BEHAVIORAL MACROMODELING OF CURRENT FEEDBACK AMPLIFIERS AND DRIVE-R – AMPLIFIERS

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This paper presents new current feedback amplifier and drive-R – amplifier macromodels at behavioral level. They accurately models basic differential-mode electrical characteristics, the offset input voltage and current, the input voltage noise, the output voltage swing, short-circuit current and the input and output impedances. For creating the model, simplification and build-up techniques known from modeling voltage feedback amplifiers have been adapted. As examples model parameters are extracted for the AD8001 and OPA860 from Analog Devices and Texas Instruments, respectively. To confirm the validity of the proposed macromodels, simulation results are compared with the manufacturer's data. The proposed behavioral macromodels leads to a low analysis time, with higher accuracy and a better convergence in comparison with other op amps methods of modeling.

Keywords: analog circuit design, current feedback amplifier, drive-R – amplifier, behavioral modeling, simulation.

1. INTRODUCTION

Current feedback amplifiers (CFAs) and drive-R – amplifiers (or diamond transistors), as a variety of op amps family, have been realized to overcome the finite gain-bandwidth product of voltage feedback amplifiers (VFAs). The internal structure of CFAs consists of a unity gain buffer (input stage), connecting the non-inverting input to the inverting input. Since the output impedance of this buffer is approximately zero, the feedback signal is treated as a current rather than a voltage. This current is then mirrored by a current-to-voltage converter (middle stage), which consists of a large transimpedance ($|Z_t| \geq 1M\Omega$), and an output buffer (output stage). In fact, CFAs amplify currents rather than voltages, which make it possible for CFA-based circuits to operate at higher frequencies than those, realized with VFAs. Drive-R – amplifiers or current-controlled current sources can by obtained by CFAs, if the output buffer is removed. Drive-R – amplifiers can be viewed as *ideal transistors*. Like transistors, they have three terminals – a high impedance input (*base*), a low-impedance input/output (*emitter*), and the current output (*collector*). Drive-R – amplifiers, however, are self-biased and bipolar. The output collector current is zero for a zero base-emitter voltage. For the AC mode of operation the output current is bipolar and centered about zero. Some of monolithic drive-R – amplifiers also include uncommitted closed-loop unity gain buffer. This provides an opportunity to realize a CFA.

The majority of published PSpice based CFA and drive-R – amplifiers macromodels are presented as *device– (transistor–) level models* or as high level complexity models (ordinary the input stage is device – level model and other stages consists quite a number of common RLC components, controlled sources and ideal diodes) [1-6]. In order to decrease the simulation time and improving the convergence behavioral macromodels for CFA and drive-R – amplifiers have been developed. The proposed simulation macromodels present basic dc and ac electrical characteristics and parameters, as well noise voltage spectral density effects are included.

2. MACROMODELS DEVELOPMENT

The proposed macromodels of CFAs and drive-R – amplifiers are developed following the design method based on a Top-Down analysis approach and applying simplification and build-up technique, known from modeling voltage feedback amplifiers. The circuit diagrams of new macromodels are shown in Fig. 1 and Fig. 2, respectively. Various stages include Analog Behavioral Macromodeling (ABM) elements, passive components and two ideal diodes. The model parameters are given without concrete numerical values. During the modeling of a particular op amp the numerical values are obtained by datasheet parameters for the actual device.

2.1 Macromodeling of current feedback amplifiers

The equivalent circuit of the CFA model, represented in Fig. 1, is subdivided into three stages. *The input stage* consists of ideal independent current and voltage sources (Vio, Iib+, IiB- and Iio), linear controlled sources (E1, F1, FN0, GN0, FN1, GN1 and HN), resistors (RINP, RINN, RN0, RN1 and RX1) and capacitors (CINP and CINN). RINP, RINN, CINP and CINN model the non-inverting (in+) and inverting (in-) input impedances. Input bias currents of the inverting and non-inverting pins is generated by independent current sources Iib+, IiB- and Iio, connected to node in+ and in-, respectively.

(1a) $I_{in+} = I_{iB} + \frac{I_{io}}{2}$ and

(1b) $I_{in-} = I_{iB} - \frac{I_{io}}{2}$.

In this way, the complexity of the original *transistor- level* model is reduced. Also it's solving some dc convergence problems observed in simulation experiments with original macromodel.

The approach used for improving the noise effects modeling to the CFA macromodel is similar to the techniques used in [7]. As it is shown in Fig. 1, the equivalent circuit of the input stage including noise sources that simulate the thermal (white) noise and 1/f noise (Flicker noise) of an actual CFA. The current-controlled voltage source HN reflects the voltage from the additionally defined noise voltage stage (HN - device convert the noise current into a voltage). The noise stages of the model consists two resistors RN0 and RN1 that generate white noise current, two current-controlled current sources FN0 and FN1, which are measure noise currents and RX1-CN1 - group defining the corner frequency of the 1/f noise. The *VVal* parameter used in the equation for the resistor value defined level of the white noise generated by the circuit. The rms voltage $\overline{e}_{N_o} = VVal$ is the white noise of the op amp per $\sqrt{Hz}$ and can be found by

$$(2) \qquad \overline{e}_{N_o} = \sqrt{\overline{e}_{N,DS}^2 - \overline{e}_{N,\mathrm{Res}}^2}$$

where the rms voltage $\overline{e}_{N,DS}$ is the datasheet value of the white noise per $\sqrt{Hz}$ and the rms voltage $\overline{e}_{N,\mathrm{Res}}$ is the white noise generated by large-value resistors commonly used in macromodels.

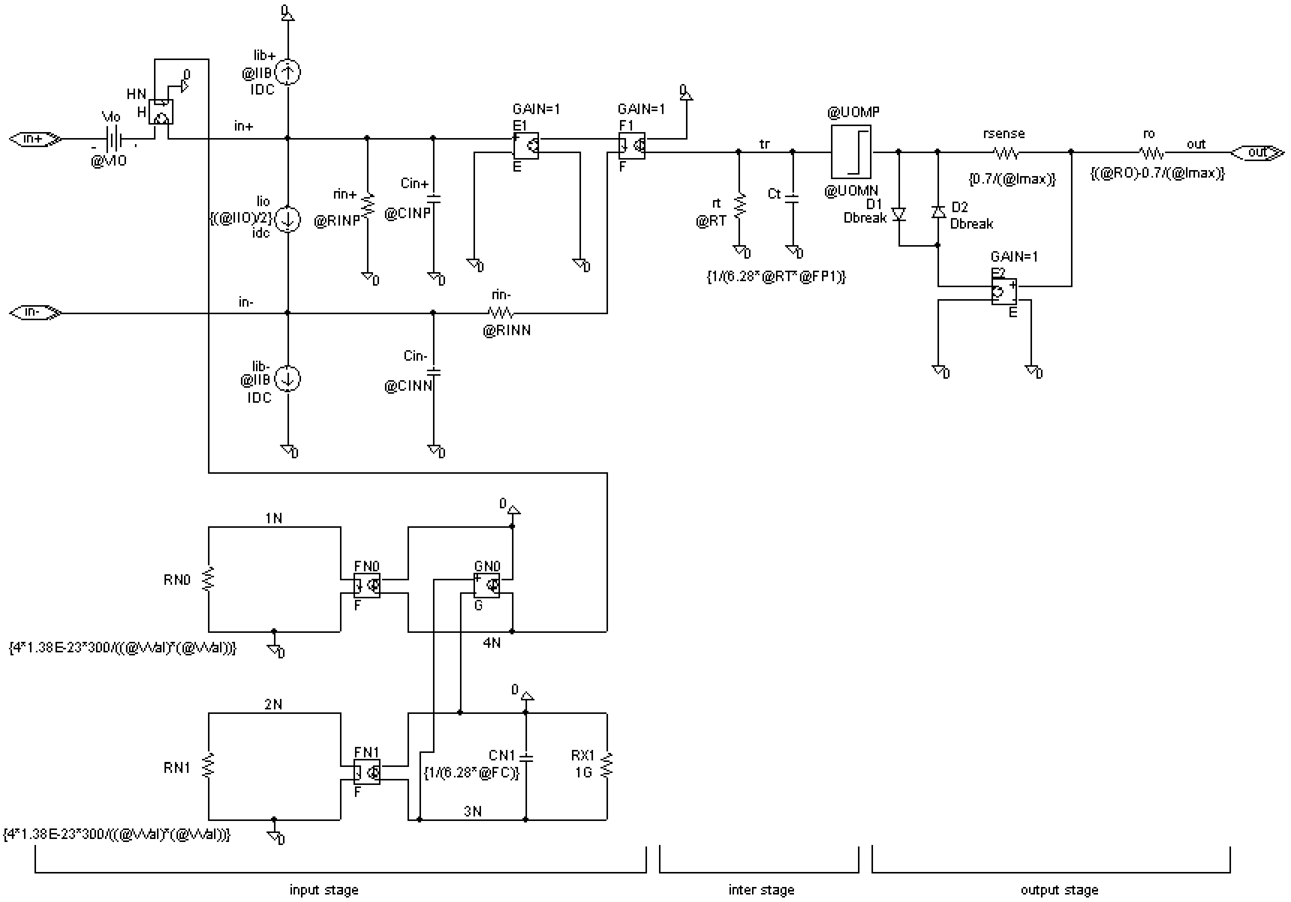

Fig. 1. Equivalent circuit of the current feedback amplifier macromodel.

From the equivalent circuit it can be observed that the inverting terminal is driven by a unity gain buffer, which is realized with the linear voltage-controlled voltage source E1. The function of the unity gain buffer is to drive the inverting input to the same voltage as the non-inverting input much like a VFA does via negative feedback. Since the output impedance of this buffer is small ($50...100\Omega$), the feedback error signal is treated as a current rather than a voltage. During input transients, an error current will flow into or out of the input buffer. This current is then mirrored by a current-controlled current source F1. The coefficient k_{F1} of the controlled source F1 is selected equal to unity, which is corresponding to the transfer function of the real CFA.

The middle stage of the equivalent circuit represents the ac small-signal transfer function of the real op amp. The transimpedance of the CFA is provided by the resistor RT and capacitor CT. The voltage at node *tr* is then converted by a second buffer, realized with voltage-controlled voltage source Elimit. This buffer set up the voltage of the output of the macromodel. The transfer function of the non-inverting configuration can be adequately modeled by the following expression:

(3)

$$A_U(p) = \frac{\left(p + \dfrac{1+\dfrac{R_F}{R_N}}{R_F C_{in-}}\right)\dfrac{1}{C_T R_{in-}\left(1+\dfrac{R_o}{R_L}\right)}}{p^2 + p\dfrac{1}{C_{in-}R_{in-}}\left(1+\dfrac{R_{in-}}{R_N}+\dfrac{R_{in-}}{R_F}\right) + \dfrac{1}{C_T C_{in-} R_{in-} R_F\left(1+\dfrac{R_o}{R_L}\right)}} = \frac{(p+\omega_z)H}{p^2 + \dfrac{\omega_p}{Q_p}p + \omega_p^2},$$

where the resistor R_F is connected between the inverting input and the output of the model, the resistor R_N is connected between the inverting input and the analog ground (resistors R_F and R_N set up negative feedback), $\omega_z = \dfrac{1+\dfrac{R_F}{R_N}}{R_F C_{in-}}$ is the frequency of the dominant zero, $\omega_p = \dfrac{1}{\sqrt{C_T C_{in-} R_{in-} R_F\left(1+\dfrac{R_o}{R_L}\right)}}$ is the frequency of the dominant pole, p denotes the Laplace variable, $Q_p = \dfrac{1}{1+\dfrac{R_{in-}}{R_N}+\dfrac{R_{in-}}{R_F}}\sqrt{\dfrac{C_{in-}R_{in-}}{R_F C_T\left(1+\dfrac{R_o}{R_L}\right)}}$ is the quality factor of the non-inverting configuration, R_G is the resistance of the load and $H = \dfrac{1}{C_T R_{in-}\left(1+\dfrac{R_o}{R_L}\right)}$ is a coefficient at high frequency.

In an expression (3) dc voltage gain ($\omega \approx 0$) of the amplifier is determined with: $A_{Uo} = 1 + \dfrac{R_F}{R_N}$. At low frequency ($\omega < \omega_z$) the frequency of the dominant pole (using the condition $R_o << R_T$) is

$$f_p = 1/\left\{2\pi C_T R_F\left(1+\frac{R_{in-}}{R_N}+\frac{R_{in-}}{R_F}\right)\left(1+\frac{R_o}{R_L}\right)\right\}. \qquad (4)$$

The data required for implementing $A_U(p)$ are obtained from the manufacturer datasheet, by simulations (if the device-level model is available) or by means of experimental procedures of the actual device. More complex transfer function can be reproduced by adding high frequency poles and zeros.

The output stage of the CFA macromodel like VFA macromodel simulates, proper dc and ac *output resistance* ($R_{o,DC}, R_{o,AC}$), *output voltage swing* (U_{omp} and U_{omn}) and *maximum output current* ($I_{o\max}$). The output stage consists of a voltage follower, realized with voltage-controlled voltage source Elimit, short-circuit current limiting stage (E2, D1-D2 and Rsense) and resistor Ro represent output resistance which determines the behavior of the model when driving heavy loads R_L. The parameters UOMP and UOMN of the voltage source Elimit produce the desired maximum output voltage.

2.2 Macromodeling of drive-R – amplifiers

The equivalent circuit of the drive-R – amplifier model, represented in Fig. 2, is subdivided into two stages (input and output stage). The large part of elements corresponds to the elements from the CFA macromodel. The new elements are the voltage-controlled voltage source Elimit and two voltage-controlled switches (Somp and Somn). The Elimit define the maximum input voltage and the switches Somp and Somn produce the desired maximum output voltage. The voltages $\pm 0{,}2V$ from the equations for the VOFF parameters reflect the saturation voltages of the output transistors in the actual device.

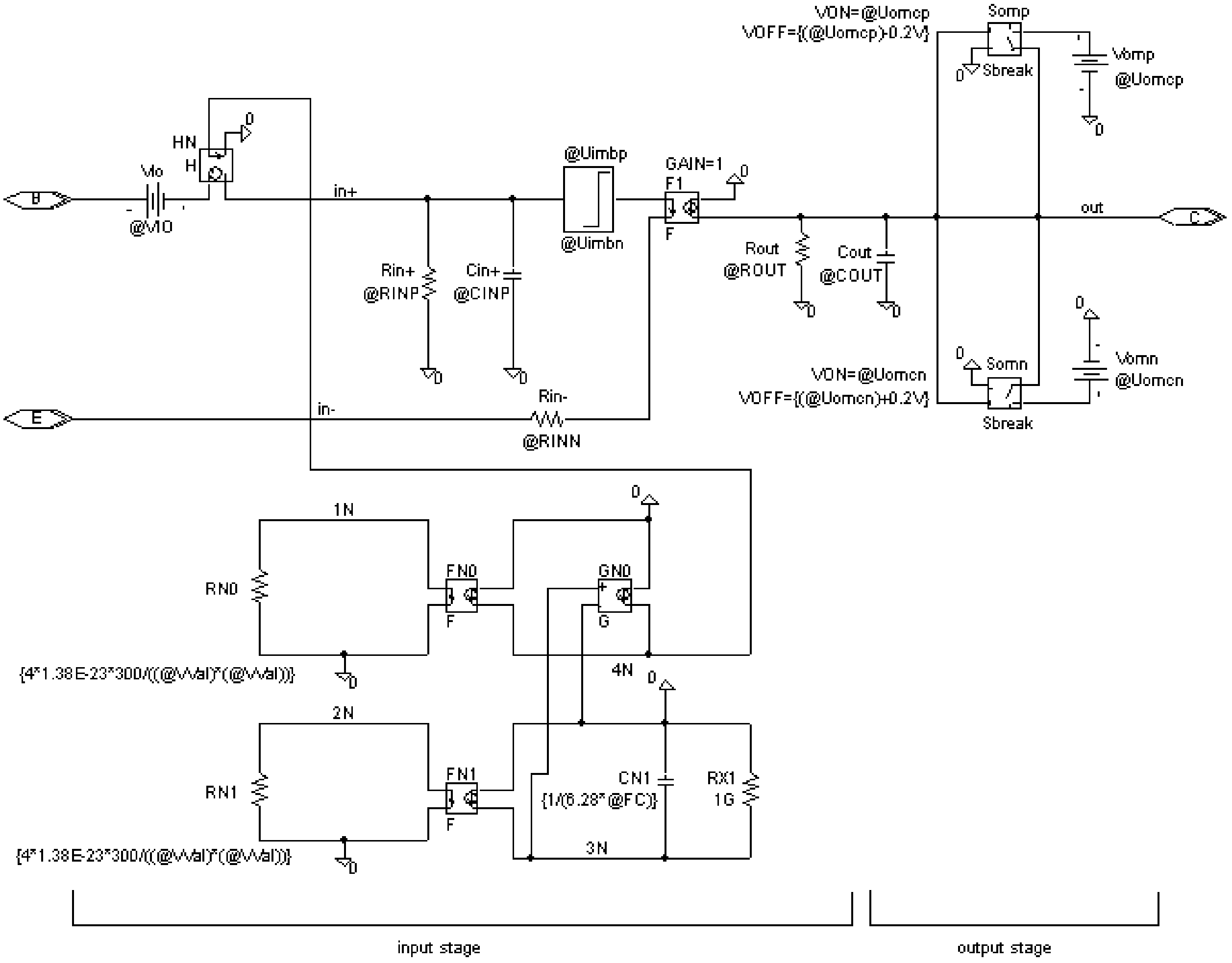

Fig. 2. Equivalent circuit of the drive-R – amplifier macromodel.

The transfer function of the forward amplifier (or common-E amplifier) with drive-R – amplifier can be modeled by the following expression

$$(5)\qquad \dot{A}_U = \frac{A_{Uo}}{\left(1 + j\dfrac{f}{f_{p1}}\right)\left(1 + j\dfrac{f}{f_{p2}}\right)},$$

where $f_{p1} = 1/[2\pi(R_{in+} \parallel R_G)C_{in+}]$ (R_G is the resistance of the input generator) and $f_{p2} = 1/[2\pi(R_{out} \parallel R_L)C_{out}]$ is the $-3dB$ frequencies for the dominant and second pole, respectively.

In an expression (5) dc voltage gain of the amplifier is determined with:

$$(6)\qquad A_{Uo} = (R_L \parallel R_{out})/(R_E + R_{in-}),$$

where the resistor R_E is connected between the inverting input (E-emitter) and the analog ground.

Some of drive-R – amplifiers also include uncommitted closed-loop unity gain buffer. The equivalent circuit of the closed-loop unity gain buffer is shown in Fig. 3. The circuit has non-symmetrical input and output stage. The structure and behavior of various elements corresponds to the elements from input and output stage of the VFA model, presented in [7].

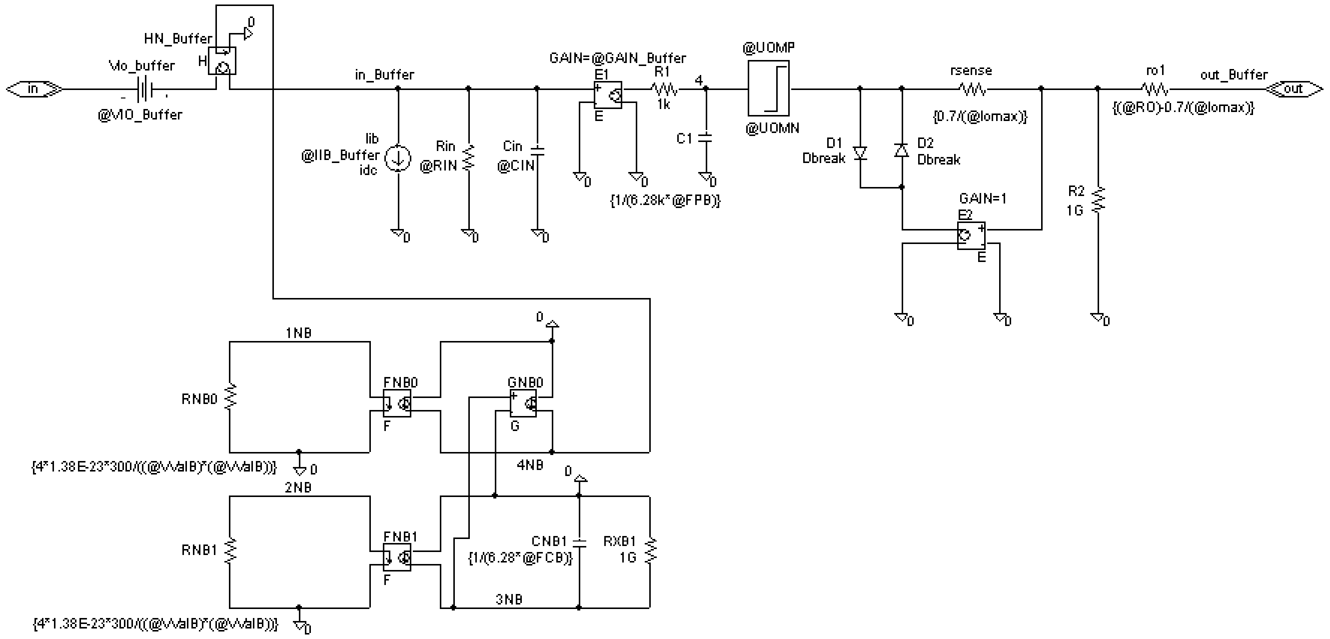

Fig. 3. Equivalent circuit of the closed-loop unity gain buffer macromodel.

3. MACROMODELS PERFORMANCE

In this section, a numerical examples are used to illustrate the development of the parameters of the CFA macromodel and drive-R – amplifier. For examples, the electrical characteristics and parameters of the AD8001AN CFA and the OPA860 drive-R – amplifier are used. In Table 1 and 2 comparisons between simulation results and data sheet parameters are given.

Table 1. CFA performance characteristics ($T_A = +25°C$, $V_{CC} = \pm 5V$ and $R_L = 100\Omega$)

Parameter	**Conditions**	**CFA_lin macromodel**	**AD8001/AD macromodel**	**AD8001AN data sheet**
DC performance				
Input offset voltage	-	$2mV$	$5mV$	$2mV$
− Input bias current	-	$5\mu A$	$6\mu A$	$5\mu A$
+ Input bias current	-	$3\mu A$	$25\mu A$	$3\mu A$
Open-loop transresistance	-	$600k\Omega$	$316k\Omega$	$600k\Omega$
AC performance				
–3 dB Small Signal Bandwidth	$A_U = +1$ $A_U = +10$	$1000MHz$ $256MHz$	$360MHz$ $408MHz$	$880MHz$ $260MHz$
Dominant pole frequency	open-loop	$700kHz$	$896kHz$	$700kHz$
Slope	open-loop	$-20dB/dec$	$-20dB/dec$	$-20dB/dec$
Noise performance				
Input voltage noise	$f = 1kHz$ $R_G = 0$	$2nV/\sqrt{Hz}$	$1nV/\sqrt{Hz}$	$2nV/\sqrt{Hz}$
Corner freq. for 1/f noise	$R_G = 0$	$12{,}5Hz$	no simulate 1/f n.	$12{,}5Hz$
Input characteristics				
+ Input resistance − Input resistance	-	$10M\Omega$ 50Ω	$3{,}3M\Omega$ 51Ω	$10M\Omega$ 50Ω
+ Input capacitance	-	$1{,}5pF$	$1{,}5pF$	$1{,}5pF$
Output characteristics				
Output voltage swing	$R_L = 150\Omega$	$\pm 3{,}14V$	$\pm 2{,}68V$	$\pm 3{,}1V$
Short circuit current	$R_L = 0\Omega$	$86{,}13mA$	$85{,}64mA$	$85mA$
Output resistance	open-loop	50Ω	50Ω	50Ω

Table 2. Drive-R – amplifier performance characteristics ($T_A = +25°C$, $V_{CC} = \pm 5V$ and $R_L = 500\Omega$)

Parameter	**Conditions**	**Drive-R_lin macromodel**	**OPA860 data sheet**
Drive-R – amplifier DC and AC performance			
Input offset voltage	-	$3mV$	$3mV$
Transconductance	$R_E = 0\Omega$	$95{,}03mA/V$	$95mA/V$
–3 dB Small Signal Bandwidth	$A_U = +5$ $u_i = 200mV$	$79{,}3MHz$	$80MHz$
Input voltage noise	$f = 1kHz$ $R_G = 500\Omega$ $R_E = 89{,}5\Omega$	$2{,}403nV/\sqrt{Hz}$	$2{,}4nV/\sqrt{Hz}$
Corner freq. for 1/f noise	$R_G = 500\Omega$	$300Hz$	$300Hz$
+ Input resistance − Input resistance	-	$455k\Omega$ $10{,}52\Omega$	$455k\Omega$ $10{,}5\Omega$
+ Input capacitance	-	$2{,}1pF$	$2{,}1pF$
Output Voltage Swing	-	$\pm 4{,}2V$	$\pm 4{,}2V$

Output impedance	-	$54k\Omega \parallel 2pF$	$54k\Omega \parallel 2pF$
Buffer DC and AC performance			
Voltage gain	-	$0{,}997V/V$	$1V/V$
–3 dB Small Signal Bandwidth	$u_i = 200mV$	$1200MHz$	$1200MHz$
Input offset voltage	-	$16mV$	$16mV$
Input bias current	-	$3\mu A$	$3\mu A$
Input impedance	-	$1M\Omega \parallel 2{,}1pF$	$1M\Omega \parallel 2{,}1pF$
Output voltage swing	-	$\pm 3{,}98V$	$\pm 4V$
Short circuit current	$R_L = 0\Omega$	$67mA$	$60mA$
Output resistance	-	$1{,}4\Omega$	$1{,}4\Omega$
Drive-R – amplifier + Buffer performance			
–0,1 dB Small Signal Bandwidth	$A_U = +2$ $u_i = 200mV$	$40MHz$	$42MHz$

4. CONCLUSIONS

In this paper behavioral macromodels of CFA and Drive-R – Amplifier based on the datasheet electrical characteristics has been presented. The proposed models including effects such as accurate inverting and non-inverting input impedance, dc transfer function, ac small-signal characteristic, transient response under a wide range of conditions, noise, input and output voltage/current limitation and output impedance. The models are not capable of simulating PSRR, temperature effects, board parasitics, differences between package styles, distortion (harmonic, intermodulation), etc. The created op amp macromodels can be useful parts for simulation modeling of various analog electronic circuits and digitally programmable analog circuits such as PGAs, attenuators, SHAs, programmable active filters, oscillators etc.

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5. REFERENCES

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