Application Report
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Extending Op Amp Bandwidth using Active Feedback Phase Correction

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ABSTRACT

In image processing and SONAR applications, the phase relation between the input and output is very important to extract the information contained within. These systems require flat-phase response in their amplifier circuitry to minimize the measurement errors. Most of these errors can be reduced by using an expensive wide-bandwidth amplifier.

Also, the high frequency effects of the op amps become evident when we approach the –3 dB point of the amplifier, which will limit the usable bandwidth of the amplifier to 1/10th of the actual bandwidth (with reasonable phase accuracy). Much of this phase error can be reduced by using passive compensation techniques, which is inexpensive, but the component variation with respect to temperature and tolerance makes this choice less acceptable for precision signal processing application. This application note describes an active feedback compensation scheme to reduce the phase error and extend the amplifiers usable bandwidth.

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1 Passive Compensation Scheme

One way to implement the compensation using a passive feedback mechanism is depicted in Figure 1.

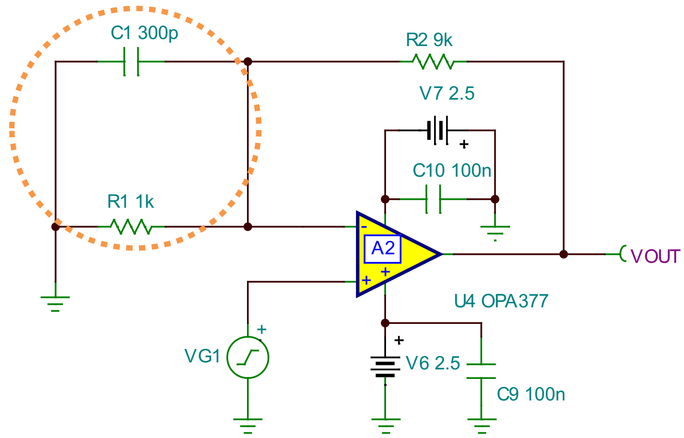


Figure 1. Phase Compensation Using RC Circuit

This RC circuit creates a zero in the feedback path of the op amp, which effectively cancels out the amplifiers pole. The gain of the circuit is 10. From this, we achieve frequency compensation, which in turn, improves the phase accuracy of the circuit. The disadvantage of this method is that it requires extensive tuning of the RC zero to match the amplifiers pole. Also, a capacitor right in front of the inverting input of the op amp can cause stability issues. Apart from this, the temperature variations and component tolerance causes the RC zero to drift reducing the efficiency of this method.

Figure 2 shows the amplitude and phase response of the passive RC method.

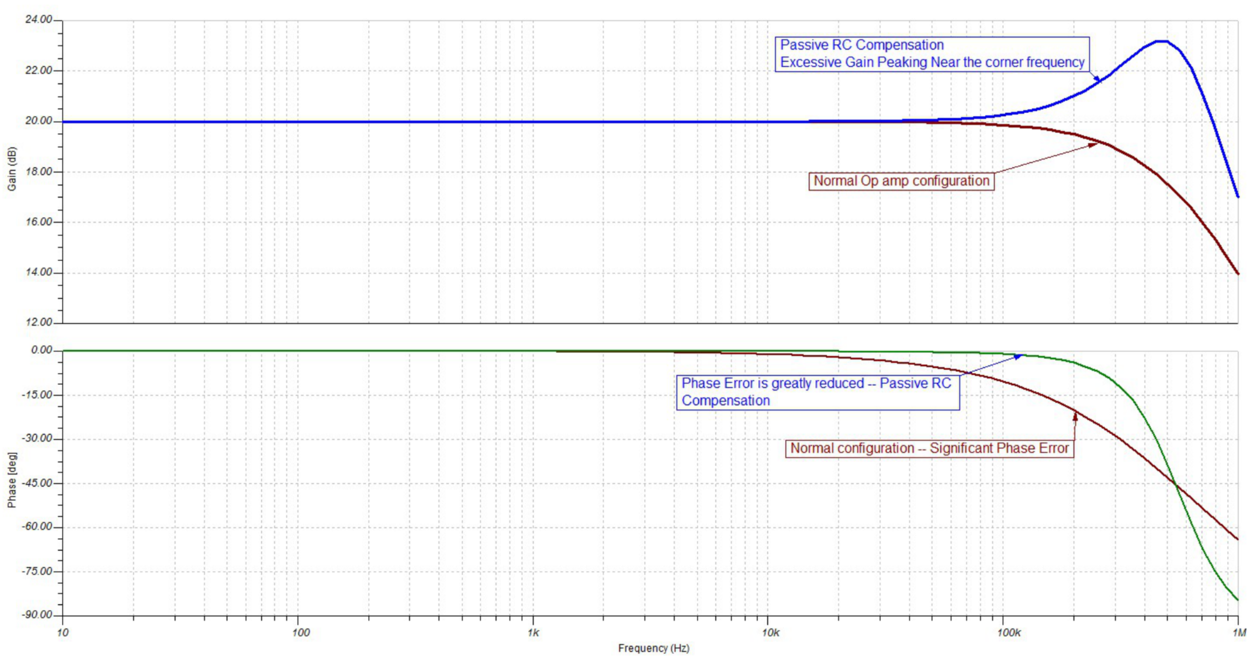


Figure 2. Amplitude and Phase Response of the Passive RC Method

2 Active Compensation

By placing an op amp in the feedback loop of the amplifiers, we can overcome the pitfalls of the RC circuit design. The main criteria for this to work effectively is the feedback op amp should be matched with the forward amplifier. A monolithic dual op amp package is a good choice for this application.

Figure 3 shows the feedback compensation scheme with the op amp in the feedback path.

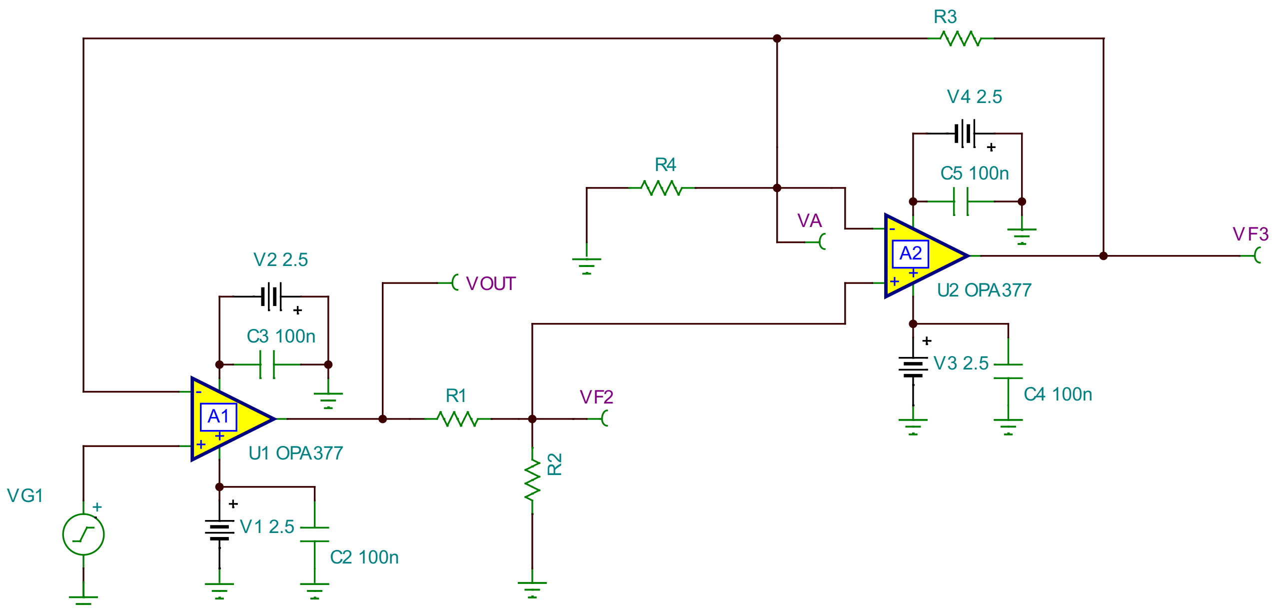


Figure 3. Active Feedback Compensation Scheme

The forward op amp's A1 gain is characterized with the equation G = 1 + R1 / R2 and VF1, the output of the amplifier. Op amp A2 is in the feedback path of A1, whose gain is characterized by 1 + R3 / R4. The ratio of the R3 and R4 resistors and the R1 and R2 resistors determines the amount of phase error cancellation achieved using this method. Ideally, for better phase error correction we have to make R3 = R1 and R2 = R4.

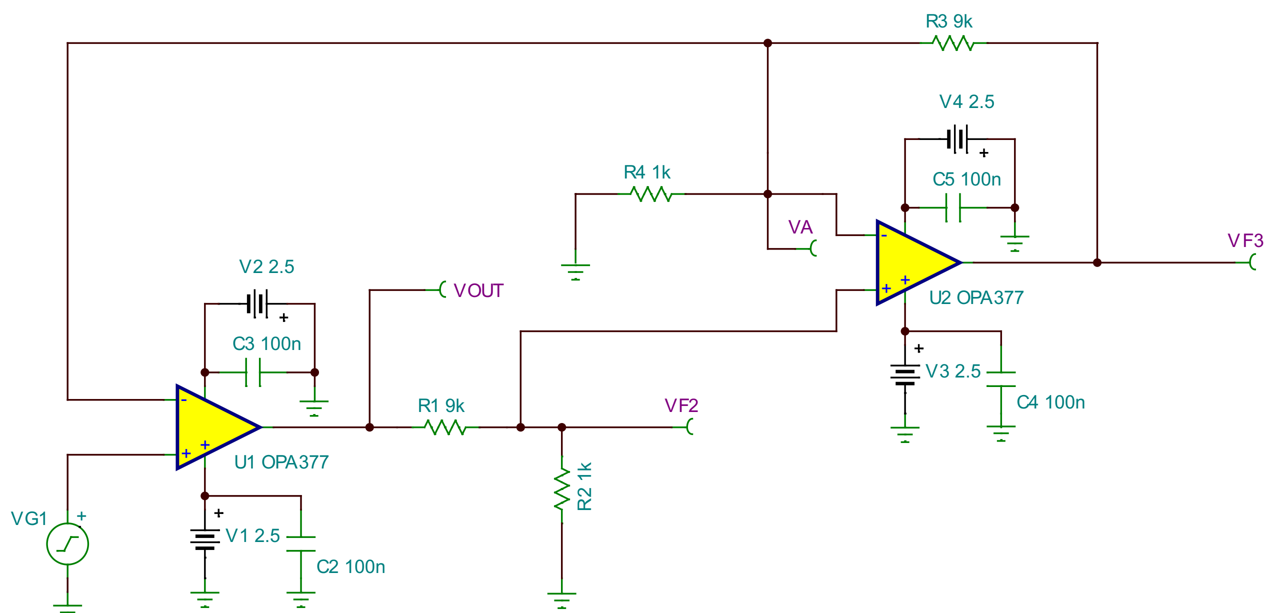
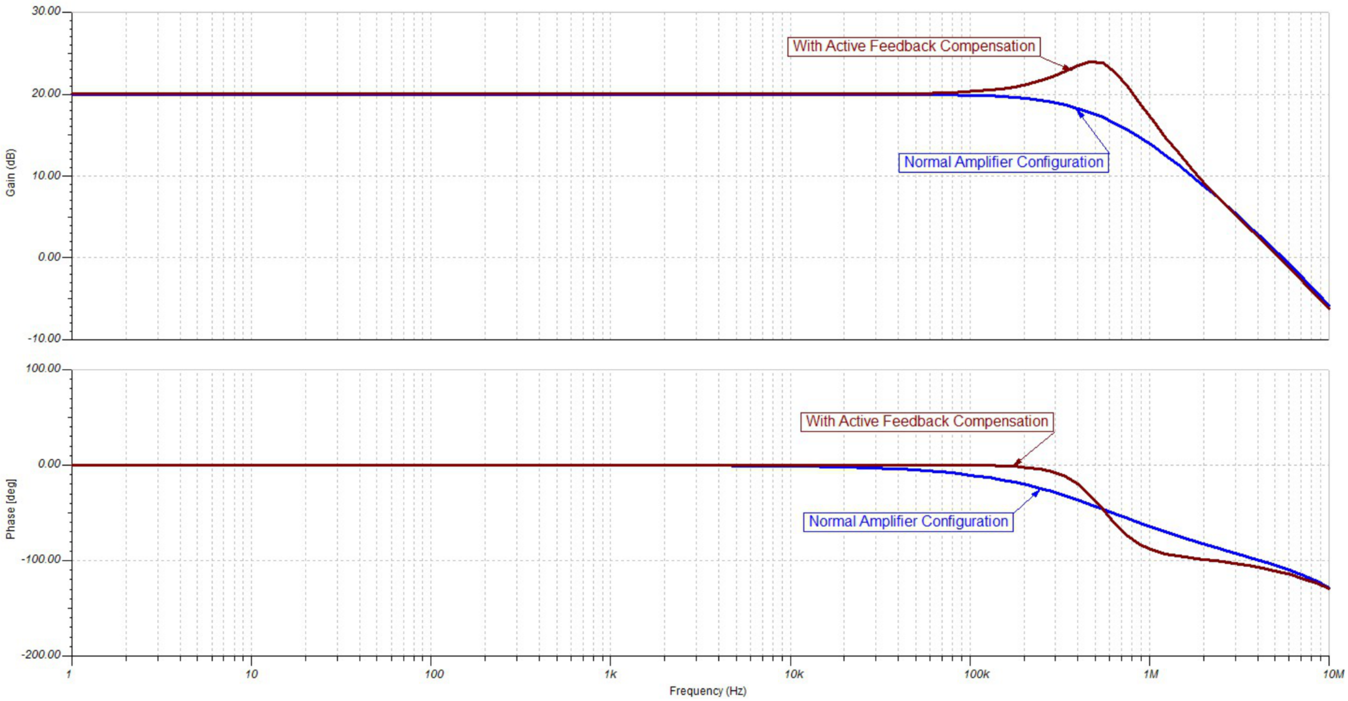


Figure 4. Active Feedback Compensation Scheme with a Gain of 10

Figure 5 shows the amplitude and phase response of OPA377 (5.54-MHz bandwidth) with a gain of 10 in both the configurations (normal and active feedback compensated).



Note the improvement in the phase response and the increase in the usable bandwidth.

Figure 5. Phase Response of Normal and Active Feedback Compensation Scheme

The active compensation scheme runs flat up to 100 kHz, with negligible phase shift up to 100 kHz, whereas the single stage op amp's phase response falls from 5 kHz onwards. Also, the roll off is much steeper for the active compensation scheme, when compared with the single-stage system. Figure 3 clearly shows that the active compensation scheme maintains its phase response up to 100 kHz (virtually zero).

Table 1. Phase Error Comparison at Different Frequencies for Normal and Active Feedback Compensation Scheme

Phase Error (In Degrees) Comparison			
Frequency (kHz)	Normal Configuration	Passive Feedback Compensation	With Active Feedback Compensation
1	–104.49 m	–7.28 m	–2.11 m
3	–313.41 m	–19.24 m	–6.32 m
5	–521.39 m	–25.37 m	–10.5 m
10	–1.04	–50.46 m	–20.76 m
50	–5.21	–200.04 m	–65.26 m
100	–10.34	–720.2 m	–115.27 m
554	–44.98	–45.2	–44.86

As shown in Table 1, the dominant pole of the op amp occurs at exactly 554 kHz for both the schemes. (Since simulation is done with OPA377, a 5.54-MHz unity gain bandwidth amplifier). From Table 1, it is evident that active feedback compensation virtually eliminates the phase error up to 100 kHz, whereas the single stage amplifier is usable only up to 5 kHz. If your targeted application requires a phase error of less than a degree, then the active feedback compensation scheme has a clear advantage over traditional configurations.

Seeing the advantages of this scheme; let's look into the amplifiers amplitude response curve shown in Figure 6.

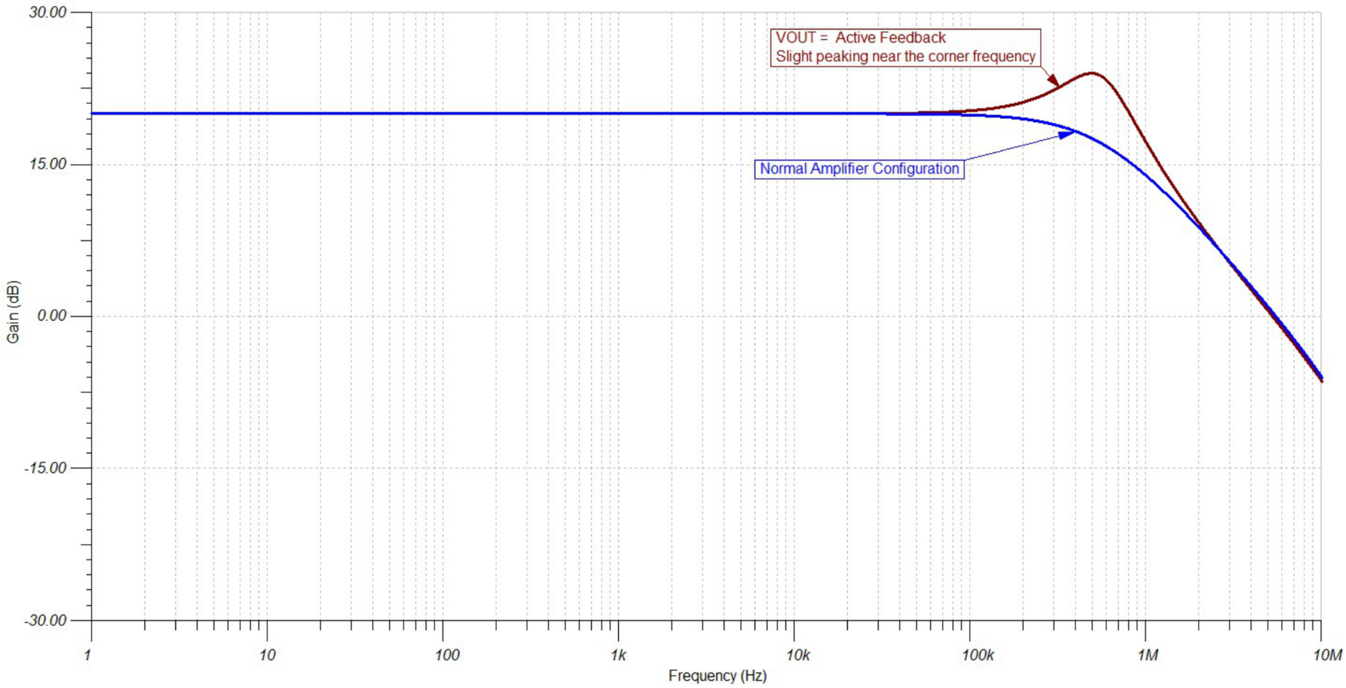


Figure 6. Amplitude Response of Normal and Active Feedback Compensation Scheme

As you can see from the plot, there is gain peaking around the corner frequency that is well above the usable bandwidth (in this case 100 kHz). That is not a major concern, considering the amount of phase error reduction achieved with the scheme. Table 2 shows the gain peaking at various frequencies.

Table 2. Gain Peaking at Various Frequencies

Gain Peaking (dB) for Different Methods and Frequencies		
Frequency (kHz)	**Passive Feedback**	**Active Feedback**
100	0.33	0.31
200	1.21	1.1
300	2.44	2.3
400	3.51	3.5

3 Stability Concern

In theory, the second-order active compensation works for any gain configuration. In reality, at higher gains (less than 10), the circuit may become unstable, due to the phase degradation introduced with the active feedback compensation scheme.

Figure 7 and Figure 8 show the transient response of the system with different gains.

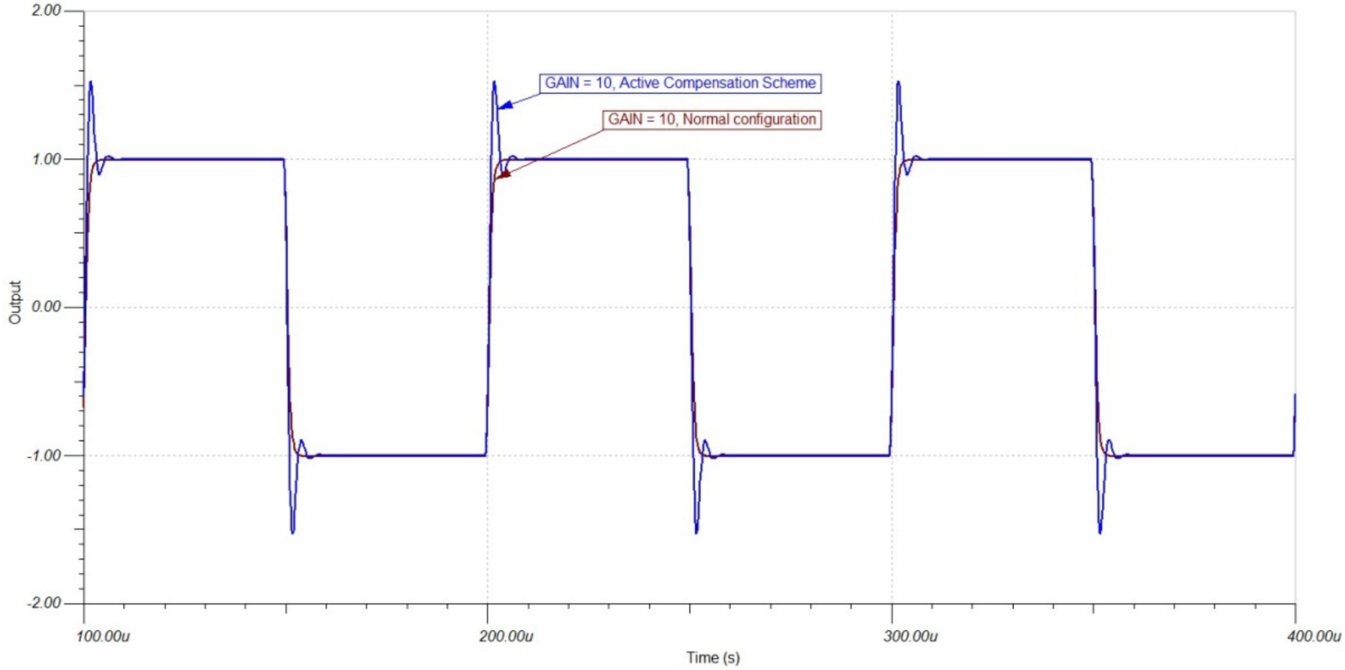


Figure 7. Transient Response of the System with Gain 10

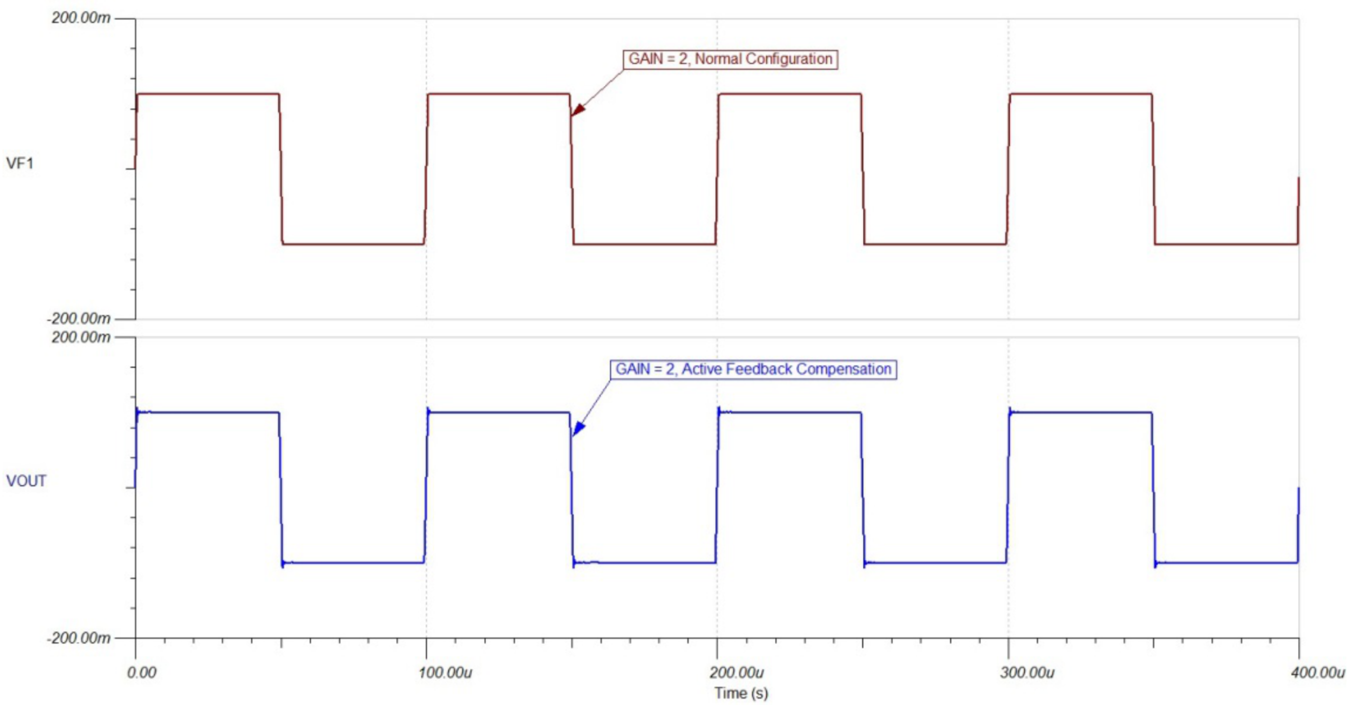


Figure 8. Transient Response of the System with Gain 2

The bandwidth of the op amp from 100 kHz to 200 kHz is easily extended using additional passive components around amplifier A1 and A2.

Figure 9 shows the active feedback compensation scheme with external RC components to extend the available bandwidth. Essentially, it's a combination of both the active and passive compensation scheme.

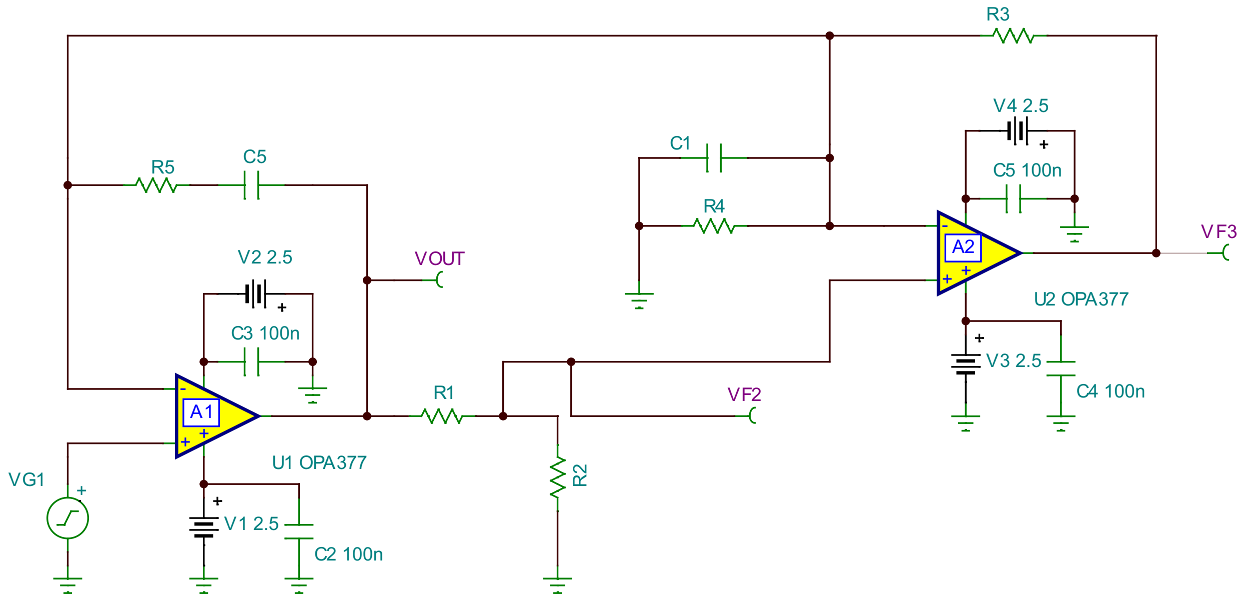


Figure 9. Active Feedback with Secondary Compensation

R4 and C1 create zero in the feedback path of amplifier A2 and R5, C5 combination creates pole which will counteract each other to nullify the effects of A2's mismatch in phase with respect to A1. Care must be taken to design C1 as it can affect the stability of amplifier A2. Careful calculation of A2's gain bandwidth product and open loop gain defines the accuracy of this method.

Figure 10 shows the amplitude and phase response of the modified compensation scheme.

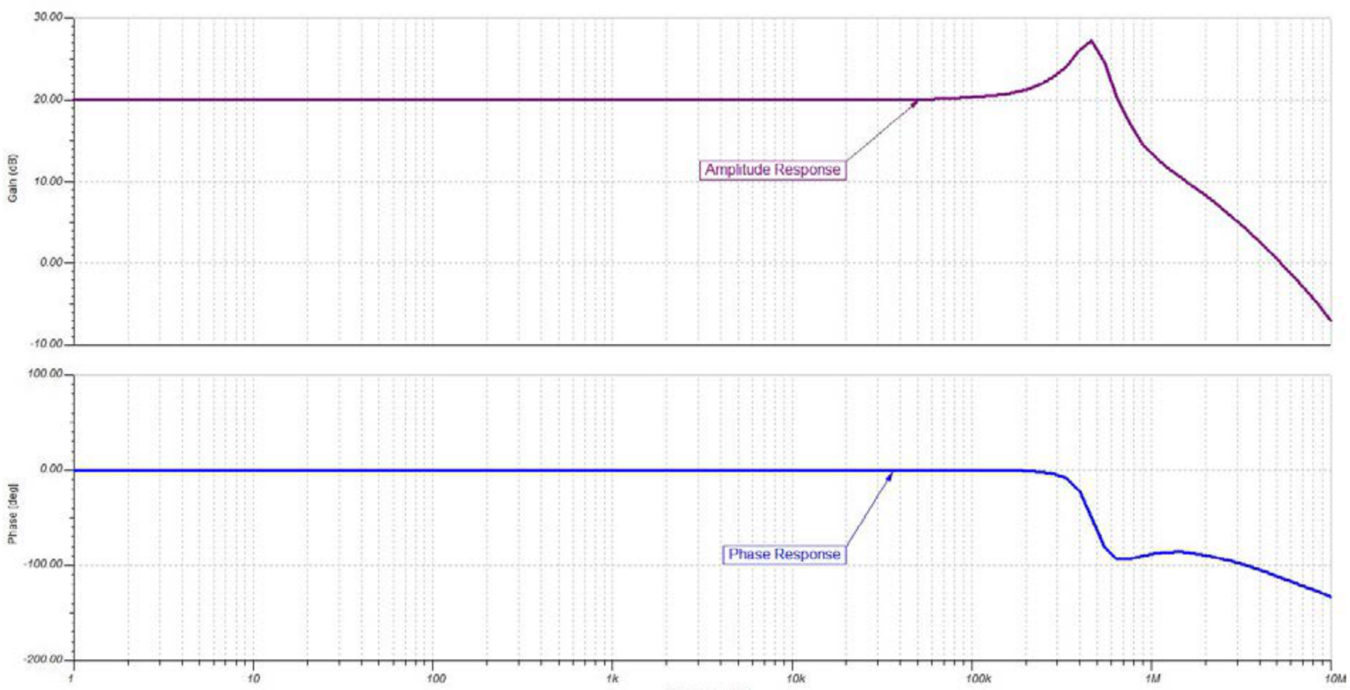


Figure 10. Amplitude and Phase Response of Secondary Compensation

Table 3 shows the phase error at various frequencies.

Table 3. Phase Error Comparison of Active Feedback with Secondary Compensation

Phase Error (In Degrees) Comparison		
Frequency (kHz)	**With Active Feedback**	**Active Feedback with Secondary compensation**
1	–2.11 m	–2.11 m
3	–6.32 m	–6.33 m
5	–10.5 m	–10.44 m
10	–20.76 m	–20.58 m
50	–65.26 m	–59.26 m
100	–115.27 m	–108.23 m
200	–2.2	–646.2 m

Table 4 shows the phase error at various frequencies.

Table 4. Gain Error Comparison of Active Feedback with Secondary Compensation

Gain Error (in dB) Comparison		
Frequency (kHz)	**Passive Feedback**	**Active Feedback**
100	0.31	0.3
200	1.1	1.26
300	2.3	3.19
400	3.5	6.1

Compared with the active feedback, the modified approach improves upon phase error by increasing gain peaking. A dramatic reduction in the phase is achieved by adding 0.1 dB gain error to the active compensation with this method.

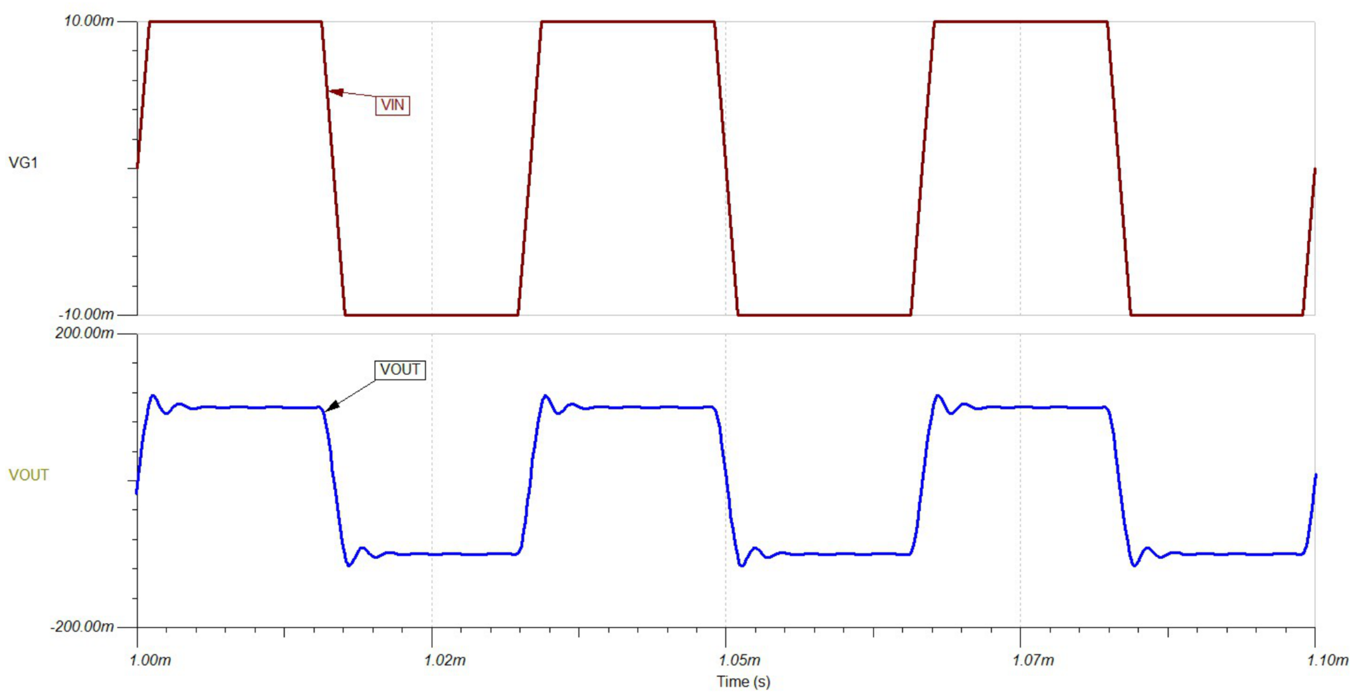


Figure 11. Transient Response - Active Feedback with Secondary Compensation

4 Mathematical Analysis

Referring to the figure below, assuming no band limiting of the amplifier, the open loop transfer function can be written as,

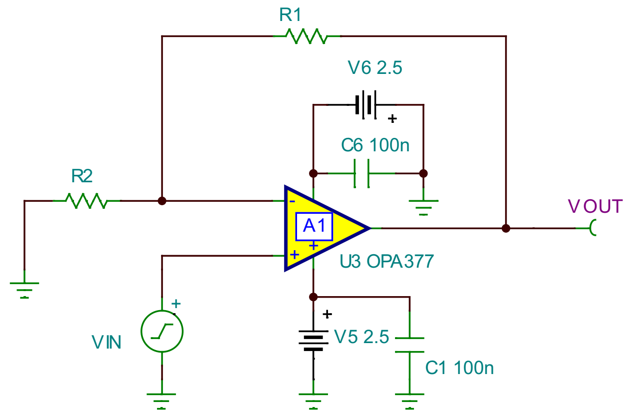


Figure 12. Open Loop Gain

$$A(S) = \frac{A_0}{1 + S\frac{A_0}{\omega_T}} \tag{1}$$

Where:

A_0 = Amplifier open loop gain
ω_T = Unity gain frequency of the amplifier

Assuming the amplifier has only single-pole response, write the closed-loop response of the amplifier as,

$$\text{Closed loop Gain, } A_{CL}(S) = \frac{1}{\beta}\left(\frac{1}{1 + \frac{1}{\beta A_0} + \frac{1}{\beta\omega_T}S}\right) \tag{2}$$

$$\text{Where } \beta = \frac{R_2}{R_1 + R_2}$$

Since the loop gain is much greater than unity, equation (2) is rewritten as,

$$A_{CL}(S) = \frac{1}{\beta}\left(\frac{1}{1 + \frac{1}{\beta\omega_T}S}\right) \tag{3}$$

Referring to Figure 2:

$$\text{Let } R_1 = \frac{R_2}{X} \text{ and } R_4 = \frac{R_3}{Y} \tag{4}$$

By writing the transfer function of the individual amplifiers A1 and A2, the complete transfer function of the active feedback compensation scheme is solved.

At the junction of R1 and R2,

$$V_B = V_{OUT}\left(\frac{R_1}{R_1 + R_2}\right) = V_{OUT}\left(\frac{1}{1 + X}\right) \tag{5}$$

At the junction of R3 and R4,

$$V_A = V_{OUT1}\left(\frac{R_4}{R_3 + R_4}\right) = V_{OUT1}\left(\frac{1}{1+Y}\right) \tag{6}$$

AC response equation of Amplifier A1,

$$V_{OUT} = \left(V_{IN} - V_{OUT1}\left(\frac{1}{1+Y}\right)\right)\frac{\omega_T}{S} \tag{7}$$

AC response equation of Amplifier A2,

$$V_{OUT1} = \left(V_{OUT}\left(\frac{1}{1+X}\right) - V_{OUT1}\left(\frac{1}{1+Y}\right)\right)\frac{\omega_T}{S} \tag{8}$$

Simultaneously solving Equation 7 and Equation 8 yields,

$$\frac{V_{OUT}}{V_{IN}} = (1+X)\left(\frac{1+\left(\frac{1+Y}{\omega_T}\right)S}{1+\left(\frac{1+X}{\omega_T}\right)S + \left(\frac{(1+X)(1+Y)}{\omega_T^2}\right)S^2}\right) \tag{9}$$

Assuming time constants $\tau_1 = \frac{1+X}{\omega_T}$ and $\tau_2 = \frac{1+Y}{\omega_T}$, then we can write the above equation as,

$$\frac{V_{OUT}}{V_{IN}} = (1+X)\left(\frac{1+\tau_2 S}{1+\tau_1 S + \tau_1\tau_2 S^2}\right) \tag{10}$$

For optimum compensation, R3, R4 and R1, R2 should be equal, which implies that the time constants τ_1 and τ_2 must be equal.

Let $\tau_1 = \tau_2 = \tau$, Then $\frac{V_{OUT}}{V_{IN}} = (1+X)\left(\frac{1+\tau S}{1+\tau S + \tau^2 S^2}\right)$ (11)

For sinusoidal response, it is better to convert Equation 11 to a complex form by substituting S = jω,

$$\frac{V_{OUT}}{V_{IN}}(j\omega) = (1+X)\left(\frac{1+j\tau\omega}{1+j\tau\omega - \tau^2\omega^2}\right) \tag{12}$$

Multiplying with complex conjugates to get the complex form a + jb,

$$\frac{V_{OUT}}{V_{IN}}(j\omega) = (1+X)\left(\frac{(1+j\tau\omega)\left(1-\tau^2\omega^2 - j\tau\omega\right)}{(1-\tau^2\omega^2)^2 + \tau^2\omega^2}\right)$$

$$\frac{V_{OUT}}{V_{IN}}(j\omega) = (1+X)\left(\frac{(1-j\tau^3\omega^3}{1-\tau^2\omega^2 + \tau^4\omega^4}\right) \tag{13}$$

From Equation 13, the magnitude and phase error of the active feedback compensation method is calculated.

Amplitude error of

$$\frac{V_{OUT}}{V_{IN}}(j\omega) = (1+X)\left(\frac{(1-j\tau^3\omega^3}{1-\tau^2\omega^2 + \tau^4\omega^4}\right) = \left|\left(\frac{(1-j\tau^3\omega^3}{1-\tau^2\omega^2 + \tau^4\omega^4}\right)\right|$$

$$\left|\frac{V_{OUT}}{V_{IN}}(j\omega)\right| = \frac{1}{1-\tau^2\omega^2} = 1+\tau^2\omega^2 \tag{14}$$

Thus, the phase error is reduced to a negligible value at the expense of simply doubling ($\tau^2\omega^2$), the very low magnitude error.

Phase error of

$$\frac{V_{OUT}}{V_{IN}}(j\omega) = (1+X)\left(\frac{(1-j\tau^3\omega^3}{1-\tau^2\omega^2+\tau^4\omega^4}\right) = \arg\left(\frac{(1-j\tau^3\omega^3}{1-\tau^2\omega^2+\tau^4\omega^4}\right)$$

$$\arg\left(\frac{V_{OUT}}{V_{IN}}(j\omega)\right) = 1-\tau^3\omega^3 \tag{15}$$

From Equation 15 it is evident that the phase error is reduced by a factor of τ^3 ω^3 at the expense of amplitude error by a factor of τ^2 ω^2.

5 References

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