An Approach to Effectiveness Increasing of SPICE Macromodels

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Abstract – **In this paper transformed macromodels are proposed to effectiveness increasing of behavioral SPICE macromodels. The modifications of the *PSpice* library models allow to reduce the simulation time, the number of iterations and the order of the circuit matrix. The original and the modified models are compared and their effectiveness is evaluated.**

Keywords – **Behavioral models, Modified Nodal Analysis, OrCAD PSpice, Model Effectiveness**

I. Introduction

Contemporary electronic devices are characterized with increasing complexity, a huge number of elements and high degree of integration. The standard electronic circuits contain hundreds, sometimes even thousands of elements. The effectiveness during the modeling of these circuits is of great importance. The circuit and the system simulators can run much faster today due to the availability of powerful computers and workstations. The circuits are more complex with each new generation of computers. This leads to huge computer resources assigned to circuit simulation in the design process in order to verify the circuit behavior [1,2,3].

The analysis of large electronic and electrical circuits and systems requires repeatedly solutions of sparse linear and nonlinear systems of equations. The sparsity can be used to accelerate circuit and system analysis. The nodal analysis equation have the form [4,5]:

$$[Y].[V]=[J] \tag{1}$$

where $[Y]$ is the nodal admittance matrix; $[V]$ is the vector of unknown voltages; $[J]$ is the vector of the independent currents. The matrix $[Y]$ is sparse, because it contains a high proportion of zero-valued elements [1,2,3]. Every node is not connected to every other circuit node, and for nodal analysis nonzero-valued elements result only from direct connections. The dependence of the sparsity on the circuit size n is presented in Table I. It increases with circuit size and this can be used to reduce storage requirements and the number of floating point operations entailed in the solution of the circuit equations [1,2].

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TABLE I
DEPENDENCE OF THE SPARSITY AND THE SIMULATION TIME ON THE MATRIX SIZE

n	% sparsity	Simulation time	Matrix type
10	50%	n^3	dense matrix
40	90%		
100	96%	$n^{1.5}$	sparse matrix
400	99%		
1000	99.9%	$n^{1.1}$	large sparse matrix

In order to increase the effectiveness, the modified nodal analysis (MNA) is used [1,2]. MNA allows to include all types of dependent and independent sources in the circuit matrix. The computer implementation of this procedure is easy, which is a substantial advantage for automated solution. According to the MNA, one equation is written for each of the circuit nodes and the equations for the voltage sources are included in the augmentation.

II. Effectiveness Increasing

A. Effectiveness Increasing of Linear PSpice Operational Amplifier Behavioral Models

For the computer simulation of circuits containing operational amplifiers, macromodels of different complexity are used [1,7,8,9]. The linear macromodel of OpAmp is described by a voltage controlled voltage source (**VCVS**), which depends on the input signal. The frequency response of the output voltage is defined in the form:

$$V_{out}(f)=H(f).V_{in}(f), \tag{2}$$

where $V_{in}(f)$ is the input voltage. The open-loop gain $H(f)$ has the form:

$$H(f)=\frac{A_0}{1+\mathrm{j}\dfrac{f}{f_c}} \tag{3}$$

where A_0 is the DC open-loop gain, f_c is the cut-off frequency.

The standard linear macromodels of OpAmp are based on the equivalent circuit, shown in Fig. 1.

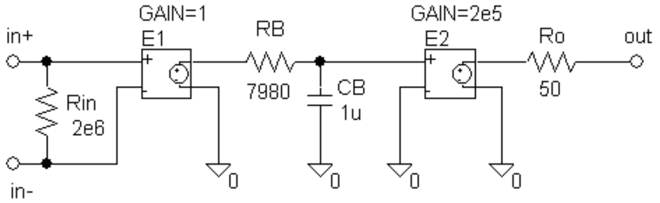

Fig. 1. Equivalent circuit of OpAmp macromodel

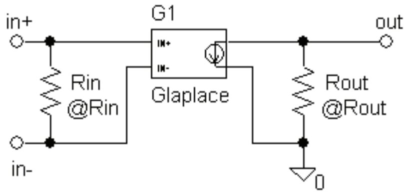

Fig. 2. Modified equivalent circuit of OpAmp macromodels

The frequency dependence of the OpAmp open-loop gain with one-pole approximation is modeled by a *RC*-circuit and dependent sources of **VCVS** type. The equivalent circuit of the macromodel adds internal nodes and each of the **VCVS**s extends the matrix order by 1. This leads to $\Delta n = 5$ additional rows and columns in the circuit matrix, for each OpAmp macromodel unit used in it.

The avoidance of these two dependent sources is the first step of the optimizing of the equivalent circuit. The macromodel can be realized more effectively by using of the analytical description of the frequency dependence of the open-loop gain $H(f)$. It is achieved in PSpice by the following expression, describing the OpAmp gain:

$$H(f) = \frac{A_0}{1 + + \dfrac{s}{\omega_c}} , \qquad (4)$$

$$s = \mathrm{j}\omega = \mathrm{j}2\pi f \qquad (5)$$

Taking into account the equation (4), it is possible to described the OpAmp model by only one *Laplace* element of the **E** type, since it preserves all its characteristics. The simulation is also reliable, but significantly faster. An additional order reduction can be achieved by transforming the connected in series voltage source and resistance in current source and resistor, connected in parallel.

The modified equivalent circuit of the OpAmp is shown in Fig. 2. The resulting macromodel does not introduce any additional rows and columns to the circuit matrix.

B. Equivalent Transformations of More Complex PSpice Operational Amplifier Behavioral Models

In order to improve the effectiveness of the OpAmp macromodels, the elements that increase the order of the **Y** matrix should be replaced by other elements, which do not add additional nodes. The elements *R, C, L,* voltage controlled current source **VCCS** meet this requirement, while the elements without admittance matrix description (independent voltage source **E**, **VCVS,** current controlled voltage source **CCVS** and current controlled current source **CCCS**) increase the matrix order, as shown in Table II.

TABLE II
MATRIX ORDER INCREASING FOR ELEMENTS WITHOUT ADMITTANCE MATRIX DESCRIPTION

Type of source	E	VCVS	CCVS	CCCS
Δn	1	1	2	1

The improving the model by avoiding additional elements and nodes of the circuit, leads to a matrix of reduced order and to a decreased number of iterations made by the simulator. As a result, the simulation time is reduced and the effectiveness of the behavioral model is increased.

The dependent source **VCVS** can be converted to **VCCS** in the model and thus two additional rows and columns are eliminated from the original matrix (one from the **VCVS** and one from the extra node), as shown in Fig.3. If the voltage of the **VCVS** controls other electric voltage or current in the circuit, this transform cannot be applied. The voltage source E_{P2} and the resistance R_{P2} connected in series, are equivalently represented by the current source G_{P2} and resistor R_{P2} connected in parallel.

The macromodel of the HA-2500 [6] from the library HARRIS of the *OrCAD PSpice* is used as an example to illustrate the equivalent transformations.

The statements for EP2 and RP2 in the model section *Poles* are replaced by:

GP2 0 13 11 0 0.031407
RP2 0 13 3.184E+01

As a result, one node is skipped and one row and column are removed from the matrix due to the EP2 replacement. The voltage source EP1 in the original model can be transformed in **VCCS** in the similar way as shown in Fig. 3.

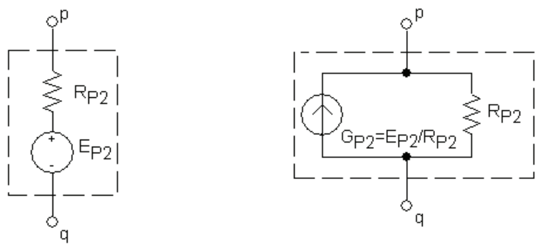

Fig. 3. Transformation of the VCVS into the VCCS

In this way, the statements describing the *Input Stage* in OpAmp HA-2500 model (current sources FP, FN, GC, GPP, GPN and IRX), the resistance RT and the statements of the *Poles* section describing EP1 and RP1, are replaced by the following statements:

FP1 11 0 VP 38.189
FN1 0 11 VN 38.189
GC1 0 11 8 0 5.127014E-10
GPP1 11 0 4 0 2.883069E-10
GPN1 11 0 5 0 5.127014E-10
IRX 0 11 –8.823707E-11
RP1 0 11 +1.0613E+02

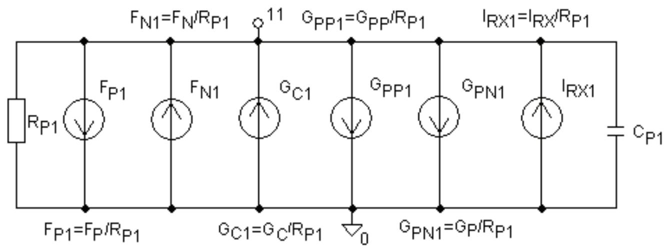

Fig. 4. Equivalent transformation in the OpAmp model

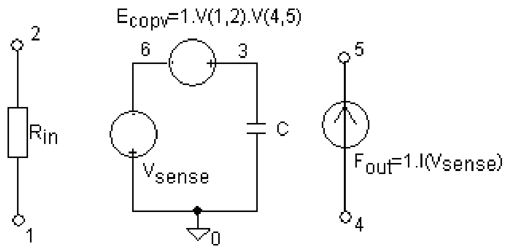

Fig. 5. Equivalent circuit of the variable admittance

The description of CP1 is not changed in the model. So nodes 9 and 10 are skipped and EP1 removed. The transformation is shown in Fig. 4.

The order of the **Y** matrix for the modified model is reduced by $\Delta n = 5$ with comparison to the matrix order of the original mode – nodes 9, 10 and 12 are skipped and two **VCVS** are removed.

C. Effectiveness Increasing of PSpice Variable Admittance Behavioral Models

The equivalent circuit of the variable admittance is shown in Fig. 5. It contains dependent voltage source E_{copy}, short circuit V_{sense} and dependent current source F_{out}. $V(1,2)$ is the input voltage. $V(4,5)$ is the output voltage. Y_c is the reference admittance. The following equations are valid in this equivalent circuit:

$$I(V_{sense}) = Y_c . V(1,2) . V(4,5) \tag{6}$$

$$Y_{out} = I(V_{sense}) / V(4,5) = Y_c . V(1,2) \tag{7}$$

The modified equivalent circuit is shown in Fig. 6. It realizes the same function $Y_{out} = Y_{ref} . V_{control}$, as E_{copy} and V_{sense} are replaced by source V_1 and F_{out} is replaced by G_{out}.

The following equations are used in the modified equivalent circuit of the variable admittance:

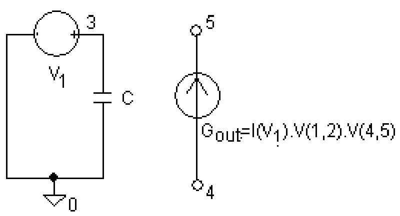

Fig. 6. Modified equivalent circuit of the variable admittance

$$I(V_1) = V_1 . Y_c = 1.Yc \tag{8}$$

$$I(4,5) = Y_c . V(1,2) . V(4,5) \tag{9}$$

$$Y_{out} = I(4,5) / V(4,5) = Y_c \, . \, V(1,2) \tag{10}$$

The original matrix order for the standard model is $n_{st} = 8$, while the order of the modified one is $n_m = 6$ (source V_{sense} is removed).

D. Effectiveness Increasing of Behavioral PSpice Model of Sinusoidal Voltage Controlled Oscillator

The output voltage of the voltage controlled oscillator VCO-Sin is a sine wave, which frequency is controlled by a table voltage. The *PSpice* model has a form:

```
.subckt vco_sin in out Params: Fcenter=1k Frange=50
+ Vmin=1 Vmax=5 phase=0
Rin  in  0  1G
Rtable  table  0  1G
Etable  table  0  Value {Table (V(in),Vmin,-1,Vmax,1)}
Esin   out   0  Value{sin(6.28318*
+ (Fcenter*time+Frange*SDT(V(table)))+phase*
+ (3.14159/180))}
.ends
```

The dependent voltage source E_{table} is converted to the dependent source G_{table} of **VCCS** type. The **Y** matrix is decreased by $\Delta n = 1$, because there is not resistance connected in parallel with the source E_{table}. The modified *PSpice* model of the *VCO-Sin* has the form:

```
.subckt vco_sin in out Params: Fcenter=1k Frange=50
+ Vmin=0 Vmax=5 phase=0
Rin  in  0  1G
Rtable  table  0  1
Gtable 0 table Value{Table (V(in),Vmin,-1,Vmax,1)}
Esin out 0 Value{sin(6.28318*(Fcenter*time+Frange*
+ SDT(V(table)))+phase*(3.14159/180))}
.ends
```

The original model matrix for one *VCO-Sin* unit is of order $n = 5$, while the order of the modified one is $n_m = 4$ (source E_{table} is removed).

E. Effectiveness Increasing of Behavioral PSpice Models of Square Voltage Controlled Oscillators

The output voltage of the voltage controlled oscillator *VCO-Sqr* is a square wave, which frequency is controlled by a table voltage. The *PSpice* model has the form:

```
.subckt vco_sqr in out Params: Fcenter=1k Frange=50
+ Vmin=1 Vmax=5 phase=0
Rin  in  0  1G
Rtable  table  0  1G
Etable table 0 Value{Table (V(in),Vmin,-1,Vmax,1)}
```

```
Esin sine   0 Value{sin(6.28318*(Fcenter*time+Frange*
+ SDT(V(table)))+phase*(3.14159/180))}
Esqr out 0 table{V(sine)} (0,0) (1n,1)
.ends
```

The dependent voltage source E_{table} and $E_{\sin}$ are converted to the dependent source G_{table} and $G_{\sin}$ of **VCCS** type. The **Y** matrix order is decreased by $\Delta n = 2$. The modified *PSpice* model of the *VCO-Sin* has the form:

```
.subckt vco_sqr in out Params: Fcenter=1k Frange=50
+ Vmin=1 Vmax=5 phase=0
Rin in 0 1G
Rtable table 0 1
Gtable 0 table Value{Table (V(in),Vmin,-1,Vmax,1)}
Gsin 0 sine Value{sin(6.28318*(Fcenter*time+Frange*
+ SDT(V(table)))+phase*(3.14159/180))}
Rsin 0 sine 1
Esqr out 0 table{V(sine)} (0,0) (1n,1)
.ends
```

The original model matrix (for one VCO-Sqr unit) is of order n_{st} = 7, while the order of the modified one is n_m = 5 (sources E_{table} and $E_{\sin}$ are removed).

III. Simulation Results

The investigation of effectiveness is realized using the standard and modified *PSpice* OpAmp models. These models are included in test circuits. The simulation results using different OpAmp macromodels [7,8,9] are shown in Table III, where t_{st} is the simulation time using the standard model, t_m is the simulation time using the modified model, ε_n,% is the relative reduction of the matrix order using the modifid macromodel. ε_t,% is the relative reduction of the simulation time using the modifid macromodel.

The effectiveness of *PSpice* variable admittance model is investigated by comparison of the standard and modified models with respect to the simulation time and matrix order.

The simulation results are presented in Table IV. The simulation results for the standard and modified model of VCO-Sin and VCO-Sqr are shown in Table V.

Table III
Simulation results for the original and modified OpAmp model

OpAmp model	n_{st}	n_m	ε_n,%	t_{st}, s	t_m, s	ε_t,%
HA2500	82	67	18.3	23.75	21.67	8.8
HA2539	97	79	18.6	23.17	19.97	13.8
HA2541	211	160	24.2	39.75	36.52	8.1
HA5221	124	85	31.4	32.16	28.03	12.8

Table IV
Simulation results for the original and modified model of variable admittance

n_{st}	n_m	ε_n,%	t_{st}, s	t_m, s	ε_t,%
9	7	22.2	159.08	162.4	159

Table V
Simulation results for the original and modified model of VCO

Type of model	n_{st}	n_m	ε_n,%	t_{st}, s	t_m, s	ε_t,%
VCO-Sin	11	97	18.2	1.81	1.77	2.2
VCO-Sqr	35	25	28.6	36.72	35.75	2.6

The OpAmp model HA-2500 is characterized by a reduction of the simulation time of about 8 %, the model HA-2539 - by 14 %, the model HA-2541 - by 8 % and the model HA-5221 - by 13 %.

IV. Conclusion

An approach has been proposed to effectiveness increasing of *PSpice* macromodels based on modified macromodels. They are characterized by a reduced order of the circuit matrix using modified nodal analysis approach. A number of modified macromodels are developed for operational amplifiers, variable admittance, as well as voltage controlled oscillators. The model description is presented in accordance with the input language of the *PSpice* simulator.

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