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Impulse Based Substructuring Applied To Offshore Wind Turbine Jackets

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Abstract

Load simulations for offshore wind turbines are still a challenging task. The accurate analysis of the entire offshore wind turbine in time-domain is time-consuming and computational demanding and often unfeasible, since wind turbine supplier are usually reluctant to share detailed data. Substructuring techniques are therefore widely used by industry. However, these approaches do not capture the dynamic interactions between wind turbine and substructure accurate enough. **Impulse Based Substructuring**, a method which is based on the principle of superposition of impulse responses, matches these requirements. In this study Impulse Based Substructuring is applied to an offshore wind turbine with an **OWEC Quattropod®** substructure. Results show that Impulse Based Substructuring enables **high accuracy** in representing **coupled dynamics** of offshore wind turbines and **lowers the computational costs** required for a load simulation. It is therefore a viable substructuring method for the offshore wind industry and allows for an **intellectual property-friendly** working framework for both substructure and wind turbine designer.

Impulse Based Substructuring

Impulse Based Substructuring[1] (IBS) is used to compute the dynamic behavior of the multibody system composed of turbine, tower, and substructure.

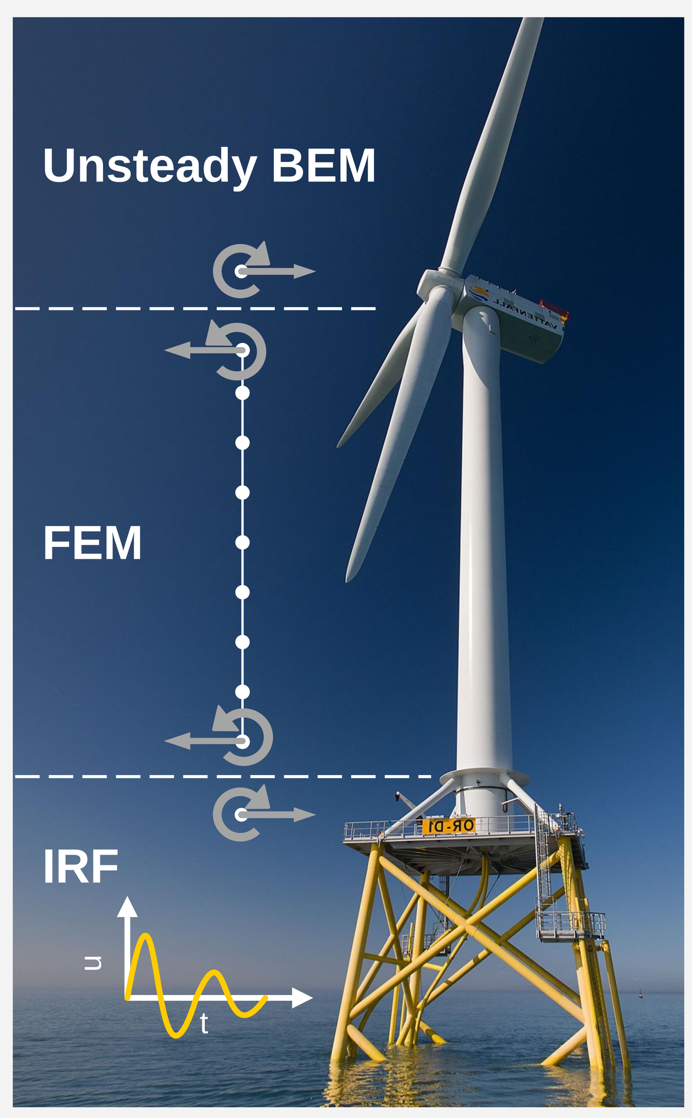
Wind Turbine (NREL 5-MW[2])

Aero-elastic model of the turbine is used, while the tower is modelled with finite elements.

Substructure (OWEC Quattropod®)

Dynamics of the substructure are represented by a set of Impulse Response Functions:

$$\boldsymbol{H}_{t_n} = \begin{bmatrix} [H_{t_n}]_{11} & \cdots & [H_{t_n}]_{1N} \\ \vdots & \ddots & \vdots \\ [H_{t_n}]_{N1} & \cdots & [H_{t_n}]_{NN} \end{bmatrix}$$



Assembling Conditions

Compatibility: Displacements at interface nodes have to be equal

$$\boldsymbol{Bu} = \boldsymbol{0}$$

Equilibrium: Forces at interface nodes have to be equal in magnitude and opposite in sign

$$\left[\boldsymbol{g}^{(turbine)} \quad \boldsymbol{g}^{(tower)} \quad \boldsymbol{g}^{(substructure)}\right]^T = -\boldsymbol{B}^T\boldsymbol{\lambda}$$

Impulse Response Functions

The response of a linear system $u(t)$ due to an excitation $f(t)$ can be computed by calculating the convolution of the excitation with its impulse response function $H(t)$.

$$u(t) = \int_{\tau=0}^{t} H(t-\tau) f(\tau) d\tau$$

$H(t)$ represents the response of the system due to a unit impulse load over time and includes the complete dynamic behaviour of the system. IBS calculates the response of a substructure by assembling its component Impulse Response functions.

Computation of Impulse Response Functions

IRFs are often obtained numerically by calculating the response of the system due to a unit impulse load. This study uses modal decomposition[3] to obtain IRFs analytically.

The modal equation of motion can be separated per mode j, since the set of impulse response functions, $\boldsymbol{H}_{t_n}$, is uncoupled:

$$\tilde{m}_j \ddot{q}_j(t) + \tilde{c}_j \dot{q}_j(t) + \tilde{k}_j q_j(t) = \tilde{f}_j(t)$$

A 2nd order system is considered and the response due to an impulse has the same form as its free response with initial conditions obtained by Dirac delta function:

$$\boldsymbol{u}(0) = \boldsymbol{0};\ \dot{\boldsymbol{u}}(0) = \boldsymbol{M}^{-1}\boldsymbol{1};\ \ddot{\boldsymbol{u}}(0) = \boldsymbol{M}^{-1}(-\boldsymbol{Cu})$$

Hence, the element $[H_{t_n}]_{a,b}$ of the impulse response matrix, which represents the response for DOF a at time $t = t_n$ to a unit impulse applied at time $t = 0$ on DOF b is:

$$[H_{t_n}]_{ab} = \sum_{j=1}^{n} \Phi_{aj}\,\Phi_{bj} \frac{1}{\tilde{m}_j} \frac{1}{\omega_{d,j}} e^{-\zeta_j\,\omega_{0,j} t_n} \left(sin(\omega_{d.j} t_n) \right)$$

Parameterisation of Impulse Response Functions

In order to reduce the computational cost, the IRFs are parameterized with respect to structural parameters such as diameter, D, and thickness, T. $[H_{t_n}]_{ab}$ is then rewritten as:

$$[\hat{H}_{t_n}]_{ab} = \sum_{j=1}^{n} \hat{\Phi}_{aj}\,\hat{\Phi}_{bj} 1_b \frac{1}{\hat{m}_j} \frac{1}{\hat{\omega}_{d,j}} e^{-\zeta_j\,\hat{\omega}_{0,j} t_n} \left(sin(\hat{\omega}_{d.j} t_n) \right)$$

where $[\hat{H}_{t_n}]_{ab} = [H_{t_n}(D,T)]_{ab}$; $\hat{\Phi}_{(\cdot)} = \Phi_{(\cdot)}(D,T)$; $\hat{m}_j = \tilde{m}_j(D,T)$; $\hat{\omega}_{0.j} = \omega_{0.j}(D,T)$; $\hat{\omega}_{d.j} = \omega_{d.j}(D,T)$.

The multivariable IRFs are solved for multiple combinations of D and T and a polynomial fit is applied to the obtained solutions. Subsequently, the polynomial can be used to find approximate IRFs for other combinations of D and T.

Mode Truncation and Flexibility Compensation

The cost efficiency of the analytical computed IRFs can be increased by truncating higher modes with frequencies above the excitation frequency, i.e. $[H_{t_n}]_{ab}$ only uses modes for $j = 1, \ldots, m$ with $m < n$. The truncation of higher modes results in a stiffer structure and has to be corrected for.

The total static flexibility of the substructure defined in terms of the modal flexibility $\tilde{k}_j^{-1}$ is split in three intervals:

$$K_{ab}^{-1} = \sum_{j=1}^{c_1} \Phi_{aj}\,\Phi_{bj} \tilde{k}_j^{-1} + \sum_{j=c_1+1}^{c_2} \Phi_{aj}\,\Phi_{bj} \tilde{k}_j^{-1} + \sum_{j=c_2+1}^{n} \Phi_{aj}\,\Phi_{bj} \tilde{k}_j^{-1}$$

where the first interval represents the non-truncated modes, the second interval represents the modes which have to be compensated for the truncated modes, and the last interval represents the truncated modes. The compensation is done by multiplying the amplitude of the second interval with the factor κ_{ab} given by:

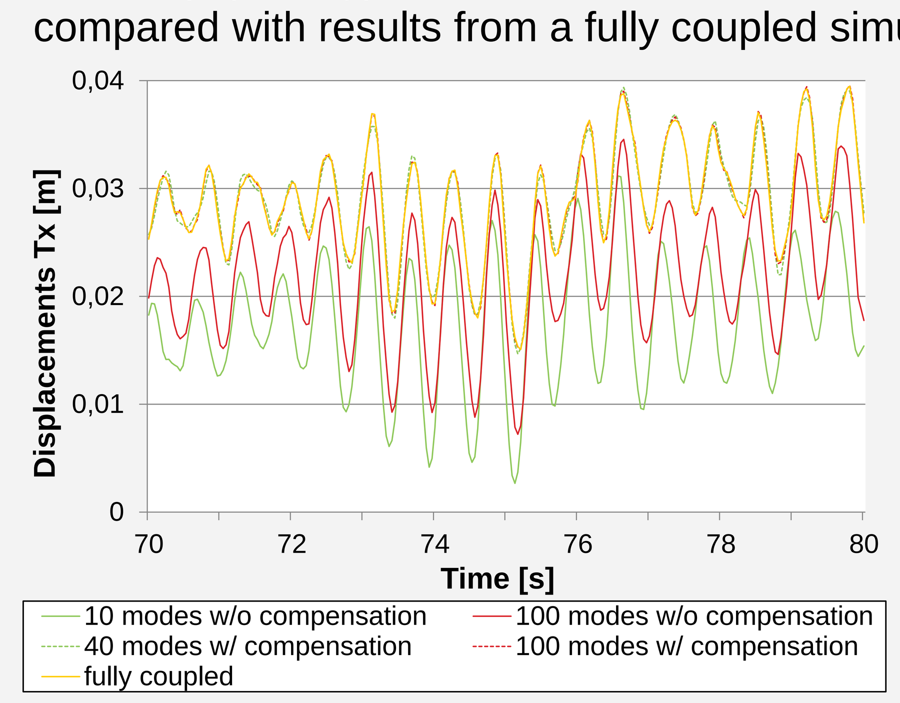
$$\kappa_{ab} = \frac{\sum_{j=c_1+1}^{c_2} \Phi_{aj}\,\Phi_{bj} \tilde{k}_j^{-1} + \sum_{j=c_2+1}^{n} \Phi_{aj}\,\Phi_{bj} \tilde{k}_j^{-1}}{\sum_{j=c_1+1}^{c_2} \Phi_{aj}\,\Phi_{bj} \tilde{k}_j^{-1}}$$

Hence, the impulse response function can be rewritten as:

$$[H_{t_n}]_{ab} = \sum_{j=1}^{c_1} \Phi_{aj}\,\Phi_{bj} \frac{1}{\tilde{m}_j} \frac{1}{\omega_{d,j}} e^{-\zeta_j\,\omega_{0,j} t_n} \left(sin(\omega_{d.j} t_n) \right) + \kappa_{ab} \sum_{j=c_1+1}^{c_2} \Phi_{aj}\,\Phi_{bj} \frac{1}{\tilde{m}_j} \frac{1}{\omega_{d,j}} e^{-\zeta_j\,\omega_{0,j} t_n} \left(sin(\omega_{d.j} t_n) \right)$$

Results

Load simulations with varying environmental conditions were performed. Forces and moments at tower top (Fx, My) and translational and rotational displacements at tower bottom (Tx, Ry) were compared with results from a fully coupled simulation in order to assess the accuracy.



Number of modes

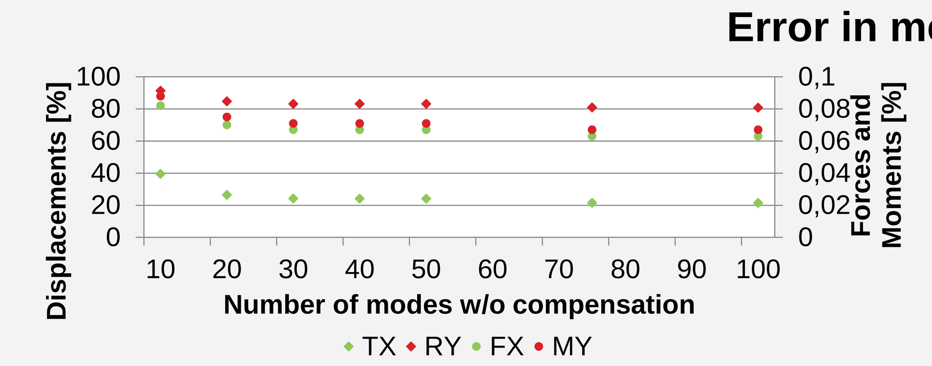
- 10 modes clearly leads to a stiffer system
- With 100 modes the error between the IBS method and the fully coupled simulation is still significant.

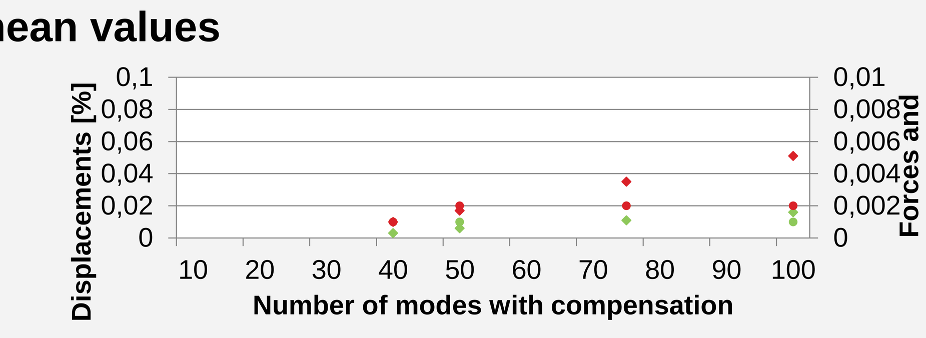
Flexibility compensation

- The dotted lines clearly show that the flexibility compensation leads to more accurate results.

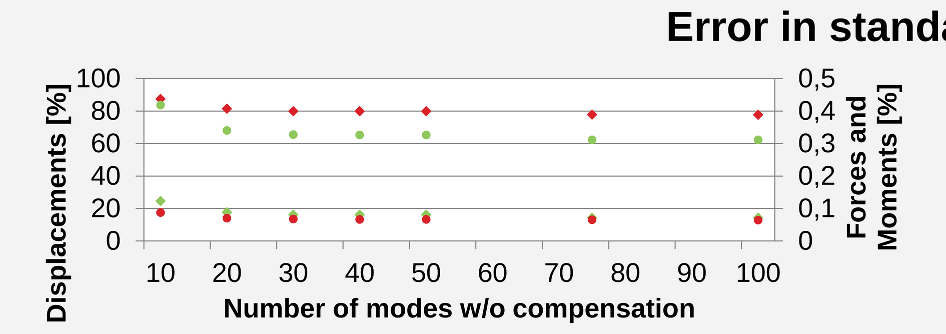
Error measurements confirm this observations

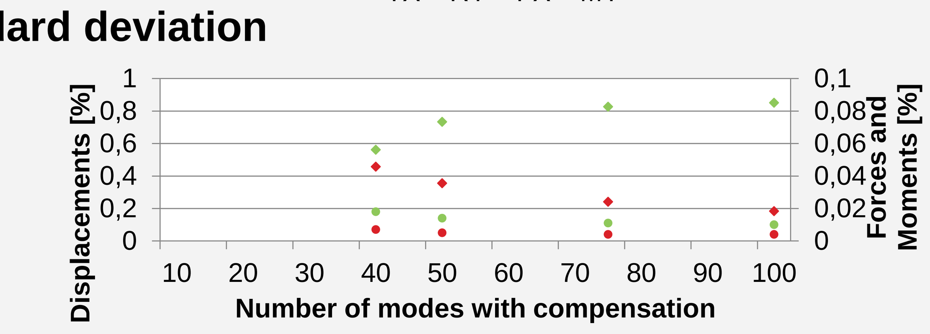
Error in mean values





Error in standard deviation





Parameterisation of IRFs

Errors in mean value, standard deviation, and absolute maximum were calculated for both the fitted (FIT) and the original IRF (ORG).

⇨ Results obtained by parameterised IRFs differs only marginally

Error in	Mode	TX [%]	RY [%]	FX [%]	My [%]
Mean value	FIT	0.009	0.008	0.001	-0.001
	ORG	0.009	0.008	0.000	-0.001
Standard deviation	FIT	-0.231	-0.466	0.017	0.017
	ORG	-0.212	-0.469	0.017	0.017
Absolute maxima	FIT	7.618	6.550	0.579	0.740
	ORG	7.545	6.421	0.582	0.741

Conclusions

Impulse Based Substructuring enables high accuracy in representing the coupled dynamics of an offshore wind turbine and lowers the computational costs required for a load simulation. Furthermore, Impulse Based Substructuring allows the protection of intellectual property, which is of high importance for the wind turbine supplier as well as the substructure designer.

Moreover, this study showed that the computational costs can be further decreased by computing IRFs analytically and that the parametrisation of IRFs enables a multibody structural optimisation by adjusting only the substructure parameters.

Impulse Based Substructuring is therefore a suitable approach for the offshore wind industry.

References

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2. J. Jonkman, S. Butterfeld, W. Musial, and G. Scott, "Definition of a 5-MW reference wind turbine for offshore system development", Technical Report NREL/TP-500-38060, National Renewable Energy Laboratory Golden, CO, 2009.
3. M. Bampton and R. CRAIG, "Coupling of substructures for dynamic analyses", AIAA Journal, 6:7 (1968) pp. 1313-1319.

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