Thermo-Mechanical Analyses of Large and Complex Structures

Pan Micaleris
Associate Professor
Mechanical and Nuclear Engineering
pxm32@psu.edu
www.mne.psu.edu/michaleris

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Acknowledgment

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- Prasad Marugabandhu Research & Development Engineer, Maglev Inc.
- UNISYS
Outline

• Algorithmic optimization of weld distortion modeling on large shared memory computers
• Anisotropic H-adaptivity methods
Maglev Guideway Beam Model

- Lower Chord 40mm
- Stator Flange 25mm
- Cross Beam 25mm
- Inlet 10mm
- Stator Web 15mm
- Bulkhead 25mm
- Guidance Rail 30mm
- Deck Plate 18mm
- Web Plate 12mm
- Penn State University
Welds for 1/8 Maglev Beam

Symmetric plane
X direction fixed

Symmetric plane
Y direction fixed

Node 1

Curve 1

Curve 2
3D-3D Decoupled Approach: Small Models for all Welds

Weld 1

Weld 2

Weld 3

Weld 4

Weld 5

Weld 6

Weld 7
Numerical Model for Weld 3
Plastic Strain Distribution near the Weld (from the Center Plane of Weld 1)
Structural decoupled 1/8 Maglev Model
Large scale computing approach

1. Unisys ES7000 system.
   - 16-way SMP based on 64-bit Intel Itanium2 1.5 GHz processors, with 6 MB cache each
   - 32 GB shared memory
   - RedHat Enterprise 3 Linux, and Intel ifort, version 8.
2. OpenMP multi-threaded technology for memory parallelism.
3. IBM Watson Sparse Matrix Package (WSMP)
4. Modules are implemented for shared data along with dynamic allocation and deallocation.
5. Intel Math Kernel Library, version 7.0. (BLAS) for optimum CPU usage
6. Buffered writes are used to improve the efficiency of disk I/O when the hard disk is non-local.
Mesh for moving source 1/8 Maglev Model
## Run times for moving source models

<table>
<thead>
<tr>
<th>Type</th>
<th>DOF's</th>
<th>Time increments</th>
<th>Wall CPU (H)</th>
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3D Moving Source Method
(From Viewpoint 4, Large Deformation Analysis, 50 X Magnified)

Decoupled Applied Plastic Strain Method
LEGEND
- X-direction distortion, moving source result
- X-direction distortion, decoupled plastic strain result
- Z-direction distortion, moving source result
- Z-direction distortion, decoupled plastic strain result

Length of Curve B (mm)
Distortion Results (mm)

(Free end)
Anisotropic H-adaptivity concept

- a) Static mesh
  - 513 nodes, 580 elements
- b) Isotropic adaptivity
  - 345 nodes, 286 elements
- c) Anisotropic adaptivity
  - 213 nodes, 174 elements
Isotropic and Anisotropic h-Adaptivity

- Isotropic h-adaptivity refines an element in all x-, y- (and z- for 3D) directions.

- Anisotropic adaptive analysis scheme acquires separately in each direction the need to refine an element.

![Diagram showing isotropic and anisotropic refinement](image)

Figure 1: Isotropically and anisotropically refined 2D elements.
Figure 2: Isotropically and anisotropically refined 3D elements.
Flow diagram of anisotropic adaptivity

1. **Read model data file**
2. **Read input control file**
3. **Initialize the information arrays associated with nodes and elements**
   - \( \text{inc} = 1 \)
4. **Calculate the gradient norms of the elements**
5. **Evaluate the need to refine or coarsen elements**
6. **Acquire the location and range of the moving spheres**
7. **Coarsen the elements outside the spheres**
8. **Refine elements (norms and spheres)**
9. **Check dependent nodes**
10. **Pre-processing for the condensed matrices**
   - \( \text{iter} = 0 \)
   - \( \text{iter} = \text{iter} + 1 \)
11. **Assemble the residual and stiffness**
12. **Solve the system**
13. **Update the solution vector**
14. **Recover the constrained DOFs**
15. **Check secondary quantities**
16. **Acquire the secondary quantities**
17. **If \( \varepsilon \) (L2 norm of incremental solution) < \( \varepsilon_{\text{lim}} \)**
   - **No**
   - **Yes**
18. **Analysis finished**
19. **If time < \text{maxtime}**
   - **No**
   - **Yes**
20. **Inc = Inc + 1**

The procedures utilized in ordinary FEA (static mesh)

The procedures for AH-adaptive analysis ability
Gradient norm definition

Since at any interior point of an element, the temperature $T$ is calculated by

$$T = \mathbf{N} \cdot \mathbf{T}$$  \hfill (1)$$

the temperature gradient $[G_{r1}, G_{r2}, G_{r3}]^T$ in the element local coordinate system is given by

$$[G_{r1}, G_{r2}, G_{r3}]^T = \left| \left( \frac{d\mathbf{N}}{dr} \right)_{\text{centroid}} \cdot \mathbf{T} \right|$$  \hfill (2)$$

Then, if the desired permissible gradient is $G_p$ the order of refinement or coarsening is

$$R_i = \log_2 \frac{G_{ri}}{G_p}$$  \hfill (3)$$

where $R_i (i = 1, 2, 3)$ represents the need to refine or coarsen in the three directions. And a positive number shows the need to refine the element, while a negative number represents the element can be coarsened.
Forced refinement based on proximity to heat source
Refining an element in (a) r1- (b) r2- (c) r3- direction
Element Coarsening

Mutually Coarsenable Elements

(a1) Generation : 0
(An element in the initial mesh)

(a2) Generation : 1

(b) Generation : 2

...........

Index : 1

Index : 2

Index : 1

4 3 2 1
Element Coarsening (Cont’d)

The new coarsened element has the following properties

\[
\begin{align*}
I_k &= I_{Ak} (= I_{Bk}) \\
G_k &= G_{Ak} (= G_{Bk}) \\
I_n &= m \\
G_n &= G_{an} - 1 (= G_{bn} - 1)
\end{align*}
\]

(4) for \( k = 1, 2, 3, k \neq n \)

(5)

(6)
Sequence of Element Coarsening

Different sequences of coarsening may induce different elements in the new mesh.

$(A,B,C)$ : the remaining generations to remesh (coarsen) for an element
Dependent degrees of freedom

\[ u_a = \frac{1}{2}(u_1 + u_2) \]
\[ u_b = \frac{1}{2}(u_2 + u_3) \]
\[ u_c = \frac{1}{2}(u_4 + u_5) \]
\[ u_d = \frac{1}{2}(u_5 + u_6) \]
Condensation of dependent DOF’s

Newton-Raphson system of equations

\[ A \delta u = b \]  \hspace{1cm} (7)

Separate retained and condensed DOFS

\[
\begin{bmatrix}
A_{rr} & A_{rc} \\
A_{cr} & A_{cc}
\end{bmatrix}
\begin{bmatrix}
\delta u_r \\
\delta u_c
\end{bmatrix}
= 
\begin{bmatrix}
br \\
b_c
\end{bmatrix}
\]  \hspace{1cm} (8)

The general representation of constraint equations is

\[
\begin{bmatrix}
C_r & C_c
\end{bmatrix}
\begin{bmatrix}
\delta u_r \\
\delta u_c
\end{bmatrix}
= 
\begin{bmatrix}
0
\end{bmatrix}
\]  \hspace{1cm} (9)
Condensation of dependent DOF’s (cont.)

Rearrange Equation (9)

\[
\{ \delta u_c \} = -[ C_c ]^{-1} [ C_r ] \{ \delta u_r \} = [ C_{rc} ] \{ \delta u_r \}
\]  

(10)

By substituting Equation (10) into Equation (8),

\[
[ A_{rr} + A_{rc} C_{rc} + C_{rc}^T A_{cr} + C_{rc}^T A_{cc} C_{rc} ] \{ \delta u_r \} = \{ b_r + C_{rc}^T b_c \}
\]  

(11)
Nonzero Fill-ins in Sparse Tangent Matrix

• The tangent matrix is generally a sparse matrix.

• The AH-adaptive analysis utilizes the IBM WSMP solver,
  – a sparse matrix solver which only utilizes information from the nonzero components and saves it into linear arrays
  – reduces computational overhead
Nonzero Fill-ins in Sparse Tangent Matrix (Cont’d)

- The condensed tangent matrices actually can be perceived as splitting the columns and rows of the constrained DOFs into the columns and rows of the DOFs on which they are dependent.
- The figures on the following pages demonstrate this effect. ¹

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¹
- The example mesh contains only three elements and sixteen nodes, so the non-zeros appear dense in the tangent matrix.
- Practical structures contain more elements and DOFs so that the tangent matrix is still sparse.
Nonzero Fill-ins in Sparse Tangent Matrix (Cont’d)
Nonzero Fill-ins in Sparse Tangent Matrix (Cont’d)

Original tangent matrix for the system of equations

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X : nonzero elements
Nonzero Fill-ins in Sparse Tangent Matrix (Cont’d)

Condensed tangent matrix

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X : original nonzeros in the stiffness matrix

Δ : nonzero enforcements (fill-ins) due to the condensation effect
Insert laser weld example

R = 0.152 m

0.457 m

0.304 m

0.914 m

5mm thick DH36 steel

10mm thick EH36 steel

Support

Weld Path
Weld joint detail

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<th>$g$</th>
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<td>0 - 1.6 mm</td>
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<td>60°</td>
<td>2mm</td>
<td>0 - 1.6 mm</td>
</tr>
<tr>
<td>HLAW</td>
<td>30°</td>
<td>3mm</td>
<td>0 - 1.6 mm</td>
</tr>
</tbody>
</table>
Static mesh example

Number nodes: 77979, Number of elements: 70800
Temperature solution in static mesh

Peak temperature: 1760, CPU time usage: 8977.18 sec
Adaptive mesh zoom in

Initial number nodes: 240, Number of elements: 120

Peak number of nodes: 6713, Peak number of elements: 5078
Temperature solution in adaptive mesh

Peak temperature : 1660, CPU time usage : 258.4 sec
Full plate adaptive mesh
Zoom in at $t=40.4$ sec
## Thermal Analysis statistics

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Time Increments</td>
<td>1144</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>Initial 440 Peak 14438</td>
</tr>
<tr>
<td>Number of Elements</td>
<td>Initial 288 Peak 11193</td>
</tr>
<tr>
<td>Average number of nodes per iteration</td>
<td>7817</td>
</tr>
<tr>
<td>Total Analysis CPU Time</td>
<td>9050 sec</td>
</tr>
<tr>
<td>CPU Time for Residual Assembling</td>
<td>501 sec</td>
</tr>
<tr>
<td>CPU Time for Tangent Matrix Assembling</td>
<td>623 sec</td>
</tr>
<tr>
<td>CPU Time for Solving $KU = R$</td>
<td>1008 sec</td>
</tr>
<tr>
<td>CPU Time for Adaptive Mesh Information Processing</td>
<td>6906 sec</td>
</tr>
</tbody>
</table>
Comparison to static mesh analysis

- The AH-adaptive analyses of the 3ft × 3ft plate resulted in total CPU usages per time increment are $9050/1144 = 7.91$ sec.

- The CPU time reduction against the static mesh is thus
  
  $100\% \times (1 - 7.91/2139.5) = 99.63\%$
Conclusions

- Efficient multi-scale analysis method
- Laser welding and welding distortion analysis in large structures is now feasible in mid-size computers
- Method is applicable to other fields with localized loads
- Can model intermittent and back stepping welding
- Currently using method in laser forming modeling
Future work

- Expand method on 20 node elements
- Implement sensitivity analysis and optimization for adaptivity
- Combine method with fluid dynamic analyses for analyses of welding penetration and keyhole welding
- Technology transfer to end users