Accuracy of calculation procedures for offshore wind turbine support structures

Pauline de Valk – 27th of August 2013

TU Delft SIEMENS

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- Introduction
- Approach
- Modeling
- Results
- Conclusions and recommendations

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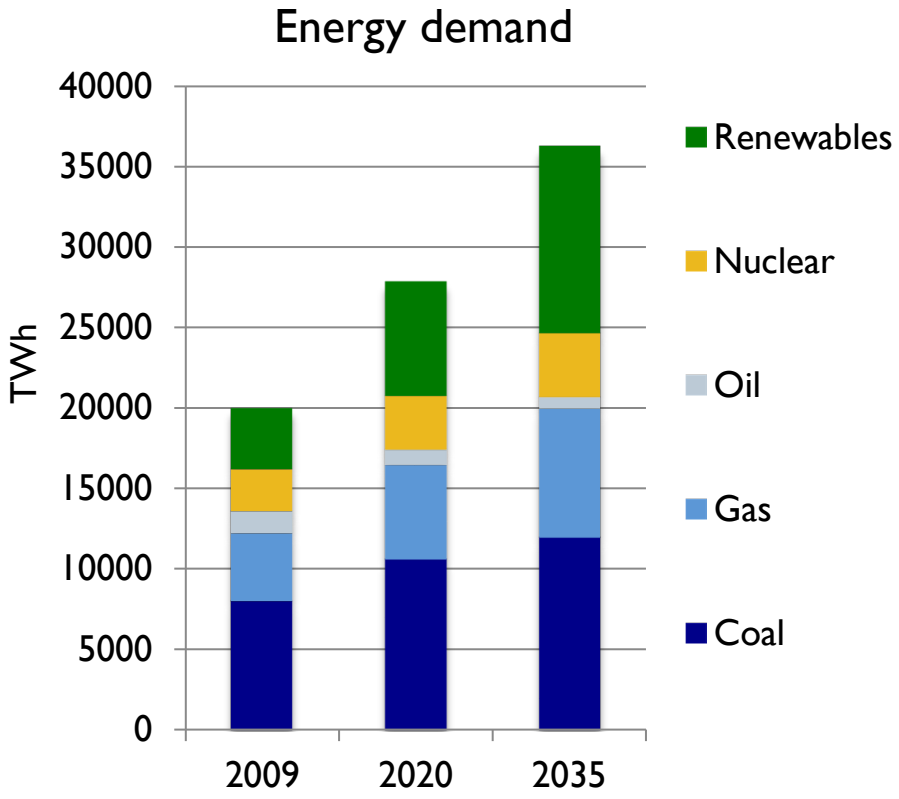
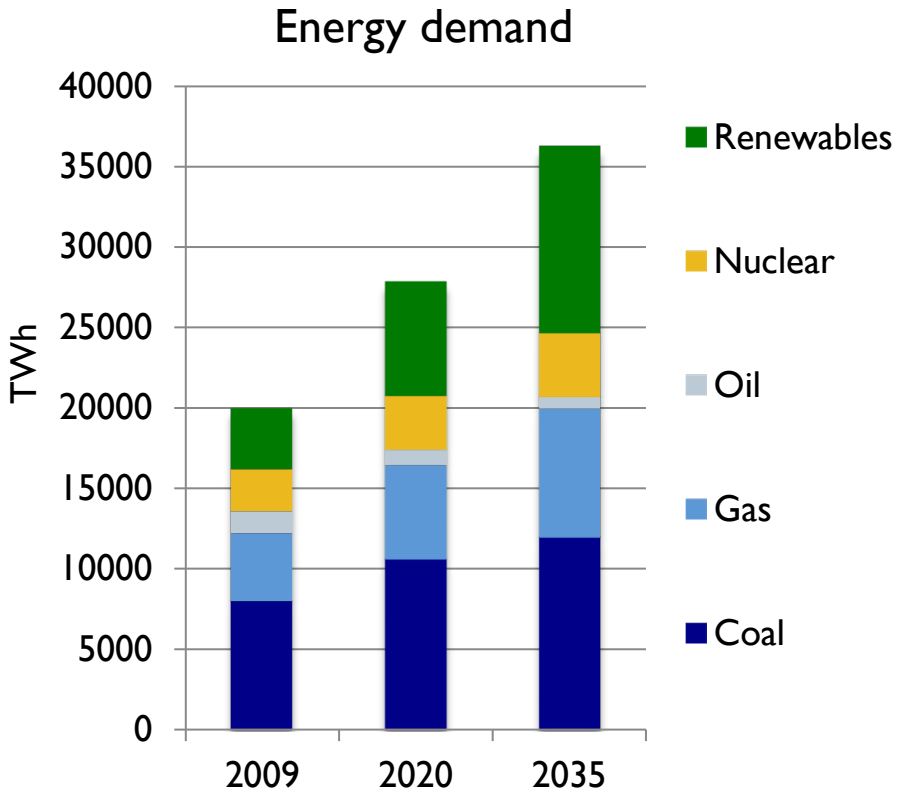
Offshore wind energy shows potential to become one of the main energy suppliers

- Demand for energy continues to increase
- Offshore wind energy
  - More steady wind flow and average wind speed is higher than onshore

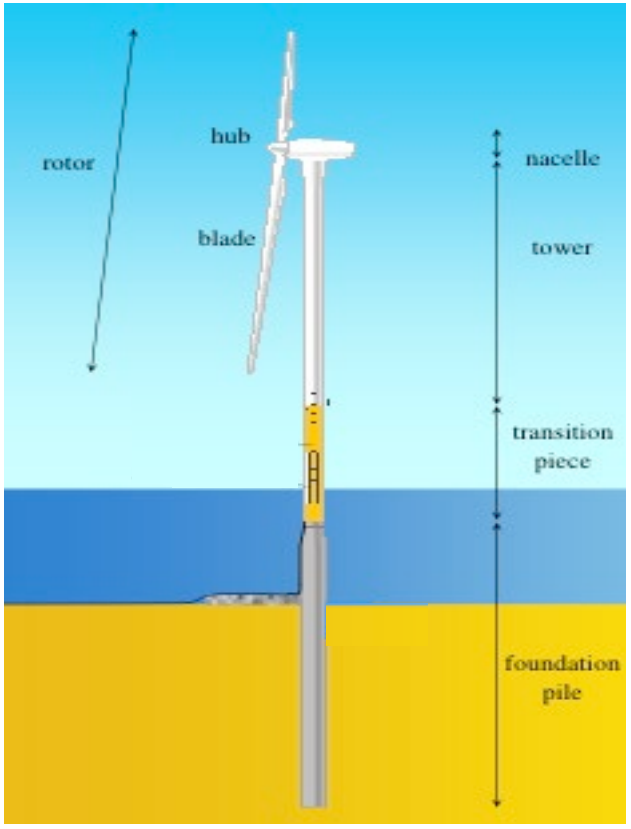


Offshore wind energy shows potential to become one of the main energy suppliers

- Demand for energy continues to increase
- Offshore wind energy
  - More steady wind flow and average wind speed is higher than onshore
- Cost of energy (€/kWh) should be decreased
  - Structural optimization design



Optimize structural design of the support structure



- Support structure one of the main cost items
- In order to optimize one should have confidence in the outcome of calculation procedures

Thesis objective

"Investigate the validity and conservatism

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"Investigate the validity and conservatism of the current calculation procedures

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"Investigate the validity and conservatism of the current calculation procedures for offshore wind turbine support structures

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"Investigate the validity and conservatism of the current calculation procedures for offshore wind turbine support structures and propose improved procedures

Thesis objective

"Investigate the validity and conservatism of the current calculation procedures for offshore wind turbine support structures and propose improved procedures based on these findings."

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Offshore wind turbine support structure is custom engineered for every wind farm

Foundation designer (FD)

Turbine designer (TD)

Offshore wind turbine support structure is custom engineered for every wind farm

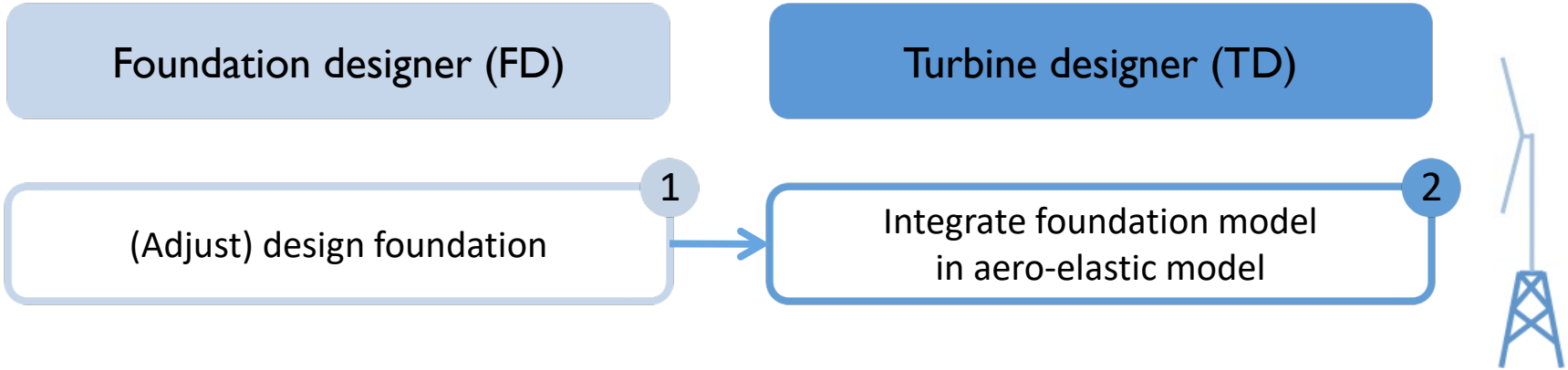
Foundation designer (FD)

Turbine designer (TD)

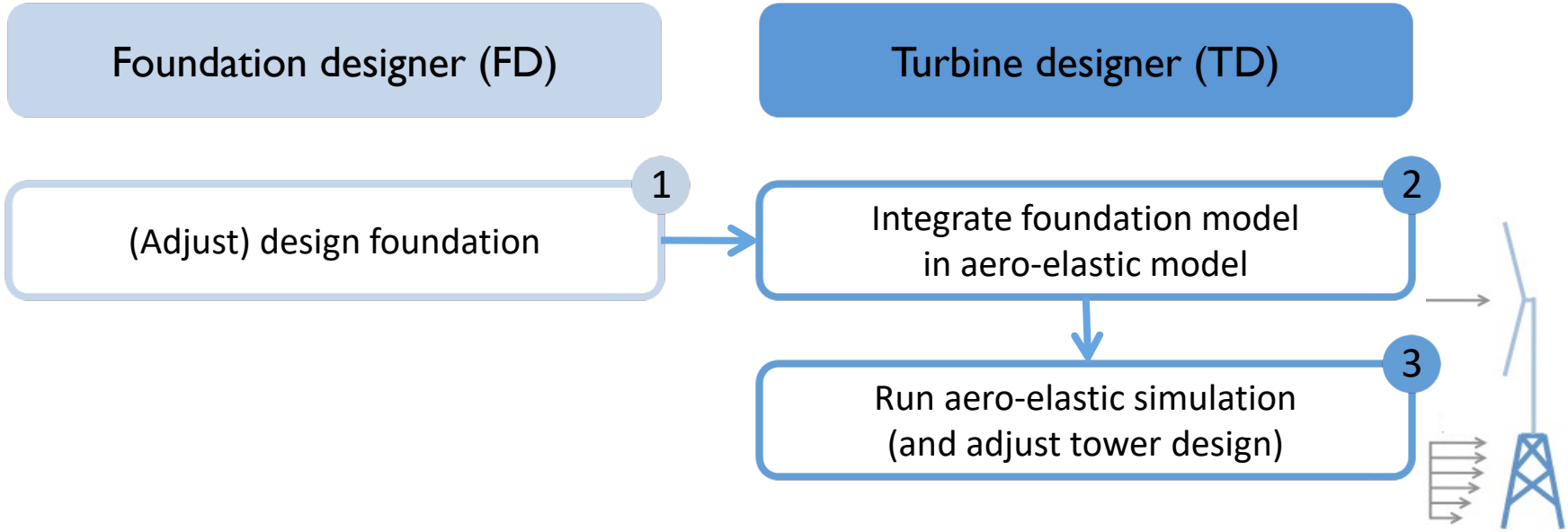
1

(Adjust) design foundation

Offshore wind turbine support structure is custom engineered for every wind farm



Offshore wind turbine support structure is custom engineered for every wind farm



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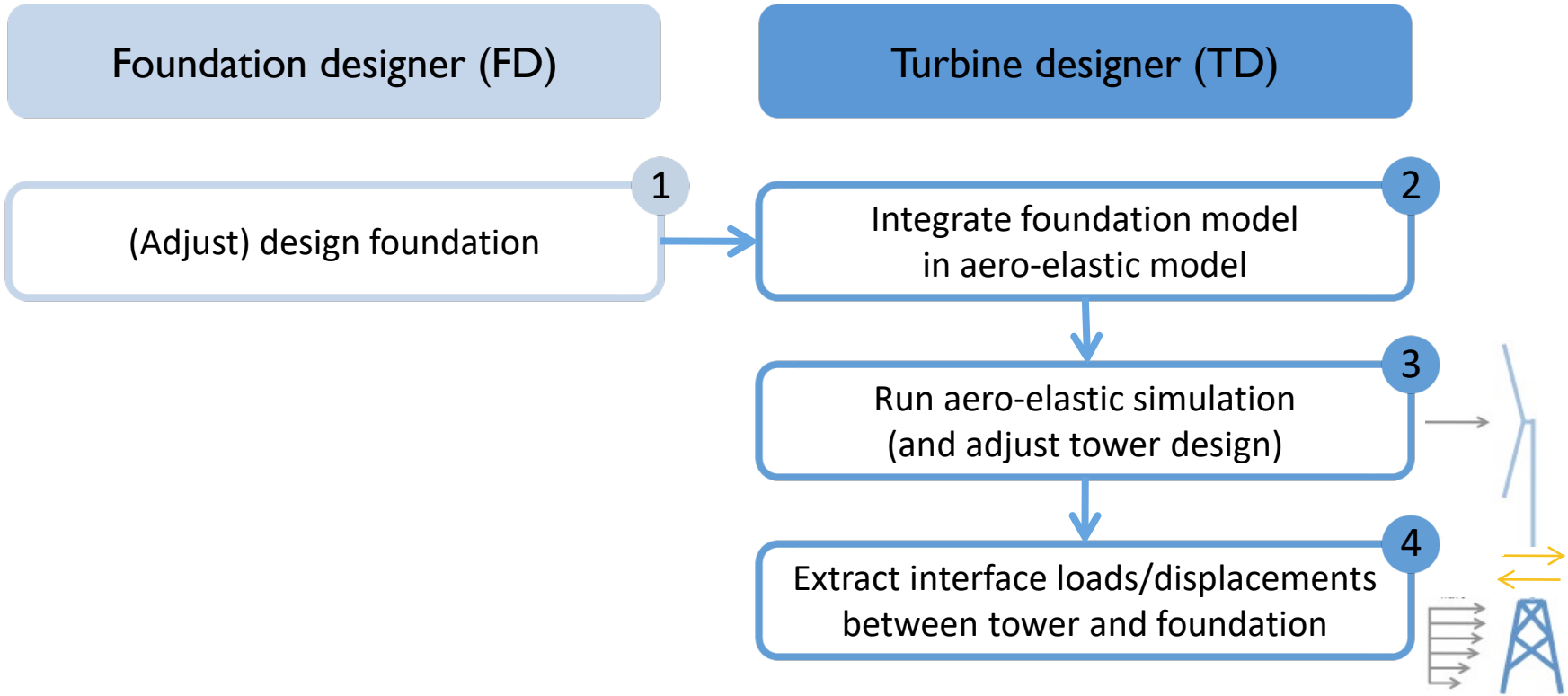

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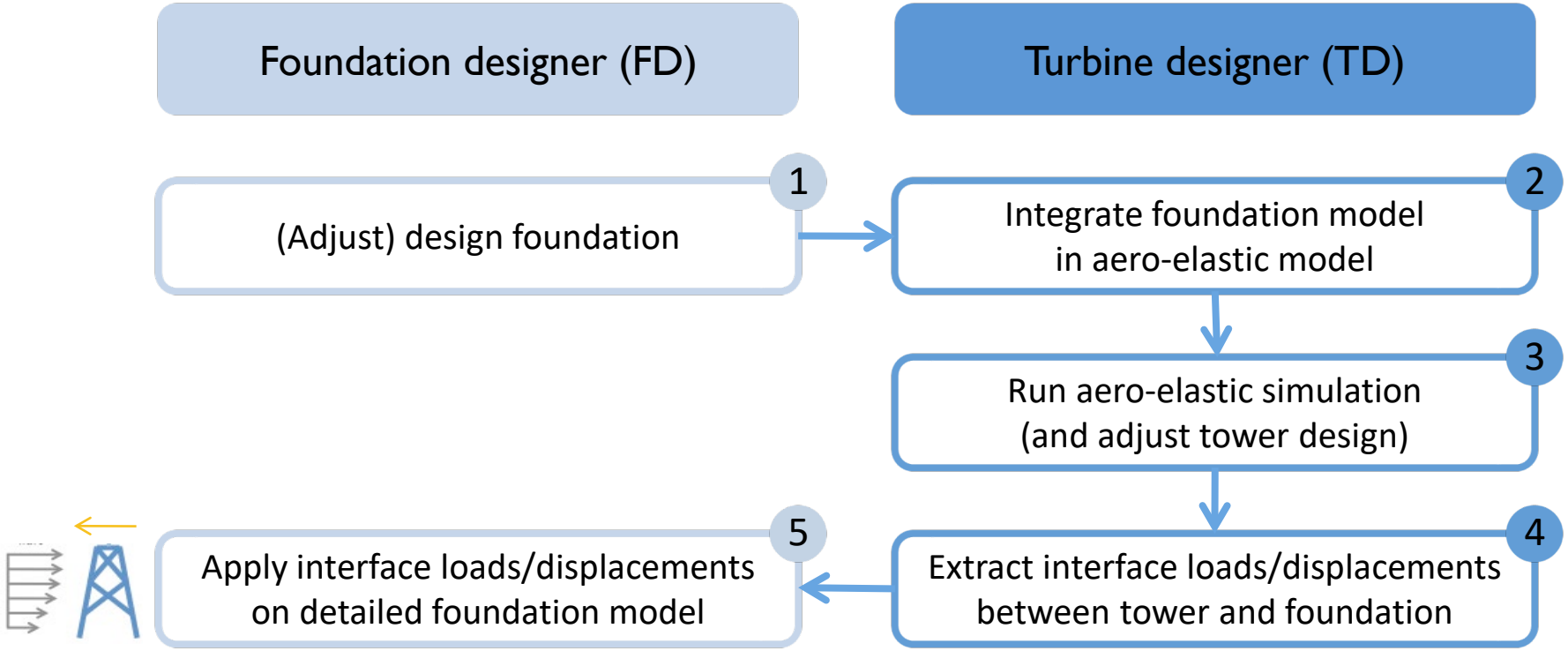

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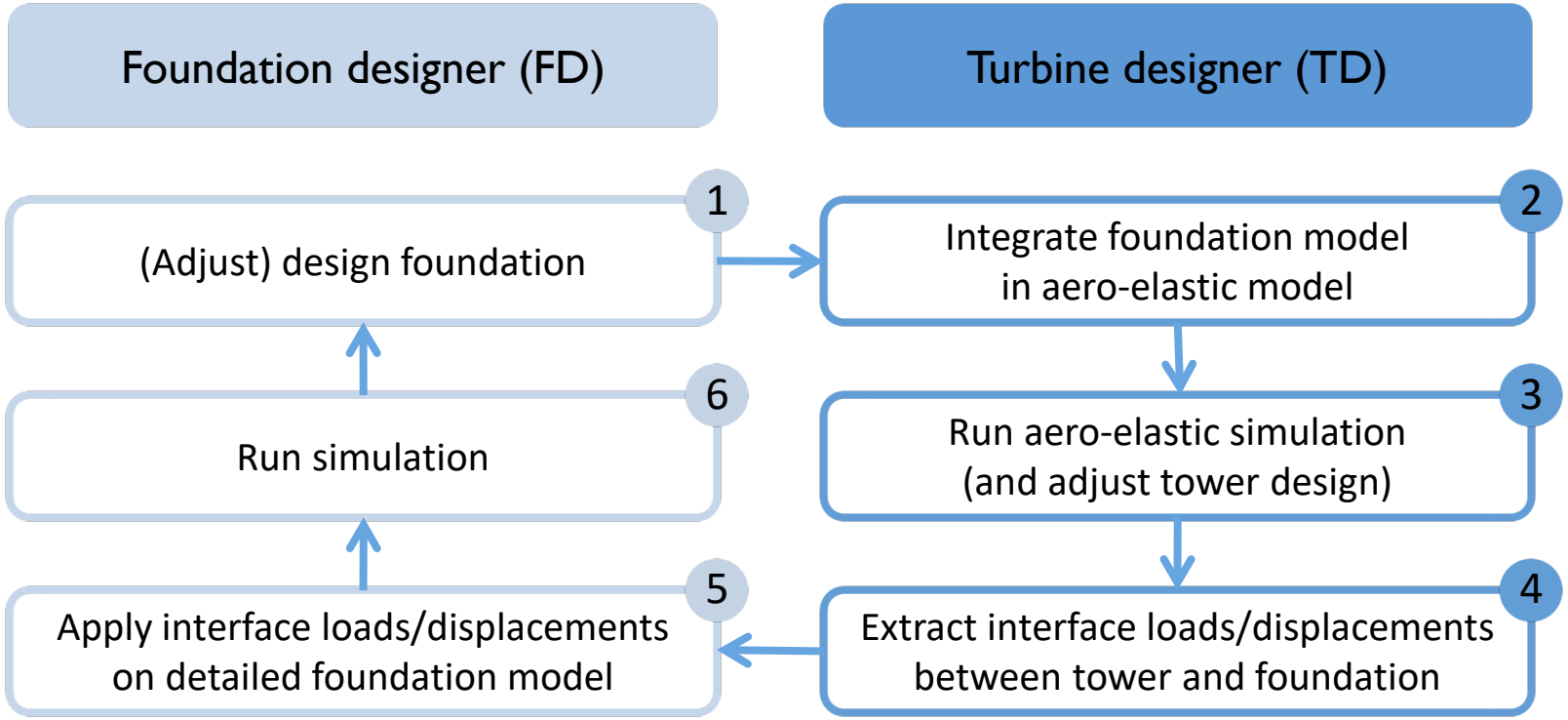

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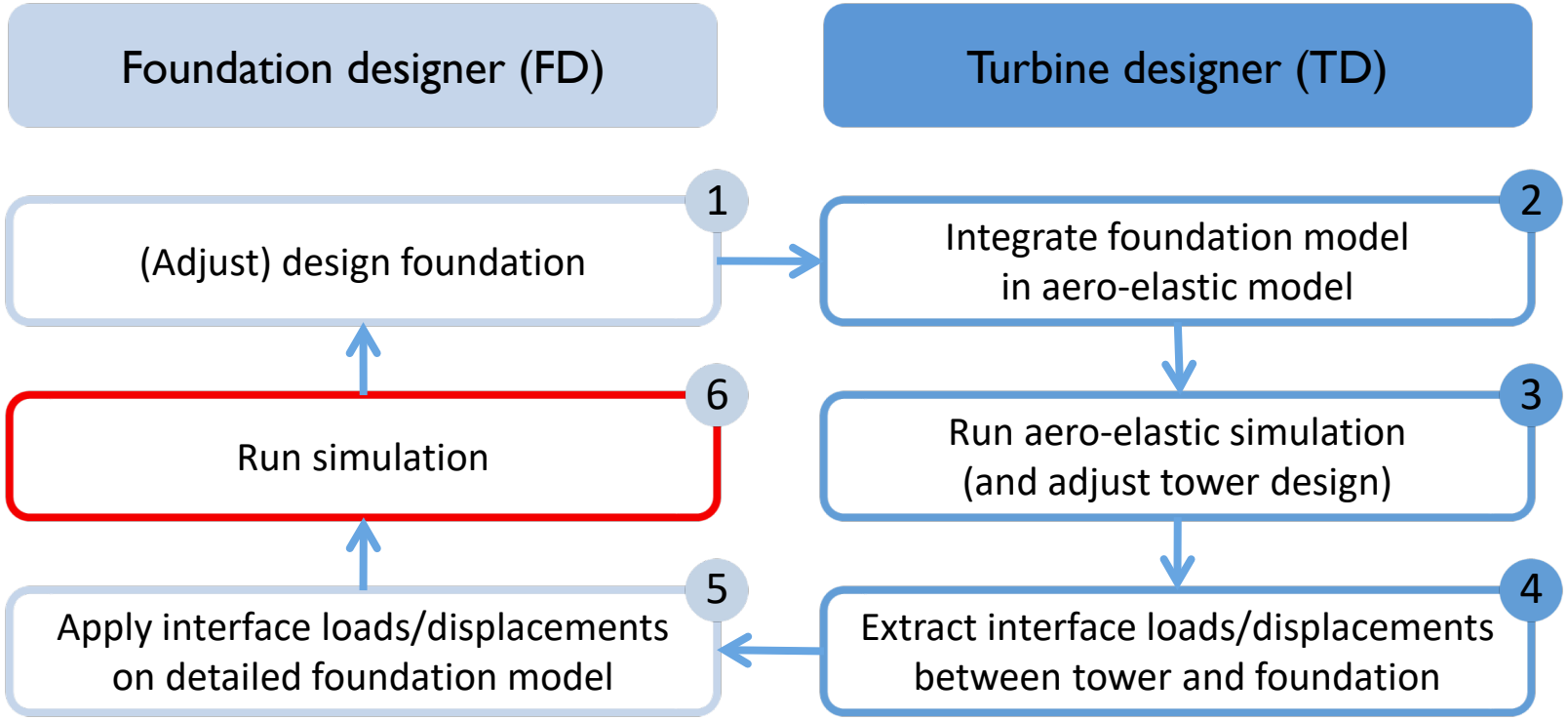
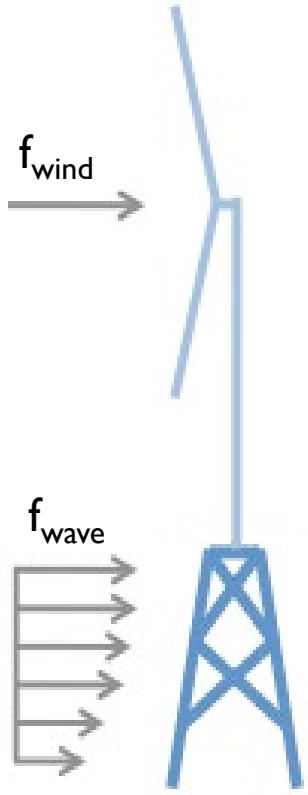
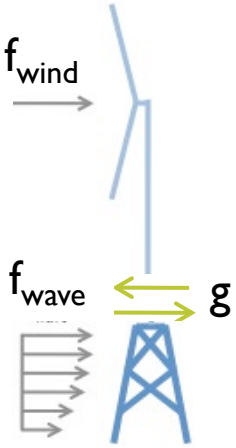


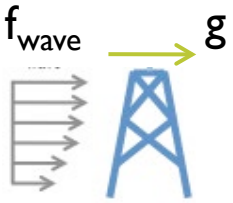
Calculation post-processing analyses

Dynamic analysis





Force controlled



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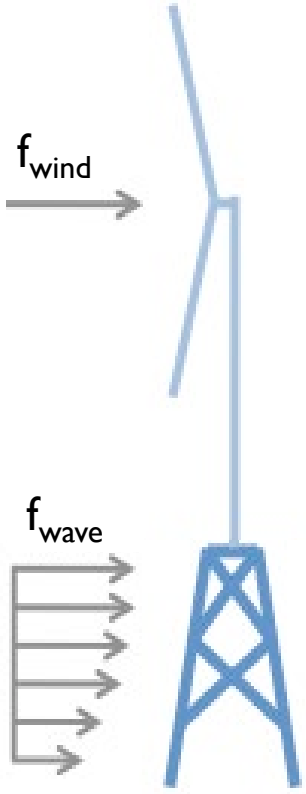
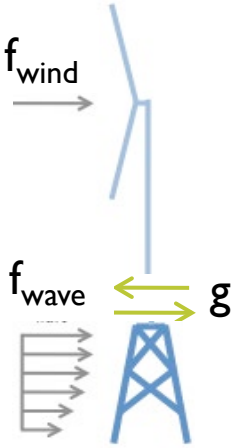
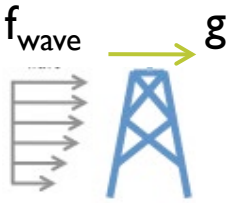




Force controlled

Dynamic or Quasi-static



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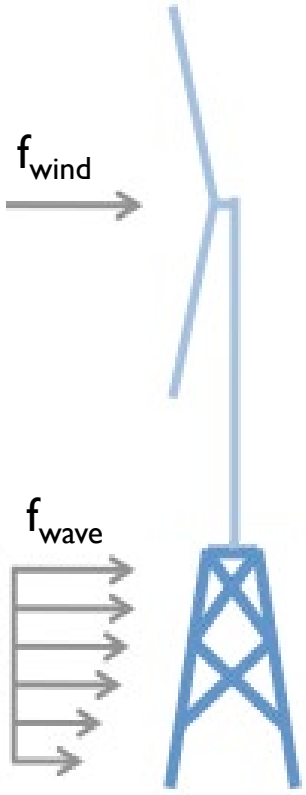

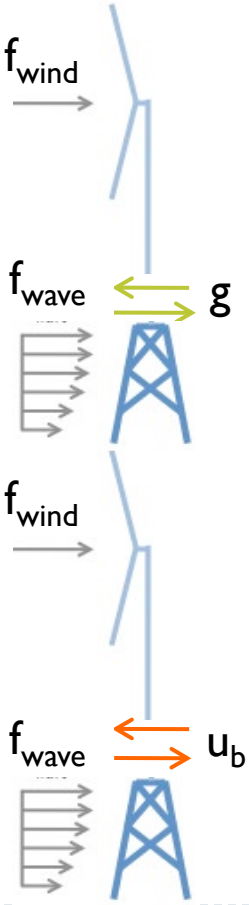

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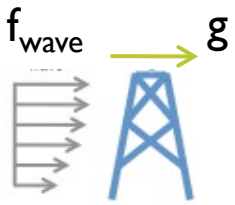
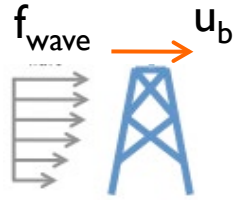


Displacement controlled



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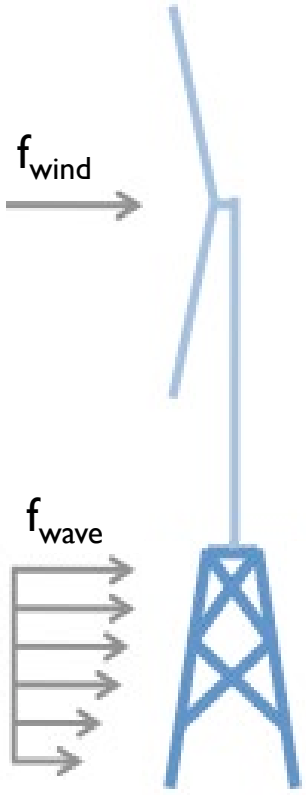

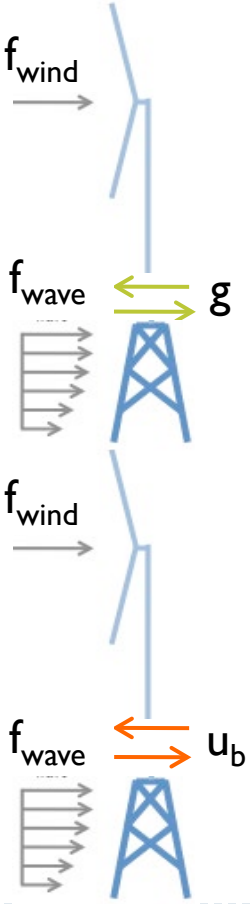

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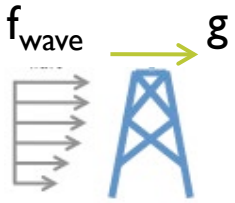

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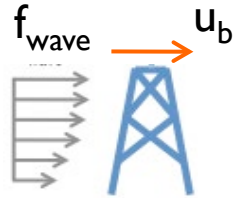

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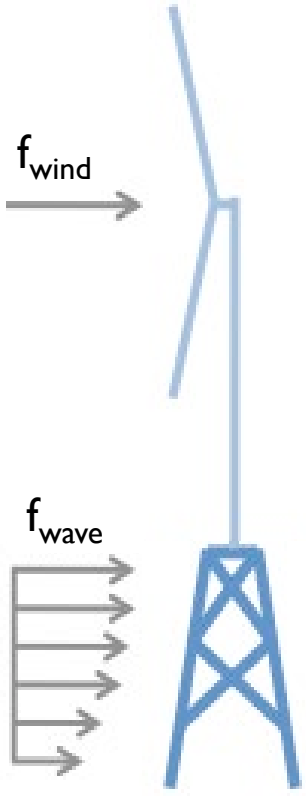

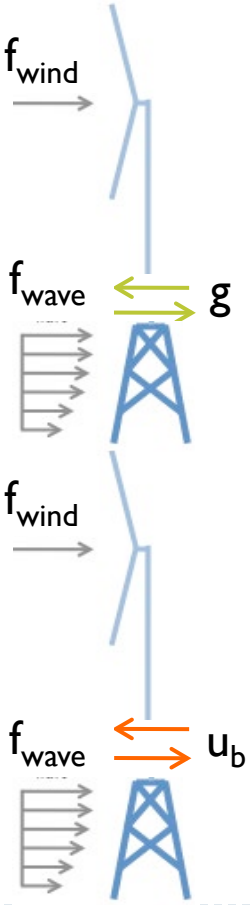

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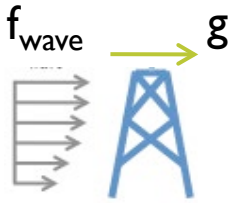

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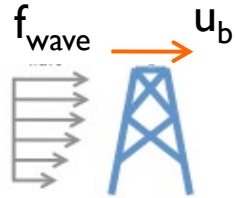
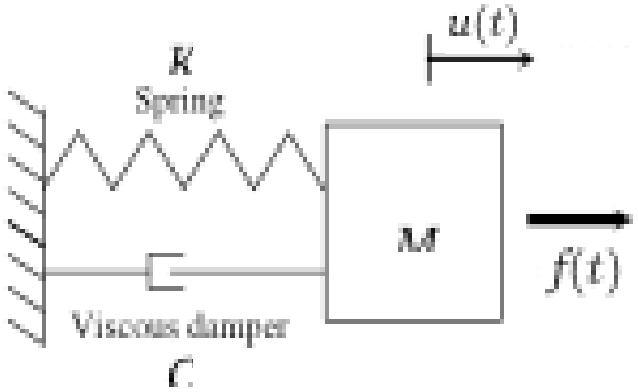


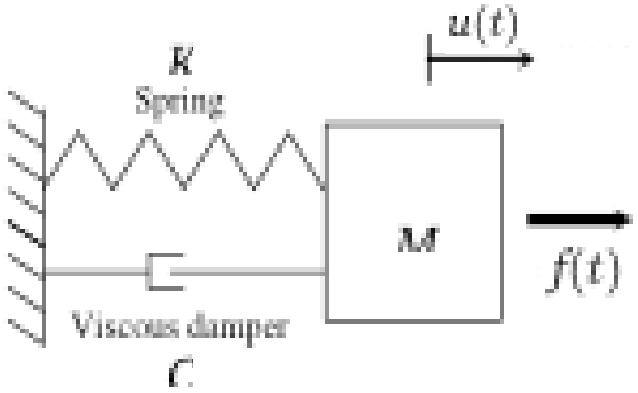
Dynamic versus quasi-static analysis



- Dynamic analysis

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = f(t)$$

Dynamic versus quasi-static analysis



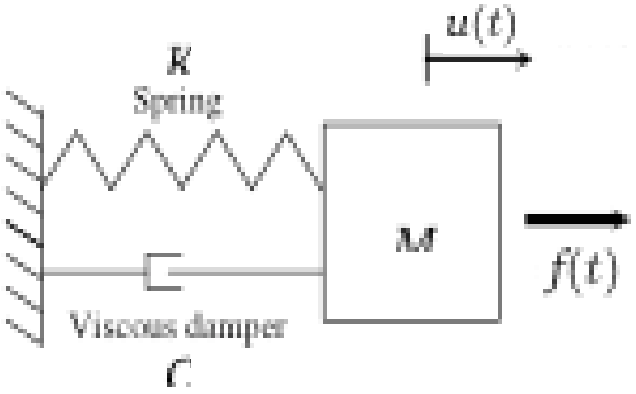
- Dynamic analysis

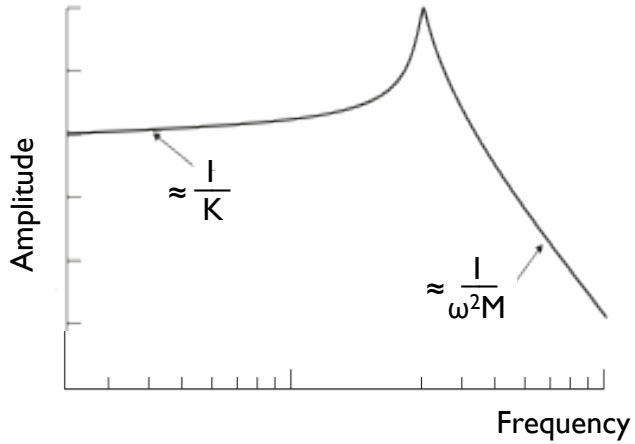
$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = f(t)$$

- Quasi-static analysis

$$Ku(t) = f(t)$$

Dynamic versus quasi-static analysis





- Dynamic analysis

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = f(t)$$

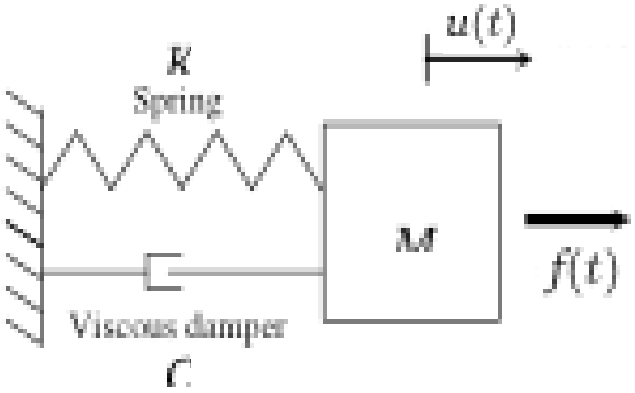
$$(-\omega^2 M + j\omega C + K)u(\omega) = f(\omega)$$

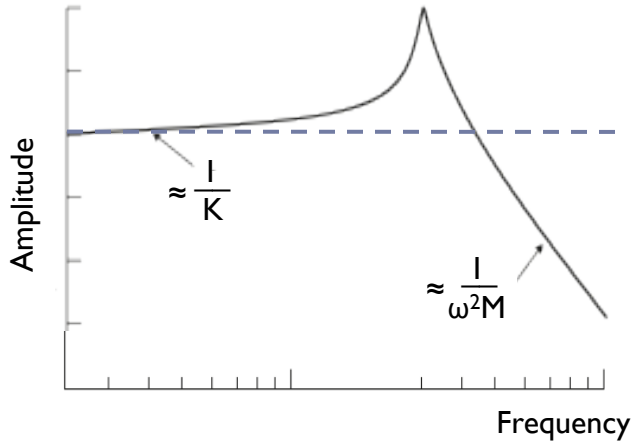
- Quasi-static analysis

$$Ku(t) = f(t)$$

$$Ku(\omega) = f(\omega)$$

Dynamic versus quasi-static analysis





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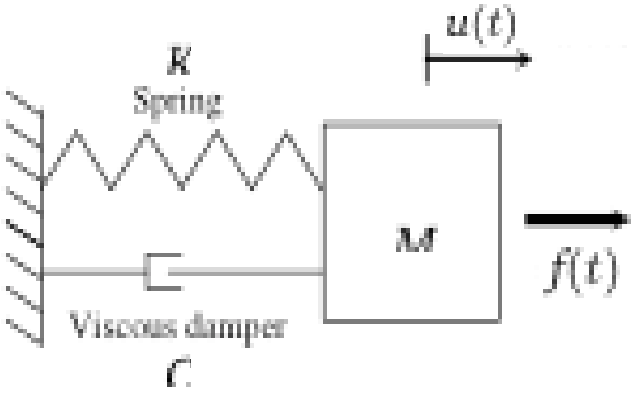

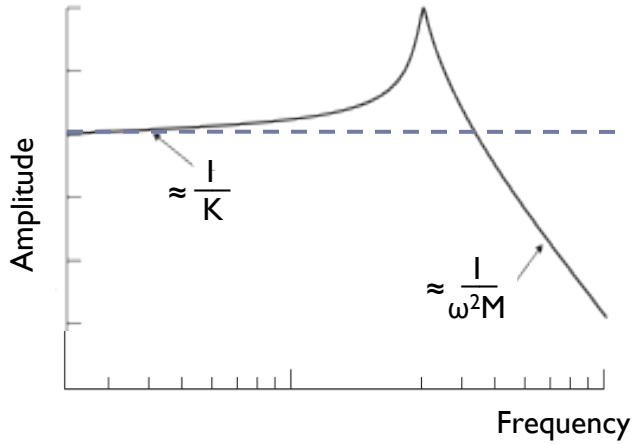

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$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = f(t)$$

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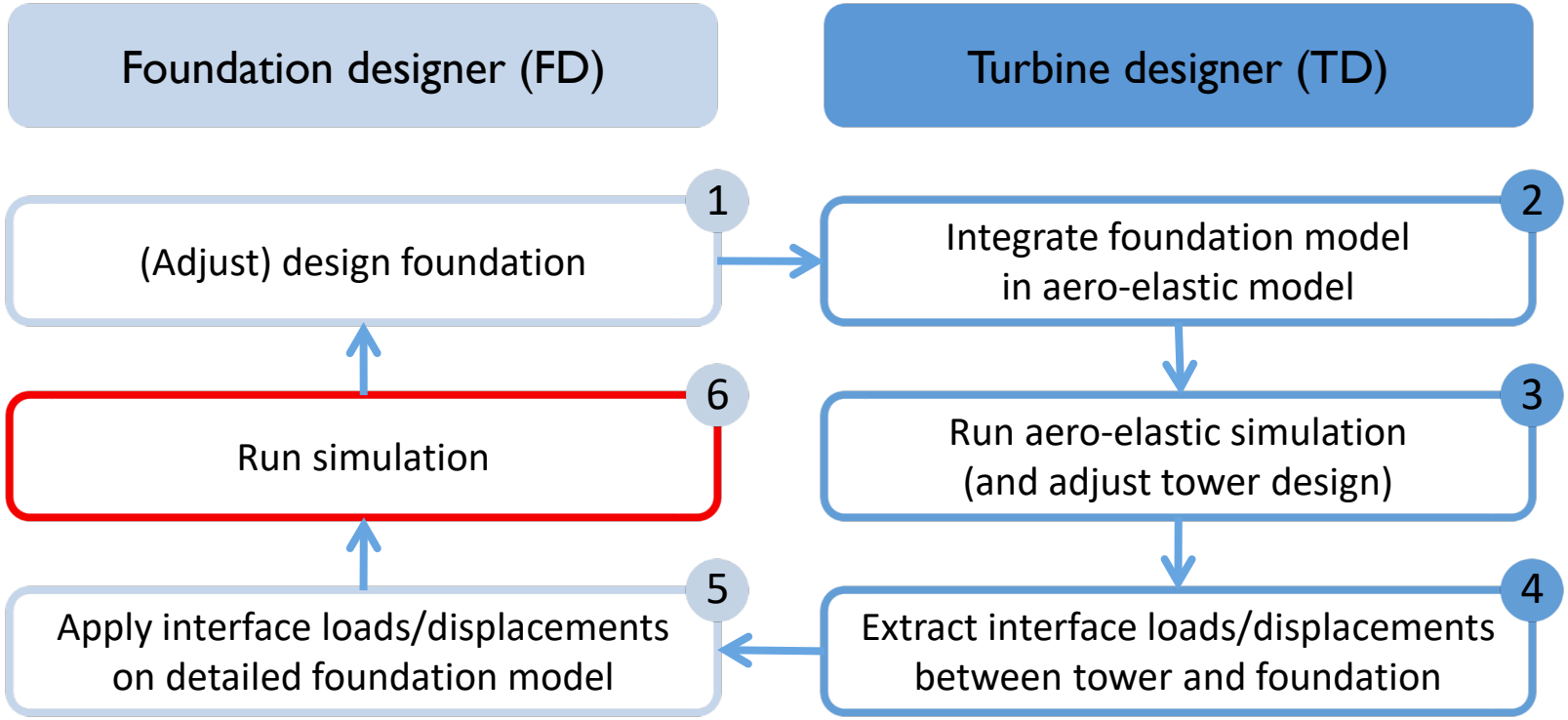
- Quasi-static analysis

$$Ku(t) = f(t)$$

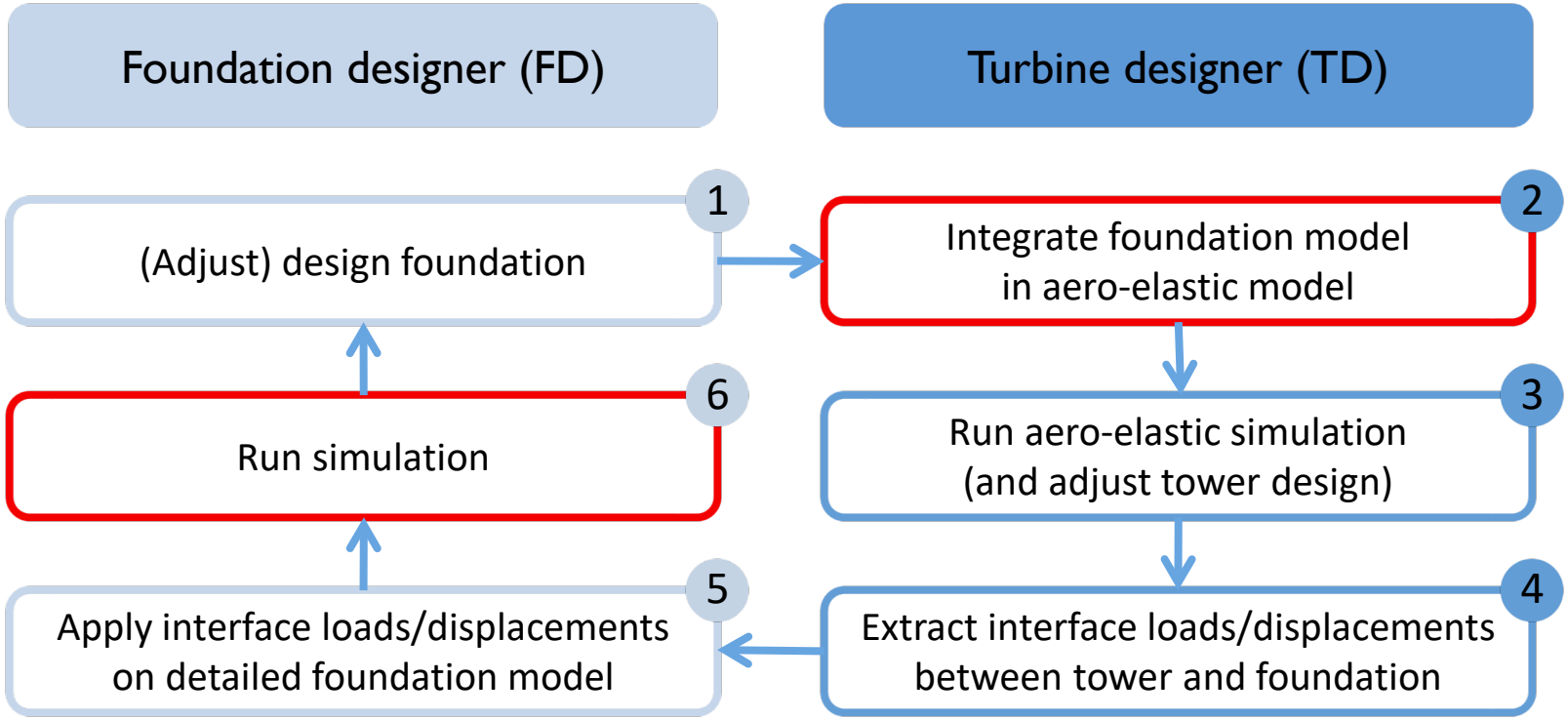
$$Ku(\omega) = f(\omega)$$

  - Only accurate if structure is excited below first eigenfrequency

Design cycle for offshore wind turbine support structure



Design cycle for offshore wind turbine support structure



Reduction of foundation to lower computation costs

$$(-\omega^2 \boldsymbol{M} + j\omega \boldsymbol{C} + \boldsymbol{K})\boldsymbol{u} = \boldsymbol{f}$$

$$\boldsymbol{u} = \boldsymbol{R}\tilde{\boldsymbol{u}}$$

- Reduce large number of DoF into smaller set of generalized DoF
  - Size(ũ) << size(u)
  - Lower computation costs
  - Approximation of exact solution

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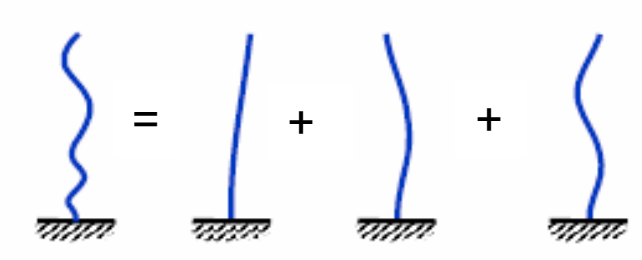

- Reduce large number of DoF into smaller set of generalized DoF
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Reduction of foundation to lower computation costs

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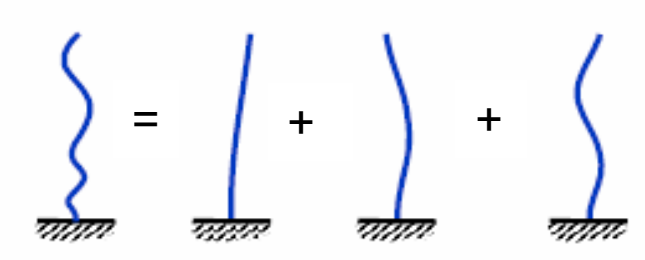
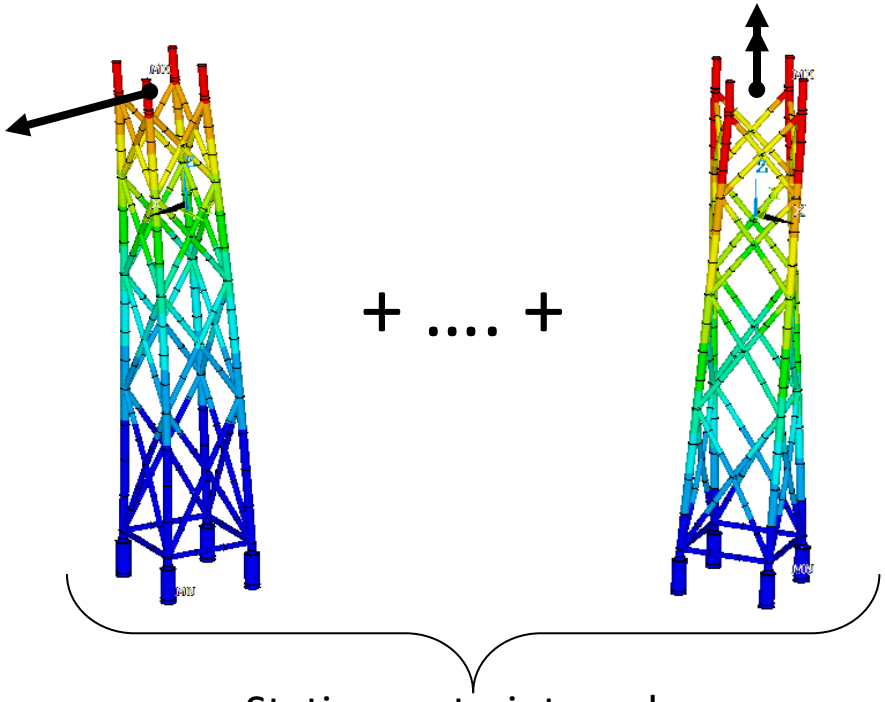


- Reduce large number of DoF into smaller set of generalized DoF
  - Size(ũ) << size(u)
  - Lower computation costs
  - Approximation of exact solution
- Reduction basis contains limited number of deformation shapes
- Only accurate if
  - Spectral convergence
  - Spatial convergence

Reduction methods

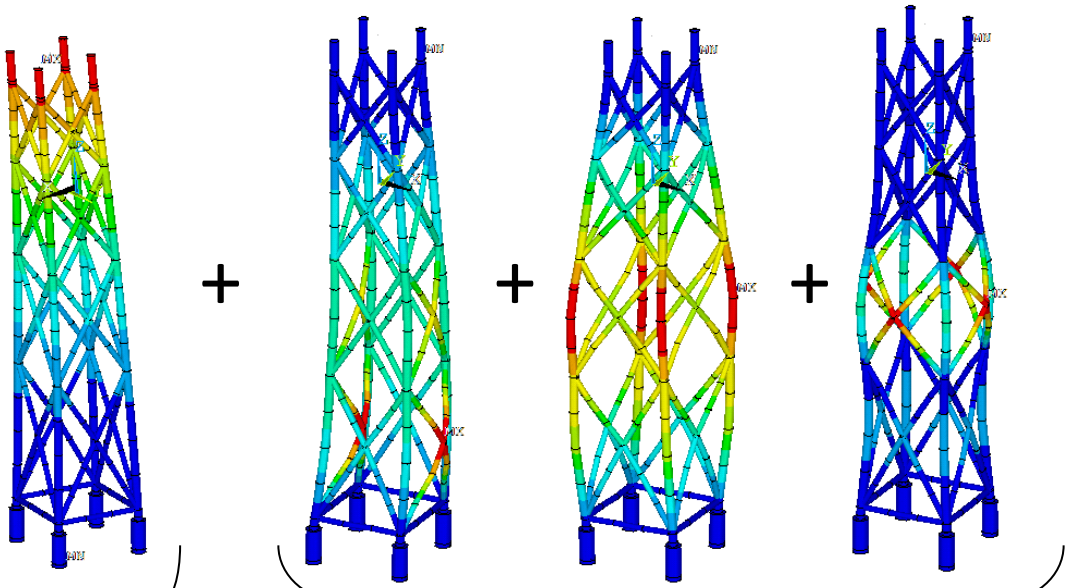
Guyan reduction

$$R =$$



Reduction methods

Craig-Bampton reduction

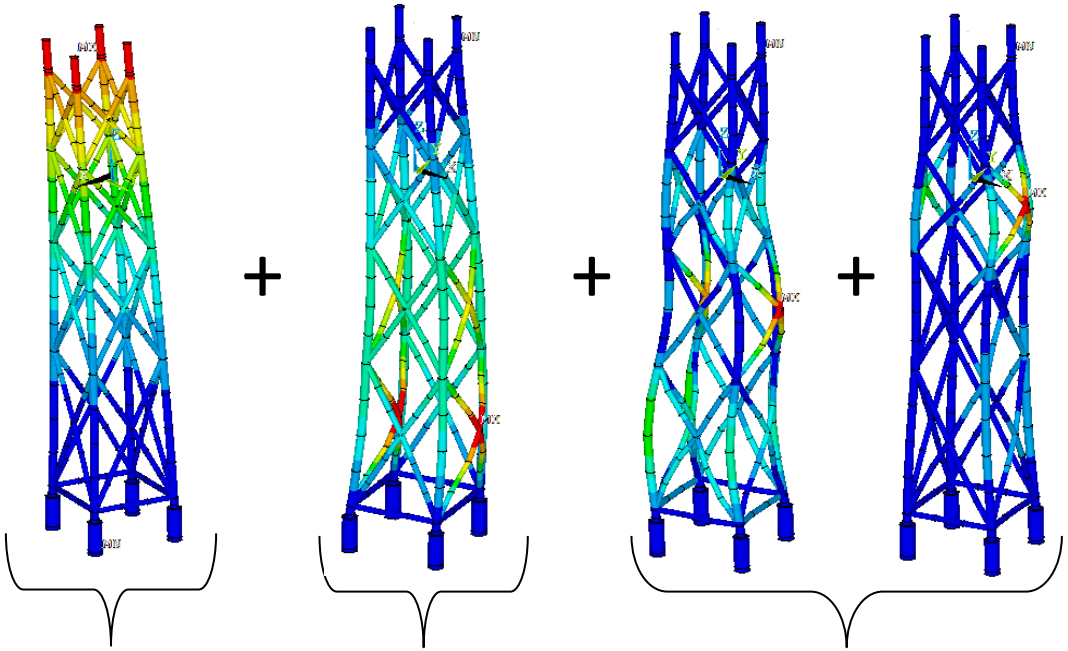
$$R =$$  + + +

Static constraint modes

Fixed interface vibration modes

Reduction methods

Augmented Craig-Bampton reduction

$$R =$$  $+$ $+$ $+$

Static constraint modes | Fixed interface vibration modes | Modal Truncation vectors

Impact on fatigue damage results

- Offshore wind turbine exposed to cyclic loading
- Fatigue is one of the main design drivers
- Impact of error in the reponse on the accuracy of the fatigue damage results

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Monopile versus Jacket

Eigenfrequency	OWT model [Hz]	Foundation ω_{free} [Hz]	Foundation ω_{fixed} [Hz]
1st	0.30	6.73	42.8

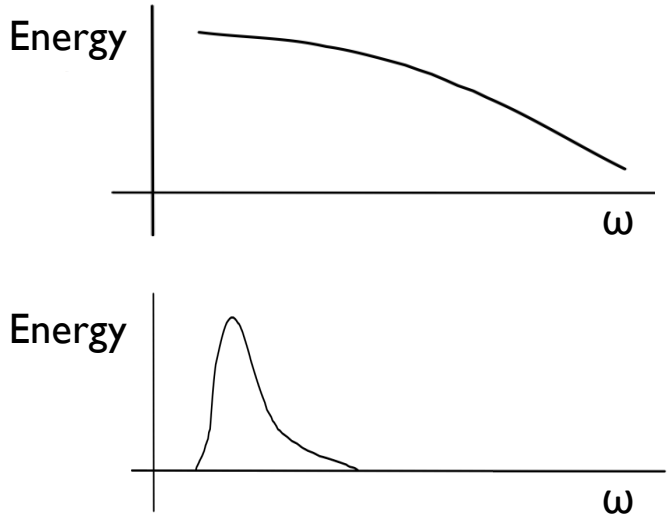
Eigenfrequency	OWT model [Hz]	Foundation ω_{free} [Hz]	Foundation ω_{fixed} [Hz]
1st	0.27	1.06	4.09

Wind, wave and operational loads

- Wind loads
  - Random load, wide frequency spectrum
  - Excite frequencies up to 7 Hz

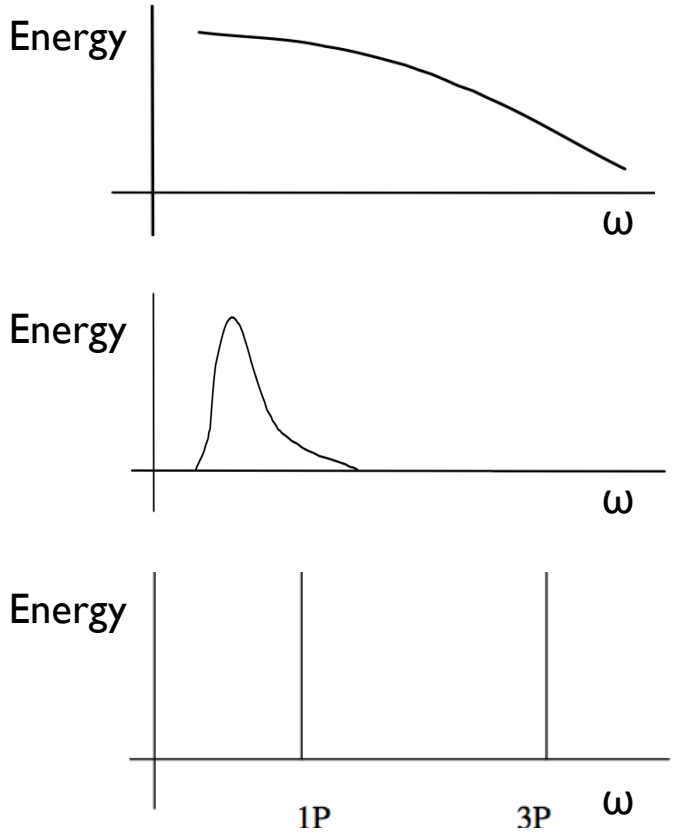
Wind, wave and operational loads

- Wind loads
  - Random load, wide frequency spectrum
  - Excite frequencies up to 7 Hz
- Wave loads
  - Wave frequencies are generally lower
  - Excite frequencies up to 0.5 Hz



Wind, wave and operational loads

- Wind loads
  - Random load, wide frequency spectrum
  - Excite frequencies up to 7 Hz
- Wave loads
  - Wave frequencies are generally lower
  - Excite frequencies up to 0.5 Hz
- Operational loads
  - Rotation frequency of the rotor (1P)
  - Blade passing frequency (3P)



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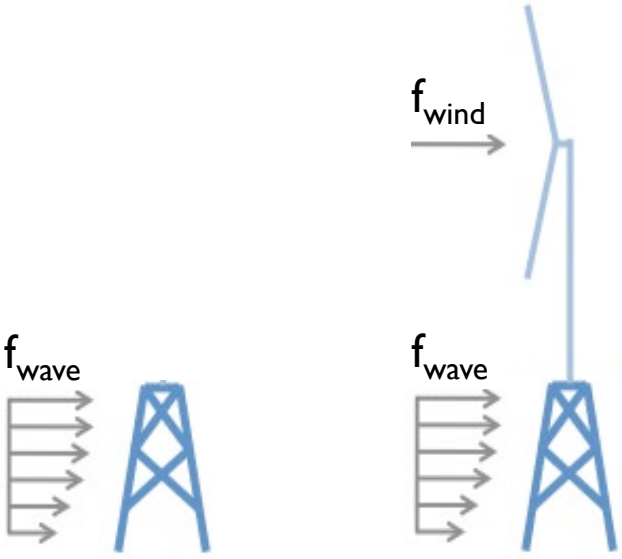
Quasi-static post-processing analyses

Dynamic analysis



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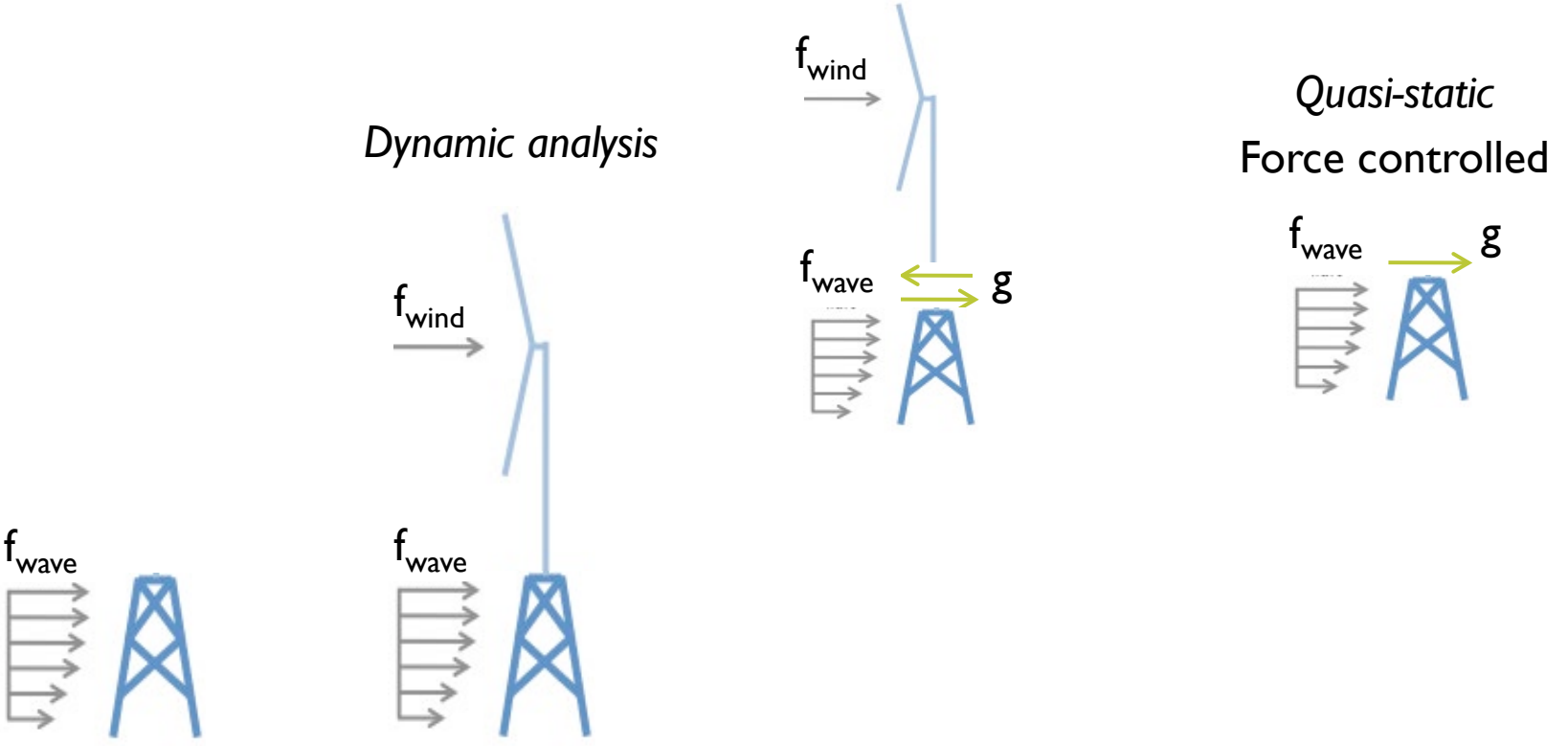

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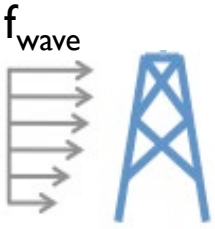
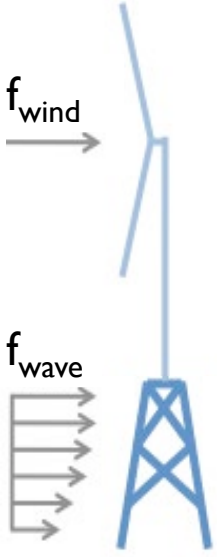
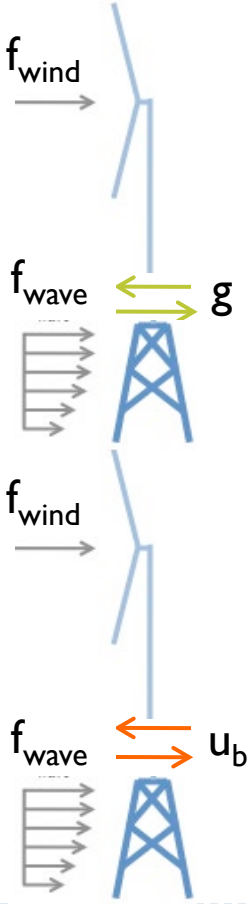


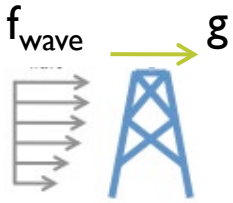
Dynamic analysis





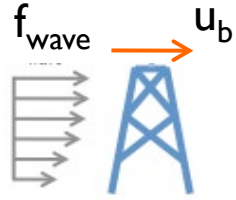
Quasi-static

Force controlled

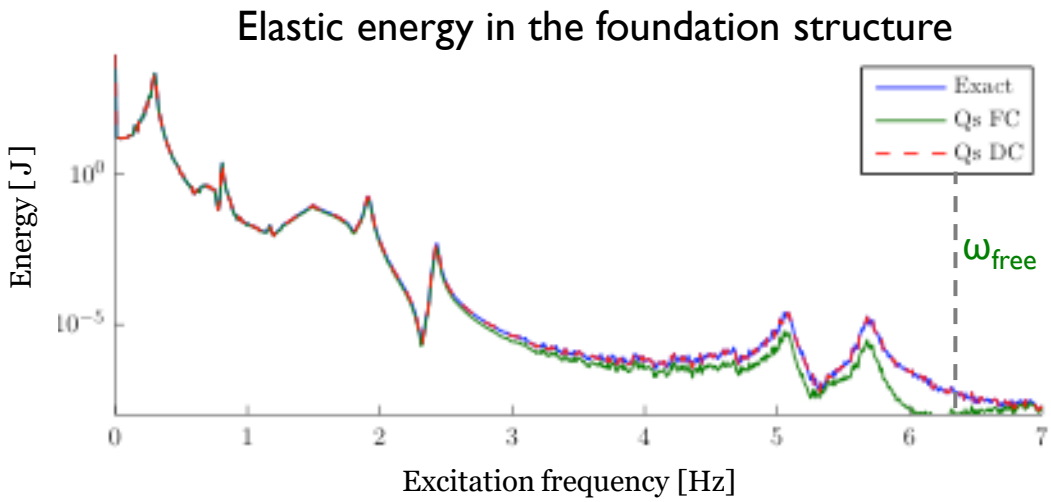


Quasi-static

Displacement controlled



Accuracy of quasi-static post-processing



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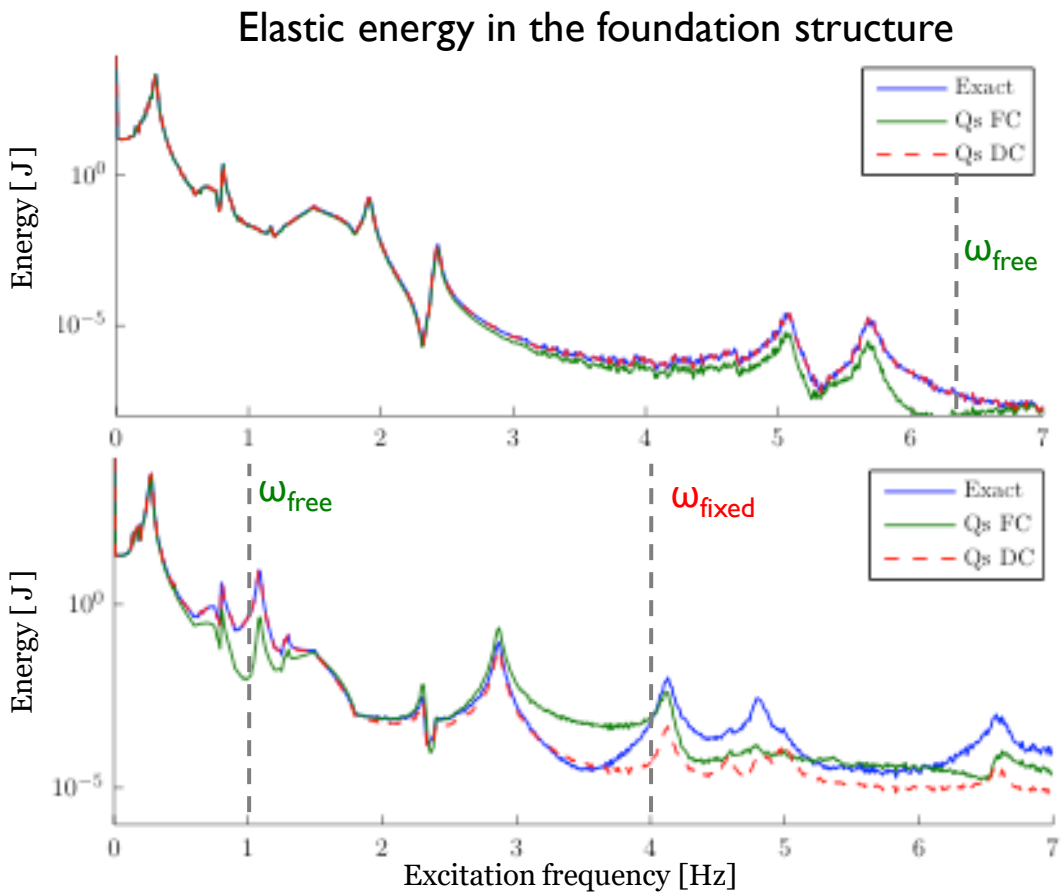
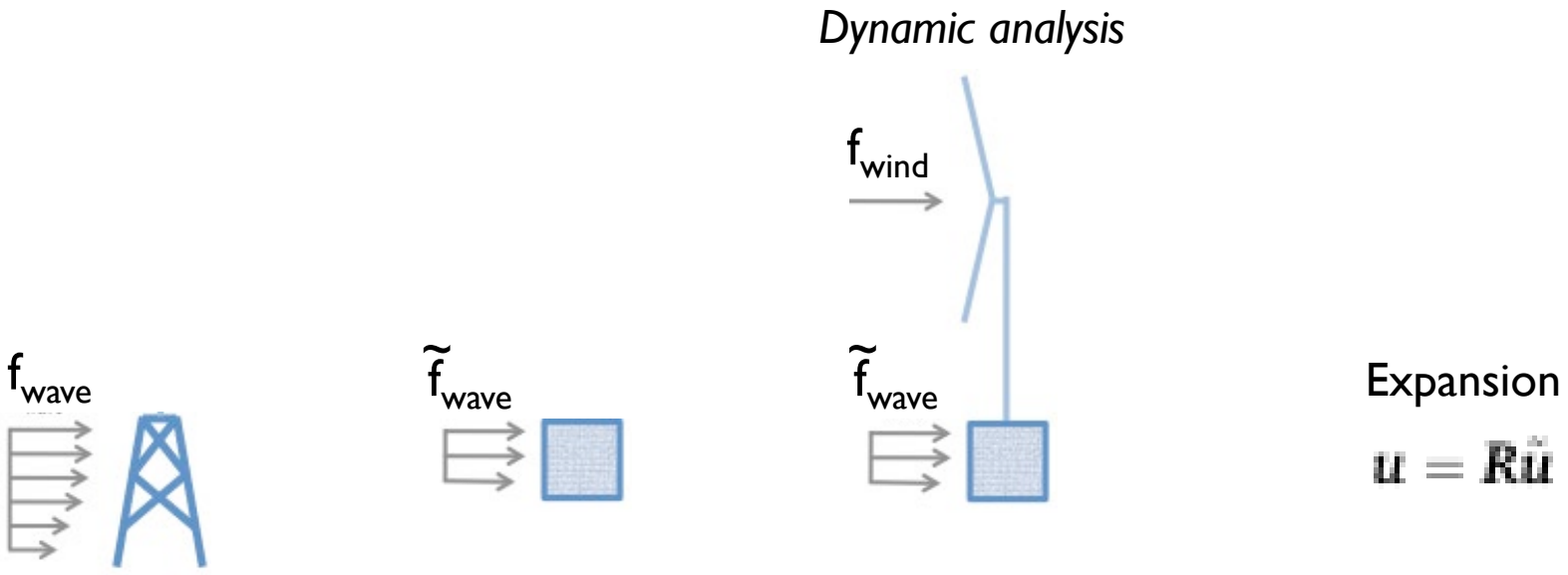
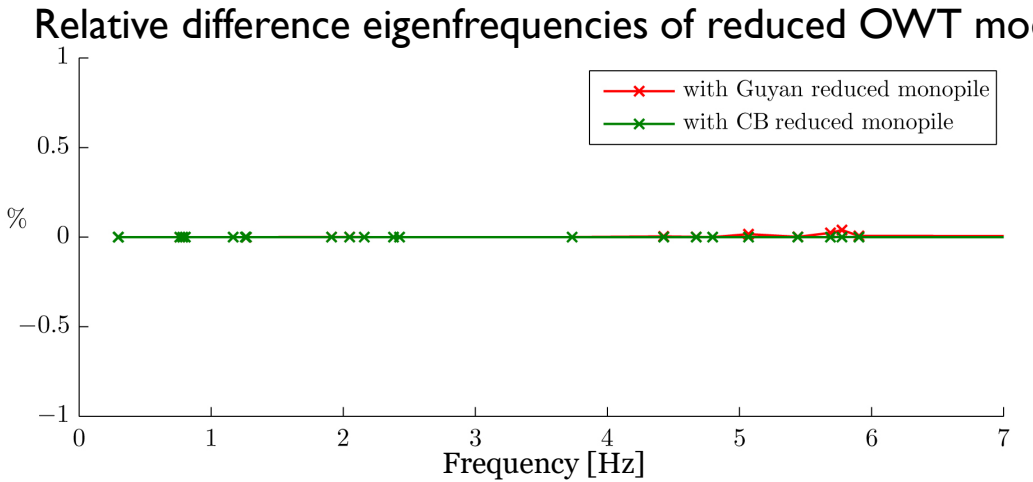


Expansion of reduced response

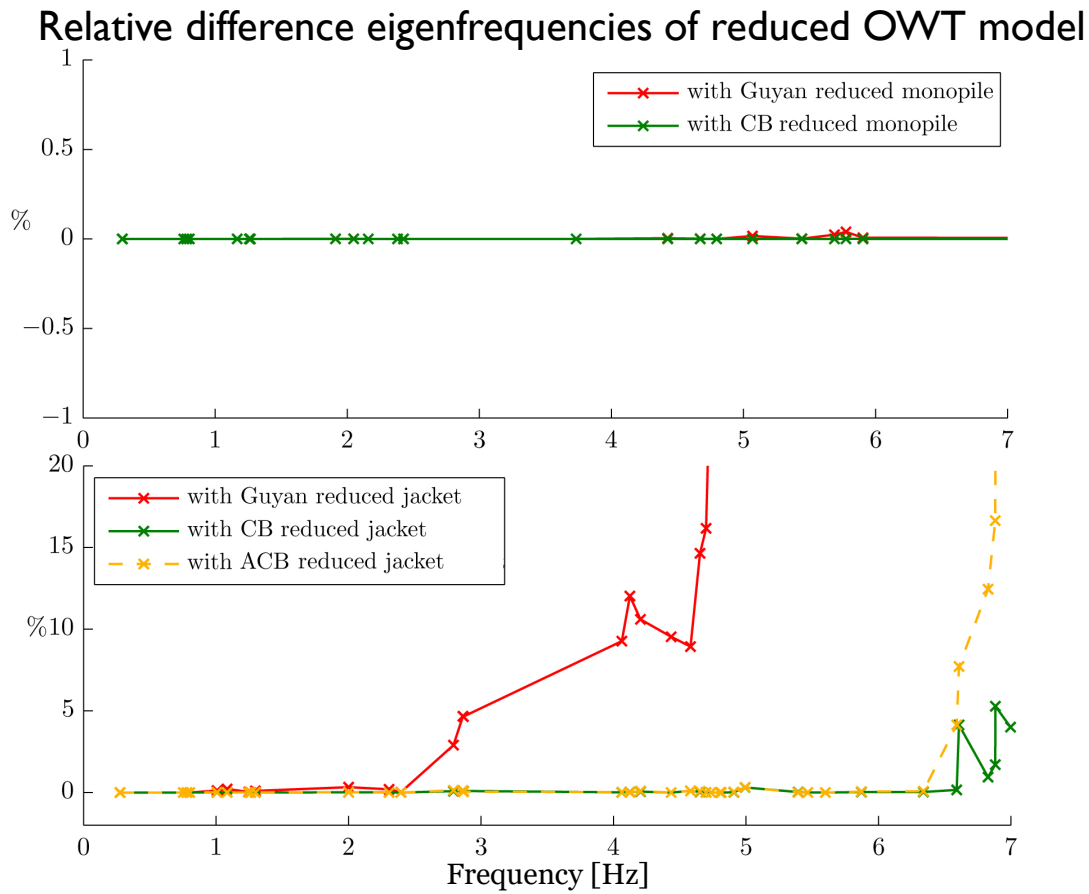


- Response detailed foundation model obtained by expanding the reduced response of the foundation
- Only accurate if model converges spectrally and spatially

Spectral convergence

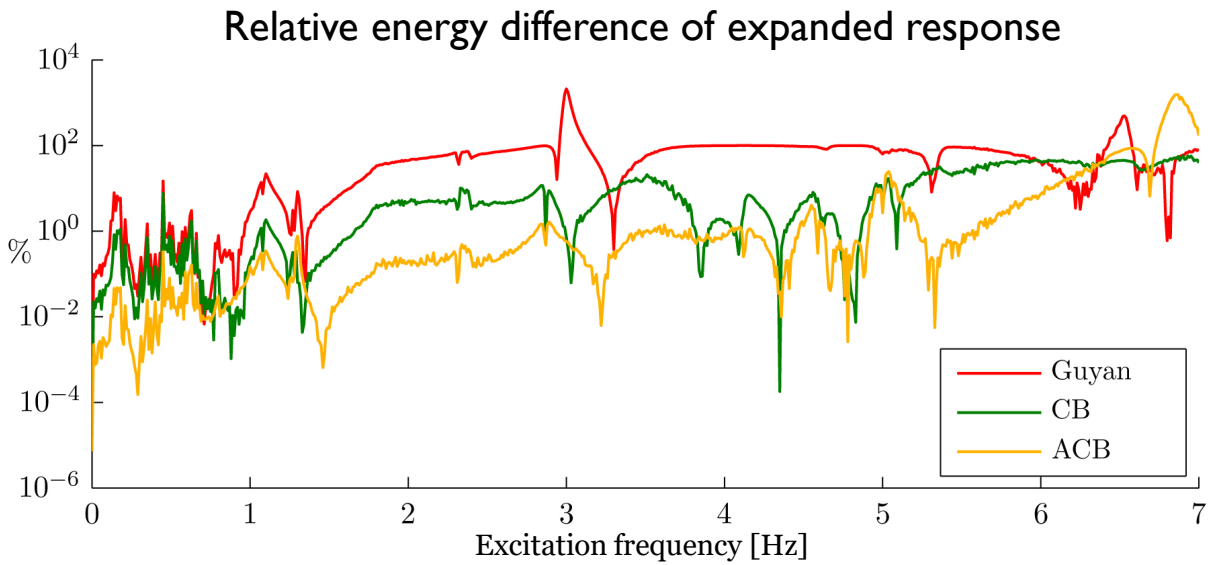


Spectral convergence



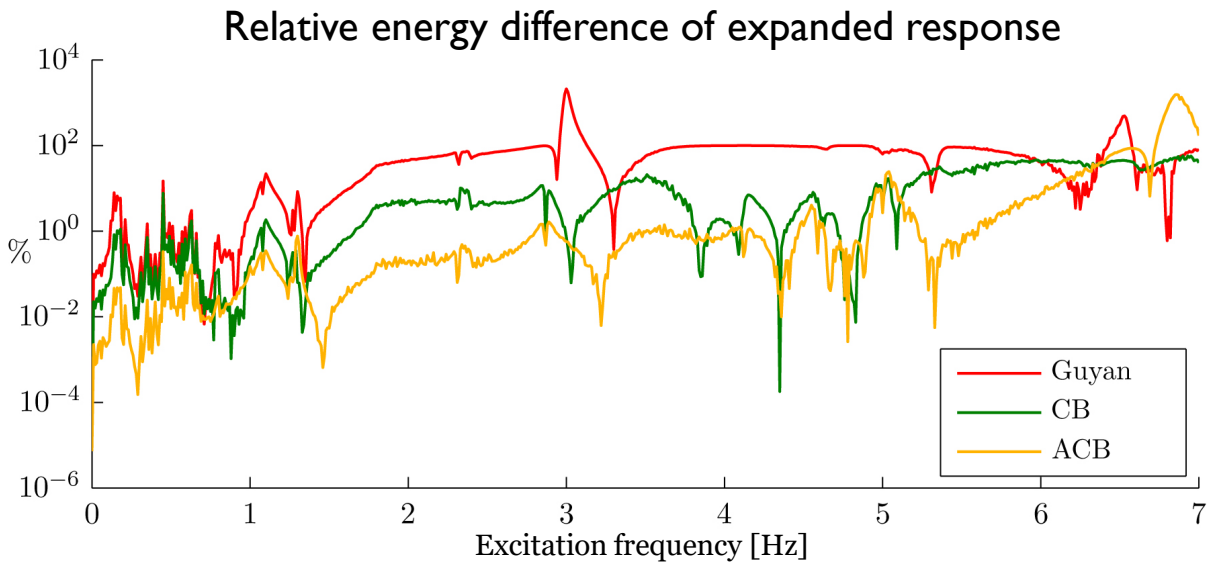
Expansion of reduced response

$$u = R\tilde{u}$$



Expansion of reduced response

$$\boldsymbol{u} = \boldsymbol{R}\tilde{\boldsymbol{u}}$$



$$(-\omega^2\boldsymbol{M} + j\omega\boldsymbol{C} + \boldsymbol{K})\boldsymbol{R}\tilde{\boldsymbol{u}} = \boldsymbol{f} + \boldsymbol{r}$$

Residual correction

$$\boldsymbol{u} = \boldsymbol{R}\tilde{\boldsymbol{u}} - \boldsymbol{K}^{-1}\boldsymbol{r}$$

Expansion of reduced response

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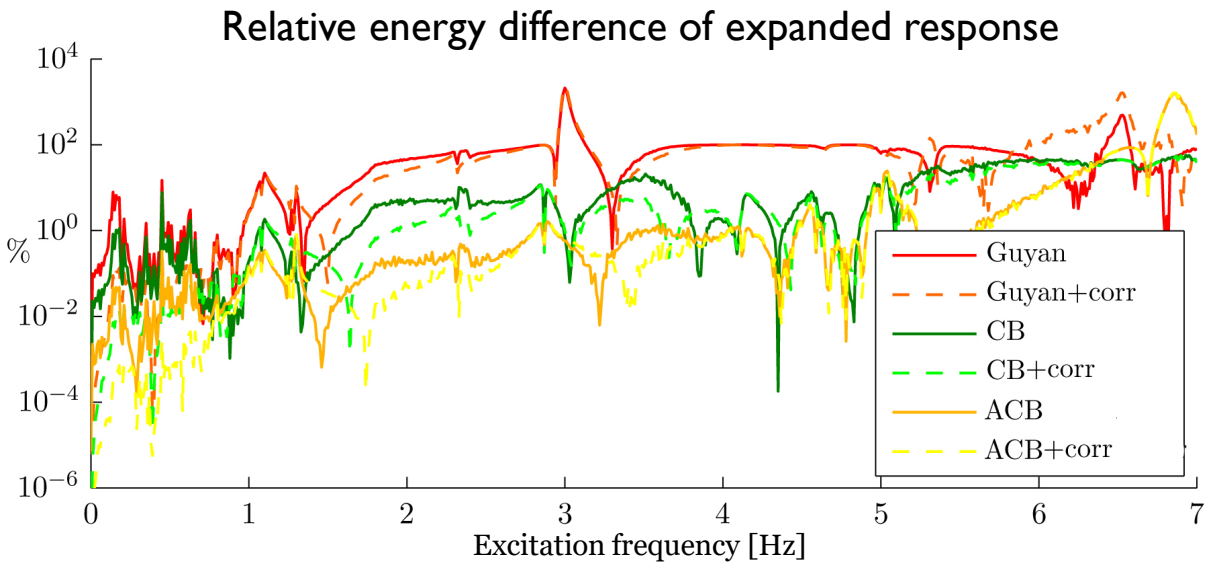

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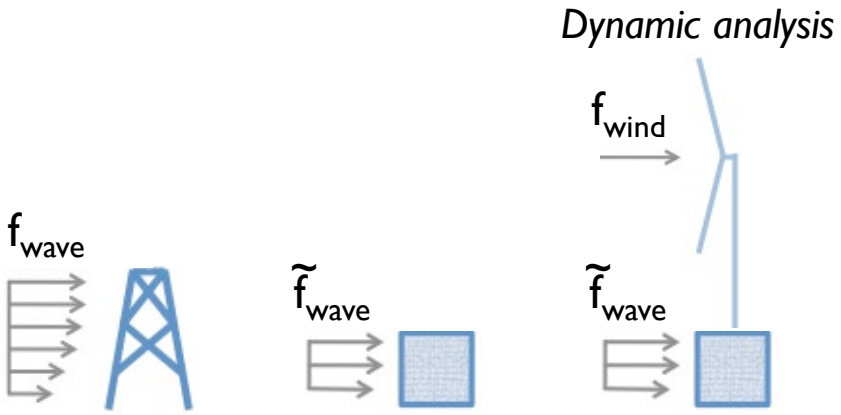
Post-processing analysis with reduced foundation in complete OWT model



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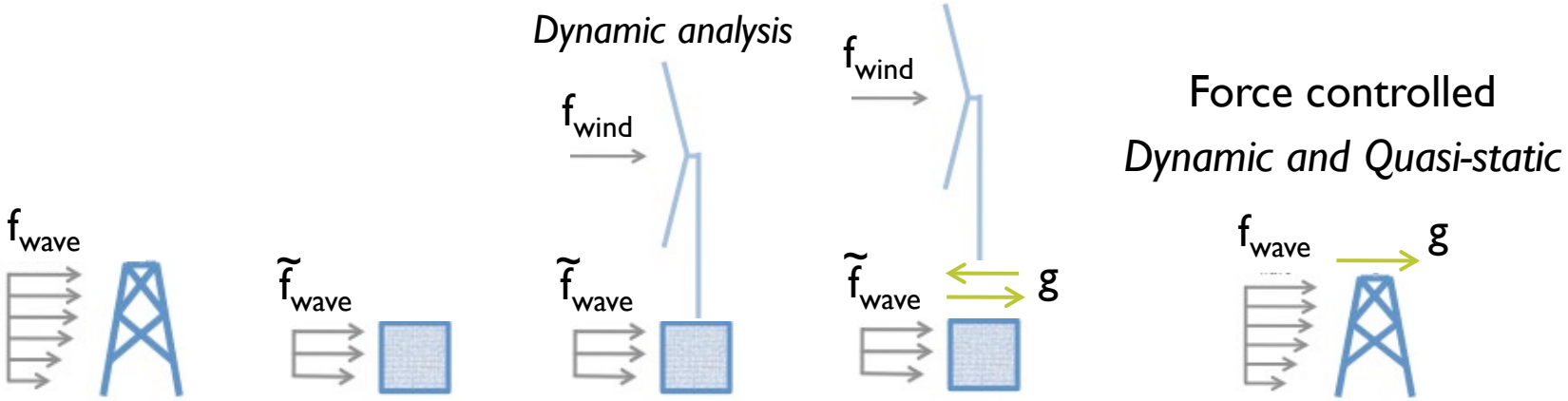

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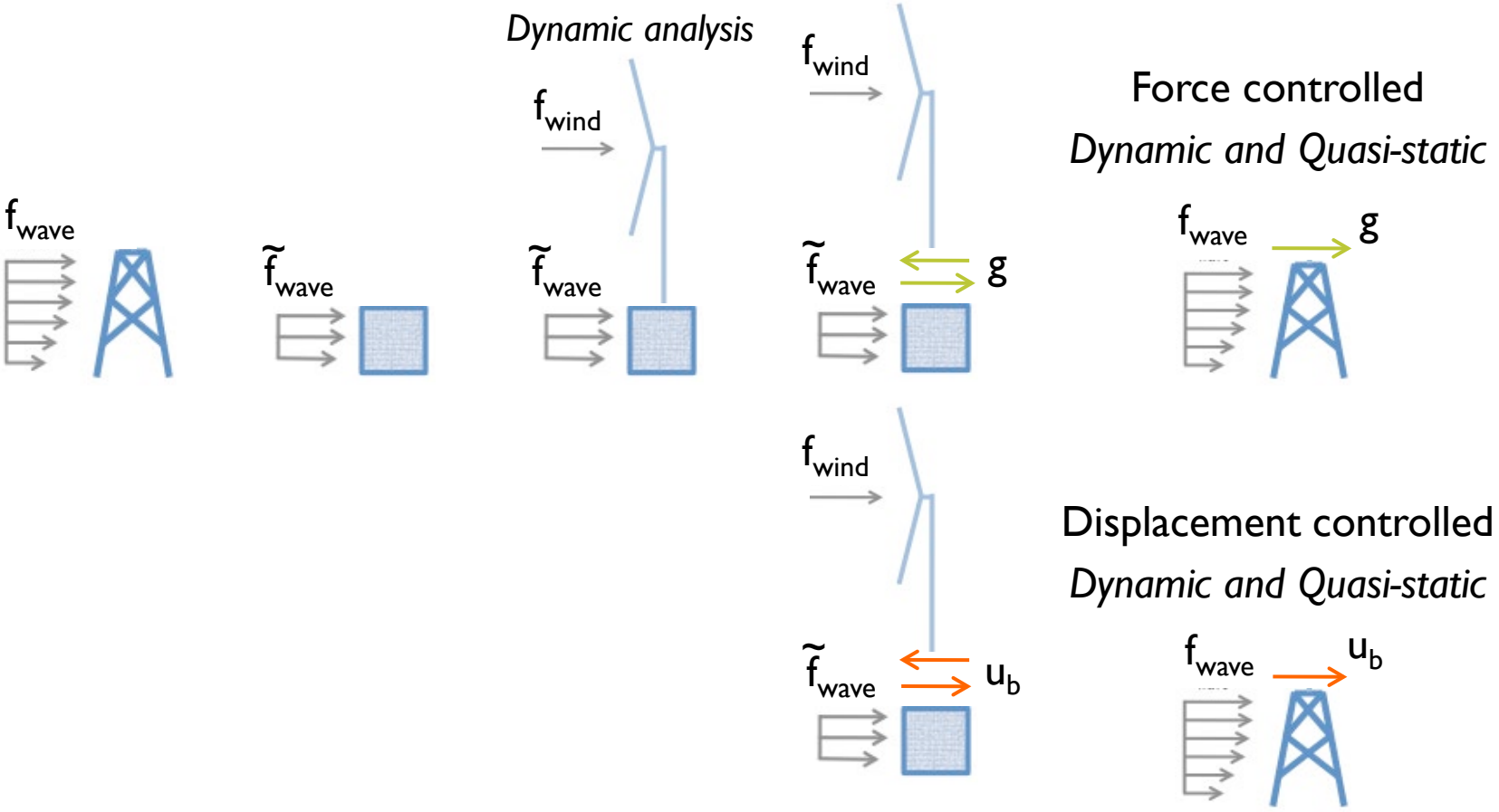

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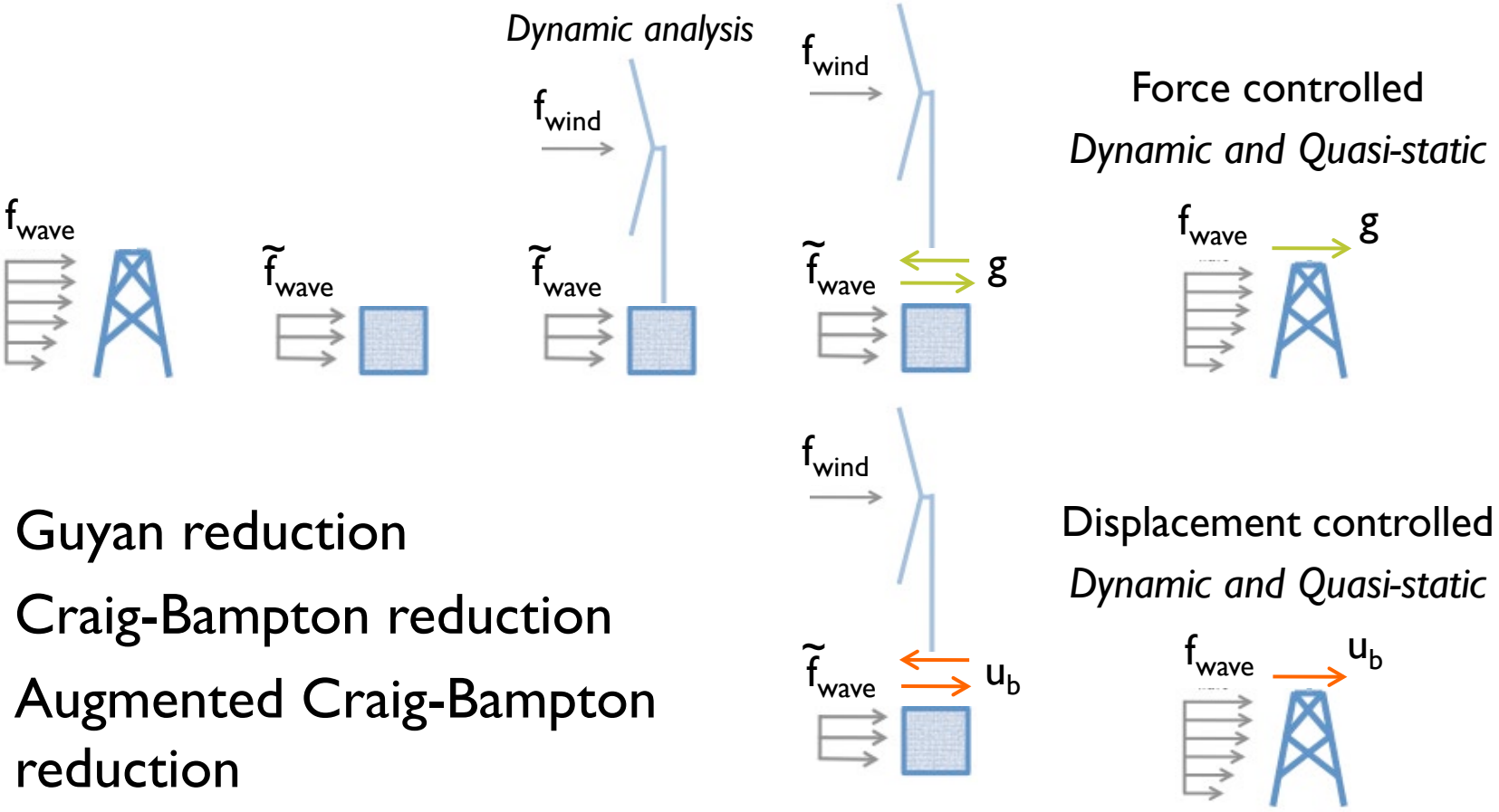
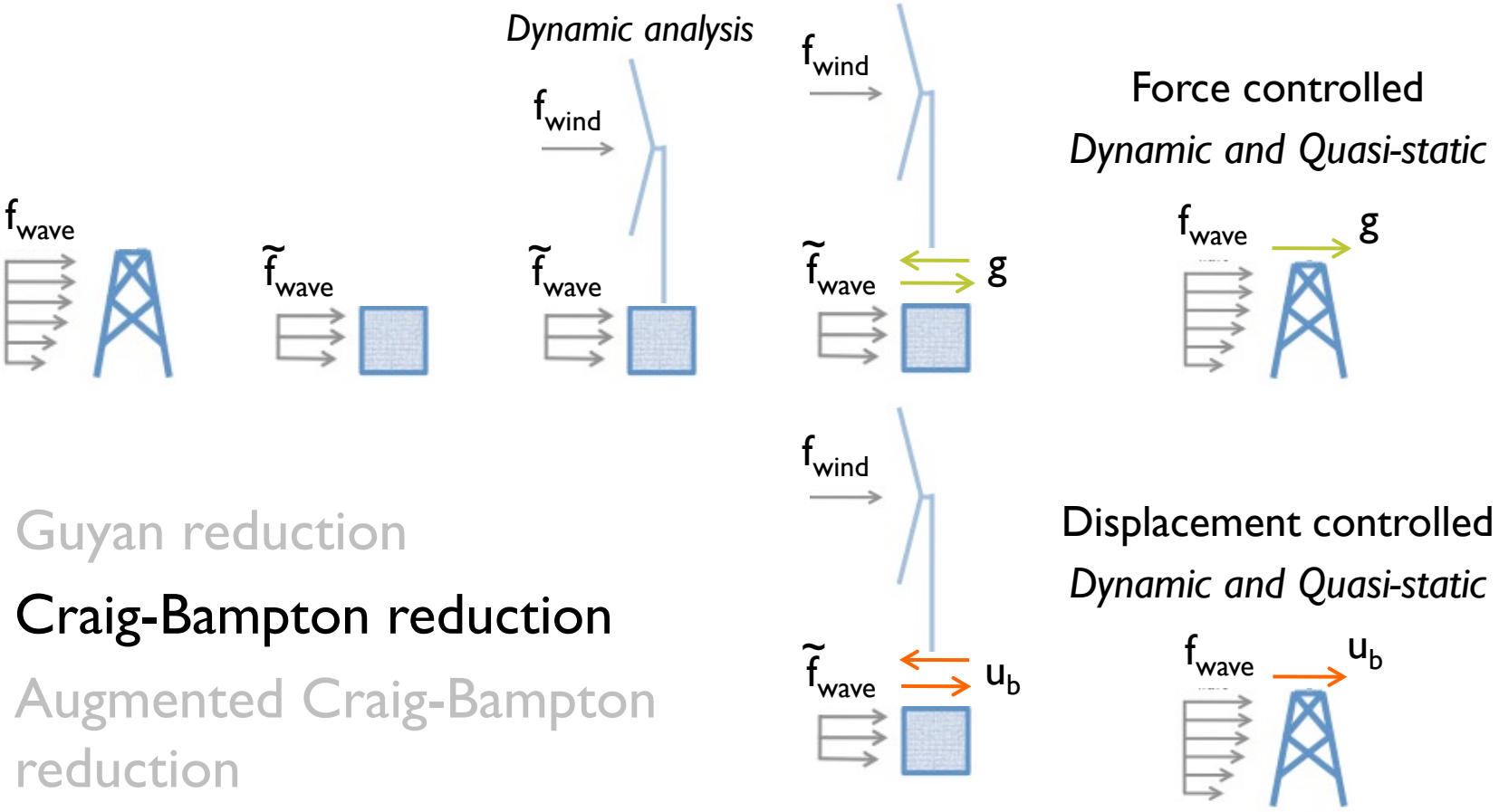


- Guyan reduction
- Craig-Bampton reduction
- Augmented Craig-Bampton reduction

Post-processing analysis with reduced foundation in complete OWT model



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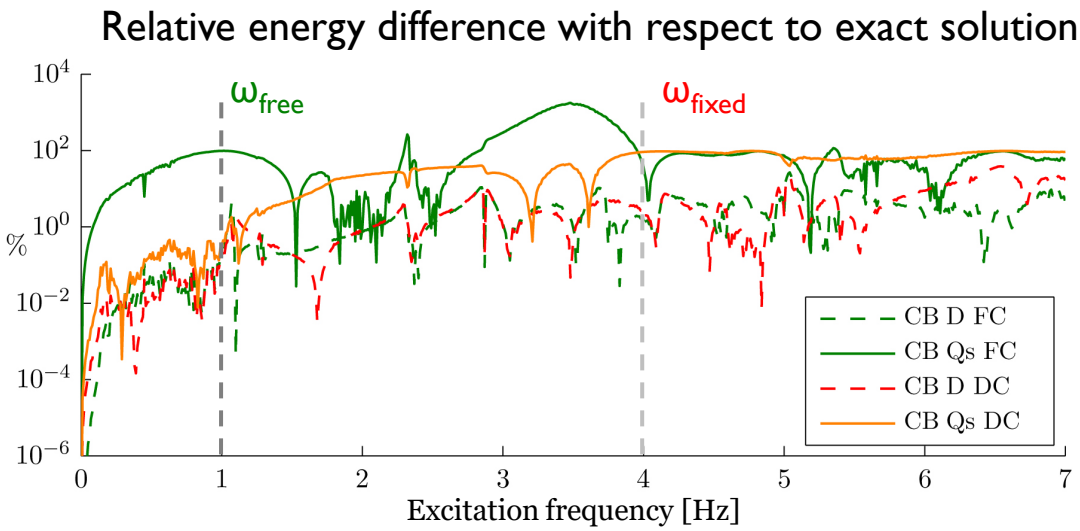
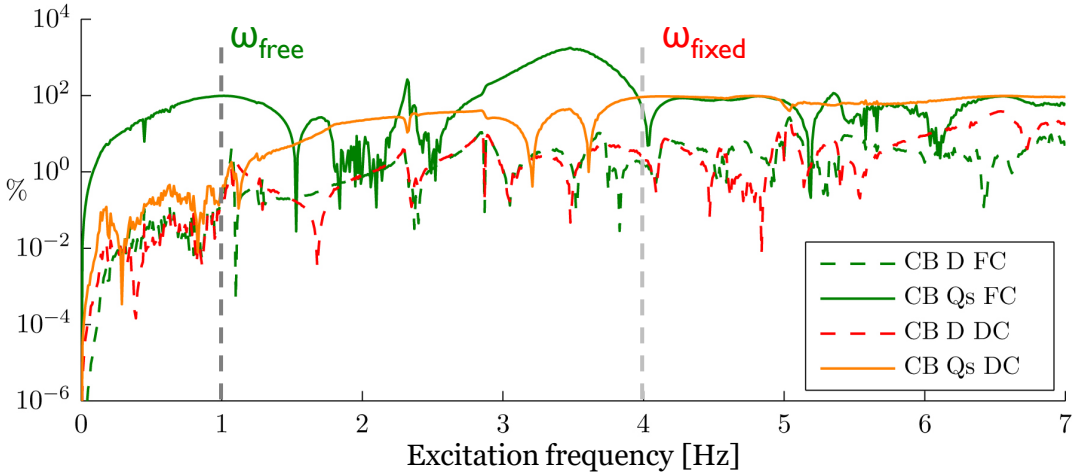
Post-processing analysis with Craig-Bampton reduced foundation in OWT model



Post-processing analysis with Craig-Bampton reduced foundation in OWT model

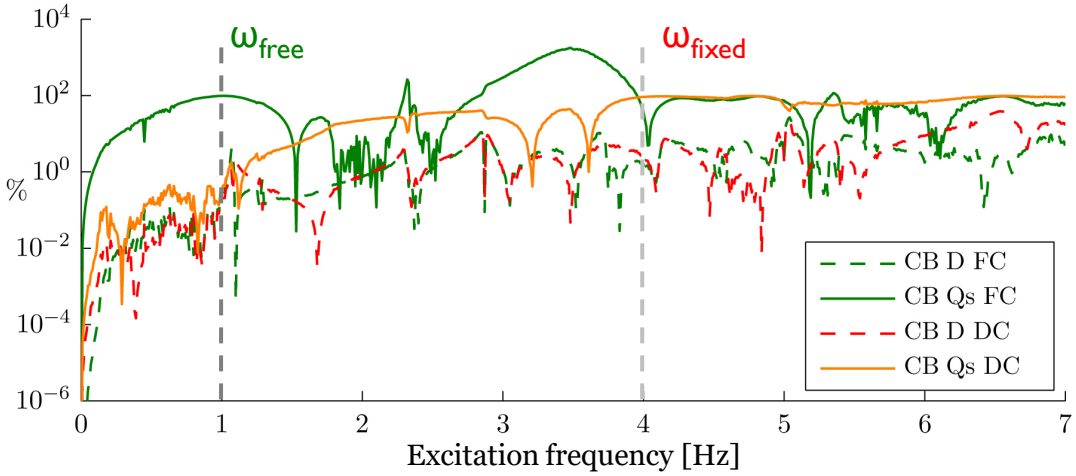
Relative energy difference with respect to exact solution



- Quasi-static post-processing inaccurate
  - ω_{free} and ω_{fixed} within excitation spectrum

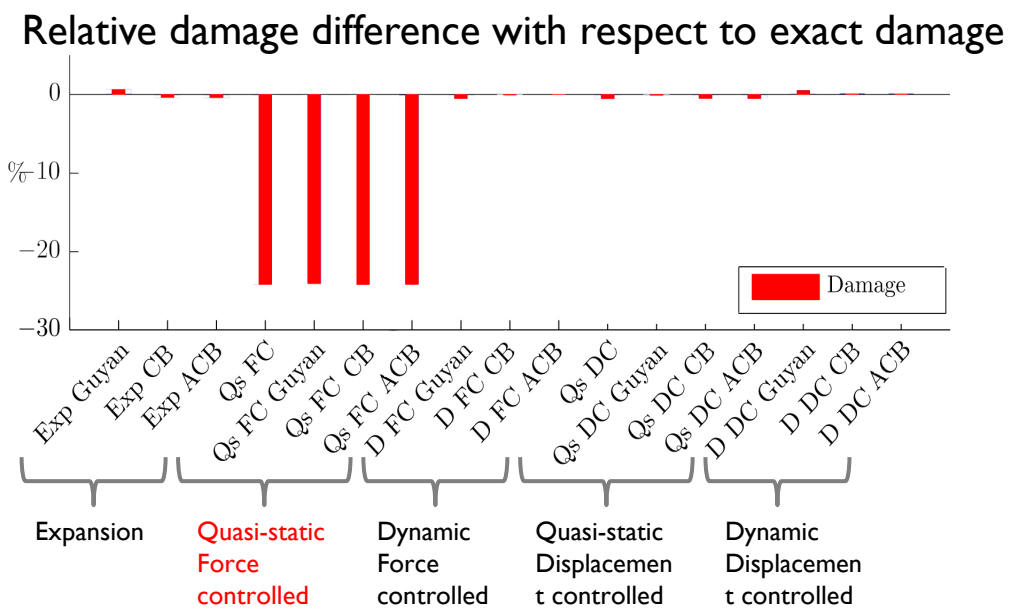
Post-processing analysis with Craig-Bampton reduced foundation in OWT model

Relative energy difference with respect to exact solution



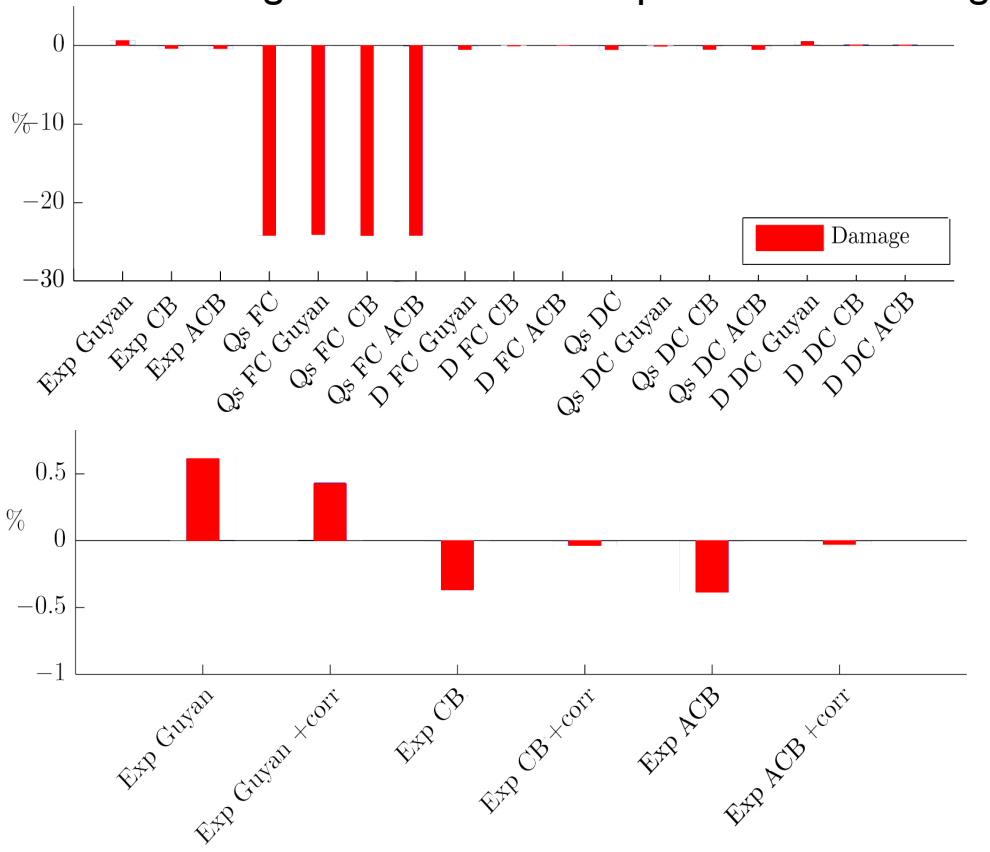
- Quasi-static post-processing inaccurate
  - ω_{free} and ω_{fixed} within excitation spectrum
- Dynamic post-processing accurate
  - CB reduced model converges spectrally
  - Internal dynamics included

Fatigue damage - Jacket



Fatigue damage - Jacket

Relative damage difference with respect to exact damage



Content

- Introduction
- Approach
- Modeling
- Results
- Conclusions and recommendations

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  - Use of a reduced foundation model in complete OWT model
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  - Post-processing method
    - Dynamic post-processing provides accurate fatigue damage results despite use of reduced foundation

Recommendations

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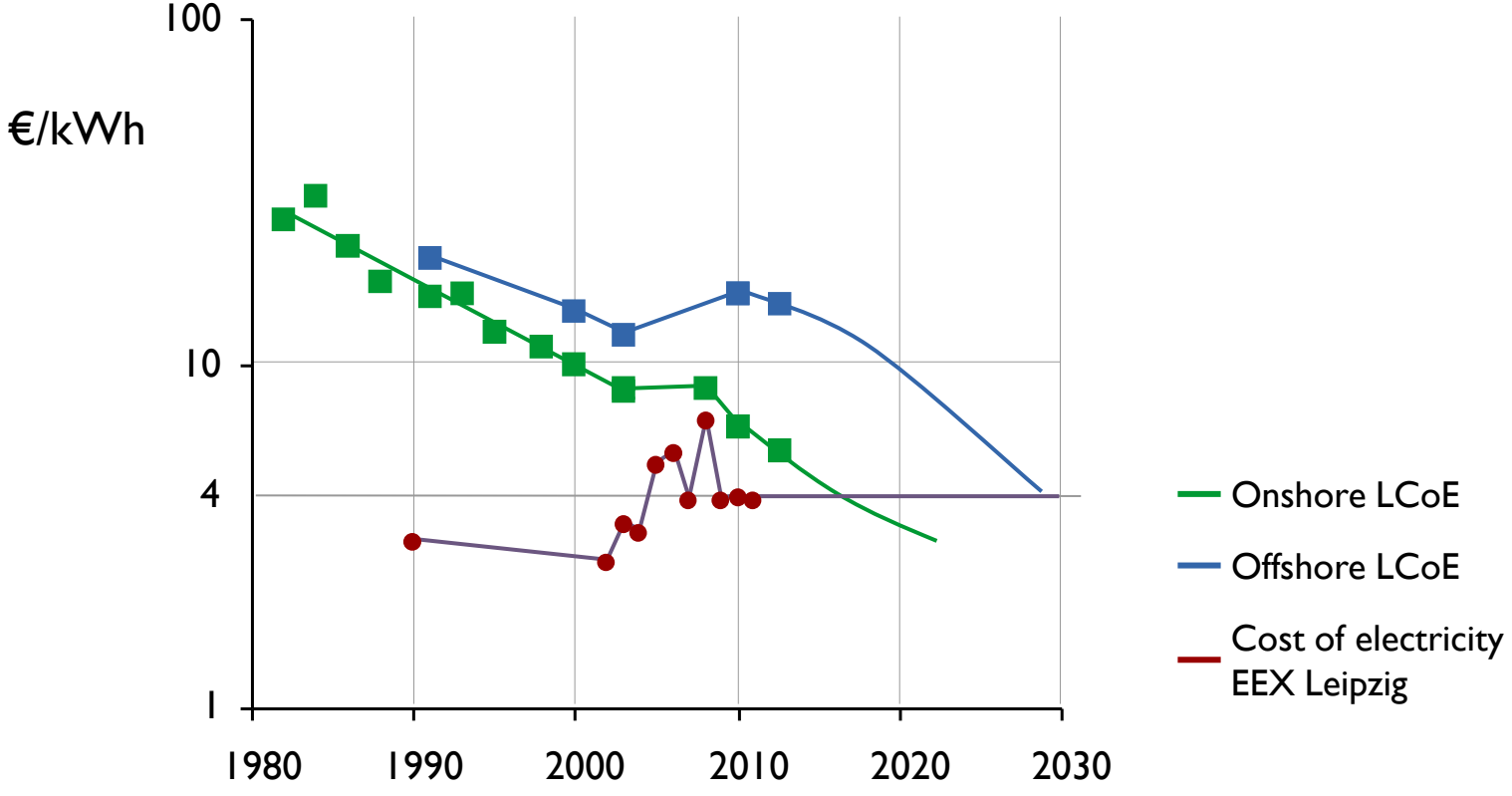
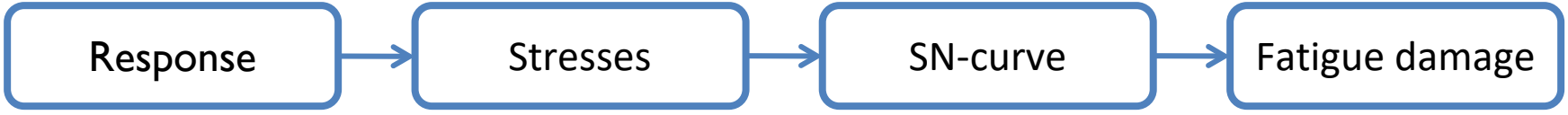
- Validate results with real OWTs and loads

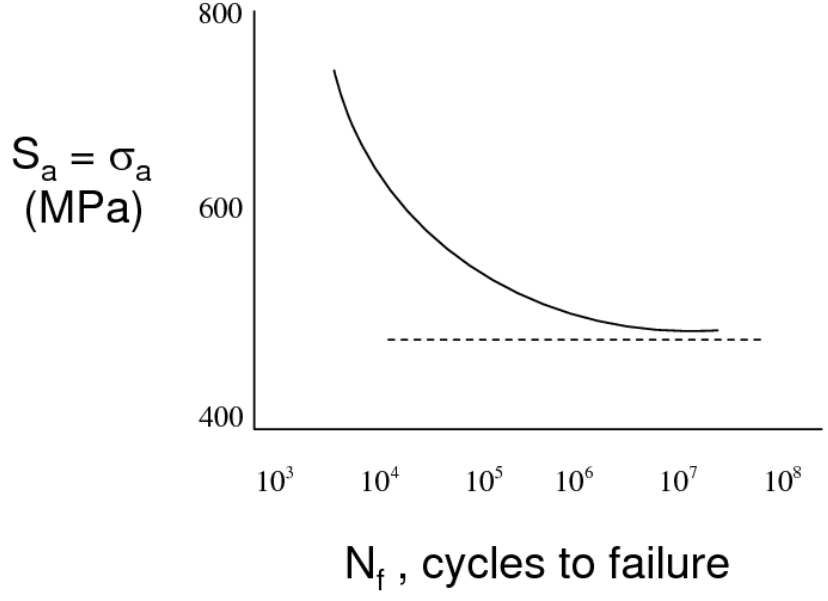
Thank you for your attention

Levelized Cost of Electricity



Fatigue damage computation





$$D = \sum \frac{n_i}{N_i}$$

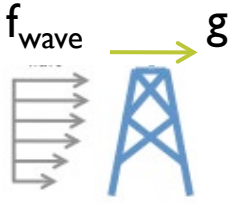
Force versus displacement controlled

$$\left(-\omega^2 \begin{bmatrix} \boldsymbol{M}_{ii} & \boldsymbol{M}_{ib} \\ \boldsymbol{M}_{bi} & \boldsymbol{M}_{bb} \end{bmatrix} + j\omega \begin{bmatrix} \boldsymbol{C}_{ii} & \boldsymbol{C}_{ib} \\ \boldsymbol{C}_{bi} & \boldsymbol{C}_{bb} \end{bmatrix} + \begin{bmatrix} \boldsymbol{K}_{ii} & \boldsymbol{K}_{ib} \\ \boldsymbol{K}_{bi} & \boldsymbol{K}_{bb} \end{bmatrix}\right) \begin{bmatrix} \boldsymbol{u}_i \\ \boldsymbol{u}_b \end{bmatrix} = \begin{bmatrix} \boldsymbol{f}_i \\ \boldsymbol{f}_b \end{bmatrix} + \begin{bmatrix} \boldsymbol{g}_i \\ \boldsymbol{g}_b \end{bmatrix}$$

- Force controlled approach

$$(-\omega^2 \boldsymbol{M} + j\omega \boldsymbol{C} + \boldsymbol{K})\boldsymbol{u} = \boldsymbol{f} + \boldsymbol{g}$$

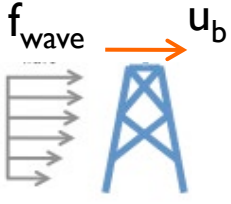
$$\boldsymbol{K}\,\boldsymbol{u} = \boldsymbol{f} + \boldsymbol{g}$$



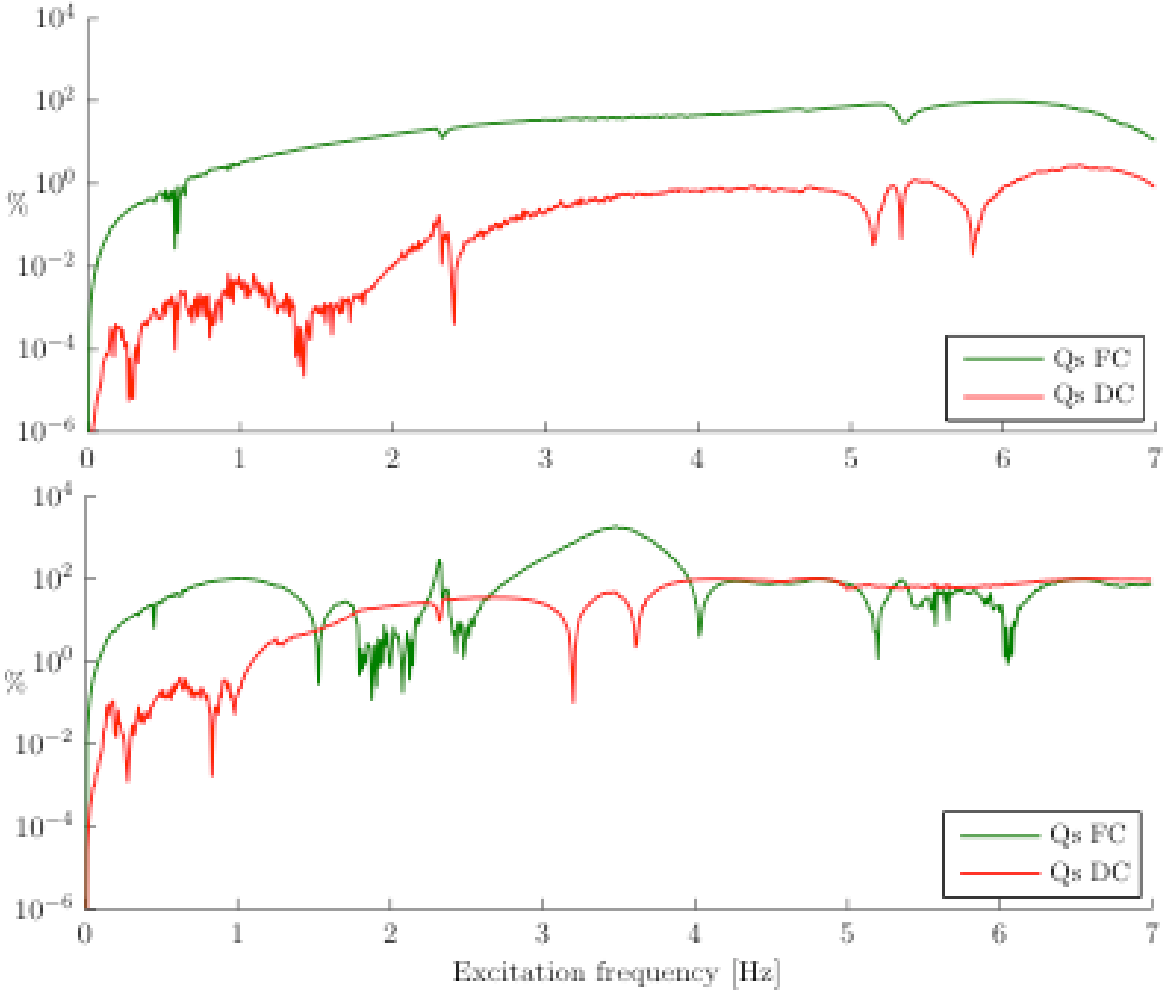
- Displacement controlled approach

$$(-\omega^2 \boldsymbol{M}_{ii} + j\omega \boldsymbol{C}_{ii} + \boldsymbol{K}_{ii})\boldsymbol{u}_i = \boldsymbol{f}_i - (-\omega^2 \boldsymbol{M}_{ib} + j\omega \boldsymbol{C}_{ib} + \boldsymbol{K}_{ib})\boldsymbol{u}_b$$

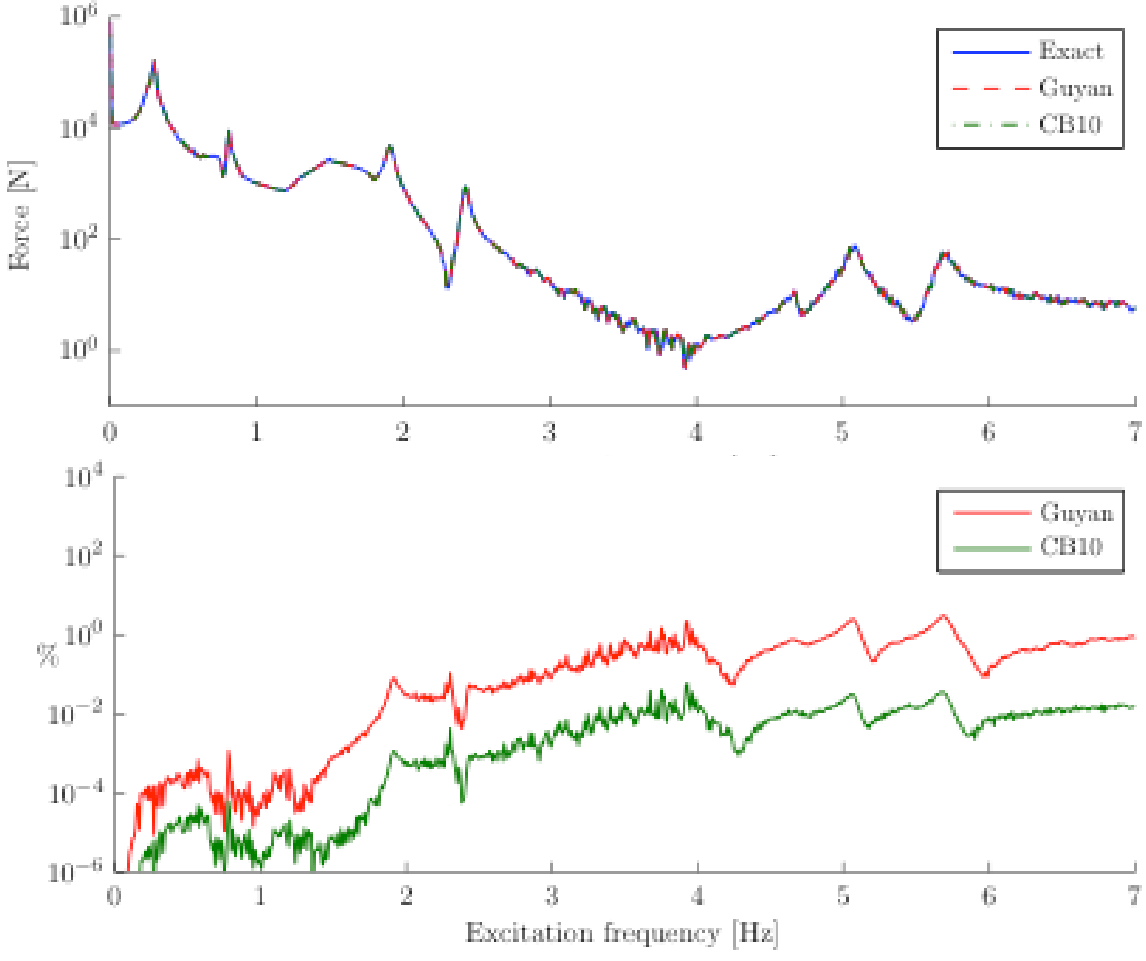
$$\boldsymbol{K}_{ii}\,\boldsymbol{u}_i = \boldsymbol{f}_i - (-\omega^2 \boldsymbol{M}_{ib} + j\omega \boldsymbol{C}_{ib} + \boldsymbol{K}_{ib})\boldsymbol{u}_b$$



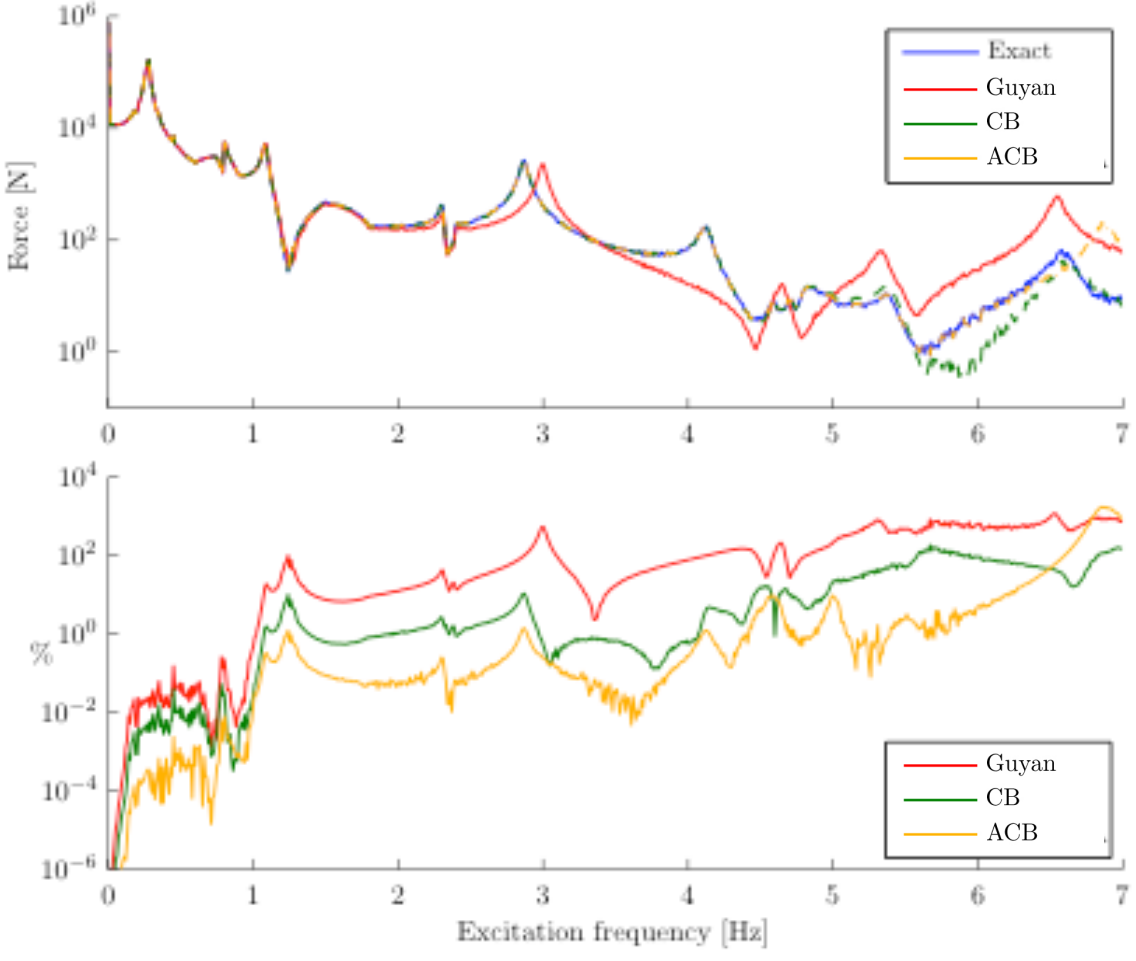
Relative energy difference quasi-static analysis



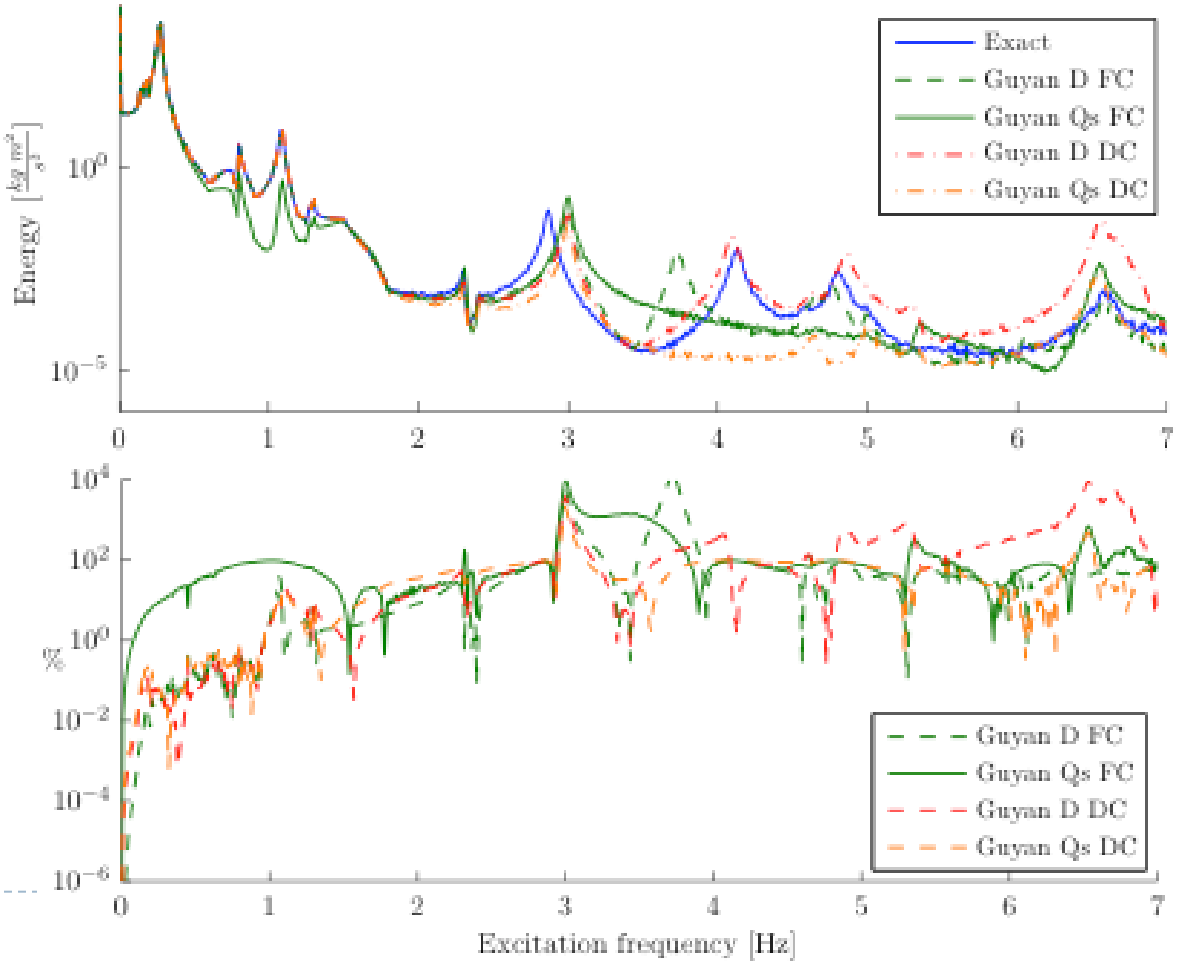
Interface loads - Monopile



Interface loads - Jacket



Guyan reduced jacket in complete OWT model



Augmented Craig-Bampton reduction

1. External load represented by a spatial and temporal part

$$\sum_{p=1}^{g} \boldsymbol{f}_p \alpha_p(t) = \boldsymbol{F}\boldsymbol{\alpha}(t)$$

1. Quasi-static response and orthogonalize w.r.t. fixed interface vibration modes

$$\tilde{\boldsymbol{\Phi}}_{MTA} = \boldsymbol{P}\boldsymbol{K}_{ii}^{-1}\boldsymbol{F}$$

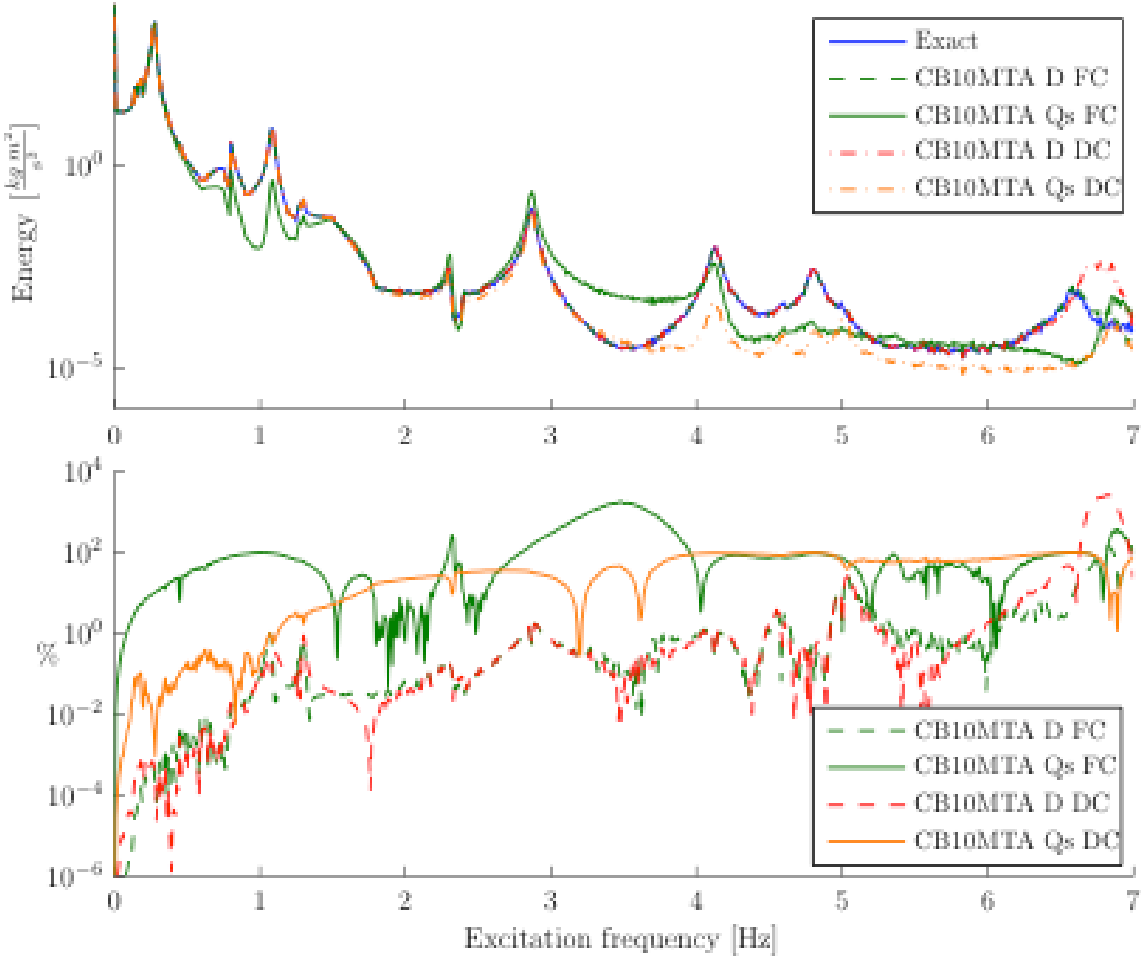
2. Orthonormalize w.r.t. each other

$$(\tilde{\boldsymbol{\Phi}}_{MTA}^{T}\boldsymbol{K}_{ii}\tilde{\boldsymbol{\Phi}}_{MTA})\boldsymbol{y} = \boldsymbol{\sigma}^2(\tilde{\boldsymbol{\Phi}}_{MTA}^{T}\boldsymbol{M}_{ii}\tilde{\boldsymbol{\Phi}}_{MTA})\boldsymbol{y} \qquad \boldsymbol{\Phi}_{MTA} = \tilde{\boldsymbol{\Phi}}_{MTA}\boldsymbol{y}$$

1. Construct reduction basis

$$\begin{bmatrix} \boldsymbol{u}_b \\ \boldsymbol{u}_i \end{bmatrix} = \begin{bmatrix} \boldsymbol{I} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{\Psi}_C & \boldsymbol{\Phi}_i & \boldsymbol{\Phi}_{MTA} \end{bmatrix} \begin{bmatrix} \boldsymbol{u}_b \\ \boldsymbol{\eta}_i \\ \boldsymbol{\zeta} \end{bmatrix} = \boldsymbol{R}_{ACB} \begin{bmatrix} \boldsymbol{u}_b \\ \boldsymbol{\eta}_i \\ \boldsymbol{\zeta} \end{bmatrix}$$

Augmented Craig-Bampton reduced jacket in complete OWT model



Facts wind energy

Wind turbine

- Power capacity
  - 3 MW
- Energy production
  - 6 – 7,5 GWh per year
  - Serves ± 2000 households

Household

- Average household
  - 2,2 persons
- Energy usage
  - 3500 kWh per year

Requirement for calculation procedures

	Detailed foundation in OWT model	Reduced foundation in OWT model
Expansion		✓ If spectrally and spatially converged
Force controlled		
Dynamic	✓	✓ If spectrally and spatially converged
Quasi-static	✓ If $\omega_{free} >> \max(\omega_{ext})$	✓ If spectrally and spatially converged If $\omega_{free} >> \max(\omega_{ext})$
Displacement controlled		
Dynamic	✓	✓ If spectrally and spatially converged
Quasi-static	✓ If $\omega_{free} >> \max(\omega_{ext})$	✓ If spectrally and spatially converged If $\omega_{free} >> \max(\omega_{ext})$

X