Dynamic Response of Offshore Triceratops-Supporting 5 MW Wind Turbine

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***Abstract*—The study focuses on the coupled hydro-aero dynamic analysis of triceratops platform as supporting structure for 5 MW (Mega Watt) offshore wind turbine for deep water applications. Triceratops is a new generation floating platform intended to enhance structural integrity, reduce risk and minimize lifecycle cost. Although triceratops platform has many advantages, studies on wind turbine installed over triceratops platform has not been investigated by the researchers. Eigen value analysis was done to check the preliminary dimensioning of the structure. Hydrodynamic analysis is carried out using NAOS (Nonlinear Analysis of Offshore Structures) and Aerodynamic analysis using FAST (Fatigue, Aerodynamics, Structures and Turbulence, developed by National Renewable Energy Limited (NREL), USA). The wind wave coupled dynamic analysis of the structure is done in NAOS to obtain coupled hydro-aero dynamic responses by coupling hydro-aero dynamic analysis in NAOS. The results revealed that the proposed structure suits well for the selected site. Response Amplitude Operators (RAO's) corresponding to six degrees of freedom (DOF's) was examined for wind speeds corresponding to different dynamic nature to check the effectiveness of coupling.**

Keywords—Triceratops platform; eigen value analysis; hydro-aero dynamic analysis; response amplitude operators

I. INTRODUCTION

The wind energy is one of the most important renewable energy resources along with solar energy. Wind energy is the most developed and cost-effective energy technology to meet the increasing electricity demands in a sustainable manner. But onshore wind farms account for human discomfort and several environmental problems. This adversity can be eliminated by establishing offshore wind farms. According to the Preliminary assessment conducted by Scottish Development International, on behalf of MNRE (ministry of new and renewable energy) shows a reasonable potential of about 1 GW (Giga Watt) in the coastline of Rameshwaram and Kanyakumari, in Tamilnadu and Gujarat coast. Offshore wind potential is considered to be higher than onshore because offshore winds are stronger and consistent. National Offshore Wind Energy Policy (released on October 2015) by MNRE, focuses on electricity generations from renewable sources. According to MNRE, the significant challenges that exist in offshore wind power deployment is the supporting structure design and operational period .This reveals the importance of an offshore supporting structure like triceratops. Triceratops is a new generation floating platform intended to enhance structural integrity, reduce risk and minimize lifecycle cost.

This study focuses on mounting an offshore wind turbine over triceratops platform. Triceratops support is a compliant support, which is flexibly linked to the seafloor through taut-moored tethers. The concept of triceratops platform for deep-water exploration was introduced by Charles and Robert [4]. Later**,** Srinivasan Chandrasekaran [9] had done dynamic analysis on offshore triceratops under critical sea states and found that, it is advantageous to upkeep more facilities on the deck for moderate sea state operations. Recently**,** Srinivasan Chandrasekaran [10] studied dynamic response characteristics of offshore triceratops through experimental and numerical investigations. Although triceratops platform has many advantages, studies on wind turbine installed over triceratops platform has not been investigated by the researchers. Its main components are namely: (1) beams (spokes) made up of hollow rectangular sections, to hold 5 MW wind turbine and tower [8], (2) three buoyant leg structure (BLS) with single water piercing cylinders each, (3) ball joints that connect BLS to beams, (4) restoring system with taut-moored tethers, (5) foundation system that can be a suction pile, multiple driven pile or gravity based structure. Fig. 1 shows the conceptual view of triceratops platform mounted with wind turbine. Ball joints are capable of transferring translation only, no rotations are transferred. This improves the operability of the platform as the deck remains horizontal under the action of wind and wave. BLS units are cylindrical, deep-drafted water piercing columns which are similar to spar and are positively buoyant like tension legged platform (TLP). This positive buoyancy, weight of topside, weight of ballast and pretension in the taut-moored tethers are counteracted along with the effect of ball joints, improves the platform characteristics compared to other compliant supports.

The entire work is divided into two sections- preliminary proportioning and coupled response analysis. As introductory step, the design inputs like wind turbine, tower and environmental factors like site, wind, and wave and water depth data are suitably chosen. A preliminary model design was proposed based on basic stability checks and restoring capacity calculation. Positive metacentric height is maintained. The capacities of the taut-moored tethers are also verified through simple structural analysis. The model dimensions were fine-tuned by monitoring the natural frequencies and mode shapes obtained from Eigen value analysis. The finite element model of the refined design was done in NAOS and a detailed response analysis and RAO's was obtained by coupling wind forces from FAST. RAO's corresponding to six DOF's was examined for wind speeds corresponding to different dynamic nature to check the effectiveness of coupling.

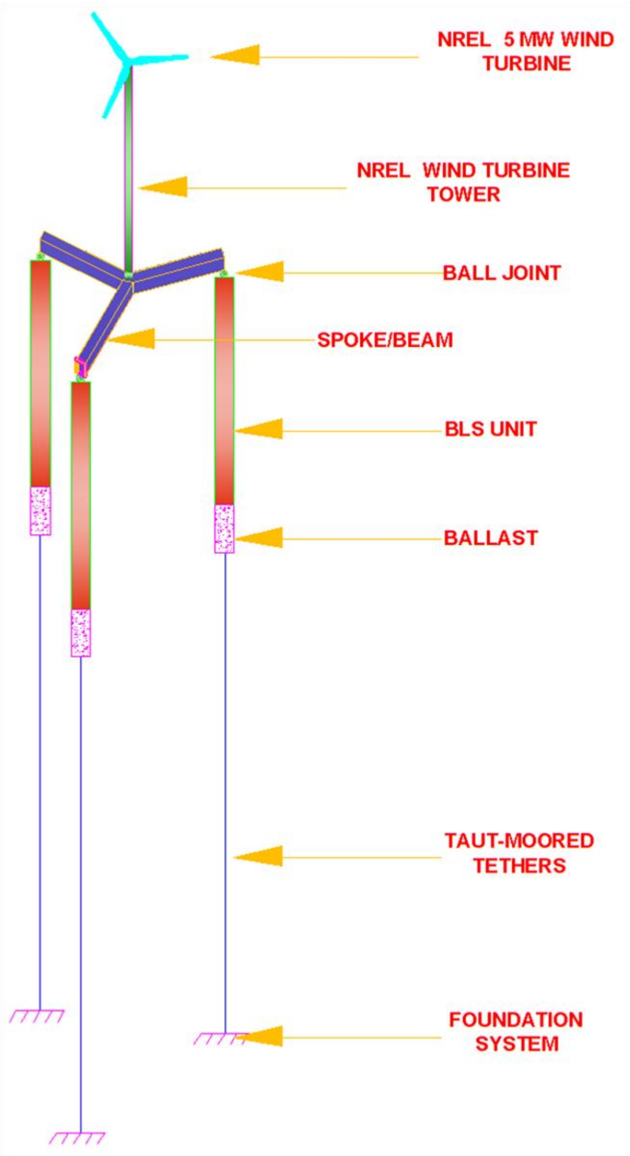

Fig. 1. Conceptual view of triceratops platform mounted with wind turbine

II. Preliminary Data

Before advancing in to the initial proportioning of the triceratops platform mounted with wind turbine, certain input parameters need to be fixed. The design inputs like wind turbine, tower and environmental factors like site, wind, wave and water depth data are suitably chosen.

A. NREL Wind Turbine and Tower

The NREL has developed the specifications of a representative utility-scale multi megawatt turbine now known as the "NREL Offshore 5-MW Baseline Wind Turbine." [8] This wind turbine is a conventional three-bladed upwind variable-speed, variable blade-pitch-to-feather-controlled turbine. The tower is in a tapered shape, hence for the simpler computation of the model the tower is modeled into equivalent mass distributed parts as suggested by Vivek Philip [11]. The Fig. 2 and table I show the equivalent mass distribution made to the NREL offshore wind turbine with each part is split in different cube shapes of height 8.76 m.

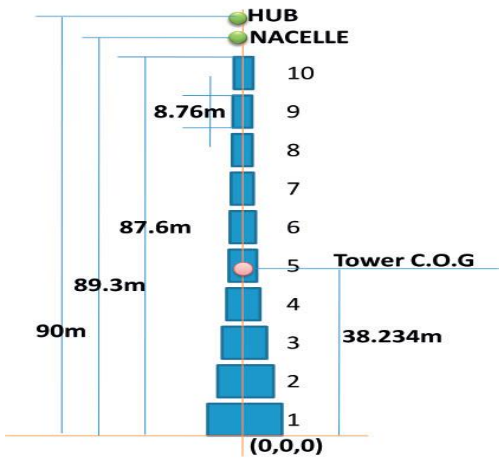

Fig. 2. Tower and turbine split in to different sections

TABLE I. EQUIVILANT MASS DISTRIBUTIONS

Tower Section	Diameter (m)	Thickness (m)	Mass (Kg)	C.O.G. (m)
Tower 1	6	0.03395	23324	0,0,4.38
Tower 2	5.752	0.03311	25587	0,0,13.14
Tower 3	5.541	0.03206	27953	0,0,21.9
Tower 4	5.361	0.0308	30423	0,0,30.66
Tower 5	5.148	0.02978	32996	0,0,39.42
Tower 6	4.935	0.02874	35671	0,0,48.18
Tower 7	4.722	0.02769	38450	0,0,56.94
Tower 8	4.509	0.02665	41332	0,0,65.7
Tower 9	4.296	0.0256	44318	0,0,74.46
Tower 10	4.083	0.02456	47406	0,0,83.22
Tower	-	-	347460	0,0,38.23
Nacelle	-	-	240000	-0.4,0,89.3
Hub	-	-	110000	-0.4,0,90

B. Site

The study area for locating the wind turbine was selected as a rectangle of 400 sq.km area, on the south coast of India. Points 7° 17' 36" N, 77° 33' 39" E and 7° 4' 56" N, 77° 46' 12" E bound the two diagonal points of the selected area. Area selected is about 100 kilometers offshore from kanyakumari coast, Tamilnadu. The water depth at this area was found to be about 314 m with a wind speed of 18 m/s and wave height of 7 m with wave period of 12 seconds.

III. Preliminary Design

From the past literatures general outline of the structural configuration is initially made as shown in Fig. 1. The structure consists of three BLS units separated apart at 120° angle with the help of spokes attached to it. The spoke is a hollow rectangular section made up of steel supporting the wind turbine. Three BLS units are interconnected through spokes. The BLS units are single water piercing hollow

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cylindrical sections deep drafted to provide excess buoyancy. They are made up of steel. At the bottom each of the BLS unit's concrete ballast is attached. Steel wired ropes are used as tethers connecting the ballast bottom with the sea floor foundation system, which acts as a restoring system.

The preliminary challenge in design is that, the various sizes of members, weight, thickness, ballast, pretension on tethers etc. are to be decided so that a control over natural frequency is achieved and these frequencies are placed in a desirable limit. The natural frequency of the compliant coupled triceratops system should be designed such that it does not coincide with the peak frequency of the dynamic loading. The general rule is that the natural periods of soft modes, surge, sway and yaw should be longer than 25 seconds. Heave, pitch and roll motions should be stiffness dominated, i.e. natural periods shorter than 3-4 seconds.

The basic dimensions are to be fixed based on fundamental stability checks, i.e. the buoyancy force should be greater than total weight and a proper restoring is achieved when deflected, i.e. the restoring moment of the structure is made greater than overturning moment. Restoring is achieved through water plane area, through ballasting and stiffness oriented restoring from taut-moored tethers. The dimensions of beams, BLS units, ballasting height, tether dimensions etc. can be fixed only by trial and error process. When the model passes the basic stability check, an Eigen value analysis was done in NAOS to find the natural frequencies and mode shapes. If the natural frequency is not falling within the desired limits, changes were made and again analyzed till the natural frequencies fall within the desirable limits. Fig. 3 shows preliminary design. Details of sections of the platform model are given in table II. The mass and sectional property of ball joints is insignificant when compared to the massive dimension of the structure. The tether should be designed in such a way that it should be capable of holding the reserve buoyancy (buoyancy force minus self-weight) exerted by the triceratops structure. For this, simple structural analysis is carried out on the three legged structure by applying maximum thrust on wind turbine as 911 KN [8] at the top. The analysis is carried out by applying 911KN all-round (360°) the structure with an interval of 30°. The reaction for each angle cases is plotted in graph corresponding to wave approach angles as shown in Fig. 4. The maximum breaking load (MBL) for wire roped tether is obtained from anchor manual [1]. Fig. 4 represents that the MBL is well away the force exerted on each of the tethers. Also, the tether should not lose its pretention i.e. if one tether experiences a high tensile force, tether in the opposite corner may lose its pretension. If this pretension falls below zero, taut-moored tether shifts to lose-moored tethers, there by leading to sinking the structure. It is clear from Fig. 4 that the minimum force acting on tether is slightly above 18000 KN, which is well above the desired limit. So the preliminary design and proportions of the various sections of the triceratops platform holds well.

IV. Finite Element Modelling In NAOS

Details of finite element model created in NAOS are given in Fig. 5. Structure was modeled using 3 elements per each leg below sea surface, 2 elements per leg above sea surface, support beam are modeled as single element, 10 elements for the tower. Ball joints are modeled as 3 spring elements each,

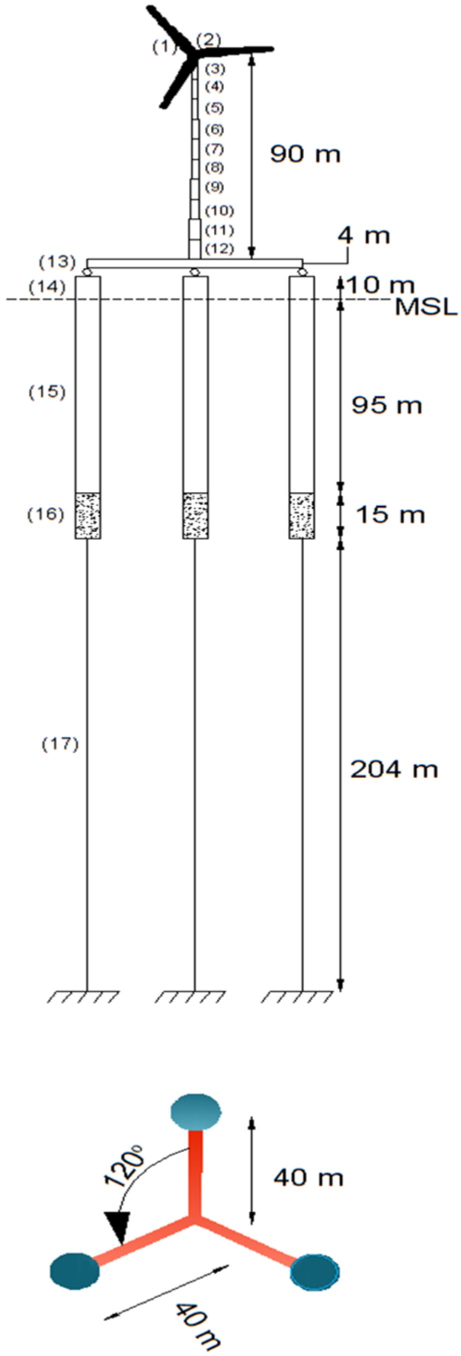

Fig. 3. Preliminary design of triceratops platform

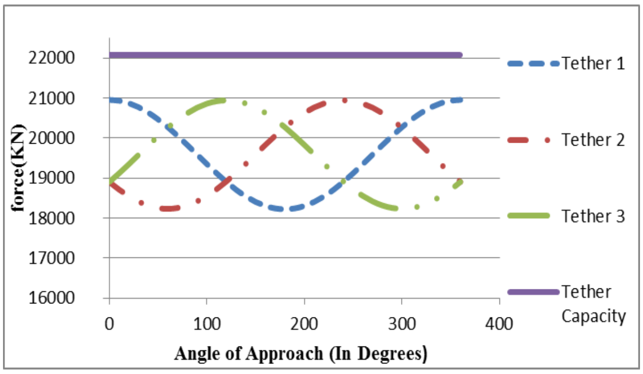

Fig. 4. Axial forces on pretensioned tethers

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TABLE II. DETAILS OF SECTIONS

Section No.	Item	Section Type	Outer Diameter (m)	Thickness (m)	Breadth (m)	Width (m)	Length (m)
1	Hub	Mass Points	-	-	-	-	-
2	Nacelle	Mass Points	-	-	-	-	-
3	Tower Section	Hollow Circular Section	4.083	0.02456	-	-	-
4	Tower Section	Hollow Circular Section	4.296	0.0256	-	-	-
5	Tower Section	Hollow Circular Section	4.509	0.02665	-	-	-
6	Tower Section	Hollow Circular Section	4.722	0.02769	-	-	-
7	Tower Section	Hollow Circular Section	4.935	0.02874	-	-	-
8	Tower Section	Hollow Circular Section	5.148	0.02978	-		-
9	Tower Section	Hollow Circular Section	5.361	0.0308	-	-	-
10	Tower Section	Hollow Circular Section	5.541	0.03206	-	-	-
11	Tower Section	Hollow Circular Section	5.752	0.03311	-	-	-
12	Tower Section	Hollow Circular Section	6	0.03395	-	-	-
13	Beam/Spoke	Hollow Rectangular Section	-	0.05	4	3	40
14	BLS (above MSL)	Hollow Circular Section	8	0.05	-	-	10
15	BLS (below MSL)	Hollow Circular Section	8	0.05	-	-	95
16	Concrete Ballast	Solid Circular Section	8	-	-	-	15
17	Tether	Solid Circular Section	0.53	-	-	-	204

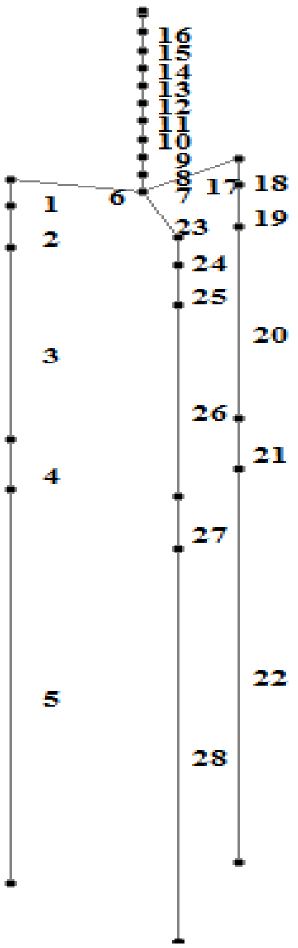

Fig. 5. Finite element model details

whose behavior is induced in the structure by adjusting the spring stiffness. 3D coupled springs were provided for water-piercing elements and turbine mass was included as point mass at tower top. Referring to the Fig. 5, elements 5, 22 and 28 represents tether modeled as beam elements of length 204 m. Elements 4, 21 and 27 represents ballast and are modeled as beam elements. Elements 3, 20 and 26 represents BLS below mean sea level (MSL) and are modeled as beam elements. Elements 2, 19 and 25 are BLS above MSL modeled as beam elements. Elements 1, 18 and 24 are modeled as spring elements whose stiffness is adjusted to obtain the characteristics of ball joints i.e. translations are transferred by restricting rotations. Elements 6, 17 and 23 represents spoke and are modeled as beam elements. Elements 7 to 16 are tower sections, which are modeled as beam elements.

V. EIGEN VALUE ANALYSIS

Eigen value analysis is used to obtain natural frequencies and corresponding mode shapes, which is used in the preliminary proportioning of the structure. Eigen value analysis is also called as the free vibration analysis. The natural frequency of the compliant structure should be designed such that it does not coincide with the peak frequency of the dynamic loading. The general rule is that the natural periods of soft modes, surge, sway and yaw should be longer than 25 s. Heave, pitch and roll motions should be stiffness dominated, i.e. natural periods shorter than 3-4 s. An Eigen value analysis was done in NAOS to find the natural frequencies and mode shapes. If the natural frequency is not falling within the desired limits, changes were made and again analyzed till the natural frequencies fall within the desirable limits. Table III shows result of Eigen value analysis. The first three modes, surge, sway and yaw are found to be soft. Heave modes are rigid. All

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other modes are found to be insignificant and are of less interest in the present study. Although the obtained modes including roll and pitch are well away from the wave period zone (4 to 25 s).

TABLE III. NATURAL TIME PERIODS

Mode	Description	Natural Time Periods (S)
1	Surge	1588.67
2	Sway	1588.67
3	Yaw	1526.34
4	Leg mode	200.08
5	Roll	131.78
6	Pitch	131.78
7	Heave	1.56

VI. COUPLED DYNAMIC ANALYSIS

A. *Wind Force Analysis in FAST*

The FAST code (Fatigue, Aerodynamics, Structures and Turbulence) developed by National Renewable Energy Lab, (NREL, USA) [7] can model the dynamic response of both two- and three-bladed, conventional, horizontal-axis wind turbines. In the present study FAST code is used to model a three-bladed Horizontal Axis Wind Turbine (HAWT) with 24 DOF's. FAST needs a number of input files corresponding to turbine parameters, wind data, blade properties, initial conditions etc. From the FAST software the result obtained are YawBrFxp (yaw bearing shear force along x axis), YawBrFyp (yaw bearing shear force along y axis), YawBrFzp (yaw bearing shear force along z axis), YawBrMxp (yaw bearing roll moment along x axis), YawBrMyp (yaw bearing pitch moment along y axis), YawBrMzp (yaw bearing yaw moment along z axis) which are the inputs corresponding to different time steps.

B. *Coupling NAOS with FAST*

Finite Element Software, NAOS has been used in the simulation of hydrodynamics of proposed triceratops platform. This formulation in the time domain is based upon Updated Lagrangian approach. The direct integration method adopted is Newmark method with equilibrium iterations at every step. Since the members of the triceratops platform are slender, their structural behavior can be described by beam theory and the wave loading on them are obtained by Morison wave force model. Nonlinear dynamic response analysis of the structure was done in NAOS, coupling the time series of wind force data from FAST. Analysis was done for several operational parameters, is discussed in the upcoming chapter.

VII. RESULTS AND DISCUSSIONS

A. *Response Amplitude Operators (RAO's)*

RAO's corresponding to six degrees of freedoms of the proposed triceratops structure were obtained by simulating with waves of unit amplitude and time periods ranging from 2 s to 30 s. Wind force corresponding to11.4 m/s wind with no shear (rated wind speed of NREL 5 MW wind turbine, which produces maximum thrust on the turbine yaw axis) [8] is simulated in FAST and the time marching wind force data is used in every finite element analysis. The constant amplitudes of the oscillations with excited wave period were recorded for six DOF's. The resulting RAO's are presented in Fig. 6.

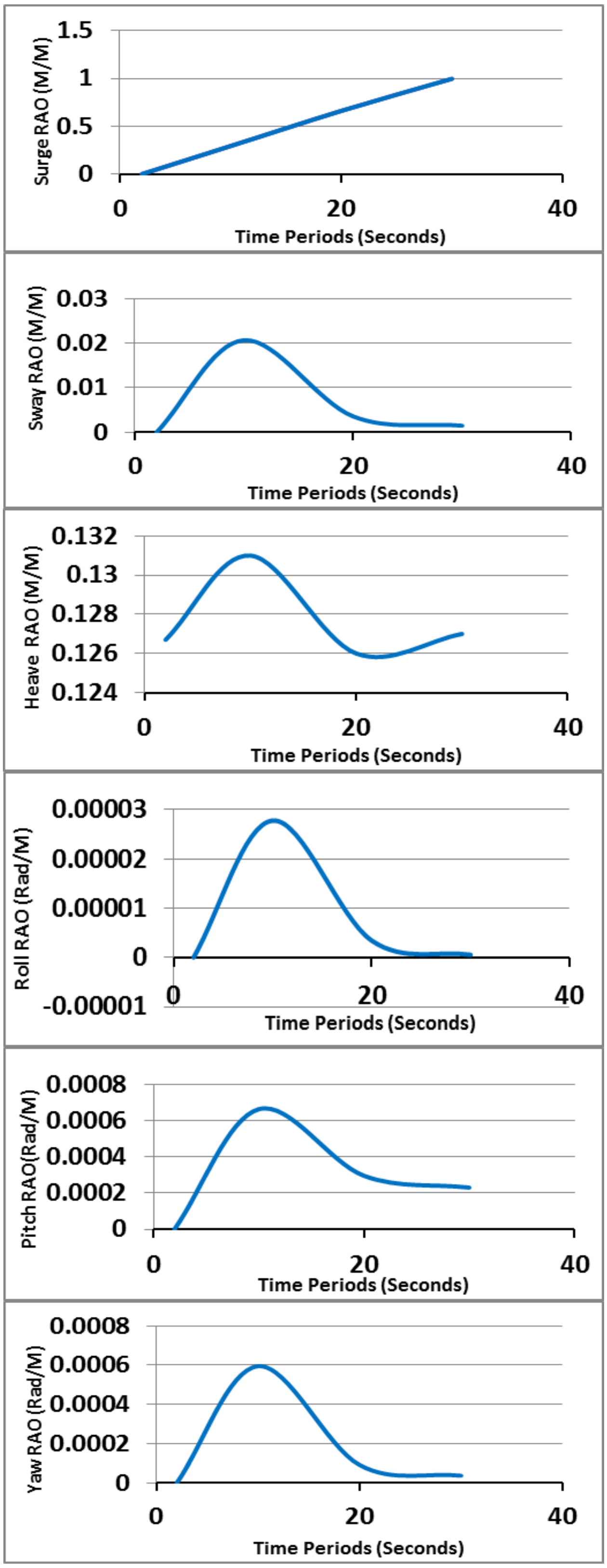

Fig. 6. RAO's corresponding to six DOF's

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The RAO plotted shows gradual change in all modes. The Surge RAO is a straight line, but shows a gradual change. In all other modes shows gradual change with soft peaks. This represents the stability of the structure against the encounter waves.

B. Wind Effects on RAO's

Wind speeds of 6, 9, 11.4, 15 and 25 m/s were selected, and RAO's corresponding to this wind speed was plotted. All the values are selected from regions were turbine has different dynamic properties as obtained from the power curve [8]. The wind speed of 6 m/s represents region one and a half of the power curve, the wind speed of 9 m/s represents the region 2 of the power curve, which is the wind speed where the turbine is producing roughly half its rated power. The wind speed of 11.4 m/s represents the turbines rated wind speed, the wind speed at which the turbine first produces its maximum power. The wind speed of 15 m/s represents the region 3 of the power curve, while the speed of 25 m/s represents the cut out speed. A wind speed from each region, as mentioned is picked up. If turbine dynamics were properly coupled with the support dynamics, the dynamic property of the system changes with the wind speed. To investigate the effectiveness of coupling RAO's for various wind speed are calculated and combined. The resultant RAO's corresponding to different wind speed is plotted in Fig. 7. RAO's corresponding to different wind speeds shows that wind speed have negligible dynamic effect on yaw and no effects on sway motion, but have significant effects on all other modes. So the turbines dynamic property is not affecting platform's sway and yaw motions. Unless and until a proper wind coupling is achieved, a difference in RAO corresponding to different wind Speed will not be obtained. Wind effect on RAO shows that the coupling of wind to the system is done effectively. One of the premier aims of the study is achieved. It was seen that the wind speed affects the

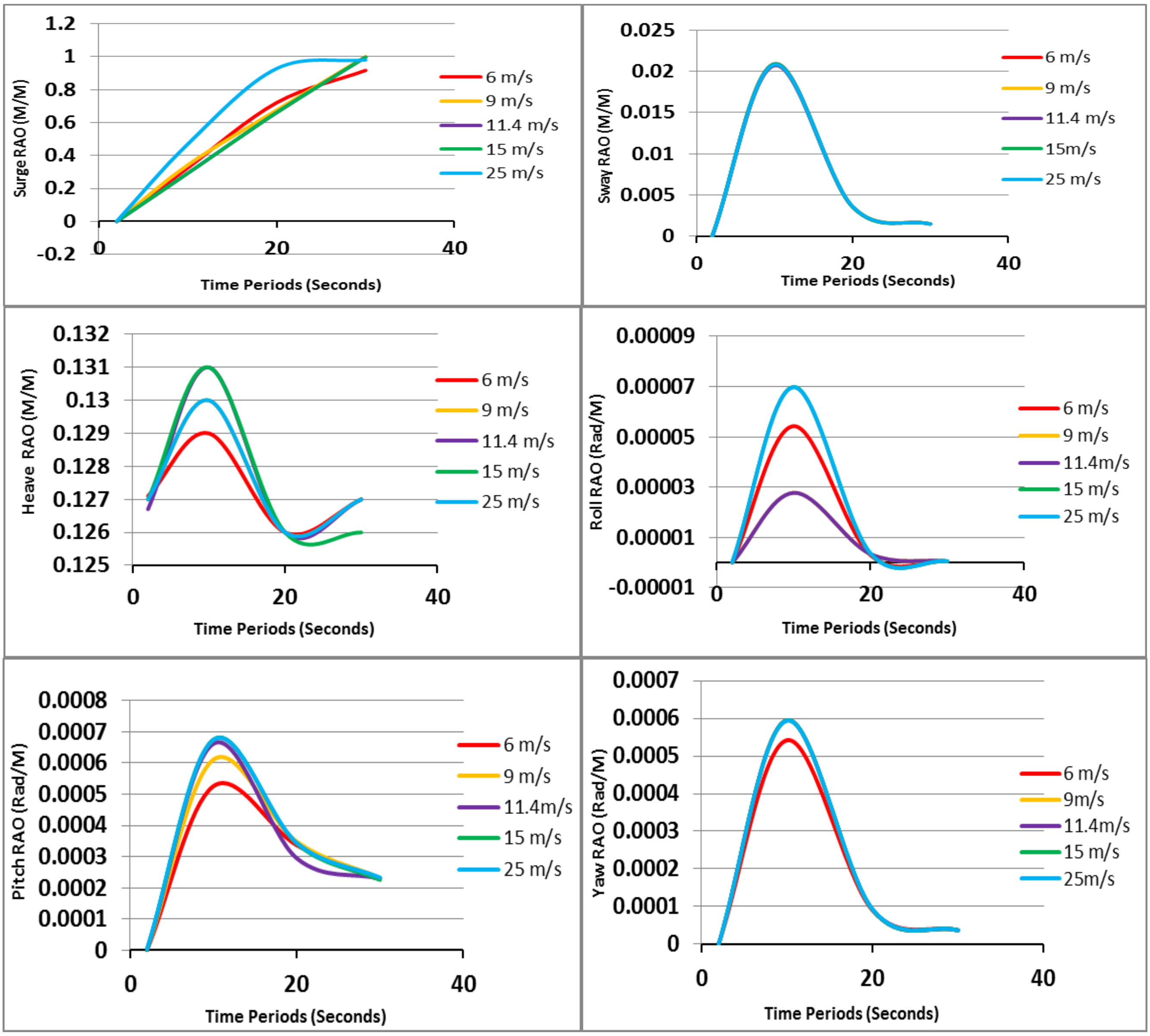

Fig. 7. RAO's corresponding to different wind speeds

coupled system dynamics primarily by inducing different levels of damping due to the wind turbine. Wind turbine damping contributes very little to total damping in sway and yaw. Wind turbine damping contributes significantly to surge, heave roll and pitch mode damping. A significant difference in RAO's of these modes clearly demonstrate wind coupling.

VIII. CONCLUSION

A suitable triceratops supporting structure configuration for 5 MW offshore wind turbine to suite Indian coastal conditions is proposed. From Eigen value analysis of the proposed triceratops support, the natural time period obtained for all modes is well away from the wave time period zone (> 25 s and < 4 s). So the preliminary configuration of the structure holds well for nonlinear coupled hydro-aero response analysis. Higher natural time periods in the surge and sway modes indicates higher compliancy to the structure, which is advantageous compared to other compliant offshore platforms. From RAO's computed, it was observed that although the system is excited by wind and wave only in surge, pitch and heave, it displays motion in the modes of sway, roll and yaw as well. The structure's response in these modes indicates the coupling of wind turbine with platform motions. The RAO's plotted shows gradual change with soft peaks, which indicates the stability of the structure against the encounter waves. Sway response at different wind speeds remains unchanged, which means the turbines dynamic properties are not affecting the platforms sway motions. Although, platforms yaw motions are slightly affected by turbines dynamic properties. All other modes (except sway and yaw) are significantly affected by turbines variable dynamic properties. Wind effects on RAO shows that the coupling of wind to the system is done effectively; the premier aim of the study is achieved. Wind turbine damping contributes very little to total damping in sway and yaw mode. Wind turbine damping contributes significantly to all other modes of damping. The presented structural configuration is advantageous for offshore industry.

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