Advanced Condensation for Dynamic Substructuring of Vehicles

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INTES GmbH, Stuttgart
www.intes.de
Privately held and independent Finite Element Technology company since 1984 located in Stuttgart, Paris, and Tokyo

Offering own FE analysis software PERMAS with VisPER, software development, and consulting services

Unified software for thermo-mechanics, vibro-acoustics, and optimization

High performance computing by parallelization (multi-threading) and special algorithms (contact, MLDR, fluid-structure coupling)

Unified concepts like incompatible meshes, substructuring, submodelling

Simulation-driven design by integrated optimization (topology, shape, sizing, bead) with local and global methods

INTES Ingenieurgesellschaft für technische Software mbH

1984: Start of software industrialization and new developments in optimization, acoustics, and reliability
1989: Start of full re-design of software for higher speed of development and Nastran compatibility
1993: PERMAS Version 5 available, the new software basis for further development
2005: Start of VisPER development, a new graphical user interface for PERMAS
2008: VisPER Version 1
2010: PERMAS Version 13 and VisPER Version 2
Use of dynamic reduction
  ▪ Current condensation method
  ▪ Guyan reduction
  ▪ Craig-Bampton reduction

Generalized Craig-Bampton reduction
  ▪ Requirements and objectives
  ▪ 1st extension: generalized transformation matrix
  ▪ 2nd extension: added modes
  ▪ Example dry tank
  ▪ 3rd extension: loaded component modes

Application
  ▪ INTES car

Conclusions
Use of dynamic reduction

- **Coupled dynamic analysis** for vehicle and various built-in equipment
  - High reduction of vehicle model size
  - Allows to analyse a large number of variants in an affordable time
  - Even for one single dynamic analysis, modal reduction can reduce run time
- **Local analysis** of main components
  - Supply of reduced vehicle models to ‘part’ teams for detailed local analysis (under realistic boundary conditions)
- **Multi-Body Dynamics (MBD)**
  - Flexible reduced models to enhance MBD analysis

> The main computational effort is spent ONCE during the condensation
Current condensation method

- Craig-Bampton method
  - Constraint modes (i.e. *Static shapes induced by unit displacements applied at interface nodes – Guyan transformation matrix*)
  - Internal eigenmodes with clamped interfaces
- Extended method in PERMAS
  - Support of multi-level substructuring
  - Support of pre-stressed effects (geometrical and pressure stiffnesses)
  - Extension to fluid-structure coupling with dry condensation option (e.g. fluid-filled tanks)
- Popular method
  - Simple and robust theoretical background
  - Classical method in FE solvers (formulation in terms of displacements)
  - Natural extension of the Guyan (static) reduction method
  - Easy to use
Condensation method: Guyan reduction

- Partition of the structure
  - Selection of interface nodes (C DOF for coupled DOF)
  - Remaining nodes are internal nodes (L DOF for local DOF)

\[
\begin{bmatrix}
K_{CC} & K_{LC}^T \\
K_{LC} & K_{LL}
\end{bmatrix}
\begin{bmatrix}
u_C \\
u_L
\end{bmatrix}
= \begin{bmatrix}
F_C \\
F_L
\end{bmatrix}
\]

- Expression of internal displacement with interface DOF

\[
u_L = -K_{LL}^{-1}K_{LC}u_C + K_{LL}^{-1}F_L = -B_T u_C + K_{LL}^{-1}F_L
\]

- Transformation matrix (constraint modes)

\[
\begin{bmatrix}
u_C \\
u_L
\end{bmatrix} = Tu_C = \begin{bmatrix}
I \\
-B_T
\end{bmatrix} u_C
\]
Condensation method: Guyan reduction

- Expression of the reduced system (interface nodes)

\[ T' M T \ddot{U}_c + T' C T \dot{U}_c + T' K T U_c = T' F \]

- Properties of Guyan reduction
  - Exact stiffness at interface nodes (static reduction)
  - Not suitable for dynamic analysis (with high reduction)
  - Fully populated reduced matrices
**Condensation method : Craig-Bampton**

- **Extension of the Guyan reduction** by addition of modal DOF for dynamic analysis (to achieve high reduction)

- **Modal DOF** are the modal coordinates $\eta$ associated to internal dynamic modes $X_L$ with clamped interface nodes

- **Expression of internal displacements** :
  \[ u_L \approx -B_T u_C + X_L \eta \]

- **Transformation matrix** :
  \[
  \begin{pmatrix}
  u_C \\
  u_L
  \end{pmatrix} =
  T u_C =
  \begin{bmatrix}
  I & X_L \\
  -B_T & X_L
  \end{bmatrix}
  \begin{pmatrix}
  u_C \\
  \eta
  \end{pmatrix}
  \]

- **Properties** :
  - Proven theory, no rank deficiency problem
  - Exact stiffness at interface nodes (Guyan reduction)
  - Exact for clamped vibrations (fixed interface nodes)
  - In general, stiffer results than those from the non-condensed model
Condensation method : Craig-Bampton

- **In practice :**
  - As the rule of thumb, the frequency limit of the internal eigenmodes has to be 2 to 3 times higher than the analysed frequency of the assembled model.
  - Could be a high computational effort for the reduction of large components.

- **Some limitations and problems :**
  - Low convergence in case of free boundary conditions.
  - Problematic to reduce large components with clamped boundary conditions (vehicle eigenmodes clamped at part interface!).
  - Bad or no-convergence with multiple interfaces (vehicle with 2 disjoint part interfaces).

  - A new condensation method is needed for a more efficient vehicle analysis!
Requirements for a new condensation method

- As a generalization of the Craig-Bampton method
  - Formulation with interface displacements (constraints modes) for natural connection between substructures
  - Exact stiffness at interface nodes (Guyan reduction)
  - Easy to check: the Craig-Bampton method has to be a special case of the new method
  - Extendible to fluid-structure coupling (FS dry condensation)
- Allow to use any kind of internal eigenmodes:
  - Mixed Boundary Craig-Bampton (MBCB) method as generalized approach
    - Clamped or free boundaries
    - Mixed boundaries
    - Set of hybrid modes (combination of free and clamped modes)
    - Loaded component modes
- Improving convergence and increasing accuracy of the condensed models
The Craig-Bampton transformation matrix $T$ is generalized as follows:

$$
\begin{bmatrix}
 u_C \\
 u_L
\end{bmatrix}
 =
 T
 \begin{bmatrix}
 u_C \\
 \eta
\end{bmatrix}
 =
 \begin{bmatrix}
 I & T_{L\eta} \\
 -B_T & T_{L}\eta
\end{bmatrix}
 \begin{bmatrix}
 u_C \\
 \eta
\end{bmatrix}
$$

This transformation allows to use any kind of component modes (free, clamped or mixed boundary interfaces).

This is an extension of the Craig-Bampton method:

- Extension for FS dry condensation available
- Same kind of matrices for the reduced system

In the literature, this approach is sometimes called: Modified Hintz Mixed-Boundary Component Mode Synthesis method.

This approach converges exactly to the Craig-Bampton method for clamped internal modes.
Expansion of the (internal) normal modes basis with any set of modal shapes by using the concept of the added static displacement modes.

This set of added modes is linearly independent of the normal modes basis and avoids rank deficiency problems.

This expansion allows to handle hybrid set of modes like:
- Free and clamped or mixed boundary eigenmodes
- Additional static modes from internal loads

Important added modes: Inertia relief attachment modes
- Displacements of internal DOF under inertia loads with fixed interfaces
- Essential correction for condensation with free normal eigenmodes
Example: Dry tank

- Shell model
- Beam elements for flanges
- Height: 2 m
- Diameter: 2 m
Eigenfrequencies $\leq 600$ Hz

Constraints variants at lower and upper interfaces
- clamped-clamped
- clamped-free
- free-free

Eigenmodes comparison between

- **Reference** model (no condensation)
  - Craig-Bampton (CB) : 165 **clamped** modes ($\leq 1200$ Hz)
  - Generalized method (CBGEN) : 81 **free** modes ($\leq 650$ Hz)
    - + 6 inertia relief attachment modes
  - Generalized method (CBGEN-V) : 81 **free** modes ($\leq 650$ Hz)
    - + 6 inertia relief attachment modes
    - + 21 **clamped** modes ($\leq 600$ Hz)

Example: Dry tank
Example : Dry tank

Deviations in terms of eigenfrequencies
Boundary condition : **clamped-clamped**

- **CB** (clamped modes) : **exact solution** (obvious !)
- **CBGEN-V** (hybrid modes) : **exact solution**
- **CBGEN** (free eigenmodes) : maximal deviation is 0.16% (worst case)
Deviations in terms of eigenfrequencies
Boundary condition: **clamped-free**

- **CB** (clamped modes): worse convergence (max. deviation 0.75%)
- **CBGEN-V** (hybrid modes): maximal deviation is 0.04% (worst case)
- **CBGEN** (free modes): better convergence vs the CB method
Deviations in terms of eigenfrequencies
Boundary condition: **free-free**

- **CB** (clamped modes) : maximal deviation is 0.80% (worst case)
- **CBGEN-V** (hybrid modes) : exact solution
- **CBGEN** (free eigenmodes) : exact solution
**Example: Dry tank**

The Mixed Boundary Craig-Bampton (MBCB) dynamic condensation gives better results with less modal DOF (lower computational effort).

<table>
<thead>
<tr>
<th>Method</th>
<th>Internal modes</th>
<th>Modal DOF</th>
<th>Maximum deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Craig- Bampton CB</td>
<td>165 clamped modes</td>
<td>165</td>
<td>0,80%</td>
</tr>
<tr>
<td>MBCB condensation (free) CBGEN</td>
<td>81 free modes 6 inertia-relief attachment modes</td>
<td>87</td>
<td>0,16%</td>
</tr>
<tr>
<td>MBCB condensation (hybrid) CBGEN-V</td>
<td>81 free modes 6 inertia-relief attachment modes  21 clamped modes</td>
<td>108</td>
<td>0,04%</td>
</tr>
</tbody>
</table>
Component modes: normal modes used for the reduction are built from the component level. In this case, the only possible boundary conditions are fixed/free interfaces or a mixed boundary condition.

But in the assembled model, the component has some elastic connections with surrounding parts.

Loaded component modes: the displacement shapes used for the reduction are the eigenmodes from the assembled model (component connected with other structures) projected to the component itself.

The component modes reduction is seen as a specific case of the loaded component modes reduction.
Application INTES Car

INTES Car model:
Substructure decomposition:

**CAR_BODY**
as subcomponent

**CHASSIS**
as top component

Interface dofs
Different condensation schemes applied to the **CAR_BODY** substructure:

<table>
<thead>
<tr>
<th>Method</th>
<th>Internal modes</th>
<th>Freq. limit</th>
<th>Nb modes</th>
<th>Variant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncondensed</td>
<td></td>
<td></td>
<td></td>
<td>Basic</td>
</tr>
<tr>
<td>Craig-Bampton</td>
<td><strong>Clamped</strong> modes</td>
<td>≤ 150 Hz</td>
<td>141</td>
<td>CB</td>
</tr>
<tr>
<td>MBCB</td>
<td><strong>Free</strong> modes + 6 inertia relief attach. modes</td>
<td>≤ 150 Hz</td>
<td>145 + 6</td>
<td>MBCB_Free</td>
</tr>
<tr>
<td>MBCB</td>
<td><strong>Loaded component</strong> modes: Prescribed modes from the full assembled model</td>
<td>≤ 150 Hz</td>
<td>185</td>
<td>MBCB_Load</td>
</tr>
</tbody>
</table>

**External dofs**

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INTES Car: Clamped component vibrations

Eigenfrequencies deviations - Clamped component vibrations

Comparison of reduced models with the uncondensed model

<table>
<thead>
<tr>
<th>Eigenmode</th>
<th>Eigenfrequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic eigenfrequencies</td>
<td>0%</td>
</tr>
<tr>
<td>Deviations CB</td>
<td>-1%</td>
</tr>
<tr>
<td>Deviations MBCB_Free</td>
<td>1%</td>
</tr>
<tr>
<td>Deviations MBCB_Load</td>
<td>2%</td>
</tr>
</tbody>
</table>

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INTES Car : Free component vibrations

Eigenfrequencies deviations - Free component vibrations

Comparison of reduced models with the uncondensed model

- Basic eigenfrequencies
- Deviations CB
- Deviations MBCB_Free
- Deviations MBCB_Load
Prescribed vibrations solution from the complete vehicle:

- Prescribed modal basis up to 150Hz
- Complete vehicle model with car body and chassis
- Comparison between the reduced models and the basic model
Eigenfrequencies deviations - Prescribed vibrations

Comparison of reduced models with the uncondensed model

<table>
<thead>
<tr>
<th>Eigenmode</th>
<th>Eigenfrequency (Hz)</th>
<th>Deviations (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deviations MBCB_Free</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deviations MBCB_Load</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

22-23 May 2014, St. Valentin, Austria

3rd International Conference on Dynamic Simulation in Vehicle Engineering,
Advanced Condensation for Dynamic Substructuring of Vehicles

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Harmonic solution from the complete vehicle:

- Prescribed modal basis up to 150Hz
- Prescribed excitation in the frequency range 0-150Hz
- Static correction with added static mode
- Uniform viscous modal damping of 3%
- Acceleration results
INTES Car: Harmonic solution - Complete vehicle

Harmonic solution - Prescribed vibrations

Comparison of reduced models with the uncondensed model

- CB
- MBCB_Free
- MBCB_Load
- Basic

Amplitude of acceleration (g)

Frequency (Hz)

22-23 May 2014, St. Valentin, Austria
3rd International Conference on Dynamic Simulation in Vehicle Engineering, Advanced Condensation for Dynamic Substructuring of Vehicles
Conclusions

- Mixed Boundary Craig-Bampton dynamic condensation
  - As an extension of the Craig-Bampton method
  - With any kind of internal modes
  - Available for FS dry condensation
  - Provides strong benefit for vehicle models
  - Available for flexible models in MBD analysis

- Significant improvements
  - Better accuracy of condensed model with less number of modes
  - Still easy to use (similar to Craig-Bampton method)
  - Available in PERMAS