APPENDIX 1
CURRENT-FEEDBACK OP AMPS

1. THE CURRENT-FEEDBACK OPERATIONAL AMPLIFIER

Fig.1 shows a *current-feedback amplifier (CFA)* in a typical noninverting configuration. The architecture of *CFA* differs from the conventional op amp in two respects [77][167][79]:

1.- The input stage is a *unity-gain voltage buffer* connected across the inputs of the op amp. Its function is to force V_n to follow V_p, very much like a conventional amplifier does via negative feedback. However, because of the low output impedance of this buffer, current can easily flow in or out of the inverting input, though it will be seen that in normal operation this current is extremely small.

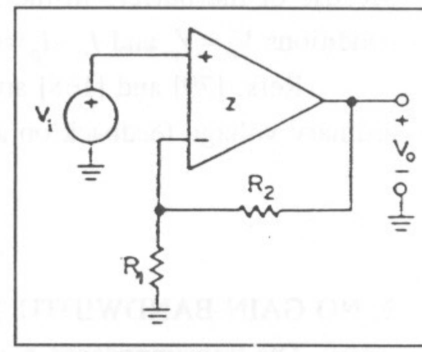

Fig.1 Noninverting CFA.

2.- Amplification is provided by a *transimpedance amplifier* which senses the current delivered by the buffer to the external feedback network, and produces an output voltage V_o such that

$$V_o = Z(jf)I_n \tag{1}$$

where $Z(jf)$ represents the *transimpedance gain* of the amplifier, in V/A or Ω, and I_n is the current out of the inverting input.

Next, let us obtain the closed-loop transfer characteristic of the noninverting amplificer of Fig.1: First, summing currents at the inverting node yields

$$I_n = \frac{V_n}{R_1} - \frac{V_o - V_n}{R_2} \tag{2}$$

and since the buffer ensures $V_n = V_p = V_i$, the result can be rewritten as

$$I_n = \frac{V_i}{R_1 \parallel R_2} - \frac{V_o}{R_2} \tag{3}$$

Note that the feedback signal V_o/R_2 is now in form of a current. Second, substuting into eq.(1), collecting, and solving for the ratio V_o/V_i yields

$$A(jf) \doteq \frac{V_o}{V_i} = \left(1 + \frac{R_2}{R_1}\right) \frac{1}{1 + \frac{1}{T(jf)}} \tag{4}$$

where $A(jf)$ represents the *closed-loop gain* of the circuit, and

$$T(jf) = \frac{Z(jf)}{R_2} \tag{5}$$

represents the *loop gain.*

In an effort to ensure substantial loop gain to reduce the closed-loop gain error, manufacturers strive to make Z as large as possible relative to the expected values of R_2. (Open loop gains of CFA CLC430 are illustrated in *Chap.4*). Consequently, since $I_n = V_o/Z$, the inverting-input current will be very small, though this input is a low-impedance node because of the buffer. In the limit, when $Z \to \infty$, $I_n \to 0$. **Thus, the conventional op amp conditions $V_n = V_p$ and $I_n = I_p = 0$ hold for CFAs as well.**

Refs. [79] and [168] are excellent application notes wheret *CFAs* are compared to ordinary voltage feedback op amps.

2. NO GAIN-BANDWIDTH TRADE-OFF

The transimpedance gain of a practical CFA rolls off with frequency according to

$$Z(jf) = \frac{Z_o}{1 + j\dfrac{f}{f_a}} \tag{6}$$

where Z_o is the *dc* value of the transimpedance gain, and f_a is the frequency at which roll-off begins.

Substituting eq.(6) into eq.(5) and then into eq.(4), and exploiting the fact that $R_2/Z_o << 1$, the following expression is obtained

$$A(jf) = \frac{1 + \dfrac{R_2}{R_1}}{1 + j\dfrac{f}{f_A}} \tag{7}$$

where

$$f_A = \frac{Z_o f_a}{R_2} \tag{8}$$

represents the *closed-loop bandwidth.* For R_2 in the $k\Omega$ range, f_A is typically in the *100 MHz*. Retracing similar steps for a classic voltage-feedback op amp [78], the following expression would have been obtained instead of eq.(8):

$$f_A = \frac{f_t}{1 + \frac{R_2}{R_1}} \qquad (9)$$

where $f_t = a_o f_a$ represents the *open-loop unity-gain frequency*. (For instance, 741 op amp has $f_t = 1\ MHz$).

To sum up, even though formally identical closed-loop gain expressions to eq.(7) have been found, comparison of eq.(8) to eq.(9) reveals that **CFA op amps bandwidth depends only on the feedback resistor, R_2, rather than on the closed-loop gain $1+R_2/R_1$. Consequently, one can use the feedback resistor, R_2, to select the bandwidth, and R_1 (the gain resistor) to select the gain. The ability to control gain independently of bandwidth constitutes a major advantage of CFAs over conventional op amps [81].** This important difference is highlighted in Fig.2.

3. ABSENCE OF SLEW-RATE LIMITING

The *slew-rate (SR)* is defined as the *maximum rate at which the output can change,*

$$SR \triangleq \left. \frac{dV_o(t)}{dt} \right|_{max} \qquad (10)$$

or, equivalently, the *rate of output change for a large-signal input step [78]*. SR is expressed in $V/\mu s$. It must be stressed that the *slew-rate is a large-signal effect* while the *rise time, t_r, is a small-signal effect*. The borderline between the two occurs for an output step amplitude $\Delta V_o = SR\, t_r/2.2$.

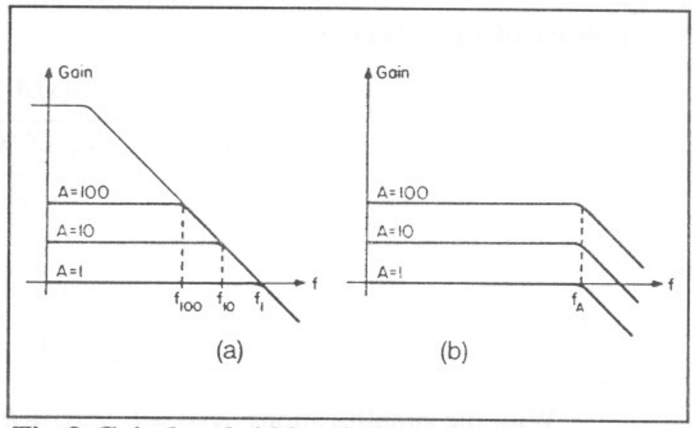

Fig.2 Gain-bandwidth relationships of conventional op amps and CFAs.

As it happened to the frequency response, the absence of slew-rate limiting for *CFAs* stems from the fact that the transient response is governed by the feedback resistor alone, R_2, regardless of the closed-loop gain. With R_2 in the $k\Omega$ range, the *slew-rate* can be as high *2000 $V/\mu s$* for the CLC430 [77], which is used in the conditioning stage of the lidar receiver.

The absence of slew-rate limiting not only allows for faster settling time, but also eliminates slew-rate related nonlinearities such as intermodulation distortion. This has made CFAs attractive in high-quality audio and video amplifier application, and in particular, for its application in the lidar receiver.

4. CFA LOOP GAIN ANALYSIS

The equivalent circuit of Fig.3 represents a real CF op amp working as a noninverting amplifier [80][167][94]. Two basic limitations must be considered :

1.- The output of the buffer, $\alpha(s)$, ideally presents a 0Ω output impedance at the inverting output, V^-. Yet, it actually shows a frequency dependent impedance, Z_i that is relatively low at DC and increases inductively at high frequencies.

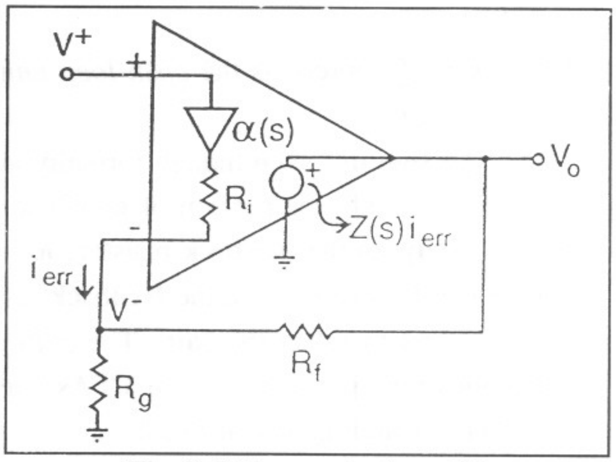

Fig.3 CFA practical model.

2.- The unity gain follower, $\alpha(s)$ is very neatly equal to *1* at DC (typ. 0.996) and typically has a *-3dB* point beyond *500 MHz*.

If these two factors are taken into account, the noninverting transfer function of the amplifier of Fig.3 becomes

$$\frac{V_o}{V^+} = \frac{\alpha(s)A_{v,ideal}}{1+\dfrac{R_f+Z_i(s)A_{v,ideal}}{Z(s)}} \tag{11}$$

where

$$A_{v,ideal} = 1+\frac{R_f}{R_g} \tag{12}$$

With the simplifications, $\alpha(s)\approx 1$, $Z_i(s)\approx R_i$ and identifying eqs.(11) and (12) with the closed-loop gain expression of eq.(4), the *loop-gain* results

$$T(s) = \frac{Z(s)}{Z_t} \;; \qquad Z_t = R_f + R_i A_{v,ideal} \tag{13}$$

Z_t is defined as the *feedback transimpedance.*

From the above equation, it can be seen that ***the point where the feedback transimpedance, Z_t, crosses the forward transimpedance curve is the frequency at which the loop gain has dropped to unity. As for the gain, note that the desired gain expression, $A_{v,ideal}$ has been decoupled from the closed loop bandwidth.*** In *Chap.4,* this method has been used to predict CFA frequency response from the manufacturer's open loop graphs. These graphs (also show in *Chap.4*) plot the forward transimpedance, that is $20\log(|Z(s)|)$, along with its phase versus frequency. Adequate phase margin at the unity gain crossover frequency is critical for stable amplifier operation.