REDUCED-ORDER MACROMODEL EXTRACTED FROM THE FREQUENCY DOMAIN SIMULATOR OF PASSIVE ON-CHIP COMPONENTS

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Abstract: *This paper focuses on the path from a frequency response obtained from the electromagnetic modeling of a passive device, towards the synthesis of a circuit described as a net-list (in SPICE language). Such an approach was implemented in the frame of the FP5/IST/Codestar European project, which referred to the compact model extraction for passive on-chip components and interconnects. The software implemented was compared with EMtoSPICE, which is commercial software that does the same task*

1. INTRODUCTION

As signal speeds grow while device size shrink in modern digital very large scale integration (VLSI) design, the correct modeling of on-chip components and interconnects became more and more important.

A typical integrated-circuit model consist of nonlinear transistor models and linear RLC networks describing the interconnects. The size of these RLC networks ca be huge which will significantly slow down the simulation of the circuit. Alternatively, an integrated-circuit model can be obtained from the electromagnetic simulation of its constitutive parts. Such a model is also huge, having a number of degrees of freedom that can reach the million order of magnitude. That is why various model-reduction algorithms have been developed.

Model reduction is a technique to transform a model with a very large number of degrees of freedom to a much smaller one, but more or less equivalent, reduced model that allows rapid simulation.

If the initial problem is passive, then any model-reduction algorithm should preserve the passivity of the original model in order to produce stable system when connected to the rest of circuit. In order to connect the reduced model with the rest of the circuit, a circuit has to be synthesized from it. Thus, the result of the reduction and synthesis should fit naturally into the modified nodal analysis procedure, which is routinely used in circuit simulators to formulate circuit equations.

This paper focuses on the path from a frequency response obtained from the electromagnetic modeling of a passive device, towards the synthesis of a circuit described as a net-list (in SPICE language). Such an approach was implemented in the frame of the FP5/IST/Codestar European project [1], which referred to the compact model extraction for passive on-chip components and interconnects. The software implemented was compared with *EMtoSPICE* [2], which is commercial software that does the same task

2. EMTOSPICE

EMtoSPICE is a software tool that converts scattering parameters (S-parameters) to SPICE macromodels (or subcircuits), allowing simulation of any device using its S-parameters in SPICE. It accepts S-parameters in Touchstone format or raw data format. S-parameters may be obtained from measurements, full-wave EM solvers or any RF analysis/simulation tools. A macromodel generated by this software may be combined with other devices in SPICE for simulation in time domain or frequency domain.

EMtoSPICE does not need a full set of data to generate a macromodel. Only a limited sample of data is needed because data can be interpolated. This is a useful feature since a full-wave EM simulation may often require a long simulation time even with modern computing resources. Obtaining data at a small number of frequency points reduces EM simulation time. Of course, a full set of S-parameter data may be used if it is available.

EMtoSPICE enforces stability at all times and passivity at user's option; provides access to the accuracy of SPICE model against the original S-parameter data via plots and RMS errors. Further refines the accuracy of SPICE model for each S-parameter at user's option

In *EMtoSPICE* the reduction can be carried out manually or automatically. In the former case the user has to specify the order of the final model, while in the latter case the user has to set the minimum order and the maximum order. The program will browse through all these ranges and it will chose the one having the smallest error. The error computed is the rms value of every component of the scattering parameters. The program does not allow minimum order less than 3 and maximum order greater than 28.

3. CODESTAR-LMN APPROACH TO REDUCTION AND SYNTHESIS OF PASSIVE COMPONENTS

Our approach in going from the frequency response to the synthesized circuit uses the vector fitting method (VFIT) [3] to find an approximate reduced order model of the characteristic. This model is expressed as a transfer function. This information is then used by a procedure that implements the Differential-Equation Macromodel (DEM) method [4] and builds a sub-circuit described in the SPICE language.

Since the input of the procedure is the frequency characteristic given in a standard Touchstone format [5], in which the files has the extension *.snp* and the output is a circuit described in the SPICE language, we will refer to our implementation as **snp2cir**. This program implements a manual reduction, to a given order that has to be specified by the user.

Among the tools developed within CODESTAR, there is one which takes as input a circuit, calls SPICE, reads its output and convert it to a Touchstone format. This tool is called **cir2snp**.

Having these two tools, it was easy to build an automatic procedure for order reduction, called **autosnp2cir2snp** which calls **snp2cir** and **cir2snp** until a specified error is reached. The idea is described by the following pseudo-code:

```
read qmin            ; minimum order
read qmax            ; maximum order
read eps             ; error for the stopping criterion
q = qmin
do
      snp2cir        ; call VFIT and DEM
      cir2snp        ; call SPICE
      er = compute_error
      q = q+1
while(er > eps) and (q <= qmax)
is_passive
```

There are many posilities for the computation of the error `er`. The first one is to use the quantity found in the initial file used by **snp2cir**. This quantity can be either an impedance **Z**, an admittance **Y** or the scattering parameters **S**. The error computed is a relative one:

$$er_1 = \frac{rms\left\|\mathbf{X} - \mathbf{X}_{ref}\right\|_F}{\max\left\|\mathbf{X}_{ref}\right\|_F}, \quad (1)$$

where **X** is **Z** or **Y** and ||.||F is the Frobenius norm**.**

The second possibility was implemented in order to be able to compare the results with the ones provided by *EMtoSPICE*:

$$er_2 = \max rms\left(S_{ij} - S_{ij,ref}\right). \quad (2)$$

It has to be noted that **autosnp2cir2snp** does the same passivity checks as *EMtoSPICE* does, i.e. it checks if all the components of the scattering parameters have the magnitude less than 1 and if all real parts of the diagonal of the impedance and admittance matrices are positive.

The next section shows the results obtained with these two codes both for manual and automatic options.

4. NUMERICAL RESULTS

q	3	4	6	8	9
EMtoSPICE error	1.9e-3	1.4e-2	4.5e-3	5.4e-3	1.5e-3
Codestar error	4e-3	1.1e-3	1.1e-3	1.1e-3	0.9e-4
EMtoSPICE no. of elements	115	143	143	256	322
Codestar no. of elements	37	47	71	94	104

Table I: Manual reduction of meander resistor benchmark

A. Manual reduction

The first tests use as input the frequency response measured for the meander resistor, which is one of the CODESTAR benchmarks. The resulted rms errors (2) and the size of SPICE circuits for several reduction order q are given in table I.

Excepting from the lowest case (q=3), for all the other orders CODESTAR provided a more accurate solution than *EMtoSPICE*. Fig.1 shows the comparison between the initial frequency characteristic obtained from measurements, the frequency characteristic obtained from the SPICE simulation of the circuit provided by *EMtoSPICE* and the one provided by *CODESTAR*, for a reduced order q=4.

The CODESTAR characteristic is just on top over the measured one, while the *EMtoSPICE* is far from the measured one.

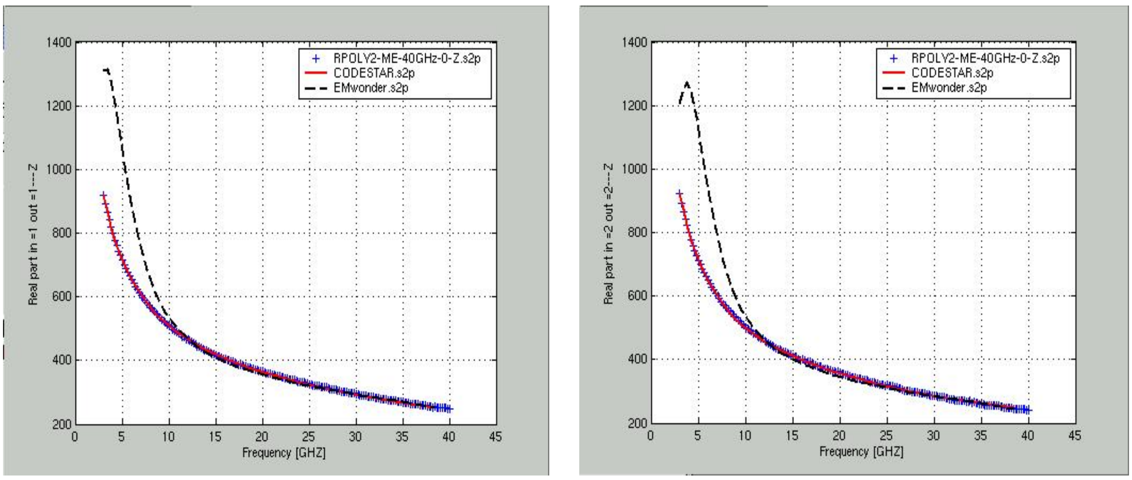

Fig.1: Comparison between initial data, EMtoSPICE and CODESTAR output: left – real part of Z11, right – real part of Z22.

B. Automatic reduction

Table II holds the results obtained using the automatic reduction procedure for both software used. *EMtoSPICE* range order chosen was between 3 and 28 which is the border interval available. As to the CODESTAR software, a relative tolerance `eps` = 1 % was imposed. Note that *EMtoSPICE* provides a different order for each component while in the CODESTAR case all components have the same order and common poles (being associated with the same system)

Code	Order	RMS error	No. of elements of the SPICE circuit
EMtoSPICE	9 for S_{11} 20 for S_{12} 12 for S_{21} 25 for S_{22}	7e-4	600
Codestar	4	1.1e-3	47

Table II: Automatic reduction of meander resistor benchmarks.

The size of the SPICE circuit provided by CODESTAR code is about 12 times lower then the size of the circuit provided by *EMtoSPICE*.

5. CONCLUSIONS

Generally, from the accuracy point of view CODESTAR code gives better results than *EMtoSPICE* when the reduction is carried out manually, to a specified order.

When running automatically, CODESTAR code is much more flexible, allowing the control of approximation by the relative tolerance. It provides a much less order and consequently a net-list with much less elements than the *EMtoSPICE* software, being more useful from a designer point of view.

When running automatically, both programs check the weak condition of passivity, which is necessary but not a sufficient condition. A plus for *EMtoSPICE* is that it also enforces this weak passivity condition during the reduction. Its documentation does not include information on how this is done.

Finally*, EMtoSPICE* is a Windows application, while *CODESTAR* code can be easily provided for Linux or for Windows, since it is Matlab code, compiled by means of the Matlab Compiler toolbox.

References

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