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Dynamic Effects of Anchor Positional Tolerance on Tension Moored Floating Wind Turbine

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Abstract.

For water depths greater than 60m floating wind turbines will become the most economical option for generating offshore wind energy. Tension mooring stabilised units are one type of platform being considered by the offshore wind energy industry. The complex mooring arrangement used by this type of platform means that the dynamics are greatly effected by offsets in the positioning of the anchors.

This paper examines the issue of tendon anchor position tolerances. The dynamic effects of three positional tolerances are analysed in survival state using the time domain FASTLink.

The severe impact of worst case anchor positional offsets on platform and turbine survivability is shown. The worst anchor misposition combinations are highlighted and should be strongly avoided. Novel methods to mitigate this issue are presented.

1. Introduction

For water depths greater than 60m floating wind turbine (FWT) will become the economical option for generating offshore wind energy. Tension mooring stabilised FWT are one type of platform under investigation by industry and academia [1–4]. Tension mooring stabilised platforms are restrained in heave, pitch and roll and compliant in surge, sway and yaw. Excess buoyancy provides the restraint through tendon pretension. For tension moored FWT, tendons are generally designed to be vertical. The "as installed" position of the anchors however may not be in exactly the same position as was designed. It is hypothesised that this anchor misposition leads to a change in platform motions and loads. This paper investigates the sensitivity of a tension moored FWT to anchor positional tolerances.

For proposed Atlantic sites, the availability of enough weather windows to carry out installation, operations and maintenance on marine energy devices has been predicted [5]. For the complex anchor tendon system type discussed in this paper this is obviously of great concern. Thus any method to decrease the temporal or sea state conditions required is vital for deployments in these harsher environments.

1.1. Anchor Type

A number of different types of anchor systems have been proposed for tension moored floating wind turbines, these include; pile, gravity, suction, drag and grouted rock anchors. High vertical

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load drag embedment plates have also been proposed by Glosten Associates for the PelaStar device, but due to the operational loading limit of 45° to the horizontal, are not compatible with the vertical moorings used in this paper. Positional tolerances for drag embedment anchors will also be much greater than for the previously mentioned anchor types. Monolithic gravity based anchors will not suffer from the inter anchor misalignment discussed in this paper. The anchor choice will depend on seabed characteristics, which may not be uniform across a proposed wind farm. To give a scale of the challenge facing the offshore floating wind industry, as of 2002 only ≈ 500 suction piles had been installed worldwide [6], a similar number which would be required for a single wind farm with number of turbines ≈ 125.

1.2. Anchor Positional Tolerance

The DNV codes [7] state that the permissible installation tolerances shall be determined taking into account the increased difficulty in accurate seabed positioning caused by large water depth and environmental conditions. Position tolerances can be an absolute, for example 1m, or depth dependant, for example 1% of water depth.

Installation of anchors requires special anchor handling vessels with dynamic positioning (DP) systems. DP systems can keep a vessel "on location" by applying an active thrust, thus making it easier to achieve the required positional accuracy. In order to apply the appropriate reactive thrust, DP systems measure wind speed but calculate wave and drift loads and thus the positional control systems used integrate a feedback feature and require some time to become positionally stable.

It is assumed that increasing the anchor positional tolerance will allow the anchors to be installed in shorter weather windows, more severe sea states, or by less expensive vessels that have less capable DP systems. This paper investigates what the effect of increasing these positioning tolerances will have on the platform dynamics (motions and tendon forces). A literature review of the topic found a surprising lack of publications. In 1993, Hamilton [8] presented a method to calculate the linear effects of anchor misposition by using linear pitch and roll motion but keeping quadratic terms in yaw motion, although no results using this method were presented. Figure 1 shows a 3D view of the platform with and without anchor misposition.

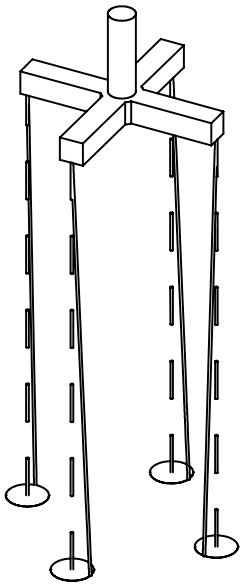


Figure 1. View of platform and anchor misposition. Dashed tendon line is the design case with no mispsoition, solid tendon line is the misposition case. Seabed circles indicate the anchor target area. Horizontal distances are exaggerated to retain clarity.

2. Methods

The tension moored floating NREL 5MW reference [9] wind turbine platform; TLPWT 4 [10] was used for this study. The water depth is taken as 150m. Hydrodynamic parameters are computed from ANSYS AQWA for 8 wave directions and 50 frequencies from 0.008Hz-0.4Hz. Time domain modelling is required due to the highly non-linear nature of the tendon stiffness and platform dynamical coupling and is carried out using the coupled Orcaflex and Fast package FASTlink v8 [11]. Additional quadratic viscous damping of the platform is added to the model using modified Morrison's equation drag only elements. Mooring tendon stiffness is not mentioned in the cited paper and are modelled with an axial stiffness of $1.5 * 10^9$N using Morrison's equation elements.

Eight anchor offset positions are chosen for each anchor ($360°/8 = 45°$) and with four anchors this allows for 4096 possible combinations. Figure 2 shows the possible anchor positions. These combinations result in a number of duplicate simulations, where the effective spacing of the anchors is equal and all are offset in the same direction. Four of these duplicates are included in the study as the wave elevation will be non-exact at the varied position (different frequencies that make up the wave spectrum having different velocities). As the waves are long-crested and do not include a y component, the four positions, which are mirror positions about the x-axis to those four mentioned previously, are not included in the study. This results in a total number of 4092 simulations. The anchor position tolerances are chosen as absolute values of 1, 2 and 3m (Tolerance/depth ratio of 0.0067, 0.0133 and 0.02). This study assumes the worst case scenario, where anchors are positioned along the limits of these tolerances.

Survival state is modelled using a JONSWAP spectrum with Hs of 12.7m, Tp of 14.1s and wind speed 50m/s for 1300s (Ignoring the first 100s to give a usable time of 20 minutes or 1200s). Wave and wind were modelled as being directionally aligned. For comparability all simulations use the same random phase seed number.

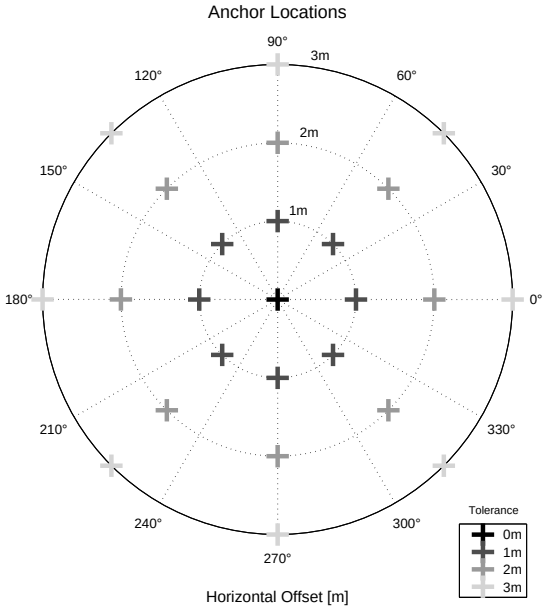


Figure 2. Possible Anchor Positional Locations

3. Misposition Results

Displacements and rotations are calculated at the platform's centre of gravity, accelerations are measured at the centre of the nacelle. Anchor misposition is weighted by the perimeter distance added to the square of the in wave positions and then normalised by the base case of 0m misposition. The perimeter distance is calculated as the path length around the as installed position of all anchors. The in wave position is calculated as the anchor position parallel to the wave direction. In this case the wave direction has no y component and thus this value purely relates to the anchors x position. It should be noted that this normalisation process does not represent any physical quantity and is solely used in order to visually represent the results in Figure 4. Equation 1 shows the normalisation function, where $\bar{P}$ is the normalised position, p is the perimeter length, i is the anchor number, n is the number of anchors, xw is the in wave position, j is the misposition number and 0 is the zero misposition baseline case. The results of the normalisation process are values between 0.69 and 1.41.

$$\bar{P_j} = \frac{p_j + \sum_{i=1}^{n} xw_i^2}{p_0 + \sum_{i=1}^{n} xw_0^2} \tag{1}$$

Figure 3 shows the mooring misalignment which results in the most severe accelerations from the simulation study, where the anchors parallel (Tendons 1 & 3) and the anchors perpendicular (Tendons 2 & 4) to the wave direction are shifted to the maximum relative distances. Figure 3a shows this relative anchor position, the reader should note that the X and Y axis dimensions are distorted for the inter anchor cases to retain clarity. Figure 3b shows the surge displacement, Figure 3c the nacelle acceleration and Figure 3d the tension in Tendon 1. A segment of the simulation time series (from 168s - 182s) which shows the largest deviation between the 0m and 3m case across all the dynamics is shown to retain reader clarity. The most significant result is a 53% increase in maximum nacelle acceleration. Figure 4 shows all the cases. Figure 4a-d shows the maximum surge, heave and pitch displacement and maximum nacelle acceleration, Figure 4e-h shows the maximum tendon forces. Of particular note are the large motions and

forces that are located in the range of 0.95 - 1.1 normalised anchor position. xZ is surge, Z is heave, RY is pitch, A is acceleration and T1-4 are the tensions in tendon 1-4

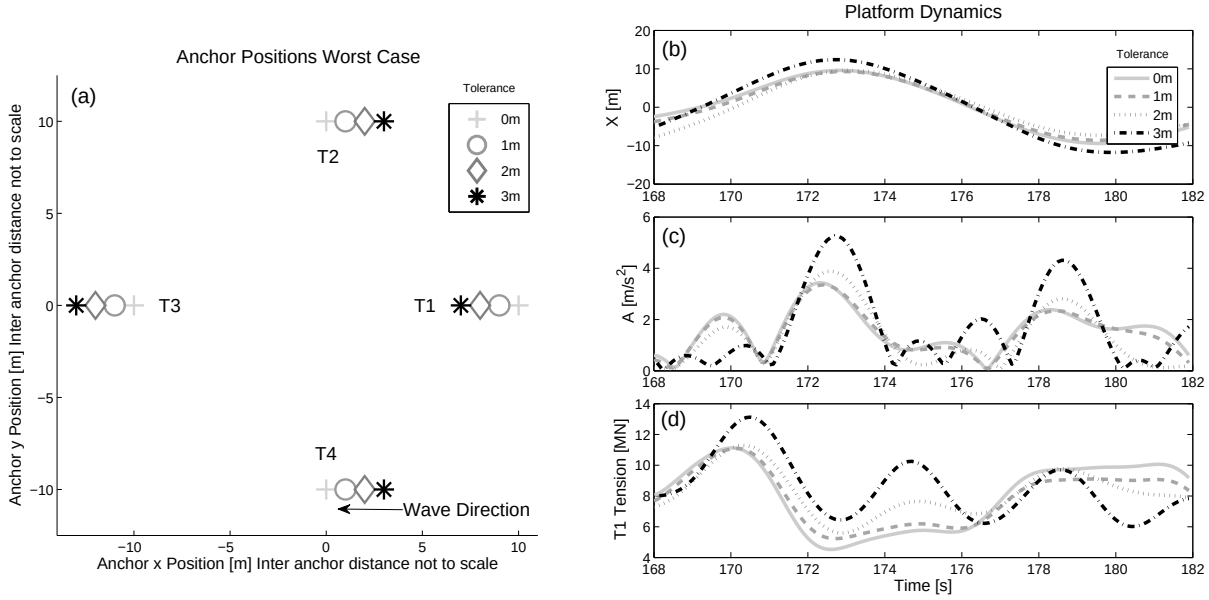


Figure 3. Anchor misposition effects on Dynamics: Worst Case, where X is the platform surge, A is the nacelle acceleration and T1 is Tendon 1

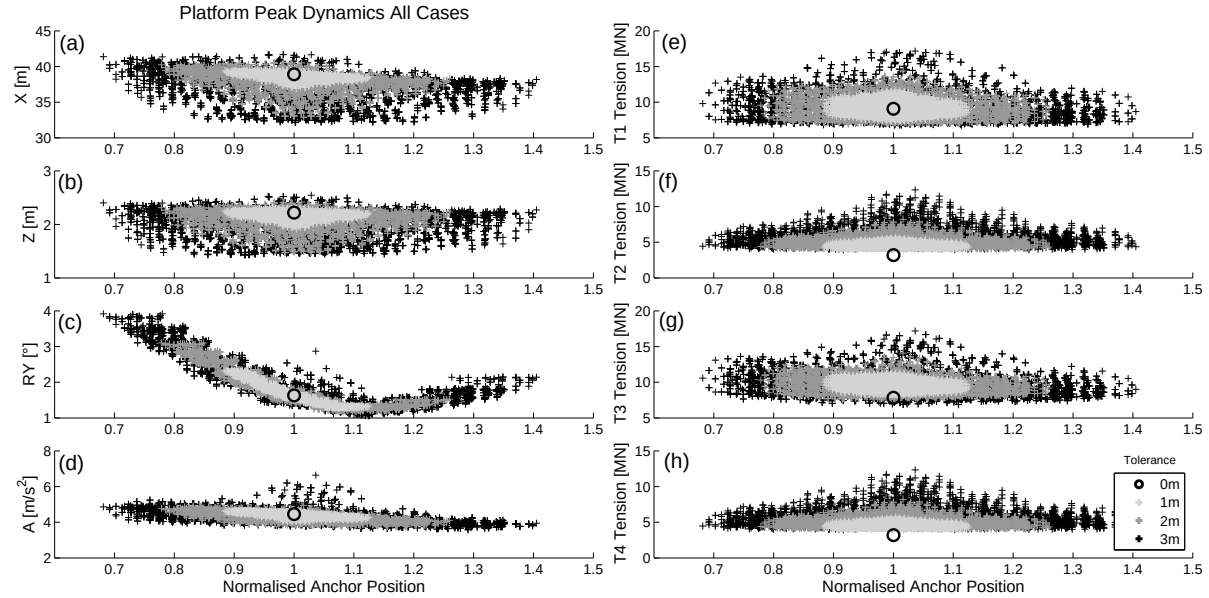


Figure 4. Anchor Misposition effects on Dynamics: All Cases, where X, Z, RY is the platform surge, heave, pitch, A is the nacelle acceleration and T1-4 is Tendon 1 - 4

4. Mitigation Methods

This paper proposes two novel mitigation methods for the issues addressed here. Both methods involve changing the target anchor position based on the position of previously installed anchors. This is in contrast to a traditional method, where anchor targets are identified before installation and are rigid as they do not evolve as anchors are installed. First a nearest neighbour installation method is proposed, followed by a furthest neighbour installation method. If the distances between the anchors are equal, the first one anticlockwise of those already installed is chosen. The ten anchor offsets, at 3m tolerance, that show the most severe results are used as test comparison cases to compare each method. An example for the same offset positions of both of these methods is shown in Figure 5, where x and y are the two horizontal positional coordinates, a) shows the nearest neighbour installation method and b) shows the furthest neighbour installation method. Anchor names are the same as Figure 3a

4.1. Nearest Neighbour Installation Method

The nearest neighbour installation method (NNIM) installs the anchors in order of which is closest to those already installed. The offset of each previous anchor is used to determine the location of subsequent anchors. The first anchor is installed in the original target area. The as installed position of the anchor is recorded. The order of subsequent anchors are chosen based on which minimises the distance to the already installed anchor(s). If the distance between two possible anchors are equal, the one in an anticlockwise to those already installed is chosen. A new target area for this next anchor is identified based on position of previous anchor(s). This procedure is continued for each subsequent anchor using the average offset of the previous anchors. The methodology is described for the four anchor case in Equations 2 to 5 with the governing formula in Equation 6. Here the x and y positions are a subset of P (P = [x,y]) P_I, P_D and ΔP_O denotes the installed, design and offset positions respectively. The possible values for ΔP_O are shown in Figure 2.

$$P_{I,1} = P_{D,1} + \Delta P_{O,1} \tag{2}$$

$$P_{I,2} = P_{D,2} + \Delta P_{O,2} + \Delta P_{O,1} \tag{3}$$

$$P_{I,3} = P_{D,3} + \Delta P_{O,3} + (\Delta P_{O,2} + \Delta P_{O,1})/2 \tag{4}$$

$$P_{I,4} = P_{D,4} + \Delta P_{O,4} + (\Delta P_{O,3} + \Delta P_{O,2} + \Delta P_{O,1})/3 \tag{5}$$

$$P_{I,i} = P_{D,i} + \Delta P_{O,i} + \frac{\sum_{n=1}^{i-1} \Delta P_{O,n}}{(i-1)} \tag{6}$$

4.2. Furthest Neighbour Installation Method

The furthest neighbour installation method (FNIM) follows the NNIM, except in the order of anchor installation. In this method the order of subsequent anchors are chosen based on which are furthest apart from those already installed. The first anchor is installed in the original target area. The anchor that is furthest from this first anchor is then installed using the first anchors offset position. Subsequent anchors are installed in order of which are furthest from their nearest neighbour first. The results presented here weight all previous installations equally, that is the average of all previous offsets are used to determine the new anchor positions. Equations 2 to 6 also describe this method, although the anchor order will be different.

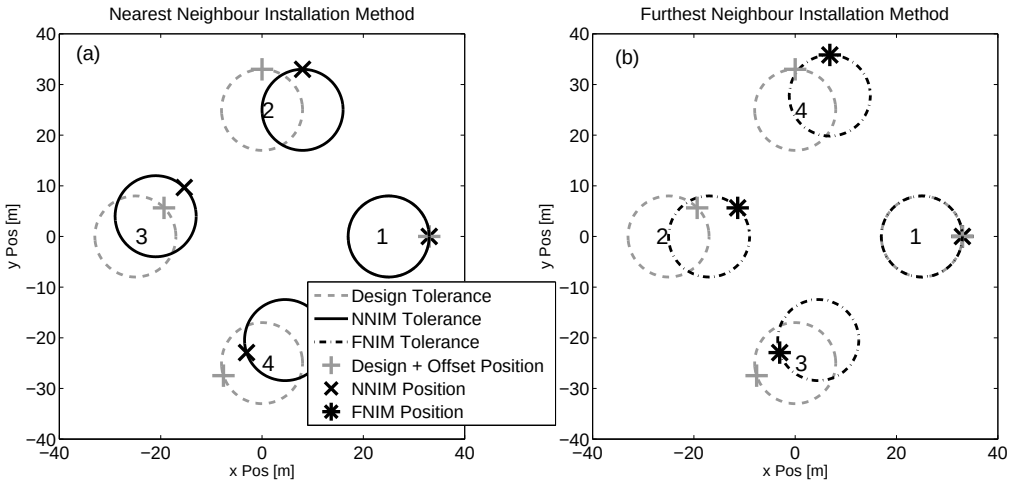


Figure 5. Examples of NNIM and FNIM positional results. Horizontal offset distance has been distorted to retain clarity. Numbers indicate installation order

5. Mitigation Results

Figure 6 compares the results of the two proposed mitigation methods against the "as designed" plus offset case for the ten simulations cases. Negative and positive results indicate reductions and increases respectively for the relevant dynamics. Results for the NNIM are inconclusive, with some offset cases showing reduced and some showing increased peak dynamics. Results for the FNIM are conclusive, as all simulations show the same trend and are shown in Table 1. The percentage change in results compared to the design case are shown here. All ten cases show decreased platform motions and nacelle accelerations over the design case. The upwind T1 tendon shows decreased peak loadings but these positive results come at the expense of increased peak loadings in all other tendons.

Results for root mean square (rms) motions and loading follow the same trend as the peak values presented here and are thus not shown.

Table 1. Results of the FNIM [% Change to design case], where X, Z and RY is the platform surge, heave, and pitch, A is the nacelle acceleration, and $T1-4$ is the tendon tension in line 1 - 4

	X	Z	RY	A	$T1$	$T2$	$T3$	$T4$
Mean	-9.8	-18.8	-22.3	-9.5	-5.0	4.3	6.0	20.7
Standard Deviation	1.3	3.1	12.1	5.3	1.4	2.6	1.6	3.9

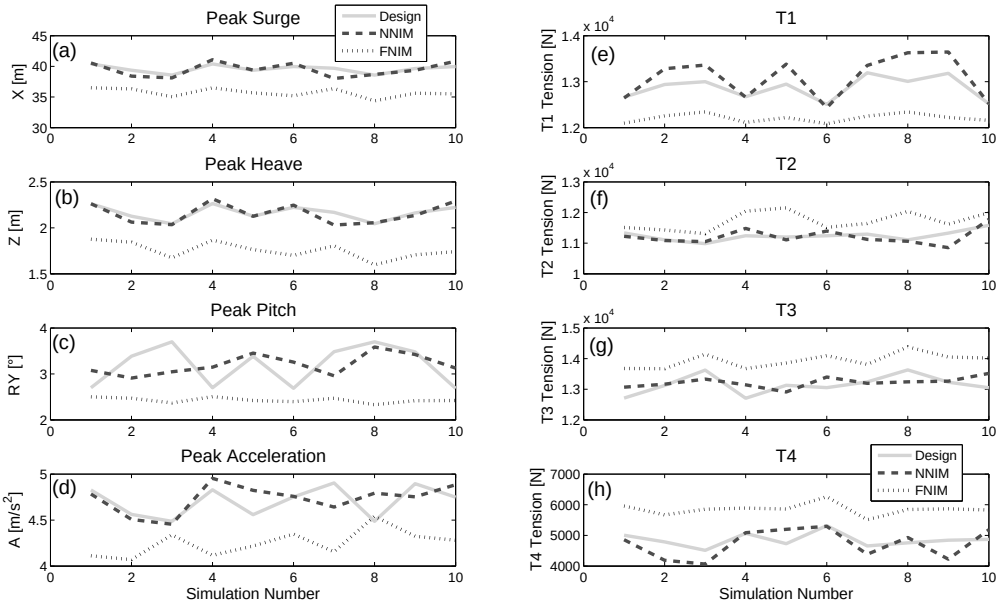


Figure 6. Results of NNIM and FNIM compared to the design offset for ten worst case simulations, where X, Z, RY is the platform surge, heave, pitch, A is the nacelle acceleration and T1-4 is Tendon 1 - 4

6. Conclusions

This paper identifies anchor misposition as a major design concern for the deployment of tension moored floating wind turbine platforms. The results from this paper rule out the possibility of using vertical (90°) loaded drag embedment anchors because the current positional accuracy technology for this anchor type is much greater than those tolerances used in this study. This would lead to a further increase in dynamics and would require a larger platform design in order to accommodate this increase. The current aim of FWT platform design is opposing this, decrease size in order to increase economic competitivity.

The severe negative dynamic effects of anchor misposition are shown, especially which positional combinations should be strictly avoided. The worst case misposition locations at a 3m tolerance increase nacelle acceleration by 53%. Two mitigation methods are proposed and tested in order to reduce the need for positional accuracy. The NNIM is deemed as unsuitable for this purpose. The FNIM shows great promise for reducing platform dynamics, although at the expense of increased downwind tendon forces. Future work will involve refining this method to take this into account, testing for wind and wave misalignment, and a statistical study on the probability of these mispositions. The effect of changing the number of tendons on the misposition results will also be analysed.

Acknowledgments

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