

A NEW CFA FREQUENCY MODEL INCLUDING LOAD-DEPENDENT INSTABILITIES

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A NEW CFA FREQUENCY MODEL INCLUDING LOAD-DEPENDENT INSTABILITIES

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Abstract. *The current-feedback operational amplifier (CFA) is an active device which uses the supply-current sensing technique in order to achieve high performance features for analog signal processing applications. However, under certain load conditions the CFA exhibits an unstable behavior. This work presents a new frequency model which takes into account the non-unilateral characteristics of the CFA buffer stages and includes the load-dependent instabilities. The model can be easily incorporated into a standard macromodel for simulation purposes or used analytically for accurate circuit design based on CFAs. As a consequence of this approach, some improvements in the CFA structure could be suggested.*

1. INTRODUCTION

The recent developments in complementary bipolar processes have become a major factor in the availability of current-feedback operational amplifiers (CFAs). It is well known that a CFA is an active device whose structure uses the supply-current sensing technique in order to achieve very fast dynamics and very high slew rate capabilities. These characteristics makes the CFA suitable for analog signal processing applications requiring such high performance features [8].

Nevertheless, as previous works [1,7] and the manufacturer's data sheets [2] point out, there is a high sensitivity to loading conditions in the frequency response. In general, the phase margin decreases with increasing load resistance, and for load capacitances the circuit can easily fall into an unstable behavior.

As far as CFA modeling is concerned, we can generally consider two kinds of models. On one hand, there exists simple conceptual models useful for analytical purposes [3]-[4], and on the other hand, complex simulation macromodels [5],[1],[2] are considered. Most of the models do not predict the unstable behavior with load variations. Only a few of the more complex macromodels predict instability, since they include the whole transistor output stage [1]. Hence, they do not give an explanation of which is the cause of the load-dependent instabilities. The proposed new frequency model, obtained through the analysis of the different stages of the standard CFA, correctly models this behavior at circuit level.

2. CFA STAGE MODELING

The basic simplified block diagram in Fig.1 illustrates the CFA architecture based on an input buffer, two complementary current mirrors and a transimpedance stage followed by an output buffer.

The input buffer's task is to force V_{in}^- to follow V_{in}^+ . Because of the buffer's low output impedance, current can flow in or out of the inverting input. This current equals the difference of the buffer bias currents. Since these currents are conveyed via a pair of complementary Wilson current mirrors, the error current is recovered and converted to voltage in the transimpedance node. Finally there is a need for buffering this node in order to achieve low output impedance, so that the output signal is a voltage.

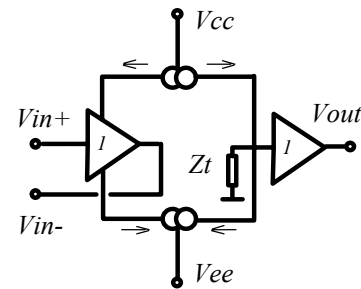


Fig.1 Conceptual schematic CFA model

2.1. BUFFERS

Broadly, the most basic CFA buffer depicted in Fig.2 can be seen as a four transistor Darlington push-pull stage, or a dual complementary CC-CC (common collector-common collector) emitter follower stage.

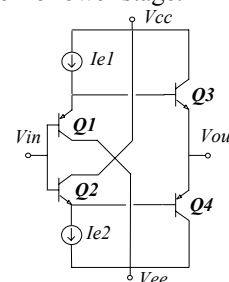


Fig.2 CC-CC buffer stage.

Input and output impedances of this stage are critical in the circuit implementation of a CFA. The input

$$Z_{in}(s) = \frac{\beta^2 (R'_L + r_e) r_o}{\left[\beta^2 r_o (R'_L + r_e) C_\mu + \beta (\beta (R'_L + r_e) + 2r_o) r_e C_\mu \right] s + \beta (R'_L + r_e) + r_o} \left\{ \begin{array}{l} R_{in} = \beta [\beta (R'_L + r_e) / r_o] \\ C_{in} = C_\mu + \frac{\beta (R'_L + r_e) + 2r_o}{\beta (R'_L + r_e) r_o} C_\pi \end{array} \right. \quad (1)$$

$$Z_{out(cc-cc)}(s) = r_e \frac{\frac{R_s (C_\pi + 2C_\mu)}{\omega_T} s^2 + \left(\frac{2}{\omega_T} + R_s \left(\frac{2C_\pi}{\beta} + C_\mu \right) \right) s + 1 + \frac{R_s}{\beta^2 r_e}}{\left(\frac{s}{\omega_T} + 1 \right) \left(\frac{2s}{\omega_T} + 1 \right) (R_s C_\mu s + 1)} \quad (2)$$

impedance affects the non-inverting input impedance and transimpedance. On the other hand the inverting low input impedance and the CFA's output impedance are directly related with the buffer's output impedance. The expressions (1) and (2) describe these input and output impedances derived from hybrid- π small-signal [6] analysis of the CC-CC implementation.

These expressions show the effect of the resistances R_L (load) or R_s (source) over these impedances. Indeed, any variation in the buffer input impedance will directly affect the parasitic impedance in the transimpedance node and therefore the CFA dynamics will strongly change. Although usually not considered in amplifier stages, the non-unilaterality of the unity-gain follower must be taken into account in the CFA modeling, since its effect is increased by the nature of the transimpedance opamp.

Therefore, the classic model of buffers with constant values of input and output impedances will be no longer valid, and a model including a parameter of bilaterality is needed. This model will improve bandwidth and frequency response predictions (even instability). In order to include the non-unilaterality effect, a two-port g -parameter model, depicted in Fig.3, has been selected.

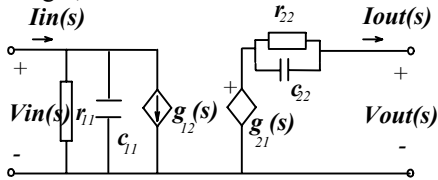


Fig. 3 g -parameter model of CFA buffers

The first-order models of parameters g_{11} and g_{22} (modeling input and output impedances of the buffer stage under ideal load conditions, *i.e.*, $R_L = \infty, R_s = 0$), are:

$$R_{11} \cong \frac{\beta r_o}{2}, \quad C_{11} \cong \frac{2C_{jc}}{\left(1 + \frac{V_{CC}}{0.75}\right)^{1/3}} \quad (3)$$

$$R_{22} \cong 1/2g_m, \quad C_{22} \cong 2C_\pi \cong \frac{2g_m}{\omega_T}, \quad \frac{1}{R_{22}C_{22}} \cong \omega_T \quad (4)$$

The parameter modeling the signal transfer from input to output can be expressed as $g_{21}(s) \cong 1$, since it has a very close pole/zero with $\omega_z / \omega_p = 1 + (V_T / V_A)$.

Finally the parameter that models the unilaterality, $g_{12}(s)$, is given in equation (5). This parameter has a low frequency value of $1/\beta^2$ and it approaches unity at high frequencies, as C_π tends to shorten the base and the emitter of the bipolar transistor in the emitter follower. Fig.4 depicts the HSPICE simulation at the transistor level of the buffer stage for the parameter $g_{12}(s)$, showing a good agreement with the theoretical expression.

$$g_{12}(s) = \frac{1}{\beta^2} \frac{(\beta s / \omega_T + 1)^2}{(s / \omega_T + 1)^2} \quad (5)$$

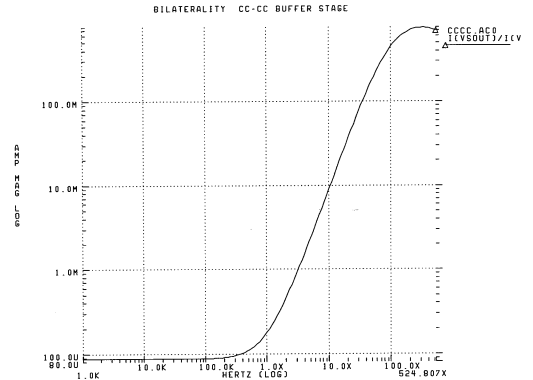


Fig.4 Simulation of g_{12} parameter frequency response.

The combination of the effect of fixed parameter g_{11} and load dependent parameter g_{12} results in the correct modeling of the whole input impedance of buffer stages expressed in (1). Note that now the effect of loads over performance is concentrated in one frequency dependent parameter.

2.2. MIRRORING STAGE

As has been introduced, bias currents of the input buffer are sensed and conveyed to the transimpedance node. A pair of complementary Wilson or improved Wilson current mirrors are used with this objective [1]. The whole stage (both NPN and PNP mirrors) can be modeled as an ideal current controlled current source, with a certain frequency

dependent transfer function given in expression (6), and a finite output impedance, shown in expression (7).

$$F(s) = \frac{\frac{2}{\omega_T} s + 1}{\frac{2}{\omega_T^2} s^2 + \frac{2}{\omega_T} s + 1} \cong \frac{1}{\frac{1}{\omega_T} s + 1} \quad (6)$$

$$Z_{out}^{Wilson}(s) = \frac{\beta r_o}{4} \frac{\frac{2}{\omega_T^2} s^2 + \frac{2}{\omega_T} s + 1}{\left(\frac{1}{\omega_T^2} s^2 + \frac{1}{\omega_T} s + 1 \right) (\beta r_o C_\mu s + 1)} \cong \frac{\beta r_o}{4} \frac{1}{\beta r_o C_\mu s + 1} \quad (7)$$

Expression (7) shows that for modeling purposes, the Wilson mirror's output impedance can be modeled as a first-order RC parallel combination. Unlike the transimpedance part due to output buffer's input impedance, this RC contribution is not dependent on load conditions. This output impedance, in parallel with output buffer's input impedance results in the parasitic high value impedance $Z_T(s)$ at the I-V conversion node.

2.3. CFA FREQUENCY MODEL

As has been previously mentioned, the CFA consists of two buffers and a mirroring stage. Thus, the complete CFA frequency model can be composed from previous stage models. The resulting model is depicted in Fig.5. Although this is a linearized model which predicts the small-signal behavior, it can be made more complete with other elements modeling large-signal effects such as saturation, and offset effects. Hence, the model becomes valid for transient simulation predicting the instabilities and the actual overshoot amount in pulse responses for different load conditions, owing to the inclusion of the proposed dynamic model.

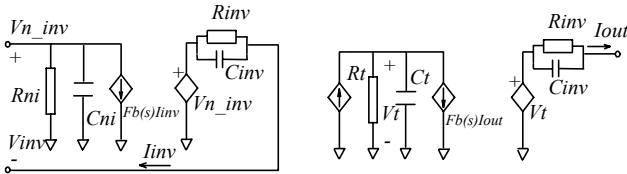


Fig. CFA frequency model

3. SIMULATION RESULTS

The CFA presents good performance when driving low impedance cables, such as in video amplifier circuits, but it becomes unstable with high loads. For instance, a typical experimental configuration of the device as a follower presents instability when it is directly measured with an oscilloscope. In Fig.6, there is depicted a simulation with the proposed model and the manufacturer's macromodel in a closed-loop CFA buffer loaded with $Z_L = 1M\Omega / 20pF$, with this being the typical input impedance of a probe or an oscilloscope. The figure shows that the new model predicts the instability while the

manufacturers macromodel shows a discrepancy from experimental qualitative results.

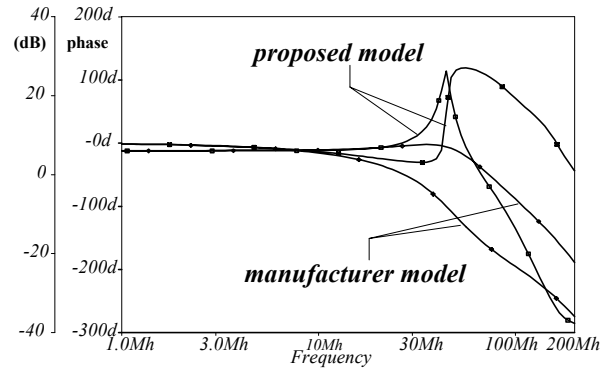


Fig.6 Simulation of both macromodels of a closed-loop CFA buffer with load $Z_L = 1M\Omega / 20pF$

In the following comparisons in Fig 7, it can be seen that the proposed model predicts the performance expected from the data sheets under different resistive and capacitive loading, while the manufacturer macromodel does not predict the actual results. The device EL2020 from ELANTEC was selected [9], but other manufacturers' devices (such as OPA603, Burr-Brown or OP-260, Analog Devices) present the same variations with load.

The progressive instability can be interpreted analytically from our model, since the transimpedance complex function related with (1) increases its order as $Z_L(s) = 1/Cs$, and therefore reduces the phase margin. The model also predicts the instability due to reactive feedback caused by the current-feedback nature.

4. CONCLUSIONS

A new modeling of the input and output buffer stages of the CFA including their non-infinite isolation between output and input has been presented. This frequency-dependent model, which is able to be added to every model independently of its complexity, predicts accurately the frequency performance of CFA circuits with different loads, gives insight into the nature of some effects like unwanted instability and, therefore, improves circuit design. Some improvements over the CFA structure are inferred from the previous analysis. For instance, CMOS implementations of CFAs will provide better independence of transfers and impedances on loads at low and medium frequencies, where the MOS transistor is mostly unilateral. In addition to this, a possible improvement in performance is foreseen if the output buffer is changed by an amplifying stage, which would make the transimpedance more insensitive to loads.

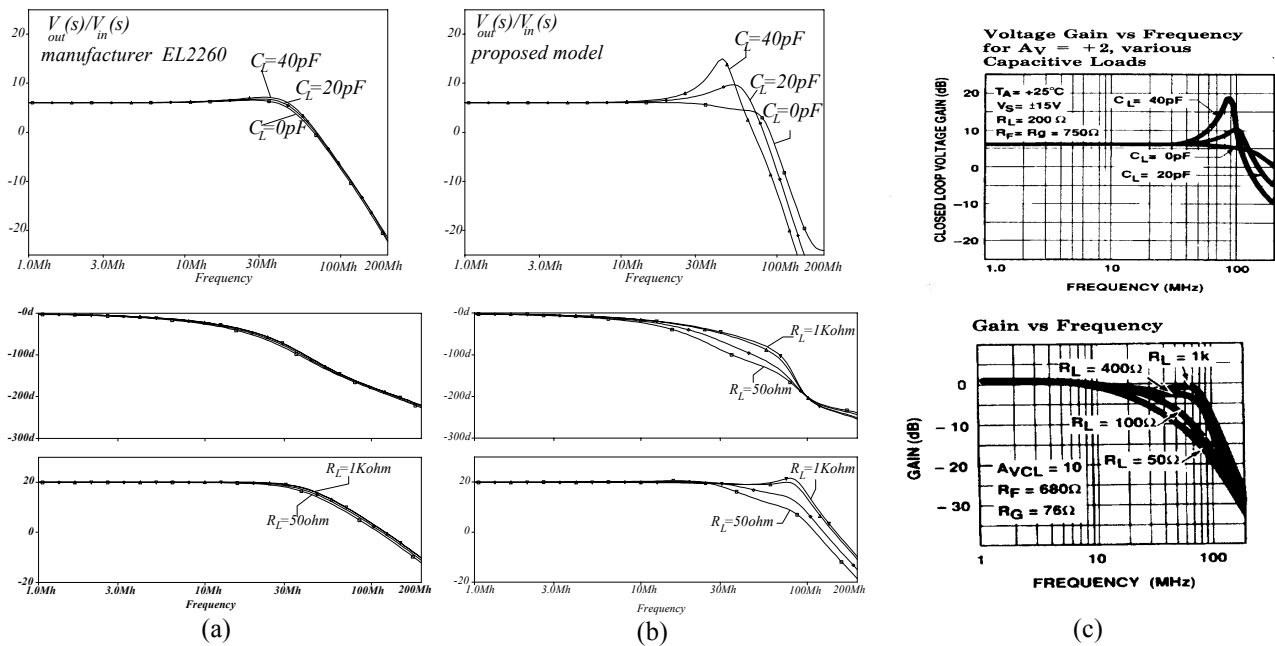


Fig. 6. Several responses. Comparisons between manufacturers (a) and new model (b) plus data sheet curves (c).

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