

# Hydro-Aerodynamic Coupling For Analysis of Articulated Tower Supporting NREL Offshore Wind Turbine

Jiss K. Abraham<sup>1</sup>, Vivek Philip<sup>2</sup>P.G. Student, Department of Civil Engineering, Saintgits College of Engineering, Kottayam, Kerala, India<sup>1</sup>Assistant Professor, Department of Civil Engineering, Saintgits College of Engineering, Kottayam, Kerala, India<sup>2</sup>

**ABSTRACT:** This project study discusses the preliminary design of a four-legged articulated supporting structure for 5 MW Offshore Wind Turbine. Dynamic coupling of wind acting on wind turbine and wave acting on supporting structure is very important while analysing an offshore wind turbine support. An effective coupling of finite element software NAOS (Nonlinear Analysis of Offshore Structures developed at Department of Ocean Engineering, IIT Madras) with aerodynamic code FAST (Fatigue, Aerodynamics, Structures and Turbulence, developed by National Renewable Energy Limited (NREL), USA) was done to simulate hydro-aerodynamic coupling. A candidate supporting structure is designed based on basic stability considerations as well as natural frequency ranges. Eigen value analysis was carried out to check the preliminary dimensioning of the structure. Response Amplitude Operators (RAOs) corresponding to six degrees of freedom (DOF) were examined for wind speeds corresponding to different dynamic nature to check the coupling effect.

**KEYWORDS:** Articulated tower supports, Wind turbine, Responses, Response Amplitude Operator

## I. INTRODUCTION

The solar energy and wind energy are the most important renewable energy resources which can cover worldwide energy demands. Worldwide, wind energy is accepted as one of the most developed, cost-effective and proven renewable energy technologies to meet increasing electricity demands in a sustainable manner. The scarcity of land and public resistance to wind parks in the immediate surroundings have become some of the main challenges faced by the wind industry. With over 7500 kilometres of coastline and arguably 500 GW of offshore wind power potential in India, there is a strong case to consider offshore wind as a potential energy source both from the perspective of energy security and climate change. According to Ministry of Non-Renewable Energy Resources (MNRE), the wind resource data collected for the coastline of Rameshwaram and Kanyakumari in Tamil Nadu and Gujarat Coast shows reasonable potential. Preliminary assessment conducted by Scottish Development International showed Tamil Nadu has potential of about 1 GW in north of Rameshwaram and 1 GW in south of Kanyakumari. Offshore wind potential is considered to be higher than onshore because offshore winds are more stronger and consistent.

At present offshore wind farms adopt fixed supports. But when technology advances to greater depths, fixed platforms are uneconomical. Conventional fixed offshore structures require excessive physical dimensions to obtain stability. So as an economically feasible solution, compliant offshore structures are to be considered. Compliancy is the capability to move along with the external forces acting on the structure. These structures strongly rely on a restoring buoyancy force, ballasting and mooring lines to maintain the stability, after any lateral movement occurs on the structure. These structures avoid resonance by operating at a frequency well below that of the ocean wave's frequency.

Articulated support platform is a type of compliant platforms and is suited for sea depth of around 200 m. Articulated joints are connected to the sea floor, by allowing them to move freely under the action of current, waves and wind; which are the lateral forces acting on the structure. Articulation is a term related to rotation. Articulated towers, are those towers which are connected to the sea bed through a universal joint. So universal joints offer position restraint, but

no restrain against rotation. Hence, since there is no rotation, or there is no moment we can go for a very simple foundation system.

A preliminary structure of model was designed considering the two basic conditions on basic stability checks and restoring moment capacity. Free vibration analysis was carried out for the proposed candidate structure and from the displacement results mode shapes were plotted. Finite element model was formed from the candidate structure. From the natural frequencies obtained it was crosschecked for the soft and rigid modes are within limit. The finite element model was developed and structure was passed through nonlinear time domain dynamic analysis in NAOS where responses and RAO's were obtained by effectively coupling wind forces acting on wind turbine from FAST.

## II. PRELIMINARY DESIGN

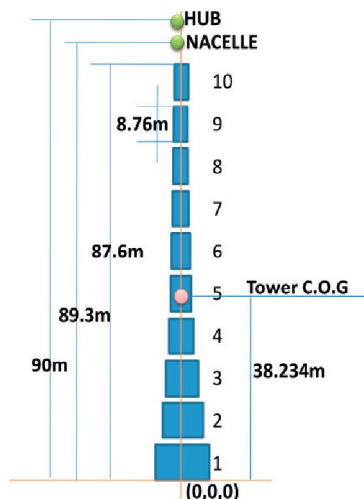
### 2.1 Input Design Parameters

Certain design initial parameters are to be fixed before advancing to the next stage of designing of four legged articulated tower such as the location of offshore wind turbine, selection of type of offshore wind turbine, environmental conditions of the selected location.

#### 2.1.1 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." [1] 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 modelled into equivalent mass distributed parts.

Table.1 Equivalent Mass Distribution



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	0.02560	44318	0,0,74.46
Tower 10	4.083	0.02456	47406	0,0,83.22
<b>TOWER</b>			<b>347460</b>	<b>0,0,38.23</b>

Fig.1 Tower and Turbine

The Figure 1 [2] and table 1 shows the equivalent mass distribution made to the NREL offshore wind turbine with considering all the specification details as specified from the Jonkman's definition of 5 MW offshore wind turbine [1]. Each part is splitted into different cube shapes with a height of 8.76m.

#### 2.1.2 Environmental Conditions

The site selected for the location of wind turbine as a rectangle of 400 sq.km area at 7°20'14"N, 77°33'57"E and 7°51'40"N,77°28'53"E as diagonal points. Site is about 90 Kilometres offshore from south of Kanyakumari. The depth of water at the location of wind turbine was found to be 160 m. The waves were having the properties of wave height of 7m and wave period of 12 seconds.

### 2.1.3 Preliminary Design

The basic form of the Multi Legged Articulated support for wind turbine, proposed for present investigation is given in Fig.2 (a). This basic form of Four Legged Articulated Support consists of four separate vertical columns to which buoyancy chambers (b) are attached near the water surface and to which ballast (f) is usually added near the bottom, on each leg. The tower is connected to the seafloor through a universal joint (d) fixed to a base (e). The tower itself is a tubular column (c). The four legs are connected by beams (a), over which the tower is supported. The basic criteria's to be satisfied in design of a articulated tower as suggested by Kirk & Jain [2] are that the buoyant force should be 1.5 times greater than total weight of structure and the ratio of restoring moment to overturning moment should be greater than 1.5 thereby ensuring the proper restoring when deflected and attaining of stability. The dimensions of buoyancy chamber, ballasting height, tower diameter, thickness etc. can be fixed only by trial and error process. The heights fixed for various parts of the articulated tower are given in Fig 2 (b). The details of sections selected are given in Table 2 by conducting trial and error in MS –Excel.

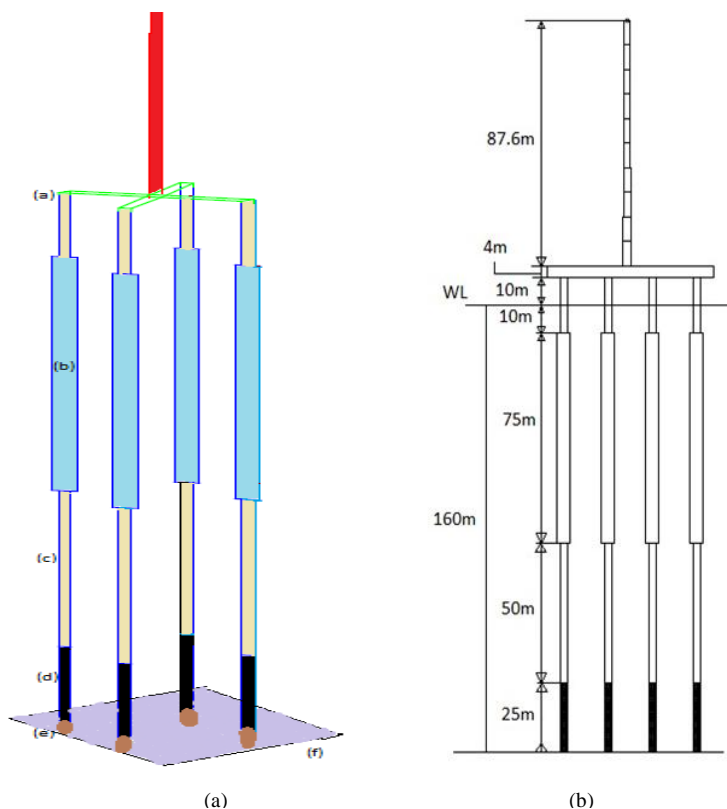


Fig.2 (a) Articulated support selected (b) Preliminary Proportioning

# International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 10, October 2015

Table 2 Details of Sections Adopted

Sec. No.	Details	Sec. Type	Dia (out) (m)	Thickness (m)	Breadth (m)	Height (m)
1	Top Mass	Point Mass	-	-	-	-
2	Tower Section	Circular	6	0.03395	-	-
3	Tower Section	Circular	5.752	0.03311	-	-
4	Tower Section	Circular	5.541	0.03206	-	-
5	Tower Section	Circular	5.361	0.0308	-	-
6	Tower Section	Circular	5.148	0.02978	-	-
7	Tower Section	Circular	4.935	0.02874	-	-
8	Tower Section	Circular	4.722	0.02769	-	-
9	Tower Section	Circular	4.509	0.02665	-	-
10	Tower Section	Circular	4.296	0.02560	-	-
11	Tower Section	Circular	4.083	0.02456	-	-
12	Support Beam	Rect.	-	0.20	3	4
13	Tower	Circular	2.5	0.05	-	-
14	Buoyancy Chamber	Circular	5	0.05	-	-
15	Ballast	Circular	2.5	0.05	-	-

### III. FINITE ELEMENT MODELLING AND EIGEN VALUE ANALYSIS

#### 3.1 Finite Element Modelling

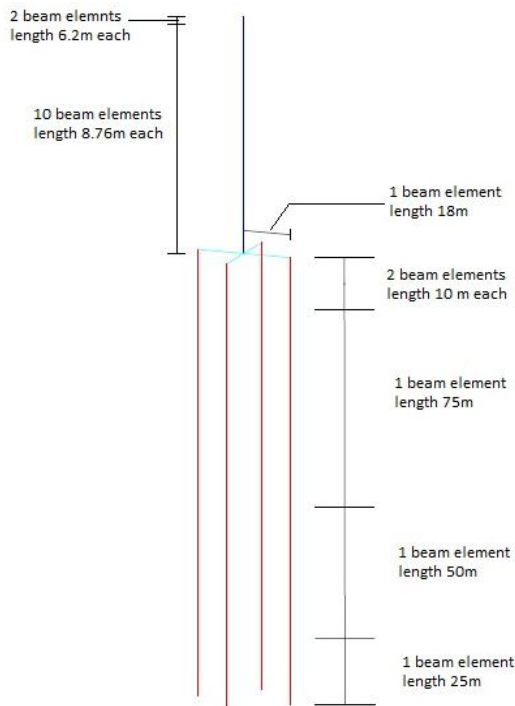


Fig. 3 Finite Element Model

# International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 10, October 2015

Details of finite element model created in NAOS are given in Fig. 3. Structure was modelled with 5 beam element for each leg, 4 beam element for support beam, 12 beam elements for tower. 3D general springs are provided at top of legs joining with beam. The spring stiffness value is selected as that the least stiffness value is provided for the spring since its aim is only for providing the supporting structure to act along the external forces. 3D coupled springs were provided for water-piercing elements. The coupled spring value is selected as (i) heave stiffness  $K_h = \rho g A_{wp}$  and (ii) roll and pitch stiffness  $K_r = K_p = \rho g I_{wp}$  where  $\rho$  is the mass density of water,  $g$  is the acceleration due to gravity and  $A_{wp}$  &  $I_{wp}$  are the area and second moment of water plane area. Turbine mass was included as point mass at tower top.

### 3.2 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 support parameters. Eigen value analysis is also called the free vibration analysis and the effect of damping is not considered. The natural frequency of the compliant support 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 analysed till the natural frequencies fall within the desirable limits.

Table 3 Natural Frequencies

Mode	Natural Frequencies / Periods		Remarks
	$F_n$ (Hz)	$T_n$ (s)	
1	.1122167E-03	8911.332	Surge
2	.1122167E-03	8911.332	Sway
3	.1340987E-03	7457.194	Yaw
4	.2345423E-02	426.3623	Leg -Tower mode
5	.5304687E-02	188.5125	Leg mode
6	.8888334E-02	112.5070	Leg + small Tower mode

Table 3 shows result of Eigen value analysis. The first three modes, surge, sway and yaw are found to be soft modes. Other modes are found to be insignificant.

## IV. COUPLED DYNAMIC ANALYSIS

### 4.1 Wind Forces Calculation in FAST

The FAST code (Fatigue, Aerodynamics, Structures and Turbulence) developed by National Renewable Energy Lab, (NREL, US) can model the dynamic response of both two- and three-bladed, conventional, horizontal-axis wind turbines. The FAST code can model a three-bladed Horizontal Axis Wind Turbine (HAWT) with 24 DOFs. FAST needs a number of input files corresponding to turbine parameters and conditions. Fig 5 shows one of the output force file corresponding to the wind speed of 11.4 m/s. From the FAST software we will get YawBrFxp, YawBrFyp, YawBrFzp, YawBrMxp, YawBrMyp, YawBrMzp which are the inputs corresponding to different time steps.

## 4.2 Combining FAST in NAOS

Finite Element Software, NAOS has been used in the simulation of hydrodynamics of proposed four legged articulated tower. 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 articulated support proposed are slender, their structural behaviour can be described by beam theory and the wave loading on them can be estimated reasonably by Morison wave force model. Non linear dynamic response analysis of the structure was done in NAOS, coupling the time series of wind force from FAST. Analysis was done for several operational parameters and results are discussed in next chapter.

## V. RESULTS AND DISCUSSIONS

### 5.1 Response Amplitude Operators (RAO's)

$$RAO = \frac{\text{amplitude of response}}{\text{amplitude of wave}}$$

RAOs corresponding to six degrees of freedoms of the four legged articulated support were obtained by simulating with waves of unit amplitude and time periods ranging from 2 s to 50 s. Wind force corresponding to 11.4 m/s wind with no shear (rated wind speed of NREL 5 MW wind turbine, which produces maximum thrust on the turbine yaw axis) is simulated in FAST and the time marching wind force data is used in every finite element analysis. The resulting RAOs are presented below in Fig.4.

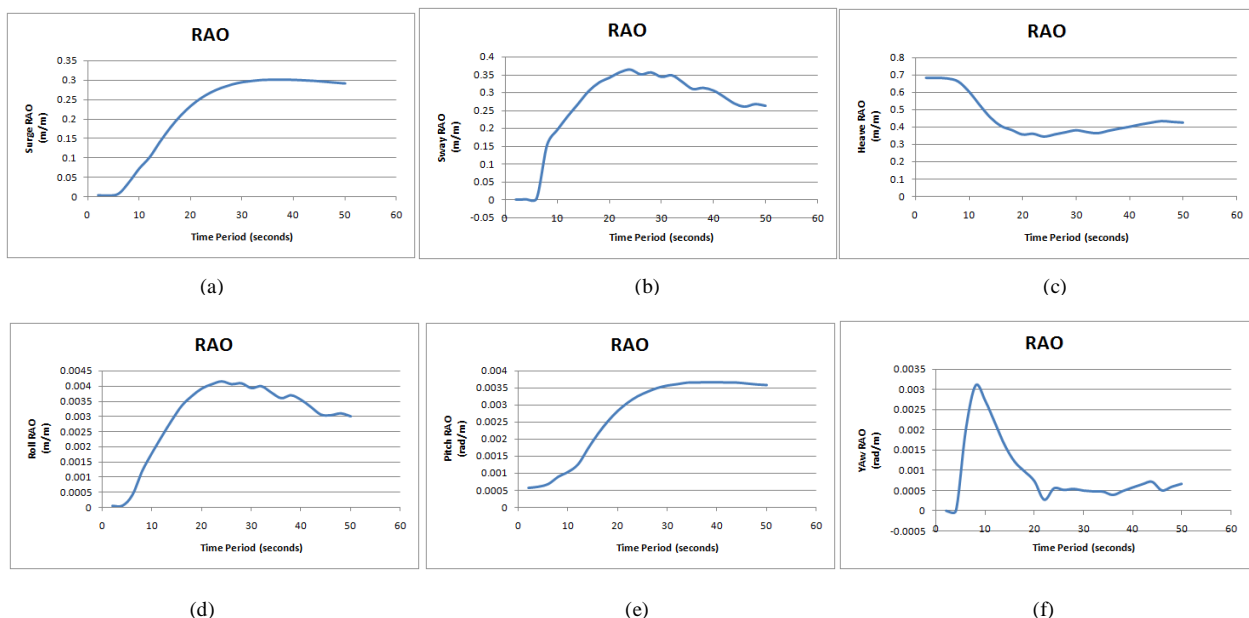


Fig.4 Response Amplitude Operators (a) Surge RAO (b) Sway RAO (c) Heave RAO (d) Roll RAO (e) Pitch RAO

The RAO's plotted above shows a gradual change in all modes except in the yaw mode. The gradual curve with very soft peaks ensures the stability of the structure against the encounter wave frequency. In the yaw plot a steep peak is seen in the 0 to 10 seconds range, which is a crucial observation but with response analysis it is seen that yaw response is not at all significant and hence this peak in yaw can be neglected.

## 5.1.1 Wind Speed Effects On RAO

The effective coupling of wind and wave is examined by the plotting of RAO's corresponding to different wind speeds. The wind speeds were selected for 6 m/s, 9 m/s, 11.4 m/s, 25 m/s from the energy curve plotted for the NREL 5 MW offshore wind turbine in which these wind speeds corresponds to the various regions specified in its definition [2].

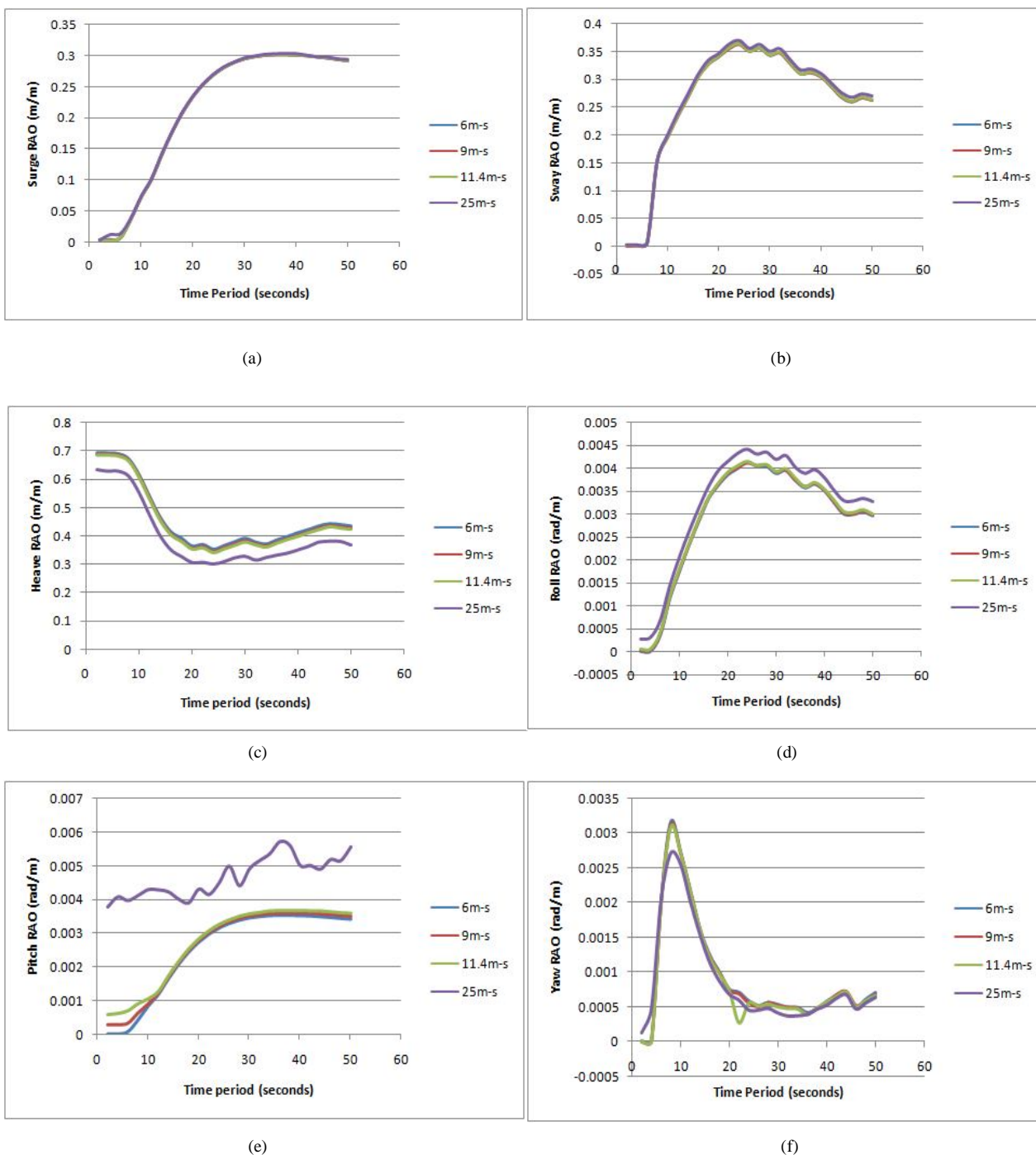


Fig.5 Response Amplitude Operators (a) Surge RAO (b) Sway RAO (c) Heave RAO (d) Roll RAO (e) Pitch RAO

# International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 10, October 2015

Considering the surge motion there is no significant difference is seen which means that turbines dynamic property is not affecting the platforms surge movements. But it is seen that when the wind is 25 m/s and at an encounter frequency in between 2 to 6 seconds, there is a peak is seen in surge response. But while considering the sway motion, according to the varying wind speed there is changes are seen. This is due to the damping property of turbine. This concludes that turbines sway motion affects platform sway thereby the damping is arising. In the case of heave motion we may see significant changes in the RAO plot which shows that the platforms heave motion is affected by the turbines heave motion thereby damping is seen in plot. In the case of roll motion we observe the same RAO plot as in case of sway motion and that is due to the damping. In the pitch RAO plot, an irregular curve is seen for 25m/s but all other wind speed have similar curves but in the initial ranges we can see the damping but reaching to the end of curve it becomes aligned. In the yaw plot a peak is seen in the 0 to 10 seconds range, which is a crucial observation but with response analysis it is seen that yaw and heave responses are not at all significant and hence this peak in yaw can be neglected.

## VI. CONCLUSION

An initial design for four-legged articulated support structure for supporting 5 MW offshore wind turbine to construct in Indian ocean. From the preliminary eigen value analysis of the proposed candidate structure it is seen that the structure's natural frequency lies much above the limiting values in sea conditions as proposed by different researchers, hence the structure was forwarded for the non linear coupled response analysis. From RAO computations, it was seen that although the system is excited by wind and wave only in surge and pitch, it displays motion in the modes of sway, roll, heave and yaw as well. The system's response in these modes indicates the coupling of wind turbine with platform motions. Considering the surge motion there is no significant difference is seen in RAOs corresponding to different wind speed which means that turbines dynamic property is not affecting the platforms surge movements. But it is seen that when the wind is 25 m/s and at an encounter frequency in between 2 to 6 seconds, there is a peak is seen in surge response. But while considering the sway motion, according to the varying wind speed RAOs show significant variations. This is due to the damping property of turbine. This concludes that turbines sway motion affects platform sway thereby causing damping. In the case of heave motion we may see significant changes in the RAO plot which shows that the platforms heave motion is affected by the turbines heave motion there by damping is seen in plot. Turbine dynamics have significant influence in Roll RAOs also. In the pitch RAO plot, an irregular curve is seen for 25m/s but all other wind speed have similar curves but in the initial ranges we can see the damping but reaching to the end of curve it becomes aligned. In the yaw plot a peak is seen in the 0 to 10 seconds range, which is a crucial observation but with response analysis it is seen that yaw and heave responses are not at all significant and hence this peak in yaw can be neglected. Wind effect on RAO shows that the aero-hydrodynamic coupling to the system is done effectively, the preliminary aim of the study was fulfilled.

## REFERENCES

- [1] Vivek Philip et.al., "Three Legged Articulated Support for 5 MW Offshore Wind Turbine", International Conference On Water Resources, Coastal And Ocean Engineering (ICWRCOE 2015), Aquatic Procedia 4, pp 500-507, 2015.
- [2] C.L. Kirk and R.K. Jain, "Response of Articulated Towers to Waves and Current", Proceedings of the 1977 Offshore Technology Conference, Houston, Texas pp, 545-552, 1977.
- [3] Jonkman, J., Butterfield, S., Musial, W. and Scott, G. "Definition of a 5-MW reference wind turbine for offshore system development", National Renewable Energy Laboratory Technical Report, 2009.
- [4] Jonkman, J. M. and Buhl, M. L., Jr. "FAST User's Guide", NREL/EL- 500-29798, Golden, CO: National Renewable Energy Laboratory, 2004.
- [5] Chakrabarti, S.K., "Handbook of Offshore Engineering, Volume1", Offshore Structure Analysis, Inc. Plainfield, Illinois, USA, 2005.
- [6] Gerwick Ben C, Jr, "Construction of Marine and Offshore Structures", Third edition, CRC press, Taylor and Francis group, Florida, USA, 2007.