Different Approach in Design And Analysis of an Instrumentation Amplifier

Alireza Rahrooh, Walter W. Buchanan, Bahman Motlagh
University of Central Florida/Middle Tennessee State University/University of Central Florida

Abstract

This paper presents a different instrumentation amplifier design to minimize the magnitude and phase errors of conventional instrumentation amplifier using single-pole model of the operational amplifier. This analytical approach ensures maximum flat magnitude and phase responses over an extended frequency range. Simulation results are given to support the proposed technique.

Design And Analysis Using Single-Pole Model

There are numerous applications in which a differential signal needs to be amplified. These include low-level bridge measurements, balanced microphone lines, communication equipment, thermocouple amplifiers, data acquisition, and more [1]. The immediate answer to these applications is the differential operational amplifier configuration. There are limitations to differential amplifiers, unfortunately. It is practically impossible to achieve matched high-impedance inputs while maintaining high gain and satisfactory offset and noise performance. For that matter, the input impedances are not isolated; indeed, the impedance of one input may very well be a function of the signal present on the other input[2]. Thus, this is an unacceptable situation when a precision amplifier is needed, particularly if the source impedance is not very low.

An instrumentation amplifier (I-Amp) overcomes these problems. Instrumentation amplifiers offer very high impedance, isolated inputs along with high gain, and excellent common-mode rejection performance. Instrumentation amplifiers can be fashioned from separate Op-Amps. They are also available on a single IC for highest performance. The common structure of an I-Amp is given in figure 1. The fist-order model of operational amplifier open-loop gain is given by

$$A(j\omega) = \frac{A_0 \, \omega_c}{j\omega + \omega_c} = \frac{\omega_u}{j\omega + \omega_c} \tag{1}$$

where A_0 is the open-loop dc gain, ω_c is the corner frequency, and ω_u is the unity gain bandwidth of the operational amplifier. An approximated model at higher frequency can be written as

$$A(j\omega) = \omega_u / j\omega \tag{2}$$

Using Kirchhoff's Current Law to write a set of none equations in circuit of figure 1 gives the following

$$(V3 - V_{01})/R_2 + (V_3 - V_0)/R_1 = 0, \quad (V_1 - V_{01})/R_3 + (V_1 - V_2)/R_c = 0 \tag{3}$$

$$(V_2 - V_{02})/R_3 + (V_2 - V,)/\&= 0, \quad (V_3 - V_{02})/R'_2 + (V_3 - 0)/R'_1 = 0$$

Using (3) and the approximated model (2), the transfer function $H(j\omega)=V_0/(V_2 - V_1)$ for the matched resistors $R_1/R_2 = R'_1/R'_2 = 1$, yields

$$H(j\omega) = \frac{0.5k\omega^2_u}{k(j\omega)^2 + \omega_u(1+0.5k)j\omega + 0.5\omega^2_u} \tag{4}$$

where $k = 1 + 2R_3/R_c$.

If H_o and $\angle H_o$ are the ideal magnitude and phase angle of the transfer function $H(j\omega)$, respectively, at zero frequency in (4), then it is possible to present the magnitude and phase angle of $H(j\omega)$ as

$$|H(j\omega)| = H_o\,[1 - E_H(j\omega)], \quad \angle H(j\omega) = \angle H_o - E_\phi(j\omega) \tag{5}$$

where $E_H(j\omega)$ and $E_\phi(j\omega)$ are the magnitude and phase errors. These error functions defined in (5) maybe approximately put in the following form

$$E_H(j\omega) = (0.5k^2 + 2)(\omega/\omega_u)^2, \quad E_\phi(j\omega) = -(k+2)\,\omega/\omega_u \tag{6}$$

It should be clear from equation (6) that the magnitude error is of a second-order, whereas the phase error is of a fist-order magnitude.

The proposed I-Amp structure (figure 2) consists of five Op-Amps and eleven passive resistors that minimizes the magnitude and phase errors. Necessary conditions are derived to ensure the maximally flat magnitude and phase responses over an extended frequency range. A set of node equations for the matched resistors ratio R_1/R_2 = R'1111'z = 1 and $R_5/R_4 = R'_5/R'_4 = M$, gives

$$(V_3 - V_{01})/R_2 + (V_3 - V_0)/R_1 = 0, \quad (V_4 - V_{01})/R_4 + (V_4 - V_{03})/R_5 = 0, \quad (V_1 - V_{03})/R_3 + (V_1 - V_2)/R_c = 0$$

$$(V_2 - V_1)/R_c + (V_2 - V_{04})/R_4 = 0, \quad (V_5 - V_{04})/R'_5 + (V_5 - V_{02})/R'_4 = 0, \quad (V_3 - V_{02})/R'_2 + (V_3 - 0)/R'_1 = 0 \tag{7}$$

Simplification of equations (7) and employing the single-pole model (2) will result in the following transfer function ($H(j\omega)=V_0/(V_2 - V_1)$) for the proposed I-Amp

$$H(j\omega) = \frac{0.5k\omega^3 + 0.5k\omega_u^2(1+M)j\omega}{k(1+M)(j\omega)^3 + .5k\omega_u(1+M)(j\omega)^2 + \omega_u^2(1+.5k)j\omega + .5\omega^3_u} \tag{8}$$

where $k = 1 + 2R_3/R_c$, and $M = R_5/R_4$ = R's/R'4. It should be noted that the transfer fiction in equation (8) satisfies the Routh Hurwitz stability criterion [3] for all positive values of k and M.

The optimization of equation (8) gives the condition for the maximally flat magnitude and phase responses, respectively, when

$$\mathbf{M = M_m = sqrt\,(2k^2{+}4)\ {-}1{-}k,\ M = M_\phi = k{+}1} \quad \textbf{(9)}$$

Under condition (9) the magnitude and phase errors may be approximately put in form

$$E_H(j\omega) = [1.5k^2 - (k^2+4)\mathrm{sqrt}(2k^2+4) + 8k](\omega/\omega_u)^4,\ E_\phi(j\omega) = -k(k+2)^2(\omega/\omega_u)^3 \quad \textbf{(10)}$$

The above expressions clearly indicate that the magnitude and phase errors are fourth-order and third-order as opposed to the second-order and first-order terms found in conventional instrumentation amplifiers.

Simulation Results

The transfer function for conventional instrumentation amplifier using the Op-Amp model parameters ($A_o = 10^5$, ω_c = 29 rad/sec, and $R_3/R_c = 5$) and equation (4) is

$$H(j\omega) = \frac{4205\times10^9}{(j\omega)^2 + 1713636.4\,(j\omega) + 3.823\times10^{11}} \quad (11)$$

The value of M for proposed I-Amp is obtained from equation (9) to yield maximally flat magnitude and phase responses; $\mathbf{M_m}$ = 3.7, and $\mathbf{M_\phi}$ = 12. The corresponding transfer functions of proposed I-Amp for above values are

$$H(j\omega) = \frac{4205\times10^9\,j\omega + 2.5946\times10^{18}}{(j\omega)^3 + 145\times10^4(j\omega)^2 + 1.05735\times10^{12}\,j\omega + 2.3587\times10^{17}} \quad (12)$$

$$H(j\omega) = \frac{4205\times10^9\,j\omega + 9.38\times10^{17}}{(j\omega)^3 + 145\times10^4(j\omega)^2 + 3.823\times10^{11}j\omega + 8.5276\times10^{16}} \quad (13)$$

The frequency response of the proposed I-Amp for its magnitude and phase responses for $\mathbf{M_m}$ = 3.7 are illustrated in figure 3 and figure 4, respectively. The simulated magnitude and phase responses of conventional I-Amp are also plotted in figures 3 and 4 to facilitate performance comparison. Figures 5 and 6, on the other hand, illustrate the way in which magnitude and phase responses of the proposed I-Amp vary with frequency for $\mathbf{M_\phi}$ = 12 which is computed to yield maximally flat phase response.

Conclusion

A simple modification in the conventional instrumentation amplifier is proposed to minimize magnitude and phase errors at the expense of two additional Op-Amps and four passive resistors. Superior performance is accomplished in comparison to the conventional instrumentation amplifier. The necessary analytical conditions are obtained to ensure flat magnitude and phase responses over an extended frequency range. The resistor R_c

in the proposed I-Amp controls the gain whereas the resistors $\mathbf{R_5}$ and $\mathbf{R'_5}$ **in** relation to R'_4 and R'_4 control the flatness of the responses for magnitude and phase. The circuit is stable for all positive values of k and M.

References

1. Stanley W. D., (1989). Operational Amplifiers With Linear Integrated Circuits. Merrill Publishing Company, Columbus, Ohio.

2. Fiore, J. M., (1992). Operational Amplifiers and Linear Integrated Circuits: Theory and Application. West Publishing Company, St. Paul MN.

3. Kuo, B. C., (1995). Automatic Control Systems (5th ed.). Englewood Cliffs, NJ: Prentice-Hall.

Dr. ALIREZA RAHROOH is Assistant Professor of Engineering Technology at the University of Central Florida. He received his B. S., M. S., and Ph.D. in Electrical Engineering from the University of Akron. Dr. Rahrooh was previously on the faculty at the Penn State Univ. at Harrisburg. He has had many papers published in different area of Electrical Engineering. He is a member of ASEE, IEEE, IASTED, and ISCA.

Dr. WALTER BUCHANAN is Industrial Studies Department Chair at Middle Tennessee State Univ. He received his BSE and MSE from Purdue Univ. and his Ph.D. and J.D. from Indiana Univ. Walt is a P.E. and is Secretary of NSPE's Professional Engi. in Education. Within ASEE, he is Secretary of ETD and the ETLI. He has written over 40 papers, and is an Alternate Member of TAC of ABET and a member of IEEE's CTAA.

Professor BAHMAN MOTLAGH is Assistant Professor of Engineering Technology at the university of Central Florida. He received his B. S. in Engineering form Istanbul Academy of Sciences, M. S. in Computer Engineering from University of Central Florida, and he is currently a Ph.D. candidate at University of Central F Florida (expected to complete by May, 1996). He is a member of IEEE, and Eta Kappa Nu.

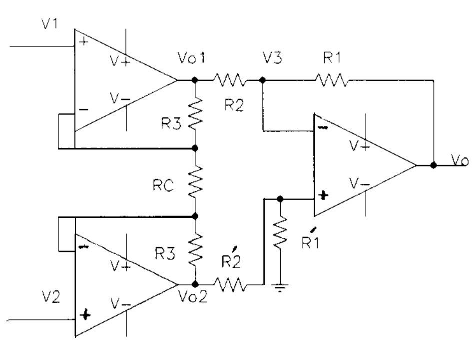

Figure 1. Conventional instrumentation amplifier

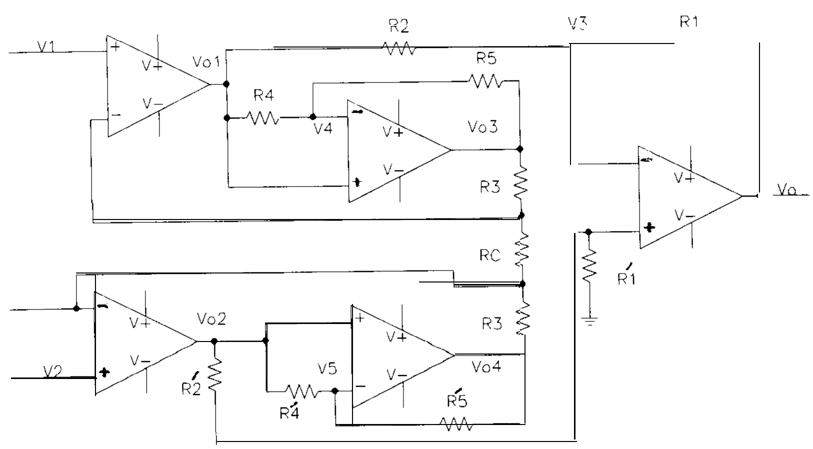

Figure 2. Proposed instrumentation amplifier

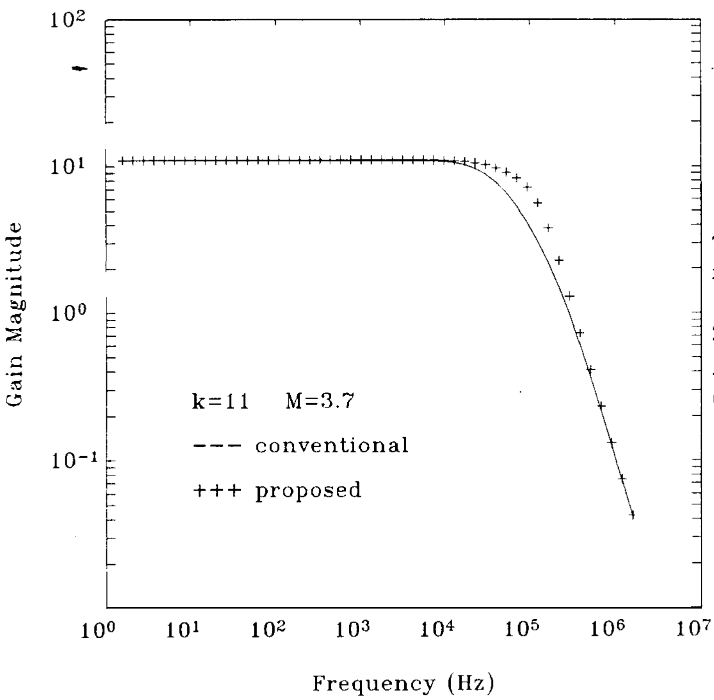

Figure 3. Simulated magnitude compensated for maximally flat magnitude response

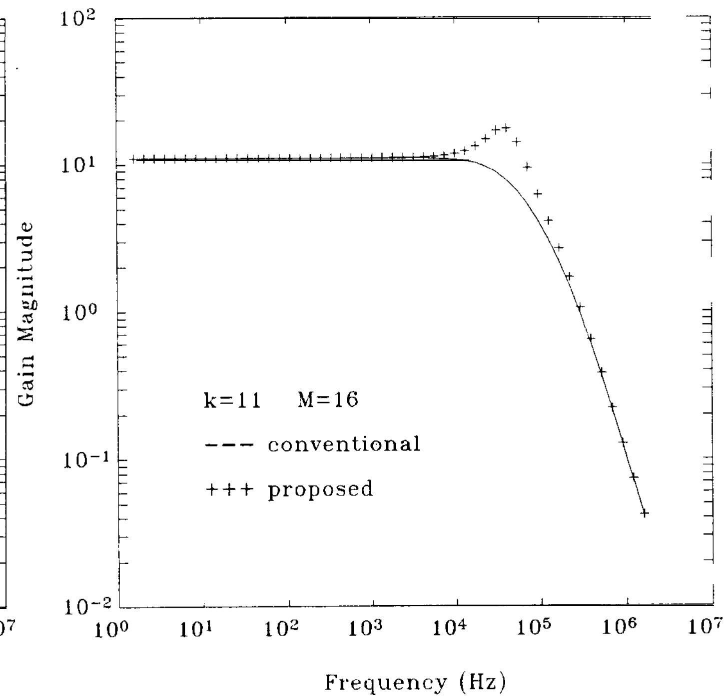

Figure 5. Simulated magnitude compensated for maximally flat phase respone

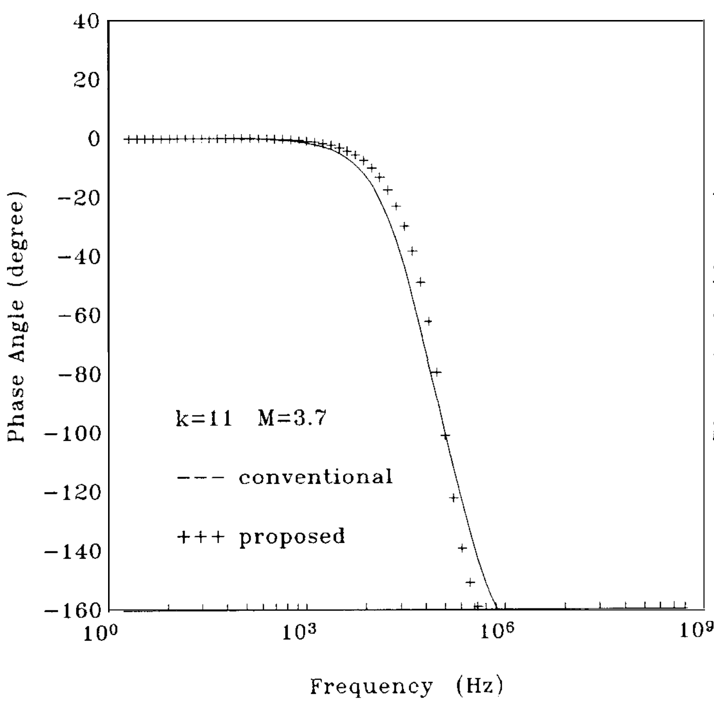

Figure 4. Simulated phase angle compensated for maximally flat magnitude response

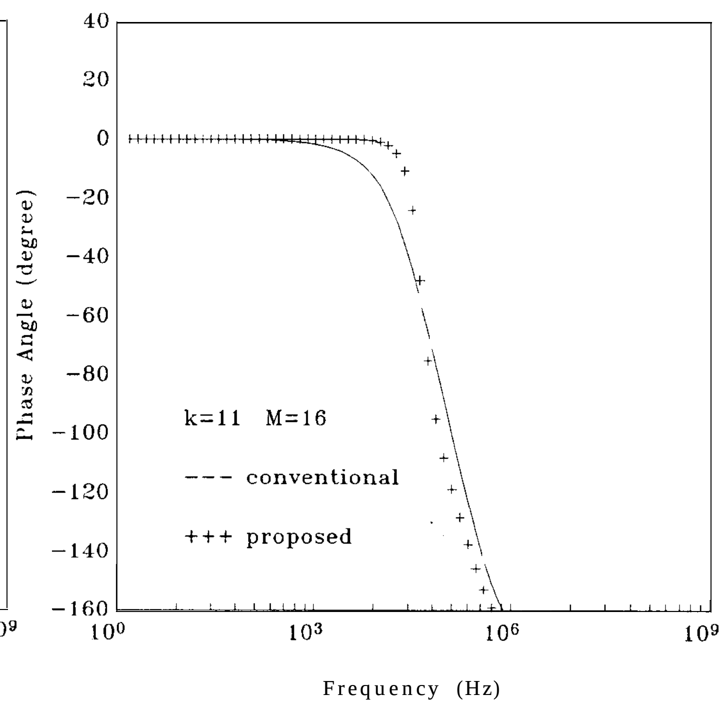

Figure 6. Simulated phase angle compensated for maximally flat phase response