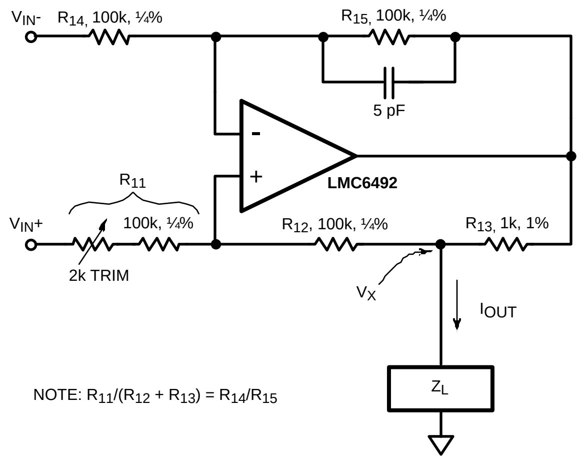


Figure 6. The “Improved Howland” with Trim for Z_{OUT}

4 Dynamics

Most engineers know (if you remind them) that it's a good idea to add a feedback capacitor across the feedback resistor of an inverting amplifier. The Howland Current Pump does like a little bit of feedback capacitor there, across R4 (or R15). A small feedback cap of 3 to 5 to 10 pF is almost always a good idea. If you are putting in a really slow current, and if the rate of change of the output voltage at the output node is not high, you could make the Cf equal to 100 or 1000 pf, to cut down the bandwidth and the noise.

Most engineers have not analyzed the dynamics of this circuit. According to the detailed analysis (in Appendix D) the "output capacitance", as seen at the output node can be as large as 80 pF, for an ordinary 1 MHz op amp. However, there are many fast amplifiers available these days, so it is usually easy to select one with a lot more bandwidth than that, if you need it. But you have to remember to design for that.

The equation for the output capacitance of the Improved Howland is derived in the latter part of Appendix E. This may be slightly better than for the standard Howland.

5 Choice of Amplifiers

Almost any op-amp can be used in a Howland current pump. However, if you need a wide output voltage range, a high-voltage amplifier, running on ±15 volts (or more) may be needed. Conversely, if you only need a small Vout range, a low-voltage CMOS amplifier may work just fine. As with any amplifier application, choosing the amplifier may take some engineering, to choose the right type. For high impedance applications (resistors higher than 0.1 Megohm), FET inputs may be a good choice. If you have one left-over section of LM324, it can even do an adequate job, for resistors below 100k. A list of amplifiers with Bipolar inputs (and generally wider signal ranges) is found in Appendix B. A list of CMOS amplifiers with very high Zin (but smaller output range) is in Appendix C.

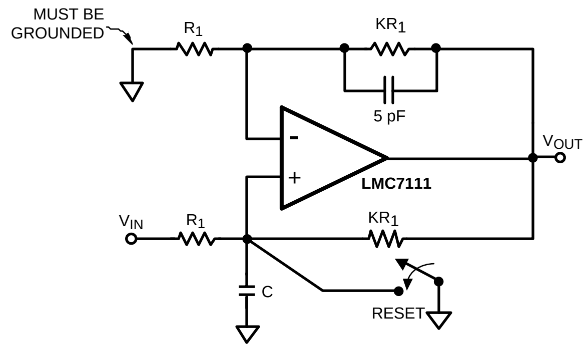
If you needed a ±6 volt output swing, you might not need a ±15-volt op-amp. The "Improved Howland" may be able to swing that far, using a good CMOS op-amp running on ± 7 volts, such as LMC6482. The "Improved" Howland is much more effective in terms of output swing.

Current-feedback amplifiers are not normally good choices for the Howland current pump, as they mostly work best at low impedances. And their CMRR is rarely as good as 58 dB. But if you need a blindingly fast current pump at fairly low impedance levels (100 ohms to 2k), current-feedback amplifiers can do a good job. Be aware that they may need a good bit of trimming to counteract their poor CMRR.

6 Special Applications

7 The Howland Integrator

One of the obscure applications for the Howland Current pump is the "Howland Integrator", shown in Figure 7. This is sometimes called a “DeBoo Integrator”. If a capacitor is used as the load, the Amplifier's Vout can be easily seen to be: Vout = 2 x 1/RC x ∫ Vin/dt . (This assumes that R1/R2 = R3/R4 = 1.) Of course, this integrator has to have some means to reset it, just as every integrator does. However, it is fairly easy to reset the integrator with a single FET or switch to ground, as shown. The Howland Integrator only works using its + input, as the - input must be grounded. It has a positive gain, as opposed to the conventional inverting integrator.

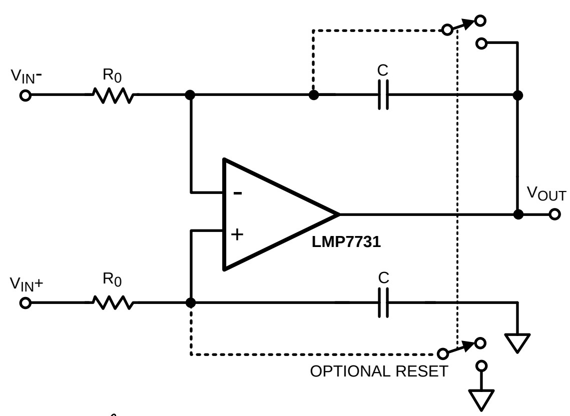


$$V_{OUT} = (1 + K)\frac{1}{(R_1C)}\int V_{IN}\,dt$$

$$= \left(\frac{2}{R_1C}\right)\int V_{IN}\,dt, \text{ if } K = 1$$

Figure 7. The Howland Integrator

This is much easier to use than the rarely-used Positive Integrator (see Figure 8), which would need TWO FET switches to reset it. That integrator is rarely used, for obvious reasons, but it can be used in loops which inherently provide some feedback to bring the output back to a low level, and to keep it zeroed. For example: a servo integrator, that will pull an error back to zero, can work well. This "positive integrator" actually is a differential integrator, with positive and negative signal input gains. It can be used with either input active, or BOTH.



$$V_{OUT} = \frac{1}{R_0C}\int (+V_{IN}+ - V_{IN}-)\,dt$$

Figure 8. The Positive or Differential Integrator (not a Howland Circuit)

8 Multi-Range Current Pump

If you want to use a Current Pump with various different ranges (such as connecting in various Gain resistors of 1 ohm, 10 ohms, ... , 1k, 10k, ..., 1 M, etc., etc....) it is possible to add one precision op amp to allow you to change ranges without affecting the other resistors. A precision FET-input op amp with good CMRR can be used as the unity-gain follower, as shown in Figure 9. The resistors should be trimmed to take into account, (and trim out the effect of) the CMRR of BOTH operational amplifiers. A typical trim scheme is shown.

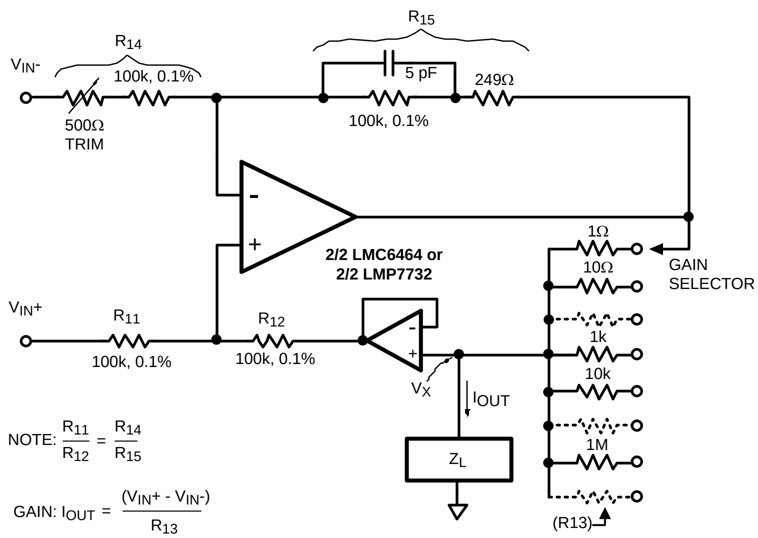


Figure 9. Multi-Range Current Pump

Appendix A Output Impedance as a Function of Trimming

If a basic Howland Current pump has 4 equal resistors, it is easy to see that the tolerance of any one resistor can cause the output impedance of the circuit to be as bad as (R1 x 1/tolerance). If the tolerance is 1% and you are using 10k resistors, the output impedance could be as high as 1 megohm. In fact, the output impedance could be as high as " plus 1 megohm" or it could be a negative output impedance of MINUS 1 megohm.

Most engineers are not very familiar with the concept of "negative resistance". In a case like this, if the Howland Current Pump is connected to a small capacitor, a conventional "positive" output resistance would mean the output would gradually droop down toward ground (assuming small Vos of the op amp). If the output impedance were very high, the Vout would just stay constant. If the output impedance were negative, the output voltage would rise up faster and faster! Or it would descend NEGATIVE, faster and faster!

If R1 is too low, the output impedance will be "positive". If R4 is also too low, that helps make the output impedance lower, and positive. If R2 and R3 are too high, they all add up to the worst case, where Zout would be 1/4 megohm.

If R1 and R4 were HIGH in tolerance, and R2 and R3 were too LOW, the output impedance could be as poor as NEGATIVE 250k. Both of these cases would be usually unacceptable, for any precision application, because the circuit is normally capable of being 200x higher than that, in its output impedance.

Some of the possible solutions to this tolerance problem are

1. Buy resistors with tighter tolerances - or
2. Sort and match them by pairs. This is cheap and simple if you only need a small number of well-matched resistors, and you don't want to go out and buy special parts. Just match the R's you have.
3. Add a trim-pot in series with one of the resistors, and add a compensating resistor of about half that size, on the opposite side, to let you trim the ratio up or down a little. Of course, if any pot can be adjusted, it can also be mis-adjusted.... Per Section 2, Figure 3 or Figure 4.
4. Buy matched sets of tightly-matched resistors. These can be purchased in sets of 4 for a couple dollars, in an SOIC package, such as four 10k resistors matched to 0.1% or even to 0.01% of ratio. See Figure 10. Resistors such as Caddock T914's (in SIP packages) can be found at: www.caddock.com/Online_catalog/Mrktg_Lit/TypeT912_T914.pdf These are available with matching down to 0.01%. Resistors such as Vishay Beyschlag ACAS 0612's are at www.vishay.com/ The catalog lists these as good as 0.1% matching, in Surface Mount packages. Bourns has thin-film networks in DIPS (4100T Series) and in surface mount packages (4400T Series) at: www.bourns.com/. Their tolerance is better than 0.1% but the matching specs are not listed.
5. Use the techniques of TI's Linear Brief LB-46 to make snip-trimmed resistors, to avoid the problems with pots. See Figure 11.

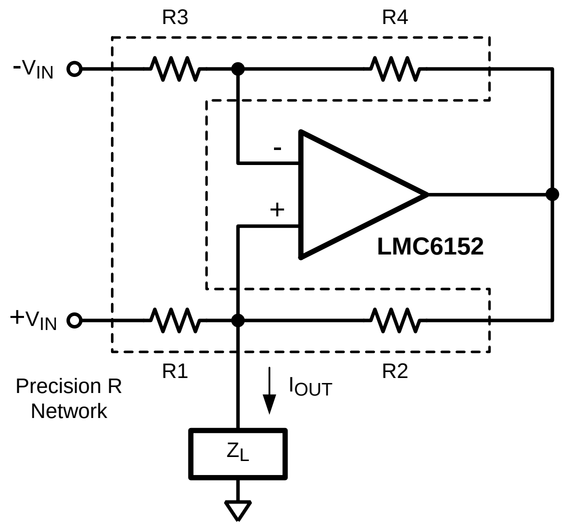


Figure 10. Basic Howland Current Pump with Precision Resistor Network

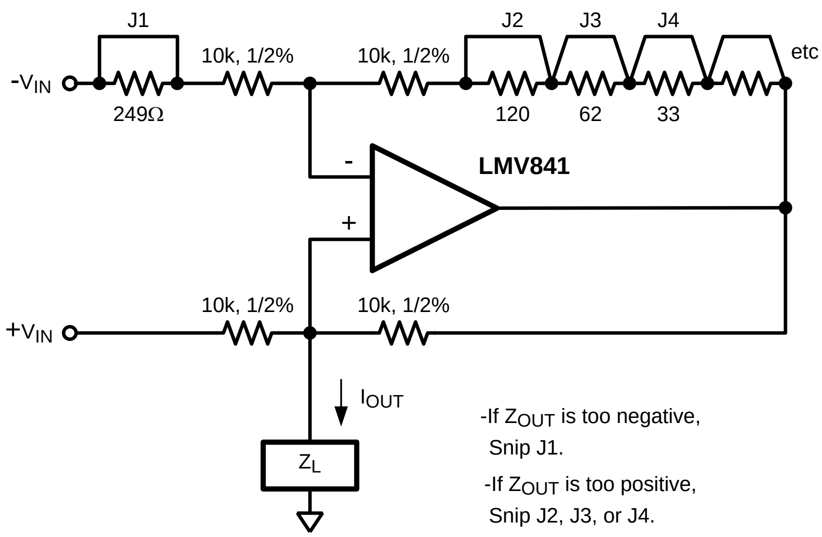


Figure 11. Trimming Z_{OUT} without a Trim-Pot

Appendix B

List of TI amplifiers with rail-to-rail inputs using bipolar transistors (NPN and PNP):

- LMV931, LMV932 (dual), LMV934 (quad) - down to 1.8-volt supplies.
- LMV7301 (2.2 to 30 V supplies)
- LM6132 (dual), LM6134 (quad) - 10 MHz per 0.36 mA
- LM6142 (dual), LM6144 (quad) - 17 MHz
- LM6152 (dual), LM6154 (quad) - 75 MHz.
- LMV981 (single), LMV982 (dual)
- LMH6645, 6646, 6647.
- LM8261, LM8262 (dual)
- LMP7731 (single).
- LMP7732 (dual)
- and many more.

Note, Rail-to-Rail Input Common-Mode Range is not usually needed for a Howland Current Pump, but may be advantageous for the "Improved Howland".

To find the full range of these amplifiers with Rail-to-Rail common-mode range, go to www.ti.com/lsds/ti/analog/amplifiersandlinears/amplifiersandlinears.page and look for bias currents larger than 10 nA.

Appendix C

List of TI amplifiers with rail-to-rail inputs using CMOS inputs:

- LMC6492 (dual), LMC6494 (quad) - standard
- LMC6482 (dual), LMC6484 (quad) - precision
- LMC6462 (dual), LMC6464 (quad) - precision low power
- LMC7111 - single, low power
- LMC8101 - 2.7 V
- LMP710 - 5MHz
- LMV7701
- LMV712 (dual) - with shutdown
- LMV841
- LMP7704

and several more...

Note, Rail-to-Rail Input Common-Mode Range is not usually needed for a Howland Current Pump, but may be advantageous for the "Improved Howland".

To find the full range of these amplifiers with Rail-to-Rail common-mode range, go to go to www.ti.com/lsds/ti/analog/amplifiersandlinears/amplifiersandlinears.page and look for bias currents smaller than 10 nA.

Appendix D

Output Capacitance of the Basic Howland Current Pump (Figure 1).

An operational amplifier can move its output quickly, only if there is a significant Vin transient or Error Voltage ($V\varepsilon$) applied across the inputs. Typically, this can be millivolts, or dozens of millivolts, according to the need for fast output speed.

The rate of change of Vout, dVout/dt, is equal to: dVout/dt = - (2πfh) x Vin where (fh) is the Gain Bandwidth Product. Thus, $V\varepsilon$ = dVout/dt x 1/(2 π fh)

The best way to analyze this current pump is to apply a long, slow ramp at Vx. The dVx/dt is the same as the dV(sum)/dt, and dVout/dt = (R4 + R3)/R3 x dVx/dt.

To move dVout/dt at this rate, there must be an error voltage at the - input (V(sum)), even when Vx = 0 and moving. When we apply a long ramp from a negative voltage and Vx just passes 0 volts, with a rate of change equal to dVx/dt, this error voltage $V\varepsilon$ will be generated:

When the momentary voltage at the applied voltage Vx is: Vx = 0 + dVx/dt, V(sum) = dVx/dt - $V\varepsilon$,

Then Vout has a rate of change, (dVx/dt) (R4 + R3)/R3 and a momentary offset of:

$- V\varepsilon \times (R4 + R3)/R3 = -1/(2 \pi fh) \times dVx/dt \times ((R4 + R3)/R3)^2$.

The current i1 through R1 = 0, since Vx = 0. The current through R2 is:

$i2 = Vout/R2 = - dVx/dt \times 1/(2 \pi fh) \times 1/R2 \times ((R4 + R3)/R3)^2$.

This current acts as a capacitive current, as it is a direct function of dVx/dt. This virtual capacitance is:

$C = 1/(2 \pi fh) \times 1/R2 \times ((R4 + R3)/R3)^2$.

For a 1 MHz op amp, in a typical application when R1 = R2 = R3 = R4 = 10k, this capacitance will be 200 pf / π, or about 64 pF, (in addition to the actual capacitance at the + input of the operational amplifier). This capacitance is inversely proportional to the gain bandwidth product fh. It gets smaller as a faster amplifier is employed. This capacitance will also be inversely proportional to R2, so for 1 kilohm, it would be 636 pF. For 100 kilohms, it would be just 6.4 pF. This capacitance will also be modified by the ratio of (R4 + R3)/R3, if that is not 2. The apparent capacitance may be different if a large feedback capacitance is connected, across R4. A small feedback capacitance of 3 to 10 pF across R4 is normally a good idea, even if fast signals are not contemplated.

With modern fast op-amps, this capacitance may or may not be a significant factor, but it should be taken into account, depending on the application.

Appendix E Output Capacitance of the "Improved" Howland Current Pump

The analysis of this circuit is similar to the analysis of the basic Howland Current Pump of Figure 1.

An operational amplifier can move its output quickly, only if there is a significant Vin transient or Error Voltage (Vε) applied across the inputs. Typically, this can be millivolts, or dozens of millivolts, according to the need for fast output speed.

The rate of change of Vout, dVout/dt, is equal to: dVout/dt = - (2 π fh) x Ve where (fh) is the Gain Bandwidth Product. Thus Vε = dVout/dt x 1/(2 π fh)

The best way to analyze this is to apply a long, slow ramp at Vx. To move dVout/dt at a quick rate, there must be an error voltage at the - input (V(sum)), even when Vx = 0 and moving. When we apply a long ramp, starting from a negative voltage in a positive direction, and when it exactly passes 0 volts, with Vx = dVx/dt, this error voltage Vε will be generated:

When the momentary voltage at the applied voltage Vx is: Vx = 0 + dVx/dt,

The rate of change at V+ is R11/(R11 + R12) x dVx/dt, and the rate of change at Vsum is the same dV/dt, plus an offset: Vsum = R11/(R11 + R12) x dVx/dt + Vε

The rate of change of Vout is the rate of change at V(sum), magnified by (R14 + R15)/R14: (R14 + R15)/R14 x dV+/dt = R11/(R11 + R12)x (R14 + R15)/(R14) x dVx/dt - Vε x (R14 + R15)/R14:

Since dVout/dt = 2 (π) fh x Vε, then Ve = dVx/dt x 1/(2 π fh) x R11/(R11 + R12) (R14 + R15)/R14 ,

and the momentary value of Vout = (R14 + R15) / R14 x Vε =

= -1/(2πfh) x dVx/dt x R11/(R11+R12) x$[(R14+R15)/R14]^2$.

When the momentary voltage at the applied voltage Vx is: Vx = 0 + dVx/dt,

the current i12 through R12 = 0. The current through R13 is: i13 = Vout/R13 = - 1/(2 π fh) x dVx/dt x R11/(R11 + R12) x $[(R14 + R15)/(R14)]^2$ x (1/R13).

This current acts as a capacitive current, as it is related only to dVx/dt. This current is equivalent to Cx x dVx/dt This virtual capacitance is: Cx = 1/(2 π fh) x (1/R13) x R11/(R11 + R12) x$[(R14 + R15)/R14]^2$.

For a 1 MHz op amp, in a typical application when R11 = 11k, and R12 = R14 = R15 = 10k, and R13 is relatively small compared to R12, such as R13 = R12/10 = 1k, this capacitance will be about 334 pF.

If R11 = 110k and R12 = R14 = R15 = 100k, and R13 = R12/10 = 10k, the Cx will be 34 pF. The capacitance depends inversely on the value of R13, and is also inversely proportional to the op amp's gain bandwidth product fh. It gets smaller as the amplifier is faster. This capacitance will also be inversely proportional to R13, so for 1 kilohm, it would be 334 pF. For 100 kilohms, it would be just 3.4 pF. This capacitance will also be modified by the ratio of (R15 + R14)/R14, if that ratio is not 2. The capacitance does not depend on R11, R12, R14, or R15, but only on their ratios. The apparent capacitance may be different if a large feedback capacitance is connected, across R15. A small feedback capacitance of 3 to 10 pF is normally a good idea, even if fast signals are not contemplated.

With modern fast op-amps, this capacitance may or may not be a significant factor, but it should be taken into account, depending on the application.

Appendix F Testing and Trimming of Z_{OUT}

Techniques for the testing of output impedance of a current pump are not well known, nor published, so they will be presented here for the first time. In concept, you could make dc measurements of output current at different levels of Vout, but that is not effective. Visual testing on an oscilloscope is better.

In concept, you can apply a sine wave through a transformer to the Vout node of a current pump. Read the current that flows out of the bottom of the transformer, at the input of an oscilloscope, which is very close to ground. See Figure 12. This does seem to work, but to be sure it is working well, you have to be sure that the transformer does not have any leakage or capacitive strays that can corrupt the reading. That is hard to prove, so it is not a recommended technique. A floating (battery-powered) sine or triangle-wave generator could be used, but that is not necessary.

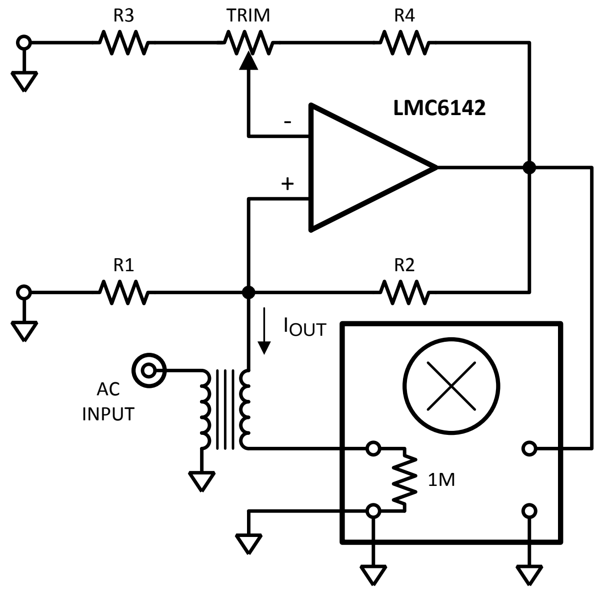


Figure 12. Transformer-Coupled Test for Z_{OUT}

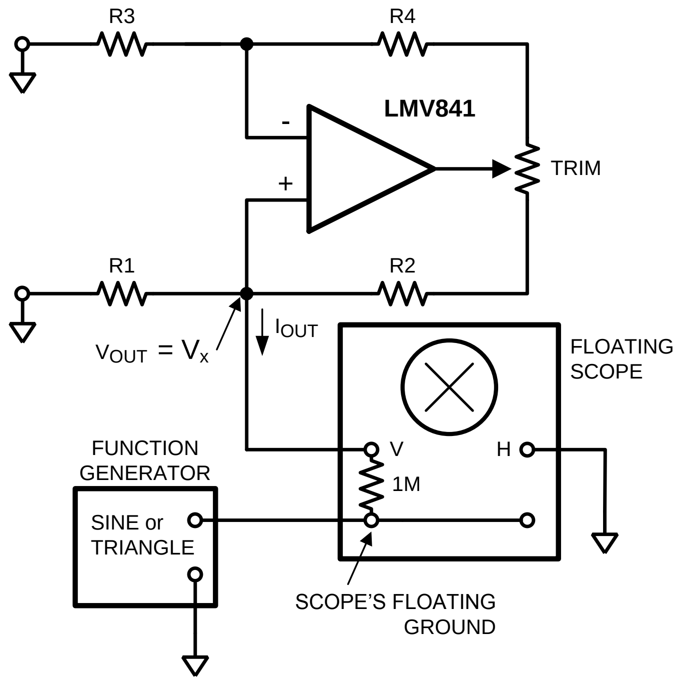


Figure 13. Good Test for Z_{OUT} Using Floating Scope

Refer to Figure 13. An ordinary sine or triangle wave function generator can be used to drive the Vout node. A floating scope is inserted between the function generator and the Vout. Any current flowing into or out of Vout, can be seen on the scope's vertical display. When this is cross-plotted against the main Vout, by connecting ground to the horizontal (X) input, it is easy to see the slope of Iout versus Vout. Then it is easy to adjust the trim pot as in Figure 2, Figure 3, or Figure 4, to trim for very high Zout. It is easy to get the curve just about flat, for the range of interest to you. Of course, if you want a very wide voltage range, you may find some curvature or nonlinearity. Most op-amps are not perfect for linearity of Common Mode Range, but some are better than others.

A scope with its 1 megohm of Zin can be used to easily resolve an output impedance better than 100 or 1000 megohms. If you have very low resistor values such as 1k or 100 ohms in your current pump, you can put a comparable low-value resistor across the scope's input. If you needed even higher resolution, a floating preamp could be added.

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