Capacitive Load Compensation of Voltage Followers using the ISL7xx44 Amplifiers

Introduction

The voltage follower is the most demanding configuration for an operational amplifier as the device operates at its phase margin. Loading the follower output capacitively reduces this phase margin, which can lead to instability. This manifests itself in output signal overshoot, ringing, and at worst in self-sustaining oscillations.

To help engineers design stable buffer amplifiers despite capacitive loading, this application note describes the two most popular phase compensation techniques, which are passive and active cap-load compensation.

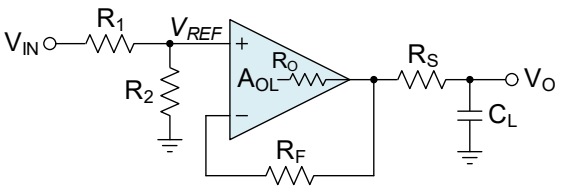
The ISL7xx44 family of wideband amplifiers includes the ISL70244SEH, ISL73244SEH, ISL70444SEH, ISL73444SEH, and ISL71444M devices.

Contents

1. Design Equations

This section provides a summary of the design equations for both compensation techniques. Both circuits use a series resistor R_S that isolates the load capacitance C_L from the op-amp output.

The simpler and more widespread *passive* cap-load compensation (Figure 1) applies direct feedback from output to inverting input and relies on R_S to provide the necessary phase compensation. Its main disadvantage is the loss of DC accuracy at the circuit output due to the voltage drop across R_S.

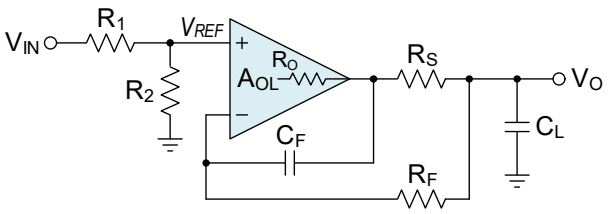


$$R_F = \frac{1}{1/R_1 + 1/R_2}$$

$$R_S = \frac{1 + \sqrt{1 + 0.8\pi C_L \times GBW \times R_O}}{0.4\pi C_L \times GBW}$$

Figure 1. Passive Cap-Load Compensation with R_S and Single Feedback Path

The more complex active cap-load compensation (Figure 2) uses two feedback loops around R_S. The feedback path using R_F restores DC accuracy at the output while the feedback through C_F maintains stability at high frequencies.



$$R_S = \frac{1 + \sqrt{1 + 0.8\pi C_L \times GBW \times R_O}}{0.4\pi C_L \times GBW}$$

$$R_F = \frac{1}{1/R_1 + 1/R_2} \geq 100R_S$$

$$C_F = C_L \times \frac{10R_S}{R_F}$$

Figure 2. Active Cap-Load Compensation with R_S and Dual Feedback

Table 1 lists the key parameters to use in the design equations for the ISL7xx44 op-amp family of wideband amplifiers recommended for this application.

Table 1. ISL70244 Parameters

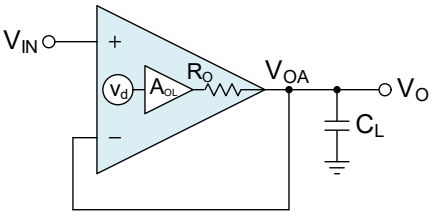
Parameter	Symbol	Value			Unit
Supply Voltage Range	V_S	±18	±5	±1.5	V
Minimum Gain Bandwidth	GBW	17	15	10	MHz
Open-Loop Output Impedance	R_O	100			Ω

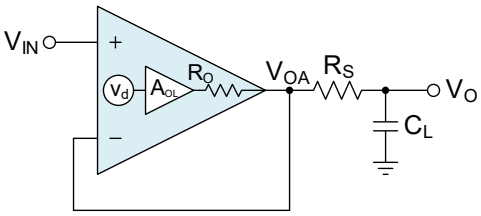
2. Stability Analysis using Rate-of-Closure

Stability analysis uses the rate-of-closure (ROC) between the circuit's open-loop gain A and the noise-gain 1/β (reciprocal of the feedback factor β) as criteria to determine whether a circuit is stable (ROC = 20dB/dec) or instable (ROC = 40dB/dec).

3. Passive Cap-Load Compensation

In the unloaded case, the op-amp's A_{OL} crosses the 1/β line at an ROC of 20dB/decade, meaning the circuit is stable. In the loaded case, the load capacitance (C_L) forms a low-pass filter with the op-amp output impedance (R_O). This adds phase lag to A_{OL}, resulting in the loaded, uncompensated open-loop gain response, A_{LU}. A_{LU} has a roll-off of 40dB/decade, starting at the pole frequency $f_{pu} = 1/(2\pi R_O C_L)$. It crosses 1/β at an ROC of 40dB/dec, indicating instability.





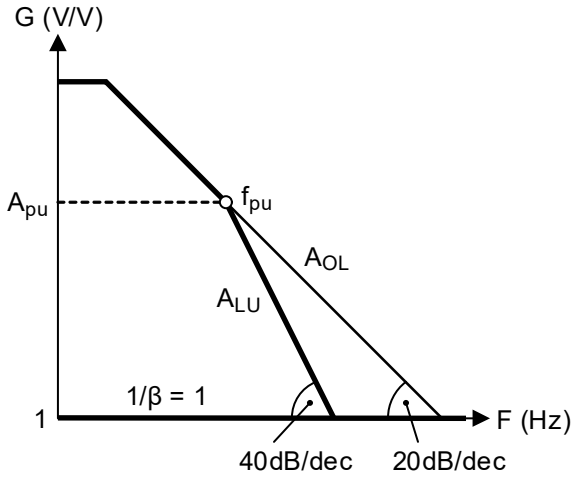


Figure 3. Loading Op-amp with C_L makes ROC = 40dB/dec and the Circuit unstable

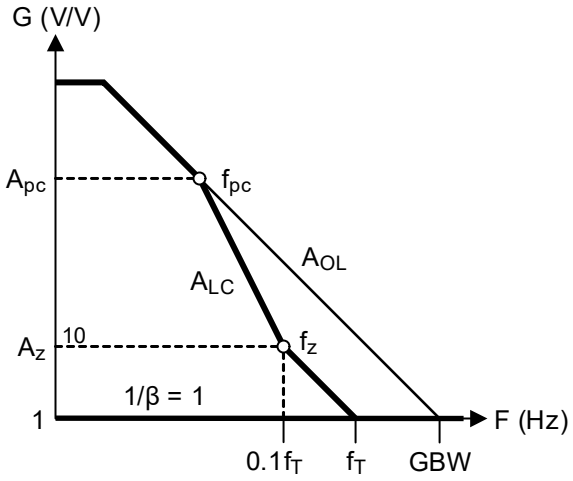


Figure 4. Inserting R_S reduces ROC to 20dB/dec and restores Stability

To restore circuit stability, place a series resistor, R_S, between C_L and the op-amp output (Figure 4). R_S and C_L introduce a phase-lead at the zero frequency $f_z = 1/(2\pi R_S C_L)$ that neutralizes the phase lag from R_O and C_L, resulting in the loaded but compensated open-loop gain, A_{LC} (Figure 4). As A_{LC} crosses the 1/β line at an ROC of 20dB/decade, circuit stability has been restored.

Note: The use of R_S also reduces the pole frequency from $f_{pu} = 1/(2\pi R_O C_L)$ to $f_{pc} = 1/[2\pi(R_O+R_S)C_L]$.

3.1 Determining the Value of R_S

To find an equation for calculating R_S the location of f_Z must be derived by completing the following steps.

1. Set the gain at f_Z to $A_Z = 10$. This places f_Z one decade below f_T, allowing the phase lead to fully develop and A_{LC} to achieve maximum phase margin.
2. Along the 40dB/dec slope, the ratio of pole-gain to zero-gain is:

(EQ. 1) $$\frac{A_{pc}}{A_z} = \frac{f_z^2}{f_{pc}^2}$$

3. As f_{pc} lies on the op-amp's open-loop gain slope of constant gain-bandwidth, the pole-gain is:

$$A_{pc} = GBW/f_{pc}$$

4. Then, substituting all variables in Equation 1 with their pre-established values and time constants:

$$\frac{GBW/f_{pc}}{10} = \frac{1/(2\pi R_S C_L)^2}{1/[2\pi(R_O + R_S)C_L]^2}$$

5. Solve for R_S and receive a quadratic equation, whose solution is:

(EQ. 2)
$$R_S \geq \frac{1 + \sqrt{1 + 0.8\pi C_L \times GBW \times R_O}}{0.4\pi C_L \times GBW}$$

4. Active Cap-Load Compensation

This compensation circuit adds dual feedback around R_S. The feedback path using R_F restores the DC accuracy that would be lost because of the voltage drop across R_S. The feedback path using C_F provides access to the op-amp output at high frequencies to act like passive cap-load compensation (Figure 5).

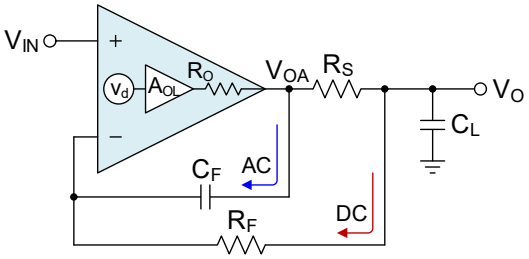
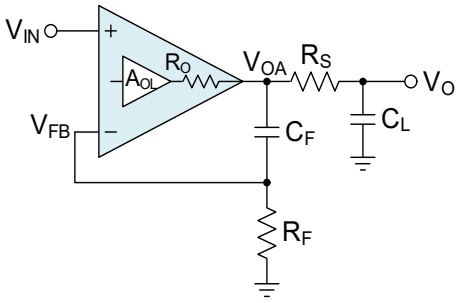


Figure 5. Phase Compensation with Dual Feedback Restores DC-Accuracy and Circuit Stability

Therefore, C_F and R_F operate as a frequency-dependent switch or high-pass that gradually directs feedback from the circuit output V_O to the op-amp output V_{OA}. As stability analysis focuses on A_{LC} phase margin at f_T, C_L presents a short, allowing R_F to be grounded (Figure 6).



$$A_{LC} = A_{OL} \times \frac{1 + j\omega R_S C_L}{1 + j\omega(R_O + R_S)C_L} \Rightarrow f_{z(A_{LC})} = \frac{1}{2\pi R_S C_L}$$

$$\frac{1}{\beta} = \frac{1 + j\omega R_F C_F}{j\omega R_F C_F} \Rightarrow f_{z(1/\beta)} = \frac{1}{2\pi R_F C_F}$$

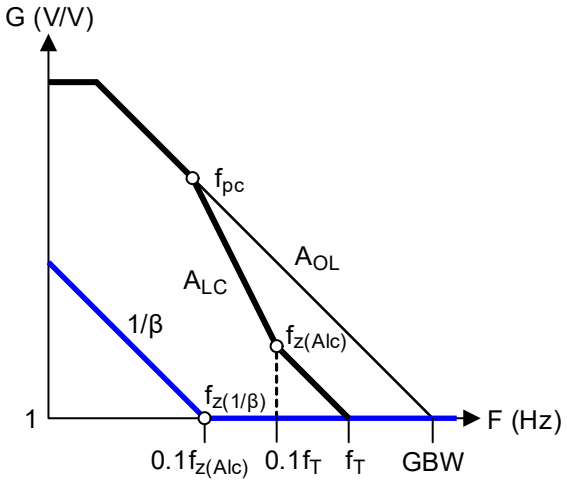


Figure 6. Making $R_F \cdot C_F = 10 \cdot R_S \cdot C_L$ ensures Circuit Stability

As previously mentioned, the open-loop gain response A_{LC} is the same as for passive compensation:

$$A_{LC} = A_{OL} \times \frac{1 + j\omega R_S C_L}{1 + j\omega(R_O + R_S)C_L} \text{ with a zero frequency at } f_{z(A_{LC})} = \frac{1}{2\pi R_S C_L}$$

Deriving the noise gain or 1/β response yields:

$$\frac{1}{\beta} = \frac{1 + j\omega R_F C_F}{j\omega R_F C_F} \text{ with a zero frequency at } f_{z(1/\beta)} = \frac{1}{2\pi R_F C_F}$$

For maximum phase margin of A_{LC} at f_T, the phase lead due to C_F-R_F must be fully developed at $f_{z(A_{LC})}$, which requires that $f_{z(1/\beta)} = 0.1 f_{z(A_{LC})}$. Expressing this relation in terms of time constants gives:

(EQ. 3) $$R_F C_F = 10 \times R_S C_L$$

4.1 Calculating Component Values

To design a stable active cap-load compensation, complete the following steps.

1. Calculate RS the same way as for passive compensation, using Equation 2:

$$R_S \geq \frac{1 + \sqrt{1 + 0.8\pi C_L \times GBW \times R_O}}{0.4\pi C_L \times GBW}$$

2. To minimize the loading effects of the feedback path, make

$$R_F \geq 100 R_S$$

3. Solving Equation 3 for C_F, calculate:

$$C_F = C_L \times \frac{10 R_S}{R_F}$$

5. Conclusion

Both passive and active cap-load compensation circuits have the same -3dB signal bandwidth.

Passive cap-load compensation is simple in both design and implementation. It can achieve fast settling times while minimizing overshoot and generally remains stable with reasonable variation in the transient response over a wide range of capacitive loads.

Its main disadvantage is that the voltage drop across R_S is dependent on the output current, which can make this compensation impractical for precision applications.

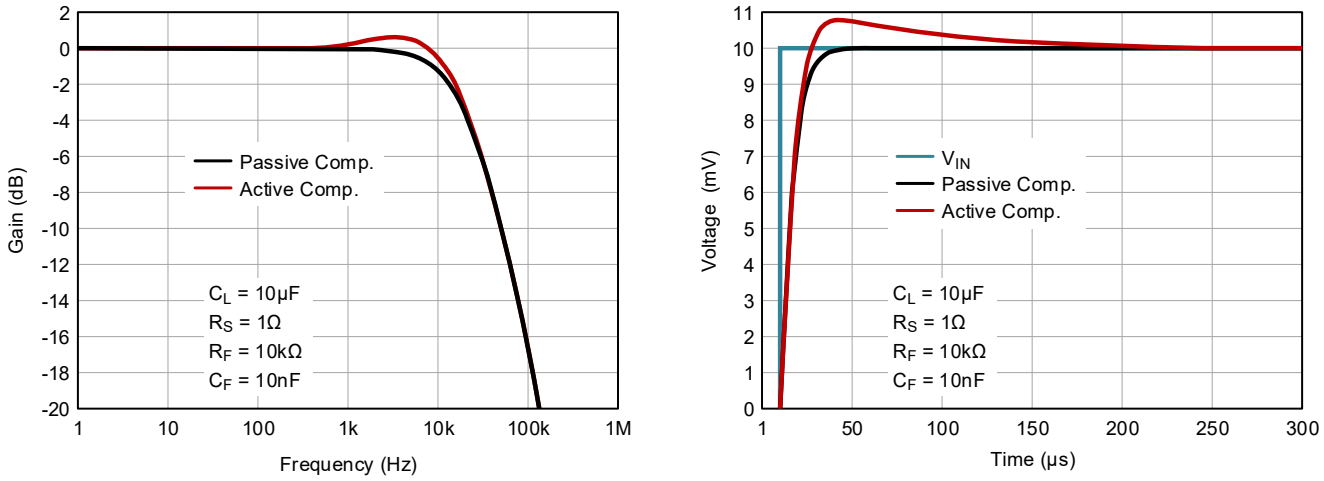


Figure 7. Bandwidth and Overshoot Comparison

Active cap-load compensation solves the DC accuracy issue of passive compensation. However, its dual feedback must be aligned with the capacitive load and isolation resistor. This makes it less tolerant to changes in the output capacitance, allowing it to quickly become unstable. Thus, active cap-load compensation is best applied in situations where the output capacitance is known and does not vary significantly.

Also, this compensation technique has longer settling times and higher overshoot than passive compensation. While smaller C_F values reduce settling time, they usually produce higher overshoot.

6. Revision History

Revision	Date	Description
1.00	May 19, 2025	Initial release.

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Corporate Headquarters

TOYOSU FORESIA, 3-2-24 Toyosu,
Koto-ku, Tokyo 135-0061, Japan
www.renesas.com

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