Ansys Mechanical Linear and Nonlinear Dynamics

Module 10: Component Mode Synthesis

Release 2022 R2

Please note:
- These training materials were developed and tested in Ansys Release 2022 R2. Although they are expected to behave similarly in later releases, this has not been tested and is not guaranteed.
- The screen images included with these training materials may vary from the visual appearance of a local software session.

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Module 10 Learning Outcomes

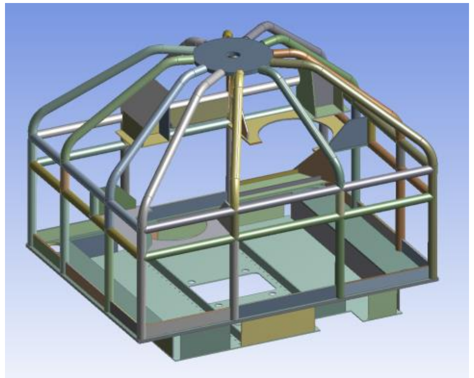
- After completing this module, you will:
  - Have a fundamental understanding of substructuring and how it can be used to reduce solution computation time.
  - Be able to use the Component Mode Synthesis substructuring solution method within a Modal, Random Vibration, Response Spectrum and/or MSUP Harmonic analysis.
  - Be able to used Condensed Parts to represent equivalent mass, stiffness, and damping of components within a large assembly.
  - Learn how to properly connect Condensed Parts to a system-level model while maintaining their contributions to the dynamic response of the system.
  - Understand how damping is accounted during a Component Mode Synthesis solution.

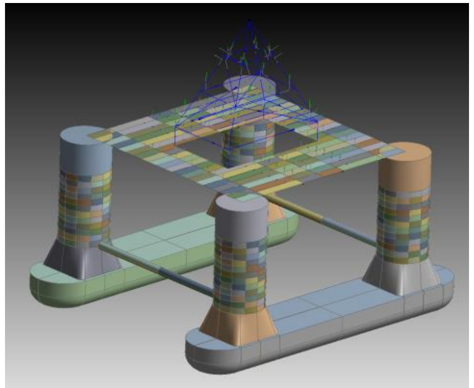
Module 10 Topics

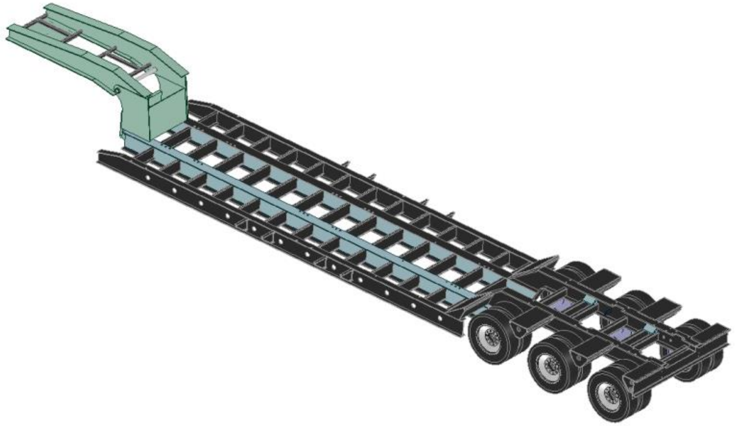
- Definition and Purpose
- Benefits of Substructuring
- Equations
- Workflow of CMS
- CMS in Mechanical
- Condensed Parts
- Expansion Settings
- Damping within CMS
- Use Case for CMS

A. Definition and Purpose

- Substructuring
  - Allows characterization of a group of elements by their equivalent mass, stiffness, and damping matrices within a single superelement having far fewer DOF
  - Computational time-saving technique whereby the substructures can be assembled together to form more complex system level models, without adding excessive DOF
  - Often used in Dynamic analysis of large structures/systems
    - Aircraft
    - Nuclear Power Plants
  - Often used when a structure contains many repeated components







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B. Benefits of Substructuring

- Reduces computational time allowing solution of very large problems with limited computer resources
- Allows characterization of structures with repeating geometry
  - Create a single superelement of the repeating geometry and “copy” throughout the structure
- Linear portion of a model in a nonlinear analysis can be substructured
  - Prevents recalculation of element matrices for that portion at every equilibrium iteration
- Reduces computation time during optimization / DOE studies by substructuring the non-parametric portion of the model
- Different design groups can work independently on components then “assemble” them later in a system-level model

C. Equations

- A substructure has its displacement vector, $\{u\}$,represented by a set of reduced coordinates,$\{\hat{u}\}$ and a transformation matrix $[T]$
- Substituting the displacement vector in reduced coordinates into the equation of motion gives:

$$[\hat{M}]\{\ddot{\hat{u}}\}+[\hat{C}]\{\dot{\hat{u}}\}+[\hat{K}]\{\hat{u}\}=\{\hat{F}\}$$

$$\{u\} = [T]\{\hat{u}\}$$

$$\{\hat{K}\} = [T]^T\ [K]\ [T]$$ Reduced stiffness matrix

$$\{\hat{M}\} = [T]^T\ [M]\ [T]$$ Reduced mass matrix

$$\{\hat{C}\} = [T]^T\ [C]\ [T]$$ Reduced damping matrix

$$\{\hat{F}\} = [T]^T\ \{F\}$$ Reduced load vector

… Equations

- Two methods are available for producing the reduced matrices shown previously
  - Substructuring: Static reduction of the system matrices to a smaller set of nodal DOF
    - Available within structural and non-structural analysis types
  - Component Mode Synthesis: System matrices are reduced to a smaller set of interface DOFs between components (known as master DOF) and normal mode generalized coordinates
    - Structural analysis only
    - Only method supported by Mechanical

… Equations

- Component Mode Synthesis (CMS)
  - Recalling the equation of motion

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\}$$

  - the displacement vector and matrices of the superelement are partitioned as

$$\{u\}=\begin{Bmatrix}\{u_m\}\\ \{u_s\}\end{Bmatrix},\ [M]=\begin{bmatrix}[M_{mm}] & [M_{ms}]\\ [M_{sm}] & [M_{ss}]\end{bmatrix},\ [C]=\begin{bmatrix}[C_{mm}] & [C_{ms}]\\ [C_{sm}] & [C_{ss}]\end{bmatrix},\ [K]=\begin{bmatrix}[K_{mm}] & [K_{ms}]\\ [K_{sm}] & [K_{ss}]\end{bmatrix},\ \{F\}=\begin{Bmatrix}\{F_m\}\\ \{F_s\}\end{Bmatrix}$$

  - Subscripts m and s are:
    - m = master DOF at the interface nodes
    - s = all DOF that are not masters

… Equations

- Component Mode Synthesis (CMS)
  - Here, the displacement vector, $\{u\}$, is represented in terms of masters and generalized coordinates

$$\{u\} = \begin{Bmatrix} \{u_m\} \\ \{u_s\} \end{Bmatrix} = [T] \begin{Bmatrix} \{u_m\} \\ \{y_\delta\} \end{Bmatrix}$$

  - {yδ} = truncated set of generalized coordinates
  - The transformation matrix $[T]$ can be obtained by one of three methods
    - Fixed-Interface method
    - Free-Interface method
    - Residual-Flexible Free-Interface method

For information on the Free and Residual Interface methods see the [ANSYS Theory Manual.]

… Equations

- Component Mode Synthesis (CMS)
  - Fixed-Interface method has a transformation matrix

$$[T] = \begin{bmatrix} [I] & [0] \\ [G_{sm}] & [\varphi_s] \end{bmatrix}$$

  - $[\varphi_s]$= eigenvectors obtained with interface nodes fixed
  - [0] = null matrix
  - With the transformation matrix known and the mass, stiffness, and damping matrices of the superelement known, the reduced matrices of the superelement are obtained and used within the general equation of motion

D. Workflow of CMS

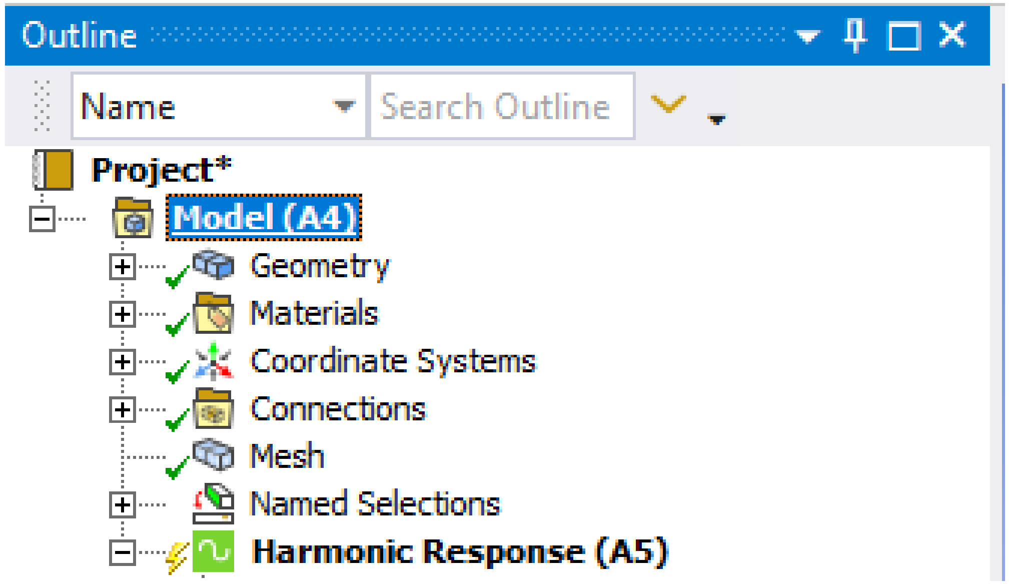
- Workflow consists of three steps
  - *Generation*: A “generation pass” is a computation in which a group of elements and their associated interface nodes (connections to the rest of the model) are reduced to a single superelement represented by a reduced mass, stiffness, and damping matrix
  - *Use*: A “use pass” is a second computation in which the superelement is used within a model to represent a portion of the structure being analyzed
    - Results from this computation include full displacement/stress results within the non-superelement regions of the model, and displacement results at the interface nodes (master DOF) of the superelement
  - *Expansion*: An optional “expansion pass” in which the master DOF displacements of the superelement are used along with the generalized coordinates and transformation matrix to compute displacements and stresses within the superelement

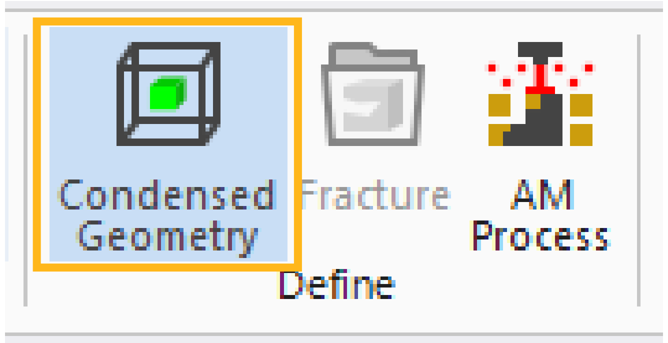
… Workflow of CMS

- There are generally two approaches used when creating a substructure
  - Top-Down Substructuring
    - The components of the substructure already exist within the complete model of the structure being analyzed
    - The generation pass is run without considering the non-substructured components
  - Bottom-Up Substructuring
    - The components of the substructure exist as independent models not contained within the overall structure
    - After the generation pass is complete, the substructure is imported into the overall model of the structure, and the use pass is performed
  - This lesson discusses Top-Down Substructuring

E. CMS in Mechanical

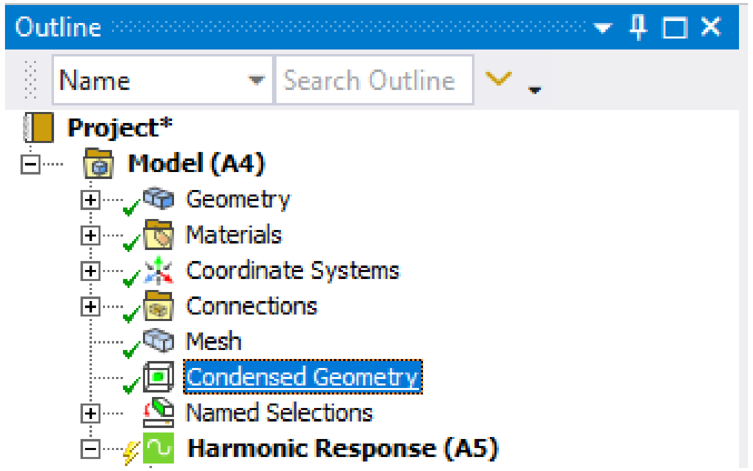
- CMS in Mechanical supports Modal, Random Vibration, Response Spectrum and MSUP Harmonic analysis
  - Rigid Dynamics is also supported, but will be covered elsewhere in the ANSYS Mechanical Rigid Body Dynamics course
- CMS in Mechanical is largely automated
- Most of the workflow is captured within a Condensed Geometry object

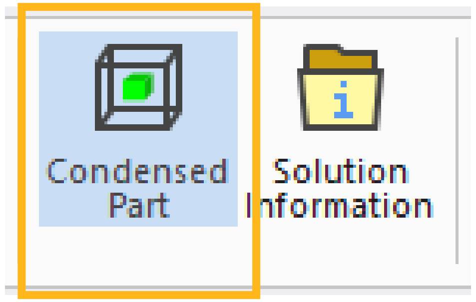




F. Condensed Parts

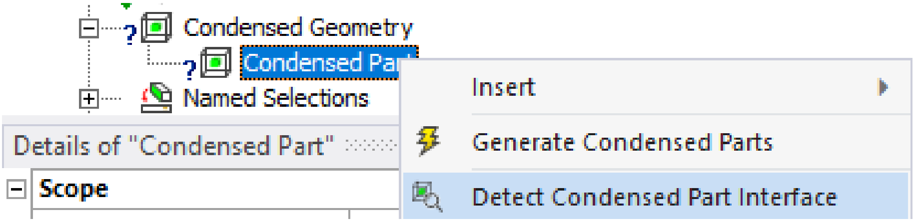
- Condensed Parts can be added within the Condensed Geometry object
  - The Condensed Part provides all the information needed for the generation pass
    - Matrix Reduction method
    - Interface Method and Solution Settings
    - Interfaces
      - Defines Master DOFs at interfaces to the rest of the model (usually contacts/joints)
      - Masters also needed at locations of applied loads, supports, added masses, remote points, named selections contained within the condensed part
      - *Interfaces can be detected automatically!*

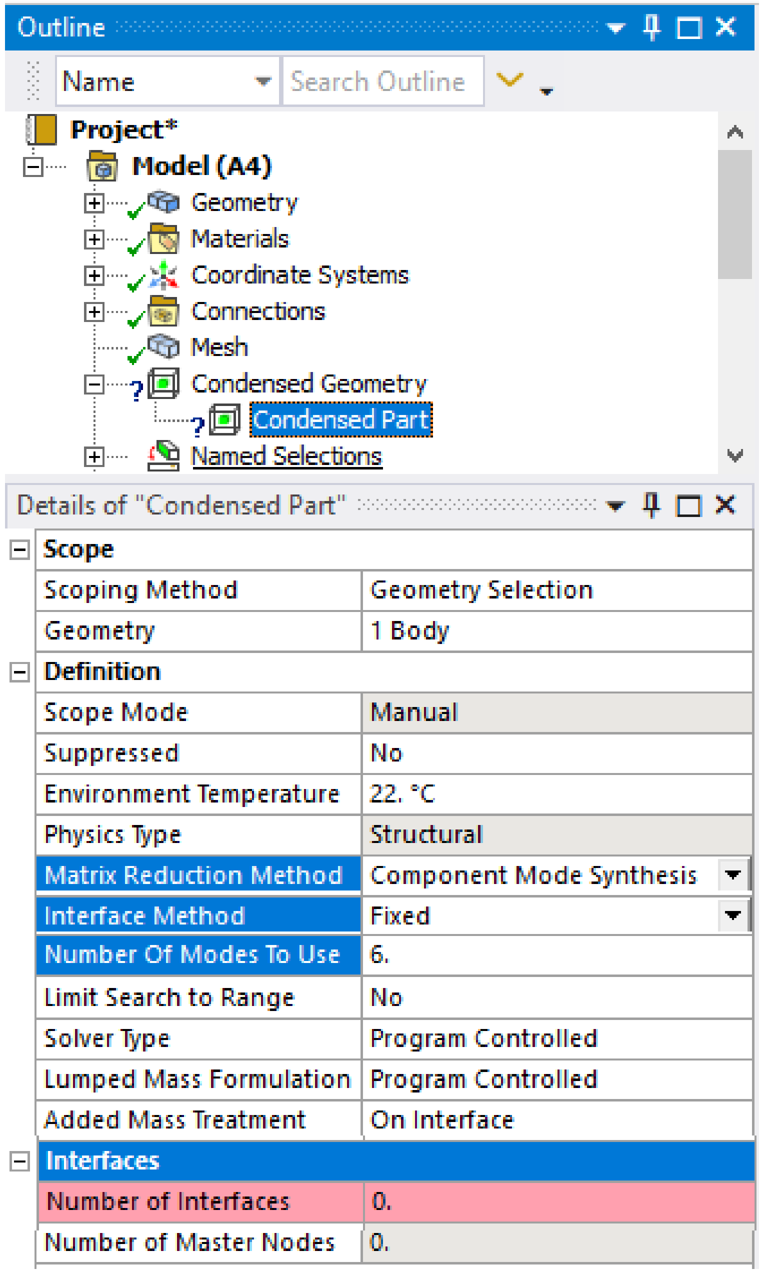




… Condensed Parts

- Details of the Condensed Part
  - Matrix Reduction Method: CMS is only option
  - Interface Method: Fixed is only option
    - Eigenvectors are calculated with fixed supports at all interface locations
  - Number of Modes to Use: number of eigenvectors used to characterize the superelement
  - Interfaces: Defines the DOF connecting to the rest of the model
    - Tip: Define all loads, supports, point masses, contacts that will be used by the superelement prior to defining the interfaces; then use the automatic Detect…Interface feature



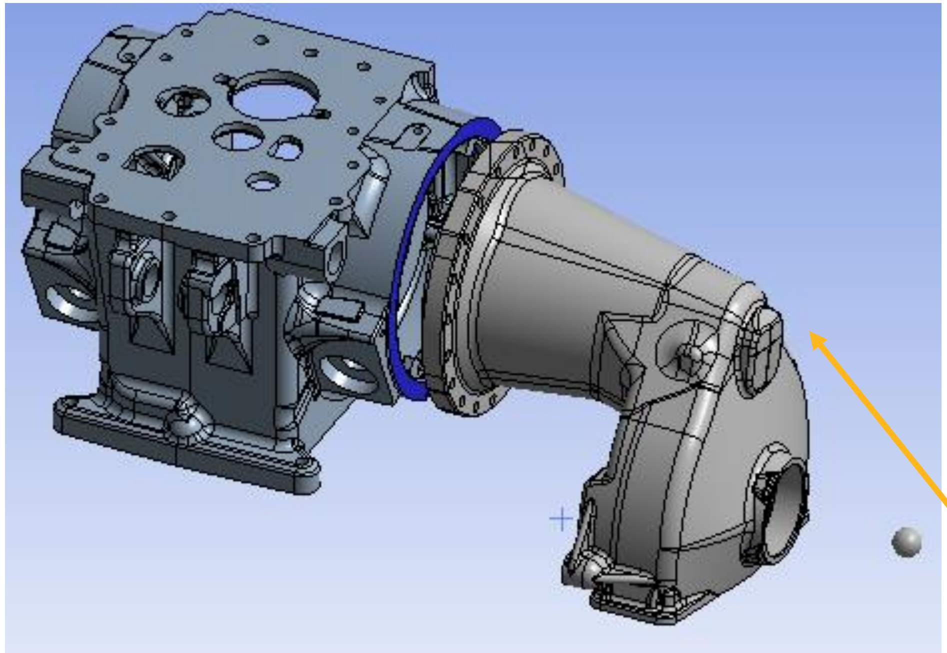


… Condensed Parts

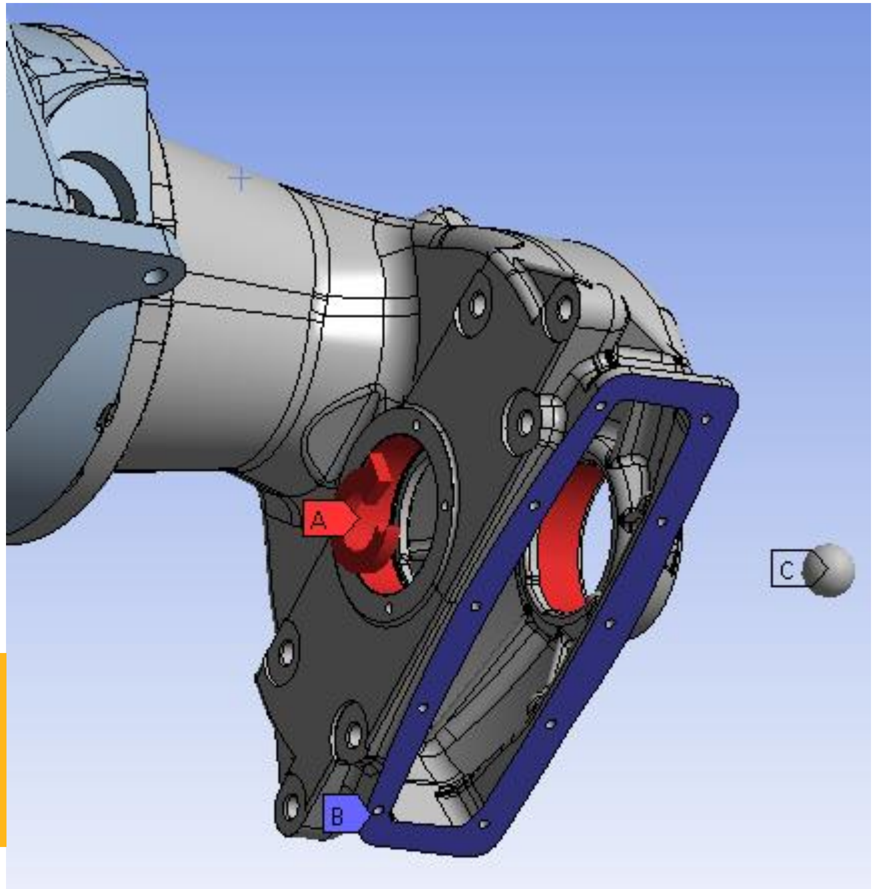
- Consider the following example of two-part casing assembly
  - The part to be substructured is joined by bonded contact, and has a moment, fixed support, and point mass defined on the surfaces shown

A: CMS Harmonic Response
Harmonic Response
Frequency: 200. Hz

A Moment: (Real) 200., (Imag) 0. N·m
B Fixed Support 2
C Point Mass



Substructure part (shown slightly exploded for clarity of contact region)



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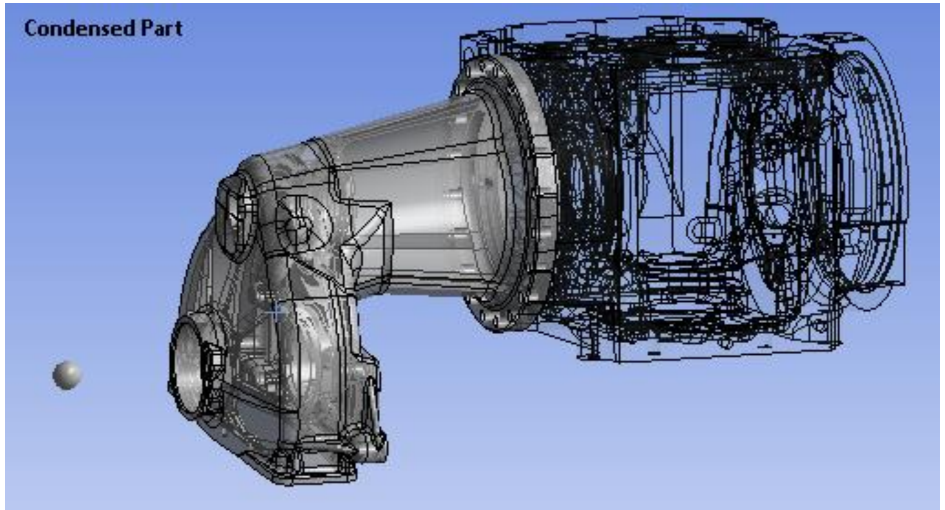
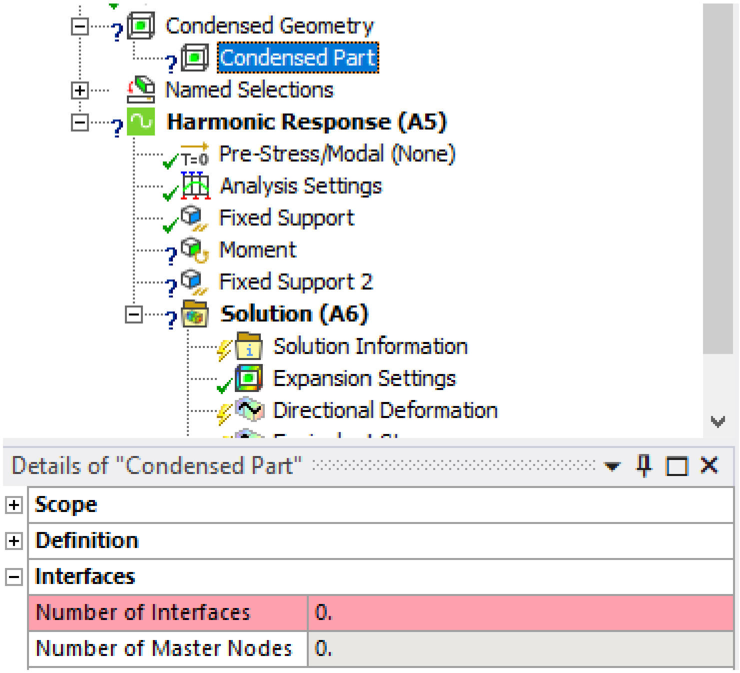
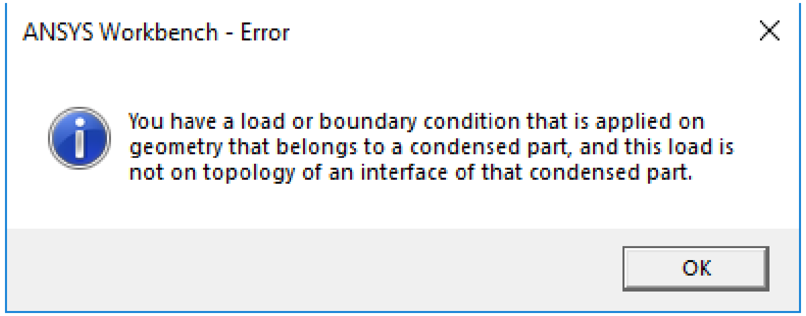
… Condensed Parts

- With the loads and contacts defined first, add a Condensed Geometry object and define the Condensed Part
  - The loads and supports scoped to that part may temporarily become underdefined until the Interfaces are generated for the condensed part

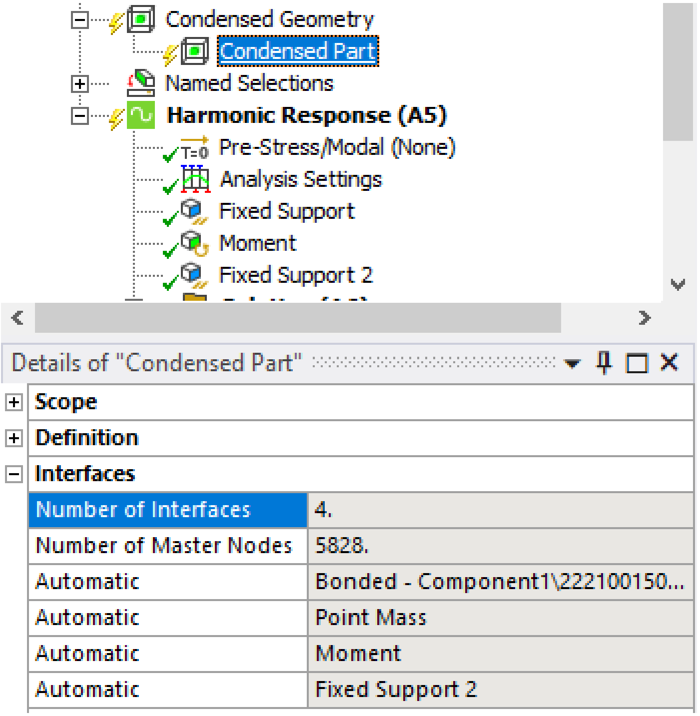


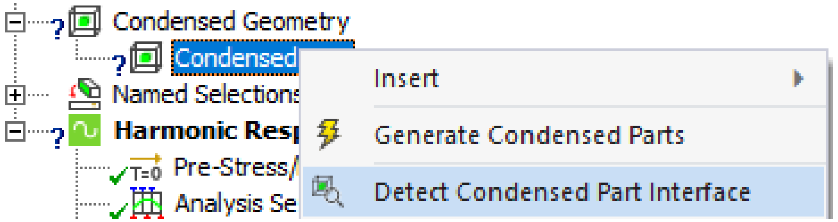


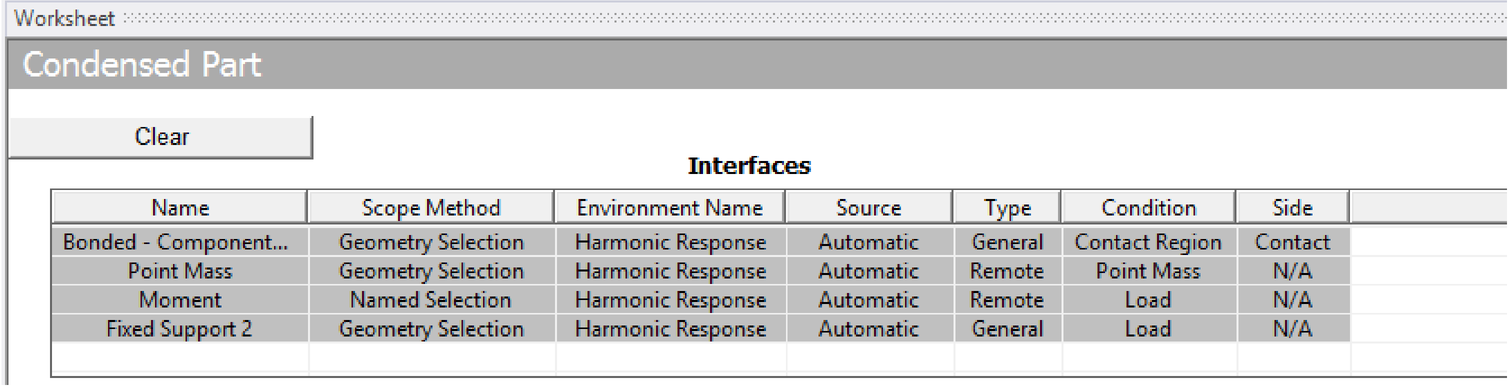


… Condensed Parts

- Use the automatic Detect Condensed Part Interface capability under right mouse button on the condensed part
  - The bonded contact and all load/support surfaces become Interfaces (Worksheet view)
  - The underdefined objects are once again fully defined

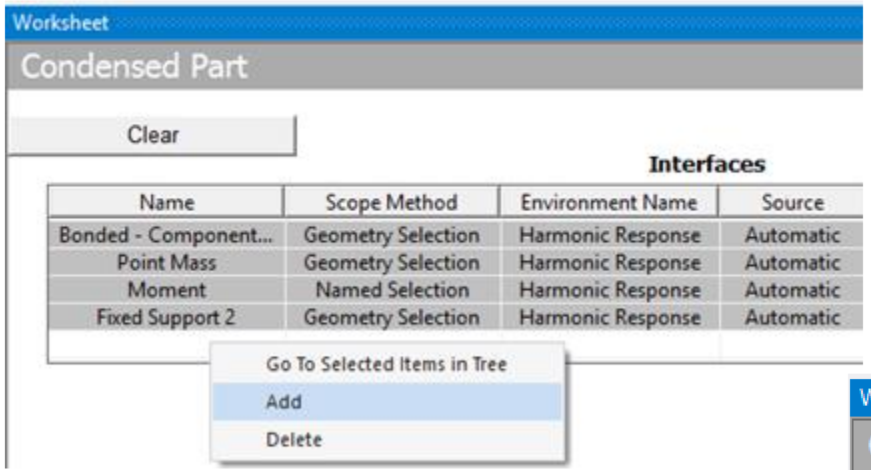


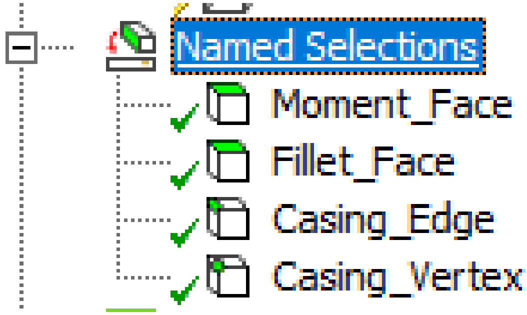


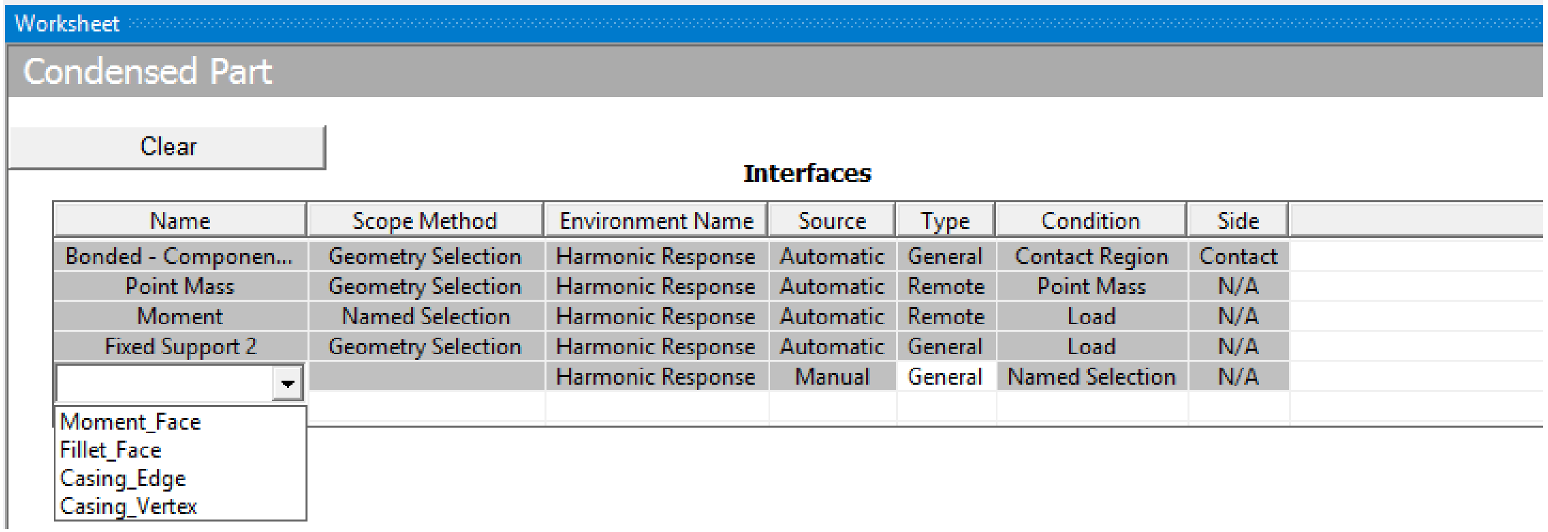


… Condensed Parts

- Interfaces can also be defined manually as needed using the worksheet
  - Requires Named Selection of the vertex, edge, face







… Condensed Parts

- Additional Information on Condensed Parts
  - Can consist of one or more interconnected bodies
  - Nonlinearities should not be included within the condensed parts (they are ignored)
  - Valid connections within interconnected bodies of a condensed part include:
    - Shared Topology
    - Beam Connections
    - Bonded Contact
    - Distributed Mass
    - Fixed Joint
    - Point Mass
    - Spring Connections

… Condensed Parts

- Additional Information on Condensed Part Interfaces
  - Interfaces define the master nodes and therefore usually consist of regions where the condensed part is connected to the rest of the model
  - Valid Interface types for a condensed part are based upon:
    - Geometry
    - Remote Points
    - Connections
    - Loads and Supports
    - Point Masses
    - Named Selections

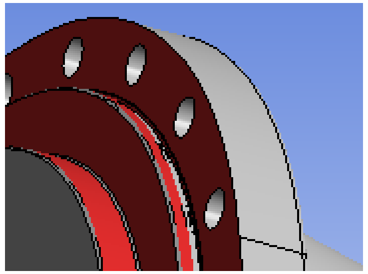
    Detected automatically as long as these objects already exist within the condensed part
  - Since Interfaces directly determine the number of master DOF within the condensed part, care should be taken when choosing condensed part interfaces as the number of masters will directly influence the solution time needed to Generate the condensed part (i.e the Generation Pass). Example given next…

… Condensed Parts

- Often, automatic contact detection includes additional surfaces that aren’t really needed within a contact pair:

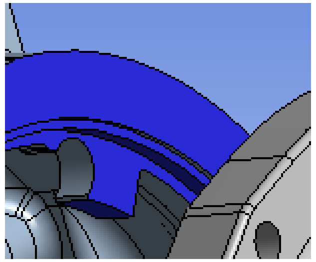
Details of "Contact Region"

Scope	
Scoping Method	Geometry Selection
Contact	7 Faces
Target	9 Faces
Contact Bodies	Component1\222100150010_ACH...
Target Bodies	Component3\210103050031_HA_...



Details of "Contact Region"

Scope	
Scoping Method	Geometry Selection
Contact	7 Faces
Target	9 Faces
Contact Bodies	Component1\222100150010_ACH...
Target Bodies	Component3\210103050031_HA_...



Condensed Geometry
Condensed Part
Solution Information
Named Selections

Details of "Condensed Part"

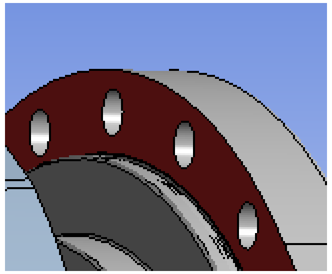
Scope	
Definition	
Interfaces	
Number of Interfaces	4.
Number of Master Nodes	17345
Automatic	automatic scope bonded region
Automatic	Point Mass
Automatic	Moment
Automatic	Fixed Support 2

7 and 9 contact/target faces
17345 masters

60 minutes to run the gen pass!

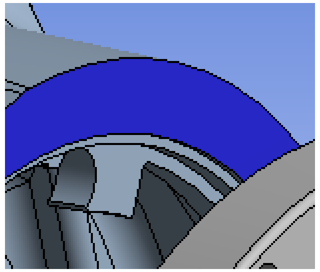
Details of "Contact Region"

Scope	
Scoping Method	Geometry Selection
Contact	1 Face
Target	1 Face
Contact Bodies	Component1\222100150010_ACHS...
Target Bodies	Component3\210103050031_HA_G...



Details of "Contact Region"

Scope	
Scoping Method	Geometry Selection
Contact	1 Face
Target	1 Face
Contact Bodies	Component1\222100150010_ACHS...
Target Bodies	Component3\210103050031_HA_G...



Condensed Geometry
Condensed Part
Solution Information
Named Selections
Harmonic Response (F5)

Details of "Condensed Part"

Scope	
Definition	
Interfaces	
Number of Interfaces	4.
Number of Master Nodes	5828.

With more realistic contact/target scoping:
1 contact/target face
5828 masters

6 minutes to run the gen pass!

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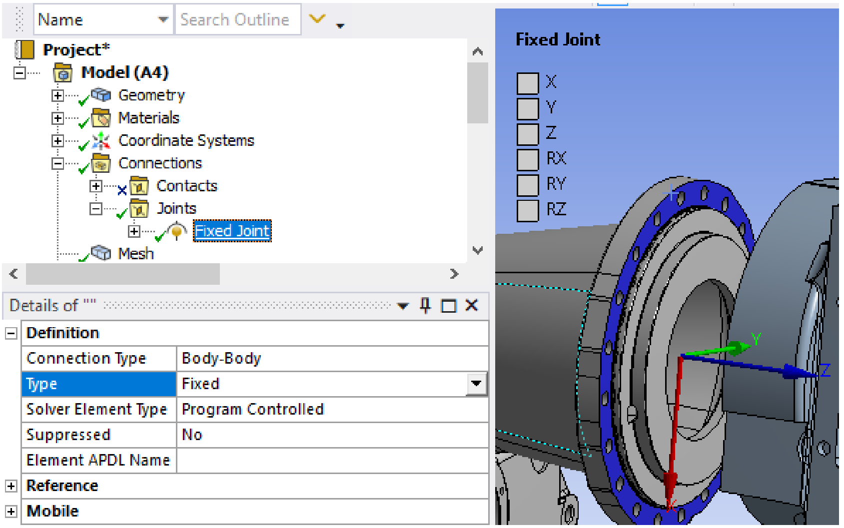
… Condensed Parts

- Best practice is to use Fixed Joints in place of Bonded Contact at interfaces between condensed parts and the rest of the model:



Details of "Condensed Part"

Scope	
Definition	
Interfaces	
Number of Interfaces	4.
Number of Master Nodes	637.
Automatic	Fixed Joint
Automatic	Point Mass
Automatic	Moment
Automatic	Fixed Support 2

Same model as previous slide, masters reduced from 5828 to 637

102 SECONDS to run the gen pass!

- Check contact pairs for extra surfaces scoped or replace with Fixed Joints.
- For best performance, try to limit number of master nodes to 10% of total nodes in entire model, or 3000, whichever is less.

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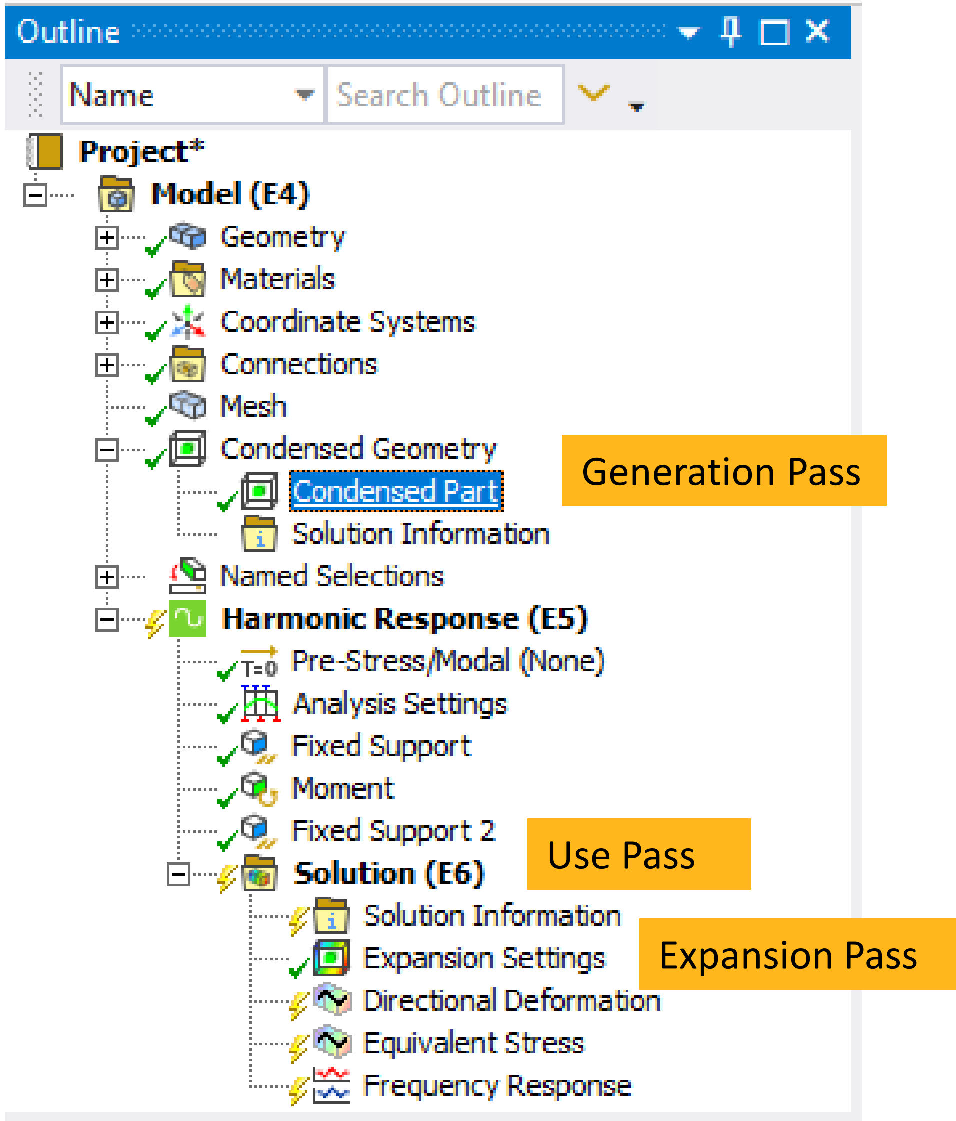
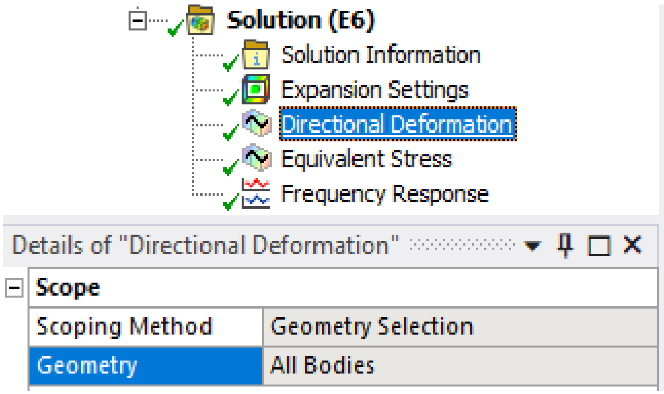
G. Expansion Settings

- With the Condensed Part generated (generation pass complete), the Use Pass is handled automatically by Mechanical as part of the Modal or Harmonic Solution
- The addition of a Condensed Geometry object in the model outline also creates an Expansion Settings object within the Solution branch
  - Expansion Settings controls the calculation of the substructure displacement (and stress if desired) from the displacements at the masters
  - By default, substructure results are not expanded as part of the model solution

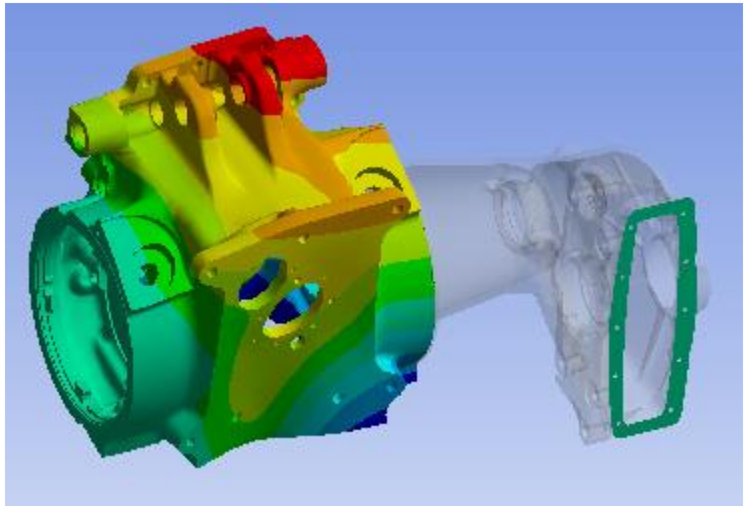


… Expansion Settings

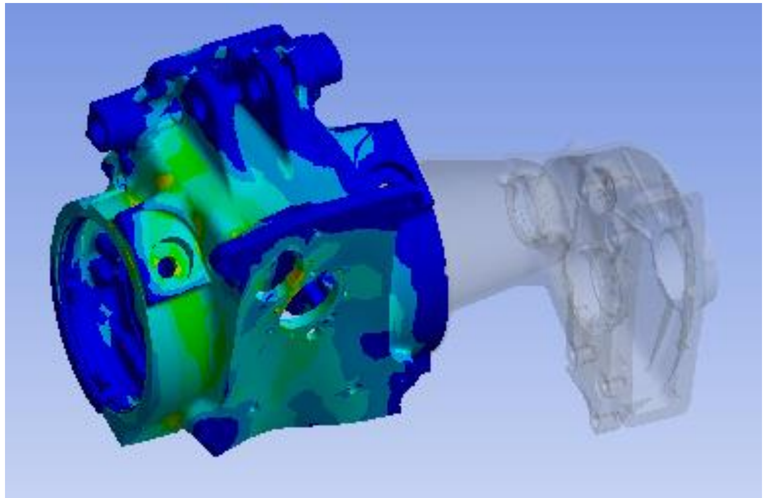
- Following solution of the model, postprocessing is as discussed in other modules of this course.
  - A full set of results is available for all non-substructured parts of the model
  - Without running an Expansion Pass, only displacements are available at the Interfaces (masters) of the substructure



All bodies scoped; displacement results available on full model but only on fixed support of the condensed part

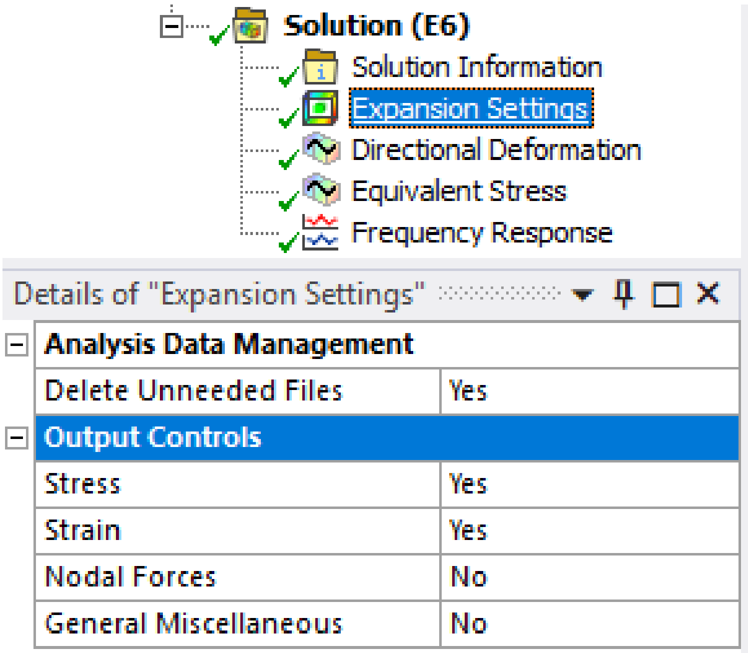


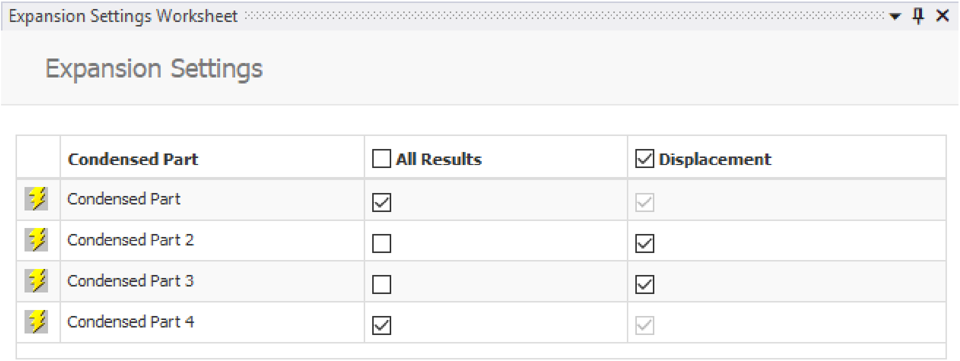
No stress results on condensed part

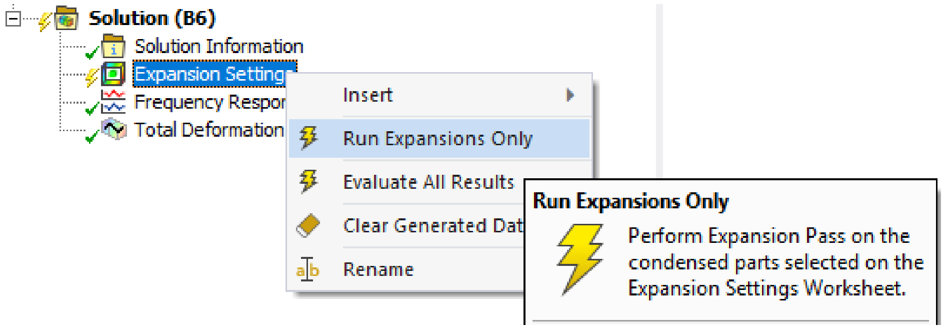


… Expansion Settings

- Use the Expansion Settings worksheet to control what results you’d like to see within the condensed part
  - Can be specific to each condensed part, if more than one exists
  - All Results: provides displacement and all the result types requested within the Output Controls of the Expansion Settings
  - Displacement: provides only displacement results within the condensed part







H. Damping within CMS

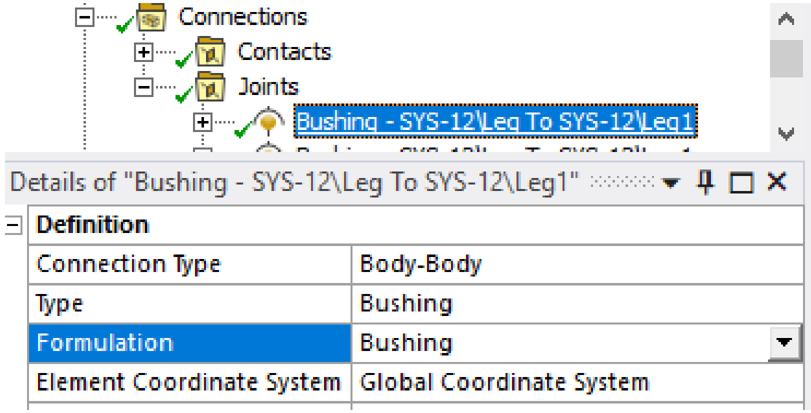
- Damping for the condensed part may be defined within Engineering Data on the material assigned to the condensed part
  - Mass Matrix Damping Multiplier (α), and/or
  - K-Matrix Damping Multiplier (β)
  - Damping Ratio not supported

Properties of Outline Row 4: Structural Steel

	A	B
1	Property	Value
2	Material Field Variables	Table
3	Density	0.2836
4	Isotropic Secant Coefficient of Thermal Expansion	
6	~~Material Dependent Damping~~	
9	Damping Factor (α)	
10	Mass-Matrix Damping Multiplier	10
11	Damping Factor (β)	
12	k-Matrix Damping Multiplier	0.000227
13	Isotropic Elasticity	

… Damping within CMS

- Damping is also available through Body-Body Bushing Joints within the condensed part
  - Allows stiffness and damping values in all 6 DOF
  - Formulation must be set to Bushing (MPC formulation is not supported)



Worksheet

Bushing - SYS-12\Leg To SYS-12\Leg1

Stiffness Coefficients

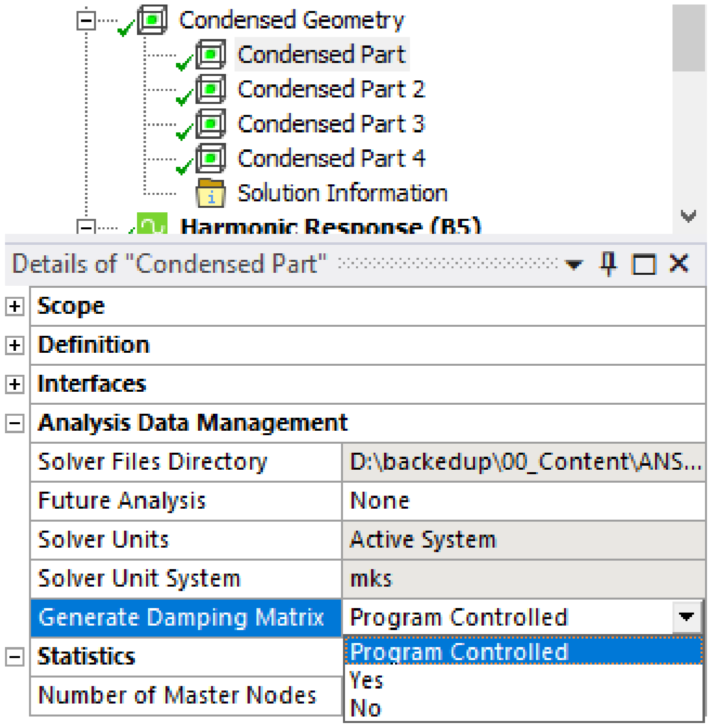
Stiffness	Per Unit X (m)	Per Unit Y (m)	Per Unit Z (m)	Per Unit θx (°)	Per Unit θy (°)	Per Unit θz (°)
Δ Force X (N)	87500					
Δ Force Y (N)		87500				
Δ Force Z (N)			87500			
Δ Moment X (N·m)				0.		
Δ Moment Y (N·m)					0.	
Δ Moment Z (N·m)						0.

Damping Coefficients

Viscous Damping	Per Unit X (m)	Per Unit Y (m)	Per Unit Z (m)	Per Unit θx (°)	Per Unit θy (°)	Per Unit θz (°)
Δ Force * Time X (N·s)	875.					
Δ Force * Time Y (N·s)		875.				
Δ Force * Time Z (N·s)			875.			
Δ Moment * Time X (N·m·s)				0.		
Δ Moment * Time Y (N·m·s)					0.	
Δ Moment * Time Z (N·m·s)						0.

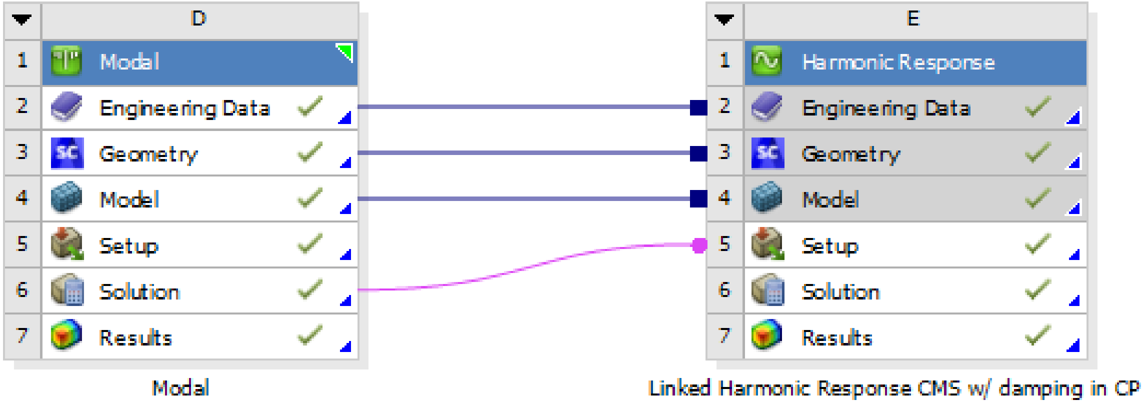
… Damping within CMS

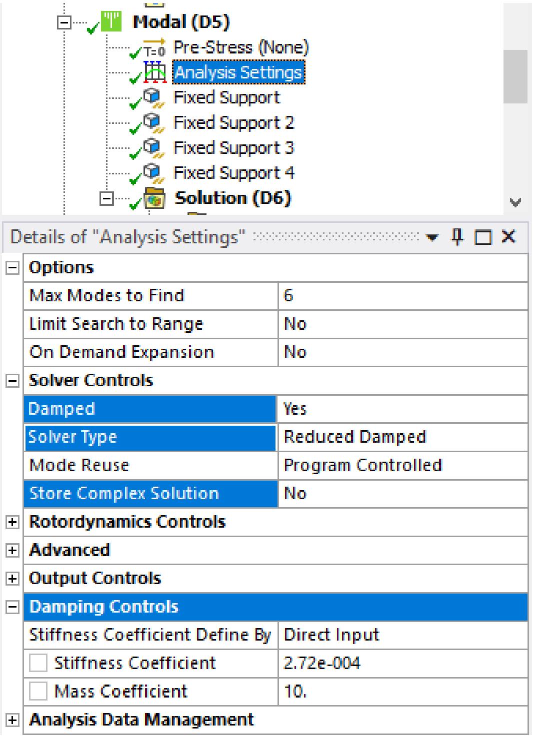
- Creation of the reduced damping matrix within the Condensed Part is controlled within the Analysis Data Management detail of each part
  - Program Controlled is the default, which generates the damping matrix
  - Select No to neglect damping in the condensed part



… Damping within CMS

- To see the effect of damping within a condensed part in a downstream analysis, a damped modal solver must be used.
  - Implies that MSUP Harmonic must be run as a linked analysis from the Project Schematic





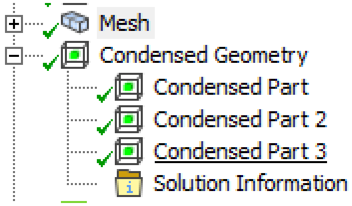
- Damping defined in Engineering Data, or Global Damping in Modal
- Damped Modal Solver requirements:
  - Solver Type = Reduced Damped
  - Store Complex Solution = No

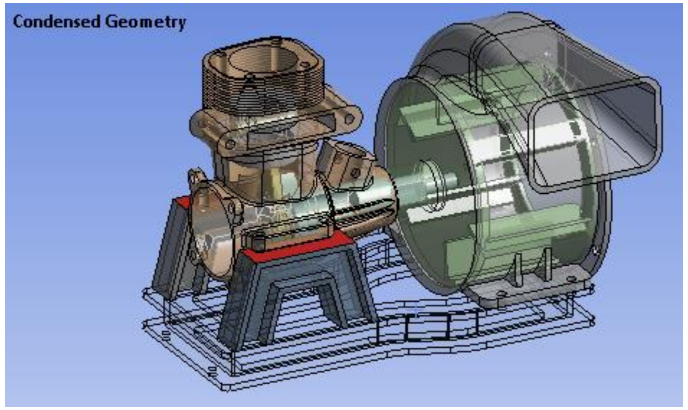
I. Use Case for CMS

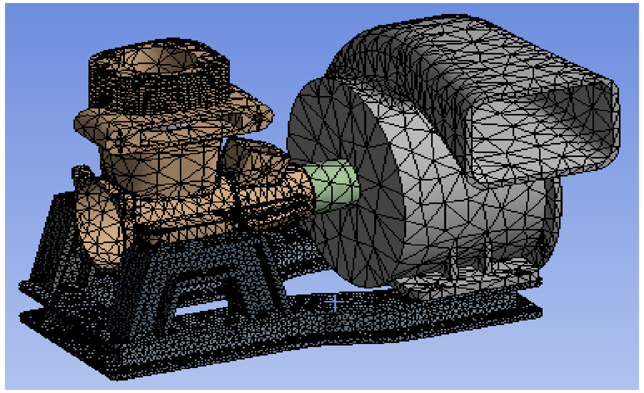
- The main use case for Top Down Substructuring is when performing multiple design point studies within a parametric model
  - Condensed Parts can be generated within non-parametric regions of the model
  - When performing geometry updates of the parametric region of the model, the generated Condensed Parts will not lose their generated status

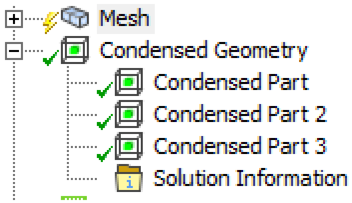
… Use Case for CMS

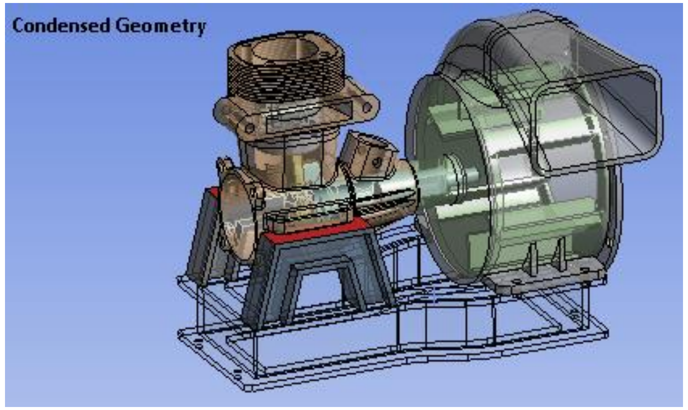
- Lower frame geometry (wireframe) will undergo design change
  - All other parts are condensed parts that have already been generated
  - After design change, condensed part status remains up to date; lower frame can be re-meshed followed by a Use Pass.
    - No need for Gen Pass!

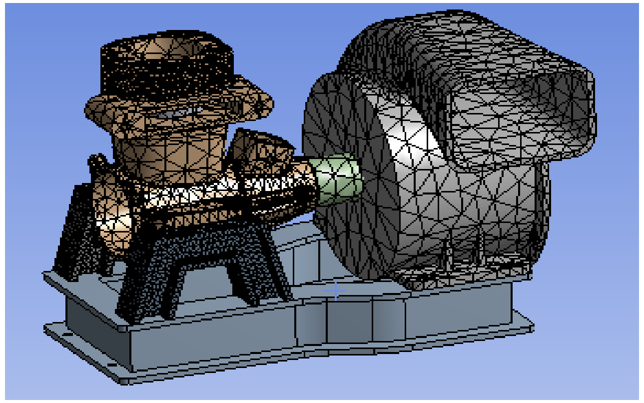




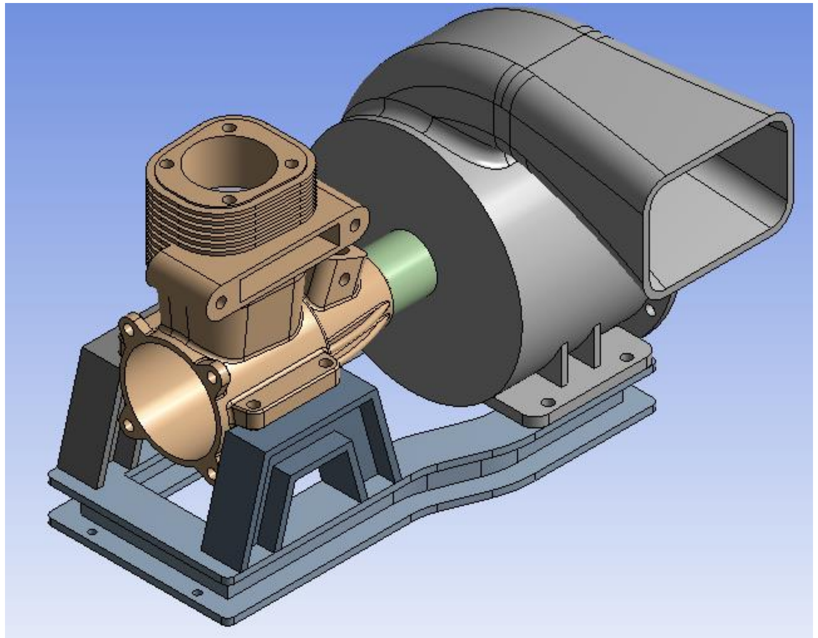


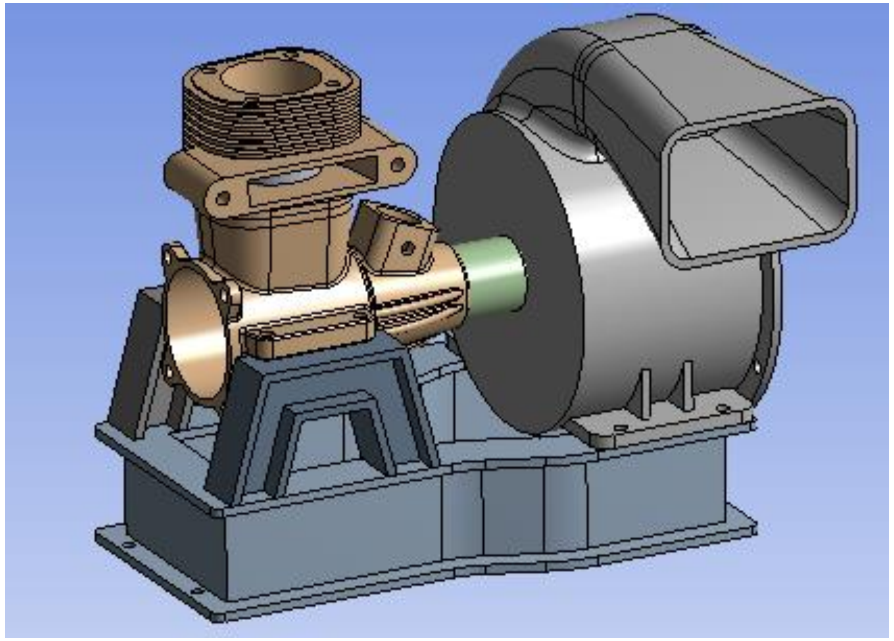


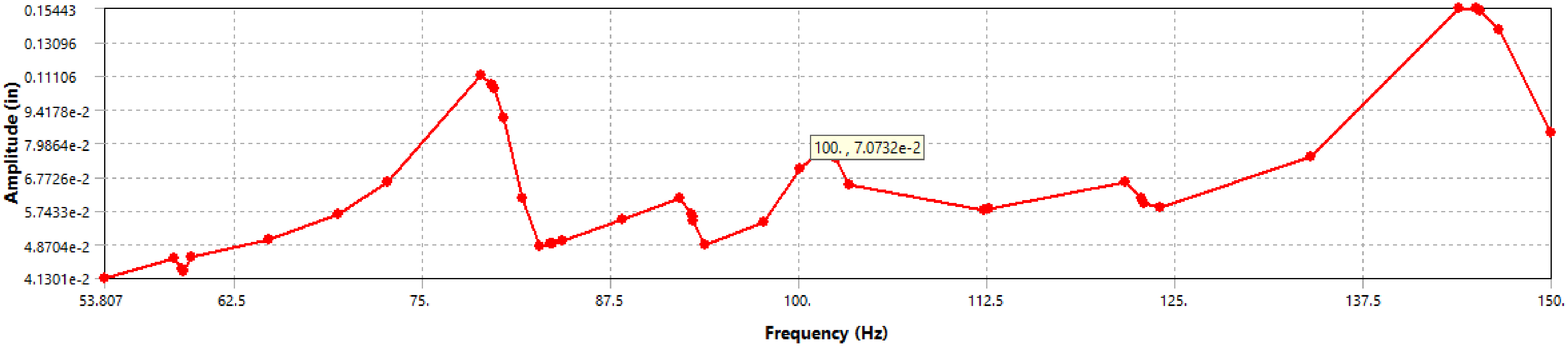




Workshop 10.1: Blower Frame CMS







Ansys

End of presentation