PSpice Subcircuits for Passive Reduced Order Interconnect Models

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Abstract – **In this paper, we describe the PSPICE models of CODROM which was introduced as a passive reduced order model of RLCG interconnect networks.**

1 Introduction

As integrated circuits and systems continue to be designed smaller and for faster operation, passive interconnect effects have a more dominant impact on signal integrity than ever before. In addition, parasitic coupling effects and reduced power supply voltage levels make interconnect modeling increasingly important. Since these models can contain thousands of coupled R, L, C components, reduced order models are imperative

The Method of Moment Components was introduced as a new concept to obtain passive reduced-order models of RLCG interconnect networks and used in fast timing simulators such as ILLIADS [1]. In this method, the impedance moments of the interconnect network are partitioned into their inductive, capacitive and mixed inductive/capacitive moment components. Then *Congruently Diagonalizable Reduced Order Model* (CODROM) is introduced as a passive reduced order model of a RLC interconnect network

In this paper, we will give a brief survey on PSPICE models of CODROM.

2 CODROM Submatrices

In this section, CODROM, which was introduced in [1], will be briefly explained; detailed information can be found in [2,3].

The Tableau Equations of an RLCM interconnect network are of the form:

$$\begin{bmatrix} -C_n & 0 \\ 0 & L \end{bmatrix} \begin{bmatrix} \dot{V}_n \\ \dot{I}_L \end{bmatrix} = \begin{bmatrix} A & B \\ B^T & -E \end{bmatrix}^{-1} \begin{bmatrix} V_n \\ I_L \end{bmatrix} - M U_s \qquad (1)$$

where C_n, L, A, E represent respectively the node capacitance, inductance submatrices and submatrices of the inverse matrix due to resistors. The key issue here is that the non-negativeness of C_n, L, A, E ensures (is a sufficient condition) the passivity of the interconnect network. To guarantee the passivity of CODROM and to simplify the calculations of the parameters, these four submatrices will be chosen to be diagonal i.e.

$$A_r = \begin{bmatrix} d\{\alpha_j\} & 0 \\ 0 & d\{\gamma_j\} \end{bmatrix}, \; C_r = \begin{bmatrix} d\{\delta_j\} & 0 \\ 0 & 0 \end{bmatrix}$$

$$L_r = d\{\lambda_j\} \quad , \quad E_r = d\{\beta_j\} \qquad (2)$$

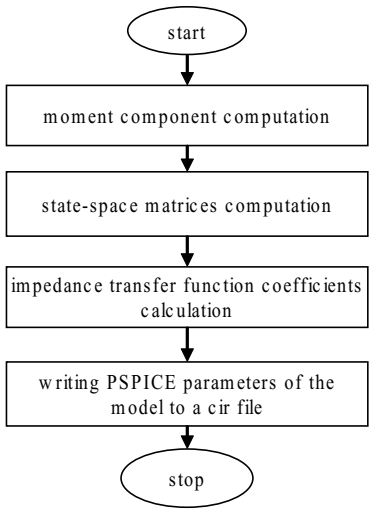
How the transition from submatrices in (1) into diagonal submatrices with nonnegative diagonal entries in (2) using Moment Components is achieved, is explained in detail in [2,3]. It is important to observe that all matrix operations in this method, other than moment calculations (which is common to all moment-based methods) are pxp matrices where p is the number of ports.

3 Obtaining PSPICE Models

The computation of the PSPICE model parameters can be divided into three main stages, which are explained below.

3.1 Moment Components Computation

Moment components of the interconnect are computed using the procedure explained in [2,3] with analysis equations. It should be noted that the input variables of this process are: DC solutions of



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node voltages, inductance currents and system matrices of the network. The output values of this routine are the moment components of the original interconnect and constitute the input values of the next stage.

3.2 State-Space Matrices Computation

This process consists of two main sub-stages; CODROM model parameters calculation and the state-space matrices calculation.

The CODROM model parameters are calculated as explained in Section 2. The system and connection matrices can be constructed using these parameters. To remedy the ill-conditioning problem, which may occur during inversion of the coefficient matrix, the balancing transformation has been applied to the original submatrices.

3.3 Impedance Transfer Function Coefficients Calculation

The coefficients of the numerator and denominator polynomials are used as the parameters of the PSPICE model. These coefficients are calculated from state-space matrices using MATLAB functions.

4 PSPICE Model for CODROM

PSPICE allows the modeling of a device in terms of the relation between its input and output. The relationship is specified as an extension to voltage controlled voltage source (E) and voltage controlled current source (G) and is of the forms:

<VALUE> <LAPLACE> <TABLE>< FREQ>

This type of modeling is known as *Behavioral Modeling*.

LAPLACE extension allows a relation to be described by a LAPLACE transform function and can be specified by the following general form [4].

E<name> N+ N- LAPLACE {<expression>} = {<transform>}

In this section, the impedance transfer functions of CODROM will be used to form PSPICE models using E and H devices and it will be shown that how this model can be called in any PSPICE circuit file and how parameters can be passed to these PSPICE models.

Since there is no definite circuit structure for CODROM, it can't be modeled as a RLC circuit and therefore the mathematical description of CODROM is used to develop its PSPICE model.

Analog Behavioral features of PSPICE are used to model CODROM. To be able to use Laplace domain transfer function of CODROM, E devices are used with LAPLACE extension. Additionally, to convert input currents to input voltages of E devices, current controlled voltage sources (H devices) are used with a gain of 1.

Figure 1 shows the PSPICE model of a 2-port CODROM.

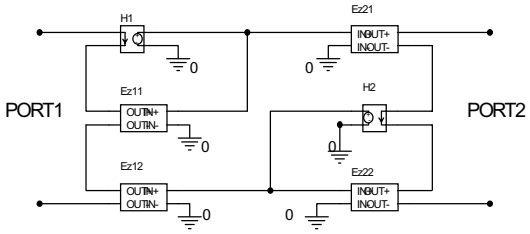


Figure 1 PSPICE model of 2-port CODROM

It can be seen from Fig.1 that the transfer functions, $\mathbf{Z_{11}}(s)$, $\mathbf{Z_{12}}(s)$, $\mathbf{Z_{21}}(s)$, $\mathbf{Z_{22}}(s)$ are realized with E devices, E_Ez11, E_Ez12, E_Ez21, E_Ez22, respectively. The coefficients of the transfer functions are passed to the PSPICE model using parameters a_j, b_j, c_j, d_j, the parameters e_j are used for the parameters of the characteristic polynomial of CODROM.

The description of the E_Ez11 device is given below.

E_Ez11 1 2 LAPLACE { V(3) } =
+{ (a4*s*s*s*s+a3*s*s*s+a2*s*s+a1*s+a0) /
+(e4*s*s*s*s+e3*s*s*s+e2*s*s++e1*s+e0) }

For a four port CODROM, the PSPICE model is shown in Fig.2.

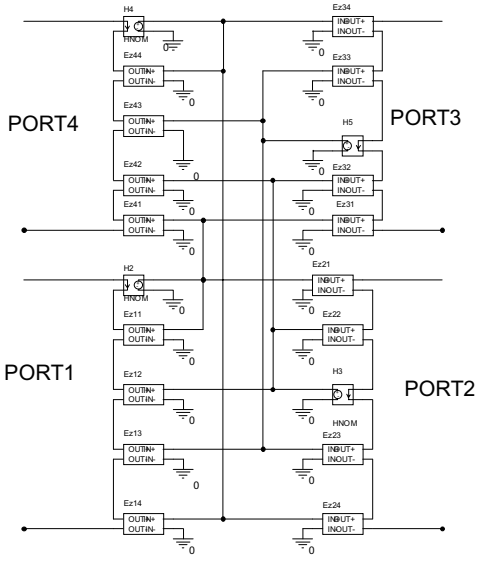


Figure 2 PSPICE model of 4-port CODROM

5 Simulation Results

5.1 The PSPICE model of 2-Port CODROM model

In order to simulate PSPICE models of CODROM, a ladder structured of interconnect network shown in the Fig.3 was chosen. The interconnect network has 40 segments, and each segment consists of elements with values of R=5.084Ω, L=1.2nH, C=0.194pF, G=0.1e-6 Ω^{-1}. The driver and the sink nodes are treated as the input and output ports of the network respectively. PORT1 is the input port of both interconnect and PSPICE models.

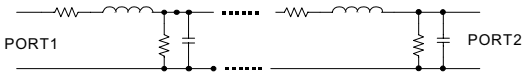


Figure 3 The ladder type interconnect network

The pulse current source, shown in the Fig.4, is applied to the input ports of both original interconnect and CODROM models and the transient voltage waveforms at both ports are calculated. Simulation results are given Figures (5-8). The order of the original interconnect is 80 and the order of the CODROM model is 8.

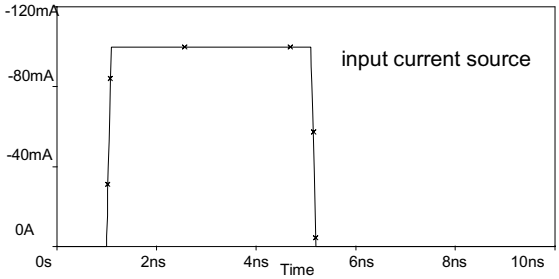


Figure 4 the input current source

The simulation results for this circuit show that the voltage waveforms of 2-port PSPICE model of CODROM close to those of the original interconnect network.

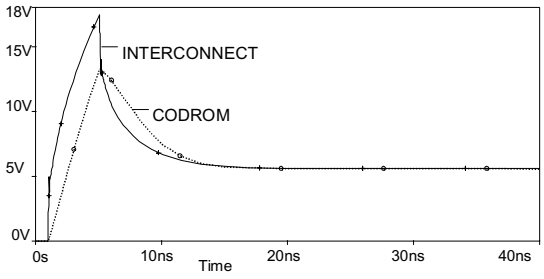


Figure 5 The input port voltages of the 2 port models

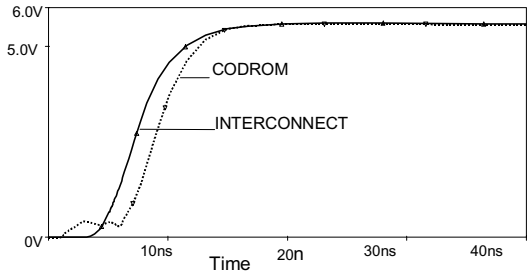


Figure 6 The output port voltages of the 2 port models

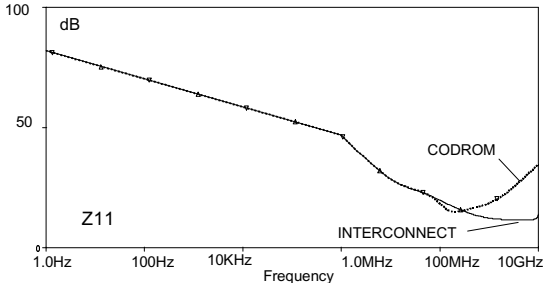


Figure 7 $Z_{11}(s)$ input impedance frequency response of 2 port model

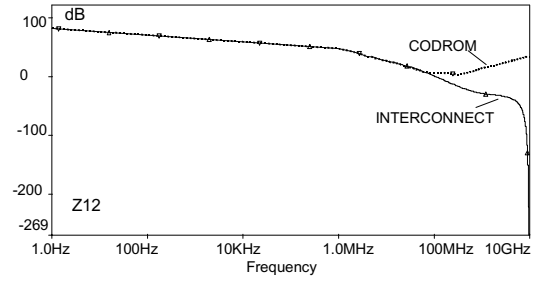


Figure 8 $Z_{12}(s)$ transfer impedance frequency response of 2 port model

5.2 The Results of the PSPICE Model of 4-port CODROM

As a second example, a capacitive coupled RLCG interconnect network, which has 40 segments in each line was chosen. The element values of the segments are the same with those in the previous example. These two lines are capacitively coupled at every node with a capacitance of C=0.1nF. The impulse current source in the Fig.4 is applied to the PORT1 of the aggressor line. The transient voltage waveforms at all ports were simulated. The order of the original interconnect is 160 and the order of CODROM is 8.

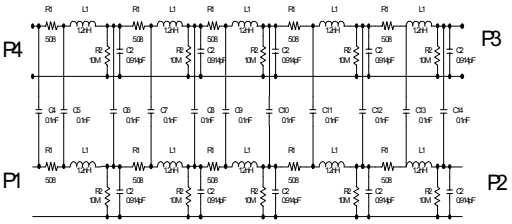


Figure 9 The capacitively coupled RLCG interconnect network

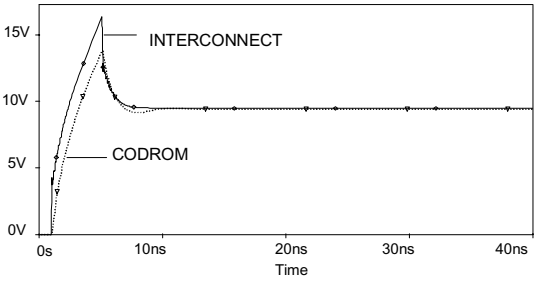


Figure 10 The voltage waveforms at PORT1

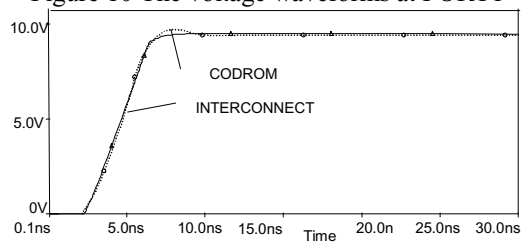


Figure 11 The voltage waveforms at PORT2

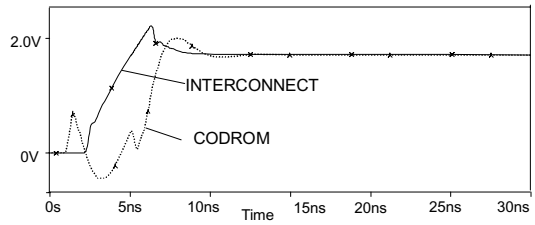


Figure 12 The voltage waveforms at PORT3

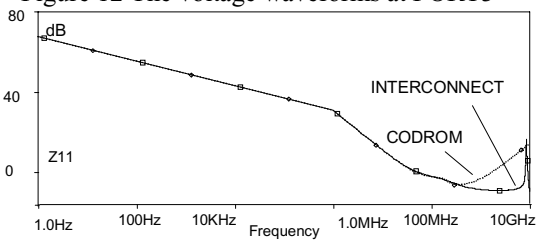


Figure 13 Z_{11} (s) input impedance frequency response of the models

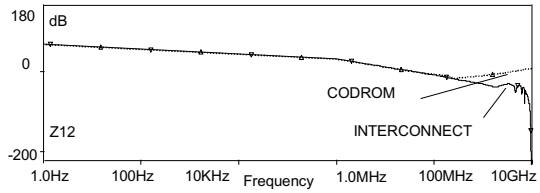


Figure 14 Z_{12} (s) impedance transfer function frequency response of the models

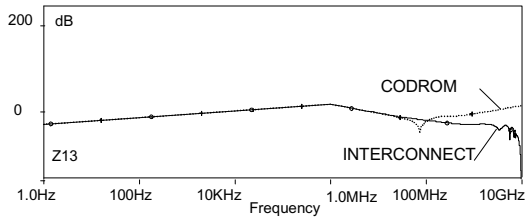


Figure 15 Z_{13} (s) impedance transfer function frequency response of the models

6 Conclusion

Although there is some difference in frequency response between the PSPICE models and the interconnect above 1GHz, PSPICE models can catch the dominant behavior of the interconnect network. To make PSPICE simulation correctly, transient analysis parameters should be chosen appropriately.

The PSPICE models have been developed and successfully applied to m-port interconnect network, but some numerical problems may occur due to the fact that PSPICE is a solver for any kind of circuit. In a specific solver such as ILLIADS, a fast timing simulator for digital circuits, CODROM waveforms were much closer to interconnect waveforms.

References

[1] KÜTÜK, H., GÖKNAR İ.C., KANG, S.M., "Interconnect Simulation in a Fast Timing Simulator ILLIADS-I", IEEE Transactions on Circuits and Systems, Part I, vol.CAS-46, no.1,pp.178-190, Jan. 1999.

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