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Feedback Analysis of Transimpedance Operational Amplifier Circuits

Erik Bruun

***Abstract*—The transimpedance or current feedback operational amplifier (CFB op-amp) is reviewed and compared to a conventional voltage mode op-amp using an analysis emphasizing the basic feedback characteristics of the circuit. With this approach the paradox of the constant bandwidth obtained from CFB op-amps is explained. It is demonstrated in a simple manner that the constant gain-bandwidth product of the conventional op-amp and the constant bandwidth of the CFB op-amp are both in accordance with basic feedback theory and that the differences between the traditional op-amp and the CFB op-amp are due to different ways of controlling the closed-loop gain. For the traditional op-amp the closed-loop gain is altered by altering the loop gain whereas the closed-loop gain in a CFB op-amp configuration is altered by altering the input attenuation to the feedback loop while maintaining a constant-loop gain.**

I. INTRODUCTION

The transimpedance or current feedback operational amplifier (CFB op-amp) as introduced by Nelson and Evans [1] has been available as a monolithic op-amp for a number of years. One of the most prominent features of this amplifier is the constant bandwidth, independent of the closed-loop voltage gain in a feedback configuration. This characteristic has been treated in the literature as a property almost violating traditional feedback theory that prescribes that an amplifier with feedback has a constant product of closed-loop gain and bandwidth [2], [3]. Hence, an analysis of the CFB amplifier with reference to familiar concepts in feedback theory seems appropriate.

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II. THE VOLTAGE MODE OPERATIONAL AMPLIFIER

Fig. 1 shows a traditional voltage mode op-amp in both an inverting and a noninverting feedback configuration. Assuming that the op-amp differential voltage gain is $A_d(s)$ we find the signal flow graphs shown in Fig. 2. From these we find the closed loop $A(s)$ and the loop gain $T(s)$:

$$A(s) = \frac{\alpha A_d(s)}{1+T(s)} \tag{1}$$

$$T(s) = -\beta A_d(s). \tag{2}$$

For the inverting amplifier we note that

$$\alpha = \frac{-R_2}{R_1+R_2} \tag{3}$$

$$\beta = \frac{-R_1}{R_1+R_2}. \tag{4}$$

For the noninverting amplifier we find

$$\alpha = 1 \tag{5}$$

$$\beta = \frac{-R_1}{R_1+R_2}. \tag{6}$$

Assuming that $A_d(s) = A_0/(1+s/\omega_c)$ we find the closed-loop gain and bandwidth relations

$$2\pi BW = \omega_c(1-\beta A_0) \tag{7}$$

and

$$2\pi GBW = \alpha\omega_c A_0. \tag{8}$$

For the noninverting amplifier of Fig. 1(b) with $\alpha = 1$ the latter expression shows that the product of gain G and bandwidth BW is constant and equal to the unity gain bandwidth $A_0\omega_c/2\pi$ for the op-amp. For the inverting amplifier (8) shows that the product of gain and bandwidth is actually not constant as α is dependent on the closed-loop gain. Assuming $A_0 \gg 1$ we note that the low frequency gain is $G = -\alpha/\beta = -R_2/R_1$ implying that (8) for the inverting configuration results in

$$2\pi GBW = \frac{1}{1+1/|G|}\omega_c A_0. \tag{9}$$

Only for $|G| \gg 1$ does this equation express a constant gain-bandwidth product.

An important property of feedback is that it reduces distortion, sensitivity to component variations, etc., with a factor of $F(s) = 1+T(s)$. For the configurations based on voltage mode operational amplifiers we find

$$\begin{aligned} F(s) &= 1 + \frac{R_1}{R_1+R_2} \times \frac{A_0}{1+s/\omega_c} \\ &\simeq \begin{cases} \frac{A_0/(|G|+1)+s/\omega_c}{1+s/\omega_c} & \text{inverting amplifier} \\ \frac{A_0/G+s/\omega_c}{1+s/\omega_c} & \text{noninverting amplifier.} \end{cases} \end{aligned} \tag{10}$$

Obviously, $F(s)$ is dependent on the gain G and hence the improvements in distortion, sensitivity, etc., are strongly dependent on G (approximately inversely proportional to G).

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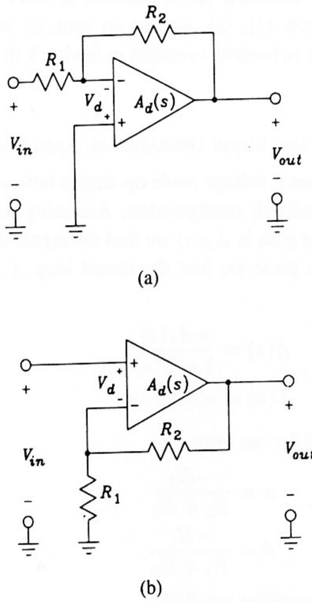

Fig. 1. (a) Inverting op-amp configuration. (b) Noninverting op-amp configuration.

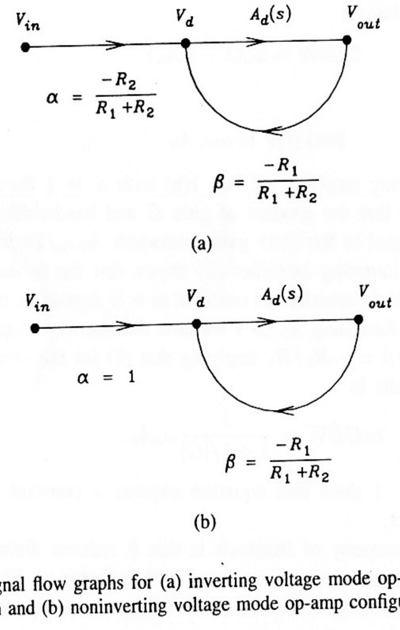

Fig. 2. Signal flow graphs for (a) inverting voltage mode op-amp configuration and (b) noninverting voltage mode op-amp configuration.

III. The Current Feedback Amplifier

The current feedback operational amplifier is a transimpedance amplifier with the simplified equivalent diagram shown in Fig. 3. In contrast to a conventional voltage mode op-amp the CFB op-amp does not provide a direct differential voltage gain. Rather, it creates a voltage gain by sensing the current flowing into the inverting input and impressing a mirror of the input current onto a high impedance node. It should be noted that the inputs to the CFB op-amp are nonsymmetric. The noninverting input is a high impedance voltage mode input and the inverting input is a low impedance current mode input. The CFB op-amp can be used in exactly the same configurations as shown in Fig. 1. However, the signal flow graphs for the current feedback configurations have very different branch transmittances. Fig. 4 shows the signal flow graphs for the CFB configurations. From these graphs we find, using the conventional feedback notation,

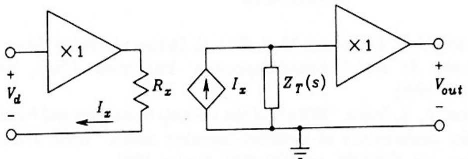

Fig. 3. Simplified block diagram of CFB op-amp.

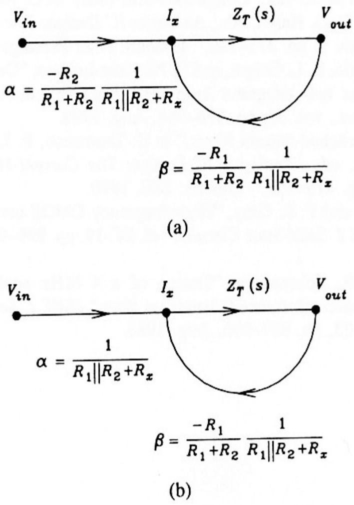

Fig. 4. Signal flow graphs for (a) inverting CFB op-amp configuration and (b) noninverting CFB op-amp configuration.

$$A(s) = \alpha\frac{Z_T(s)}{1 - Z_T(s)\beta} \tag{11}$$

with

$$\alpha = \begin{cases} \frac{-R_2}{R_1+R_2} \times \frac{1}{R_1\|R_2+R_x} = \frac{-R_2}{R_1R_2+R_x(R_1+R_2)} \\ \text{inverting amplifier} \\ \frac{1}{R_1\|R_2+R_x} = \frac{R_1+R_2}{R_1R_2+R_x(R_1+R_2)} \\ \text{noninverting amplifier} \end{cases} \tag{12}$$

and

$$\beta = \frac{-R_1}{R_1+R_2} \times \frac{1}{R_1\|R_2+R_x} = \frac{-R_1}{R_1R_2+R_x(R_1+R_2)}. \tag{13}$$

Assuming Z_T to be a parallel connection of a resistor R_T and a capacitor C_T we have

$$Z_T(s) = \frac{R_T}{1 + s/\omega_c} \tag{14}$$

with $\omega_c = (R_TC_T)^{-1}$. The closed-loop gain and bandwidth relations for the CFB amplifier are then calculated as

$$2\pi BW = \omega_c(1 - \beta R_T) \tag{15}$$

and

$$2\pi GBW = \alpha\omega_cR_T. \tag{16}$$

These expressions are the same as (7) and (8) for the voltage mode op-amp with A_0 replaced by R_T. For the voltage mode op-amp α and β are dimensionless whereas for the CFB op-amp they have

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the dimension of Ω^{-1}. Inserting (12) and (13) in (15) the following bandwidth relations result:

$$2\pi BW = \omega_c\left(1 + \frac{R_1 R_T}{R_1 R_2 + R_x(R_1 + R_2)}\right)$$
$$= \begin{cases} \omega_c\left(1 + \frac{R_T}{R_2 + R_x(1+|G|)}\right) \\ \text{inverting amplifier} \\ \omega_c\left(1 + \frac{R_T}{R_2 + R_x G}\right) \\ \text{noninverting amplifier.} \end{cases} \tag{17}$$

Assuming

$$R_T \gg R_2 + R_x|G| \tag{18}$$

and

$$R_x \ll R_2/G \tag{19}$$

this reduces to the constant bandwidth equation

$$2\pi BW = \omega_c\left(1 + \frac{R_T}{R_2}\right) \simeq \frac{1}{C_T R_2}. \tag{20}$$

Equation (20) shows that the bandwidth BW is independent of the gain G provided R_2 is left unchanged when changing G. We now notice that the important difference between the voltage mode op-amp and the CFB op-amp is that in the voltage mode op-amp configuration the closed-loop gain is changed by changing β and hence the loop gain and bandwidth whereas in the CFB op-amp configuration the closed-loop gain is changed by changing α while keeping β and hence the loop gain and bandwidth constant. Intuitively, this might be explained as follows: In a conventional voltage mode op-amp configuration the closed-loop gain is controlled by the attenuation of the output voltage by the feedback network. A large attenuation (small β) leads to a large gain. In the CFB op-amp configuration the closed-loop gain is controlled by the attenuation of the input signal such that a large attenuation (small α) results in a small closed-loop gain. It might seem strange that the noninverting input configuration of Fig. 1(b) has an input attenuation. However, this is explained by the fact that there is an implicit conversion of the input voltage to a current and that the conversion is given by $(R_1 \| R_2 + R_x)^{-1}$, i.e., by $(R_2/G + R_x)^{-1}$.

With this explanation in mind a relevant question is whether the CFB op-amp attains its properties at the expense of a reduced loop gain and thus a reduced improvement in distortion, sensitivity, etc. From (13) we find

$$F(s) = 1 + T(s) = 1 - \beta Z_T(s)$$
$$= 1 + \frac{R_T}{1 + s/\omega_c} \times \frac{R_1}{R_1 R_2 + R_x(R_1 + R_2)}$$
$$\simeq \begin{cases} \dfrac{\frac{R_T}{R_2 + R_x(|G|+1)} + s/\omega_c}{1 + s/\omega_c} \\ \text{inverting amplifier} \\ \dfrac{\frac{R_T}{R_2 + R_x G} + s/\omega_c}{1 + s/\omega_c} \\ \text{noninverting amplifier.} \end{cases} \tag{21}$$

The bandwidth of $F(s)$ is ω_c just as for the voltage mode op-amp, compare (10). Comparing the noninverting amplifiers we find a low frequency value of $F(s)$ of A_0/G for the voltage mode op-amp and $R_T/(R_2 + R_x G)$ for the CFB op-amp. With conventional amplifier architectures employing a single high gain stage with a very high load impedance (e.g., a cascode amplifier with an output buffer) we may assume A_0 to be on the order of g_m/g_o where g_m is a device transconductance and g_o is a device output conductance, a device being a transistor or a compound device (e.g., a cascode circuit). Hence,

$$F(0) = \frac{A_0}{G} \simeq \frac{g_m}{g_o G} \tag{22}$$

for the voltage mode op-amp. Similarly, we often find $R_x \simeq g_m^{-1}$ and $R_T \simeq g_o^{-1}$ for the CFB op-amp, hence

$$F(0) = \frac{R_T}{R_2 + R_x G} \simeq \frac{g_m}{g_o(G + R_2 g_m)}. \tag{23}$$

Comparing (22) and (23) we note that with equal values of g_m and g_o for the voltage mode op-amp and the CFB op-amp the voltage mode op-amp indeed has a larger value of $F(s)$. We also note that the difference is insignificant if $R_2 g_m < G$ but this conflicts with the constant bandwidth requirement (19). Thus, the CFB op-amp sacrifices loop gain if the feedback resistor is designed to provide a gain independent bandwidth.

For both types of amplifiers ω_c is on the order of g_o/C_T where C_T is a compensation capacitor. This leads to a bandwidth of

$$2\pi BW = \frac{g_m}{C_T G} \tag{24}$$

for the voltage mode op-amp and

$$2\pi BW = \frac{g_m}{C_T(G + R_2 g_m)} \tag{25}$$

for the CFB op-amp. With equal values of g_m and C_T we find that the CFB op-amp actually sacrifices bandwidth compared to the voltage mode op-amp.

A similar comparison can be made for the inverting amplifier configurations, leading to the same conclusion.

Often, however, C_T is selected smaller for the CFB op-amp than for a comparable voltage mode op-amp. This is due to the fact that a voltage mode op-amp is often compensated to allow its use in a unity gain configuration, i.e., ω_c has been set by proper choice of the dominant pole to a frequency yielding an adequate phase margin when the feedback loop is closed. If the voltage mode op-amp is then used in a feedback configuration with a higher closed-loop gain the bandwidth will decrease in proportion to the gain increase as indicated by (8) provided ω_c is left unchanged. However, with a reduction in the loop gain $T(s)$ the open-loop bandwidth ω_c may be increased correspondingly while maintaining the same phase margin. Hence, the closed-loop bandwidth can be kept at a constant value. However, often the possibility of increasing ω_c by decreasing a capacitor value is not present because the compensation capacitor has been included on-chip with the op-amp. For the CFB op-amp configuration a similar possibility of a decrease in compensation capacitor with an increase in closed-loop gain does not exist if the loop gain $T(s)$ has been designed to be independent of the closed-loop gain. If the bandwidth has been designed to be limited by $R_x G$ rather than by R_2 we find from (17) and (18) that the CFB op-amp in the noninverting configuration has a bandwidth of

$$2\pi BW = \frac{1}{C_T R_x G} \tag{26}$$

which with $R_x \simeq g_m^{-1}$ is the same as (24), valid for the voltage mode op-amp. In this situation the compensation capacitor may be optimized just as in a voltage mode op-amp.

With these observations in mind one might be inclined to conclude that the CFB op-amp provides little—if any—improvement over a conventional voltage mode op-amp. However, one important feature of the CFB op-amp in most architectures available today [3], [4] is a very high slew rate. This is related to the specific realization of the CFB input stage and cannot be achieved in a conventional voltage mode op-amp amplifier architecture. Thus, the primary advantage of the CFB op-amp is its superior slew rate performance. A secondary advantage of the CFB op-amp is an easier optimization of the frequency response of the loop gain because there is only one high-impedance node in the feedback loop whereas voltage mode op-amps may have more than one high impedance node, even in the case of single gain stage op-amps, because of the high impedance of the inverting input.

IV. Conclusion

A comparison of a traditional voltage mode op-amp and a current feedback op-amp has been made for an inverting and a noninverting amplifier configuration. It is concluded that the constant bandwidth feature often associated with the CFB op-amp is due to the fact that the closed-loop gain in the CFB configurations is changed by changing the input attenuation while maintaining a constant-loop gain. This has the implication that if the CFB amplifier should be designed to have a constant bandwidth this is only achieved at the cost of a decreased loop gain and bandwidth because the feedback resistor has to be fairly large. For designs optimized for bandwidth at a specific gain similar results can be expected from a conventional voltage mode op-amp and a CFB op-amp. However, a main attribute of the CFB op-amp is a high slew rate yielding a large signal bandwidth which is superior to most voltage mode op-amps. It should be pointed out, though, that the slew rate characteristics do not rely on the current feedback but rather on the internal architecture of the op-amp. Recent evidence has been given [5], [6] that a similar slew rate performance can be achieved from voltage mode op-amps using an internal architecture resembling the architecture of the CFB op-amp.

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