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Mailing Address: PO Box 11400, Tucson, AZ 85734 • Street Address: 6730 S. Tucson Blvd., Tucson, AZ 85706 • Tel: (520) 746-1111
Telex: 066-6491 • FAX (520) 889-1510 • Product Info: (800) 548-6132 • Internet: www.burr-brown.com/ • FAXLine: (800) 548-6133

TUNING IN AMPLIFIERS

By Bonnie Baker

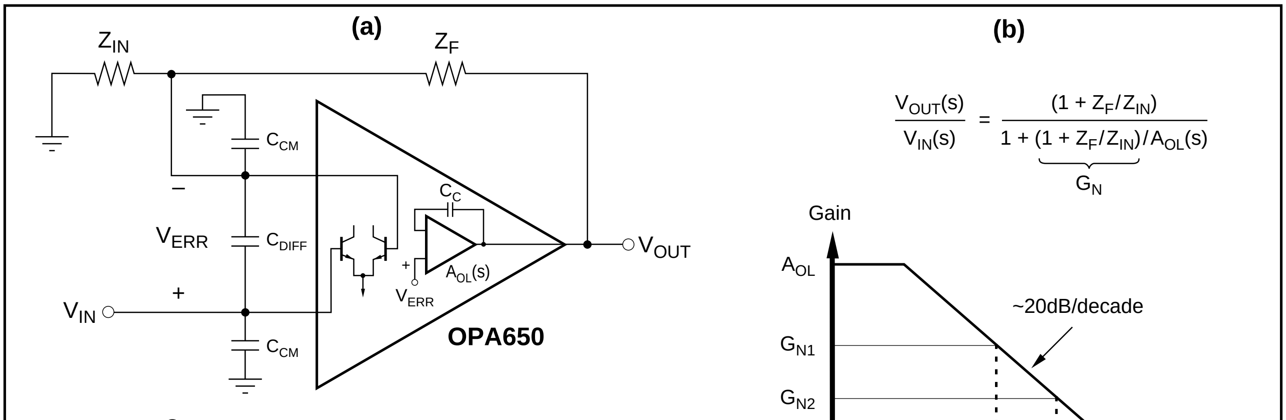
Have you ever had the experience of designing an analog gain block with an amplifier that is specified to be unity gain stable only to find that it is oscillating out of control in your circuit? Or have you ever replaced a stable voltage feedback amplifier with a current feedback amplifier to find that the current feedback amplifier immediately oscillates when placed in the amplifier socket? Oscillation problems are a nuisance to track down, particularly if there is no clear game plan. When troubleshooting an oscillating amplifier circuit, several questions come to mind, such as, has the feedback loop been properly configured to insure stability? Have the effects of loading the output of the amplifier been considered? Are the by-pass capacitors properly positioned on the board in respect to the amplifier? Is the PCB layout executed properly to avoid the ill effects of trace parasitics and cross-talk? This simple check-list with some general knowledge about what determines amplifier stability, or lack thereof, can help the designer identify oscillation problems and implement effective, stable solutions.

DESIGNING AROUND THE AMPLIFIER

When beginning the troubleshooting process, the first step the designer should take determines whether or not the resistors, capacitors and inductors that are used around the amplifier's input, feedback and output are appropriately applied. The selection of these components is dependent on first and foremost the type of amplifier that is being used, i.e., voltage feedback as opposed to current feedback amplifier. Once the amplifier type is known the stability equations quickly fall out of simple calculations. Take, as an example, an amplifier configured in a non-inverting circuit as shown in Figure 1a. The amplifier is configured in a non-inverting circuit where the low frequency gain is $(1 + R_F/R_{IN})$. Here, R_F and R_{IN} are the low frequency equivalent impedance of Z_F and Z_{IN}. In the case of Figure 1a, a voltage feedback amplifier is used in the circuit. A current feedback amplifier could be used instead while still achieving good circuit stability.

VOLTAGE FEEDBACK AMPLIFIER ANALYSIS

The voltage feedback amplifier is the most prolific amplifier on the market. Dependent on the characteristics of the specific amplifier, they are used in high speed as well as precision applications. Since the preferred frame of reference for most analog designers is the voltage feedback amplifier, the stability analysis begins with the topology shown in Figure 1a. This simplified block diagram illustrates many of the key characteristics needed in a frequency analysis of the voltage feedback amplifier. Starting with the input segment of the amplifier, the inputs to the voltage



$$A_{OL}(s) = \frac{G_{DC}}{1 + r_O C_C s}, \quad s = jw$$

$$V_{OUT} = A_{OL}(s) \cdot V_{ERR}$$

$$\frac{V_{IN} - V_{ERR}}{Z_{IN}} = \frac{V_{OUT} - (V_{IN} - V_{ERR})}{Z_F}$$

$$\frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{(1 + Z_F/Z_{IN})}{1 + \underbrace{(1 + Z_F/Z_{IN})}_{G_N}/A_{OL}(s)}$$

FIGURE 1a). The Model of a Voltage Feedback Amplifier Configured in a Non-Inverting Closed-Loop Configuration. 1b). Bode Plot Response of Various Closed-Loop Non-Inverting Systems Using a Voltage Feedback Amplifier.

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feedback amplifier are evenly matched. The input transistors of this amplifier type could be bipolar (NPN or PNP), FET, or CMOS, with the input differential capacitance and common-mode capacitance modeled as C_{DIFF} and C_{CM}, respectively. In most cases, the input bias currents are very close to being the same magnitude and the difference between the two input bias currents is usually small. Additionally, the input impedances of the amplifier are close to equal and relatively high. Input bias current can range from femto amps, as in the case of the OPA129, to 100s of micro amps, depending on the input transistors.

A small error voltage at the input of the amplifier is gained by the open-loop gain, $A_{OL}(s)$, which is usually fairly high. The open-loop gain is frequency dependent and starts rolling off at a relatively low frequency. The resulting open-loop voltage output is the product of the open-loop gain times the input voltage error.

The voltage feedback amplifier can be analyzed across the frequency spectrum in this non-inverting circuit. By using the simple model shown in Figure 1, a second equation is quickly derived from a nodal analysis. These calculations assume there are no contributions to the frequency behavior of the circuit from the input bias currents of the amplifier. This is a good assumption for this small signal analysis in the amplifier's linear region.

The open-loop gain of the amplifier is modeled as a single pole system, although there are typically multiple poles and zeros at the higher frequencies. The single pole in the $A_{OL}(s)$ equation represents the dominant pole. This formula is not an accurate representation of the open-loop gain over the entire frequency spectrum. Poles can be added to this transfer function with a capacitive or inductive load interacting with the output resistance of the amplifier. In this example, a single pole system is used to simplify the derivation. The DC open-loop gain is symbolized with the variable, G_{DC}. The element, r_O represents the effective impedance of the open-loop gain equation. C_C and r_O are used to set the frequency of the dominant pole.

Rigorous calculation of the transfer function reveals characteristics and limitations of the voltage feedback amplifier in this closed-loop system.

As expected, the calculation in Figure 1b proves that the closed-loop DC gain is equal to $1 + R_F/R_{IN}$. At low frequencies the open-loop gain of the amplifier is sufficiently high to allow for ignoring the gain error. As frequency increases, $A_{OL}(s)$ begins to decrease and finally becomes the dominant controlling factor in the gain of the circuit. The calculation of the intersection of the open-loop gain, $A_{OL}(s)$ and the noise gain (also called $1/\beta$), $G_N = (1 + Z_F/Z_{IN})$, gives a close approximation to the bandwidth of the closed-loop amplifier circuit. In the case of the OPA650 wideband, voltage feedback amplifier, the extrapolated zero crossing of the open-loop gain is typically 180MHz and the DC open-loop gain is typically 50dB. If Z_F and Z_{IN} are both equivalent to 402Ω, the signal bandwidth of the circuit would be a theoretical 90MHz.

Gain peaking, which is caused by the phase response of the amplifier and the feedback circuit, can increase the bandwidth of the closed-loop system at the expense of decreased stability. The criteria for stability is determined where the closed-loop noise gain intersects the open-loop gain of the amplifier. Generally, if the phase margin, at that frequency, is smaller than a theoretical 45 degrees, the circuit can oscillate given part-to-part variation. A conservative phase margin is more like 60 degrees for flat frequency response.

The transfer function of the voltage feedback amplifier in a non-inverting configuration is shown graphically in Figure 1b. The open-loop gain plot of the amplifier assumes a single pole system. Although this is not totally realistic, the generalization of closed-loop gain versus closed-loop bandwidth shown here is still true. As the closed-loop gain increases, the closed-loop bandwidth decreases. The circuit designer needs to take this characteristic under consideration when selecting the right amplifier for his application.

Matched inputs may or may not be a benefit when using voltage feedback amplifiers. The high impedance can be a saving grace at times when line termination is otherwise difficult. In addition, offset voltages and offset currents are relatively low compared to the current feedback amplifier topology. A possible disadvantage of the voltage feedback amplifier is the intimate relationship between the bandwidth and closed-loop gain.

CURRENT FEEDBACK AMPLIFIER ANALYSIS

The current feedback amplifier's block diagram in Figure 2a illustrates how this amplifier differs from the voltage feedback amplifier. The inputs to the current feedback amplifier are not matched, consequently the input bias currents are different along with the input impedances. Typically, the current feedback amplifier's input bias current is in the micro ampere region. The ratio between the input bias currents is dependent on the current feedback input stage topology and can vary from ±2X to 5X. In the case of the OPA658, the inverting input bias current is ±35mA(max) and the non-inverting input bias current is ±30mA(max). The inverting input generally has a higher input bias current magnitude and very low input resistance (ideally zero) as compared to the non-inverting input. On the other hand, the non-inverting input is buffered, having a high impedance. The buffer's gain is approximately +1V/V and its bandwidth is significantly wider than the bandwidth of the remaining internal stages of the amplifier.

A small error current from the inverting input of the current feedback amplifier is gained by the open-loop transimpedance of the amplifier, Z(s), which is usually fairly high. The resulting open-loop output voltage of the current feedback amplifier is the product of the open-loop transimpedance (Z(s)) times the input current error (I_{ERR}).

The current feedback amplifier can also be used in the non-inverting circuit. By using the simple model shown in Figure 2, a nodal analysis reveals a second equation. This calculation assumes there are no contributions to the fre-

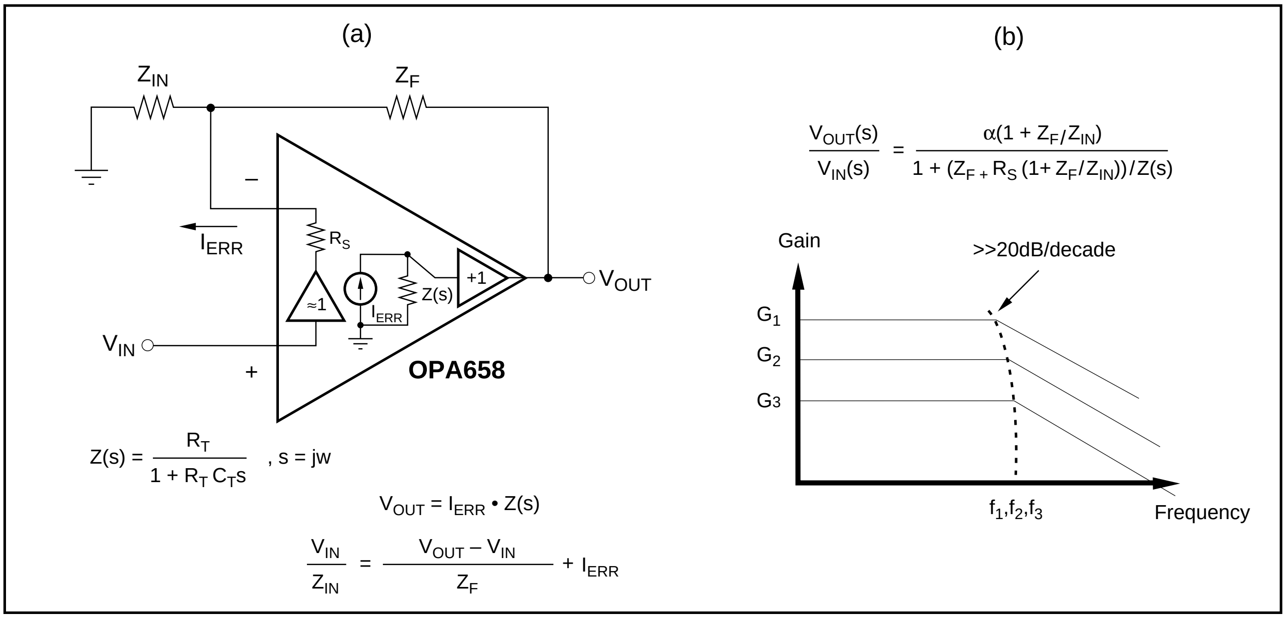

FIGURE 2a). The Model of a Current Feedback Amplifier Configured in a Non-Inverting Closed-Loop Configuration. 2b). Bode Plot Response of Various Closed-Loop Non-Inverting Systems Using a Current Feedback Amplifier.

quency behavior of the circuit from the input offset voltage or buffer stage of the amplifier. Since this analysis assumes the amplifier is operating in its linear region and this is a small signal analysis, these are good assumptions.

The open-loop transimpedance of the amplifier is modeled as a single pole system. The single pole in the equation on the slide represents the dominant pole. This formula is not an accurate representation of the open-loop transimpedance over the entire frequency spectrum, however, it is adequate for purposes of this discussion. The DC open-loop transimpedance is symbolized with the variable, R_T where C_T and R_T are used to derive the dominant pole for the open-loop transimpedance gain.

Rigorous calculation of the transfer function reveals characteristics and limitations of the current feedback amplifier in this closed-loop system.

The DC gain of this circuit is the same regardless of whether a current feedback or voltage feedback amplifier is used. The bandwidth for the closed-loop response, when a current feedback amplifier is used, is dependent principally on the feedback resistor, Z_F, in conjunction with the transimpedance of the amplifier. The resistor, Z_{IN} , has minimal effect on the bandwidth. This fundamental difference in the closed-loop response between the two amplifier topologies allows for each to have an advantage or disadvantage, as the case may be, dependent on the circuit topology selected.

The transfer function of the closed-loop system shown in Figure 2 is:

$$\frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{\alpha(1 + Z_F / Z_{IN})}{1 + (Z_F + R_S(1 + Z_F / Z_{IN})) / Z(s)}$$

where α represents the gain of the input buffer, which is typically +0.996V/V as opposed to +1V/V. R_S represents the non-zero output impedance of the input buffer, which ranges from 10 to 40Ω depending on the particular amplifier used.

From this formula, it is easy to see the limitations on the current feedback amplifier's frequency response performance. Because of the effects of R_S, the closed-loop bandwidth does vary slightly with changes in Z_{IN}, however, the bandwidth and stability is more dependent on the feedback impedance, Z_F, particularly with lower closed-loop gains.

The current feedback amplifier is easier to design with than the voltage feedback amplifier as long as the correct feedback impedance is selected. The bandwidth and stability of the current feedback amplifier in a closed-loop configuration is dependent and adjustable with the feedback element. If the wrong feedback impedance is used, the amplifier circuit could oscillate.

BY-PASS, BY-PASS, BY-PASS (Effectively)

By-pass capacitors are an absolute necessity in analog circuits. The selection of the proper capacitors and placement could be as critical as insuring that the amplifier circuit is designed for stability. Capacitors that are used to by-pass power supplies must satisfy two important criteria: 1) filter out high frequency noise from the power supplies, 2) serve as a charge reservoir to deliver high frequency load current. These two tasks can only be accomplished by using two capacitors as opposed to one.

The first capacitor type mentioned above should be selected to filter out higher frequency noise from the power supply at the frequencies where the analog amplifier's power supply rejection is not good enough and the amplifier still has ample open-loop gain. Appropriate values for this function is dependent on the amplifier and typically range from 0.01μF up to 1μF. A good by-pass value for the OPA130, which is a unity gain stable, 1MHz bandwidth device, would be 0.1μF. Ceramic capacitors most appropriately serve this need as long as they are positioned *as close to the amplifier as possible*.

The second capacitor used in the circuit can provide a reservoir of charge for more than one amplifier in the circuit and can be positioned a few inches away from the amplifier on the board. Tantalum capacitors are a good choice for this function and typical values range from 1μF to 10μF depending on the circuit requirements.

LAYOUT DESIGNED FOR SUCCESS

Layout can make or break a circuit just as much as poor design or improper by-passing techniques. Some basic guidelines for analog amplifier for layout are as follows:

1. Use a heavy copper ground plane on the component side of the PC board to provide low inductance ground.
2. By-pass power supply pins directly at the active device. Supply pins should not be left un-by-passed.
3. Signal paths should be short and direct. Passive components should have short lead lengths.
4. Parasitic inductance and capacitance should be avoided particularly in high frequency circuits.
5. Capacitive loads can causes loop instability if not compensated for.
6. Terminate transmission loads in high speed circuits. Unterminated lines can appear to the amplifier as a capacitive or inductive load. By terminating a transmission line the characteristic impedance will appear as purely resistive.
7. Plug-in prototype boards and wire-wrap boards become less and less satisfactory as the signal frequencies increase. Use these breadboards with caution.

Analog circuit oscillation problems can be overcome with careful thought up front in the design process. Oscillation problems are difficult to solve, particularly if there is no clear troubleshooting guide. In order to reduce the chances of oscillations from the beginning, the checklist should include design stability techniques, proper by-passing and appropriate board layout methods. This simple checklist with some general knowledge about what determines amplifier stability, or lack thereof, can help the designer identify oscillation problems and implement a stable amplifier circuit.

References

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