Application Report

Parallel Amplifiers for Higher Output Power: An Improved Howland Pump Approach

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ABSTRACT

A common problem facing circuit designers is that the amplifier they want to use does not have the current drive capability that their application requires, or that their heatsinking/cooling resources are insufficient to operate the amplifier in a sustained fashion with a high output current. Typical solutions are to either compromise and use a different amplifier, or to use multiple buffer amplifiers in parallel as load drivers. The latter approach sounds simple, but in practice tends to become complicated quite quickly.

However, there is another variation of the parallel buffer approach, one that many circuit designers may not be aware of. It involves using the driver amplifiers to regulate current rather than regulate voltage, by employing an improved Howland current pump approach. An error amplifier regulates the pump input voltage to achieve the desired output voltage. The current pumps can be paralleled to significantly increase the output current drive capability. Because they effectively regulate current instead of voltage, the parallel circuits' output currents are additive, which helps evenly distribute the load current between the channels. This topology is also effectively immune to trace resistance mismatches between channels, reducing the need for star routing and other matching approaches that can cause headaches during PCB layout. Note also that this approach could be extended to include as many driver channels in parallel as are desired or required, although this document will only address a two-channel condition for simplicity.

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1 Circuit Theory

1.1 Overview of Parallel Amplifier Approaches

When implementing a multiple-buffer arrangement, it is theoretically possible to use a very simple circuit where the desired input signal is applied to the noninverting input of each driving amplifier, with the feedback of both amplifiers taken at the load. However, this can lead to stability issues as the amplifiers' differing offsets cause them to fight over the proper load voltage, and can even force the amplifiers into current limit as they source/sink current between each other. Thus, to be practical the buffer approach usually requires the use of ballast resistors to isolate the amplifier outputs and feedback from each other, effectively limiting the output voltage swing when sourcing or sinking significant currents.

Additionally, high output currents will cause a voltage drop across the ballast resistance (as per Ohm's law), degrading the accuracy of the system. To fix this problem, an error amplifier (with its feedback taken at the load) is often used to drive the non-inverting inputs of the driving amplifiers instead. Input and feedback resistors will typically be required for impedance matching and input protection of the drivers, while feedback capacitances are often required (both for the driving amplifiers and for the error amplifier) to improve the circuit phase margin and make the circuit stable. Thus, in practice the conventional parallel buffer arrangement actually looks more like the circuit shown in Figure 1-1, where R_{traceX} is the parasitic resistance of the PCB or cabling.

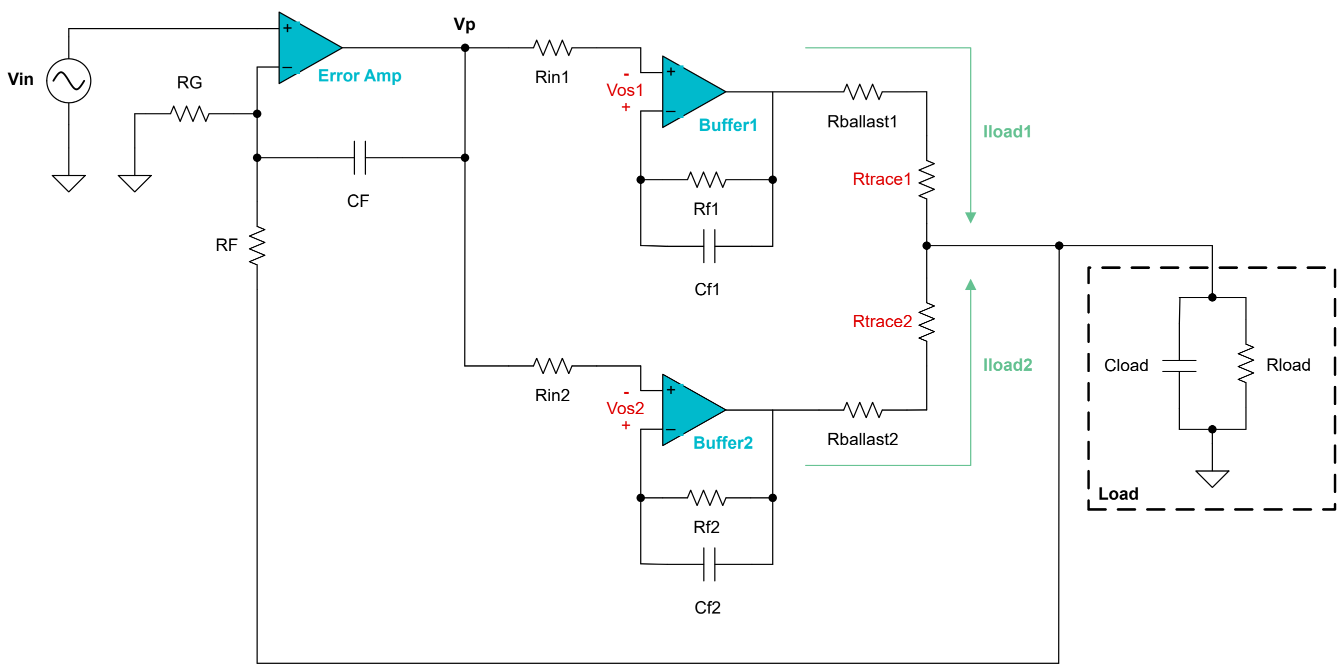

Figure 1-1. Conventional Buffer Circuit

By simply adding two additional resistors per channel to the circuit of Figure 1-1, it is possible to dramatically modify the mechanics of the circuit. Each driving amplifier will now be operated as an improved Howland current pump, regulating the voltage across (and thus the current through) the ballast resistance instead of simply regulating the voltage at one node of the ballast resistance. The resulting circuit is shown in Figure 1-2.

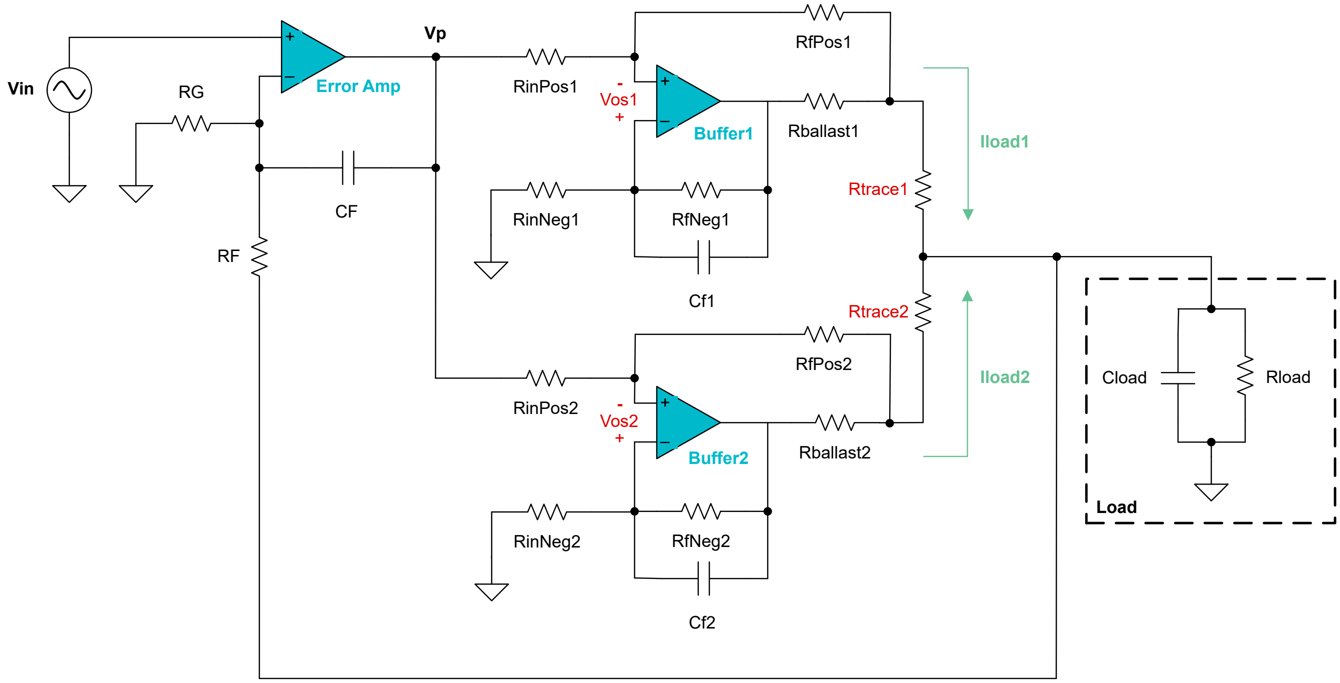

Figure 1-2. Parallel Improved Howland Pump Circuit

This approach makes the circuit practically immune to mismatches in the trace resistances of the two channels, at the expense of only two additional components. Typically, the pumps will be used in an attenuating gain configuration – this has the benefit of reducing the circuit's susceptibility to mismatches in the ballast resistors, as compared to the conventional buffer arrangement, as well as reducing the sensitivity of the circuit to offset mismatch. Limiting the driving amplifier bandwidth (often required for stability purposes) can confer additional benefits in the form of limiting the circuit's integrated noise.

1.2 Considerations

When deciding whether to employ a parallel improved Howland pump configuration versus a conventional parallel buffer configuration, there are many factors that must be considered. How well one arrangement works when compared to another is highly dependent on the amplifier used, and how it interacts with the circuit load. Which circuit approach is best for solving a given problem is thus dependent on the problem nuances and available components. It should be noted that to achieve the best resilience to offset and ballast resistor mismatch, the pumps must be operated in an attenuating gain, which means the error amplifier will need to have sufficient headroom for cases where the desired output current is very high.

The parallel improved Howland pump circuit is best suited for situations where the trace resistances of the channels are expected to be mismatched, such as when the channels are scattered around the board; cases where the offset of the amplifier to be used is fairly low; and cases where the required bandwidth is low, or the load is resistive rather than capacitive. For best results the driving amplifier selected should be well suited to driving high output currents and capacitive loads, such as the ALM2402-Q1, ALM2402F-Q1, or ALM2403-Q1. It is important that the gain setting resistors of the channels are well matched, and so the INA1620 is another excellent option for solutions requiring high integration, with its multiple on-chip precision matched resistors and 100mA drive capability.

While the parallel pump circuit does require more components than the conventional buffer circuit, its inherent immunity to trace mismatch means the circuit can be instantiated wherever there is space on the board – the channels do not need to be located directly next to each other or even on the same circuit board to share the load fairly evenly, and *all* of the driver channels can actually be located quite far from the load and still operate in an accurate fashion as long as the error amplifier takes its feedback from very close to the load.

1.3 Current Mismatch Equations

One of the main reasons to use this circuit is to balance the currents between multiple channels such that the output current, and resulting heat dissipation, is approximately the same for each channel. This prevents distortion issues that could otherwise occur as amplifiers dip in and out of current limit or even thermal shutdown from uneven load sharing. Therefore, it is worth exploring the current mismatch equations for each of the two approaches. Here, we will only be considering two channels at a time, and will disregard the losses through the feedback path as negligible. Consider the expression for the mismatch current for a conventional buffer circuit (the circuit shown in Figure 1-1).

$$I_{load1} - I_{load2} = \left(V_{load} - V_p\right)^*\left(\frac{1}{R_{ballast2} + R_{trace2}} - \frac{1}{R_{ballast1} + R_{trace1}}\right) + \frac{V_{os1}}{R_{ballast1} + R_{trace1}} - \frac{V_{os2}}{R_{ballast2} + R_{trace2}} \quad (1)$$

Note the expression is fairly straightforward, and exhibits a strong dependence on the proper matching of the trace and ballast resistances between the two channels. Compare this to the same expression for the parallel improved Howland pumps (the circuit shown in Figure 1-2). Let $M_x = R_{ballastx} + R_{tracex}$, $N_{Px} = \frac{R_{inPosx}}{R_{inPosx} + R_{fPosx}}$, $N_{Nx} = \frac{R_{inNegx}}{R_{inNegx} + R_{fNegx}}$, and $L_x = 1 - \frac{R_{tracex}{}^*N_{Px}}{M_x{}^*N_{Nx}}$, where “x” represents one of the two channels under consideration.

$$I_{load1} - I_{load2} = V_{load}{}^*\left[\frac{\frac{R_{ballast1}}{M_1{}^2}}{L_1} - \frac{\frac{R_{ballast2}}{M_2{}^2}}{L_2} + \frac{R_{ballast1}}{M_1{}^*R_{trace1}} - \frac{R_{ballast2}}{M_2{}^*R_{trace2}} + \frac{1}{R_{trace2}} - \frac{1}{R_{trace1}}\right] - V_p{}^*\left[\frac{\frac{N_{P1}-1}{N_{N1}{}^*M_1}}{L_1} - \frac{\frac{N_{P2}-1}{N_{N2}{}^*M_2}}{L_2}\right] + \left[\frac{\frac{V_{os1}}{N_{N1}{}^*M_1}}{L_1} - \frac{\frac{V_{os2}}{N_{N2}{}^*M_2}}{L_2}\right] \quad (2)$$

There are three main kinds of loss in the parallel pump circuit – the loss due to the offset mismatch, the losses related to the V_p term, and the losses related to the V_{load} term. As long as the gain of the inverting path is equivalent to that of the noninverting path for each amplifier channel (that is to say, $N_{Nx} = N_{PX}$), then the V_{load} term will not contribute any error. If the above condition is met and additionally, the gains of the two channels are matched ($N_{N1} = N_{P1} = N_{N2} = N_{P2}$), then the mismatch due to the V_p term will be dependent on how well matched the ballast resistances are ($R_{ballast1} = R_{ballast2}$ for zero loss).

When the gain of the inverting path is equivalent to that of the noninverting path for each amplifier channel (that is to say, $N_{Nx} = N_{PX}$), then the loss due to the offset becomes $\left[\frac{V_{os1}}{N_{N1}{}^*R_{ballast1}} - \frac{V_{os2}}{N_{N2}{}^*R_{ballast2}}\right]$.

Logically $N_{NX} * R_{ballastX} < R_{traceX} + R_{ballastX}$ (since $N_{NX} < 1$), and so the parallel improved Howland pump circuit will be more susceptible to mismatches caused by offset than the conventional buffer circuit. However, when the losses due to the V_{load} and V_p terms are considered, it becomes clear that in certain cases the parallel improved Howland pump approach will balance the currents better than the normal parallel buffer approach (so long as the gain setting components of each channel are properly matched). This is most prevalent in cases where the trace impedance is high and the ballast resistors are mismatched, or when the difference of the trace impedances of the two channels approaches or surpasses the size of the $R_{ballast}$.

Recall there is an underlying assumption that the $R_{ballast}$ resistance is small enough (relative to the R_{fPos} and R_{fNeg} resistors) that the loss through the feedback path may be neglected. This may be accomplished by using large resistors in the 10s of kΩ for the feedback path and/or using small ballast resistors.

1.4 Stability

One important nuance of the circuit that must be mentioned is its stability. The stability analysis of the parallel improved Howland pump circuit is complex due to the dual feedback paths of each channel, and there are several different ways to compensate the circuit. In some cases, the circuit can be difficult to stabilize for large capacitive loads unless large ballast resistors can be used. Depending on the load current, this may result in significant power dissipation across $R_{ballast}$, requiring sufficient supply headroom for the amplifier as well as the use of high-power resistors for $R_{ballast}$. A snubber circuit may be employed at the noninverting input of the amplifier to adjust the amplifier noise gain to give sufficient phase margin – typically, the driver phase margin should be at least 45 degrees to ensure stability regardless of process variation. While it is often necessary to limit the driving amplifiers' bandwidth with large feedback capacitances (C_{fx}) to achieve stability, this has the corresponding benefit of limiting the broadband or integrated noise of the circuit.

In many cases the error amplifier will have a much higher gain bandwidth than the driving amplifier, although this is not neccesarily a requirement. The phase of the error amplifier's loop gain must remain greater than 45 degrees until the loop gain of the driving amplifier has rolled off to 0dB, as well as having a phase margin of at least 45 degrees when its own loop gain rolls off to 0dB, for the circuit to be thoroughly and robustly stable. Likewise, in cases where the error amplifier has less gain bandwidth, the phase of the driver amplifier loop gain should remain at or above 45 degrees until the error amp loop gain has rolled off to 0dB in order for the circuit to be stable. Because the various compensation elements can interact with each other in complex ways, it is suggested that circuit designers thoroughly verify their circuit stability via simulation and bench testing before deploying this circuit in the field.

2 Qualitative and Empirical Comparisons

2.1 Overview Comparison

The summary in Table 2-1 is based on the results of multiple simulations where the ALM2403-Q1 was used for the buffer amplifiers and an OPA210 acted as the error amplifier. A complex load of 20Ω || 820pF was utilized. To compare the bandwidth, both circuits were constructed such that the trace resistances (10mΩ), ballast resistances (1Ω), and all other component values were matched between the two channels. A stability analysis was performed on each and the feedback capacitances were selected (using standard component values) for stability. The -3dB bandwidth of the circuits (measured for an AC input to the error amplifier) were then recorded. Note that the qualitative comparison below assumes the same $R_{ballast}$ value is used for each circuit.

Table 2-1. Qualitative Comparison of Circuit Approaches

Circuit	Conventional Buffers	Parallel Improved Howland Pumps
Component Count	Medium	Medium
Total Circuit Bandwidth	High	Low
Step Response Settling Time (small signal)	Low	High
Capactive Load Drive Capability (complex load)	Low	High
Offset Mismatch Error	Medium	High (best results when 1 > R_{fX}/R_{inX})
Ballast Mismatch Error	High	Medium (best results when 1 > R_{fX}/R_{inX})
Trace Mismatch Error	High	Very Low-Negligible
Resistor Matching Importance (non-ballast)	Very Low	High (best results when $R_{ballast}$ is large)

For this load example, the conventional buffer arrangement was found to result in approximately 21x higher -3dB bandwidth versus the parallel improved Howland pump arrangement (with gain R_{fX} / R_{inX} = 0.1), despite using the same C_F and C_{fx} values. Correspondingly, the settling time of the parallel improved Howland pump circuit for a 50mV input step was significantly longer.

However, it was noted during further tests that as the load capacitance increased tenfold to 8.2nF, the parallel improved Howland pump circuit remained stable without requiring any modifications, whereas the conventional buffer arrangement exhibited a ringing response and poor stability unless the ballast resistances were significantly increased to 10Ω. In fact, the same unaltered parallel improved Howland pump circuit was able to drive as much as 50nF of load capacitance and remain stable. This implies that under certain load conditions the parallel improved Howland pump circuit can actually prove more adaptable and resilient to capacitive loading effects than the conventional buffer. As stated earlier, however, this is highly dependent on the specific circumstances of the application and the amplifiers used.

2.2 Monte Carlo Comparison

Additional simulations in PSPICE for TI were performed to compare the two circuit configurations. The test conditions were Vin = 5V, C_{load} = 20pF and R_{load} = 20Ω for a total I_{load} of 250mA. A 0.1% tolerance, 1Ω ballast resistance was utilized on each channel. However, one of the two channels was configured to have an additional 80mΩ trace resistance to the load, consistent with a ~5800mil trace of 25mil wide, 1oz copper on an outer PCB layer (or ~3100mils on an internal layer), to represent the two channels being spaced apart on the board. The offset voltage of each channel's driving amplifier was modified to emulate a zero-mean, σ = 100uV case. Monte Carlo simulations (1000 runs) were performed using various component tolerances for the ballast resistors and gain-setting resistors, and the histograms of the current mismatch for the settled circuit were compared. The ideal mismatch value would be 0mA, meaning the load current would be evenly balanced with each driver amplifier sourcing 125mA.

As Figure 2-1 shows, it was found that while the current mismatch of the conventional buffer circuit was centered on about 9.32mA (σ = 0.43mA), the mean of the current mismatch for the parallel improved Howland pump circuit (with R_{fX} / R_{inX} = 0.1 V/V) was significantly closer to the desired value of 0mA.

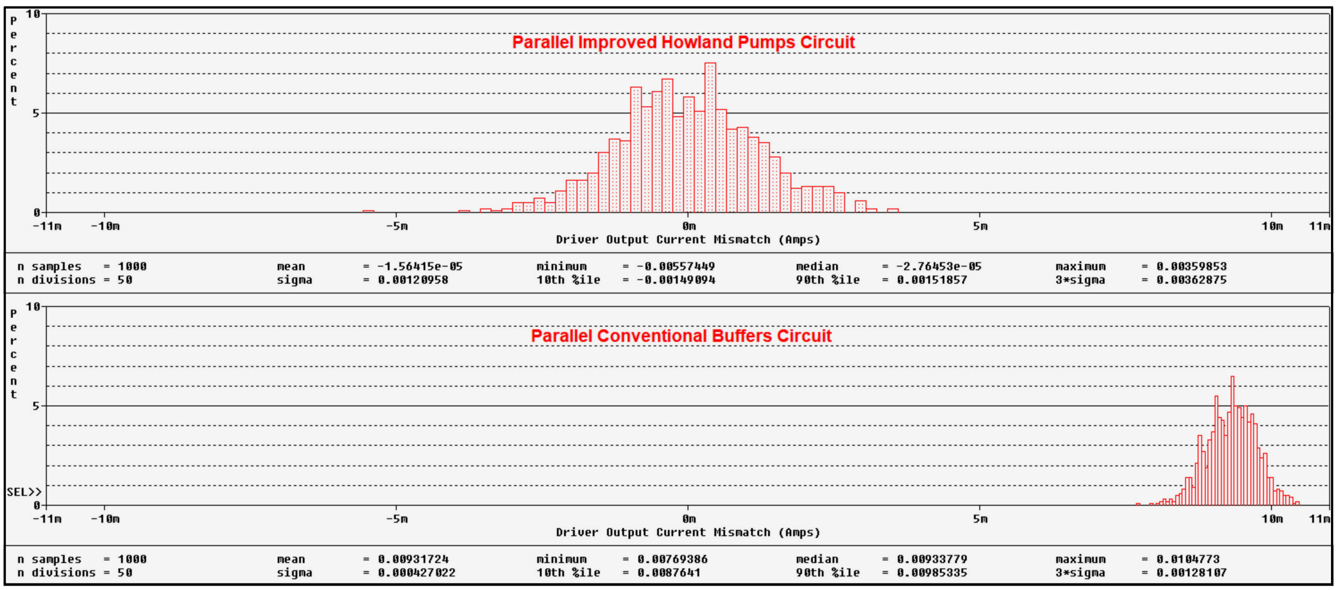

Figure 2-1. Comparison of Current Mismatch Histograms for Circuit Approaches

In the case where 0.1% tolerance resistors were utilized for the gain setting resistances of the parallel improved Howland pump circuit (as shown in Figure 2-1), the mean was -15.6μA with a standard deviation of 1.2mA, compared to a mean of 75.6μA and standard deviation of 11.1mA when 1% tolerance resistors were used for R_{inX} and R_{fX}. This highlights the importance of utilizing high-quality resistors for these components when building a parallel improved Howland pump circuit, to better control the distribution of the current mismatch. The overall results support the conclusion that the parallel improved Howland pump circuit is significantly more immune to trace mismatch, and that provided well-matched components are used and the pumps are in attenuating gain, this approach can in many cases result in superior circuit performance when compared to the conventional buffer arrangement.

3 References

- Texas Instruments, Analysis of Improved Howland Current Pump Configurations application report.
- Texas Instruments, A Comprehensive Study of the Howland Current Pump application report.