Unstructured meshes calculation method for reponse amplitude operators of TLP wind turbines

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Abstract

Here we propose a new method for calculating the pitch Response Amplitude Operators (RAOs) for a Tension Leg Platform (TLP) wind turbine. The traditional method is limited for finding the stability of a body in water; the traditional method is also limited regarding the development requirement of worldwide floating offshore wind energy. The TLP is modeled and meshed in GID software, and a time domain analysis at a particular wind speed was carried out using FEM analysis on an unstructured mesh (UM-FEM). The calculations of mass and hydrodynamic matrices are discussed in detail. Also, translation of these matrices from the origin, which is typically on the free surface of a body of water, to the center of gravity for the platform is discussed in detail. Finally, a linear analysis of a mooring system is discussed, and pitch RAOs were calculated and validated against prior data. The result from the proposed new method closely fits the NREL results and reaches the same conclusion as other studies. This implies that this computation process is correct and that this new method can be used with low error and in conjunction with other methods for offshore wind energy generation applications.

Keywords: Offshore Wind Turbine; Floating Foundation; Tension Leg Platform; Unstructured Mesh

1 Introduction

In order to find variations in the stability of an object, it is necessary to calculate body motions. Several methods can be implemented to determine the variation in stability [1, 14], which include simplified and advanced methods. Simplified methods include strip theory based on the use of potential theory, whereas advanced methods are based on the use of computational fluid dynamic (CFD) methods. In strip theory, the object under consideration is divided into vertical two-dimensional (2D) strips or sections, then the forces, moments, and hydrodynamic coefficients on each strip are calculated followed by a summation of the results on each strip to obtain the final effect [1]. Panel methods [2] can also be implemented in lieu of the strip theory method, in which the object is divided into small panels rather than vertical sections of mesh. When Navier-Stokes equations are solved, as is the cases in typical CFD implementations, it is possible to catch some viscous effects along with non-linear effects such as green water on deck and bottom slamming. Nowadays, CFD implementation has become increasingly popular; however, strip theory is still commonplace in comercial software implementations due to the speed and accuracy such as Wave Analysis MIT (WAMIT) [2]. Computational costs (CPU-time and hardware cost) are a major disadvantage of CFD implementation. Here, a new time domain solver based on finite element formulation based on an unstructured mesh (UM-FEM), which uses the potential theory along with Stokes perturbation approximation is proposed. This method was first used in a study by Borja [3] which introduces UM-FEM and compares the results with analytical solutions It is in agreement with other results and induces the CPU time, showing the potential of this method. In this study, we introduce UN-FEM into a floating wind turbine field and to use it to obtain the pitch RAO value.

A floating wind turbine field is different than other offshoring structures. The physical model used to demonstrate the implementation of the proposed time domain solver can be subdivided into three major components: the wind turbine, the floating platform, and the mooring system. In the present analysis, the floating platform and the mooring system were modeled in GID software which is a universal pre- and postprocessor for numerical simulations in field of engineering [4]. The time domain analysis was carried out at a constant wind speed using appropriate mass, damping, and stiffness matrices for the wind turbine [5, 6]. The combination of the wind turbine and floating platform were assumed to undergo rigid body motion in the standard modes of motion. These were based on wave-body interaction theory, as well as translation and rotational motions along the x-, y-, and z-axes. Modes 1 to 3 were translational modes of surge, sway, and heave; each representing translation along the x-, y-, and z-axes, respectively. Modes 4 to 6 are rotational modes of roll, pitch, and yaw; each representing rotation about the x-, y-, and z-axes, respectively [7].

1.1 EQUATIONS OF MOTION

The equations governing the rigid-body motion of a floating object consist of the standard Newtonian equations of motion. The six modes of motion are described and summarized in matrix form as [8]:

$$\left(M_{added}(\omega)+M_{WT}+M_{structure}\right)\ddot{\zeta}(t)+ \left(B_{structure}(\omega)+B_{WT}\right)\dot{\zeta}(t)+ \left(C_{WT}+C_{structure}+C_{mooring}\right)\zeta(t)=X(\omega)$$

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$$M_{total}(\omega)\ddot{\zeta}+B_{total}\dot{\zeta}(t)+C_{total}\zeta(t)=X(\omega), \quad (1)$$

where M_{added} is the added mass matrix; M_{WT} is the mass matrix of the wind turbine at a constant wind speed; $M_{structure}$ is the mass matrix of the platform; $B_{structure}$ is the damping matrix of the platform; B_{WT} is the damping matrix of the wind turbine; C_{WT} is the stiffness matrix of the wind turbine; $C_{structure}$ is the stiffness matrix of the platform; $C_{mooring}$ is the stiffness matrix of the mooring system; $\ddot{\zeta}$, $\dot{\zeta}$, and ζ are acceleration, velocity, and displacement of the system.

To solve the equations of motion, two methods are used: the frequency domain and the time domain. In the frequency domain, the amplitude of the motion was calculated over a range of frequencies, and in the time domain, the actual time history of the motion was calculated at a given frequency.

1.2 RESPONSE AMPLITUDE OPERATORS

A Response Amplitude Operator (RAO) is defined as the response of a floating structure in a given mode of motion to a wave of unit amplitude as a function of frequency [5]. The RAOs of the rotation degree are normalized by the platform length. The length of the platform is 9 m. It is a complex function and gives information related to the magnitude and phase of the response of the floating structure. The RAO for each of the six modes of motion is given by solving the equations of motion in the frequency domain. The expression is shown below:

$$-\omega^2 M_{total}(\omega) RAO + i\omega B_{total}(\omega) RAO + C_{total} RAO = X(\omega)$$

$$\begin{bmatrix} RAO_1(\omega) \\ RAO_2(\omega) \\ RAO_3(\omega) \\ RAO_4(\omega) \\ RAO_5(\omega) \\ RAO_6(\omega) \end{bmatrix} = \begin{bmatrix} -\omega^2 M_{total}(\omega) RAO + \\ i\omega B_{total}(\omega) RAO + \\ C_{total} RAO \end{bmatrix}^{-1} X(\omega). \quad (2)$$

From Equation (2), it is clear that RAOs are complex in nature. The real and imaginary parts give the magnitude and the phase of the RAO. If RAO in one direction is $x+iy$, then

$$Magnitude\ of\ RAO = \sqrt{x^2+y^2}\ , \quad (3)$$

$$Phase\ of\ RAO = \arctan\left(y/x \right). \quad \textbf{(4)}$$

2 NREL 5-MW turbine and TLP troperties

In order to analyze and compare the date with former result, the baseline turbine properties are taken from the National Renewable Energy Laboratory (NREL), which represents a typical state-of-the-art multi-megawatt turbine. Many papers have adopted this wind turbine as baseline and easy to find enough information and research result we can use and compare [8, 9, 10, 11]. The important specifications of the turbine are listed in Table 1. An in-depth description of the turbine can be found in [12].

TABLE 1 Baseline turbine properties from the NREL *report*

Rated power	5 MW
Hub height	90 m
Wind speed:	
Cut-in	3 m/s
Rated	11.4 m/s
Cut-out	25 m/s
Cut-in rotor speed	6.9 rpm
Rated rotor speed	12.1 rpm
Over hung	5 m
Rotor mass	110,000 kg
Nacelle mass	240,000 kg
Tower mass	347,460 kg
CM location	-0.2 m, 0.0 m, 64.0 m

The tension leg platform used in floating wind turbines has been studied by Tracy at MIT [6] and Matha at the NREL [5]. Tracy's thesis contains a parametric optimization study conducted for several different floating-platform concepts for NREL's 5-MW base line wind turbine, and finally he show some concept models including the TLP model [6], which Matha referred to as the MIT-TLP model. At the NREL, Matha researched the MIT-TLP model and changed it in different tension leg spoken length.

The properties of the TLP are taken from Tracy's Parametric Design of Floating Wind Turbines and are listed in Table 2 [6].

TABLE 2 Properties of MIT-TLP model [10]

Platform diameter	18 m
Platform draft	47.89 m
Water depth	200 m
Ballast at platform bottom:	
Concrete mass	8,216,000 kg
Concrete height	12.6 m
Average steel density	7850 kg/m^3
Average concrete density	2562.5 kg/m^3
Steel wall thickness	0.015 m
Total displacement	12,187,000 kg
Wind speed (constant)	11.0 m/s
Sea state significant wave height	10.0 m
Peak spectral wave period	17.6394 s

The properties of the mooring system used in the present model are listed in Table 3 [6].

TABLE 3 Properties of the mooring system

Number of mooring lines	8
Mooring system angle	90°
Fairlead distance from center	18 m
Average mooring system tension per line	3931 kN
Unstretched mooring line length	151.73 m
Line diameter	0.127 m
Line mass per unit length	116.03 kg/m
Line extensional stiffness	1.5 GN

3 Calculation matrices

3.1 MASS PROPERTIES

The mass matrix of any structure can be represented by Equation (5) shown below,

$$MassMatrix = \begin{bmatrix} M & 0 & 0 & 0 & M_{Z_G} & -M_{yG} \\ 0 & M & 0 & -M_{Z_G} & 0 & M_{xG} \\ 0 & 0 & M & M_{yG} & -M_{xG} & 0 \\ 0 & -M_{Z_G} & M_{yG} & I_{xx} & I_{xy} & I_{xz} \\ M_{Z_G} & 0 & -M_{xG} & I_{yx} & I_{yy} & I_{yz} \\ -M_{yG} & M_{xG} & 0 & I_{zx} & I_{zy} & I_{zz} \end{bmatrix}, \quad (5)$$

where M is the mass of the structure; x_G, y_G, and z_G are coordinates for the center of gravity (CG) of the structure and I is the moment of inertia. The mass matrix for the turbine is obtained from [6] where the matrix is calculated with origin at the free surface of a body of water. The mass matrix of the turbine is as follows:

$$M_{WT} = \begin{bmatrix} 0.7 & 0 & 0 & 0 & 44.3 & 0 \\ 0 & 0.7 & 0 & -44.3 & 0 & 6.6 \\ 0 & 0 & 0.7 & 0 & -6.6 & 0 \\ 0 & -44.3 & 0 & 3499 & 0 & 0 \\ 44.3 & 0 & -6.6 & 0 & 3560 & 0 \\ 0 & 6.6 & 0 & -513.3 & 0 & 101.2 \end{bmatrix} \times 10^6 . \quad (6)$$

Theoretically, the mass matrix should be symmetric; however, the mass matrix of the turbine shown here in Equation (6) is not symmetric due to absence of the I_{xz} term. Tracy and Matha used WAMIT and fatigue, aerodynamics, structure, and turbulence (FAST) software to analyze the turbine platform assembly in different environmental states [5,6]. FAST software is CAE tool which was developed by the NREL and Oregon State University, and it is a comprehensive aero-elastic simulator capable of predicting extreme and fatigue loads of two- and three-bladed horizontal-axis wind turbines [8, 13]. FAST and WAMIT software are used to perform the analysis with the coordinate system at the free surface of the body of water. However, in the present analysis, all calculations were performed with the coordinate system at the CG of the turbine-platform assembly. Therefore, all the matrices obtained from Tracy's thesis must be translated to the CG for the assembly.

The mass matrix of the platform can be calculated from Equation (6). From the platform data reported in the previous section, the mass of the platform including the ballast is 8,654,734 kg, and the CG is at (0, 0, -40.6). The mass matrix calculated at the center of gravity is as follows:

$$M_{platform} = \begin{bmatrix} 8.6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 8.6 & 0 & 0 & 0 & 0 \\ 0 & 0 & 8.6 & 0 & 0 & 0 \\ 0 & 0 & 0 & 453.7 & 0 & 0 \\ 0 & 0 & 0 & 0 & 453.7 & 0 \\ 0 & 0 & 0 & 0 & 0 & 362.4 \end{bmatrix} \times 10^6 . \quad (7)$$

The turbine mass matrix calculated at the origin and the platform mass matrix calculated at CG were translated to the CG of the whole structure, which lies at (-0.015, 0, -32.716). The translation of different components of the mass matrix is explained below:

Let the terms with superscript '*tf*' refer to translated quantity of the turbine mass matrix, while 'to' refers to the quantity calculated at the CG of the turbine. Similarly, '*pf*' is the final quantity of the platform mass matrix while '*po*' is the original term. Different terms in mass matrix change and are discussed below. The turbine mass matrix translated from the origin to the CG of the structure is:

$$I_{xx}^{tf} = I_{xx}^{t0} + m_T \left(y_{gs}^2 + z_{gs}^2 \right), \quad (8)$$

$$I_{xy}^{tf} = I_{xy}^{t0} - m_T \left(x_{gs} y_{gs} \right). \quad (9)$$

The platform mass matrix translated from the CG of the platform to the CG of the structure is:

$$I_{xx}^{pf} = I_{xx}^{p0} + m_p \left(\left(y_{gs} - y_{gt} \right)^2 + \left(z_{gs} - z_{gt} \right)^2 \right), \quad (10)$$

$$I_{xy}^{pf} = I_{xy}^{p0} - m_p \left(x_{gs} - x_{gp} \right) \left(y_{gs} - y_{gp} \right), \quad (11)$$

where m_T and m_P are masses of turbine and platform, respectively, x_{gs}, y_{gs}, and z_{gs} are the coordinates of the CG of the structure, and x_{gp}, y_{gp}, and z_{gp} are the coordinates of the CG of the platform. The rest of the terms in the mass matrix are translated similarly. The terms corresponding to M_x, M_z, and M_y in the off diagonal are changed corresponding to changes in the coordinate axis. The summation mass matrix is frequency-dependent and was calculated internally by SeaFEM for every frequency.

3.2 TRANSLATION OF MATRICES

The R.H.S. term in the equation of motion is a 6×1 matrix containing forces and moments in the x-, y-, and z-directions. When the coordinate system is changed, forces are unchanged in the new coordinate system, but moments will change depending on the location of the new coordinate system. This change of moment can be incorporated by transformation of the stiffness and damping matrices.

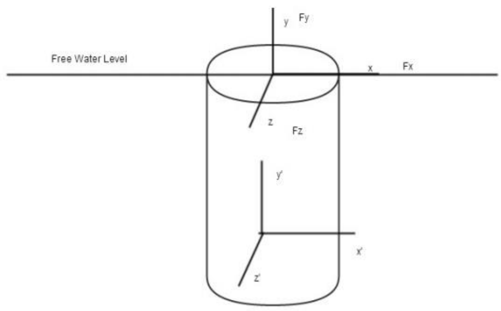

FIGURE 1 Schematic of the translation of B and C matrices

In the Figure 1, F_x, F_y, and F_z are the forces in the positive x-, y-, and z-directions. Translating the coordinate system to CG of the structure will create additional moments in addition to the existing ones. These additional moments can be calculated directly and are listed as:

$$\begin{aligned} &Moment\ in\ x\text{-}direction = y_g F_z - z_g F_y \\ &Moment\ in\ y\text{-}direction = z_g F_x - x_g F_z \ . \\ &Moment\ in\ z\text{-}direction = x_g F_y - y_g F_x \end{aligned} \quad (12)$$

The moments in Equation (11) can be merged into the stiffness and damping matrices and are show in Equation (12). Let a_{ij} denotes the *ij* component of either the stiffness or damping matrix. A_{ij} is the *ij* component of transformed matrix. Then, the transformation can be performed as follows:

$$\begin{aligned} &A_{i,j} = a_{i,j} + y_g a_{i-1,j} - z_g a_{i-2,j} \ \ for\ i = 4,\ j = 1,2,3,4,5,6 \\ &A_{i,j} = a_{i,j} + z_g a_{i-4,j} - x_g a_{i-2,j} \ \ for\ i = 5,\ j = 1,2,3,4,5,6 \ . \\ &A_{i,j} = a_{i,j} + x_g a_{i-4,j} - y_g a_{i-5,j} \ \ for\ i = 6,\ j = 1,2,3,4,5,6 \end{aligned} \quad (13)$$

As force components are unaffected by the change of coordinate system, only the bottom three rows of the stiffness and damping matrices are changed.

3.3 STIFFNESS PROPERTIES

The stiffness properties of the wind turbine are directly taken from [6]. The matrix is as follows:

$$C_{WT} = \begin{bmatrix} 0 & 0 & 0 & 0.3 & 0.2 & 0 \\ 0 & 0 & 0 & -0.1 & 0.3 & -0.07 \\ 0 & 0 & 0 & -0.3 & -0.4 & 0 \\ 0 & 0 & 0 & 8.5 & -22.4 & 59.7 \\ 0 & 0 & 0 & 26.8 & 28.9 & -4.1 \\ 0 & 0 & 0 & -1.2 & 1.1 & -4.8 \end{bmatrix} \times 10^6 \ . \quad (14)$$

The stiffness properties of the structure include restoring effects of the platform. The non-zero terms in the total restoring matrix of the platform are as follows:

$$C_{33} = \rho g A_{\omega p} \ , \quad (15)$$

$$\begin{aligned} &C_{44} = \rho g V \left(z_b - z_g \right) + \rho g \iint y^2 ds \\ &C_{55} = \rho g V \left(z_b - z_g \right) + \rho g \iint x^2 ds \end{aligned} \ , \quad (16)$$

where $A_{\omega p}$ is the water plane area, V is the volume of the platform, and z_b and z_g are z-coordinates of buoyancy and CG, respectively. If only the hydrostatic force matrix is considered, the term $\rho g V z_g$ can be omitted as this term gives the restoring effect due to the weight of the platform. The matrix given in the NREL report does not include this term as only hydrostatic restoring was considered. The corresponding values for the above terms in the present analysis are as follows:

$$C_{33} = 2558750 \ , \quad (17)$$

$$C_{44} = C_{55} = 2.09 \times 10^6 \ . \quad (18)$$

The above values are calculated at the origin, i.e. at the free surface level. The translation of the restoring matrix from the origin to the CG of the structure can be done as follows:

$$\begin{aligned} &C_{CG}(3,3) = C_0(3,3) \\ &C_{CG}(3,4) = C_0(3,4) + y_{cg} C_0(3,4) \\ &C_{CG}(3,5) = C_0(3,5) - x_{cg} C_0(3,3) \\ &C_{CG}(4,4) = C_0(4,4) + 2y_{cg} C_0(3,4) + y_g^2 C_0(3,3) \\ &C_{CG}(4,5) = C_0(4,5) + y_{cg} C_0(3,5) \\ &\qquad\qquad - x_g C_0(3,4) - x_{cg} y_{cg} C_0(3,3) \\ &C_{CG}(4,6) = C_0(4,6) \ , \end{aligned} \quad (19)$$

where C_{CG} refers to translated matrix component to the CG of the structure, C_0 refers to the components calculated at the origin, x_{cg}, y_{cg}, and z_{cg} are the coordinates of the CG of the structure.

3.4 LINEAR MOORING ANALYSIS

In steady state operations, thrust forces cause a horizontal displacement of the platform along the x-direction. This thrust is resisted by a horizontal restoring force produced by the tethers as their fair lead position is moved from the rest position, which is directly above the anchor point for each tether. As the floater surges away from the rest position, drift increases with the tethers acting as rods in tension. This increase in drift would cause an increase in line tension. However, for small surge displacements, a linearization assumption can be made that the line tension remains constant. This assumption is based on the fact that the tethers will have a very large tension stress at rest. The drift of the platform is also assumed to be small for small surges. The surge and the sway restoring coefficients are identical due to symmetry. The restoring coefficient can also be obtained by setting the moment about the tethers anchors on the bottom of the water body to zero and then solving for the force, which produces a moment in the opposite direction to the moment resulting from excess buoyancy for a given displacement. For small displacements, the surge and sway restoring coefficients are given by the following equation [17]:

$$C_{11} = C_{22} = \frac{F_{tethers}}{L_{tethers}} \ , \quad (20)$$

where $L_{tethers}$ is the length of the tether lines and $F_{tethers}$ is the force in the tethers. Heave restoring forces are from both tether and hydrostatic effects. If the structure moves only in the heave direction, the tethers extend and contract. For a system using stiff lines for tethers, this restoring mechanism is much larger than the hydrostatic restoring mechanism. The heave restoring coefficient is given by the following equation:

$$C_{33} = \frac{8 E_{tethers} A_{tethers}}{L_{tethers}} + \rho g A_{\omega p} \ . \quad (21)$$

The factor 8 corresponds to the number of tethers in the present case. Wave loading on the submerged structure creates pitch and roll moments on the system. Thrust on the rotor acting along with the moment arm of the tower creates a moment about the y-axis, which also results in pitch of the oater. Pitch and roll restoring coefficients are similar due to symmetry. Pitch and roll restoring are calculated by taking into the account the moments produced by the lines due to extension and contraction, the moment due to line tension, the moment due to system mass, and the moment due to system buoyancy. For stiff lines the largest restoring moment is due to extension and contraction of the lines on the opposite sides of the axis while the moment is applied. The restoring coefficients can be obtained by assuming a small rotation at any point along the center of the tower and summing the moments produced. The following is a derivation of the roll restoring coefficient [17].

$$\sum M_{Base} = M_{Extend} + M_{Contract} + M_{Buoyancy} + M_{gravity} + M_{tethers}$$

$$F_{tethers} = F_{Buoyancy} - m_{total} \text{g}$$

$$M_{Extend} = -2\frac{E_{tethers}A_{tethers}}{L_{tethers}}\left(L_{spoke}+\frac{d}{2}\right)\sin(\zeta_4)\left(L_{spoke}+\frac{d}{2}\right)$$

$$M_{Contract} = 2\frac{E_{tethers}A_{tethers}}{L_{tethers}}\left(L_{spoke}+\frac{d}{2}\right)\sin(\zeta_4)\left(-L_{spoke}-\frac{d}{2}\right)$$

$$M_{Extend} + M_{Contract} = -4\frac{E_{tethers}A_{tethers}}{L_{tethers}}\left(L_{spoke}+\frac{d}{2}\right)^2\sin(\zeta_4)$$

$$M_{buoyancy} = F_{buoyancy} z_b$$

$$M_{gravity} = m_{total} \text{g}\, z_g$$

$$M_{tethers} = \left(F_{buoyancy} - m_{total} \text{g}\right)T \text{ ,} \tag{22}$$

where d is the platform diameter and T is the drift of the platform. The center of the buoyancy is at $z=z_b$. The CG for the system at rest is $z=z_g$. The length of the spokes extending beyond the platform is L_{spoke}.

$$\sum M_{Base} = \left\{ \begin{array}{l} 4\frac{E_{tethers}A_{tethers}}{L_{tethers}}\left(L_{spoke}+\frac{d}{2}\right)^2 + \\ F_{buoyancy} z_b - m_{total} \text{g}\left(z_g + T\right) \end{array} \right\} \zeta_4 \text{ .} \tag{23}$$

Therefore, the roll and pitch restoring coefficients are [17]:

$$C_{44} = C_{55} = 4\frac{E_{tethers}A_{tethers}}{L_{tethers}}\left(L_{spoke}+\frac{d}{2}\right)^2 + F_{buoyancy} z_b - m_{total} \text{g}\left(z_g + T\right) \text{ .} \tag{24}$$

Although wave forces will not generate significant yaw motion of the oater, wind turbine loading can cause yaw motion. The restoring coefficient for yaw is similar to the surge-restoring coefficient. Movement of the tether produces horizontal force components, which act along the spokes and platform diameter to generate moments that counteract the yaw motion. The yaw restoring coefficient and yaw displacements is found using the following equation [17]:

$$C_{66} = \frac{\left(L_{spoke}+\frac{d}{2}\right)^2}{L_{tethers}} F_{tethers} \tag{25}$$

The diagonal elements of the linear mooring system matrix calculated by the analysis and get basing on Equation (19, 20, 23, 24).

$$\text{C}_{\text{mooring}} = \begin{bmatrix} 153200 & 0 & 0 & 0 & 0 & 0 \\ 0 & 153200 & 0 & 0 & 0 & 0 \\ 0 & 0 & 81654330 & 0 & 0 & 0 \\ 0 & 0 & 0 & 12000000000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 12000000000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 49630000 \end{bmatrix} \text{ .} \tag{26}$$

The total translated stiffness matrix is the sum of turbine stiffness, restoring effects, and mooring properties.

$$\text{C}_{\text{total}} = \text{C}_{\text{turbine}} + \text{C}_{\text{restoring}} + \text{C}_{\text{mooring}} \text{ ,} \tag{27}$$

$$\text{C}_{\text{total}} = \begin{bmatrix} 0.015 & 0 & 0 & 0.03 & 0.02 & 0 \\ 0 & 0.015 & 0 & -0.01 & 0.03 & -0.007 \\ 0 & 0 & 8.421 & -0.03 & -0.03 & 0 \\ 0 & -0.808 & 0 & 1410 & -3.22 & 6.199 \\ 0.195 & 0 & -0.126 & 3.66 & 1413 & -0.41 \\ 0 & 0 & 0 & -0.12 & 0.11 & 4.48 \end{bmatrix} \times 10^7 \text{ .} \tag{28}$$

3.5 DAMPING PROPERTIES

The damping matrix for the platform, which depends on the frequency of the incident waves, was calculated internally using SeaFEM software at each frequency and was obtained from [6]:

$$B_{WT} = \begin{bmatrix} 0.04 & 0 & -0.01 & -0.25 & 4 & 0.08 \\ 0 & 0 & 0 & -0.11 & -0.18 & -0.05 \\ -0.01 & 0 & 0 & -0.04 & -0.92 & -0.33 \\ 0.27 & -0.31 & 0 & 16.17 & 50.3 & 13.88 \\ 3.42 & 0.06 & -1 & -23.92 & 400.1 & 59.01 \\ 0.05 & -0.02 & 0.22 & 11.08 & -52.6 & 101.2 \end{bmatrix} \times 10^6 \text{ .} \tag{28}$$

The damping matrix of the wind turbine depends on wind loads, natural damping due to friction of rotor and other components, aerodynamic loads, and so on. This is calculated by the FAST for the wind load and rated speed.

4 FEM model

SeaFem is a new simulation tool to simulate sea keeping capabilities of ships and offshore structure, which have been developed for more realistic simulations to solve potential flow equations in the time domain and to use the FEM on unstructured meshes [3]. It has been used for the computational analysis of the effect of waves, wind, and currents on naval and offshore structures.

A model for the platform was created in SeaFEM, and properties of the turbine based on the matrices discussed in the prior sections were used here.

The depth of the domain was chosen to be 150 m according to the guidelines given in the SeaFEM manual. The intermediate area with a radius of 50 m represents the analysis area where there is no artificial dissipation. The rest of the computational domain was used to absorb the refracted and radiated waves from the body. A schematic of the computation domain is shown in Figure 2. The radius of the platform is 9 m. The analysis area has a radius of 50 m while the computational domain has in total 300 m. The actual depth of the sea is 200 m while in the model a depth of 150 m is used. In the analysis, the wave spectrum type is white noise, and the wave amplitude is 1 m. The smallest wave length and longest wave length are 4 m and 20 m, respectively. The number of nodes used in the mesh was 35,768 with and 205,648 elements. The mesh of the computational domain is shown in Figure 3.

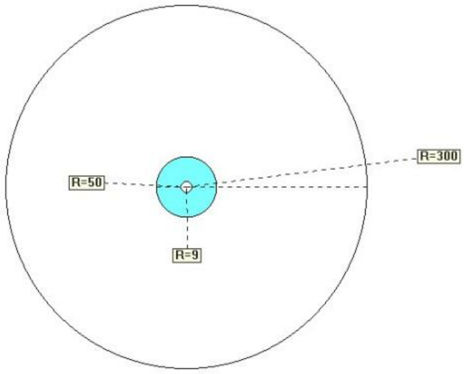

FIGURE 2 Computational domain

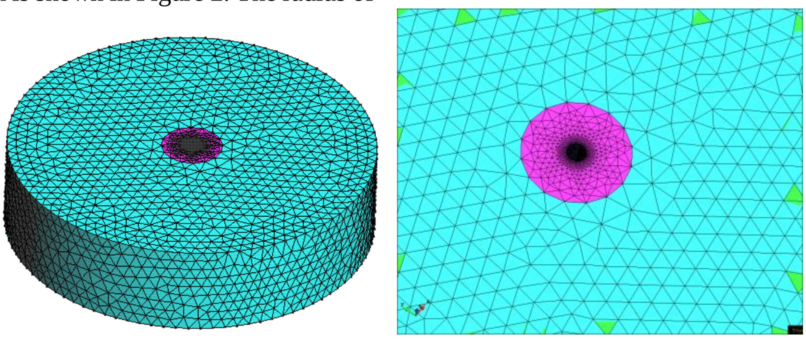

FIGURE 3 Mesh is show for different part

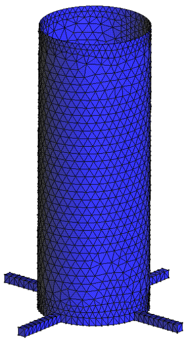

FIGURE 4 TLP model mesh

5 Results and analysis

The TLP model was created using GID software (shown in Figure 4) and a time domain analysis was carried out using the above appropriate matrices. The pitch RAOs were extracted from the analysis and compared against the NREL data [5] (shown in Figure 5). The results obtained were close to one obtained in the NREL results. Regarding the MIT results, Matha shows that the RAO in pitch from the FAST calculation has increased five times compared to the MIT calculation by Tracy, which in reality would mean the destruction of the mooring line and the failure of the TLP [5]. In our calculation, we also find the same situation as that of Matha's result (green curve in Figure. 5), which means the process is correct.

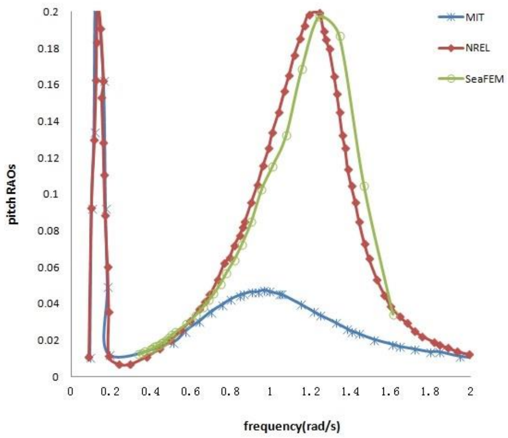

FIGURE 5 Pitch RAOs vs. frequency for compartioni

Let us check the NREL and SeaFem curve in Figure 5; the two plots appear to be in close agreement at the resonance frequency and magnitude of the pitch RAO at resonance, and the curve trend is same. This resonance frequency and magnitude of RAO can also be obtained by linear analysis. As stated earlier in the report, the natural frequency of the entire structure can be obtained from the equation of motion.

$$\omega = \sqrt{\frac{C_{total}}{M_{total}}} \,. \qquad (29)$$

Therefore, to calculate the natural frequency in pitch, C_{55} and M_{55} components are required which are derived earlier in the report. Neglecting the added mass coefficient and using these values, the frequency obtained is 1.31 rad/s. The resonance frequency obtained by our new method is around 1.2 rad/s. In Matha report, the result is 1.2 rad/s [5]. The real value deviation for our method and equation calculation is 8%. This narrow discrepancy can be attributed to the negligence of the mass term in the computations.

In this report, we calculate pitch RAOs using the FEM method on unstructured mesh (UM-FEM) and compare them with other results based on the same situation and model. We prove that the process is correct and the value deviation is small to satisfy the engineering requirements. Based on the UM-FEM method, GID and SeaFem are good choices for future calculations and applications for RAOs in offshoring wind energy.

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