Model Reduction & Interface Modeling in Dynamic Substructuring

Application to a Multi-Megawatt Wind Turbine

MSc. Presentation

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SIEMENS

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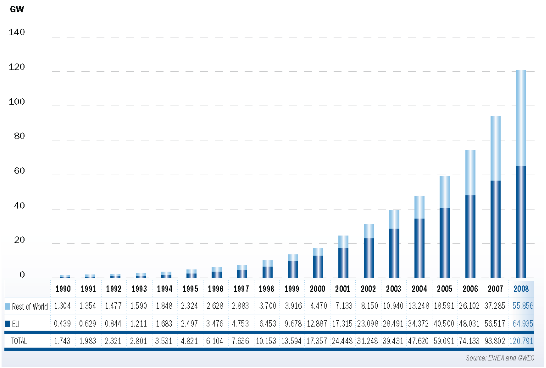
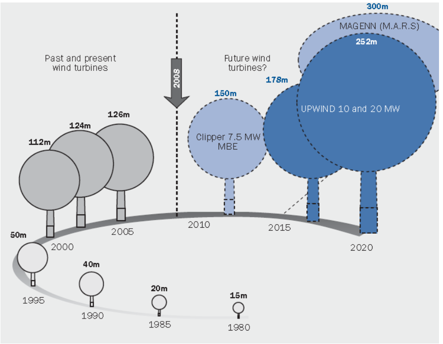
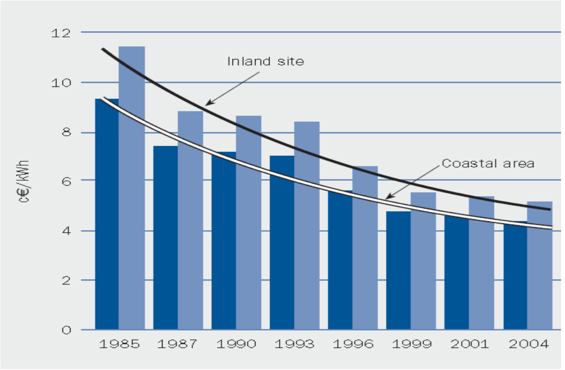
Introduction

- Trends in wind power
  - Increase in installed GW
  - Larger turbines
  - Decrease of cost (€/kWh)

- Turbines become larger and more optimzed







Introduction

Optimization of components:

- Less material used
  - Decrease in turbine weight
  - Transport and installation is easier
  - Smaller foundations

  - Increase in flexibility of component
  - Local dynamic behavior
  - Higher component loading

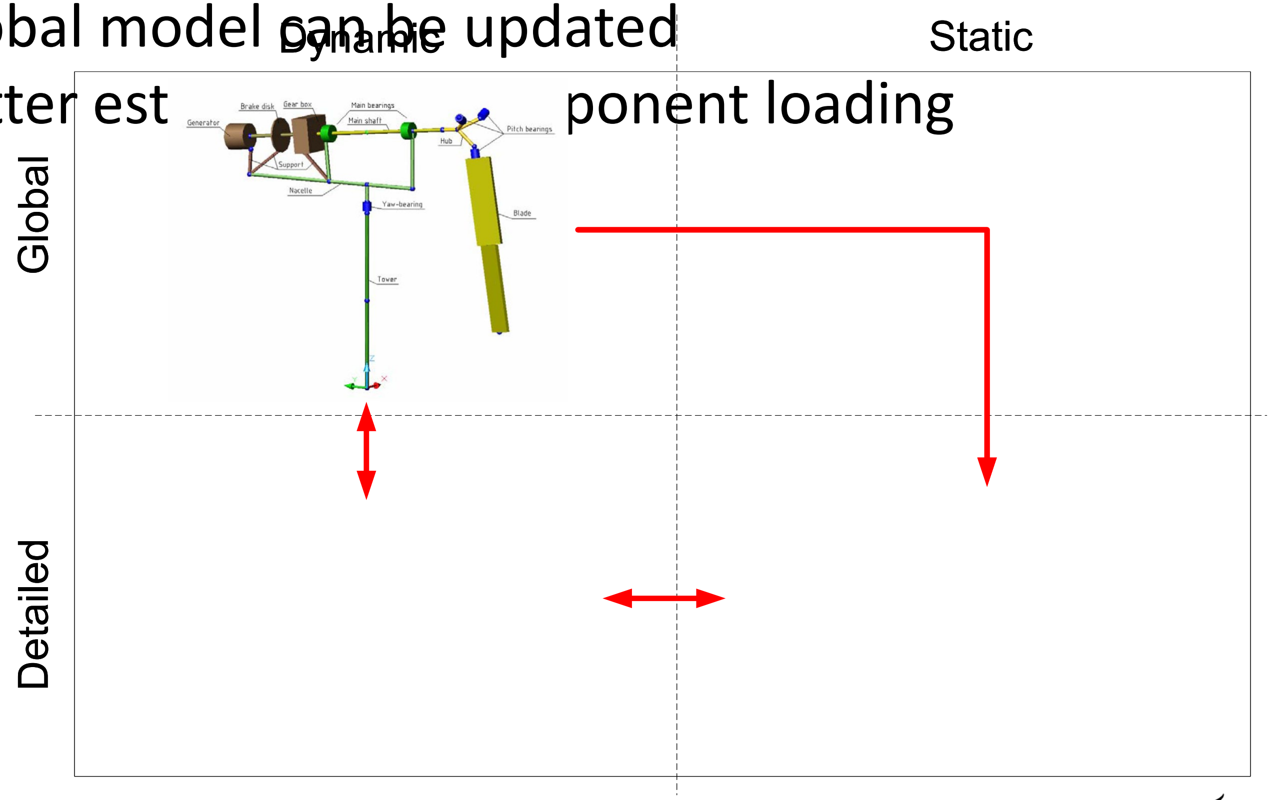
Introduction

Current workflow in WT engineering

- Local dynamic behavior not taken into account

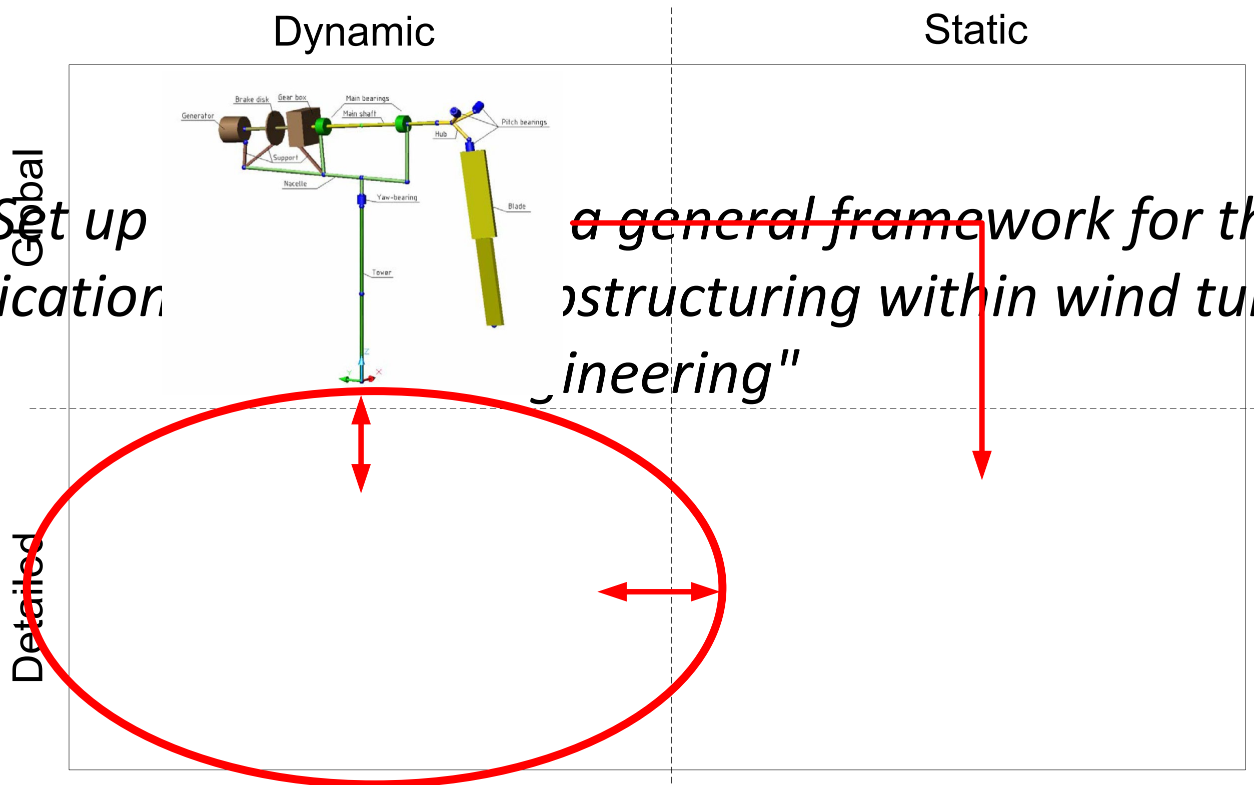
Desired workflow in WT engineering

- Crucial component dynamics can be identified
- Global model can be updated
- Better est ponent loading



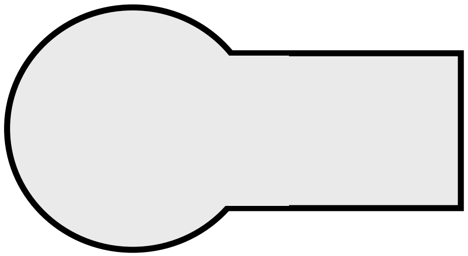
Introduction

Dynamic substructuring is proposed to fill this need for a more detailed dynamic analysis tool



"Set up a general framework for the applicati bstructuring within wind turbine gineering"

Content



- Theory of dynamic substructuring
  - What is dynamic substructuring?
  - Techniques for dynamic substructuring

- Application to a multi-MW wind turbine
  - Yaw system
  - Component models
  - Validation measurements
  - Analysis results

- Conclusions and recommendations

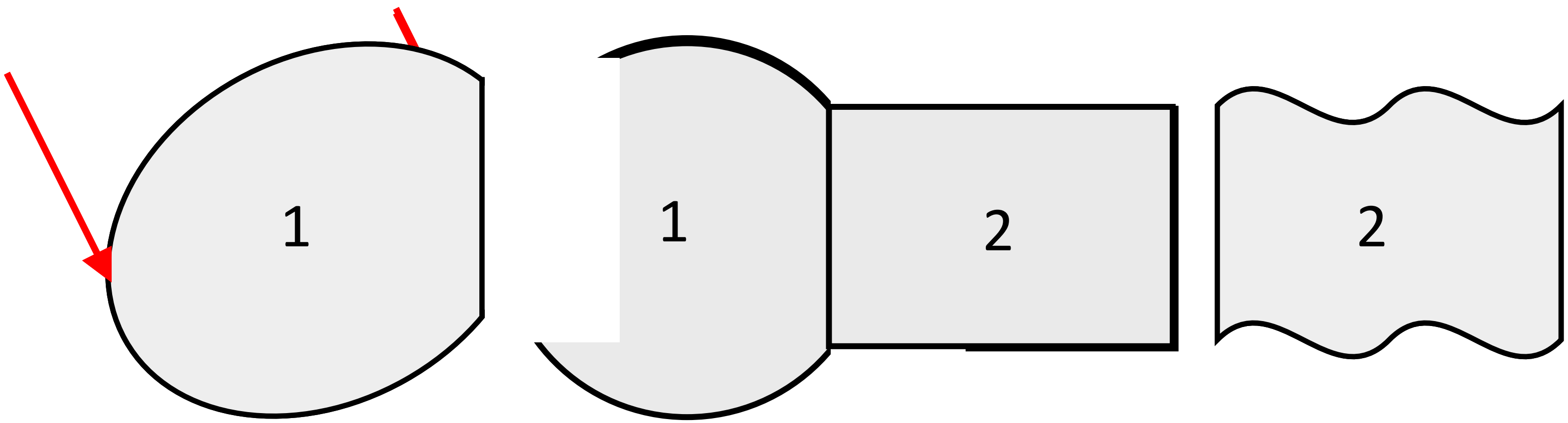
Theory of dynamic substructuring

What is dynamic substructuring?

Complex structure

Split into two substructures

[illegible] component models in terms of most important dynamic behaviour



Theory of dynamic substructuring

What is dynamic substructuring?

Assemble simplified substructures

Solve simplified problem

[illegible] in terms of most important dynamic behaviour

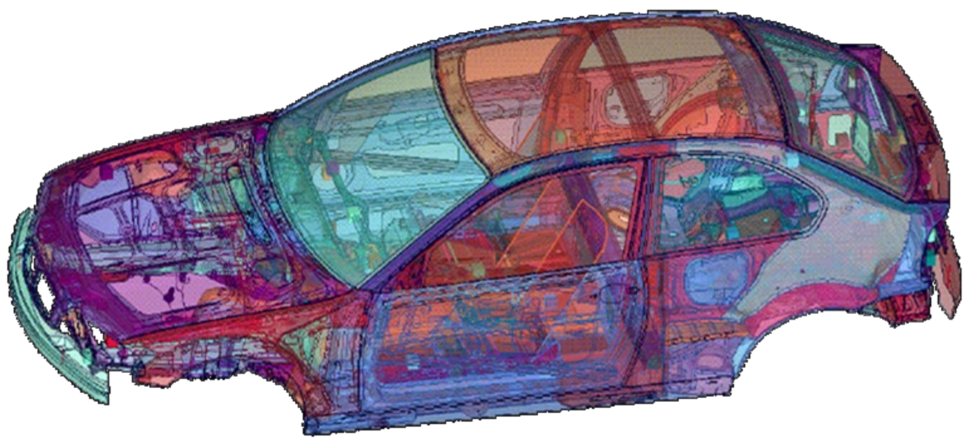
Results in a less complex and more compact set of equations, while accurately describing the assembled behavior

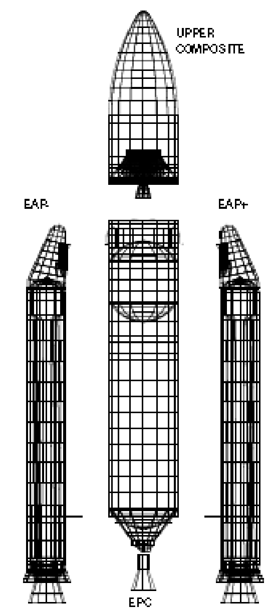
Theory of dynamic substructuring

What is dynamic substructuring?

Several advantages:

- Allows evaluation of large complex structures
- Experimental substructures combined with numerical (component) models
- Local dynamic behavior is easier to identify



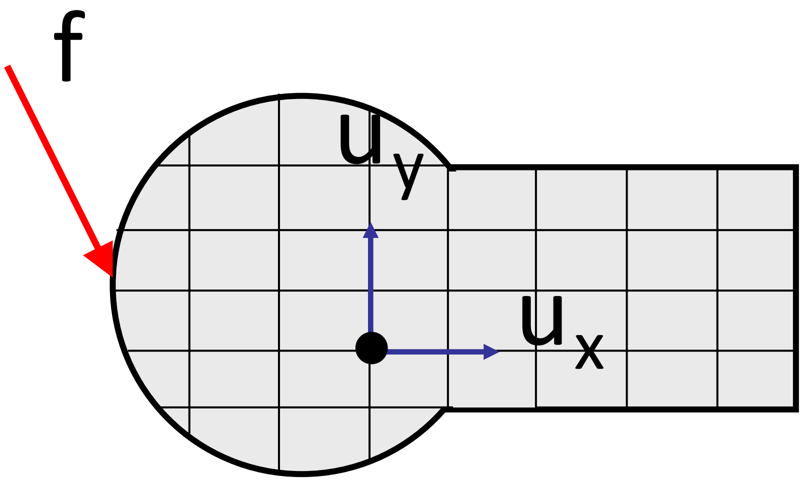


Theory of dynamic substructuring

What is dynamic substructuring?

Equations of motion of total structure:

$$M \ddot{u} + K u = f$$



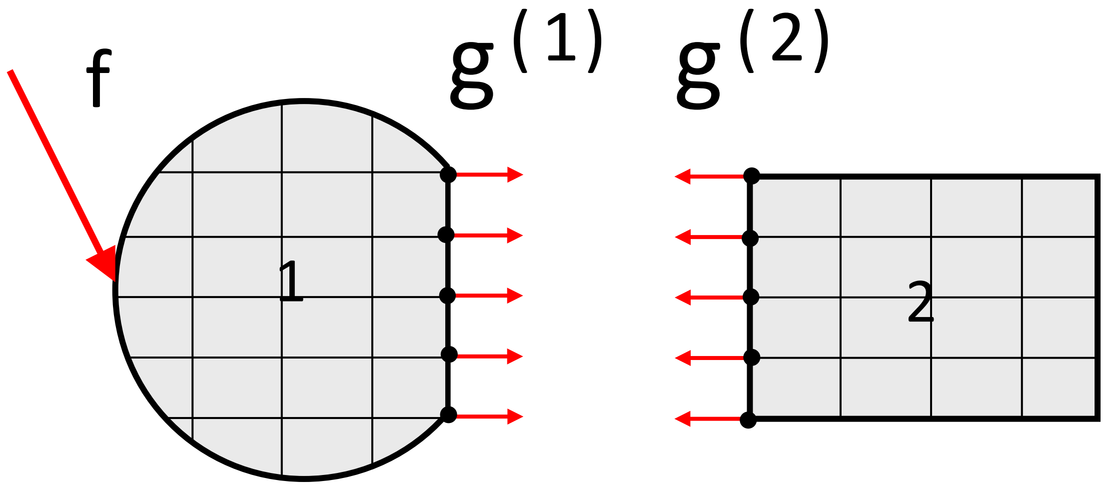
Theory of dynamic substructuring

What is dynamic substructuring?

Equations of motion of separate substructures:

$$M^{(1)} \ddot{u}^{(1)} + K^{(1)} u^{(1)} = f + g^{(1)}$$

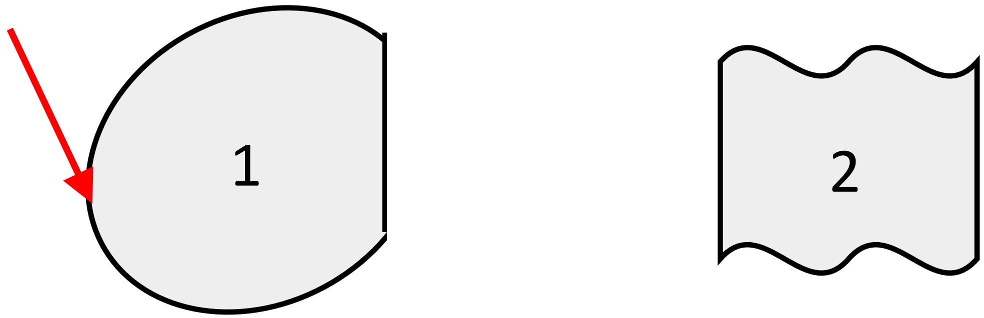
$$M^{(2)} \ddot{u}^{(2)} + K^{(2)} u^{(2)} = g^{(2)}$$



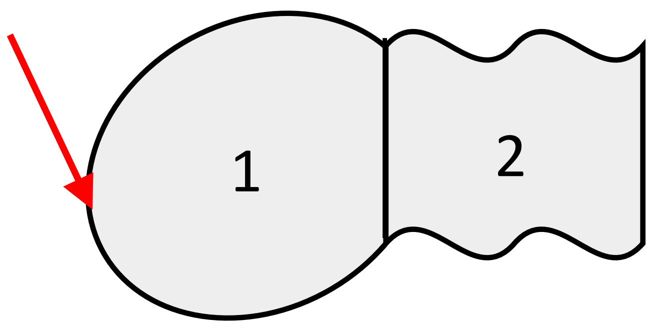
Theory of dynamic substructuring

Techniques for dynamic substructuring

- Reduction of components

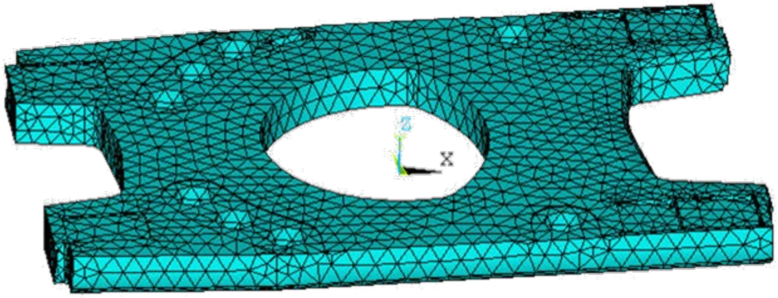


- Assembly of components



Theory of dynamic substructuring

Reduction of component models



Often FE models are very refined

- High accuracy
- Large number of DoF

→ Results in high computational effort for dynamic problems

- Re-meshing could be very expensive

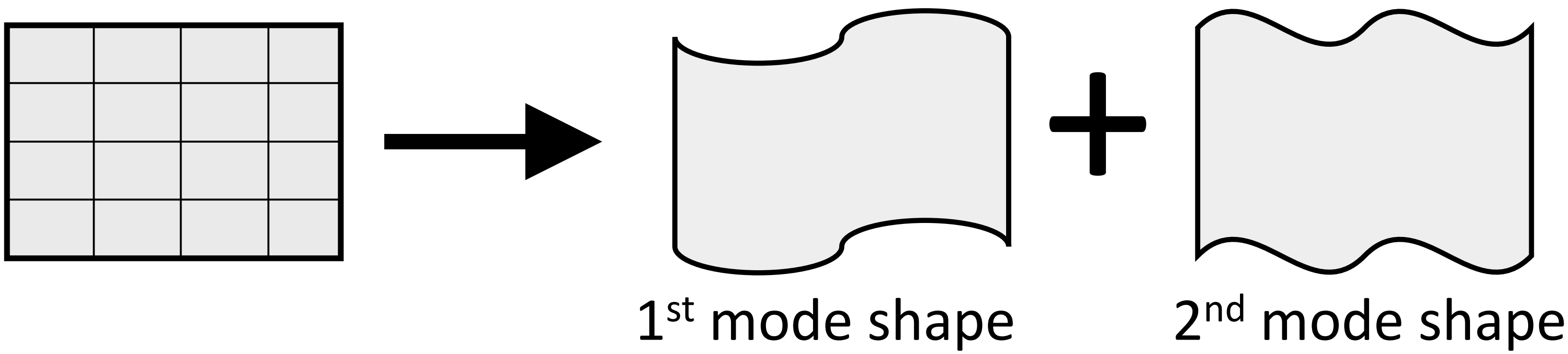
→ *Component model reduction methods*

Theory of dynamic substructuring

Reduction of component models

Basic idea:

- Description in terms of vibration mode shapes instead of nodal displacements:

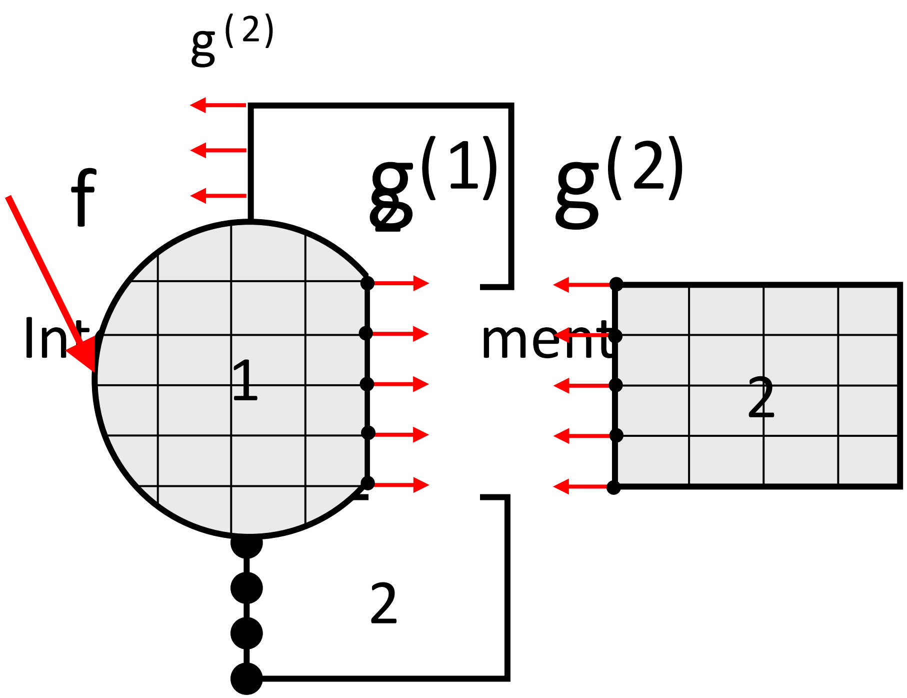


- Exact if all mode shapes are included
- Reduction is performed by only including a number of mode shapes

Theory of dynamic substructuring

Reduction of component models

- “Communication” between substructures needed
  - →Add DoF on the interface
    - Interface forces (g_b)
    - Int ment



Theory of dynamic substructuring

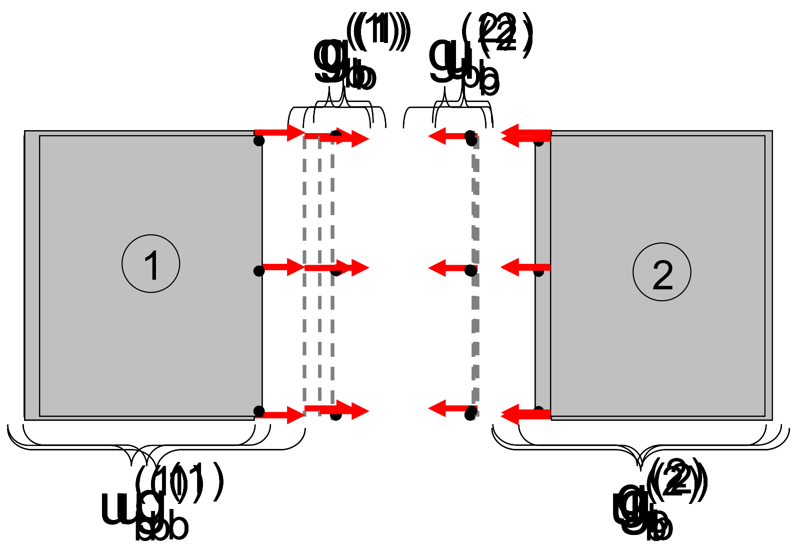
Assembly of component models

Three possible assembly cases:

- $u_b \; \$ \; u_b$

- $g_b \; \$ \; g_b$

- $u_b \; \$ \; g_b$



Theory of dynamic substructuring

Assembly of component models

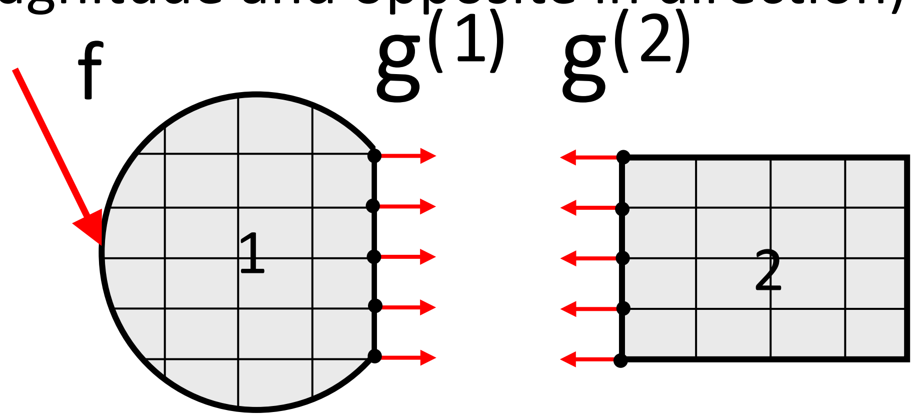
Two conditions:

- *Compatibility*

  → Displacements on both sides of the interface must be the same

- *Equilibrium*

  → Connecting forces must be in equilibrium (i.e. equal in magnitude and opposite in direction)



Theory of dynamic substructuring

Assembly of component models

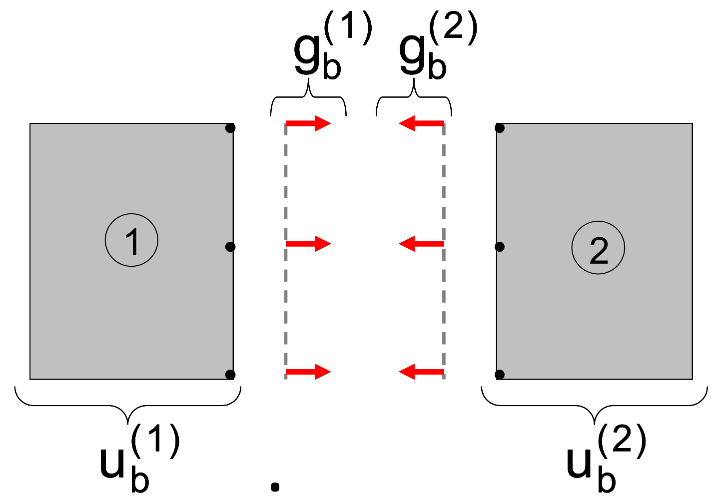
Interface displacements (u_b) to Interface displacements (u_b)

- Compatibility

$$u_b^{(1)} - u_b^{(2)} = 0$$

- Equilibrium

$$g_b^{(1)} + g_b^{(2)} = 0$$



$$\begin{bmatrix} K^{(1)} & 0 \\ 0 & K^{(2)} \end{bmatrix} \begin{bmatrix} u^{(1)} \\ u^{(2)} \end{bmatrix} = \begin{bmatrix} g^{(1)} \\ g^{(2)} \end{bmatrix}$$

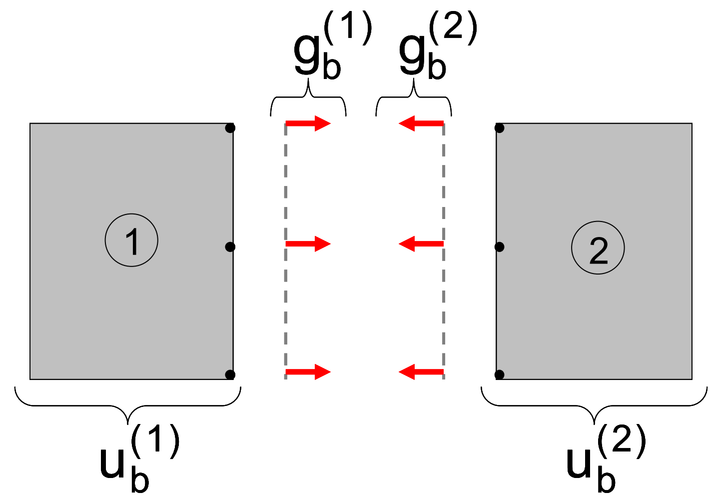
Theory of dynamic substructuring

Assembly of component models

Interface displacements (u_b) to Interface displacements (u_b)

$$u_b^{(1)} - u_b^{(2)} = 0$$

$$\begin{bmatrix} u^{(1)} \\ u^{(2)} \end{bmatrix} = L\, u$$



$$g_b^{(1)} + g_b^{(2)} = 0$$

- Relation between Boolean matrices:

$$L^T B^T = 0$$

$$B\, L = 0$$

Application to a multi-MW wind turbine

- Yaw system
- Component models
- Measurements for component validation
- Analysis results

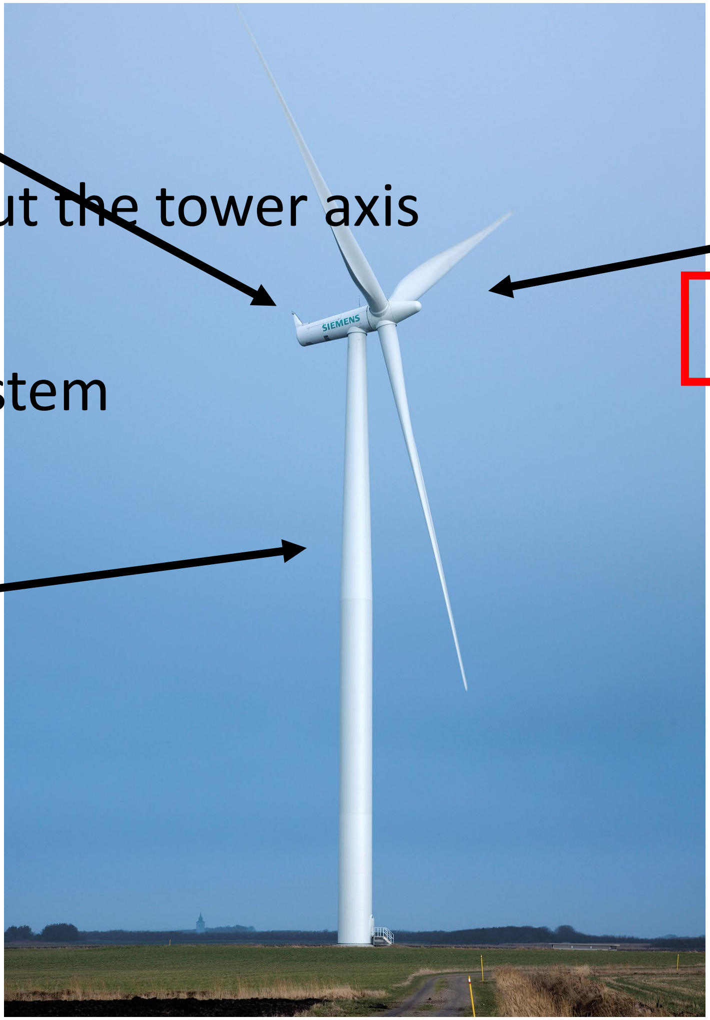
Application to a multi-MW wind turbine

Yaw system

- Yawing:

  Rotation about the tower axis

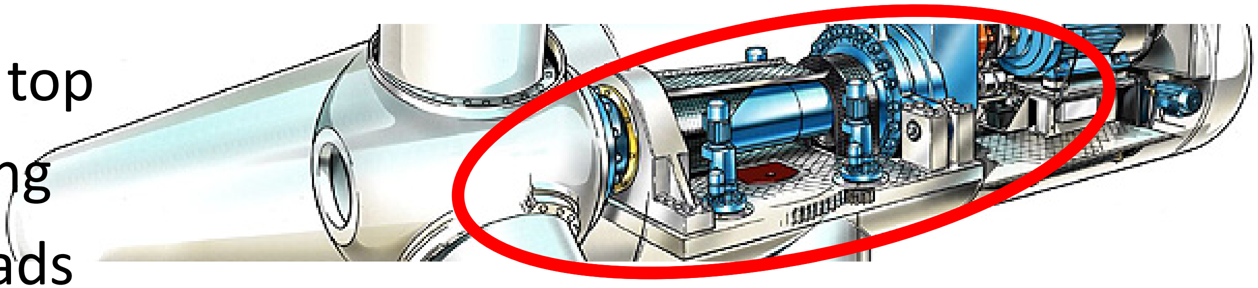
- Active yaw system

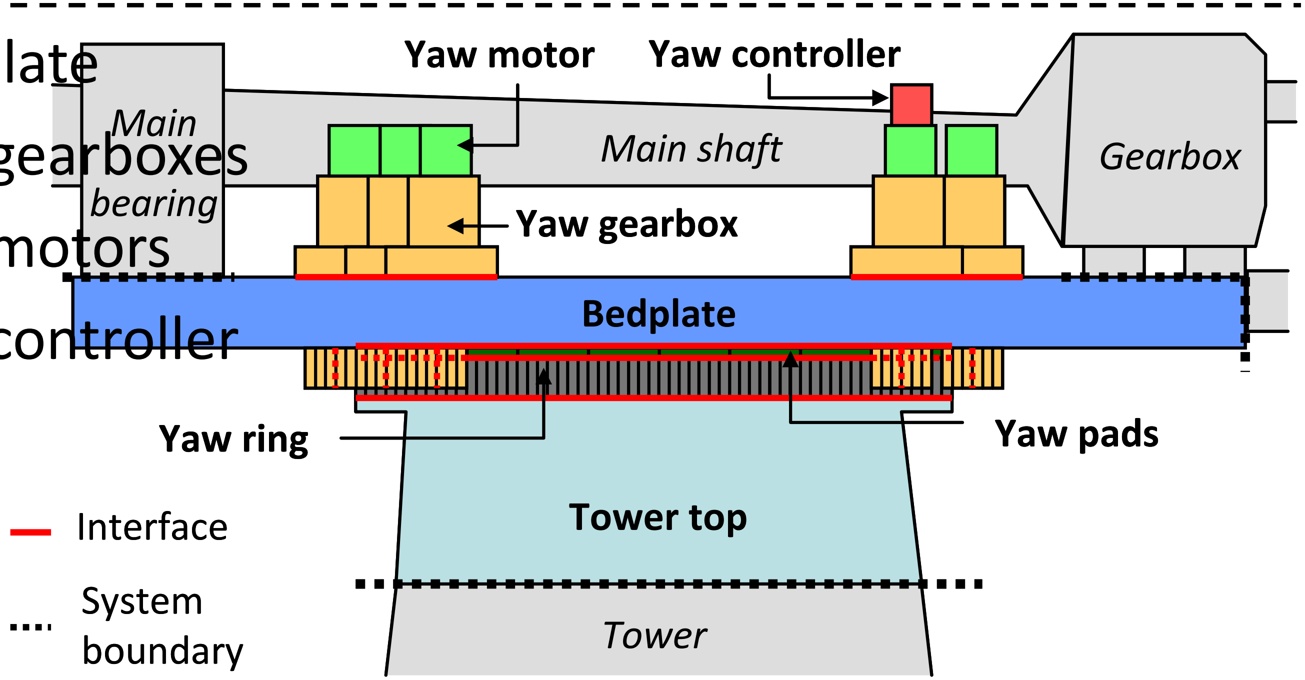


Application to a multi-MW wind turbine

Yaw system

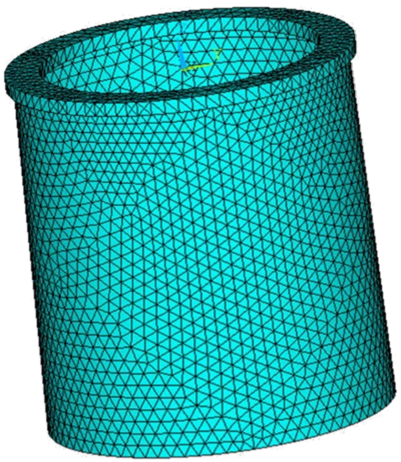
- Tower top
- Yaw ring
- Yaw pads
- Bedplate
- Yaw gearboxes
- Yaw motors
- Yaw controller



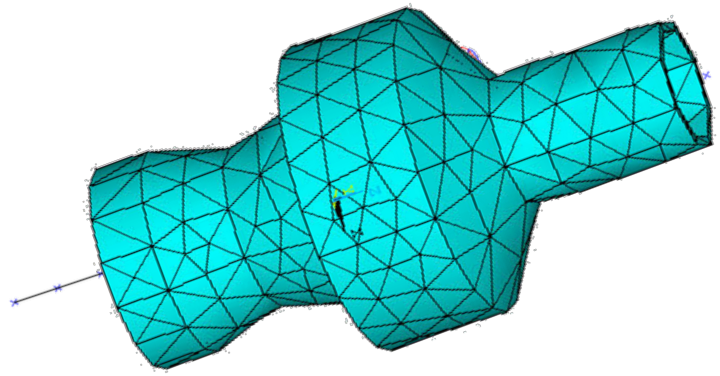


Application to a multi-MW wind turbine

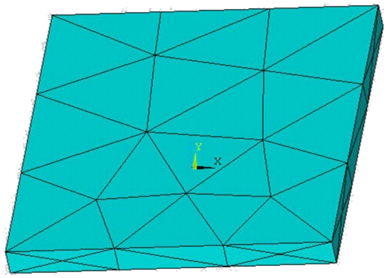
Component models



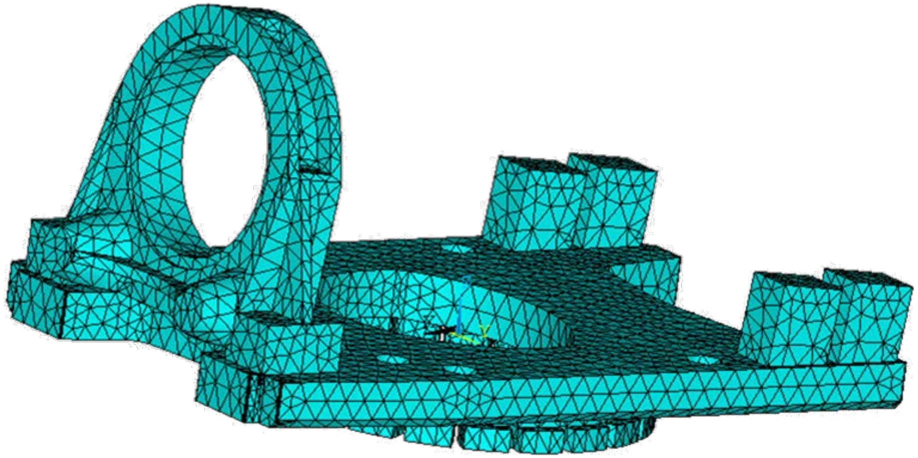
Tower top and yaw ring



Yaw gearbox



Yawpad

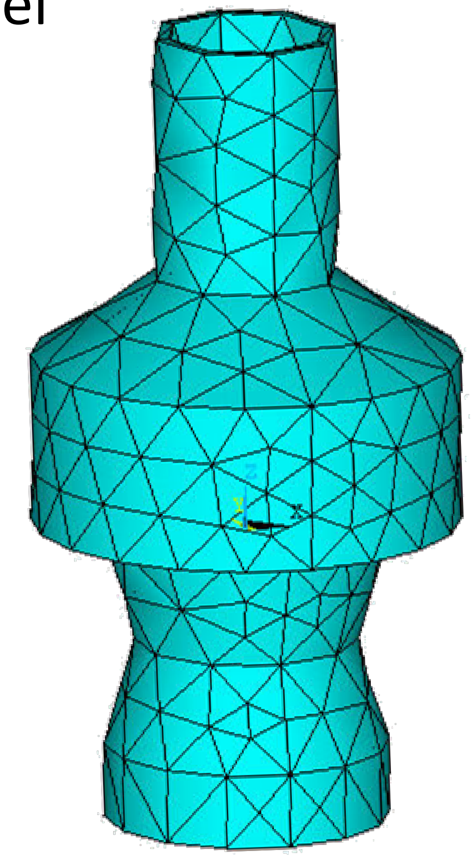


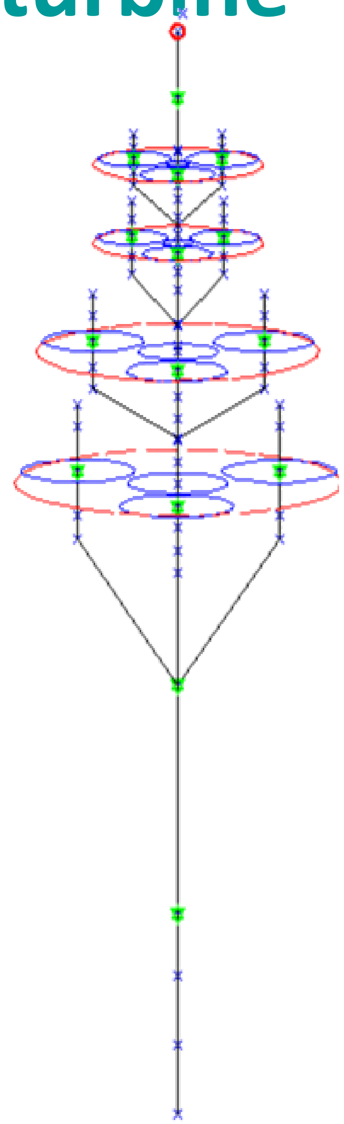
Bedplate

Application to a multi-MW wind turbine

Component models

- Yaw gearbox model is built from 2 submodels:
  - Yaw gearbox housing model
  - Yaw gearbox gear model



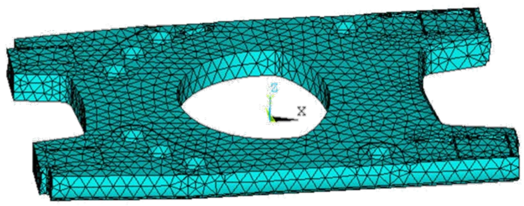


Application to a multi-MW wind turbine

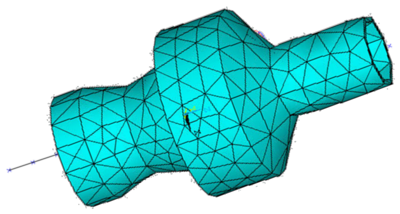
Measurements for component validation

Measurements performed to validate:

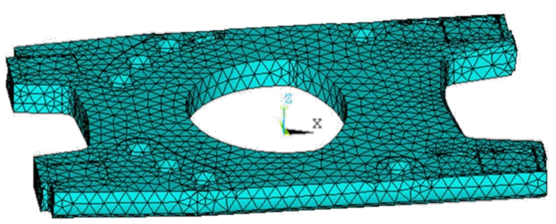
- Simple bedplate model:



- Yaw gearbox model:



- Assembly of bedplate and 4 yaw gearboxes:



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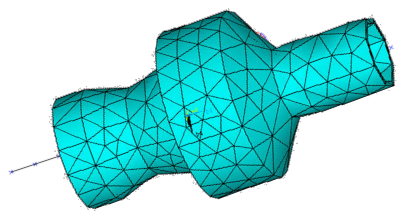
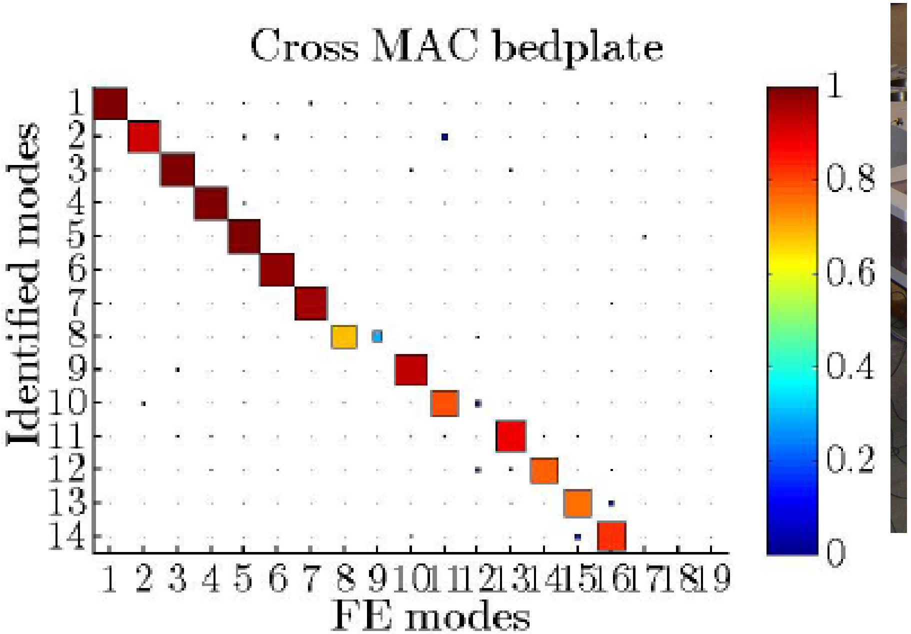


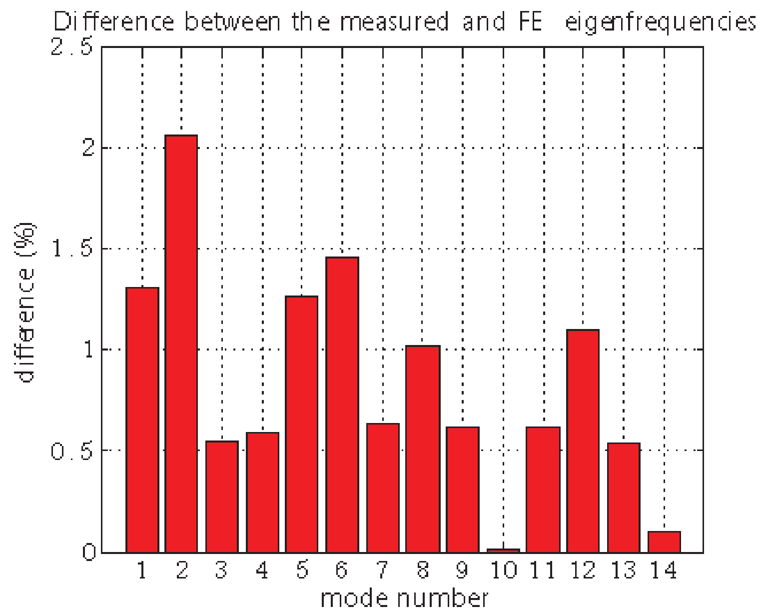
Application to a multi-MW wind turbine

Measurements for component validation
Bedplate

Measurement performed to validate the bedplate model

- 33 locations measured using 3D acceleromters
- Excitation in z-direction using random signal





Application to a multi-MW wind turbine

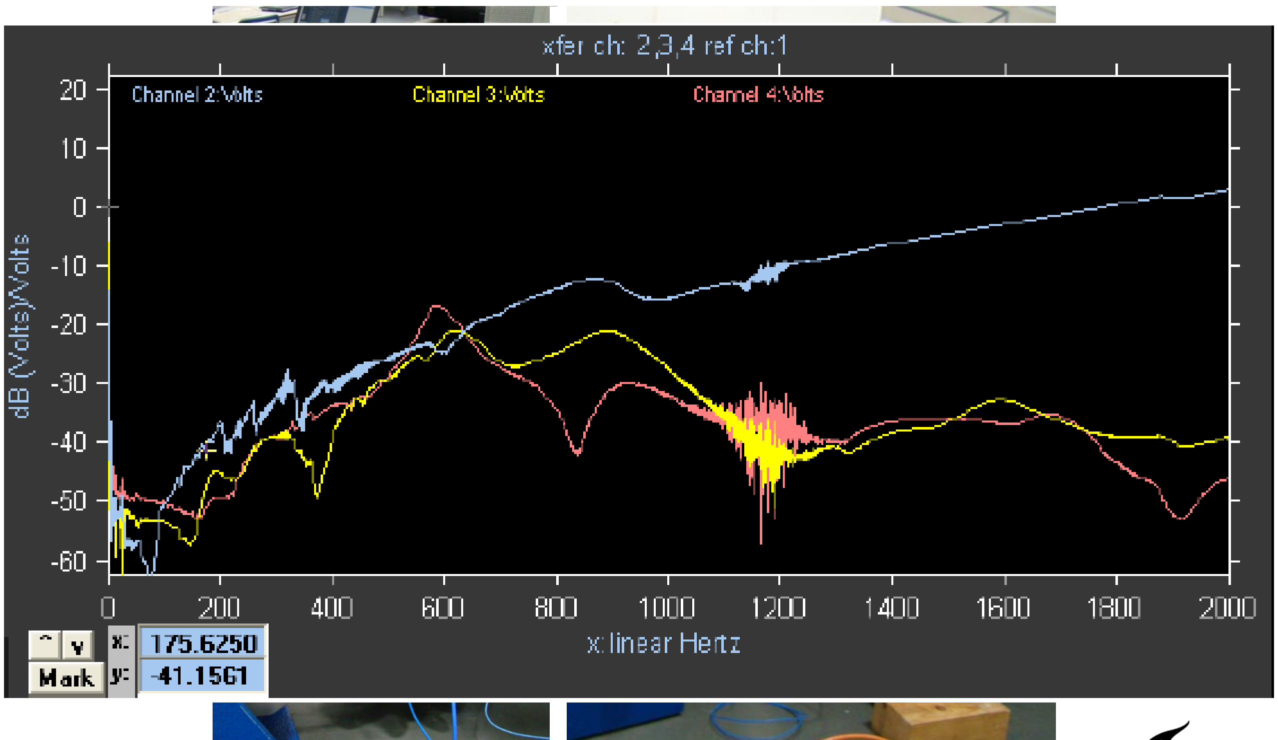
Measurements for component validation

Yaw gearbox

- Shaker attached to output pinion
- 3D accelerometer at input pinion

Crucial

- Gea
- Prel



Application to a multi-MW wind turbine

Measurements for component validation

Yaw gearbox

Preload applied:

- Using a mass suspended on a cable

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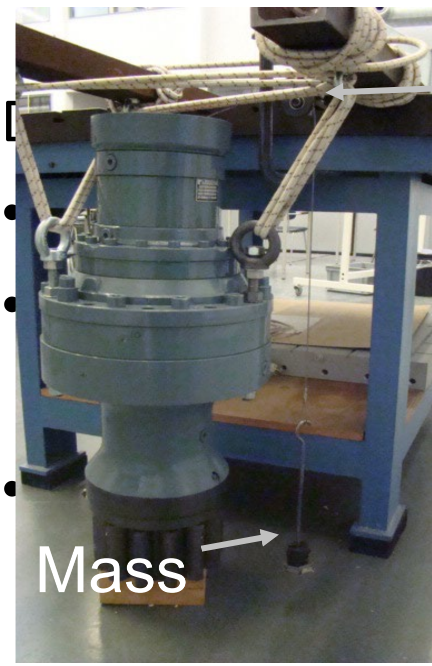
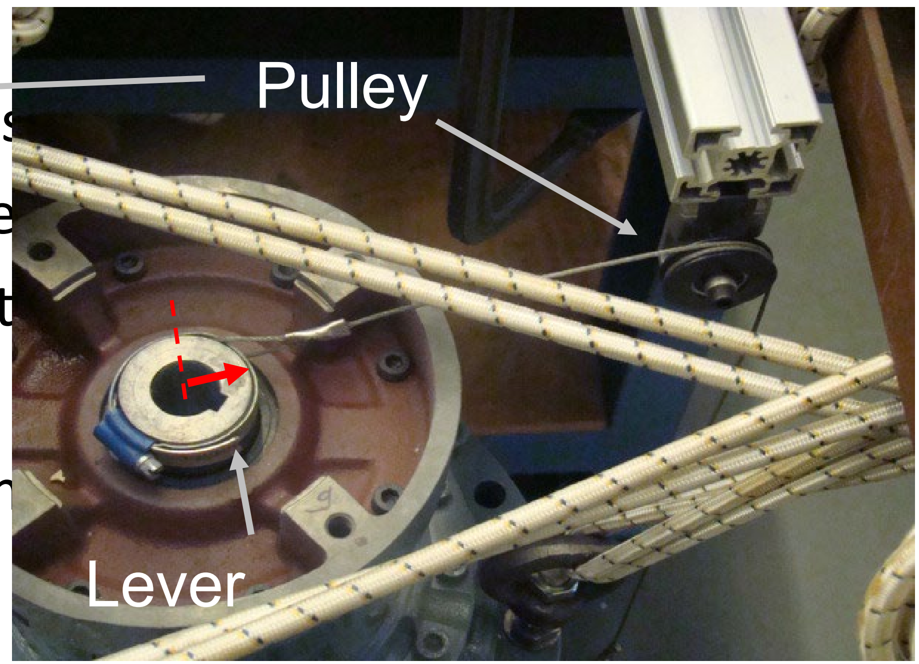




Application to a multi-MW wind turbine

Measurements for component validation

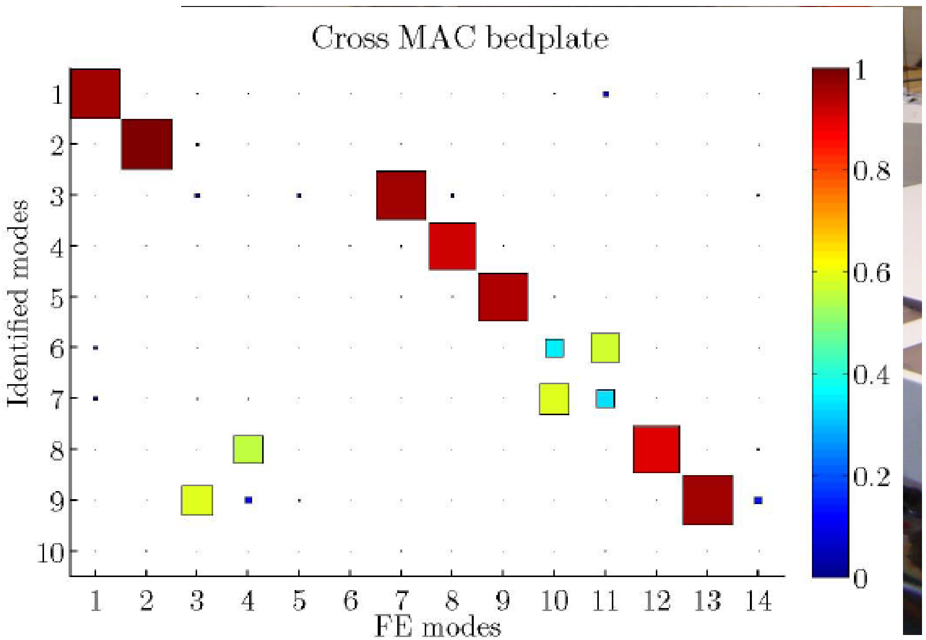
Bedplate – yaw gearboxes assembly

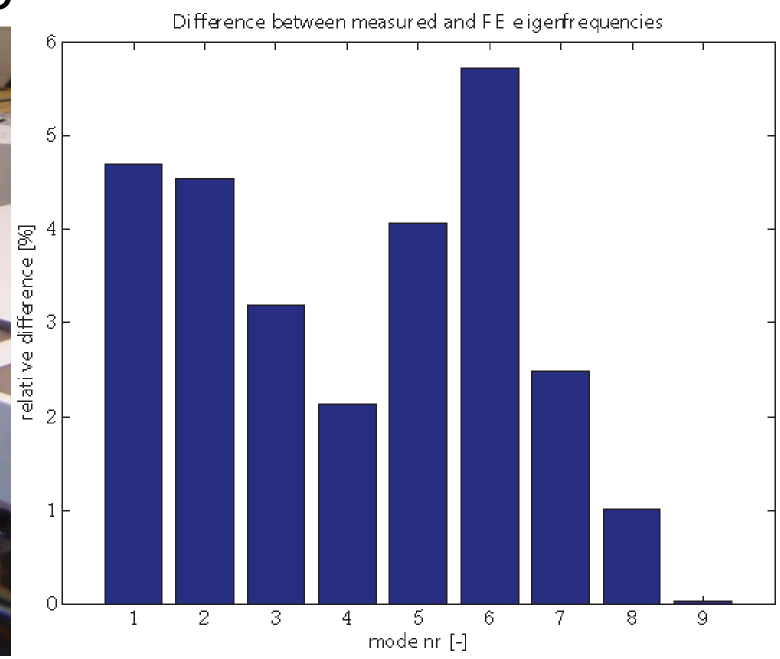
An Assembly was created of a bedplate and 4 yaw gearboxes

- Again, 33 locations measured using accelerometers
- Random signal used for excitation

- **Assembly also created from component models**

Eigenfrequencies and mode shapes compared



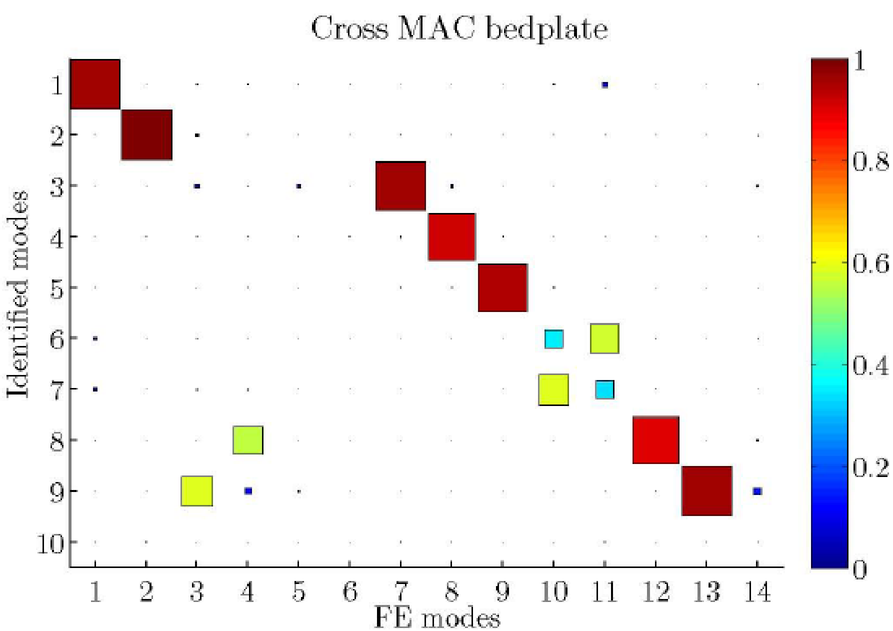


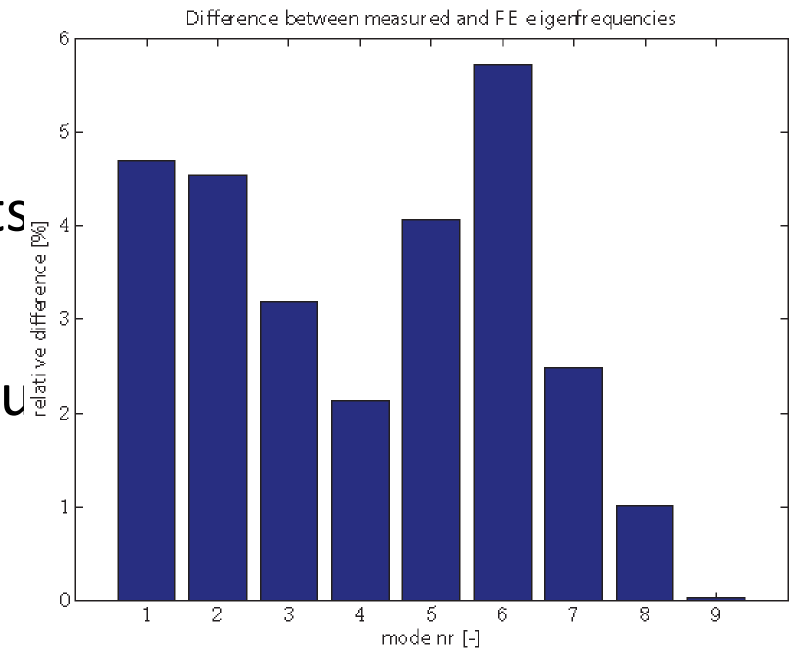
Application to a multi-MW wind turbine

Measurements for component validation

An assembly was created of a bedplate and 4 yaw gearboxes

- First 5 eigenmodes and 8 and 9 show a high correlation
- Frequency difference < 5%

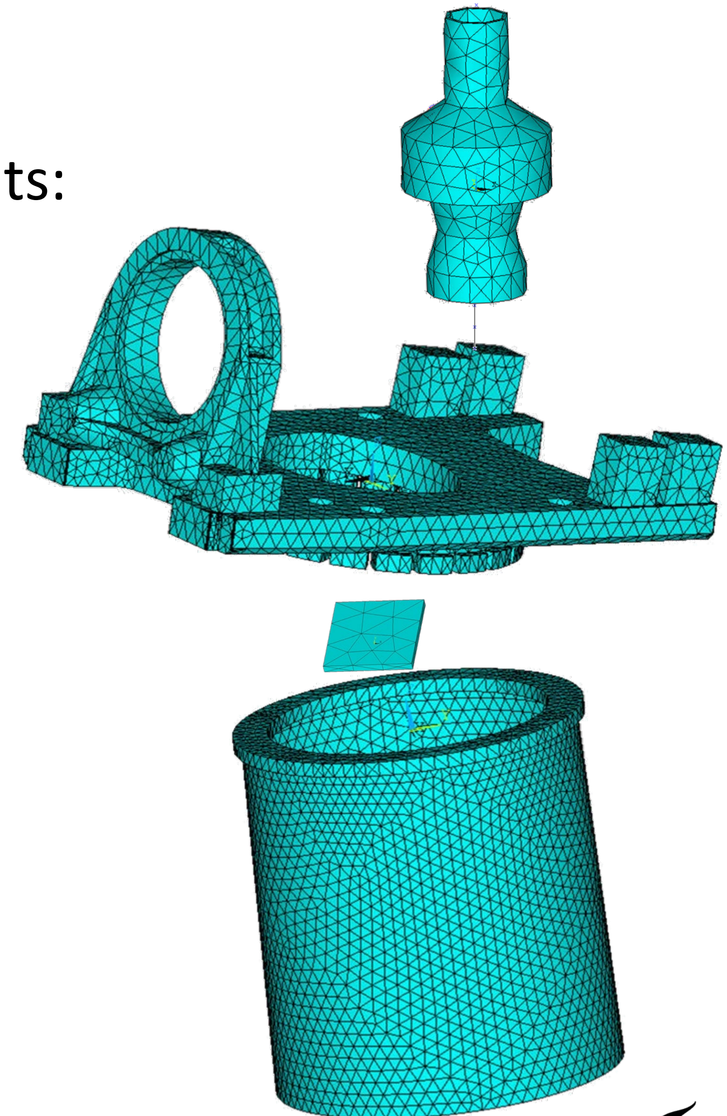




Application to a multi-MW wind turbine

Analysis results

- Assembly of all components:
- 8 Yaw gearboxes
- 1 Bedplate
- 22 Yaw pads
- 1 Tower top and yawring



Application to a multi-MW wind turbine

Analysis results

Full structure model as reference (293.000 DoF):

Frequency error [%]

- 1-MAC value [-]

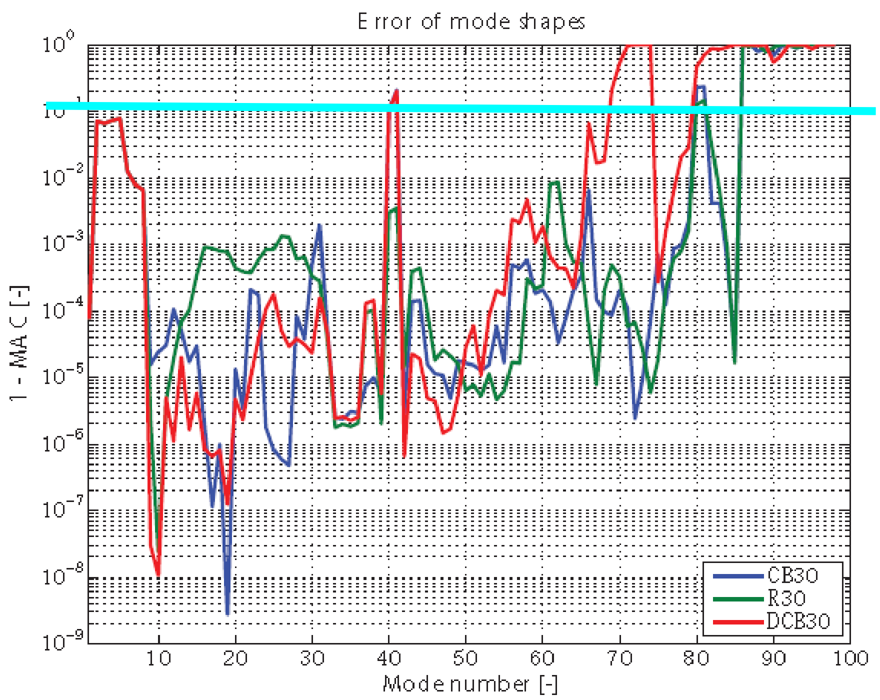
Reduced structure models

- Craig Bampton method (7929 DoF)
- Dual Craig Bampton method (8637 DoF)
- Rubin's method (7881 DoF)

Comparison of results
Reduction methods

Error on frequencies [%]

1 - MAC [-]



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Comparison of results

Reduction methods

- Reduced models accurate up to the 80th eigenmode
- Reduction of approximately a factor of 35!
- Large number of DoF are interface DoF (> 90%)

- Apply an extra reduction step to reduce the interface DoF

Reduced models

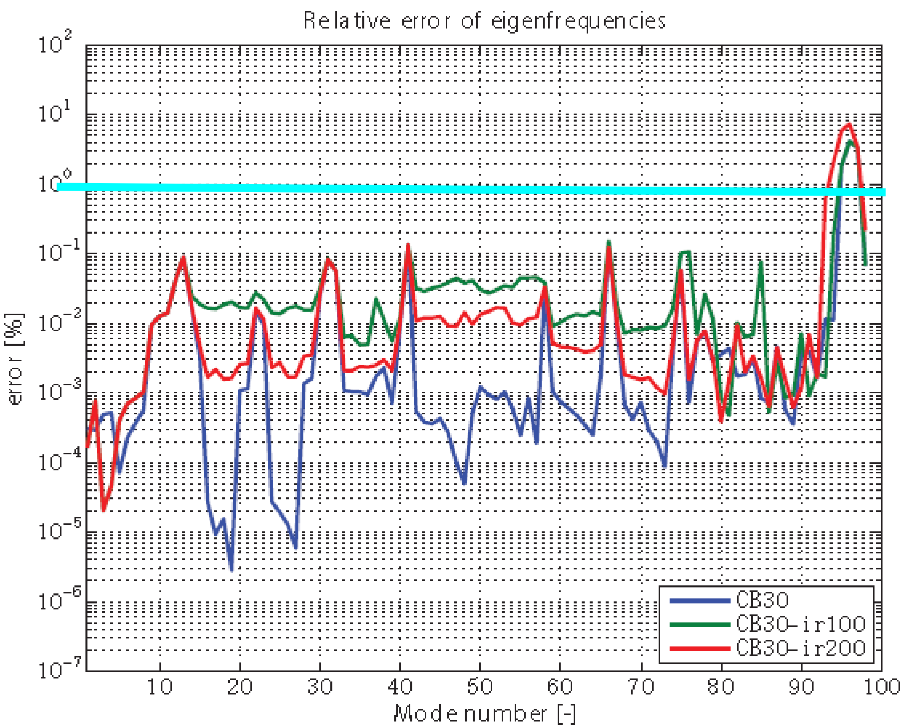
- Craig Bampton, 100 interface modes (730)
- Craig Bampton, 200 interface modes (830)

Comparison of results

Interface reduction methods

- Accurate up to the 80th eigenmode
- Small number of total DoF (730 vs. 293.000)

Error on frequencies [%]



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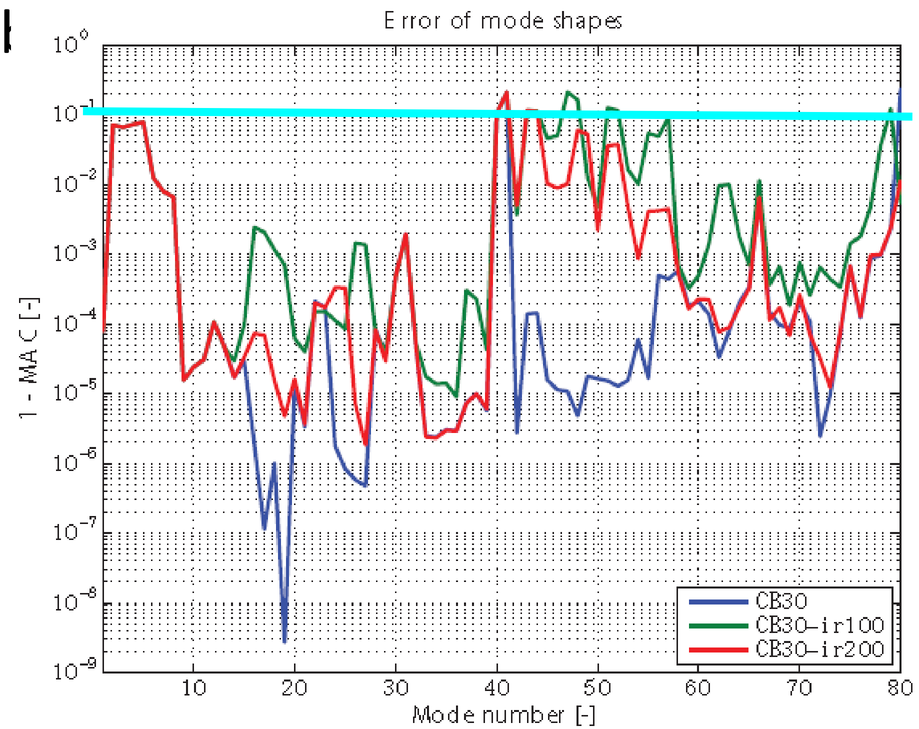

Conclusions and recommendations

Conclusions

- The general framwork was implemented
- Y system was accurately modeled using only 730 DoF
- Total reduction of a factor 400!

- The goal of the MSc assignment has been achieved:

"Set up and implement a general framework for the application of dynamic substructuring within wind turbine engineering"

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Questions