Current feedback op-amps

References:
National Semiconductor application notes: OA15, AN-597
Texas Instruments: OpAmps for Everyone, Chapter 8: CFOA
Intersil Elantec EL-5166 datasheet
What is a CFOA?

A CCII-, a voltage follower, and a node impedance
How did the idea come about?

Supply mirroring: CC

Supply mirroring + Buffer

Current conveyor

Current feedback op-amp
Loop gain calculation

V_{OUT} Becomes V_{TO}; The Test Signal Output

Break Loop Here

Apply Test Signal (V_{TI}) Here

V_{OUT} = V_{TO}
Basic usage: Non inverting amplifier

\[ G_{NINV} = \frac{dV_{OUT}}{dV_{IN}} = \frac{Z \left( Z_F + Z_G \right)}{ZG + ZFZB + ZGZB +ZFZG} \]

\[ \lim_{Z \to \infty} G_{NINV} = 1 + \frac{Z_F}{Z_G} \]

Note that we have not introduced explicit frequency dependence!
Not common usage: Inverting

\[ G_{INV} = \frac{-ZZ_F}{ZZ_G + Z_BZ_F + Z_BZ_G + Z_FZ_G} \]

\[ \lim_{Z \to \infty} G_{INV} = -\frac{Z_F}{Z_G} \]
Gain calculation – frequency response

\[ G_{NINV} = \frac{Z_{ZF} + Z_{ZG}}{Z_{ZG} + Z_B Z_F + Z_B Z_G + Z_F Z_G} \]
\[ Z_B = h_i b + \frac{R_B}{\beta_0 + 1} \left( \frac{1 + s \beta_0 \tau_T}{1 + s \tau_T / (1 + 1/\beta_0)} \right) \]

\[ Z_T = \frac{Z_0}{(1 + s \tau_1)(1 + s \tau_2)} \]

Transimpedance \( Z_T \) has two poles: due to the impedance of the high Z node and also due to the current mirror delay. 
\( Z_B \) is the output impedance of the input buffer, small but not necessarily much smaller than \( Z_G \).
Gain calculation – frequency response (2)

\[ G_{NINV} = \frac{ZZ_F + ZZ_G}{ZZ_G + Z_B Z_F + Z_B Z_G + Z_F Z_G} \]
\[ Z_T = \frac{Z_0}{(1+s\tau_1)(1+s\tau_2)} \]

Neglect \( Z_B \) since it is much smaller than anything else. Then,

\[ Z_{NINV} \approx \frac{Z(Z_F + Z_G)}{ZZ_G + Z_F Z_G} = \left(1 + \frac{Z_F}{Z_G}\right) \frac{1}{1 + \frac{Z_F}{Z}} \]

Observe that the gain and bandwidth have been decoupled. The bandwidth depends only on \( Z_F \) (and \( Z_B \), really), while the gain depends on both \( Z_F \) and \( Z_G \).

There is no magic involved. The CFOA is a dominant pole transimpedance amplifier, while the voltage and current buffers have poles at much higher frequencies.
Gain vs. frequency with $R_F$ (EL5166)
Gain vs frequency with $R_G$ (EL5166)

Notice that despite what our approximations say the BW still depends on gain!
Gain bandwidth product – example

Gain and Bandwidth vs Feedback Resistor

<table>
<thead>
<tr>
<th>GAIN (A_{CL})</th>
<th>( R_F \ (\Omega) )</th>
<th>BANDWIDTH (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 1</td>
<td>1000</td>
<td>125</td>
</tr>
<tr>
<td>+ 2</td>
<td>681</td>
<td>95</td>
</tr>
<tr>
<td>+ 10</td>
<td>363</td>
<td>65</td>
</tr>
</tbody>
</table>
The transimpedance has a dominant pole at 100kHz
Slew rate: VFOA vs CFOA

- VFOA: \( I_{outVFOA} \propto \tanh(V_+ - V_-) \)

- CFOA: \( I_{outCFOA} \propto \exp(V_y) \)

In the limit of large input voltages, in the VFOA:
\[
\frac{dI_{out}}{dV_{in}} \rightarrow 0
\]

While in the CFOA we get:
\[
\frac{dI_{out}}{dV_{in}} \rightarrow \propto I_{out}
\]

The slew rate in the CFOA is power limited.
Re-visit the non inverting amplifier

The CFOA is a transimpedance amplifier, i.e. equivalent to the block diagram.

The response is, in terms of the transimpedance $Z$ is the usual FB expression:

$$G_{NINV} = \frac{Z(Y_G + Y_F)}{1 + ZY_F} \Rightarrow \lim_{Z \to \infty} G_{NINV} = 1 + \frac{Y_G}{Y_F} = 1 + \frac{Z_F}{Z_G}$$

Notice that the loop gain is $ZF$ and that $Z$ is typically second order beyond the first pole, so that, for a parallel RC in the feedback path we get a second order underdamped system.
Avoid capacitances!
Effect of Feedback capacitance

\[ A_\beta = \frac{Z (1 + R_F C_F s)}{R_F \left(1 + \frac{R_B}{R_F \| R_G}\right) \left( R_B \| R_F \| R_G \left(C_F + C_G\right) s + 1\right)} \]

\[ \rightarrow \text{INSTABILITY unless we introduce extra pole!} \]
Input capacitance
Brute force compensation

Low pass the non-inverting input to compensate for stray capacitance, i.e. brute force compensation
Effect of input (stray) capacitance

$V_{CC}=+5V$
$V_{EE}=-5V$
$R_L=150\,\Omega$
$R_F=R_G=392\,\Omega$

- $C=4.7p$
- $C=2.5p$
- $C=1.5p$
- $C=1p$
- $C=0$
Output (load) capacitance
Applications I

Inverting receiver

\[ V_{OUT} = \frac{R_F}{R_G} \cdot V_{IN} \]

For input impedance of 50Ω, select \( R_i \parallel R_G \) equal to 50Ω

Non-inverting receiver

\[ V_{OUT} = \left(1 + \frac{R_F}{R_G}\right) \cdot V_{IN} \]

\( R_i \) set the input impedance.
Applications II

Differential amplifier

\[ V_{OUT} = (V_2 - V_1) \]

Differential line driver

\[ V_{OUT} = (V_2 - V_1) \]

Differential input resistance is 50Ω
Antenna circuits

Coax cable driver

Distribution amplifier
CFOA can be combined with other stages...

With emitter follower

$V_{OUT} = V_1 \left(1 + \frac{R_F}{R_G}\right) - V_2 \left(\frac{R_F}{R_G}\right)$

With op-amps

$V_{OUT} = -\left(\frac{1500}{R}\right) V_{IN}$

$R_A \cong 9.5R$

$R_B \cong 0.5R$

$R_C \cong 10K - 15K \parallel (R_A + R_B)$
Bandwidth and stability

Adjust BW by increasing inverting input impedance!
Integrator

Integrating capacitance NOT in feedback path.
Capacitance must be lossy enough!

For stable operation,
\[
\frac{R_2}{R_1 R_A} \geq \frac{R_F}{R_G}
\]

All resistors are 1%

\[
V_{OUT} = V_{IN} \left[1 + \frac{R_F}{R_G} \frac{sR_1 C}{12.8 \text{MHz}}\right]
\]

\[
V_{OUT} \sim V_{IN} \frac{2\pi (12.8 \text{MHz})}{s}
\]
Implementation note:
Supply bypassing is NOT optional!