Tutorial: Advanced Topics in Signal and Power Integrity

Parameterized Models for Efficient Design in EMC and SI Applications

F. Ferranti*, T. Dhaene*, L. Knockaert*, G. Antonini**, A. Ciccomancini Scogna†

* Department of Information Technology (INTEC), Ghent University – IBBT
** Dipartimento di Ingegneria Elettrica e dell'Informazione, Università degli Studi dell'Aquila
† CST of America
Outline

Introduction

Parameterized Macromodels

Numerical examples
  • EMC example
  • SI example

Conclusions
Outline

Introduction

Parameterized Macromodels

Numerical examples
  • EMC example
  • SI example

Conclusions
input $\rightarrow$ output

$\text{out} = f(\text{in})$

Department of Information Technology – Internet Based Communication Networks and Services (IBCN)
Design variables: width, temperature, angle, frequency, ...

Response variables: lift, S-parameters, pressure, stress, ...

Simulation Model:
Fluent®, HSPICE®, CST®, Comsol®, Abaqus®, ...

Parameterized Macromodel:
Neural network, Kriging, SVM, rational function, spline, ...

Adaptive Modeling

Distributed Computing

CAD/CAM/CAE Environment

Prototyping

Optimization

Sensitivity Analysis

Department of Information Technology – Internet Based Communication Networks and Services (IBCN)
Design process

- several decisions
  - materials
  - geometrical dimensions
  - shape
  - constraints
    - space
    - cost
    - performance
Simulators

- implementation of models
- describe systems behavior
- help designers

Measurements

- post tuning
- verification
- help designers
A typical design process requires

- design space optimization
- design space exploration
- sensitivity analysis
  - multiple simulations (measurements)
  - different design parameters values (e.g. layout features)
A typical design process requires

- Multiple simulations (measurements)
  - computationally expensive (time and memory)

- Can we do better?

- Yes
  - By parameterized macromodels
Outline

Introduction

Parameterized Macromodels

Numerical examples
  • EMC example
  • SI example

Conclusions
Modeling and discretization by simulators lead to a model that can be described by the PDE $sX = AX + BU$. The output of the model is given by $Y = CX + DU$. The parameterized macromodel is obtained from this model, represented by $H(s, g)$. This approach is used in the Department of Information Technology – Internet Based Communication Networks and Services (IBCN).
discretisation by simulators

real world

modeling

model

PDE

U(s,g)

sX = AX + BU

Y(s,g)

Y(s,g)

U(s,g)

H(s,g)

Y(s,g)

model-driven PMOR

data

Data-driven PMOR

parameterized macromodel

Department of Information Technology – Internet Based Communication Networks and Services (IBCN)
measurements

real world

modeling

discretisation by simulators

Data-driven PMOR

Model-driven PMOR

U(s,g) -> sX = AX + BU, Y(s,g) -> Y(s,g)

PDE

Department of Information Technology – Internet Based Communication Networks and Services (IBCN)
PMOR concepts

Two design space grids are used in the modeling process

- estimation grid
- validation grid

Design space

\[ g = (g^{(n)})^N \]
Rational Fitting Methods

- VECTFIT
- MULTIPOSE
- STABILITY
- PASSIVITY
- NOISY DATA

+ Interpolation Least Squares

- SYSTEM MATRICES
- TRANSFER FUNCTIONS
- POLES/RESIDUES

data-driven PMOR

scatter data

H(s,g)

- accuracy
- efficiency
- stability guaranteed
- passivity guaranteed
**Rational Fitting Methods**

- VECTFIT
- MULTIPORT
- STABILITY
- PASSIVITY
- NOISY DATA

**Interpolation Least Squares**

- SYSTEM MATRICES
- TRANSFER FUNCTIONS
- POLES/RESIDUES

**data-driven PMOR**

\[ H(s, g) = \sum_{p=1}^{p} \frac{Q(g)}{s - a_p(g)} \]

\[ H(s, g) = C(g)(sI - A(g))^{-1}B(g) + D(g) \]
Rational Fitting Methods

Interpolation

data-driven PMOR

\[ H(s, g) = \sum_{p=1}^{P} \frac{Q(g)}{s - a_p(g)} \]

\[ H(s, g) = C(g)(sI - A(g))^{-1}B(g) + D(g) \]

scattered data
Design space \( g = \left( g^{(n)} \right)^N \)
Features

- local approach (cell by cell)
Features

- local approach (cell by cell)
- independent from a specific state-space realization
- stability and passivity guaranteed over the design space
- suitable to robust adaptive sampling
- different flavours
Compute root macromodels $R(s, g_k^{\Omega_i})$
in the estimation design space grid

Compute scaling and frequency shifting coefficients
$\alpha_{1,k}(g_j^{\Omega_i}), \alpha_{2,k}(g_j^{\Omega_i})$
in the estimation design space grid

Multivariate interpolation of
scaling and frequency shifting coefficients
$\alpha_1(g), \alpha_2(g)$

Multivariate interpolation of
scaled and shifted root macromodels
$\alpha_1(g)R(s\alpha_2(g), g)$
\[ R(s, g_j^{\widehat{\Omega}}) = C_0(g_j^{\widehat{\Omega}}) + \sum_{n=1}^{N(\widehat{\Omega})} \frac{C_n(g_j^{\widehat{\Omega}})}{s - p_n(g_j^{\widehat{\Omega}})} \]
Compute root macromodels $R(s, g^\Omega_k)$ in the estimation design space grid.

Compute scaling and frequency shifting coefficients $\alpha_1,k(g_j^\Omega_i), \alpha_2,k(g_j^\Omega_i)$ in the estimation design space grid.

Multivariate interpolation of scaling and frequency shifting coefficients $\alpha_1(g), \alpha_2(g)$.

Multivariate interpolation of scaled and shifted root macromodels $\alpha_1(g)R(s\alpha_2(g), g)$. 
\[
\min_{\alpha_{1,k}(g_j^{\Omega}), \alpha_{2,k}(g_j^{\Omega})} Err(\tilde{R}(s, g_k^{\Omega}), R(s, g_j^{\Omega}))
\]

\[
\tilde{R}(s, g_k^{\Omega}) = \alpha_{1,k}(g_j^{\Omega}) R(s, \alpha_{2,k}(g_j^{\Omega}), g_k^{\Omega})
\]

\[
\alpha_{1,k}(g_j^{\Omega}) = \alpha_{2,k}(g_j^{\Omega}) = 1, \quad j = k
\]
\[
\min_{\alpha_1,k(g_j^\Omega), \alpha_2,k(g_j^\Omega)} \text{Err}(\tilde{R}(s, g_k^\Omega), R(s, g_j^\Omega))
\]
\[
\tilde{R}(s, g_k^\Omega) = \alpha_{1,k}(g_j^\Omega)R(s\alpha_{2,k}(g_j^\Omega), g_k^\Omega)
\]
\[
\alpha_{1,k}(g_j^\Omega) = \alpha_{2,k}(g_j^\Omega) = 1, \ j = k
\]
\[
\alpha_{2,3}(g_j^\Omega), j = 1, \ldots, 4
\]
\[
\alpha_{1,3}(g_j^\Omega), j = 1, \ldots, 4
\]
Compute root macromodels $R(s, g^\Omega_k)$ in the estimation design space grid.

Compute scaling and frequency shifting coefficients $\alpha_{1,k}(g^\Omega_j), \alpha_{2,k}(g^\Omega_j)$ in the estimation design space grid.

Multivariate interpolation of scaling and frequency shifting coefficients $\alpha_1(g), \alpha_2(g)$.

Multivariate interpolation of scaled and shifted root macromodels $\alpha_1(g)R(s\alpha_2(g), g)$. 

Department of Information Technology – Internet Based Communication Networks and Services (IBCN)
\begin{align*}
\alpha_{1,3}(\hat{g}^\Omega) &= R(\alpha_{2,3}(\hat{g}^\Omega) s, g_3^\Omega) \\
\alpha_{1,4}(\hat{g}^\Omega) &= R(\alpha_{2,4}(\hat{g}^\Omega) s, g_4^\Omega) \\
\alpha_{2,3}(\hat{g}^\Omega) &= \text{interp}(g_j^\Omega, \alpha_{2,3}(g_j^\Omega), \hat{g}^\Omega) \\
\alpha_{1,3}(\hat{g}^\Omega) &= \text{interp}(g_j^\Omega, \alpha_{1,3}(g_j^\Omega), \hat{g}^\Omega) \\
R(s, g_3^\Omega) &= \\
\alpha_{2,4}(\hat{g}^\Omega) &= \text{interp}(g_j^\Omega, \alpha_{2,4}(g_j^\Omega), \hat{g}^\Omega) \\
\alpha_{1,4}(\hat{g}^\Omega) &= \text{interp}(g_j^\Omega, \alpha_{1,4}(g_j^\Omega), \hat{g}^\Omega) \\
R(s, g_4^\Omega) &= \\
\tilde{\Omega} &= \mathcal{X} \hat{g}^\Omega \\
R(s, g_1^\Omega) &= \\
\alpha_{1,1}(\hat{g}^\Omega) &= \text{interp}(g_j^\Omega, \alpha_{1,1}(g_j^\Omega), \hat{g}^\Omega) \\
\alpha_{2,1}(\hat{g}^\Omega) &= \text{interp}(g_j^\Omega, \alpha_{2,1}(g_j^\Omega), \hat{g}^\Omega) \\
R(s, g_2^\Omega) &= \\
\alpha_{1,2}(\hat{g}^\Omega) &= \text{interp}(g_j^\Omega, \alpha_{1,2}(g_j^\Omega), \hat{g}^\Omega) \\
\alpha_{2,2}(\hat{g}^\Omega) &= \text{interp}(g_j^\Omega, \alpha_{2,2}(g_j^\Omega), \hat{g}^\Omega) \\
R(s, g_1^\Omega) &= \\
\alpha_{1,1}(\hat{g}^\Omega) &= \text{interp}(g_j^\Omega, \alpha_{1,1}(g_j^\Omega), \hat{g}^\Omega) \\
\alpha_{2,1}(\hat{g}^\Omega) &= \text{interp}(g_j^\Omega, \alpha_{2,1}(g_j^\Omega), \hat{g}^\Omega) \\
R(s, g_2^\Omega) &= \\
\alpha_{1,2}(\hat{g}^\Omega) &= \text{interp}(g_j^\Omega, \alpha_{1,2}(g_j^\Omega), \hat{g}^\Omega) \\
\alpha_{2,2}(\hat{g}^\Omega) &= \text{interp}(g_j^\Omega, \alpha_{2,2}(g_j^\Omega), \hat{g}^\Omega) \\
\end{align*}
Compute root macromodels $R(s, g_k^{\Omega_i})$

in the estimation design space grid

Compute scaling and frequency shifting coefficients

$\alpha_{1,k}(g_j^{\Omega_i}), \alpha_{2,k}(g_j^{\Omega_i})$

in the estimation design space grid

Multivariate interpolation of
scaling and frequency shifting coefficients

$\alpha_1(g), \alpha_2(g)$

Multivariate interpolation of
scaled and shifted root macromodels

$\alpha_1(g)R(s\alpha_2(g), g)$
\[ \alpha_{1,3}(\hat{g}^\Omega)R(\alpha_{2,3}(\hat{g}^\Omega)s, g_3^\Omega) \]

\[ \alpha_{1,4}(\hat{g}^\Omega)R(\alpha_{2,4}(\hat{g}^\Omega)s, g_4^\Omega) \]

\[ \Omega \]

\[ R(s, \hat{g}^\Omega) = \text{interp}(g_j^\Omega, \alpha_{1,j}(\hat{g}^\Omega))R(\alpha_{2,j}(\hat{g}^\Omega)s, g_j^\Omega), \hat{g}^\Omega) \]

\[ R(s, \hat{g}^\Omega) = \sum_{k_1=1}^{2} \sum_{k_2=1}^{2} \tilde{R}(s, (g_{k_1}^{(1)}, g_{k_2}^{(2)})^\Omega)\ell_{k_1}(g^{(1)})\ell_{k_2}(g^{(2)}) \]
Standard Interpolation

Compute root macromodels $R(s, g_k^{\Omega_i})$
in the estimation design space grid

Multivariate interpolation of
root macromodels
$R(s, g)$
Outline

Introduction

Parameterized Macromodels

Numerical examples
  • EMC example
  • SI example

Conclusions
data-driven PMOR

\[ H(s, g) = \sum_{p=1}^{P} \frac{Q(g)}{s - a_p(g)} \]

\[ H(s, g) = C(g)(sI - A(g))^{-1}B(g) + D(g) \]
3D example: Enclosure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (freq)</td>
<td>0 Hz</td>
<td>1 GHz</td>
</tr>
<tr>
<td>Length (L)</td>
<td>10 cm</td>
<td>20 cm</td>
</tr>
<tr>
<td>Width (W)</td>
<td>0.8 cm</td>
<td>2.8 cm</td>
</tr>
</tbody>
</table>
Plane wave excitation

<table>
<thead>
<tr>
<th>Probe</th>
<th>E-Field (15 6 15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Efield</td>
</tr>
<tr>
<td>Position</td>
<td>15, 6, 15</td>
</tr>
<tr>
<td>Step</td>
<td>CPU time</td>
</tr>
<tr>
<td>----------------------------------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Estimation grid by solver (6 × 6) (L,W)</td>
<td>2 h 25 min 48 s</td>
</tr>
<tr>
<td>Validation grid by solver (5 × 5) (L,W)</td>
<td>1 h 41 min 15 s</td>
</tr>
<tr>
<td>Building model</td>
<td>3.08 s</td>
</tr>
<tr>
<td>Validating model</td>
<td>0.9 s</td>
</tr>
<tr>
<td>Evaluating solver (one frequency response)</td>
<td>4 min 3 s</td>
</tr>
<tr>
<td>Evaluating model (one frequency response)</td>
<td>7.2 ms</td>
</tr>
<tr>
<td>Step</td>
<td>CPU time</td>
</tr>
<tr>
<td>-------------------------------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Estimation grid by solver (6 x 6) (L,W)</td>
<td>2 h 25 min 48 s</td>
</tr>
<tr>
<td>Validation grid by solver (5 x 5) (L,W)</td>
<td>1 h 41 min 15 s</td>
</tr>
<tr>
<td>Building model</td>
<td>3.08 s</td>
</tr>
<tr>
<td>Validating model</td>
<td>0.9 s</td>
</tr>
<tr>
<td>Evaluating solver (one frequency response)</td>
<td>4 min 3 s</td>
</tr>
<tr>
<td>Evaluating model (one frequency response)</td>
<td>7.2 ms</td>
</tr>
</tbody>
</table>

Speed-up 33750 x
W = 1.8 cm
L = 15 cm

|E| [V/m] vs. Frequency [GHz]

- L = 19 cm
- L = 11 cm

W = 1 cm
W = 2.6 cm

|E| [V/m] vs. Frequency [GHz]
Outline

Introduction

Parameterized Macromodels

Numerical examples
  • EMC example
  • SI example

Conclusions
Rational Fitting Methods

Interpolation

VECTFIT
MULTIPORT
STABILITY
PASSIVITY
NOISY DATA

TRANSFER FUNCTIONS
SCALING
SHIFTING

data-driven PMOR

\[ H(s,g) = \sum_{p=1}^{P} \frac{Q(g)}{s - a_p(g)} \]

\[ H(s,g) = C(g)(sI - A(g))^{-1}B(g) + D(g) \]

scattered data
3D example: PCB

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (freq)</td>
<td>0 Hz</td>
<td>20 GHz</td>
</tr>
<tr>
<td>Antipads radius (R)</td>
<td>0.4826 mm</td>
<td>0.6026 mm</td>
</tr>
<tr>
<td>Distance (D)</td>
<td>1.2525 mm</td>
<td>2.4525 mm</td>
</tr>
</tbody>
</table>

R = antipads radius

D = distance between signal vias and ground vias (center to center)
3D example: PCB

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (freq)</td>
<td>0 Hz</td>
<td>20 GHz</td>
</tr>
<tr>
<td>Antipads radius (R)</td>
<td>0.4826 mm</td>
<td>0.6026 mm</td>
</tr>
<tr>
<td>Distance (D)</td>
<td>1.2525 mm</td>
<td>2.4525 mm</td>
</tr>
<tr>
<td>Step</td>
<td>CPU time</td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------------------------------</td>
<td>-------------------------------</td>
<td></td>
</tr>
<tr>
<td>Estimation grid by solver (4 × 6) (R,D)</td>
<td>3 h 6 min</td>
<td></td>
</tr>
<tr>
<td>Validation grid by solver (3 × 5) (R,D)</td>
<td>1 h 56 min 15 s</td>
<td></td>
</tr>
<tr>
<td>Building model</td>
<td>5 min 49 s</td>
<td></td>
</tr>
<tr>
<td>Validating model</td>
<td>11 s</td>
<td></td>
</tr>
<tr>
<td>Evaluating solver (one frequency response)</td>
<td>7 min 45 s</td>
<td></td>
</tr>
<tr>
<td>Evaluating model (one frequency response)</td>
<td>0.1 s</td>
<td></td>
</tr>
<tr>
<td>Step</td>
<td>CPU time</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>---------------------</td>
<td></td>
</tr>
<tr>
<td>Estimation grid by solver (4 × 6) (R,D)</td>
<td>3 h 6 min</td>
<td></td>
</tr>
<tr>
<td>Validation grid by solver (3 × 5) (R,D)</td>
<td>1 h 56 min 15 s</td>
<td></td>
</tr>
<tr>
<td>Building model</td>
<td>5 min 49 s</td>
<td></td>
</tr>
<tr>
<td>Validating model</td>
<td>11 s</td>
<td></td>
</tr>
<tr>
<td>Evaluating solver (one frequency response)</td>
<td>7 min 45 s</td>
<td></td>
</tr>
<tr>
<td>Evaluating model (one frequency response)</td>
<td>0.1 s</td>
<td></td>
</tr>
</tbody>
</table>

Speed-up 4650 x
D = 1.8525 mm

R = 0.543 mm
D = 1.8525 mm  
R = 0.543 mm

R = 0.5026 mm
R = 0.5826 mm

D = 2.3325 mm
D = 1.3725 mm

Department of Information Technology – Internet Based Communication Networks and Services (IBCN)
D = 1.8525 mm
R = 0.543 mm

\[ |S_{21}| \]

\begin{align*}
\text{Frequency [GHz]} & : 0 & 5 & 10 & 15 & 20 \\
|S_{21}| & : 1 & 0.9 & 0.8 & 0.7 & 0.6 \\
\text{Data} & & & & & \\
\text{Model} & & & & & \\
\end{align*}

R = 0.5826 mm

D = 1.3725 mm

D = 2.3325 mm
Outline

Introduction

Parameterized Macromodels

Numerical examples
  - EMC example
  - SI example

Conclusions
input \rightarrow \text{out} = f(\text{in}) \rightarrow \text{output}

- electronics
- telecom
- fluid dynamics
- chemistry
- biomodeling
- geology
- automotive

Department of Information Technology – Internet Based Communication Networks and Services (IBCN)
Aerodynamics
Automotive
Chemistry
Aerodynamics
Electronics
Metallurgy

Simulation Model
Fluent®, HSPICE®, CST®, Comsol®, Abaqus®, ...

Design variables
width, temperature, angle, frequency, ...

Response variables
lift, S-parameters, pressure, stress, ...

Costly

Parameterized Macromodel
Neural network, Kriging, SVM, rational function, spline, ...
Aerodynamics

Automotive

Chemistry

Aerodynamics

Electronics

Metallurgy

Simulation Model

Fluent®, HSPICE®, CST®, Comsol®, Abaqus®...

Design variables

width, temperature, angle, frequency, ...

Response variables

lift, S-parameters, pressure, stress, ...

Costly

Adaptive Modeling

Configurable infrastructure

Parameterized Macromodel

Neural network, Kriging, SVM, rational function, spline...

Cheap

Distributed Computing

Deartment of Information Technology – Internet Based Communication Networks and Services (IBCN)
Parameterized macromodels

Multiple design variables

Compact models

Efficient design activities (excellent speed-ups)

- Multiple simulations (measurements)
  - Design space optimization, exploration, sensitivity analysis
Parameterized macromodels

Time-domain simulations
  - Non-linear drivers and receivers

Stochastic modeling
  - impact of manufacturing tolerances

Models from measurements
  - noise to handle

Applications in different domains
Recent publications


Contact info: francesco.ferranti@ugent.be