Advances in Dielectric Property and Thickness Evaluation of Layered Composite Structures using Open-Ended Waveguides

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Introduction

Background and Contribution

• Microwave Material Characterization Techniques
  – Cavity
  – Transmission line
  – Free-space
    • Far-field – Plane-wave / focused
    • Near-field – open-ended rectangular waveguide and coaxial probes [1]

• Near-field open-ended rectangular waveguide
  – No need to cut and shape the sample
  – Requires a relatively large sample
  – Advanced flange designs to reduce reflection from flange [2]
    – Computationally Intense

Introduction

Example Applications

Measure thickness and dielectric properties

Many Applications

TBC

Corrosion

Under Paint
Introduction

Contribution: Reduce Sources of Computational Complexity

• Forward problem
  – Evaluate reflection coefficient from a model
  – Adaptive segmentation
    • Increase computational accuracy
    • Reduce computational cost

• Inverse Problem
  – Determine a model from given reflection coefficient
  – Large quantity of degrees of freedom
  – Easily trapped in local minima
  – Significant reduction of the degrees of freedom using value relationships
  – Adaptive Segmentation reduces the likelihood of local minima and eliminates solver “panic” (e.g., NaN or Inf)
Forward Problem [1]

Challenges

- Large disparity (variation) in integrand value for low loss layers
  - *Singularities for no-loss layers*

- Gaussian Legendre integration is necessary but must have proper segmentation boundaries

- Segmentation is a function of layer properties and no direct relationship exists

- Main challenge: Where should integration samples be placed and with what concentration and with what weight?

Forward Problem
Adaptive Segmentation

1. Evenly distribute samples in one segment and evaluate integrand
2. Identify and locate peaks
3. Refine / solve for peak location (hill climbing / iterated local search)
4. Define segments using peak values as segment boundaries
5. Sample distribution
   – *Evenly distributed between segments regardless of segment span*
   – *Steep integrands require more samples*

• Demonstration comparing adaptive and primitive segmentation
  – *Convergence Test*
Forward Problem

Computational Example

- Infinite half-space of “air”
  - \( \varepsilon_r = 1-j0.0001 \)
  - *Loss added to allow primitive segmentation to converge*

- X-band (8.2-12.4 GHz, 22 frequencies) open-ended waveguide

- Modes: MaxM = 5, MaxN = 4

- Test Adaptive and Primitive segmentation techniques

- Root Mean Square Error (RMSE) = \( \sqrt{\frac{(R-S)^2}{\langle R^2 \rangle}} \) (dB) = 20 \( \log_{10} \) (RMSE)
Forward Problem
Computational Resource

Cisco UCS C460 M4

- 4 x Intel Xeon E7-4850 v2 2.3GHz CPU
- 48 Cores / 96 Threads
- 1TB DDR3 memory
- 10GbE enabled
- CentOS 6.6

- Notes
  - *It is a shared resource, times are approximate*
  - *Memory bottleneck due to other users*
  - “nice” levels intentionally set to +5 (lower priority)
Forward Problem

Convergence Test Procedure and Results

\( N_o = 100 \)
\( \Delta N = 100 \)
\( Tol = 0.0001 \)

1) Begin with \( N = N_o \rho \) samples, and \( i = 0 \)
2) Evaluate \( \Gamma_i \)
3) \( i = i + 1 \)
4) \( N_i = N_{i-1} + \Delta N \)
5) Evaluate \( \Gamma_i \)
6) Compute \( Error = \max | \Gamma_i - \Gamma_{i-1} | \)
7) Repeat (3)-(6) until three consecutive errors below \( Tol \)
Forward Problem

Influence of sampling and segmentation (800 samples)

Integration Domain and Range

Reflection Coefficient

$\rho$ (unitless)

$\text{Integrand (10.4 GHz)}$

$\text{Difference}$

$\text{Imaginary}$

$\text{Real}$

$1.50e^{-1}$ (-16.5 dB) RMSE before convergence
Forward Problem

Influence of sampling and segmentation (42500 samples, 1/4)

Integration Domain and Range

Reflection Coefficient

$\rho$ (unitless)

$\text{Integrand (10.4 GHz)}$

$\text{Difference}$

$\text{Imaginary}$

$\text{Real}$

$9.7e-3$ (-40 dB) RMSE before convergence
Forward Problem

Influence of sampling and segmentation (85100 samples, 1/2)

Integration Domain and Range

Reflection Coefficient

$\rho$ (unitless)

Integrand (10.4 GHz)

2.2e-3 (-53 dB) RMSE before convergence
Forward Problem

Influence of sampling and segmentation (170200 samples)

Integration Domain and Range

Reflection Coefficient

$\rho$ (unitless)

Real

Imaginary

Difference

$2.1e-4 \ (-74 \ dB) \ RMSE \ after \ convergence$
Forward Problem

Convergence Test

<table>
<thead>
<tr>
<th>Segmentation</th>
<th>Number of Samples</th>
<th>Time per freq. (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive</td>
<td>800</td>
<td>0.38</td>
</tr>
<tr>
<td>Primitive</td>
<td>170200</td>
<td>560</td>
</tr>
</tbody>
</table>
Forward Problem

Influence of small permittivity changes

• Secondary test to computing error w.r.t. $N$ (samples)
• Analyze RMSE between reflection coefficient of infinite half space of air and air $+\Delta \varepsilon_r$
• Adaptive segmentation provides predictable and smooth variation

**Primitive** is 86900 Samples / Error = 0.001
Inverse Problem

*Improvements made to benefit the inverse problem*

- Improvements to Forward Problem benefit Inverse Problem
  - *Reduced computational cost*
    - Inversion is really forward-iterative
  - *Improved computational accuracy*
    - Smooth solution space
    - May use derivative based optimization methods
    - Nearly eliminates bias to initial guess
- Reduce complexity of solution space by exploiting relationships
  - *Every independent unknown is another dimension in the solution space*
  - *Further reduce chances of local minima*
  - *Exploit value relationships between electric and dimensional properties*
    - Direct – Values are identical
    - Functional – Values are related by some function (e.g., curve fit)
Inverse Problem 1 (Air)

Experimental Trial

• Infinite half-space of “air” ($\varepsilon_r = 1-j0$)

• X-band (8.2-12.4 GHz, 201 frequencies) smoothed open-ended waveguide

• Modes: MaxM = 5, MaxN = 4

• Solve for:
  – All frequencies independent
  – Linear variation with frequency
  – Constant w.r.t. frequency
  – Using L-BFGS-B
Inverse Problem 1 (Air)

Results

Relation | RMSE | RMSE (dB) | Relative Time
--- | --- | --- | ---
Theory | 0.051 | -25.9 | -
Frequency | 0.000 | -172.0 | x1
Linear | 0.013 | -37.7 | x4
Constant | 0.029 | -30.8 | x1
Inverse Problem 2

Examples

<table>
<thead>
<tr>
<th>Label</th>
<th>( \varepsilon'_r ) - Permittivity</th>
<th>( \varepsilon''_r ) - Loss</th>
<th>Thickness (mil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>0.0000</td>
<td>4</td>
</tr>
<tr>
<td>Rogers TMM10i</td>
<td>9.9</td>
<td>0.0198</td>
<td>20</td>
</tr>
<tr>
<td>Air</td>
<td>1</td>
<td>0.0000</td>
<td>4</td>
</tr>
<tr>
<td>Rogers R04533</td>
<td>3.33</td>
<td>0.0083</td>
<td>60</td>
</tr>
<tr>
<td>Air</td>
<td>1</td>
<td>0.0000</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Measure thickness and dielectric properties constant w.r.t. frequency
## Inverse Problem (Layers)

*Results – Constant w.r.t. Frequency*

<table>
<thead>
<tr>
<th>Item</th>
<th>Theory</th>
<th>All Independent</th>
<th>Reduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>N/A</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>RMSE (dB)</td>
<td>-35</td>
<td>-44</td>
<td>-44</td>
</tr>
<tr>
<td>Air - $\varepsilon_r'$</td>
<td>1.00</td>
<td>$1.011\pm0.012$</td>
<td>1.027</td>
</tr>
<tr>
<td>Air - $\varepsilon_r''$</td>
<td>0.0</td>
<td>$(2.8\pm3.9)e^{-4}$</td>
<td>0.0</td>
</tr>
<tr>
<td>Rogers T - $\varepsilon_r'$</td>
<td>9.9</td>
<td>9.9</td>
<td>9.9</td>
</tr>
<tr>
<td>Rogers T - $\varepsilon_r''$</td>
<td>0.0198</td>
<td>0.0230</td>
<td>0.0233</td>
</tr>
<tr>
<td>Rogers T – Thk (mil)</td>
<td>20</td>
<td>20.75</td>
<td>20.63</td>
</tr>
<tr>
<td>Rogers R - $\varepsilon_r'$</td>
<td>3.330</td>
<td>3.339</td>
<td>3.339</td>
</tr>
<tr>
<td>Rogers R - $\varepsilon_r''$</td>
<td>0.0083</td>
<td>0.0147</td>
<td>0.0154</td>
</tr>
<tr>
<td>Rogers R – Thk (mil)</td>
<td>60</td>
<td>61.16</td>
<td>61.14</td>
</tr>
</tbody>
</table>

*Reduced performs similarly numerically, but ~2x faster*
Summary / Conclusion

Remarks

• Forward Problem
  – Adaptive segmentation is the only appropriate segmentation
  – More accurate and faster results

• Inverse Problem
  – Solution is largely dependent upon the accuracy of the forward problem and the number of unknowns
  – Reduce unknowns wherever possible (i.e., make overdetermined)

• Questions?
Forward Problem

Hill Climbing

1. \( i = 0, \Delta_i = \Delta \rho / 2, \rho_i = \rho_o, V_i = V(\rho_o) \)
2. \( i = i + 1 \)
3. \( \rho_i = \rho_{i-1} + \Delta_{i-1} \)
4. \( V_i = V(\rho_i) \)
5. If \( V_i > V_{i-1} \), then \( \Delta_i = \Delta_{i-1} / 2 \)
6. If \( V_i < V_{i-1} \), then \( \Delta_i = -\Delta_{i-1} / 2, \rho_i = \rho_{i-1} \)
7. Repeat (2)-(6) until \( \Delta_i < \text{Tol} \)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \rho )</td>
<td>Current ( \rho ) sampling</td>
</tr>
<tr>
<td>( i )</td>
<td>Iteration</td>
</tr>
<tr>
<td>( \Delta_i )</td>
<td>Current increment</td>
</tr>
<tr>
<td>( \rho_i )</td>
<td>Current position</td>
</tr>
<tr>
<td>( V_i )</td>
<td>Current Value</td>
</tr>
</tbody>
</table>