Challenges in Large-scale Electromagnetic Compatability Analysis

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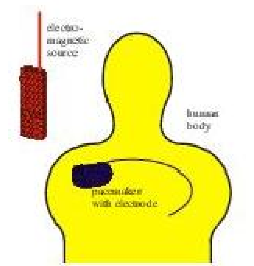
1 Talk Outline

- introduction to EMC analysis
- the ACCUFIELD application:
  - introduction
  - fast frequency stepping
  - direct solution methods
  - iterative solution methods via fast frequency stepping
  - performance and convergence issues
- related work in EMC
- challenges for large-scale analysis
- where to go from here?

2 Introduction to Electromagnetic Compatability Analysis

- Electromagnetic Compatibility (EMC) issues becoming increasingly important
  - ↑ GHz (microwave) clock speeds, increasingly complex electronic systems
  - an (oscillating) incident electromagnetic field may induce locally very strong currents and resultant fields on an electronic device
  - concern over health & system malfunction issues due to electromagnetic interference (EMI)
    - ⇒ strict EMC regulations imposed by most countries

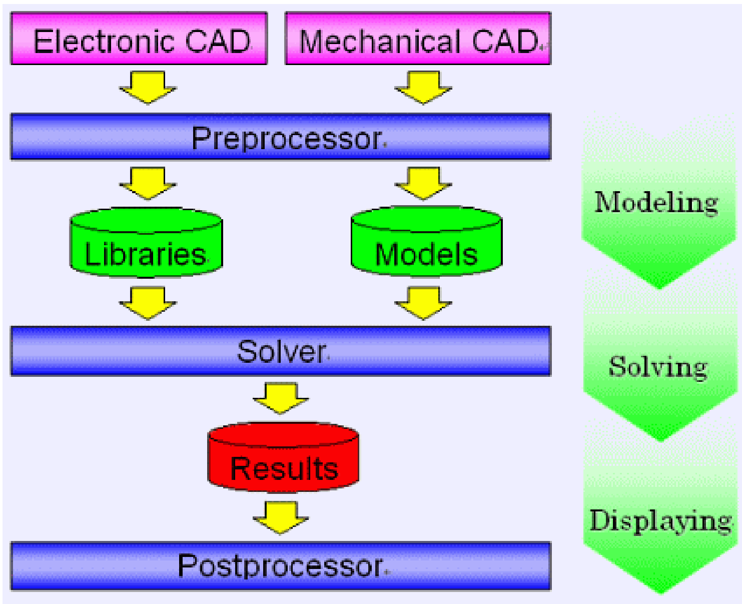
- ⇒ need accurate prediction of EMI at the system design stage



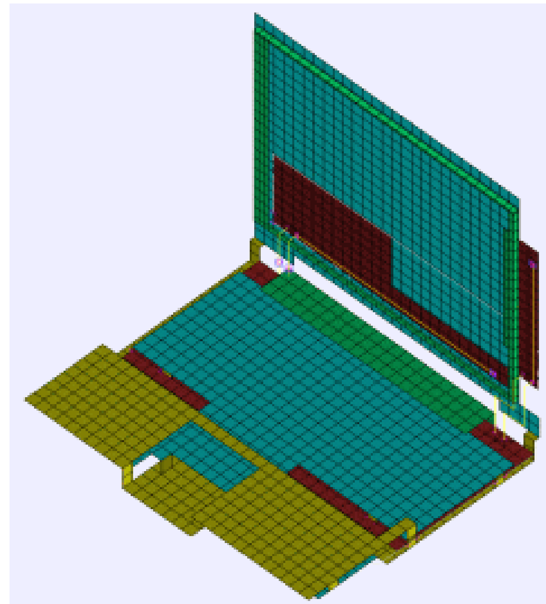
- the electromagnetic scattering problem is closely related

3 Introduction to ACCUFIELD

- ACCUFIELD is such an application (`www.accufield.com`, Fujitsu)



ACCUFIELD architecture

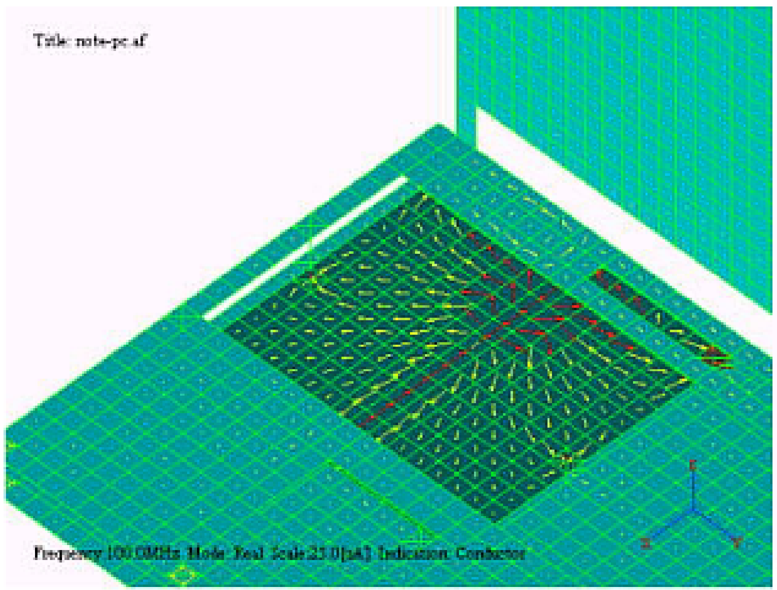


Note PC model

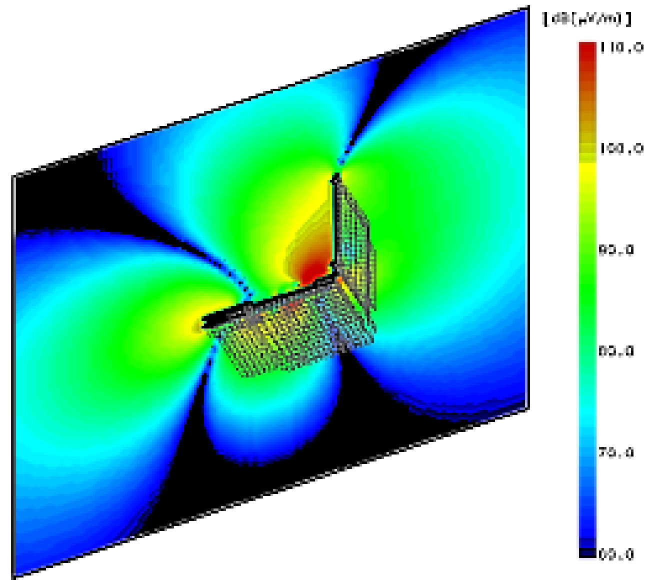
- used mainly for relatively simple electronic devices, eg. printed circuit boards
- uses the moment & transmission line approximation methods to calculate the EM field in the frequency domain (details on www page)
- models: break conductive & dielectric surfaces / wires into discrete elements

- given an incident (oscillating) electric field V (known), find the induced current I from $ZI = V$, where:
  - Z is a dense complex (indefinite) $N \times N$ matrix
    - assembled using the relatively compact model description
    - normally symmetric, unless constraints are imposed
  - for Note PC model, $N = 7041$, but $N \approx 30000$ possible for large-scale systems
  - symmetric: direct solution via $Z \rightarrow PLDL^TP^T$ requires $\frac{N^3}{3}$ FLOPs, $\approx \frac{N^2}{2}$ storage
    - store Z in lower triangular half; overwrite with L and D
    - $\Rightarrow$ a large $||$ parallel machine is required eg. AP3000, 24 nodes @ 300 MHz, 1.5GB
  - non-symmetric: direct solution via $Z \rightarrow PLU$, $2\times$ as many FLOPs & storage
- EMC analysis is usually required at different frequencies ω
  - here $V = V(\omega), Z = Z(\omega)$; the direct solution at ω_c can be used to precondition an $O(N^2)$ iterative solution for $\omega \approx \omega_c$

- using the solution vector I, can determine the induced surface fields, current emissions, the effectiveness of filters and shielding, etc
  - FFTs are used to convert results to the time domain
  - eg.



current vector diagram



EM field map

4 Fast Frequency Stepping in ACCUFIELD

- consider a analysis over set of frequencies $\Omega = \{\omega_1, \omega_2, \ldots, \omega_{n_f}\}$, $\omega_i < \omega_{i+1}$
- for linear system assembly:
  - using the model's information, explicitly assemble $Z(\omega_j)$ for $\omega_j \in \Omega_s \subseteq \Omega$
  - for $\omega_i \notin \Omega_s$, interpolate $Z(\omega_i)$ from $Z(\omega_j), Z(\omega_k)$, where $j < i < k$ and $\omega_j, \omega_k \in \Omega_s$
  - (embarrassingly) easy to parallelize
- for linear system solution:
  - choose a central frequency ω_c, eg. $\omega_c \in \Omega_s$, and obtain a direct solution here
  - the factorized $Z(\omega_c)$ is used to precondition the iterative solutions for ω_i to left *and* right of ω_c
  - do this until the iterative solution time $>$ half the direct solution time
- these methods represents space-time tradeoff

5 Direct Solution of Indefinite Systems

- a direct solution for I is the most general and potentially accurate method
- symmetric systems:
  - numerically stable algorithms exist that exploit symmetry to require only $\frac{N^3}{3} + O(N^2)$ FLOPS in the factorization:
    - (row/column) symmetric interchanges are required to eliminate some columns
    - the Bunch-Kaufman LDLT factorization algorithm $Z \rightarrow PLDL^TP^T$ has been shown to be very competitive!
    - we have developed especially efficient serial and $||$ implementations
  - back-solve computation performs: $I = V;\ I \leftarrow P^{-T}L^{-T}D^{-1}L^{-1}P^{-1}I$
    - has only $O(N^2)$ FLOPs, but high $O(N)$ associated $||$ overheads
    - is also used for preconditioning in the iterative solver
- non-symmetric systems: LU factorization is well-known;
  back-solve computation $I \leftarrow U^{-1}L^{-1}P^{-1}I$ has slightly lower overheads

6 Iterative Solution for Fast Frequency Stepping

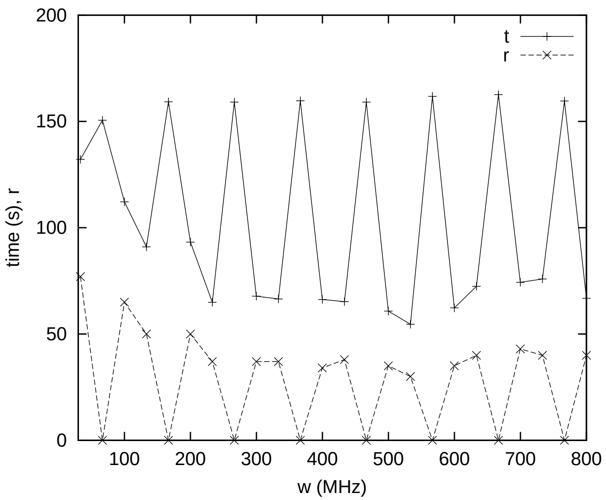
- use a preconditioned conjugate gradient method, adapted for indefinite symmetric systems
  - nb. ACCUFIELD usually generates "nearly" definite systems
- each iteration requires:
  - a symmetric matrix-vector multiply $r \leftarrow r - \alpha Z(\omega_i)p$
  - a back-solve via the factored preconditioner $p \leftarrow \beta p + Z^{-1}(\omega_c)r$
  - miscellaneous vector operations (adding a small amount of extra overhead)
- $Z(\omega_i)$ and the factored $Z(\omega_c)$ are stored in an $N \times (N+1)$ rectangular matrix
  - physical memory storage requirements still increases by 2$\times$ (very large N)
- for large matrices, (||) execution time is dominated by the matrix-vector multiply
- for smaller matrices, time is dominated by communication startups

7 Performance: Convergence and Computational Speed

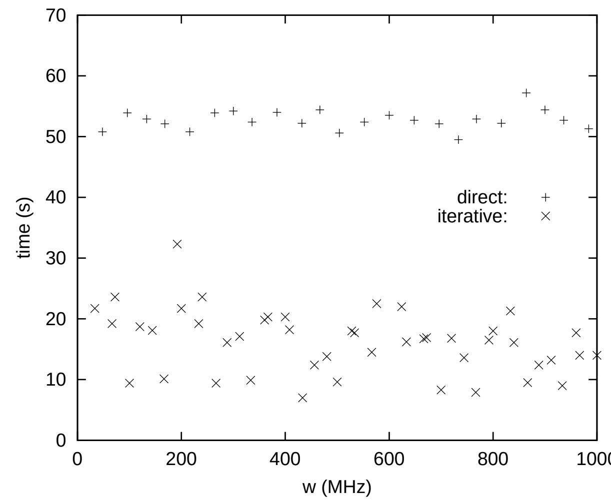
- results here are for an 8-node Fujitsu AP3000 with 360 MHz US-2 processors (startup cost $\approx 20\mu s$, transfer rate of up to 80 MB/s)
- for analysis of the Note PC model using direct solution:

# cells :	1	4	8
times (s):	293	103	59

- parallel execution times (r is the convergence rate):



POS terminal, $N = 7017$
(overall FFS speedup of 1.65;
at most 2 iterative solves per ω_c)



Note PC model, $N = 4608$
(overall FFS speedup of 2.18;
nearby ω 'pairs' converged rapidly)

8 Related Work in EMC

- frequency interpolation proposed for non-symmetric systems by Hoyler and Unbehauen (1996)
  - +ve comparisons with other (eg. block-Jacobi and GMRES) preconditioners
  - their FFS proceeds only in a single direction
- FFS is a special case of Model-Based Parameter Estimation (Miller, 1998)
  - shows how interpolation can reduce computational work on both the linear system assembly and solution
- iterative methods for EMC reported by Jakobus (2000)
  - used a conjugate gradient method with a block-Jacobi preconditioner
  - improvements reported for non-symmetric systems
  - no frequency interpolation was used
- fast multipole methods have been used in electromagnetic scattering
  - Boeing (1999), Jakobus (2000)

can also use wavelets and adaptive integral methods

9 Challenges for Large-scale EMC analysis

- EMC analysis using the moment method can be highly accurate
- combination of direct and iterative methods used in ACCUFIELD:
  - scalable & ‘efficient’ implementations have been devised
  - symmetry: halves the FLOPs (direct solution only) and storage
  - parallel processing enables feasible solution of moderate-scale systems
- iterative methods for analysis over multiple frequencies
  - still needs $||$ processing; $||$ overheads $\Rightarrow$ only moderate performance gains
  - seems to require an expensive preconditioner; has extra memory costs
- in EMC, larger-scale systems can arise from more complex models and/or finer discretizations (more accurate)
  - need fundamentally less expensive methods than the direct:
  - problem: difficulty in achieving good convergence rates
    - effects of dielectric materials
    - most analysed systems are neither large nor elongated
    - large off-diagonal ‘mass’ of the resulting linear system

10 Large-scale EMC analysis: where to go from here?

- ($\|$) out-of-core solvers (direct solution only?)
- better iterative schemes:
  - eg. (symmetric) quasi-minimum residual ?
- better / less expensive preconditioners:
  - eg. block-Jacobi, sparse approx. inverse?
- incorporation of $O(N \log N)$ techniques (wavelets, FMM, AMI)
  - usable for preconditioners if not sufficiently accurate?
- efficient and portable implementations are needed
- seeking collaborators (from ‘advisory’ to ‘active’. . .)
- possibility of collaboration with the ACCUFIELD group:
  - strategy: development on the math. rather than the modelling level, use sample linear systems