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DESIGN OF FLOATING SUPPORT STRUCTURE FOR 5 MW OFFSHORE WIND TURBINE

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ABSTRACT

This paper presents preparatory design of a tension-leg support structure for a 5 MW reference wind turbine [1]. From the design considerations tabbed from past literature, a design method was drawn up, which account for important design considerations such as performance requirements and natural frequencies. The primary design is fine-tuned by adjusting parameters that control natural frequency.

Preliminary design so developed was figured out in Sesam software developed by Det Norske Veritas (DNV). Modeling was done in GeniE module and a hydro dynamic analysis was done by WADAM (Wave Analysis by Diffraction and Morison) in HydroD module of Sesam.

Natural frequencies and Response Amplitude Operators (RAOs) of proposed structure corresponding to six degrees of freedom are obtained. The design approach developed was validated by comparing with an existing tension legged model [2]. The results presented serve as guidelines in the design process of similar tension-leg support structures for offshore wind turbines.

1.INTRODUCTION

Wind energy is a clean surrogate to non-renewable energy resources. But onshore wind farms account for several environmental problems and human discomfort. This adversity can be eliminated by establishing offshore wind farms. Offshore wind tends to move at higher speeds than onshore winds, thus allowing wind turbines to yield more electricity.

At present, offshore wind farms adopt fixed structures as supports. But at higher depths (greater than 60 m) fixed supports are not suitable since they fail to provide a better cost – performance trade off. In the past, oil and natural gas industry answered this challenge by adopting floating structures and are now in use. Design legacy of oil and natural industry cannot be adopted as it is. For example, National Renewable Energy Lab, US (NREL) 5 MW turbine and tower [1] weighs only about 750 tonnes, which is far less than the weight of a typical drilling platform (about 75,000 tonnes). This influences the design. Moreover floating offshore wind turbine can be much more subjected to wind and wave action. New floating wind turbine support structure designs should be investigated.

In1998, Tong [3] analyzed the technical and economical aspects of offshore wind farm. A spar type floating platform, FLOAT, stabilised by ballasting was also presented. Mechanics of a four spoke tension legged support wind turbine was discussed by Withee [4], along with a parametric study on how the support parameters affect natural frequency of the system. A cost effective method for installing 5 MW wind turbine along with performance requirements that are to be satisfied were detailed in [5]. In 2007 Jonkman [6] studied coupling between turbine responses and pontoon motions. Tracy [7] performed a much more elaborate parametric study on how platform dimensions affect natural frequency of the system. Matha [2] performed analysis of different platform configurations including tension leg supports, and presented a tension leg supported model along with other configurations. In 2013 Yang [8] presented an analytical model of three column Tension Leg Platform (TLP) support for offshore wind turbine, where a much detailed design of hull was brought in. Till date many studies on different facets of tension legged supported wind turbine were carried out. This study tries to sieve out the divergent design considerations demonstrated in past and amalgamate them to solid generalized design steps.

Problem Statement and Limitations

The present study is intended to iterate from past literature, a method to design tension leg supporting structure for NREL 5 MW wind turbine [1]. The study first brings about a preliminary design in which the dimensions of supporting structure are fixed and there after a detailed hydrodynamic evaluation in DNV Sesam, to obtain results that can be compared with existing concepts.

This paper addresses only the conceptual and preliminary stages of the floating support structure design process, since the aim is to propose a quick and relatively simple procedure, without addressing the detailed design and the other succeeding phases, less suitable to be represented by a generalized procedure. To do so, a number of assumptions have been made. These assumptions are linked with the particular scenario considered, and should not be taken as linked to the generalized procedure. But the proposed approach can be adapted to various scenarios.

2.INVESTIGATION METHODOLOGY

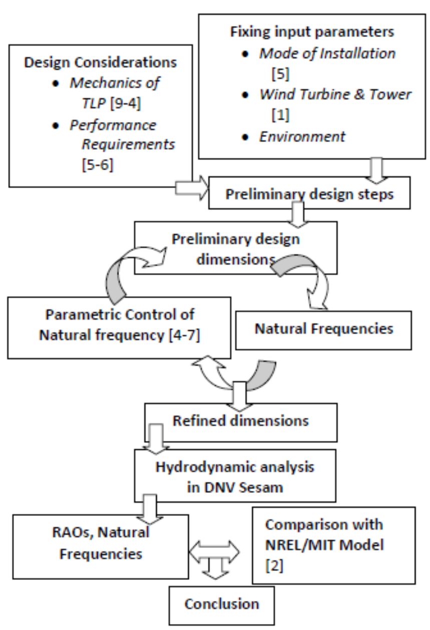


FIGURE 1. METHODOLOGY OF STUDY

Figure 1 describes the methodology adopted for the study. Mode of installation [5], Wind Turbine, Tower [1] and environmental factors like site, wind, wave and depth are fixed as the primary inputs. From the design considerations like mechanics of TLP and performance requirements, a design step was formulated to obtain primary design proportions of tension-leg support. Natural frequencies of the system analogous to six degrees of freedom were calculated. Support parameters were adjusted using parametric study [4-7], to control natural frequency to requisite limits. Model corresponding to refined dimensions was analysed in DNV Sesam to obtain natural frequencies and RAOs, which were compared with a well investigated tension leg model developed at Massachusetts Institute of Technology (MIT), the NREL/MIT Model [2] to affirm the strength of proposed design procedure.

3.INPUT DATA

The paper focuses on preliminary design of the floating support structure in which installation mode, site conditions, wind turbine and tower are the primary inputs.

3.1 Site

Site was selected as rectangle of 400 sq.km area, at east coast of India, 52 kilometers from Tuticorin coast. Points $8^0$50'40''N, $78^0$40'33''E and $8^0$29'40''N, $78^0$45'47''E conforms the two diagonal points of the selected area. The depth at this area was found to be greater than 200 m.

3.2 Wind and Wave Data: The wind effect on turbine blades are much complicated. So wherever wind effect is incorporated, the wind speed data without shear was fed to Fatigue Aerodynamics Structures and Turbulence (FAST) code [10] developed by NREL and the programme was simulated for 630 seconds, ensuring the transient effects have disappeared. From output code force on tower base was picked using MATLAB. A Wave of 10 m height and 12 seconds period was observed as site wave.

3.3 Turbine and Tower

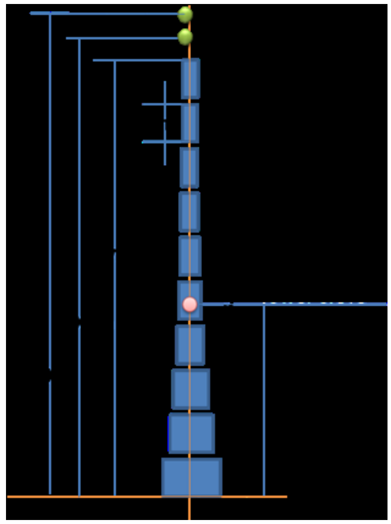
For ease of modelling and calculations, an equivalent mass distribution (figure 2 and table 1) in correlation with NREL 5 MW wind turbine and tower [1] was prepared as input.

TABLE 1. MASS DISTRIBUTION

Tower Section	Dia. (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
TOWER	347460 kg		0,0,38.234	
NACELLE	240000 kg		-0.4,0,89.3	
HUB	110000 kg		-0.4,0,90	

3.4 Installation mode

Support structure was assumed to be fabricated at shore and towed to site with turbine and tower mounted on top. This method is economical compared to site installation [5].



For a recommended pitch natural period shorter than 4 s, the 3P frequencies of wind turbine are overlapped and resonance might occur. To avoid this, the pitch natural period should be about 4 s [6].The relationship between individual parameters and their effect on the natural period [4-7] are tabulated in Table 2, which can be used as an aid to control natural frequencies to the above stated limits.

4. PRELIMINARY DESIGN

Three design considerations, the mechanics of TLP, Performance requirements and Influence of support parameters on natural frequency were clubbed together to deduce a generalized design procedure.

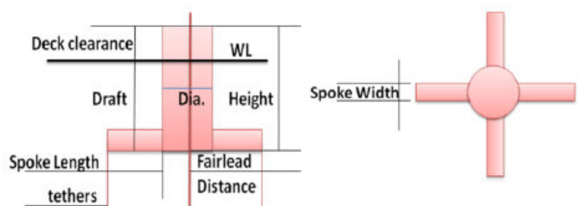


FIGURE 3. SUPPORT PARAMETERS

The general equation used to determine natural frequency of the coupled system is shown in Eqn. (1), where C is the restoring coefficient, M is the inertia term, and A is the added mass, equations of which is derived and is presented by Withee [4].

$$\omega_{0,k} = \sqrt{\frac{C_{kk}}{M_{kk}+A_{kk}(0)}} \text{ rad/sec} \qquad (1)$$

Performance requirements

Certain requirements are to be accomplished during towing, installing and operational stages of the floating support. They are:

Towing: Floating body stability is determined by position of metacentre and centre of gravity. The metacentre height should be positive and can be made so by adding concrete and water ballasting. For structure towed out to the installation site vertically, the size and shape of the floater has to be adjusted such that an adequate pitch restoring moment is achieved during towing conditions. The steady state pitch during towing and installation is set to a maximum of 10o, and the minimum hydrostatic and inertial restoring in pitch mode is found by Eqn. (2) [5],

$$C_{55,HI,min} = \frac{M_5}{\xi_5} \quad \text{Nm} \qquad (2)$$

minimum thrust force [1] during operation, since it will be greater than the maximum thrust during towing. The required restoring is obtained by adjusting the draft, radius of cylinder and the concrete ballast, for which the correlation to hydrostatic restoring in pitch [5] for a cylinder is given by Eqn. (3).

$$C_{55,HI} = F_B Z_B - (M_{total} + M_W) g Z_G + \rho g \pi \frac{R^4}{4} \quad \text{Nm} \ (3)$$

Mw is the mass of the water ballast and R is the radius of the cylinder.

Installation: The tether pretension is equal to the reserve buoyancy calculated by Eqn. (4). At the installation site the tethers are connected and pre tensioned during water ballast removal.

$$RB = F_B - M_{total} g = M_W g \quad \text{N} \qquad (4)$$

Operational conditions: The angle of the tethers with the vertical plane, θ should not exceed 50 and the corresponding maximum surge displacement is used as an initial limit for the tether tension. The minimum tether restoring coefficient in surge can be calculated by Eqn. (5), [5] where FThrust, max is the maximum thrust force [1] during operation.

$$C_{11,T,min} = \frac{F_{Thrust,max}}{\xi_1} \quad \text{N/m} \qquad (5)$$

If there are four tethers positioned in 90 degree intervals, the average tether tension is the total tension force, the pretension, divided by four.

$$F_{T,2} = F_{T,4} = F_{T,ave} = \frac{F_B - M_{total} g}{4} \quad \text{N} \qquad (6)$$

Windward tether T3, has a risk of exceeding the maximum allowable tension, as obtained from [11], and leeward tether T1, has a risk of becoming loose and can be represented by a balance of forces in the vertical direction given by equation (7) [5]. To balance the moment, tether 3 has a tension of FT,ave plus an additional tension, ΔF and tether 1 must then have a tension of FT,ave minus ΔF. RFL is the fairlead distance.

$$F_5 = F_{T,3} R_{FL} - F_{T,1} R_{FL} = (F_{T,ave} + \Delta F) R_{FL} - (F_{T,ave} - \Delta F) R_{FL} \quad \text{Nm} \qquad (7)$$

The natural frequency of the coupled system should be designed such that it does not coincide with the peak frequency of the dynamic loading. The surge and sway motions must be inertia dominated and should have natural periods longer than 30 s. Heave, pitch and roll motions should be stiffness dominated, i.e. natural periods shorter than 3-4 s.

TABLE 2. PARAMETRIC INFLUENCE ON NATURAL FREQUENCY [4-7]

Parameter	C				M				A				ω_0			
	1	3	5	6	1	3	5	6	1	3	5	6	1	3	5	6
↑Dia.	↑	-	-	↑	↑	↑	↑	↑	↑	↑	↑	-	↑	↓	↓	↑
↑Draft	↑	↑	-	↑	↑	↑	↑	↑	↑	↑	↑	-	↑	↓	↓	↑
↑Spoke length	-	-	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↓	↓	↑	↓
↑Spoke width	↓	-	↑	↓	↑	↑	↑	↑	↑	↑	↑	↑	↓	↓	↓	↓
↑No. of lines	-	↑	↑	-	-	-	-	-	-	-	-	-	-	↑	↑	-

1-surge 3-heave 5-pitch 6-yaw

For a recommended pitch natural period shorter than 4 s, the 3P frequencies of wind turbine are overlapped and resonance might occur. To avoid this, the pitch natural period should be about 4 s [6].The relationship between individual parameters and their effect on the natural period [4-7] are tabulated in Table 2, which can be used as an aid to control natural frequencies to the above stated limits.

Preliminary design steps

Design steps developed from above discussed design considerations are:

1. Choose platform diameter and draft length. Make an initial guess for concrete ballast height such that it lowers pretension.
2. Add water as ballast such that the total weight of the platform and the buoyancy force are equal at the water surface. If not possible, go back to step 1 and increase concrete ballast and possibly draft and diameter dimensions.
3. Check whether the requirement for pitch restoring during towing is fulfilled. If NO go back to step 2 and possibly to step 1. If YES, proceed to step 4.
4. Set pretension equal to the weight of water used as ballast during towing and check if the requirement for surge restoring during operation is fulfilled. If NO, reduce concrete mass and go back to step 2. If YES, proceed to step 5.
5. Choose fairlead distance such that to avoid slack in any of the lines and such that windward tether tension is less than maximum tether tension [11]. If spoke length is considered unfeasible, go back to step 1 and increase draft and diameter.
6. Check if surge, sway, pitch and roll are within limits explained in operational conditions. If not, changes could be made with the help of parametric study results given by [4] and [7].

Since the design is based on a trial and error method, same steps have to be repeated a number of times. To avoid this, an interactive excel spread sheet was prepared, which will automatically calculate frequencies with all the values and checks incorporated. Derived operational proportions of the proposed tension leg support are listed in Table 3.

TABLE 3. DERIVED PROPORTIONS

Specification	Proposed support properties
Platform Diameter (m)	13.4
Platform Draft (m)	42
Platform Deck Clearance (m)	5
Concrete Height(m)	8
Concrete Mass (kg)	2870997
Steel Mass Cylinder (kg)	354455
Center of Buoyancy (m)	-21 from water surface
Center of Gravity (m)	-18.1033
Average Line Tension (N)	4831453
Fairlead Distance (m)	29.7
Surge Natural Period (s)	57.12
Sway Natural Period (s)	57.12
Pitch Natural Period (s)	3.71
Roll Natural Period (s)	3.71

5.HYDRODYNAMIC ANALYSIS

A hydrodynamic WADAM (Wave Analysis by Diffraction and Morison) analysis was done in Sesam HydroD. The three different FEM files viz. the Morison model, Panel model and Mass model(Figure 4) were combined to create a Hydro model. Model was analyzed at an environment of waves with amplitude of 1 m and constant wind force 11 m/s without shear. These particular values were selected by Matha [2] in his analysis of MIT/NREL TLP. A direct comparison of the results is possible as same environmental conditions are selected. The significance of 11 m/s is that it is the wind speed causing maximum thrust on turbine yaw axis [1]. One amplitude wave was stimulated with a time period of 0.1 to 25s with an interval of 2s. Wind was accounted as difference in pretension at windward and leeward side.

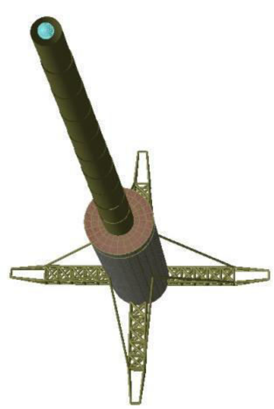


FIG 4. MASS MODEL

6. RESULTS AND DISCUSSIONS

Natural time periods of proposed tension-leg support corresponding to surge, sway, heave, pitch, roll and yaw along with design proportions are compared with the NREL/MIT Model[2] in table 4.

TABLE 4. OPERATIONAL PROPERTIES COMPARISON

Specification	Proposed Support	NREL/MIT Model [2]
Platform Diameter (m)	13.4	18
Platform Draft (m)	42	47.86
Concrete Height (m)	7.2	12.6
Centre of Gravity(m)	-18.1	-32.8
Centre of Buoyancy (m)	-21	-23.9
Average Line Tension (kN)	2101	3931
Surge Restoring (kN/m)	122	173
Fairlead distance (m)	29.7	27
Surge Natural Period (s)	63.4	60.6
Heave Natural Period (s)	1.3	2.3
Pitch Natural period (s)	4.1	4.5
Yaw Natural period (s)	24.2	10.3

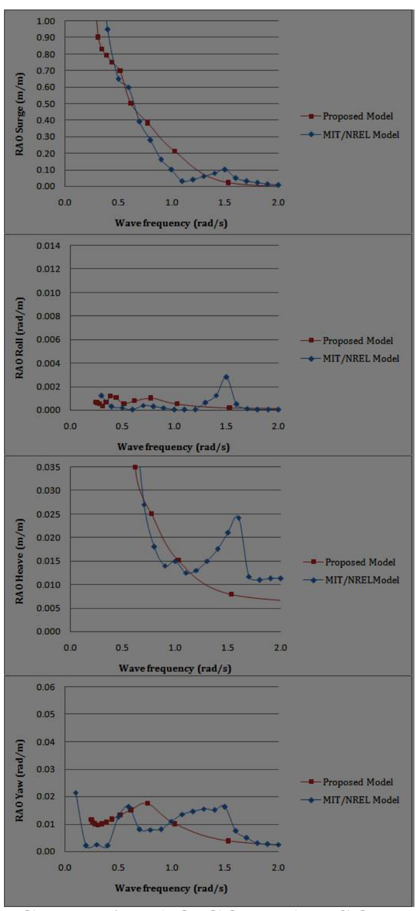


FIGURE 5. RAO COMPARISON

Surge and sway time periods of proposed tension-leg support are 63 seconds, indicating that these motions are inertia dominated. Heave, pitch and roll motions have shorter periods of range 4 seconds. A comparison of results with MIT/ NREL model shows that diameter, draft and concrete height have been reduced. The total mass and displacement are therefore reduced, giving a lower average line tension. The surge restoring coefficient of proposed tension-leg support is found to be 122 kN/m, smaller when compared to MIT/NREL model. So the steady state displacement in surge will be larger for new proposed tension-leg support. However the surge natural period is increased and pitch natural period is decreased, which is a favourable condition. The proposed tension-leg support has a centre of gravity close to centre of buoyancy, compared to MIT/NREL model, which may give a favourable performance for MIT/NREL model. The RAOs corresponding to 6 degrees of freedoms are obtained and these values were compared with that of NREL/MIT model (Refer Figure 5).

For the proposed model, a steady state variation in all six RAOs is observed, illustrating good stability to external forces. Apart from NREL/MIT model, RAOs of proposed model is not sharply tuned indicating limited susceptibility to encounter frequencies. All the RAOs of proposed model are observed to be damped due to lower pretension achieved. Heave RAO of proposed model was observed to be damped due to lower diameter and lower pretension. Divergence in Yaw RAO was due to a larger fairlead distance of proposed model. At the time when pitch reaches its maximum, surge, sway, heave and yaw modes were reduced considerably. This is a desirable quality for floating structures. From comparison it can be seen that the general trend in RAO is almost same for both NREL/MIT model and the proposed model indicating validity of design assumptions chosen.

7.CONCLUSION

This paper discusses the preliminary design of a tension-leg floating support structure for the NREL 5 MW offshore wind turbine. A design procedure was developed incorporating important design considerations like performance requirements and natural frequencies. The design approach so developed was validated by comparing with a well investigated model. The responses of the proposed model revealed better stability, owing to extended concepts conceived during preliminary design. Lower pretension and reduced dimensions achieved resulted in smoothened RAOs, indicating less susceptibility to external wave frequencies.

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