Multi-Scale Electromagnetic Simulation

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The Multi-Scale computational challenge

Overview
All real-life problems and present challenges are Multi-Scale
Example: High fidelity ship model + EBG array

Scale range: $10^4$
Example: High fidelity aircraft and wirings
Example: installed Array on EBG (HiFi naval platform)

EBGs and MetaMats are based on sub-wavelength features
Require a very fine mesh
Here some details (e.g. HF whips) are even smaller

Very fine scales:
- Deep sub-wavelength regime of MetaMats, EBG, nanoscale devices
- CAD (high-fidelity) of platform (e.g. vehicle); many details have no electronic reason –yet are there…
Challenges:

broad band simulation
antenna coupling across bands;
EMC, Signal integrity: from (nearly) DC to 10-20GHz

Large overall problems
extreme sub-wavelength features:
- intrinsic to function (e.g. MTM), and/or
- a need of geometry representation

In real-life challenging problems meshing is a major effort:
-changing mesh (in a frequency sweep) is an effort (person-time, especially) that one would like to avoid
-Would like to import CAD files with minimum (person-time) effort, no “CAD cleaning” of heterogeneous details/parts
Focus

Concentrate on (Surface) Integral Equations

• indispensable in large problems
• added in top commercial packages
• (still) growing fast

$$\mathcal{E}(J; r) = -jk \int_S g(r - r') J(r') dS(r') + \frac{1}{jk} \nabla \int_S g(r - r') \nabla_S \cdot J(r') dS(r')$$

$$\tan \theta_i \mathcal{E}_i(J)_{ss} + \tan E_i = \tan E_i^{(0)}$$

$$\mathcal{P}^+ \mathcal{P}^- = \left( \frac{\pi}{4} - \frac{\mathcal{K}^2 + T^2}{\mathcal{K} T + T \mathcal{K}} - \frac{-\mathcal{K} T - T \mathcal{K}}{\frac{\pi}{4} - \mathcal{K}^2 + T^2} \right) = 0$$

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Setting the stage…

\[
[A][x] = [b]
\]

After RWG 1982(*) (or equivalent), major enabling technology has been
Fast Factorizations for **iterative solvers**

\[
[A][x^{(n)}]
\]

- FFT based
- Low-rank (limited to “small” electrical sizes)
- FMM and MLFMA

Reduce memory storage and compute matrix-vector (matvec) product on the flight at reduced cost

Convergence remains untouched by these methods

(*) Rao, Wilton, Glisson, TAP 1982
Convergence

$$[A][x^{(n)}]$$

Multiple scales are very bad for speed of convergence.... (conditioning)

Multiple scales (conditioning) makes your iterative solution look better (treacherous.....)

Efficient approaches are necessary to accelerate convergence

Preconditioners (multiplicative)

$$[A][x] = [b] \rightarrow [M][A][x] = [M][b]$$

ideally

$$[M] \approx [A]^{-1}$$

A trivial (.....or not?) comment

The conditioning process should not cost more than the solution.....

(can nearly always make a system converge with an ILU, but at what CPU and memory costs?)
Ensure a fast convergence (*)

Two big families

1) Addressing mesh density as a global problem (acting on operator discretization): direct physics-based preconditioners

2. Domain-decomposition ("tear-and-interconnect"): "a small problem is better than a large one, no matter how bad…"
   a) Break down big problem into several smaller ("tear"), and
   b) get solution for original problem using partial solutions ("interconnect")

(*) ideal: O(1), i.e. independent from DOF and electrical size
1. Direct physics-based preconditioners

Address mesh density as a global problem, acting on operator form or discretization:

i. Multi-resolution approach to Multi-scale: MR preconditioner

ii. Modification of integral equation: especially Calderon Preconditioner

\[ \mathcal{T}^2(J) = -\frac{J}{4} + \kappa^2(J) \]

iii. In a broader sense: new formulations of integral equations emerging very recently (+)

By and large, go all the way down to DC - if of interest, e.g. broadband

(+) e.g.: F Vico et Al, J-W De Bleser et Al, F Andriulli (EUCAP-, APS-2013)
2. Domain-decomposition (“tear-and-interconnect”):

i. Compressive DD: reduce DOF on each block (up to Nyquist limit); initially thought for direct solution (as opposed to iterative): Macro BF, Synthetic BF, Characteristic BF,… (*)


ii. Non-compressive DD: intrinsically iterative (faster convergence) [Prof. Jin-Fa Lee’s group]
A Multi-Resolution solution to Multi-scale problems
A contemporary perspective:

What Multi-Resolution can do today

• It allows analysis of complex structures, with details in parts or everywhere
• Compatible (NlogN) and integrable with fast solvers
• Where algebraic preconditioners (ILU, SPAI,…) either take too much memory and CPU, or won’t work

✔ Multi-resolution analysis of multi-scale structures
✔ Stable discretization in high-density meshes, and low frequency problems
How to generate a MG family and MR basis for a general mesh

The bottom-up approach for arbitrary mesh
Multi-level cell grouping algorithm

- Hierarchical set of (generalized) meshes aggregating adjacent cells

We have a situation similar to that of a refined mesh ("hierarchic mesh")
BUT our cells are NOT triangles

We must introduce a generalization of RWG that works with non-simplex cells!

MR basis: generalized RWG functions

Basic idea: enforce the charge (density) you would have in a RWG, get the current that has that charge

Charge (scalar) function

level j generalized RWG function

Problem: charge to current is not unique (may add any solenoidal function)
Solution: restrict mapping to non-solenoidal currents
MR basis setup: complexity

Note that scheme is recursive, all SVD done on small n. of g-cells! ⇒ Low complexity

\[ N = \text{no. of unknowns} \]

sphere case

\[ \text{No. of non-zero elements in } [T] \]

\[ \text{CPU time for the generation of } [T] \]

N = no. of unknowns

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MR basis functions: use in standard MOM

**Bottom line**
1. define the MR basis functions of **all** levels
   as linear combination of **RWGs** of the “**pixel level**” (last level)

\[
\begin{bmatrix}
\mathbf{f}_1^{(MR)} \\
\mathbf{f}_2^{(MR)} \\
\vdots \\
\mathbf{f}_N^{(MR)}
\end{bmatrix}
= 
\begin{bmatrix}
t_{11} & t_{12} \\
t_{21} & t_{22} \\
\vdots & \ddots \\
t_{NN} & \ddots
\end{bmatrix}
\begin{bmatrix}
\mathbf{f}_1 \\
\mathbf{f}_2 \\
\vdots \\
\mathbf{f}_N
\end{bmatrix}
\]

2. Effect of MR appears by making **diagonal preconditioner**
effective; will **ALWAYS** use diagonal preconditioner
Multi-resolution “Single-Tier”

😊 very efficient (good conditioning and fast convergence of iterative solvers) with dense meshes and/or disparate cell size and/or low frequency\(^{(1,2)}\)

😊 the regularizing effect of the diagonal preconditioning is hampered when the support of the MR basis functions is comparable with \(\lambda\)

→ Stop hierarchy when definition domain of the MR functions is about \(\lambda/4 - \lambda/8\)
→ Use gRWG of coarse (generalized) mesh and use appropriate pre-cond there (e.g. ILU)
What MR can do now

Arbitrary structures with patch (RWG), wires (PWL) and attachment (junctions)

Fully automatic MR basis generation for ANY complexity and topology

By-product: LF automatic loop extraction for any topology in NlogN complexity
Numerical results: High fidelity ship model (2)

BiCGStab solver – frequency = 50 MHz – Ship, high fidelity model

Relative residual

Iteration no.
Applications: HIRF

Platform: aircraft
Frequency: 1500MHz
DoF: 2,668,353
CPU time: ~ 3h
RAM: 47GByte

Courtesy of IDS
Applications: antenna siting

Platform: satellite
Frequency: 1500MHz
DoF: 3,420,292
CPU time: ∼ 4h
RAM: 60GByte

Horn array

Courtesy of IDS
Incorporating homogenization into self-consistent ("full wave") simulation:

need for multi-scale, multi-resolution approaches that allow *hosting* homogenization *physics* in a numerically consistent way
Where are we going

Roadmap

- Multi-Resolution approach for Multi-Scale
- Domain Decomposition
- Intrisically multi-scale fast factorization
- “Mesoscopic” scale (e.g. surface impedance)
- Multi-scale framework
  - Automatic homogeneization of microscale (and switching to analytic version)
  - Join non-conforming meshes (“discontinuous Galerkin”)
  - Self-consistent insertion of HF Ansatz (basis functions) in macroscales
  - “Scale-hopping”: Back-and-forward connection to synthesis/optimization (e.g. Space mapping like)

Unified computational framework to incorporate all scales and methods
Glimpses…..
A new, intrinsically multi-scale fast factorization

- $O(N)$ complexity for low- to medium frequency
- kernel free
- Extension to high-freq in progress $O(N \log N)$
Large smooth portions

“Shannon” basis functions
(Plane Wave, Traveling Wave...)
- Reduction to Nyquist limit sampling → reduced DOF (ca 25)
- Extended “spectral sampling”
- Can yield basis for recovering HF asymptotics in the Integral Equation BEM scheme (“MoM”)
  (geometry-less.....)

Not easy to keep complexity to “sound barrier” (N logN)...
But possible...

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\[ \theta_{inc} = 30^\circ, \phi_{inc} = 225^\circ \]

8092 TWBF vs 22925 RWG

Plane \( xz (\phi=0^\circ) \)

\[ |E_{E_0}|/|\text{max}(E_{E_0})| \text{ [dB]} \]

- \( E_{E_0} \) - Reference
- \( E_{E_0} \) - Traveling Wave Basis Functions
Computational EM beyond simulation
Beyond Simulation-based Certification:
Simulation-Measurement Alliance
The bold and far-reaching proposal (e.g. HIRF-SE) may encounter difficulties
- “psychological” (attitude)
- substantial: the most accurate simulation cannot overcome uncertainties in geometry, materials, etc.

Use simulation to reduce the quantity of information necessary in a verification (measurement) test.
Strategy:
-Simulations: build a **model** of the DUT response
-Measurements: match the model

Model Builder
NF/FF Basis Generation

Optimal Sampler

Model Matcher

FF Pattern reconstruction

NF Pattern reconstruction

\[ \Psi_{FF} \]

\[ \Psi_{NF} \]

\[ \Psi_{NF,\text{meas}} \]

\[ \Psi_{NF,\text{REC}} \]

\[ \Psi_{FF,\text{REC}} \]

Success criteria satisfied

NO

YES

END

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Model builder:

Simulations (typically, of parts of overall structure)

1) Several simulations of structure with “parameter sweep” (that spans the uncertain parameters space)
2) SVD-based procedure to construct a basis for the structure response space

Sought-for DUT (actual) response: Lin combination of basis functions with unknown coefficients
Model matching:
Measurements (strongly reduced set)

Sought-for DUT (actual) response: Linear combination of basis functions with unknown coefficients

Determine unknown coefficients by enforcing min distance from measured samples

Measurement points selection: procedure similar to compressed-sensing “basis pursuit” (based on properties of constructed basis)
Measurements by MVG

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### Samples for Reconstructed field

| Nyquist bound (minimal sphere) | 31,416 |
| Nyquist bound (planar scan)    | 6,561 |

### Measurement System

<table>
<thead>
<tr>
<th>Measurement System</th>
<th>“Measurement Time”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical (SG-64)</td>
<td>7200s (2h) to compute 65341 points (Co &amp; Cx)</td>
</tr>
<tr>
<td>Planar (Orbit)</td>
<td>10800s (3h) to compute 15876 points (Co &amp; Cx)</td>
</tr>
<tr>
<td>Planar, robot</td>
<td>~300s to compute 100 points (Co &amp; Cx)</td>
</tr>
</tbody>
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