ACTA TECHNICA NAPOCENSIS
Electronics and Telecommunications

ANALYSING THE STABILITY OF CIRCUITS BASED ON OPERATIONAL AMPLIFIERS BY USING FREQUENCY-DOMAIN SIMULATIONS

Marius NEAG Raul ONEȚ Marina ȚOPA
Technical University of Cluj-Napoca, Faculty of Electronics, Telecommunications and Information Technology
26, G. Baritiu St, Cluj-Napoca, Romania, Phone: +40264 401470, Fax:+40264 591689, Marius.Neag@bel.utcluj.ro

Abstract: This paper analyzes in detail two of the most popular methods of determining the loop gain of OpAmp-based feedback circuits through frequency-domain Spice simulations. The limitations of the simpler method – that involves breaking the feedback loop by inserting an independent voltage source with DC=0 and AC=1 – are highlighted in comparison with a more precise method, based on the Rosenstark theorem. The discussion encompasses all types of amplifiers: the traditional (V-V) OpAmp, the Current-Feedback OpAmp (CFB-OA), the transconductance OpAmp (OTA) and the Current – Current OpAmp with asymmetric inputs (such as a second-generation current conveyor). Recommendations are made based on analytical analysis and sim results.

Key words: *OpAmp based feedback circuits, stability, small-signal loop gain, module and phase margin, Spice simulations.*

I. INTRODUCTION

The standard method for analyzing the small-signal stability of a feedback circuit at a given DC operating point is to ascertain the phase- and module-margin. For this, one has to determine the small-signal loop gain of the circuit – usually called T, the product of the forward gain of the basic amplifier and the gain of the feedback network. There are well known procedures for deriving T analytically [1]: they imply breaking the feedback loop but the loading effect of the feedback network is taken into account when calculating an equivalent gain of the basic amplifier, in order to replicate the closed-loop operating conditions. This approach allows for a simple and intuitive analysis. Its drawbacks are mainly related to its reliance on several approximations without providing a way of estimating their effects; papers such as [2] have proposed ways of dealing with such shortcomings and have extended the method to circuits with multiple inputs and outputs.

However, these analytical methods are not directly applicable for determining the loop gain of a given circuit through simulations: breaking the loop can result in significantly changing the operating point of the circuit – hence its small-signal behavior; the equivalent loadings of the basic amplifiers can be difficult to ascertain through simulations, let alone combining them in order to find out the loop gain, T. Quite a few of the methods proposed in literature for determining T through simulations require additional circuitry that make them less attractive for designers [3].

For circuits based on Operational Amplifiers (OpAmps) there are several simplified methods for determining T which are widely used in practice, due to their easy-of-use and effectiveness. However, no detailed analysis of their precision has been reported in the literature.

Two of the most popular such methods are thoroughly analyzed in this paper: a very simple approach – that involves breaking the feedback loop by using an independent voltage source with DC=0 and AC=1 – and a more precise one, based on the Rosenstark theorem [4].

Section II deals with the case of a traditional, voltage-to-voltage, OpAmp as the basic amplifier, Section III covers the case of the Current-Feedback OpAmp, Section IV presents the case of the Operational Transconductance Amplifier, while the case of the Current-Current Amplifier is presented in Section V. Conclusions are drawn based on both analytical and simulation results; finally, practical recommendations for designers are made.

II. FEEDBACK CIRCUITS BASED ON THE TRADITIONAL (V-V) OPAMP

A. A popular method for determining the loop gain, T

Figure 1 presents a circuit that uses a generic OpAmp as the basic amplifier and a reciprocal two-ports network to close a classical series-shunt feedback loop [1]. Figure 2 shows the same circuit with the feedback network replaced by its equivalent Π network and the generic OpAmp replaced by the standard model of a traditional, voltage-voltage amplifier (V-V OpAmp): the model comprises a voltage-controlled voltage source with the gain a_{vv} and the input and output impedances Z_{in} and Z_{out}.

The standard method for determining the loop gain through Spice simulations of such circuits involves two tests, one using a test voltage-source and the other a test current source, both with AC = 1 and DC = 0 [5]. It is relatively difficult to use in practice, as it implies doubling

Manuscript received April 26, 2010; revised June 16, 2010

the complexity of the testbench and significant post-processing of the sim results.

A simplified version of this method – and as such much more popular - uses only a voltage test: it requires that the feedback loop is broken by inserting an independent voltage source V_{AC}, with DC=0 and AC=1. The usual points for breaking the loop are at the inverting input of the OpAmp, as shown in Figure 2.a, points 1-2, or at the OpAmp output, as shown in Figure 2.b, points 3-4.

$$T_R = \frac{a_{VV} Z_{IN} Z_L Z_G}{Z_{IN}Z_L Z_F + Z_{IN}Z_L Z_G + Z_{IN}Z_L Z_{OUT} + Z_{IN}Z_F Z_{OUT} + Z_{IN}Z_G Z_{OUT} + Z_F Z_G Z_{OUT} + Z_L Z_F Z_G + Z_L Z_G Z_{OUT}} \quad (4)$$

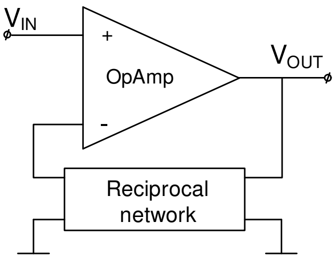

Figure 1. Circuit with a generic OpAmp as the basic amplifier and a reciprocal network closing a classical series-shunt feedback loop

The small-signal loop gain T results from a frequency-domain (AC) Spice simulation by using a simple formula:

$$T_{AC} = -\frac{V_{MEASURED}}{V_{TEST}} \quad (1)$$

It should be noted that the DC operating point of the circuit is not modified by the insertion of the voltage source V_{AC}, as its DC value is zero.

B. A precise method for finding the small-signal loop gain

Another and, as it will be shown, a more precise method for determining T is based on the Rosenstark theorem; this theorem proposes the following formula for the closed-loop gain of a feedback system with the loop gain T [1], [4], [6]:

$$A_{CL} = A_0 \frac{T}{1+T} + \frac{G_0}{1+T} \quad (2)$$

where A_{CL} is the closed loop gain, G_0 is the direct transmission term, $G_0 = A_{CL/T=0}$ and A_0 is the asymptotic gain, $A_0 = A_{CL/T\to\infty}$ (the "ideal" gain in classical feedback theory).

It follows that the loop gain is given by the expression [5], [6]:

$$T_R = -\frac{1}{\frac{1}{T_{vv}} + \frac{1}{T_{ii}}} \quad (3)$$

where T_{ii} is the current-current loop gain, determined with the basic amplifier output short-circuited to ground – for example using the arrangement shown in Figure 3.a – and T_{vv} is the voltage-voltage loop gain, determined with the basic amplifier output left open-circuited, as shown in Figure 3.b.

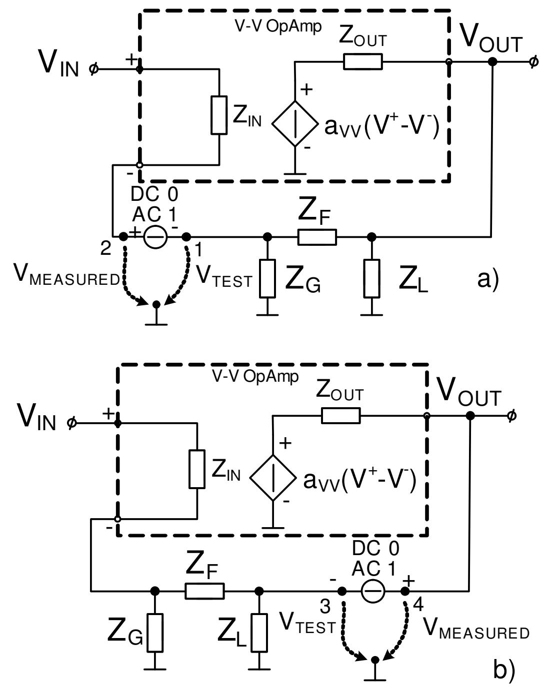

Figure 2.a). Model of the Figure 1 circuit when the basic amplifier is a V-V OpAmp and the feedback two-port is replaced by its equivalent Π network. The loop is broken by inserting an independent voltage source with DC=0, AC=1, either at the input (between points 1-2) or at the output of the OpAmp (between points 3-4).

Obviously, the loop can be broken at the inverting input of the OpAmp, using same circuitry for calculating T_{ii} and T_{vv}.

C. Analytical analysis of the popular (V_{AC}) and the Rosenstark-based methods for determining the loop gain

Equation 4 (shown at the top of this page) gives the loop gain expression determined by applying equation 3 to the circuits shown Figures 3.a. and 3.b. The notation T_R indicates the Rosenstark-based method used for determining T. It is worth noting that the expression of T_R is the same if the loop is broken at the OpAmp inverting input or output - that is, between points 1-2 or points 3-4 in Figure 3.

The analytical analysis of the circuits shown in Figures 2.a and 2.b, by following the V_{AC} method described in Section II.A, yields:

- if the loop is broken at the OpAmp input, that is V_{AC} is inserted between points 1-2 as shown in Figure 2.a:

$$T_{AC\_IN} = \frac{nom_{T_R} + Z_G(Z_L Z_F + Z_L Z_{OUT} + Z_F Z_{OUT})}{denom_{T_R} - Z_G(Z_L Z_F + Z_L Z_{OUT} + Z_F Z_{OUT})} \quad (5)$$

- if the loop is broken at the OpAmp output, that is, if the V_{AC} source is inserted between points 3 and 4 as shown in Figure 2.b:

$$T_{AC\_OUT} = \frac{nom_{T_R} + Z_{OUT}E(Z)}{denom_{T_R} - Z_{OUT}E(Z)} \quad (6)$$

where $E(Z) = (Z_L Z_{IN} + Z_{IN} Z_F + Z_{IN} Z_G + Z_F Z_G + Z_L Z_G)$ and nom_T_R / denom_T_R represent the nominator/denominator of the T_R expression given by equation (4), respectively.

The loop gain expressions should not depend on the point the loop is broken; this requirement is satisfied by the method based on the Rosenstark theorem (equation 4) but not by the V_{AC} method (equations 5 and 6). However, the results obtained using the V_{AC} method converge towards the ones obtained using the Rosenstark-based method if the OpAmp input/output impedance has a very large/small value and the loop is broken at the input/output of the OpAmp, respectively:

$$\lim_{Z_{in}\to\infty} T_{AC\_IN} = \lim_{Z_{in}\to\infty} T_R \,; \ \lim_{Z_{OUT}\to 0} T_{AC\_OUT} = \lim_{Z_{OUT}\to 0} T_R \quad (7)$$

$$\lim_{\substack{Z_{OUT}\to 0\\ Z_{in}\to\infty}} T_{AC\_IN} = \lim_{\substack{Z_{OUT}\to 0\\ Z_{in}\to\infty}} T_R = \lim_{\substack{Z_{OUT}\to 0\\ Z_{in}\to\infty}} T_{AC\_OUT} \quad (8)$$

D. Simulation results for the V_{AC} and the Rosenstark-based methods for deriving the loop gain

In general, the differences between the loop gain characteristics obtained by using the methods presented here are relatively small if the feedback network is purely resistive. However, the differences can become dramatic if the feedback network includes frequency-dependent impedances – as it is the case for most real-life circuits.

As an example, let us consider the circuit shown in Figure 4, implemented with the (model of) the LF357 OpAmp, characterized by a very high input impedance ($10^{12}\Omega$). The feedback network consists of: $R_{F\_RC}=200\Omega$; $C_{F\_RC}=99pF$; $R_F=30k\Omega$; $Z_L=1k\Omega||20nF$; $Z_G=1k\Omega||1nF$.

Figure 5 presents the loop gain characteristics yielded for the Figure 4 circuit by using the Rosenstark-based method and the V_{AC} method. As expected, the Rosenstark-based method gives the same characteristics – the continuous-line plots – if the loop is broken at the output or input of the OpAmp. The V_{AC} method gives practically same results as the Rosenstark-based method if the loop is broken at the input of the OpAmp; however, if the loop is broken at the OpAmp output the V_{AC} method yields significantly different characteristics – the interrupted line plots in Figure 5.

The differences between the characteristics yielded by the two methods considered here may not appear large but the resulting values for the unity loop gain frequency (F_{0dB}) and the phase margin are indeed significant. Table 1 summarizes the unity-gain frequency, F_{0dB}, and the phase margin values for the circuit in Figure 4.

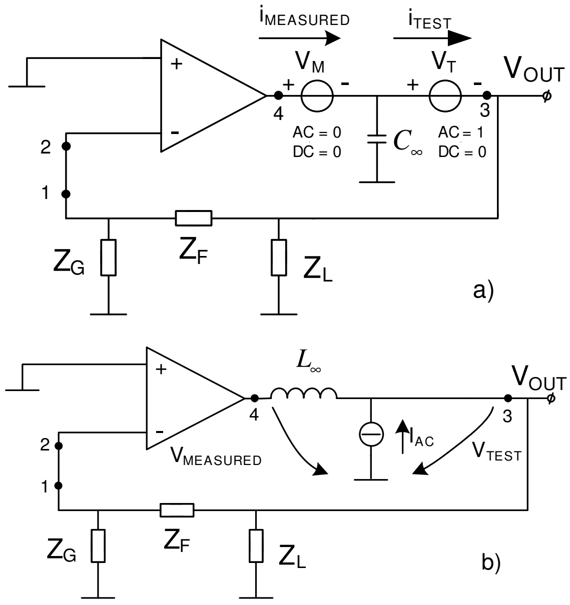

Figure 3. a). Circuit for deriving the current-current loop gain, T_{ii}, b). Circuit for deriving the voltage-voltage loop gain, T_{vv}, as required by the Rosenstark theorem (eq. 3)

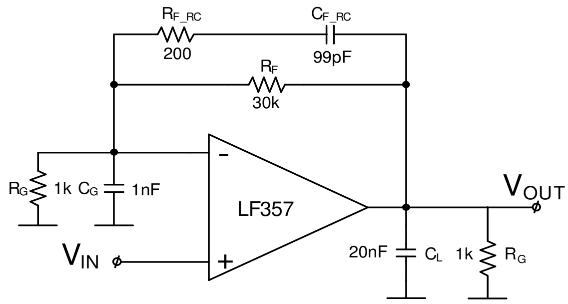

Figure 4. Example of a circuit with a V-V OpAmp basic amplifier and a frequency-dependent feedback network

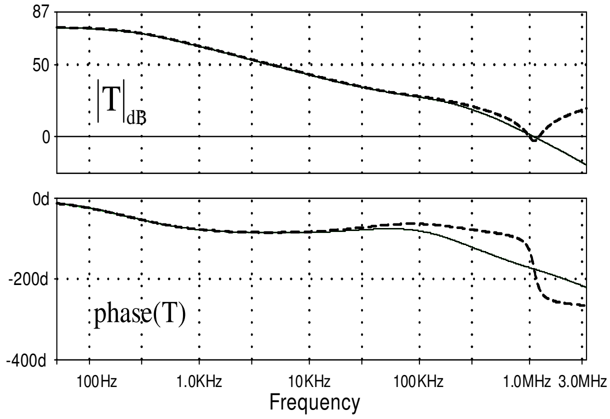

Figure 5. Loop gain characteristics of the circuit shown in Figure 4, as obtained using the Rosenstark-based method (continuous line) and the V_{AC} method with the loop broken at the OpAmp output (interrupted line).

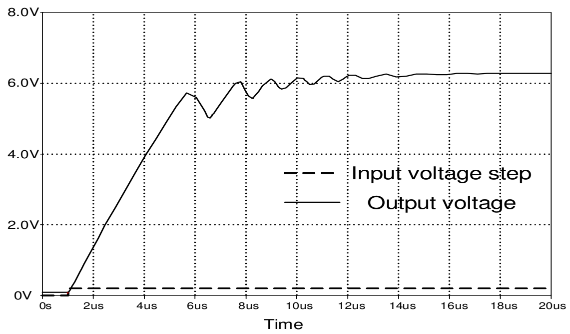

Figure 6. Step response of the circuit shown in Figure 4

Table 1. The unity-loop gain frequency and the phase margin obtained for the circuit shown in Figure 4 by using the methods for determining T compared in this paper

R_{F_RC}=200Ω; C_{F_RC}=99pF; R_F =30kΩ Z_L=1kΩ‖20nF; Z_G=1kΩ‖1nF		
Method	F_{0dB} [kHz]	PhaseMargin [degrees]
Rosenstark-based (T_R)	1100	4.9
V_{AC_IN}	1100	4.5
V_{AC_OUT}	999	51

Figure 6 presents the step response of the circuit shown in Figure 4; its aspect indicates a low phase margin value, as given by the Rosenstark-based method (4.9°) and disproves the larger value given by the V_{AC} method applied by breaking the loop at the OpAmp output (51°).

III. CIRCUITS BASED ON THE CURRENT-FEEDBACK OPAMP

A. Analytical analysis of the two methods for determining T

Figure 7 presents the standard model of a CFB-OA [6]. Let us substitute this model to the V-V OpAmp model in Figures 2.a, 2.b and Figures 3.a. and 3.b., and derive the loop gain expression following the two methods presented in Section II. Both methods require the breaking of the loop, either at the CFB-OA input or at its output, i.e. between points 1-2 or 3-4.

As in the V-V OpAmp case, the Rosenstark-based method gives the same expression – detailed by equation 9 (shown at the top of next page) - for the loop gain, irrespective of the point the loop is broken. The corresponding expressions yielded by the V_{AC} method and by breaking the loop at the CFB-OA inverting input, respectively at the CFB-OA output are:

$$T_{AC\_IN}=\frac{nom_{T_R}+Z_G(Z_F Z_L+Z_{OUT}Z_L+Z_{OUT}Z_F)}{denom_{T_R}-Z_G(Z_F Z_L+Z_{OUT}Z_L+Z_{OUT}Z_F)}$$
$$T_{AC\_OUT}=\frac{nom_{T_R}+Z_{OUT}(Z_{inI}Z_G+Z_LZ_G+Z_{inI}Z_L+Z_FZ_G+Z_{inI}Z_F)}{denom_{T_R}-Z_{OUT}(Z_{inI}Z_G+Z_LZ_G+Z_{inI}Z_L+Z_FZ_G+Z_{inI}Z_F)} \quad (10)$$

where "nom_T_R " and "denom_ T_R " represent the nominator and denominator of the T_R expression given by equation 9.

For ideal input/output CFB-OA impedances one obtains:

$$\lim_{Z_{inI}\to 0} T_{AC\_IN}=\infty;\ \lim_{Z_{OUT}\to 0} T_{AC\_OUT}=\lim_{Z_{OUT}\to 0} T_R \quad (11)$$

Note that in this case the V_{AC} method follows the Rosenstark-based one only if the loop is broken at the output of the CFB-OA, and its output impedance is very low.

B. Simulation results for a "real-life" CFB-OA

Figure 9 presents the loop gain characteristics yielded by the Rosenstark-based method – the continuous line plots – and by the V_{AC} method applied by breaking the loop at the OpAmp input – the dotted line plots – and at the OpAmp output – the interrupted line plots for the following conditions: the basic amplifier is a (model of) the AD844 CFB-OA, as given by its manufacturer. It has the following parameters: Z_{inI} = 50Ω; Z_{OUT} = 15Ω, Z_T = 3MΩ‖5pF, τ_{cm} = 3ns (the time constant of the current mirrors which determines the second CFB_OA pole). The feedback network consists of R_{F_RC}=1kΩ; C_{F_RC}=4.8pF; R_F=1kΩ; Z_L=100pF; R_G=0.9kΩ - see Figure 8.

As expected, the characteristics obtained by using the Rosenstark-based method and by breaking the loop at the output or input of the OpAmp are identical. Table 2 summarizes the F_{0dB} and the phase margin values for the Figure 8 circuit by using the three approaches compared here.

The step response of the Figure 8 circuit is presented in Figure 10. Only the Rosenstark-based method gave a low phase margin value that corresponds to the ringing step response.

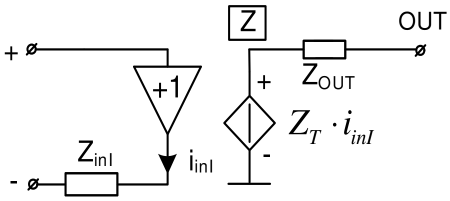

Figure 7. A simple model for the CFB-OA

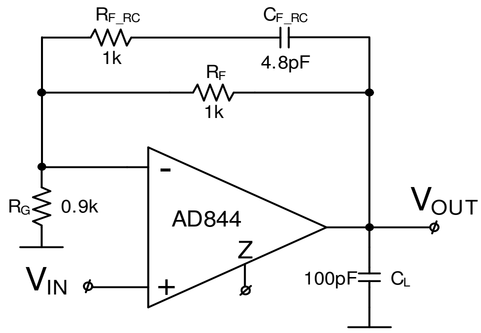

Figure 8. Example of circuit with CFB-OA basic amplifier and a frequency-dependent feedback network.

$$T_R = \frac{Z_T Z_L Z_G}{Z_{inI} Z_L Z_G + Z_L Z_F Z_G + Z_{inI} Z_L Z_F + Z_L Z_G Z_{OUT} + Z_{inI} Z_L Z_{OUT} + Z_F Z_G Z_{OUT} + Z_{OUT} Z_{inI} Z_F + Z_{inI} Z_G Z_{OUT}} \qquad (9)$$

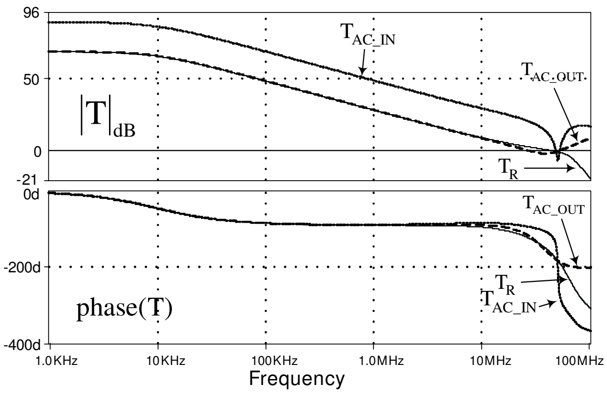

Figure 9. Loop gain characteristics of the Figure 8 circuit obtained by using the Rosenstark-based method (continuous line) and the V_{AC} method with the loop broken at the OpAmp input (dotted line) and output (interrupted line)

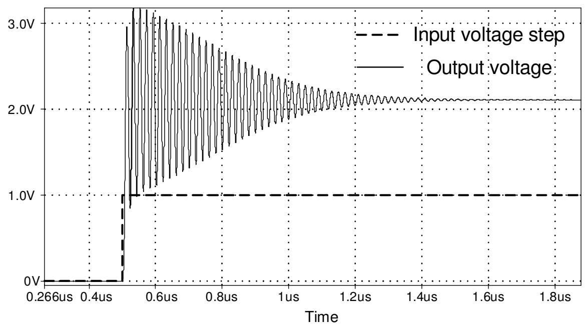

Figure 10. Step response of the circuit shown in Figure 8

Table 2. The unity-loop gain frequency and the phase margin obtained for the Figure 8 circuit by using the three approaches for determining T compared in this paper

R_{F_RC}=1kΩ; C_{F_RC}=4.8pF; R_F=1kΩ; Z_L=100pF; R_G=0.9kΩ

Method	Low freq Gain [dB]	F_{0dB} [MHz]	PhaseMargin [degrees]
Rosenstark-based (T_R)	68.53	46.65	11
V_{AC_IN}	88.97	49	40
V_{AC_OUT}	68.53	28.2	60

IV. CIRCUITS BASED ON THE OPERATIONAL TRANSCONDUCTANCE AMPLIFIER (OTA)

A. Analytical analysis of the two methods for determining T

Figure 11 presents the standard model of an OTA. Let us substitute this model to the V-V OpAmp model in Figures 2.a and 2.b and Figures 3.a. and 3.b., and derive the loop gain expression following the two methods presented in Section II.

Both methods require the breaking of the loop, either at the OTA input or at its output, i.e. between points 1-2 or 3-4.

The Rosenstark-based method gives the same expression – see equation 12 at the top of next page - for the loop gain, irrespective of the point the loop is broken. The corresponding expressions yielded by the V_{AC} method and by breaking the loop at the OTA inverting input or at its output are:

$$T_{AC\_IN} = \frac{nomT_R + Z_G(Z_L Z_F + Z_L Z_{OUT} + Z_F Z_{OUT})}{denomT_R - Z_G(Z_L Z_F + Z_L Z_{OUT} + Z_F Z_{OUT})}$$
$$T_{AC\_OUT} = \frac{nomT_R + Z_{OUT} E(Z)}{denomT_R - Z_{OUT} E(Z)} \qquad (13)$$

where $E(Z) = Z_{IN} Z_F + Z_{IN} Z_L + Z_G Z_F + Z_G Z_L + Z_{IN} Z_G$ and nom_T_R / denom_T_R represent the nominator/denominator of the T_R expression given by equation 12, respectively.

For an OTA with ideal input/output impedances one obtains:

$$\lim_{Z_{in}\to\infty} T_{AC\_IN} = \lim_{Z_{in}\to\infty} T_R ; \lim_{Z_{OUT}\to\infty} T_{AC\_OUT} = \infty \qquad (14)$$

Note that in this case the V_{AC} method follows the Rosenstark-based one only if the loop is broken at the input of the OTA, and its input impedance is very high.

B. Simulation results for a commercially-available OTA

Figure 13 presents the loop gain characteristics yielded by the Rosenstark-based method – the continuous line plots – and by the V_{AC} method applied by breaking the loop at the OTA input – the dotted line plots – and at the OTA output – the interrupted line plots for the following conditions: the basic amplifier is a (model of) the LM13600 OTA and the feedback network consists of R_{F_RC}=500kΩ; C_{F_RC}=100pF; R_F=10kΩ; Z_L=19pF; Z_G=100kΩ‖1pF – see Figure 12.

The corresponding values of the low-frequency gain and the unity-gain frequency, as well as the phase margin values are summarize din Table 3. One can observe that the phase margin values yielded by the three approaches are very different, at 6°, 90° and 81°, respectively.

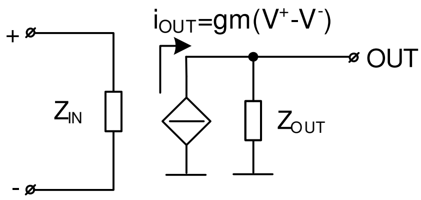

Figure 11. A simple model for the transconductance operational amplifier (OTA)

$$T_R = \frac{gmZ_G Z_L Z_{OUT} Z_{IN}}{Z_{IN}Z_L Z_{OUT} + Z_{IN}Z_L Z_G + Z_{IN}Z_L Z_F + Z_{IN}Z_{OUT}Z_G + Z_{IN}Z_{OUT}Z_F + Z_G Z_L Z_{OUT} + Z_G Z_L Z_F + Z_G Z_{OUT} Z_F} \tag{12}$$

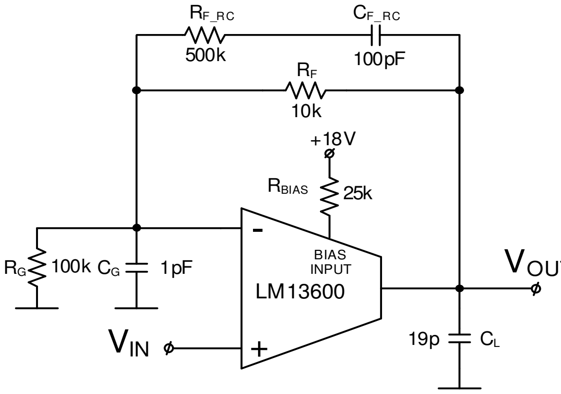

Figure 12. Example of circuit with OTA LM13600 and a frequency-dependent feedback network

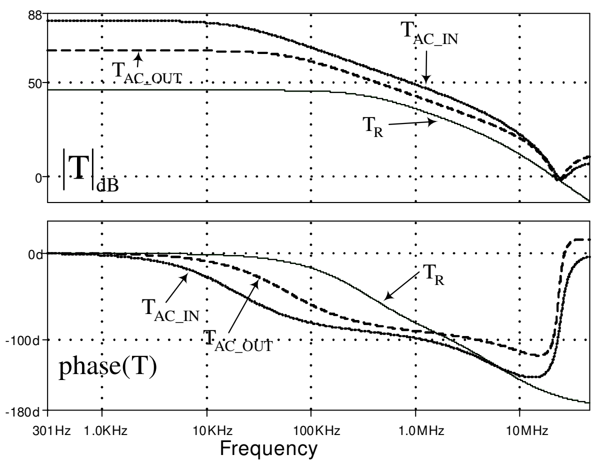

Figure 13. Loop gain characteristics of the Figure 12 circuit obtained by using the Rosenstark-based method (continuous line) and the V_{AC} method with the loop broken at the OTA input (dotted line) and output (interrupted line)

Table 3. The low-frequency gain, the unity-gain frequency of the loop gain and the phase margin obtained for the circuit shown in Figure 12

R_{F_RC}=500kΩ; C_{F_RC}=100pF; R_F=10kΩ; Z_L=19pF; Z_G=100kΩ‖1pF			
Method	Low freq Gain [dB]	F_{0dB} [MHz]	PhaseMargin [degrees]
Rosenstark-based (T_R)	46.1	41.1	6
V_{AC_IN}	67.45	21.46	90
V_{AC_OUT}	83.5	22.87	81

As predicted by the analytical analysis, the characteristics obtained by using the Rosenstark-based method do not depend on the point the loop was broken.

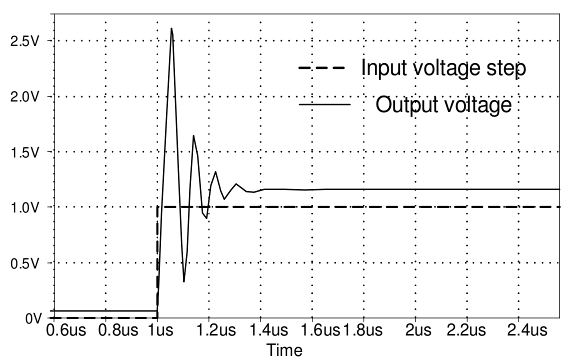

Figure 14. Step response of the circuit shown in Figure 12

The step response of the Figure 12 circuit is presented in Figure14; as for the examples given in the previous two Sections, the step response aspect corresponds only to the phase margin value given by the Rosenstark-based method.

V. CIRCUITS BASED ON THE CURRENT-CURRENT AMPLIFIER

A. Analytical analysis of the two methods for determining T

Figure 15 presents a simple model of a current-current amplifier (I-I) with asymmetric inputs, similar to the CFB-OA shown in Figure 7. A real-life example of such a circuit is the second-generation Current Conveyor (CCII) [7].

Let us substitute this model to the V-V OpAmp model in Figures 2.a and 2.b and Figures 3.a and 3.b, and derive the loop gain expression following the two methods presented in Section II. As discussed before, both methods require the breaking of the loop, either at the OpAmp inverting input or at its output, i.e. between points 1-2 or 3-4, respectively.

Similarly to the results obtained for the three OpAmp analysed in the previous Sections, the Rosenstark-based method gives the same expression for the loop gain – see equation 15 at top of page 7 - irrespective of the point the loop is broken. The corresponding expressions yielded by the V_{AC} method and by breaking the loop at the OpAmp inverting input or at its output are:

$$T_{AC\_IN} = \frac{nomT_R + Z_G(Z_L Z_F + Z_{OUT} Z_F + Z_L Z_{OUT})}{denomT_R - Z_G(Z_L Z_F + Z_{OUT} Z_F + Z_L Z_{OUT})} \qquad (16)$$
$$T_{AC\_OUT} = \frac{nomT_R + Z_{OUT} E(Z)}{denomT_R - Z_{OUT} E(Z)}$$

where $E(Z)=Z_{INi}Z_F + Z_{INi}Z_L + Z_G Z_F + Z_G Z_L + Z_{INi}Z_G$ and the terms nom_T_R/denom_T_R represent the nominator/denominator of the T_R expression given by equation 15, respectively.

$$T_R = \frac{a_i Z_{OUT} Z_L Z_G}{Z_{INi}Z_L Z_F + Z_{INi}Z_L Z_G + Z_{INi}Z_L Z_{OUT} + Z_{INi}Z_F Z_{OUT} + Z_{INi}Z_G Z_{OUT} + Z_F Z_G Z_{OUT} + Z_L Z_F Z_G + Z_L Z_G Z_{OUT}} \qquad (15)$$

For an I-I OpAmp with ideal inputs or output impedances one obtains:

$$\lim_{Z_{INi}\to 0} T_{AC\_IN} = \infty; \lim_{Z_{OUT}\to\infty} T_{AC\_OUT} = \infty \qquad (17)$$

Note that in this case the loop gain obtained using the V_{AC} method does not get closer to the Rosenstark-based results, even if the OpAmp has ideal input/output impedances.

B. Simulation results for a commercially-available I-I OpAmp

No genuine I-I OpAmp are available commercially at the moment, but several current-feedback OpAmps can be configured as second-generation current conveyors, which in turn can be seen as I-I OpAmps with asymmetrical inputs and a current-current gain of one (0dB).

The AD844 is an example at hand of such a CFB-OA: its block diagram is presented in Figure 16. One can easily observe that, between the inputs and the node Z, the AD844 comprises a current-current amplifier with the structure corresponding to the models shown in Figure 15.

Figure 17 shows a voltage amplifier implemented with the AD844 used as a unity-gain current-current OpAmp. Obviously, the loop gain of this circuit is subunitary, so the phase margin cannot be calculated. In order to compare results under same conditions as for the three types of OpAmps analysed in the previous Sections we have modified the AD844 model so that its current-current gain was pushed up to tens, then hundreds of units.

Figure 18 presents the loop gain characteristic of the Figure 17 circuit with the modified AD844 having a current-current gain of 100 (40dB): the results obtained by using the Rosenstark-based method are plotted with continuous line while the ones obtained by using the V_{AC} method are plotted with dotted line – when the loop was broken at the OpAmp input – and by interrupted line when the loop was broken at the OpAmp output. As predicted by the analytical analysis, the loop gain characteristics obtained by using the Rosenstark-based method do not depend on the point the loop is broken.

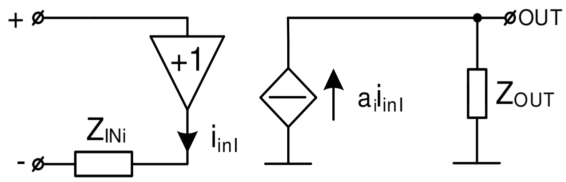

Figure 15. Model for current-current OpAmp with asymmetric inputs; an example of such a circuit is the second-generation current conveyor

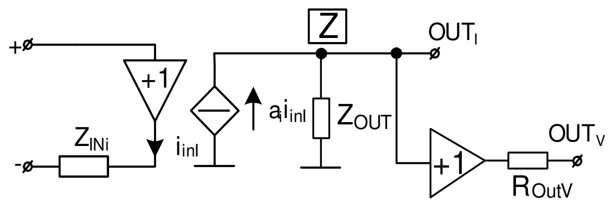

Figure 16. Block diagram of the AD844 CFB-OA; between the inputs and the node Z it implements a second-generation current conveyor, CCII+.

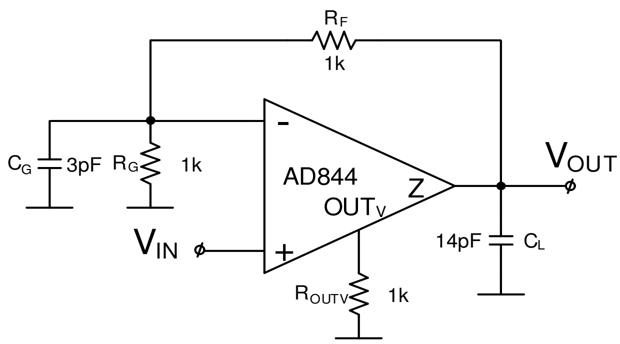

Figure 17. Example of a circuit with a frequency-dependent feedback network and the AD844 configured as an I-I amplifier for the main circuit amplifier

Also in good agreement with the analytical analysis is the fact that the parameters of the frequency characteristics shown in Figure 18 are widely different – including the low-frequency gain – see equations 15 and 17.

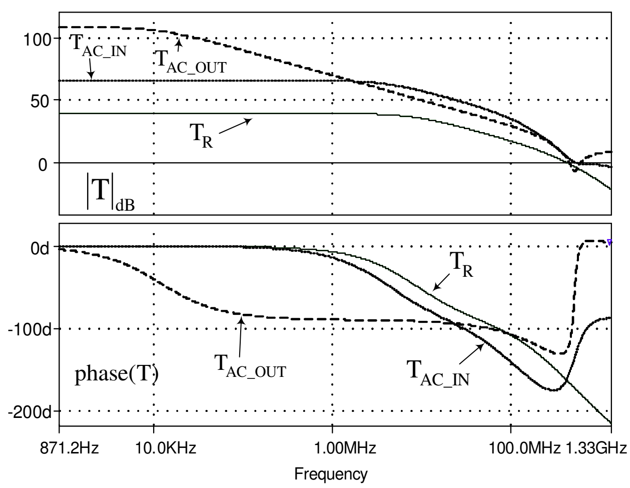

Figure 18. Loop gain characteristics of the Figure 17 obtained using the Rosenstark-based method (continuous line) and the V_{AC} method with the loop broken at the OpAmp input (dotted line) and output (interrupted line)

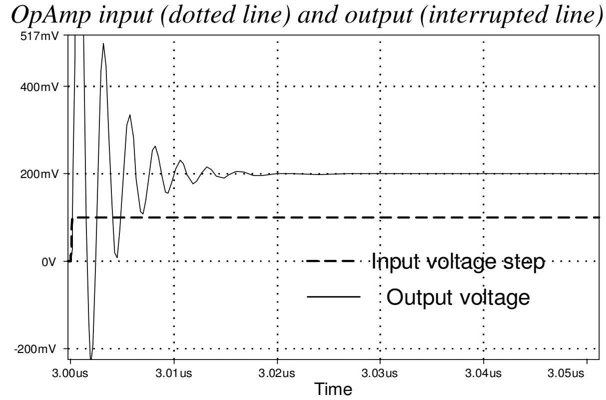

Figure 19. Step response of the circuit shown in Figure 17

Table 4. The unity-loop gain frequency and the phase margin obtained for the circuit shown in Figure 17 by using the methods for determining T compared here

R_F=1kΩ; Z_L=14pF; Z_G=1kΩ‖3pF		
Method	Low freq Gain [dB]	PhaseMargin [degrees]
Rosenstark-based (T_R)	39.57	16
V_{AC_IN}	66.1	50
V_{AC_OUT}	108.8	61

Table 4 summarizes the low-frequency gain and the phase margin of the loop gains presented in Figure 18.

Figure 19 presents the step response of the circuit shown in Figure 17, for the conditions described above (the AD844 model modified so that it yields a current-current gain of 40dB). The ringing step response is in agreement only with the low phase margin obtained by using the Rosenstark-based method (16^o) and disproves the larger phase margin values obtained using the V_{AC} method (50^o and 61^o).

VI. CONCLUSIONS

Two of the most popular methods for deriving the small signal loop gain of feedback circuits based on OpAmps have been analyzed comparatively in detail, both analytically and through extended sets of simulations. All four OpAmp types currently available commercially have been considered: the traditional OpAmp (V-V OA), the current-feedback OpAmp (CFB-OA), the Operational Transconductance Amplifier (OTA) and the Current-Current Amplifier (I-I OA) with asymmetrical inputs.

The comparison focused on two points: first, it was verified whether or not the loop gain expressions corresponding to these methods satisfied the theoretical requirement that they should not depend on the point the loop is broken. Second, the correspondence between the phase margin determined with these methods and the step response of the analyzed circuits was verified for an extended set of circuits.

Examples of circuits based on real-life OpAmps – that is, models of well known ICs provided by their manufacturers - have been presented for each OpAmp type, highlighting the differences between the analysis methods under comparison.

It was shown that the simple and widely used V_{AC} method – which involves breaking the feedback loop by inserting an independent voltage source with DC=0 and AC=1 – fails both tests described above if the feedback loop comprises frequency-dependent impedances, the usual real-life situation.

The - admittedly more elaborated but still practical - method based on the Rosenstark theorem provides loop gain characteristics that are independent on the point the loop was broken. This has been verified for circuits with series-shunt feedback using all the OpAmp types mentioned above. This method also passes the second test: simulations run for several representative circuits have shown good correspondence between the phase margin values obtained by using this method and the step response of the analyzed circuits.

Despite its limitations, the V_{AC} method can be used if two conditions are met: i) the feedback two-port is purely resistive and ii). the point at which the loop is broken is chosen by taking into account the relationship between the values of the OpAmp input/output impedances and the feedback network equivalent impedances. In particular, for OpAmps with "naturally" large input impedances – such as the traditional V-V OpAmp and the OTA – for most practical circuits the loop should be broken at the inverting input of the OpAmp rather than at its output. The opposite applies to the CFB-OA, where for most practical cases it is better to use the V_{AC} method by breaking the loop at the output of the OpAmp. The I-I OA is a special case, for which the no clear pattern was found, hence no conclusion could be drawn.

It should be noted that the results presented here have been obtained for a fairly general case – the feedback two-port was a generic reciprocal network, a class which includes all passive networks. Furthermore, although the analysis focused on circuits with the classical series-shunt feedback topology [1] the conclusions can be extended to a host of related circuits, such as the inverting OpAmp-based amplifier [2].

ACKNOWLEDGMENT

This work was supported by the Romanian National Council for Academic Research, CNCSIS, through the program PNII – IDEI, research grant ID 2534/2008.

REFERENCES

[1] P.R. Gray, P.J. Hust, S.H. Lewis, R.G. Meyer – Analysis and Design of Analog Integrated Circuits, Chapters8&9,Willey,2001
[2] Marius Neag, Oliver McCarthy, "An Extension of the Classical Feedback Theory", Proc. of the IEEE Conference ISCAS'98 Monterey, California, June 1998, pp. 562-565
[3] H. T. Russel, "A Loop-Breaking Method for the Analysis and Simulation of Feedback Amplifiers", IEEE Tr. on Circuits and Systems-I, vol. 49, no. 8, Aug. 2002, pp 1045-1061
[4] S. Rosenstark, Feedback Amplifier Principles, Macmillan, 1986, pp. 11-24 and 38-54
[5] P. W. Tuinenga, SPICE A Guide to Circuit Simulation and Analysis using PSPICE, 2nd edition, Prentice-Hall, 1992
[6] S. Franco – Design with Operational Amplifiers and Analog Integrated Circuits, McGraw-Hill, 1998
[7] A.Sedra, K.Smith - "A second generation current conveyor and its applications", IEEE Trans on Circuit Theory, vol. CT-17, 1970, pp. 132-134