Use of Component Mode Synthesis for analyzing large system level assemblies
System level Simulation

Modeling complete system with all its components & sub components together can be described as System Level Simulation.
Outline of Presentation

System level Simulation:
- Why is it needed?
- Challenges involved

Component Mode Synthesis
- Introduction
- Procedure
- Accuracy of the method: Validation Cases
  - Modal analysis1
  - Modal analysis2
  - Harmonic analysis
- Benefits of Using CMS

Best Practices

Summary
System level Simulation: Need

• To capture behavior of the system for accurately determining failures, if any, at macro level as well as sub-component level.

• Carrying out design optimization simulations at system level, as multiple configurations are possible at that level, to reduce system testing as it is cost prohibited from both a dollar and time perspective.
System level Simulation: Challenges

Challenge comes in modeling huge systems: E.g. data center Rack

• Difficulty increase with increase in the problem size:
  – Computer power & memory becomes insufficient for problems that are too large
  – Too much time to reach a solution
• Long preparation time when redesigned:
  – Full detailed assemblies need to be rebuilt, even if sub-component is redesigned
  – Full model meshing & solution required

Consequences?

– System level analysis is done using lumped mass type techniques leading to missing of sub-component failures.
– To capture sub-component behavior, standalone components subjected to assumed boundary conditions gets analyzed.
– Costly design issues are found later at system tests at sub-component levels
Limitations of Standard Reduced order techniques:

- Reduced order modeling techniques (like point mass, rigid body approximations) at system level, cannot predict how the smaller sub-components attached to components will behave, missing the failure predictions at system level simulation for these sub-components.

- System behavior cannot be predicted correctly by separately modeling components subjected to some assumed boundary conditions. They behave differently when put together in a system, than when modeled separately.
Large system modeling challenges can be overcome if:

- Model size is reduced
  - To be within machine memory constraints
  - Solution time is less on reduced model
- Reuse of unchanged & repetitive components:
  - Reducing Model preparation effort by reusing unchanged components in new simulation
  - Employing reuse at solution level for repetitive parts to reduce overall solution time.
- Accuracy maintained
  - by somehow keeping the sub-component level details
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Summary
Component mode synthesis (CMS):

CMS is a form of substructure coupling analysis frequently employed in structural dynamics. It allows you to derive the behavior of the entire assembly from its constituent components.

- First, the dynamic behavior of each of the components known as ‘Superelement’ is formulated.
- Then, by enforcing equilibrium and compatibility along component interfaces, ANSYS forms the dynamic characteristics of the full system model.

Typically used in fields like aerospace, automobile & electronics industry. A typical use of CMS involves a modal analysis of a large, complicated structure (such as an aircraft or nuclear reactor) where various teams design an individual component of the structure.
How CMS will take care of the large model challenges:

• Model size reduction
  – It breaks full assembly into manageable sub-assemblies.
  – Solution on reduced set of master nodes
• Reuse of unchanged & repetitive components:
  – Existing unchanged part can be reused in new simulation
  – Repetitive parts can be generated by transforming existing superelement part
  – Design changes to a single component affect only that component; therefore, additional computations are necessary only for the modified substructure.
• Accuracy maintained
  – CMS includes truncated sets of normal mode generalized coordinates defined for superelement components of the structural model.
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Summary
CMS Procedure

In ANSYS CMS is done in 3 steps or Passes:

Generation pass:
- Superelement (SE) from a group or elements is created
- Master nodes of these SE is defined (especially at interfaces)
- SE in form of matrices is stored to be used in USE pass

Use/ Solution pass
- Complete model is formed from SE & non-SE
- Different parts (SE or non-SE) are attached to each other at interfaces
- Analysis (Static, Modal, Harmonic, Transient, Spectrum) is carried out as usual
- Results is available at non-SE parts & master nodes of SE

Expansion pass
- Results on SE expanded from the its master nodes to rest of the nodes.
### CMS Procedure contd..

<table>
<thead>
<tr>
<th>Top-Down CMS approach:</th>
<th>Bottom-up CMS approach</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model Building</strong></td>
<td></td>
</tr>
</tbody>
</table>
| Build the full model first & then select parts one by one, from Full model to be made as SE | Build a SE part, define it as SE  
Do same for other SEs. |
| In USE pass unselect elements/nodes that are from SEs and select rest if any.  
Read in SEs made above | In USE pass build non-SE part, if any.  
Read in all SEs |
| **Connectivity between parts (SE/non-SEs)** |                       |
| Connectivity between different parts (SE & non-SE) is easy to define as contacts can be defined in Full model itself | Connectivity has to be ensured by the user manually (CPINTF/CEINTF) |
| **Workflow**           |                         |
| Good if whole model can be handled by single machine | Better suited if model is too big or; separate independent teams are working on different parts of a system |

**Diagram:**

- **Top-Down approach**
  - Full model
  - Interface
  - SE1, SE2, SE3, SE4

- **Bottom-up approach**
  - Full model
  - Interface
  - +
  - +
  - +
  - +
CMS Procedure: Top-down

**MODEL PREPARATION**
- Define:
  - Materials, Contacts
  - Boundary Conditions

**GENERATION PASS**
- Select component1
- Define Superelement for component1 (SE1)
- Select Interface Nodes (Master nodes)
- Antype, Substruct; Solve
- Similarly, define other SEs

**USE PASS**
- Select all the SEs and Non-SEs in FE model
- Define contacts, interface treatments
- Antype, Static/Modal/Harm/RS/Transient; Solve

**EXPANSION PASS**
- Select the SE of interest and Expand the results to rest of the SE nodes
CMS Procedure: Superelement

In Generation pass:
- Select part to be made Superelement
- Define Master nodes at desired locations (generally at interfaces)

In USE pass:
- Assemble all SEs (A SE is an element with master nodes representing that part’s stiffness/mass).
- Transform original SE for repetitive parts.
- Make non-SE parts, if any
- Solve
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Summary
Example Model 1: Representative chassis

Geometry: Single sample electronic chassis in a Rack is taken
BCs: SE2 part fixed at top and bottom (shown in Yellow)
Analysis: Modal frequencies and mode shapes were compared for Full & CMS
### Example 1: Modal analysis results

The CMS Modal frequency results are in excellent agreement with corresponding Full model.

Different combinations of super elements (SE) & non-SE is used in CMS.

#### Table 1: (Full vs CMS) Modal results

<table>
<thead>
<tr>
<th></th>
<th>Full (Freq(Hz))</th>
<th>CMS-All SE(3SEs) (Freq (Hz))</th>
<th>Relative Diff (%)</th>
<th>CMS_1SE+ 2non-SE (Freq (Hz))</th>
<th>Relative Diff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>185.91</td>
<td>186.77</td>
<td>0.462589</td>
<td>186.53</td>
<td>0.333495</td>
</tr>
<tr>
<td>2</td>
<td>237.9</td>
<td>239.35</td>
<td>0.6095</td>
<td>238.96</td>
<td>0.445565</td>
</tr>
<tr>
<td>3</td>
<td>287.23</td>
<td>288.33</td>
<td>0.382968</td>
<td>287.53</td>
<td>0.104446</td>
</tr>
<tr>
<td>4</td>
<td>361.5</td>
<td>362.98</td>
<td>0.409405</td>
<td>362.59</td>
<td>0.301521</td>
</tr>
<tr>
<td>5</td>
<td>406.14</td>
<td>406.55</td>
<td>0.10095</td>
<td>406.38</td>
<td>0.059093</td>
</tr>
<tr>
<td>6</td>
<td>421.2</td>
<td>422.6</td>
<td>0.332384</td>
<td>422.19</td>
<td>0.235043</td>
</tr>
<tr>
<td>7</td>
<td>466.92</td>
<td>476.4</td>
<td>2.030326</td>
<td>468.33</td>
<td>0.301979</td>
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<tr>
<td>8</td>
<td>479.15</td>
<td>479.21</td>
<td>0.012522</td>
<td>479.16</td>
<td>0.002087</td>
</tr>
<tr>
<td>9</td>
<td>486.69</td>
<td>486.97</td>
<td>0.057531</td>
<td>486.73</td>
<td>0.008219</td>
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<tr>
<td>10</td>
<td>500.49</td>
<td>500.64</td>
<td>0.029971</td>
<td>500.54</td>
<td>0.00999</td>
</tr>
</tbody>
</table>
Example 1: Modal analysis results

Mode 1
Outline of Presentation

System level Simulation:
  – Why is it needed?
  – Challenges involved

Component Mode Synthesis
  – Introduction
  – Procedure
    – Accuracy of the method: Validation Cases
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Best Practices

Summary
Example Model 2: Stacked Electronic rack
Modal analysis

**Geometry:** A sample Rack with 4 chassis is taken
**BCs:** Rack fixed at top and bottom (shown in Yellow)
**Analysis:** Modal frequencies and mode shapes were compared for Full & CMS.

Geometry used for comparison

4 CMS Super-elements

Inner details
Example 2: Modal Results comparison

The CMS Modal frequency results are in excellent agreement with corresponding Full model.

<table>
<thead>
<tr>
<th></th>
<th>Full</th>
<th>12 Super-Elem</th>
<th>4 Super-Elem</th>
<th>Super-Elem transformed</th>
<th>SE trans wrt Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>125.13</td>
<td>125.38</td>
<td>125.41</td>
<td>124.6</td>
<td>-0.42356</td>
</tr>
<tr>
<td>2</td>
<td>132.07</td>
<td>132.08</td>
<td>132.08</td>
<td>132.05</td>
<td>-0.01514</td>
</tr>
<tr>
<td>3</td>
<td>132.32</td>
<td>132.32</td>
<td>132.32</td>
<td>132.31</td>
<td>-0.00756</td>
</tr>
<tr>
<td>4</td>
<td>132.36</td>
<td>132.37</td>
<td>132.37</td>
<td>132.36</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>137.53</td>
<td>137.67</td>
<td>137.72</td>
<td>137.32</td>
<td>-0.15269</td>
</tr>
<tr>
<td>6</td>
<td>155.74</td>
<td>155.8</td>
<td>155.78</td>
<td>155.55</td>
<td>-0.122</td>
</tr>
<tr>
<td>7</td>
<td>157.06</td>
<td>157.08</td>
<td>157.06</td>
<td>157.04</td>
<td>-0.01273</td>
</tr>
<tr>
<td>8</td>
<td>157.13</td>
<td>157.15</td>
<td>157.13</td>
<td>157.11</td>
<td>-0.01273</td>
</tr>
<tr>
<td>9</td>
<td>157.99</td>
<td>158.01</td>
<td>158</td>
<td>157.99</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>159.74</td>
<td>159.81</td>
<td>159.78</td>
<td>159.6</td>
<td>-0.08764</td>
</tr>
</tbody>
</table>
Example2: Modal Results comparison
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Summary
Example Model 3: Stacked Electronic rack
Harmonic analysis

**Geometry:** A sample Rack with 4 chassis is taken (same as in example 2)

**BCs:** Rack fixed at bottom (shown in Yellow)

Harmonic displacement sweep of 0.2 at top (110-170Hz, in blue)

**Analysis:** Harmonic responses were compared for Full model & CMS.
Example 3: Harmonic analysis: Y_direction load

Total deformation (in) @116Hz

<table>
<thead>
<tr>
<th>Mode</th>
<th>Deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>3.0996</td>
</tr>
<tr>
<td>CMS</td>
<td>2.96907</td>
</tr>
</tbody>
</table>
Example 3: Harmonic analysis: \textit{Z\_direction load}

<table>
<thead>
<tr>
<th></th>
<th>Total deformation (in) @116Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>0.11455</td>
</tr>
<tr>
<td>CMS</td>
<td>0.10176</td>
</tr>
</tbody>
</table>
Example 3: Harmonic analysis: Z-direction load

Equivalent Stress (psi) @116Hz

<table>
<thead>
<tr>
<th></th>
<th>Full</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.5124e5</td>
<td>3.1305e5</td>
</tr>
</tbody>
</table>

Frequency response_Shear Stress_XY
Example 3: Harmonic analysis _Size reduction_

No. of nodes in Full model=609544; DOFs=1828632 (=609544x3)
Master nodes in CMS= 348; Master DOFs= 1044 (=348x3)
No. of Nodes in CMS use pass= from SE parts + from non-SE parts= 1392; DOFs=4176 (1392x3)

<table>
<thead>
<tr>
<th>Solution Time</th>
<th>Full Model</th>
<th>CMS-4SEs_10modes in Gen pass</th>
<th>SE transformed - 10modes in Gen pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution/USE Pass Time</td>
<td>2467</td>
<td>26</td>
<td>25</td>
</tr>
<tr>
<td>Total time</td>
<td>2467</td>
<td>1141</td>
<td>708</td>
</tr>
<tr>
<td>Total CP time</td>
<td>10549.209</td>
<td>3677.287</td>
<td>975.053</td>
</tr>
</tbody>
</table>
CMS: Observations

• Model size reduction
  – The model size was reduced from 1828632 DOFs in Full to 4176 DOFs in CMS.
  – Solution times reduced to 1141 for CMS with 4 SEs; to 708 for CMS using transformation of a repetitive SE part; from 2467 in Full. i.e. more than half time reduction

• Reuse of unchanged & repetitive components:
  – Only 1 part was made and transformed into 3 repetitive parts to make the full system

• Accuracy maintained
  – Percentage difference within 1% in Modal results & 10% in Harmonic results between CMS & Full models for the cases taken.
To get maximum benefits from CMS, Master nodes in SE should be as small as possible.

Expansion on only interested parts further maximizes time benefits.

Reusability should be used to get max benefits on preparation time.

Models with repetitive geometry (common in electronic industry) can be modeled by transforming an existing SE (SETRAN/SESYMM).

SEs can be nested inside each other for further time & modularity benefits.

Limitations of CMS:

- Only linear results within a SE are possible.
- CMS may not advantageous when a large number of master nodes are defined.
ANSYS CMS is an excellent technique for large system level analysis.

It counters the challenges posed in big models on all fronts like

- Accuracy
- Managing of model size
- Reducing solution / preparation times

Besides these, CMS in ANSYS also supports excellent features which can prove very useful in large models like data center racks & complex models through:

- Reusability
  - Super element transformation
  - Reusing existing SE
- Nested super elements