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VALIDATION OF SUPERELEMENT MODELLING OF COMPLEX OFFSHORE SUPPORT STRUCTURES

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ABSTRACT

Modern large MW wind turbines today are installed at larger water depth than applicable for traditional monopile substructure. It appears that foundation types such as jacket and tripod are gaining more popularity for these locations. For certification purposes, a full set of design load calculations consisting of up to thousands design load cases needs to be evaluated. However, even the simplest aero-elastic model of such structures has many more DOFs than monopile, resulting in excessive computation burden. In order to deal with this problem, the superelement method has been introduced for modelling such structures. One superelement method has been proven very promising in the previous project of Wave Loads [1] and a fundamental question in such DOFs reduction methods is which modes that are essential and which modes can be neglected. For the jacket structure, the introduction of a gravity-buoyancy mode (GB mode) demonstrates that this mode is needed for accurate load simulation. A case study is performed in this report to validate the proposed method based on a reference wind turbine on a jacket foundation.

ACRONYMS

DOFs = Degrees of Freedom
GB = Gravity Buoyancy
OWT = Offshore Wind Turbine
DLC = Design Load Case

INTRODUCTION

Over the last decade, the offshore wind industry has increased significantly, especially in Europe. In order to be competitive with conventional electrical sources on the market, one promising way to achieve further cost reduction is by scaling up the wind turbine size. It is expected that the 6 MW up to 10 MW wind turbines will dominate the offshore market in the near future. Furthermore, offshore wind farms are gradually installed at deeper water depths now typically reaching 30-40m. As a result of this trend, the complex support structures become economically attractive, in which jacket is the most promising option. Since the environmental conditions (water depth and soil properties) and ambient excitations (aerodynamic and hydrodynamic loading) vary greatly across different offshore sites, the foundation is custom engineered. The dynamic simulations are performed to assess whether the support structure design can withstand the loads during its specified lifetime. For certification purposes, up to thousands of load cases need to be evaluated. The aero-elastic simulation software developed at DTU Wind Energy, HAWC2 [3], which is based on multibody dynamics, was used in this study. The complex structure consists of many more DOFs than monopile, resulting in excessive computation time. Since a fast simulation speed is of importance, the reduced model is applied to represent the support structure in order to obtain a high computational efficiency. The idea to reduce the model is not new and it is often called as dynamic substructuring or superelement method. The method is based on a componentwise 'divide and conquer' approach as explained in [5]: structure decomposition, superelement modelling and component assembly.

METHODOLOGY

A. Governing Equations

Conceptually, the full HAWC2 governing equations are based on multibody formulation with floating frame of reference. For the small deflections δq, the full governing equations as reported in [1] can be linearized as:

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$$\mathrm{M_1}\delta\ddot{\mathrm{q}} + \mathrm{C_1}\delta\dot{\mathrm{q}} + \mathrm{K_1}\delta\mathrm{q} + \nabla\mathrm{g}^\mathrm{T}\delta\lambda - \delta\mathrm{F} = 0 \tag{1}$$

$$\nabla\mathrm{g}\delta\mathrm{q} = 0 \tag{2}$$

In which, $\mathrm{M_1}, \mathrm{C_1}$ and $\mathrm{K_1}$ are the mass, damping and stiffness matrices respectively. $\nabla\mathrm{g}\delta\mathrm{q} = 0$ is the algebraic constraint equations and $\nabla\mathrm{g}^\mathrm{T}\delta\lambda$ express the reaction forces required to fulfill the constraint equation. The states $\delta\mathrm{q}$ can be classified as independent states $\delta\mathrm{q_1}$ and dependent states $\delta\mathrm{q_2}$, therefore the constraint equations can be written as:

$$\nabla\mathrm{g}\delta\mathrm{q} = [\mathrm{G_1} \quad \mathrm{G_2}]\begin{bmatrix}\delta\mathrm{q_1}\\ \delta\mathrm{q_2}\end{bmatrix} = 0 \tag{3}$$

A reduction can be performed by expressing the constraint part as $\delta\mathrm{q_1} = -\mathrm{G_1^{-1}G_2}\delta\mathrm{q_2}$:

$$\delta\mathrm{q} = \begin{bmatrix}\delta\mathrm{q_1}\\ \delta\mathrm{q_2}\end{bmatrix} = \begin{bmatrix}-\mathrm{G_1^{-1}G_2}\\ \mathrm{I}\end{bmatrix}\delta\mathrm{q_2} \equiv \mathrm{T_G}\delta\mathrm{q_2} \tag{4}$$

By substituting the above equation into the full governing equations and pre-multiplication by the transpose of $\mathrm{T_G}$, a reduced governing equations can be obtained as:

$$(\mathrm{T_G^T M T_G})\delta\ddot{\mathrm{q}}_2 + (\mathrm{T_G^T C T_G})\delta\dot{\mathrm{q}}_2 + (\mathrm{T_G^T K T_G})\delta\mathrm{q_2} - \mathrm{T_G^T}\delta\mathrm{F} = 0 \tag{5}$$

This reduces the original number of equations roughly by a factor of 2, and it can be simply written respecting the common form of 2nd order governing equations:

$$\bar{\mathrm{M}}\ddot{\bar{\mathrm{q}}} + \bar{\mathrm{C}}\dot{\bar{\mathrm{q}}} + \bar{\mathrm{K}}\bar{\mathrm{q}} - \bar{\mathrm{F}} = 0 \tag{6}$$

The generalized governing equations will be further reduced using the superelement method.

B. Craig-Bampton Method

One very popular approach of superelement method, which was implemented into HAWC2 in the Wave Loads project [1], is Craig-Bampton method. In order to be able to assemble the different component models, the states vector $\bar{q}$ should be partitioned into interface (boundary) states, denoted as $\bar{q}_b$, and internal states as $\bar{q}_i$. Therefore, the states can be obtained as:

$$\bar{\mathrm{q}} = \begin{bmatrix}\bar{\mathrm{q}}_\mathrm{b}\\ \bar{\mathrm{q}}_\mathrm{i}\end{bmatrix} \tag{7}$$

The basic idea of Craig-Bampton method is by using mode shape selection. In principle, the mode shapes consists of two different shapes, static shapes obtained as static response to unit forces applied to interface DOFs and dynamic mode shapes obtained from an eigenproblem with fixed interface DOFs. The detailed explanation can be reviewed in [4] and [5] and the states $\bar{q}$ can be obtained by the mode shapes matrix T and corresponding generalized states α.

$$\bar{\mathrm{q}} = \begin{bmatrix}\bar{\mathrm{q}}_\mathrm{b}\\ \bar{\mathrm{q}}_\mathrm{i}\end{bmatrix} = \begin{bmatrix}\mathrm{T}_{\phi\mathrm{bb}} & \mathrm{T}_{\phi\mathrm{bi}}\\ \mathrm{T}_{\phi\mathrm{ib}} & \mathrm{T}_{\phi\mathrm{ii}}\end{bmatrix}\begin{bmatrix}\alpha_\mathrm{b}\\ \alpha_\mathrm{i}\end{bmatrix} \tag{8}$$

Insert $\alpha_\mathrm{b} = \mathrm{T}_{\phi\mathrm{bb}}(\bar{\mathrm{q}}_\mathrm{b} - \mathrm{T}_{\phi\mathrm{bi}}\alpha_\mathrm{i})$ back to the above equation to obtain:

$$\bar{\mathrm{q}} = \begin{bmatrix}\mathrm{I} & 0\\ \mathrm{T}_{\phi\mathrm{ib}}\mathrm{T}_{\phi\mathrm{bb}}^{-1} & \mathrm{T}_{\phi\mathrm{ii}} - \mathrm{T}_{\phi\mathrm{ib}}\mathrm{T}_{\phi\mathrm{ii}}^{-1}\mathrm{T}_{\phi\mathrm{bi}}\end{bmatrix}\begin{bmatrix}\bar{\mathrm{q}}_\mathrm{b}\\ \alpha_\mathrm{i}\end{bmatrix} \equiv \mathrm{T}_\alpha\bar{\mathrm{q}}_\mathrm{r} \tag{9}$$

In which, $\bar{\mathrm{q}}_\mathrm{r}$ is the reduced state vector and T_α is the transformation matrix.

C. Gravity-Buoyancy Mode

For the Craig-Bampton method, the static modes retain the boundary with neighboring components and the dynamic modes find a good approximation for the internal DOFs [5]. However, the deflection induced by gravity and buoyancy in the case of jacket is not considered when the interface nodes are fixed to obtain the dynamic modes, the offset between superelement model and full model was identified in previous work [1]. Thus, it is of high importance to consider the contribution from gravity and buoyancy to produce an accurate simulation. Basically, there are two feasible approaches: post-processing or inclusion of an extra mode shape. The post-processing is straightforward, but the mode shape approach is adopted because of two advantages:

1. It is uniform with the static modes and dynamic modes, thus it can be implemented in the same way.
2. It is simulated in each time step, thus it can also be applied to the dynamic gravity or buoyancy field, e.g. the jacket is subjecting to earthquake excitation.

The GB mode is included as a new separate mode shape $\mathrm{T_{gb}}$ with corresponding generalized states α_{gb}:

$$\bar{\mathrm{q}} = [\mathrm{T}_\alpha \quad \mathrm{T_{gb}}]\begin{bmatrix}\bar{\mathrm{q}}_\mathrm{r}\\ \alpha_\mathrm{gb}\end{bmatrix} \equiv \mathrm{T}_\beta\mathrm{q_{rr}} \tag{10}$$

The GB mode shape can be easily obtained as the static solution to the gravity and buoyancy forces by solving the following equation:

$$\bar{K}T_{gb} = \bar{F}_{gb} \tag{11}$$

Therefore, the final transformation equation and final reduced governing equations can be written as:

$$\delta q = T_G T_\beta q_{rr} \equiv T q_{rr} \tag{12}$$

$$(\mathrm{T^T M T})\ddot{\mathrm{q}}_\mathrm{rr} + (\mathrm{T^T C T})\dot{\mathrm{q}}_\mathrm{rr} + (\mathrm{T^T K T})\mathrm{q_{rr}} - \mathrm{T^T}\delta\mathrm{F} = 0 \tag{13}$$

In which, q_{rr} is the final generalized states and T is the corresponding transformation matrix. The selection of mode shapes should consist of the static modes, dynamic modes and GB modes. This means that the original system can be represented well by 20-30 modes, and as a result the computation speed can be greatly improved in general.

RESULTS

In order to validate its effectiveness, the proposed method is applied to a representative OWT, which is separated into a wind turbine and a substructure. The simulation results from the superelement model are compared with the full solution to validate the accuracy, and the computation time is compared to investigate the efficiency.

D. Reference Model Description

The wind turbine model is based on the ‘NREL 5 MW Baseline Wind Turbine’, which is a conventional horizontal-axis, three bladed and upwind type on a tubular tower. The detailed description can be found in [2] and thus not given here. The foundation model adopts the OC4 reference jacket, which was initially designed for the European project UpWind. The detailed specification can be found in [6] and not explained here.

E. Environmental Load Description

Two major environmental loads are taken into consideration in this study: aerodynamic load and hydrodynamic load. The aerodynamic model in HAWC2 is based on the blade element momentum theory, which is extended with models to handle the dynamic inflow, skew inflow, shear effect on induction, effect from large blade deflections and tip loss. The hydrodynamic loads in HAWC2 are calculated on the basis of Morrison’s equation. Morrison’s equation is the sum of two force components: an inertia force in phase with the local flow acceleration and a drag force proportional to the square of the instantaneous flow velocity [3]. Details about the model including general validation can be found in [7] and [8].

F. Comparison Results

The full model without any reduction is regarded as the reference model since its accuracy has been examined in the project of Wave Loads [1]. The superelement model using traditional method with 6 static modes and 20 dynamic modes has been simulated and it was found that the eigenfrequency and the time domain results on wind turbine match the full model very well, but the time domain results on the jacket has a stationary offset as it can be observed in the Figure 1.

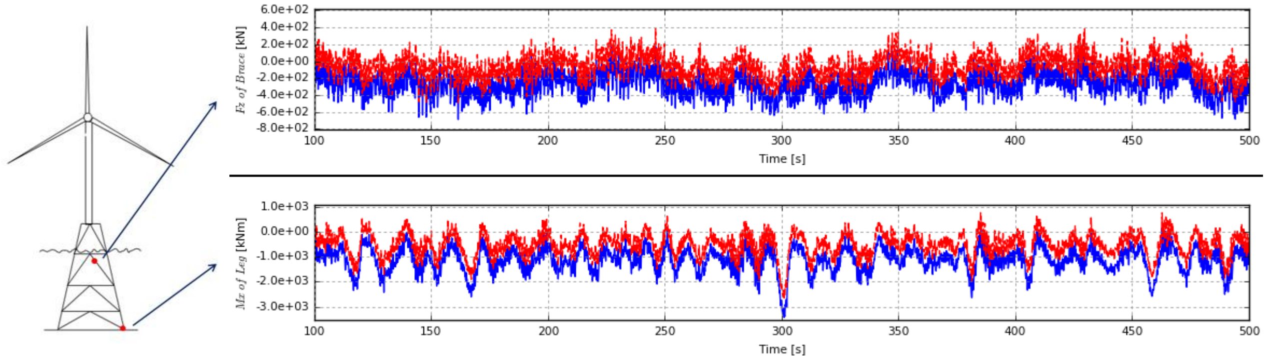

Figure 1. Time Domain Results Comparison between Full Model and Old Superelement Model

[Blue: Full Model, Red: Superelement Model]

The superelement model including GB mode on the basis of old model has also been simulated and compared here by the time domain series shown in the Figure 2 and its statistic values listed in the Table 1.

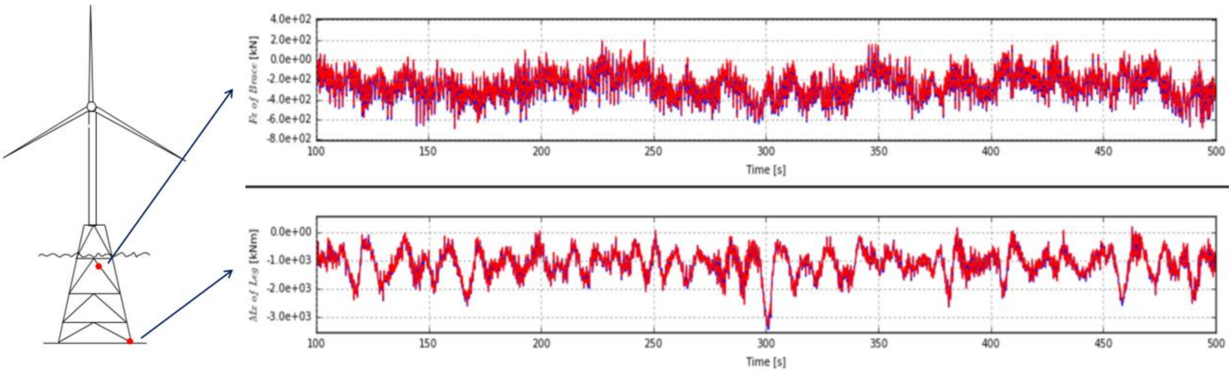

Figure 2. Time Domain Results Comparison between Full Model and New Superelement Model

[Blue: Full Model, Red: Superelement Model]

It demonstrates that the time series results for different parts on the jacket structure give a good agreement with the full model. Therefore, the new superelement model can be regarded as a right way of modelling the jacket to handle the static offset in the old superelement model.

Table 1. Statistic Comparison of Full Model and Superelement Model with GB Mode

Statistics	*Max [kN]*	*Min [kN]*	*Mean [kN]*	*Standard Derivation*	*Equivalent Load (m=3)*	*GPU Time [s]*
Full Model	*232*	*-3425*	*-1123*	*489*	*950*	*8400*
Superelement Model	*251*	*-3293*	*-1104*	*479*	*974*	*1300*

The statistical analysis for the time domain results of axial force on one brace is also performed to validate the feasibility of proposed model in another aspect. The overview of the statistical data shows a good agreement between the new superelement model and full model. Each simulation for 600s time series was run on the same PC and the computation times are compared here to give an indication of the efficiency promotion using the proposed model. The results reveal that the simulation speed will be greatly improved using superelement model in general.

CONCLUSIONS

The superelement method was presented in this paper applied to model the complex offshore support structures like jacket. Results in the time domain series as well as the statistics demonstrate a good agreement between the new superelement model and full model. The efficiency can be greatly improved by the proposed method. Furthermore, the new superelement model will be applied to a full set of DLCs to identify the most critical load cases for a given design.

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