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AN IMPLEMENTATION OF MULTI-SUPPORT SEISMIC INPUT MOTION INTO OPENFAST FOR THE EARTHQUAKE ANALYSIS OF OFFSHORE WIND TURBINES.

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Abstract. *Nowadays offshore wind energy plays a key role in the development of renewable energies in Europe. Most of offshore wind turbines installed are fixed to the seabed, with monopiles being the most commonly used substructures in this field. However, the use of multi-support substructures, such as jackets and tripods has increased considerably in recent years due to the greater depth of new wind farms locations. Dynamic behaviour and seismic risk are two factors of special importance in the design of these structures. Due to this problem, there is a need to study the seismic response of offshore wind turbines on this type of substructure. In this area, one of the most widely-used open-source advanced tool available in the literature is OpenFAST, which is a multi-physics and multi-fidelity software for the simulation of the coupled dynamic response of wind turbines in the time domain. This paper presents a formulation for the implementation of multi-support seismic input motion into OpenFAST, specifically into the SubDyn module. On the other hand, validation results for a reference offshore wind turbines on a jacket substructure are shown, conducting a number of cases with different seismic signals (translational and rotational motion) to demonstrate the correct implementation. The new modified code allows to analyse the accelerations and internal forces of offshore wind turbines on multisupport substructures, taking into account seismic input motion (including input rotation at each individual support) and soil-structure interaction.*

Keywords: OpenFAST, Offshore wind turbine, Jacket, Seismic response, Soil-structure interaction

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1 INTRODUCTION

In recent years, offshore wind energy plays a key role in the development of renewable energies in Europe. Most of the offshore wind turbines are currently installed in locations where the depth of the sea allows them to be founded directly to the seabed, with monopiles being the most common substructures used in this field. However, the use of multi-support substructures, such as jackets and tripods, has increased considerably due to the greater depth of new wind farms locations.

Two factors of special importance in the design of these structures are the dynamic behaviour and the seismic risk. Nowadays, the growth in the number of wind farm installations is due to the need of placing new offshore wind turbines in locations with worse geotechnical properties and increased seismic risk. That is why for the correct design of offshore wind turbine substructures is essential to take into account the seismic response of offshore wind turbines, regardless of their structural typology.

One of the most widely-used open-source advanced tools available in the literature is OpenFAST [1], which is a multi-physics and multi-fidelity software for the simulation of the coupled dynamic response of wind turbines in the time domain. OpenFAST is programmed in Fortran 95, and it might be considered not as a single program, but as a framework that couples computational modules. Aerodynamic loads on blades and tower are computed in AeroDyn, while HydroDyn determines the hydrodynamics loads (waves, currents...) for offshore structures. In addition, the ServoDyn module is used for the simulation of control and electrical subsystems of the wind turbine. ElastoDyn is the module where the structural dynamic responses of rotor, nacelle and tower is calculated and SubDyn is applied for modelling the dynamic response of the substructure, from the Transition Piece (TP) at the base of the tower to the base. This framework allows coupled nonlinear aero-hydro-servo-elastic simulation in the time domain. OpenFAST documentation can be found in [1].

Romero-Sánchez and Padrón [2] developed a formulation for the implementation of uniform ground input base motion and soil-structure interaction into SubDyn [3]. This paper presents an implementation of multi-support seismic input motions and dynamic soil-structure interaction into OpenFAST. The implemented multi-support seismic input motion includes translational, vertical and rotational foundation input motions at each support, while soil-structure interaction is introduced through a simplified lumped parameter model that is previously fitted to represent the dynamic response of the foundation. In this case, the use of lumped parameter models is considered as a tool to introduce dynamic soil-structure interaction into the model because, contrary to a static stiffness matrix, this approach allows to take into account the static stiffness of the foundation and an approximation to its impedance (the dynamic stiffness and damping functions). These capabilities have been implemented in OpenFAST, version 3.0.0, and the code can be downloaded at: https://github.com/mmc-siani-es/openfast_3.0.0_multisupport.

In addition, verification results are shown for a reference offshore wind turbine on a jacket substructure, conducting a number of cases with different seismic signals (translational and rotational motion). The new modified code allows to analyse the accelerations and internal forces of offshore wind turbines on multisupport substructures, taking into account seismic input motion (including input rotation at each individual support) and soil-structure interaction.

2 IMPLEMENTATION OF MULTI-SUPPORT SEISMIC INPUT MOTION AND SOIL-STRUCTURE INTERACTION MODEL INTO SUBDYN MODULE

2.1 General overview of SubDyn module

The module integrates its equations through its own solver. SubDyn [3] can be defined in three different main steps. Discretization of the substructuring following the strategies of classical linear beam Finite Elements motion equations. The existance of a substructure introduces a number of new degrees of freedom that can be very large for complex substructures (such as jackets), but more importantly, the model of a substructure with high natural frequencies leads to the necessity of smaller time steps in the general time integration framework. For this reason, the module implements Craig-Bampton modal reduction. Finally, the equations are re-arranged into State-Space type formulation for time-domain resolution and coupling with the rest of modules, specifically with the HydroDyn and ElastoDyn modules.

2.2 Generic equation of motion

Uniform base input motion is commonly adopted for the analysis of multi-degree of freedom systems subjected to earthquake excitations (see for instance Chopra [4]). This assumption leads to very easy-to-handle equations where an influence vector (Λ) is used, representing the motions of the different degrees of freedom as a consequence of the static aplication of a unit rigid support displacement or rotation. That was the strategy implemented in [2] for the study of monopile substructures. However, in the case of multi-support structures subjected to differential seismic excitations for each support, a more generic approach is needed. For this reason, in this section the formulation of the equations of motion to allow different prescribed motions at each support is generalised following the approach presented, for instance, in Clough and Penzien [5].

The original equation in the SubDyn module assumes a fixed base. The equation of motion describing the dynamic response of the substructure in partitioned matrix form can be written as:

$$\left[\begin{array}{cc} \mathbf{M} & \mathbf{M}_g \end{array}\right]\left(\begin{array}{c} \ddot{u}(t) \\ \ddot{u}_g(t) \end{array}\right)+\left[\begin{array}{cc} \mathbf{C} & \mathbf{C}_g \end{array}\right]\left(\begin{array}{c} \dot{u}(t) \\ \dot{u}_g(t) \end{array}\right)+\left[\begin{array}{cc} \mathbf{K} & \mathbf{K}_g \end{array}\right]\left(\begin{array}{c} u(t) \\ u_g(t) \end{array}\right)=F(t) \quad (1)$$

where the motion vectors have been partitioned to separate the response quantities from the input. The motions vectors contains two parts: $u(t)$ includes the degrees of freedom of the structure and $u_g(t)$ contains the components of the foundation input motions at each support. The dots represent differentiation with respect to time. The global mass, damping and stiffness matrices have been partitioned to correspond. The coupling matrices that express forces in the response of degrees of freedom due to motions of the supports are denoted with the subindex g. $F(t)$ represents the external forces acting at each degree of freedom of the structure. An expression for the effective seismic loading is obtained by separating the support motion effects from the response quantities and transferring these input terms to right hand side [5]:

$$\mathbf{M}\ddot{u}(t)+\mathbf{C}\dot{u}(t)+\mathbf{K}u(t)=F(t)-\mathbf{M}_g\ddot{u}_g(t)-\mathbf{C}_g\dot{u}_g(t)-\mathbf{K}_g u_g(t) \quad (2)$$

The beam elements in the substructure are modelled as Euler-Bernoulli or Timoshenko three-dimensional beams, and discretized using two-nodes 12-dofs finite elements defined by the stiffnes and mass matrices. The damping matrix, on the contrary, is not assembled from the element contribution. This matrix can be specified in three different ways: no damping, Rayleigh damping or user defined matrix. After the assembly in SubDyn, as described in equation (1), the system of equation can be written as:

$$\begin{bmatrix} M_{RR} & M_{RL} \\ M_{LR} & M_{LL} \end{bmatrix} \begin{pmatrix} \ddot{u}_R \\ \ddot{u}_L \end{pmatrix} + \begin{bmatrix} C_{RR} & C_{RL} \\ C_{LR} & C_{LL} \end{bmatrix} \begin{pmatrix} \dot{u}_R \\ \dot{u}_L \end{pmatrix} + \begin{bmatrix} K_{RR} & K_{RL} \\ K_{LR} & K_{LL} \end{bmatrix} \begin{pmatrix} u_R \\ u_L \end{pmatrix} = \begin{pmatrix} F_R \\ F_L \end{pmatrix} \tag{3}$$

where the subindex R identifies the boundary nodes (at the base and at the Transition Piece) and L identifies the rest of nodes (interior nodes). The applied forces include external forces, the hydrodynamic forces over the boundary nodes and the forces transfered to and from ElastoDyn through the Transition Piece. The Craig-Bampton transformation is therefore represented by:

$$\begin{Bmatrix} U_R \\ U_L \end{Bmatrix} = \begin{bmatrix} I & 0 \\ \Phi_R & \Phi_m \end{bmatrix} \begin{Bmatrix} U_R \\ q_m \end{Bmatrix} \tag{4}$$

Pre-multiplying by the Craig-Bampton transformation (eq. (4)), both sides of eq. (3), the interior degrees of freedom are hence transformed from physical DOFs to modal DOFs.

$$\begin{aligned} &\begin{bmatrix} M_{BB} & M_{Bm} \\ M_{mB} & I \end{bmatrix} \begin{pmatrix} \ddot{u}_R \\ \ddot{q}_m \end{pmatrix} + \begin{bmatrix} C_{BB} & C_{Bm} \\ C_{mB} & C_{mm} \end{bmatrix} \begin{pmatrix} \dot{u}_R \\ \dot{q}_m \end{pmatrix} \\ &\quad + \begin{bmatrix} K_{BB} & 0 \\ 0 & K_{mm} \end{bmatrix} \begin{pmatrix} u_R \\ q_m \end{pmatrix} = \begin{pmatrix} F_B \\ F_m \end{pmatrix} \end{aligned} \tag{5}$$

where:

$$M_{BB} = M_{RR} + M_{RL}\Phi_R + \Phi_R^T M_{LR} + \Phi_R^T M_{LL}\Phi_R \tag{6}$$
$$C_{BB} = C_{RR} + C_{RL}\Phi_R + \Phi_R^T C_{LR} + \Phi_R^T C_{LL}\Phi_R \tag{7}$$
$$K_{BB} = K_{RR} + K_{RL}\Phi_R \tag{8}$$
$$M_{mB} = \Phi_m^T M_{LR} + \Phi_m^T M_{LL}\Phi_R \tag{9}$$
$$C_{mB} = \Phi_m^T C_{LR} + \Phi_m^T C_{LL}\Phi_R \tag{10}$$
$$M_{Bm} = M_{mB}^T, C_{Bm} = C_{mB}^T \tag{11}$$
$$F_B = F_R + \Phi_R^T F_L \tag{12}$$
$$F_M = \Phi_M^T F_L \tag{13}$$

Once the general equation of motion after Craig-Bampton reduction is obtained, the matrices are partitioned as described in equation 2. The vector of displacements at the boundary nodes contains the displacements at the interface node with the tower (u_I) and the displacements at base nodes, which would move following the ground motion vector (u_g):

$$U_R = \begin{pmatrix} u_g \\ u_I \end{pmatrix} \tag{14}$$

Accordingly, the mass matrices after Craig-Bampton modal reduction can be decomposed as:

$$M_{BB} = \begin{bmatrix} M_{bb} & M_{bI} \\ M_{Ib} & \bar{M}_{BB} \end{bmatrix} \quad ; \quad M_{Bm} = \begin{bmatrix} M_{bm} \\ \bar{M}_{Bm} \end{bmatrix} \quad ; \quad M_{mB} = \begin{bmatrix} M_{mb} \\ \bar{M}_{mB} \end{bmatrix} \tag{15}$$

On the one hand, subindex *b* and subindex *I* represent base and interface nodes, respectively. On the other hand, the overhead bar here and below denotes matrices/vectors after the fixed-bottom boundary condition are applied. The same process is applied to the damping (C) and the stiffness (K) matrices. Finally, the new motion equation can be writting as:

$$\begin{bmatrix} \tilde{M}_{BB} & \tilde{M}_{Bm} \\ \tilde{M}_{mB} & I \end{bmatrix} \begin{pmatrix} \ddot{u}_I \\ \ddot{q}_m \end{pmatrix}^t + \begin{bmatrix} \tilde{C}_{BB} & \tilde{C}_{Bm} \\ \tilde{C}_{mB} & C_{mm} \end{bmatrix} \begin{pmatrix} \dot{u}_I \\ \dot{q}_m \end{pmatrix}^t + \begin{bmatrix} \tilde{K}_{BB} & 0 \\ 0 & K_{mm} \end{bmatrix} \begin{pmatrix} u_I \\ q_m \end{pmatrix}^t = \begin{pmatrix} (F_I + F_{Ig}) + \Phi_R^T (F_L + F_{Lg}) \\ \Phi_m^T (F_L + F_{Lg}) \end{pmatrix} - \begin{bmatrix} M_{Ib} \\ M_{mb} \end{bmatrix} \ddot{u}_g - \begin{bmatrix} C_{Ib} \\ C_{mb} \end{bmatrix} \dot{u}_g - \begin{bmatrix} K_{Ib} \\ K_{mb} \end{bmatrix} u_g \quad (16)$$

The interface nodes and the Transition Piece (that is assumed as a rigid body) are considered as rigidly connected.

$$u_I = T_I u_{tp} \quad (17)$$

$$F_{tp} = T_I^T F_I \quad (18)$$

Where T_I is a simple transformation matrix depending on the differences between the locations between both points. Including these two relation into eq. (16), one can write

$$\begin{bmatrix} \tilde{M}_{BB} & \tilde{M}_{Bm} \\ \tilde{M}_{mB} & I \end{bmatrix} \begin{pmatrix} \ddot{u}_I \\ \ddot{q}_m \end{pmatrix}^t + \begin{bmatrix} \tilde{C}_{BB} & \tilde{C}_{Bm} \\ \tilde{C}_{mB} & C_{mm} \end{bmatrix} \begin{pmatrix} \dot{u}_I \\ \dot{q}_m \end{pmatrix}^t + \begin{bmatrix} \tilde{K}_{BB} & 0 \\ 0 & K_{mm} \end{bmatrix} \begin{pmatrix} u_I \\ q_m \end{pmatrix}^t = \begin{pmatrix} \tilde{F}_{tp} \\ \tilde{F}_m \end{pmatrix} - \begin{bmatrix} F_{IsisM} \\ F_{MsisM} \end{bmatrix} \ddot{u}_g(t) - \begin{bmatrix} F_{IsisC} \\ F_{MsisC} \end{bmatrix} \dot{u}_g(t) - \begin{bmatrix} F_{IsisK} \\ F_{MsisK} \end{bmatrix} u_g(t) \quad (19)$$

These terms can be defined as:

$$\tilde{M}_{BB} = T_I^T \bar{M}_{BB} T_I \quad (20)$$

$$\tilde{C}_{BB} = T_I^T \bar{C}_{BB} T_I \quad (21)$$

$$\tilde{K}_{BB} = T_I^T \bar{K}_{BB} T_I \quad (22)$$

$$\tilde{M}_{Bm} = T_I^T \bar{M}_{BM} \quad (23)$$

$$\tilde{C}_{Bm} = T_I^T \bar{C}_{BM} \quad (24)$$

$$C_{mm} = \Phi_m^T C_{LL} \Phi_m \quad (25)$$

$$K_{mm} = \Omega_m^2 \quad (26)$$

$$\tilde{F}_{tp} = F_{tp} + T_I^T \bar{F}_{R,e} + T_I^T \bar{F}_{R,g} + T_I^T \bar{\Phi}_R^T (F_{L,e} + F_{L,g}) \quad (27)$$

$$\tilde{F}_m = \Phi_m^T (F_{L,e} + F_{L,g}) \quad (28)$$

$$F_{IsisK} = T_I^T (\bar{K}_{Ib}) \quad (29)$$

$$F_{MsisK} = K_{mb} \quad (30)$$

$$F_{IsisC} = T_I^T (C_{Ib}) \quad (31)$$

$$F_{MsisC} = C_{mb} \quad (32)$$

$$F_{IsisM} = T_I^T (M_{Ib}) \quad (33)$$

$$F_{MsisM} = M_{mb} \quad (34)$$

where $F_R = F_{R,e} + F_{R,g}$, with $F_{R,e}$ being the external loads from other modules, the hydrodynamic forces over the boundary nodes and the forces transfered to and from ElastoDyn through the Transition Piece; and $F_{R,g}$ consists of the SubDyn gravitational loads.

For the cases studied in this paper, the same input signal has been implemented on all supports due to the proximity of the foundations and to the nature of the vertically-incident plane waves assumed in this study. No different Kinematic Input Factors (KIFs) are expected on each pile if the seismic incidence is vertical. In any case, each pile head rotates independently, as the base is not considered as rigid body. Figure 1 shows the same input motion in each support.

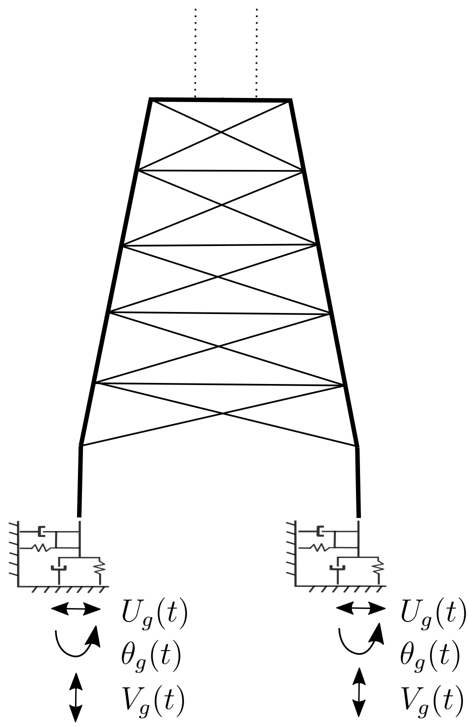

Figure 1: Ground input motion at different supports.

2.3 Simplified Lumped Parameter Model into SubDyn

The introduction of an LPM can be simply understood as adding one (or several) additional elements at the base of the substructure. At this point, the simplified Lumped Parameter Model proposed by Carbonari et al. [6], is adopted for the lateral vibrations, while the spring-damper model is adopted for vertical and torsional vibrations. More information related to the introduction of this model into SubDyn can be found at [2]. SLPM coefficients are calculated using least squares to be optimally adapted to the impedance functions defining the dynamic response of the wind turbine foundation.

2.4 State-space formulation

Variables are arranged in sets of inputs and outputs that can communicate with the rest of modules (HydroDyn and ElastoDyn). The equations are written in state-space form. The states are defined as:

$$x = \left(\begin{array}{cc} q_m & \dot{q}_m \end{array} \right)^T \tag{35}$$

The input vector are defined as:

$$u = \left(\begin{array}{ccccc} U_{tp} & \dot{U}_{tp} & \ddot{U}_{tp} & F_{L,e} & F_{R,e} \end{array} \right)^T \tag{36}$$

2.4.1 State equation

Equation (19) is cast into standard linear system state equation of the form:

$$\dot{x} = X = \mathbf{A}x + \mathbf{B}u + F_x \tag{37}$$

To do, the second row of equation (19) needs to be written down and solved for $\ddot{U}_L$. After doing so, the matrices of the state equation can be found to be:

$$\mathbf{A} = \begin{bmatrix} 0 & I \\ -\tilde{K}_{mm} & -C_{mm_f} - \tilde{C}_{mm} \end{bmatrix} \tag{38}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -\tilde{C}_{mB_f} & -\tilde{M}_{mB} & \Phi_m^T & 0 \end{bmatrix} \tag{39}$$

$$Fx = \begin{bmatrix} 0 \\ \Phi_m^T F_{L,g} + F_{MsisK} u_g + F_{MsisC} \dot{u}_g - F_{MsisM} \ddot{u}_g \end{bmatrix} \tag{40}$$

where the damping matrix is composed of the structural damping (C) and damping terms related to the LPM foundation model (C_f).

2.4.2 Output equation to ElastoDyn

The first output equation computes the interaction forces between tower and substructure at the Transition Piece.

$$y_1 = Y_1 = -F_{tp} \tag{41}$$

Writting the first row of (19) and solving for F_{tp}, the output equation can be written as:

$$-Y_1 = \mathbf{C}_1 x + \mathbf{D}_1 \bar{u} + F_{y_1} \tag{42}$$

where

$$\mathbf{C}_1 = \left[\begin{array}{cc} -\tilde{M}_{Bm}\Omega_m^2 & -\tilde{M}_{Bm}(C_{mm_f} + \tilde{C}_{mm}) + \tilde{C}_B m \end{array} \right] \tag{43}$$

$$\mathbf{D}_1 = \left[\begin{array}{ccccc} \tilde{K}_{BB} & -\tilde{C}_{mB_f}\tilde{M}_{Bm} + \tilde{C}_{BB_f} & -\tilde{M}_{mB}\tilde{M}_{Bm} + \tilde{M}_{BB} & \tilde{M}_{Bm}\Phi_m^T - T_I^T \Phi_R^T & -T_I^T \end{array} \right] \tag{44}$$

$$F_{y_1} = -T_I^T (\bar{F}_{Ig} + \bar{\Phi}_R^T F_{Lg}) - F_{IsisK} u_b - F_{IsisC} \dot{u}_b + F_{IsisM} \ddot{u}_b + \tilde{M}_{Bm} \left[F_{MsisK} u_b + F_{MsisC} \dot{u}_b - F_{MsisM} \ddot{u}_b + \Phi_m^T F_{Lg} \right] \tag{45}$$

2.4.3 Output equation to HydroDyn

The second output equation collects all the motions needed by the HydroDyn module to compute hydrodynamic loads.

$$y_2 = Y_2 = \{ \; U_I \quad U_L \quad \dot{U}_I \quad \dot{U}_L \quad \ddot{U}_I \quad \ddot{U}_L \; \}^T \tag{46}$$

$$Y_2 = \mathbf{C}_2 x + \mathbf{D}_2 u + F_{y_2} \tag{47}$$

where

$$\mathbf{C}_2 = \begin{bmatrix} 0 & 0 \\ \Phi_m & 0 \\ 0 & 0 \\ 0 & \Phi_m \\ 0 & 0 \\ -\Phi_m \tilde{K}_{mm} & -\Phi_m (C_{mm_f} + \tilde{C}_{mm}) \end{bmatrix} \tag{48}$$

$$\mathbf{D}_2 = \begin{bmatrix} T_I & 0 & 0 & 0 & 0 \\ \bar{\Phi}_R T_I & 0 & 0 & 0 & 0 \\ 0 & T_I & 0 & 0 & 0 \\ 0 & \bar{\Phi}_R T_I & 0 & 0 & 0 \\ 0 & 0 & T_I & 0 & 0 \\ 0 & -\Phi_m \tilde{C}_{mB_f} & \tilde{\bar{\Phi}}_R T_I - \Phi_m \tilde{M}_{mB} & \Phi_m \Phi_m^T & 0 \end{bmatrix} \tag{49}$$

$$F_{y_2} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \Phi_m \Phi_m^T F_{Lg} + \Phi_m (F_{MsisK} u_b + F_{MsisC} \dot{u}_b - F_{MsisM} \ddot{u}_b) \end{bmatrix} \tag{50}$$

3 VERIFICATION RESULTS

The implementation into OpenFAST of the multi-support input ground motion and the Simplified Lumped Parameter Model at the base of the substructure has been initially verified by comparison against results obtained from a simplified model written in matlab for this purpose. To begin with, the verification model is first described. Subsequently, the cases designed for verification are presented. Lastly, the results obtained from the comparison are evaluated.

3.1 Reference simple model for comparison

The model used for the comparison is a 3D Finite Element Model (FEM) with Timoshenko beam elements, consisting of two different structures: the inferior part corresponding to the jacket and the upper part corresponding to the tower, with varying properties along height. On top, the rotor-nacelle-assembly (RNA) is modeled as a punctual rigid concentrated inertia.

Again, the equation of motion can be written as:

$$\mathbf{M}\, \ddot{u}(t) + \mathbf{C}\, \dot{u}(t) + \mathbf{K}\, u(t) = -\mathbf{M_b} \ddot{u}_b(t) - \mathbf{C_b} \dot{u}_b(t) - \mathbf{K_b} u_b(t) \tag{51}$$

where the global mass, damping and stiffness matrices is partitioned into two terms. $\mathbf{M_b}$, $\mathbf{C_b}$ and $\mathbf{K_b}$ are the coupling matrices that express forces in the response degrees of freedom due to motions of the supports and $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the remaining terms of global matrices. The input ground displacement at time t is denoted by $u_b(t)$, and transfering the inputs terms to the right hand. The beam elements implemented are identical to those already implemented in SubDyn

Assuming steady–state harmonic response:

$$u(t) = U(\omega)\mathrm{e}^{\mathrm{i}\omega t} \tag{52}$$

where ω is the circular frecuency of the excitation. The time-harmonic equation of motion employed can be written as:

$$\left(\mathbf{K} + \mathrm{i}\omega\mathbf{C} - \omega^2\mathbf{M}\right) U(\omega) = \left(-\mathbf{K_b} - \mathrm{i}\omega\mathbf{C_b} + \omega^2\mathbf{M_b}\right) U_b(\omega) \tag{53}$$

This reference simplified model was implemented in an independent matlab© code. As usual, time domain response will be therefore obtained through Frecuency Domain Analysis [4] making use of the Fast Fourier Transform.

3.2 Reference configuration and verification cases

The reference configuration adopted for this study is the widely used 5MW NREL (National Renewable Energy Laboratory) reference turbine. More precisely, the base configuration is the one defined for the OC4 (Offshore Code Comparison Collaboration) for the offshore 5MW NREL reference turbine on a jacket. Specific data can be found in Popko et al. [7].

Table 1 lists the main characteristics of the foundation input motions (FIM) used for the three simplified verification cases presented. The model allows the soil-structure interaction (SSI) to be considered. ξ_t denotes the structural tower damping ratio and Rayleigh damping is used at jacket substructure ($\alpha = \beta = 2\%$). Additionally, Table 2 presents the parameters obtained for the SLPM from fitting the impedance functions corresponding to the foundation of this turbine [8]. The units of the SLPM parameters are those of the International System, as desribed in [6]. The impedance functions and the time-harmonic kinematic interaction factors corresponding to the pile foundation were obtained from a finite elements - boundary elements model [9]. These kinematic interaction factors allow to compute the translational and rotational foundation input motions

N	FIM	SSI	ξ_t	Input base motion
1	Lateral	×	5%	Quarter of sine ($f = 0.1$ Hz, $A = 0.1$ m)
2	Rotational	×	2%	Quarter of sine ($f = 0.1$ Hz, $A = 0.05$ rad)
3	Lateral & Rotational	✓	2%	Chi-Chi earthquake

Table 1: Verification cases.

3.3 Verification results

This section provides the validation results of the different cases described in Table 1. Figure 2 presents the comparisons between the results obtained using the modified version of OpenFAST and those of the reference simplified model (matlab code). Motions at the top of the tower, and at the platform are represented. It is shown that the agreement is very good in terms of displacements and rotations. It is important to keep in mind the major difference between both codes, being the OpenFAST model much more elaborated than the reference model, and being the first one solved in time domain and the second one in frequency domain.

K_{SLPM}	**Value**	C_{SLPM}	**Value**	M_{SLPM}	**Value**
k_h	1.295e+6	c_h	4.187e+6	m_h	1.0
k_r	8.952e+9	c_r	1.226e+7	I_r	32.79
k_t	9.071e+8	c_t	1.061e+7	m_t	1.757e+5
k_z	2.679e+9	c_z	7.081e+7	m_z	1.0
k_{tor}	7.131e+10	c_{tor}	4.414e+8	I_{tor}	8.602e+6
h_1	-2.488	h_2	-2.974	h_3	-0.592

Table 2: SLPM parameters.

Table 3 shows the fundamental frequencies as a function of the assumed base condition. As expected, the consideration of soil-structure interaction provides a longer period. This phenomenon also allows to see the relevant influence that the properties of the foundation exert on the system global response.

SSI	**Fundamental frequency**
×	0.316 Hz (T=3.16 s)
✓	0.301 Hz (T=3.32 s)

Table 3: Fundamental frequencies in the fore-aft direction obtained for different base conditions

4 ILUSTRATION EXAMPLE

After having verified the implementation of the kinematic input motions for a simplified model configuration, this section illustrates the use of the code for the analysis of the seismic response of the offshore wind turbine while the turbine is operating and is subjected to enviromental conditions. The NREL 5 MW reference OWT [7] described above is considered in the ilustration example. The simplified Lumped Parameter Model is used to represent the flexibility of the soil-foundation system (see Figure 3). The system is assumed to be subjected to vertically-incident shear waves. The Imperial Valley earthquake (PEER Ground Motion Database [10], RSN: 192) is considered as free-field ground-surface seismic action. The simulation is allowed to run for 200 seconds before the earthquake shaking arrive, in order to allow the dissipation of the transient response generated at the beginning of the simulation. The wind turbine remains in power production mode when the earthquake occurs. The time-harmonic kinematic interaction factors corresponding to the pile foundation were computed through the same boundary element model employed to compute the impedance functions [9]. These kinematic interaction factors allow to compute the translational and rotational foundation input motions (see Figure 4) that are then defined at the base of the SLPM.

Figure 5 presents the computed seismic response in terms of tower top accelerations and axial forces and bending moments in the jacket, specifically at the jacket node where the highest values of axial forces and bending moments occur. Each plot presents the response of the OWT computed under three different loading situations: a) only environmental loads (wind, waves and currents); b) taking into account both translational and rotational foundation input motions; and c) considering the original seismic input motion as translational input motion.

The seismic action increases the response of the structure in terms of accelerations at the tower top, by a factor of 4. In particular, considering the maximum internal forces without earthquake loads, in operational mode, the values increase by a factor of 2-3 in axial forces and 4-5 in bending moments, in the studied nodes.

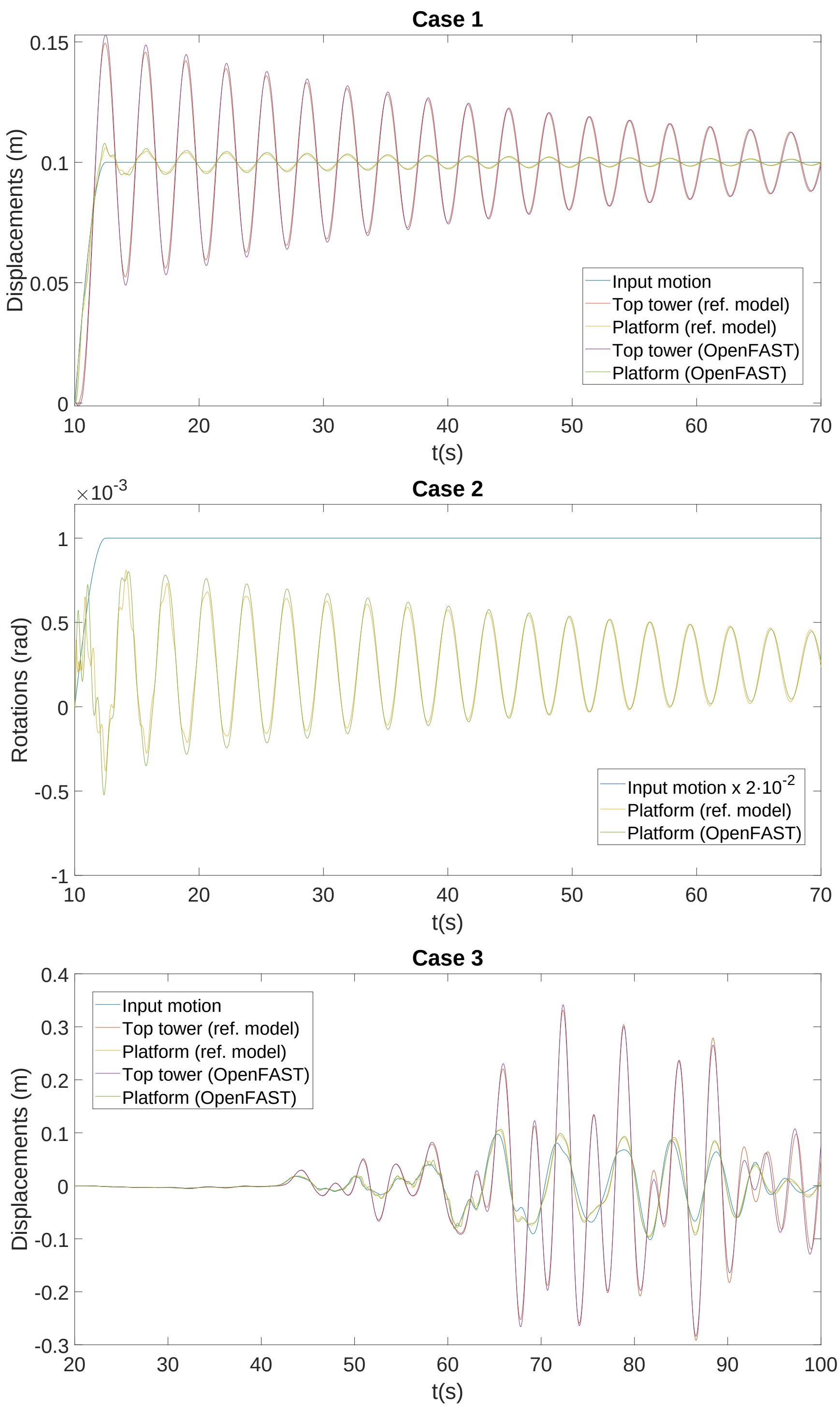

Figure 2: Results corresponding to verification cases.

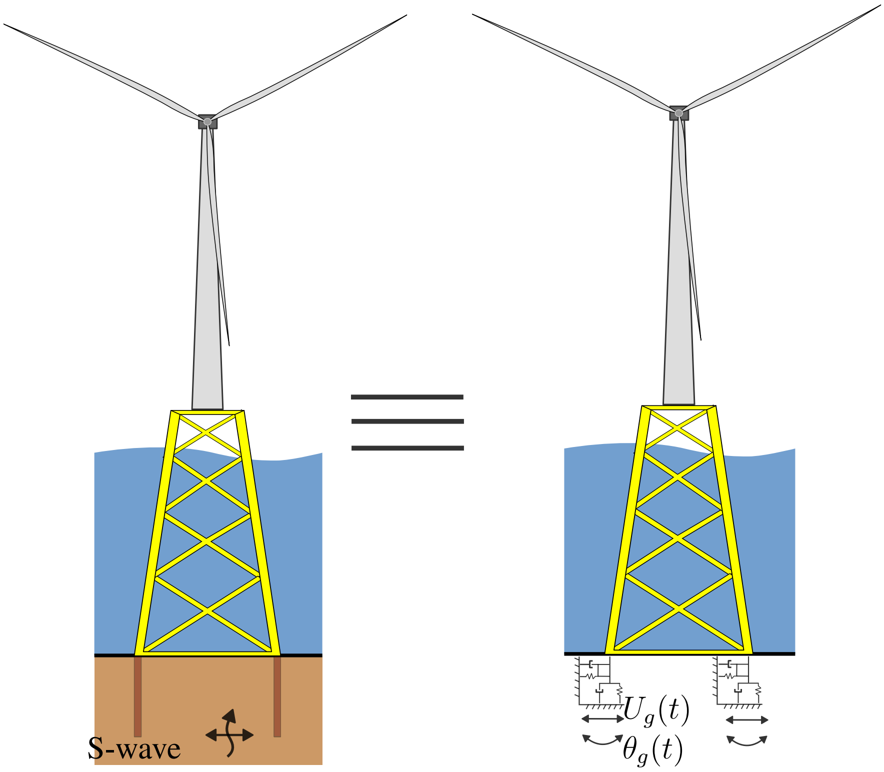

Figure 3: Ilustration Example Jacket.

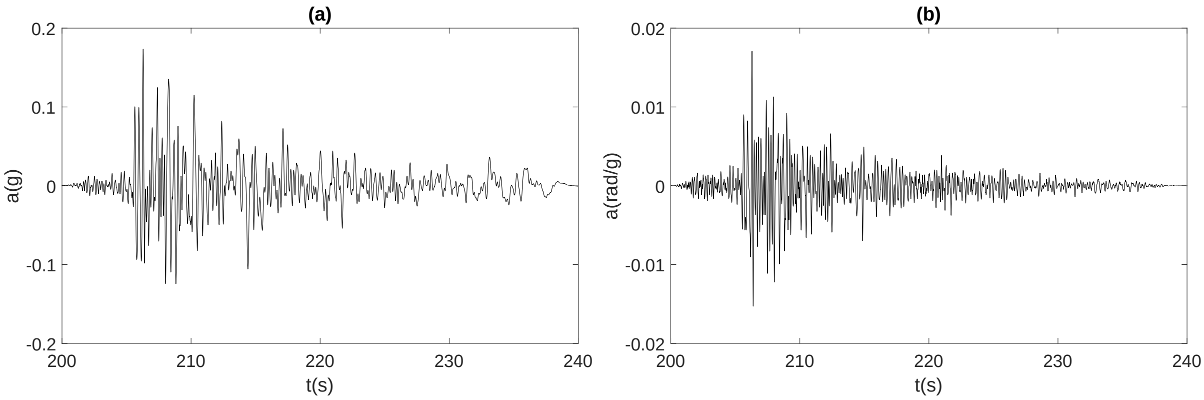

Figure 4: Lateral FIM (a) and Rotational FIM (b). Imperial Valley earthquake.

Finally, in this specific ilustration example, the difference between considering the original earthquake signal or the filtered earthquake signal is negligible in axial forces, and it is not very relevant in terms of accelerations and bending moments.

5 CONCLUSIONS

The paper develops the formulation needed for an implementation of multi-support seismic input motions into the open-source software OpenFAST, with the aim of facilitating the use of

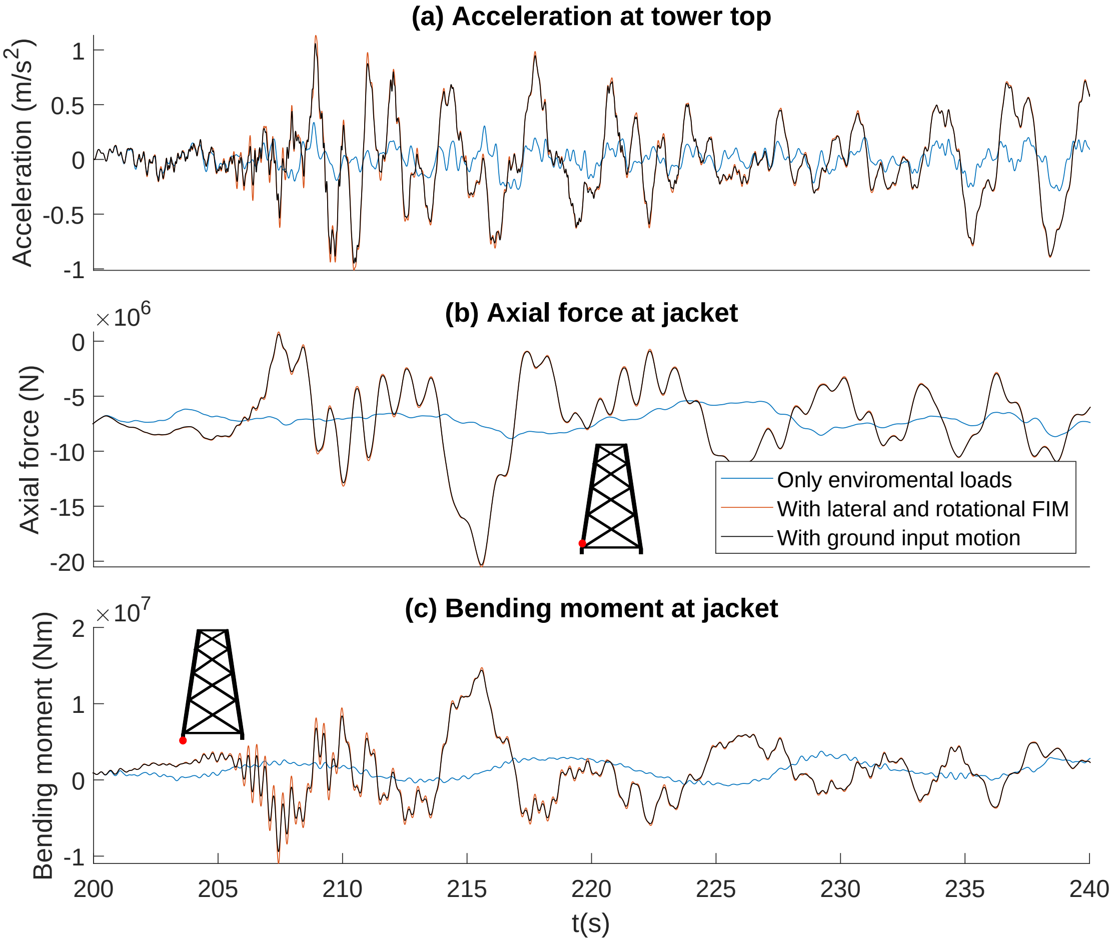

Figure 5: Results corresponding to ilustration example.

this tool for the seismic analysis of wind turbines. This code allows not only horizontal, but also vertical and rotational foundation input motions to be considered, on a single-support substructure (monopile) and with multiple supports (tripods and jackets). In the ilustration example, a wind turbine on a jacket with piles has been studied. Horizontal and rotational foundation input motions are computed taking the pile kinematic interaction factors into account.

The use of lumped parameter models is considered here as a tool to introduce soil-structure interaction into the model because this approach allows to take into account, not only the static stiffness of the foundation, but an approximation to its impedance, i.e., the dynamic stiffness and damping functions.

These capabilities have been implemented in OpenFAST, version 3.0.0, and the code can be downloaded at: https://github.com/mmc-siani-es/openfast_3.0.0_multisupport. The application of this code, which allows to stablish different input motion in each support, can be relevant for future studies where inclined seismic incidence is considered.

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