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To cite this version:
Nathalie Raveu, Julien Vincent, Jean-René Poirier, Ronan Perrussel, Luc Giraud. Physically-based preconditioner for the WCIP. Asia-Pacific Microwave Conference (APMC 2012), Dec 2012, Kaohsiung, Taiwan. pp. 1310 - 1312, 10.1109/APMC.2012.6421905 . hal-00907360

HAL Id: hal-00907360
https://hal.archives-ouvertes.fr/hal-00907360
Submitted on 21 Nov 2013

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Physically-based Preconditioner for the WCIP


#Université de Toulouse, INPT, CNRS, Laplace, 2 rue Charles Camichel, Toulouse, France
*Electromagnetic and Radar Department, ONERA, Toulouse, France
&Inria Bordeaux-Sud Ouest, joint Inria-CERFACS lab.

Abstract — A physically-based preconditioner for the 1d and 2d Wave Concept Iterative Procedure is introduced in this paper. Numerical results are provided to assess the efficiency of this technique.

Index Terms — Preconditioner, WCIP, modal method, multilayered planar circuit.

I. INTRODUCTION

The Wave Concept Iterative Procedure (WCIP) is a moment/modal method based on the wave concept [1]-[2] well suited for multilayered planar circuits. The initial scheme may be interpreted as a Richardson iteration for which the convergence is guaranteed but this convergence can be slow. In a previous work, several improvements were presented such as Krylov subspace acceleration [3]. In this paper, a physically-based right preconditioner is introduced. This preconditioner is first developed and analyzed for 1d TE and TM problems such as electromagnetic fields scattered by metallic surfaces printed over different dielectric substrate. This preconditioner contains two variable parameters optimized for the TE and TM case. Finally the same preconditioner is extended to the 2d case on an example.

II. 1D WCIP METHOD

The method is implemented on a 1d model circuit with one meshed surface separating two homogeneous media as represented on Fig. 1. In this particular case, a z-invariance is assumed. As a consequence, TE (E_y=0) and TM (H_y=0) modes are physically separated: if the source is polarized along z, only TE modes are generated, while if the source is polarized along x only TM modes are generated. The method is based on incident Bi and reflected Ai waves on the interface (where i stands for media numbered 1 or 2 in Fig. 1). These waves are defined by

\[
\begin{align*}
A_i &= \frac{1}{2\sqrt{Z_0}} \left( E_{Ti} + Z_0 H_{Ti} \wedge n_i \right), \\
B_i &= \frac{1}{2\sqrt{Z_0}} \left( E_{Ti} - Z_0 H_{Ti} \wedge n_i \right),
\end{align*}
\]

with Z_0 an arbitrary impedance, E_{Ti}, H_{Ti} and n_i the electric, magnetic tangential fields and unit normal outward vector to the surface.

Fig. 1. Example of a 1d circuit.

A-Principles

Interface conditions (metallic or insulate) over the meshed surface are applied on each mesh through a spatial operator S:

\[
A = SB, \text{ where } B = (B_1, B_2)^T \text{ and } A = (A_1, A_2)^T. (2)
\]

The homogeneous medium numbered i surrounding the surface is characterized through the modal operator \( \Gamma_i^\alpha \) defined [1]-[2] (\( \alpha = \text{TE or TM} \)) by

\[
B = \begin{pmatrix} \Gamma_1^\alpha & 0 \\ 0 & \Gamma_2^\alpha \end{pmatrix} A = \Gamma^\alpha A. \quad (3)
\]

Conversion between the modal and spatial domains is performed through a Fast Modal Transform (FMT) and its inverse (FMT^{-1}). Modal sources are expressed through a known \( B_{om} \) vector added in equation (2). Consequently, the system to be solved is

\[
(1 - \Gamma^\alpha V S V^{-1}) B = MB = B_{om}
\]

where \( V = \begin{pmatrix} \text{FMT} & 0 \\ 0 & \text{FMT} \end{pmatrix} \).

B-Preconditioner

An ideal right preconditioner \( P^{-1} \) should be close to \( M^{-1} \), since if \( MP^{-1} \) is close to the identity, the convergence of the iterative scheme is improved. The system to solve is then
\[ MP^{-1}y = B_{\text{em}}. \]  

(5)

From the analytic solution in the perfectly conducting and insulating surface, a generic right preconditioner is determined and implemented. For a perfectly conducting case, \( S \) operator is equal to \(-I\), which entails equation (4) becomes simply

\[ (I + \Gamma^a)B = B_{\text{em}}. \]  

(6)

Therefore \( P = \begin{bmatrix} 1 + \left( \begin{array}{cc} \Gamma_1^a & 0 \\ 0 & \Gamma_2^a \end{array} \right) \end{bmatrix} \). For a perfectly insulating surface, waves are directly transmitted to the other medium, implying equation (4) becomes

\[ \left( I - \Gamma^a \begin{bmatrix} 0 \\ 1 \end{bmatrix} \right) \begin{bmatrix} 0 \\ 1 \end{bmatrix}^{-1} B = \left( I - \begin{bmatrix} 0 & \Gamma_1^a \\ \Gamma_2^a & 0 \end{bmatrix} \right) B = B_{\text{em}}. \]  

(7)

Therefore \( P = \begin{bmatrix} 1 - \left( \begin{array}{c} \Gamma_1^a \\ \Gamma_2^a \end{array} \right) \end{bmatrix} \). Finally, a right preconditioner is assumed with adjustable values \((a_1, a_2)\) depending on the circuit shape:

\[ P = \begin{bmatrix} 1 + \left( \begin{array}{cc} a_1 \Gamma_1^a & a_2 \Gamma_1^a \\ a_2 \Gamma_2^a & a_1 \Gamma_2^a \end{array} \right) \end{bmatrix}. \]  

(8)

For instance, in the perfectly conducting surface \((a_1, a_2) = (1,0)\) is chosen while \((0, -1)\) corresponds to the insulating surface.

### III. NUMERICAL RESULTS

The surface is meshed into 400 cells, distance between periodic walls is 0.07m, source is composed of 20 modes. Results are presented as function of the mode type (TE or TM), the proportion of metal, the relative permittivity around the meshed surface. GMRes [4] tolerance is set to \(10^{-3}\), no restart is used and maximum iteration is set to 400.

#### A-Sensitivity to Metal/Insulate proportions

Iteration number \((N_{\text{iter}})\) is given for several insulate/metal proportion at 300MHz in the TE case and without the preconditioner in Table I for the best \((a_1, a_2)\) within \([-1,1]\). Similar results are observed in the TM case. To compare preconditioner costs in computation time 10000 iterations are achieved in the case of Table I for 50% of metal. One iteration lasts 0.12ms without preconditioner and 0.15ms with the preconditioner (same results in the TM case). Consequently the decrease in the number of iterations reported in the tables below translates in comparable computational time reduction.

<table>
<thead>
<tr>
<th>Metal proportion</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niter</td>
<td>41</td>
<td>96</td>
<td>96</td>
<td>96</td>
<td>21</td>
</tr>
<tr>
<td>CPU time (ms)</td>
<td>148</td>
<td>704</td>
<td>703</td>
<td>688</td>
<td>55</td>
</tr>
</tbody>
</table>

#### B-Sensitivity to dielectric permittivities

Let us consider different permittivities \(\varepsilon_{r2}\) for substrate 2, a ground plane at a distance 2mm for 50% metal surface, at a higher frequency (30.1GHz), so that 15 modes are propagating. Results are reported in Table II for the TM case. Iteration number is still divided at least by 2.6. Similar results are observed for the TE case.

<table>
<thead>
<tr>
<th>(\varepsilon_{r2})</th>
<th>-20</th>
<th>-10</th>
<th>1</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niter</td>
<td>90</td>
<td>94</td>
<td>120</td>
<td>215</td>
<td>233</td>
</tr>
<tr>
<td>CPU time (ms)</td>
<td>596</td>
<td>648</td>
<td>1099</td>
<td>4952</td>
<td>6195</td>
</tr>
</tbody>
</table>

#### C-Sensitivity to frequency

Let us consider different frequencies, a dielectric relative permittivity \(\varepsilon_{r2}\) of 4.4, a ground plane at a distance 2mm for 50% metal surface. Results are reported in Table III for the TE case. Iteration number is still divided at least by 2.1. The best couple value is not frequency dependent. Similar results are observed for the TM case.

<table>
<thead>
<tr>
<th>(\varepsilon_{r2})</th>
<th>-20</th>
<th>-10</th>
<th>1</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niter</td>
<td>26</td>
<td>30</td>
<td>45</td>
<td>57</td>
<td>62</td>
</tr>
<tr>
<td>CPU time (ms)</td>
<td>89</td>
<td>104</td>
<td>191</td>
<td>270</td>
<td>308</td>
</tr>
<tr>
<td>Reduction factor Niter</td>
<td>3.46</td>
<td>3.13</td>
<td>2.66</td>
<td>3.77</td>
<td>3.75</td>
</tr>
<tr>
<td>Reduction factor CPU</td>
<td>6.69</td>
<td>6.23</td>
<td>5.75</td>
<td>18.3</td>
<td>20.1</td>
</tr>
</tbody>
</table>

### Table I: Iteration number for several metal proportions.

The number of iterations is at least divided at least by 1.8. Computation time is also reduced. Best couple \((a_1, a_2)\) does not depend on the metal/insulate proportion but on the type of the excited modes (except for the perfectly insulate or metallic canonical cases). Many examples were tested and the best solutions for TE and TM problems are respectively \((0,-1)\) and \((1,0)\) whatever the frequency, the substrate permittivity and the metal/insulate proportion (except for the canonical cases: 100% metal or 100% insulate).
To understand the convergence improvement, the eigenvalues of the operators described in equations (4) and (5) are compared at 300MHz and 30.1GHz for 50% metal proportion without ground plane in vacuum and represented respectively in Figures 2 and 3. Even if preconditioned eigenvalues are better clustered than eigenvalues of the WCIP without preconditioner, no rule has been established to find out the best couples \((a_1, a_2)\) from the eigenvalue observation.

**TABLE III: ITERATION NUMBER FOR SEVERAL FREQUENCIES.**

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>0.3</th>
<th>3</th>
<th>30</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Precond Niter</td>
<td>98</td>
<td>95</td>
<td>120</td>
<td>365</td>
</tr>
<tr>
<td>CPU time (ms)</td>
<td>720</td>
<td>689</td>
<td>1107</td>
<td>22663</td>
</tr>
<tr>
<td>Precond best ((a_1, a_2))</td>
<td>(0,-1)</td>
<td>(0,-1)</td>
<td>(0,-1)</td>
<td>(0,-1)</td>
</tr>
<tr>
<td>Niter</td>
<td>45</td>
<td>42</td>
<td>47</td>
<td>147</td>
</tr>
<tr>
<td>CPU time (ms)</td>
<td>196</td>
<td>167</td>
<td>196</td>
<td>1837</td>
</tr>
<tr>
<td>Reduction factor Niter</td>
<td>2.17</td>
<td>2.26</td>
<td>2.55</td>
<td>2.46</td>
</tr>
<tr>
<td>Reduction factor CPU</td>
<td>3.67</td>
<td>4.12</td>
<td>5.64</td>
<td>12.33</td>
</tr>
</tbody>
</table>

**IV. EXTENSION TO 2D PROBLEMS**

Preconditioner (8) is applied in the 2d case with respect to (5) (TE and TM appear simultaneously). A square slot over an infinite dielectric \((\varepsilon_r = 4.4)\) is illuminated by a z-polarized electric field at 3GHz composed of 20 modes. The number of unknowns is 160000. Iteration number is observed for several metal proportions. For the sake of comparison, numerical experiments are reported in Table IV with and without preconditioner. Then its dual is studied: a square patch, results are reported in Table V. One can notice that the best couple does not depend on the metal proportion in both cases.

**TABLE IV: PRECONDITIONER IN THE SLOT CASE.**

<table>
<thead>
<tr>
<th>Metal proportion</th>
<th>19%</th>
<th>36%</th>
<th>50%</th>
<th>75%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Precond Niter</td>
<td>106</td>
<td>75</td>
<td>66</td>
<td>59</td>
<td>53</td>
</tr>
<tr>
<td>Precond best ((a_1, a_2))</td>
<td>(0.9, -0.1)</td>
<td>(0.9, 0)</td>
<td>(0.9, 0)</td>
<td>(0.9, 0)</td>
<td>(1, 0)</td>
</tr>
<tr>
<td>Reduction factor Niter</td>
<td>1.53</td>
<td>2.02</td>
<td>2</td>
<td>1.78</td>
<td>10.6</td>
</tr>
</tbody>
</table>

**TABLE V: PRECONDITIONER IN THE PATCH CASE.**

<table>
<thead>
<tr>
<th>Metal proportion</th>
<th>19%</th>
<th>36%</th>
<th>50%</th>
<th>75%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Precond Niter</td>
<td>48</td>
<td>48</td>
<td>50</td>
<td>69</td>
<td>96</td>
</tr>
<tr>
<td>Precond best ((a_1, a_2))</td>
<td>(0.4, -0.6)</td>
<td>(0.4, -0.6)</td>
<td>(0.4, -0.6)</td>
<td>(0.4, -0.6)</td>
<td>(0.4, -0.4)</td>
</tr>
<tr>
<td>Reduction factor Niter</td>
<td>12</td>
<td>6.85</td>
<td>3.57</td>
<td>2.09</td>
<td>1.4</td>
</tr>
</tbody>
</table>

**V. CONCLUSION**

A new physically-based right preconditioner is developed in this paper for the 1d and 2d WCIP. It allows at least to divide by 1.4 the iteration number compared to the initial Krylov subspace method without preconditioner for some examples. Several attempts to justify the adjustable parameter choice have been explored in the 1d case, but no rules emerge from it. Extension to the 2d case has been achieved on two examples and results are promising with a noticeable reduction of the number of iterations.

**REFERENCES**