A Sea-state Based investigation for Performance of Submerged Tensioned Mooring Supported Tidal Turbines

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***Abstract*—This paper reports the performance of a tidal turbine station keeping system based on the adoption of a tensioned mooring system in different sea states. The capabilities of introducing damp are being investigated to reduce the peak loads that tidal turbine experienced during their operational life in high energy wave-current environments and extreme sea states. The loading on the turbine rotor blades and buoy are calculated using a wave and current coupled BEMT. The modeling algorithm developed is based on an inverted triple pendulum, responding to different sea state conditions to understand the system response behavior and the blades loading in different sea states, including the extreme conditions. The results show that the tensioned mooring system reduces peak thrust loading on the turbine, but it was found that there are certain limitation when using this design in extreme waves conditions.**

I. Introduction

The global resource from tidal and other marine currents may exceed 1100 TWh/y [1], tidal-stream energy may be an important contributor to global renewable energy demand and UK has an estimated 10 to 15% of the global harvestable tidal resource [2]. Several kinds of tidal turbines has been tested in the past 10 years. There are six main types of Tidal Energy Convertors (TEC), which are horizontal axis turbine, vertical axis turbine, oscillating hydrofoil, enclosed tips (venturi), archimedes screw and tidal kites [3].

Design of tidal turbine station keeping systems varies according to the different turbine architecture being considered and the method of attachment to the seabed being employed. Gravity base structures, drilled monopiles and drilled pin pile tripods are three widely applied support structures used today for tidal turbines. In order to make tidal current generation become economically competitive with traditional types of generation, the industry must focus on reducing the cost. Two main cost factors which must be targeted are installation and maintenance, so the flexible catenary mooring based systems are being adopted for the station keeping of floating tidal turbines, such as CoRMaT [4].

A basic survey of the use of elastic mooring tendons for the mooring of tidal current turbines is presented by [5].Where it was shown that the reduction of cost and time involved in installation are reported significant reductions using flexible moorings instead of pile structure foundations, moreover the structural costs of the device and its mounting can be reduced. The utilization of orientating the device to current flow naturally reduces the cost of control systems, furthermore not only maintenance costs are reduced by allowing removal of device for onshore maintenance but also downtimes are reduced. However, the calculations undertaken by [5] did not include the thrust, torque and more dynamic characteristics of the tensioned mooring turbine.

Analysis and control of marine mooring and cable system are presented by [6], the method was used to solve the dynamics of ship and offshore platform mooring system. Mooring systems from the offshore oil & gas and ship industry have been developed and applied to the design for some wave energy converters [7], [8]. However these theories are usually works on a mooring line which is not fully tensioned and connected to a floating structure on the water surface. Modeling methods to investigate the dynamics of the tensioned mooring turbine have been discussed in this paper.

In this context. A neutrally buoyant turbine is supported from a tensioned cable based mooring system, where tension is introduced by a buoy worked as a damper and fully submersed in water, the schematic of the system in operation is shown as Figure 1.

In this paper the system is assumed to be an iverted pendulum system using inelastic mooring lines. A simple pendulum with external drives may oscillate periodically, quasi-periodically and chaotically [9], [10], [11]. A coupled pendulum with external drive is expected to experience more complicated dynamics. Existence of irregular vibrations and both periodic and chaotic trajectories of a mathematical double pendulum system have been studied in [12]. The stabilization

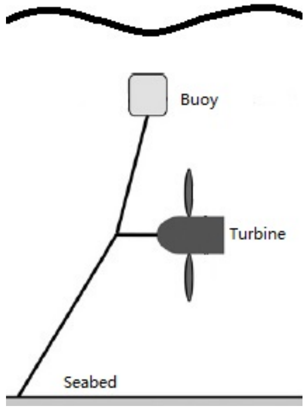

Fig. 1. Schematic of tensioned mooring turbine in operation

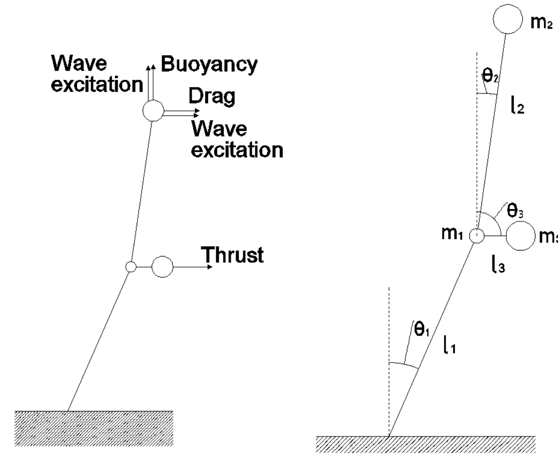

Fig. 2. Forces and model of the system

of inverted pendulums, which is highly nonlinear system has been extensively studied for control education and research purposes.

The the external forces in mooring supported turbine system are at specific axis and positions, so the model can be simplifed as [13]. However the wave excitation on the buoy is not under consideration in the previous work, the major objective of this paper is the discussion how the wave excitation on the buoy affect the system especially in the extreme sea state.

II. Methodology

The tensioned mooring system is modeled as a special type of triple pendulum which is called an inverted flail. It consists of three pendulum, the first mooring line is attached to a fixed point which is considered to be an anchor, and at its end mass the other two mooring lines attached turbine and buoy are joined. The external forces and model of the system of the tensioned mooring turbine are based on [13] is shown in Figure 2. Turbine thrusts and buoy drag can be obtained by using ESRU in house BEMT code [14] with modifications of relative velocity between the turbine and inflows. The solving scheme is given in Figure 3.

The wave excitation in two directions are exciting force and drift force, is assumed based on the work from Wu [15], the wave induced exciting and drift forces acting on a submerged sphere is given as

$$f_j = -\rho\omega^2 A_{S_\mathrm{B}}(\phi_1 + \phi_\mathrm{D}) n_j \mathrm{d}s \tag{1}$$

and

$$\bar{f}_j = \frac{1}{4}\rho\omega^2 A^2_{S_\mathrm{B}} \nabla\phi_\mathrm{ID} \cdot \nabla\phi^*_\mathrm{ID} n_j \mathrm{d}s \tag{2}$$

where ρ is the water density, ω is the wave frequency, A is the wave amplitude, S_B is the body surface, ϕ_1 is incident wave velocity potential, ϕ_D is the diffraction potential, n_j is the the body's normal vector pointing into the water, $\phi_\mathrm{ID} = \phi_1 + \phi_\mathrm{D}$ and the symbol * denotes the complex conjugate.

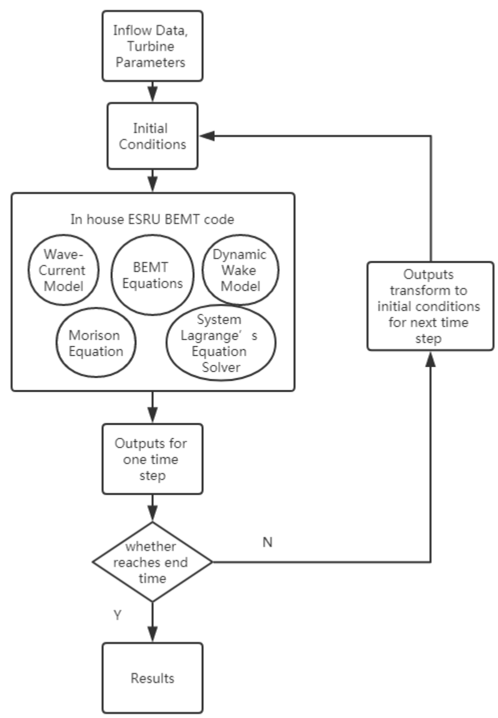

Fig. 3. Solving process

In this investigation, the diffraction potential is not taken into account in order to simplify the calculation. The the exciting and drift forces are simplified to

$$f_j = -\rho\omega^2 A_{S_\mathrm{B}} \phi_1 n_j \mathrm{d}s \tag{3}$$

and

$$\bar{f}_j = \frac{1}{4}\rho\omega^2 A^2_{S_\mathrm{B}} \nabla\phi_1 \cdot \nabla\phi^*_1 n_j \mathrm{d}s \tag{4}$$

Moreover, the added mass effect should be considered, the added mass forces on the buoy in horizontal and vertical directions are

$$F_{\rm ax} = \frac{2}{3}\rho\pi R^3 \frac{\partial^2 \phi_1}{\partial x \partial t} \quad (5)$$

and

$$F_{\rm ay} = \frac{2}{3}\rho\pi R^3 \frac{\partial^2 \phi_1}{\partial y \partial t} \quad (6)$$

where R is the buoy radius.

Parameters of a 1MW turbine and mooring system are set to be applied to deep water, parameters given below are fixed in order to control the number of variables.

$m_1 = 1$t $m_2 = 5$t $m_3 = 80$t $l_1 = 30$m $l_2 = 15$m $l_3 = 3$m turbine diameter $= 20$m water depth $= 50$m current speed $= 2.5$m/s $\Omega_r = 1.25$rad/s $R = 3m$ NRELs814

The initial conditions considered for the first itration of the calculations can be found in Table 1

TABLE I
INITIAL CONDITIONS

θ_1=0	$\dot{\theta}_1$=0	θ_2=0	$\dot{\theta}_2$=0	$\theta_3=\frac{\pi}{2}$	$\dot{\theta}_3$=0

Angles in Table 1 are all measured in radian. For analysis of pendulum dynamics, usually more initial conditions should be taken into consideration. However for the mooring supported tidal turbine, when the buoyancy and wave-current coupled force are applied on the system, the turbine will oscillate around the equilibrium position during operation no matter what the initial conditions are set. The reduction of force and torque on the turbine resulted by the tensioned mooring system during operation is the main focus of investigation, so that only one initial condition is considered in this study. It is therefore considered that mooring lines l_1 and l_2 are positioned vertically and l_3 is at horizontal position.

III. Results

Tabke 2 shows the sea states investigated in the simulation to obtain the thrusts and torques on the thurbine. Steep and swell waves are investigated to make comparison that how wave excitation on the buoy affect the loads on the turbine.

sea states	1	2	3	4	harsh winter
H_s[m]	4.322	1.07	1.07	2.665	10.12
T_z[s]	6.135	11.07	11.07	6.135	10.06
wave model	three-step	linear	random	random	three-step
steepness	steep	swell	not steep	steep	extreme steep

TABLE II
SEA STATES

A. Steep Wave

Firstly, the results with wave excitation on buoy and without it are compared in the same sea states. In sea state 1, three-step approximate wave-current interaction model [16]was applied in this simulation. Results of thrusts and torques on the turbine are shown in Figure 4. It is clear that the mooring supported turbine shows a favorable performance in reduction of peak thrust on the turbine compared to the results that considered wave excitation on the buoy shows a different waveform without wave excitation. The standard deviation of the thrust on mooring supported turbine considered wave excitation on buoy is 2.1577×10^4N and without wave excitation is 1.6119×10^4N which are 18.8% and 14.1% of that on rigid structure's value 1.1473×10^5N, because the mooring supported turbine will move along with the wave in wave crest and move against the wave in wave trough. However the peak torque on the turbine was not reduced as substantially as thrust. The standard deviation are 2.4258×10^4Nm and 1.7876×10^4Nm for the mooring structure with and without wave excitation on the buoy, and 4.8465×10^4Nm for the rigid structure. According to the result, the wave excitation on the buoy will not increase the peak loads on the mooring supported turbine in this sea state, but will increase the load dispersion. This means that the wave excitation on the buoy is an important factor in fatigue analysis. Moreover, there are shifts of curves with and without wave excitation to the rigid structure in both results, this is because of the hub height of mooring supported turbine becomes lower than the rigid supported turbine during operation. In operation, the hub height will drop to around 22.5m compared to the original height which was set at 30m from the seabed as the traces shown in Figure 5.

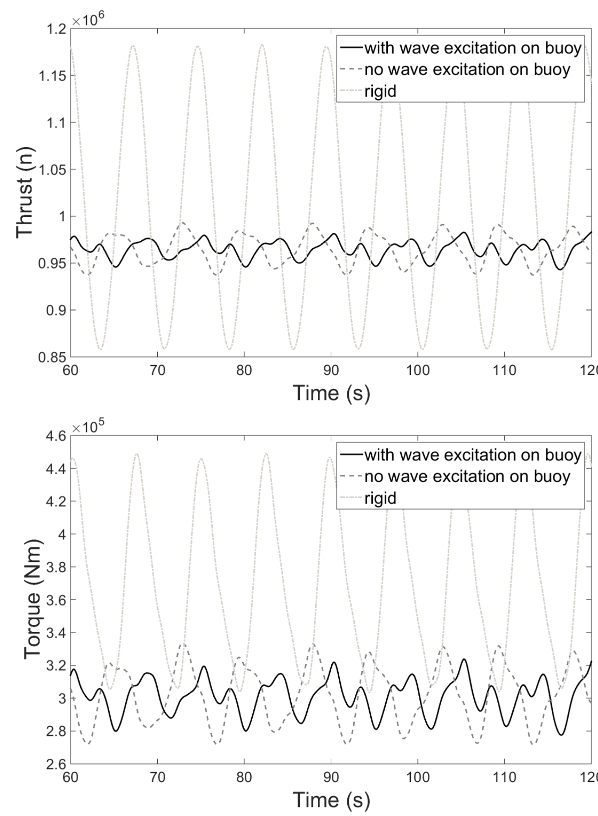

Fig. 4. Thrust and torque comparison

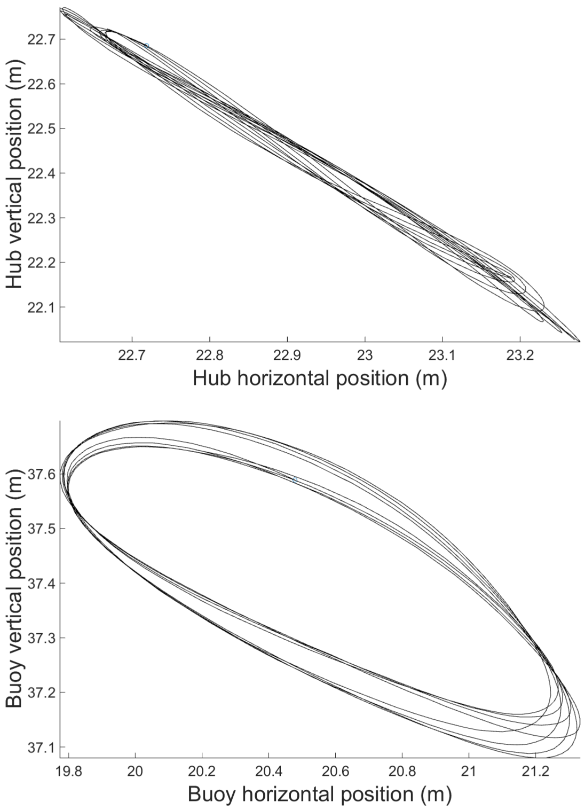

Fig. 5. The displacement of turbine and buoy with wave excitation

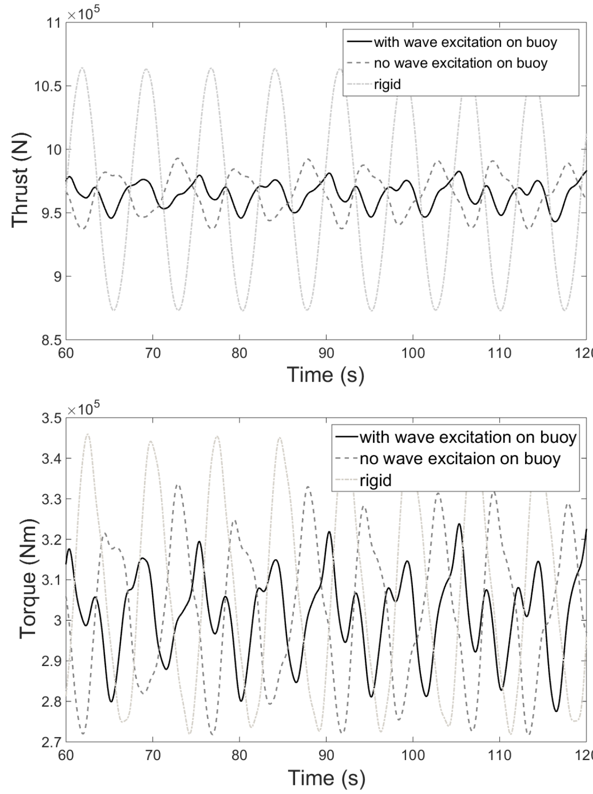

Fig. 6. Adjustment of thrust and torque comparison

As the trace of turbine shows, the hub of mooring supported turbine is not as the same height as the rigid supported turbine during operation, so the hub height of rigid supported turbine is adjusted to be 22.4m instead of 30m in Figure 6. It is showed that loads on rigid turbine decreased due to the effect of wave become weaker compared to Figure 4. The standard deviation of the thrust on rigid supported turbine now is 6.4278×10^4N and the standard deviation of the torque is 2.3599×10^4Nm. Now the thrust standard deviations for the mooring supported turbine with and without wave excitation on the buoy are lower than the rigid structure by 66.5% and 74.9% respectively. The torque standard deviations are 102.8% and 75.7% of the rigid structure. The mooring supported turbine still reduce the peak thrust on the turbine, however its effect in peak torque reduction is not obvious especially considered the wave excitation on the buoy.

B. Extreme Wave

The performance of mooring supported turbine affected by in extreme wave conditions is analysed in this section. The condition of a harsh winter sea state is applied to the simulation. The result is shown in Figure 7, the wave excitation on the buoy now shows a more obvious effect to the thrust and torque on the turbine. The trend in thrust comparison seems close to the result from previous sea state, the standard deviations for thrust with and without wave excitation on the buoy are 1.3024×10^5N and 8.4067×10^4N which are 67.2% and 78.8% lower of that on rigid structure's value 3.9655×10^5N. However, the result of torque comparison shows differences with that of previous sea state, the peak torque of mooring supported turbine has reduced obviously and the standard deviations are 1.2841×10^5Nm and 8.1540×10^4Nm separately for with and without wave excitation, they are 29.4% and 18.7% of value for rigid supported turbine 4.3710×10^5Nm. In the harsh winter sea state, the reduction in torque on the mooring supported turbine is as favorable as that in thrust, the reason is that the relative velocity generated by the relative motion between the turbine and wave-current in vertical direction has relieved the effect of the harsh wave, in sea state 1 the displacement of the turbine is not as large as the displacement shown in Figure 8 for harsh sea state so that the torque reduction is nearly neglect. Furthermore, in this extreme sea state, the peak loads on the mooring supported turbine is increased by the effect of wave excitation on the buoy.

In the harsh winter sea state, although the load reduction is satisfied compared with the rigid supported turbine, however another problem has been noticed during the simulation. Figure 9 (a) shows the sweep area of each mooring line and the trace of blade tip in the harsh winter sea state. in some cases the distance between blade tip and mooring line L2 is less than 1.7m, it is risky that the blade tip may hit the mooring line if there is a 10 degrees pitch angle of turbine attitude. In

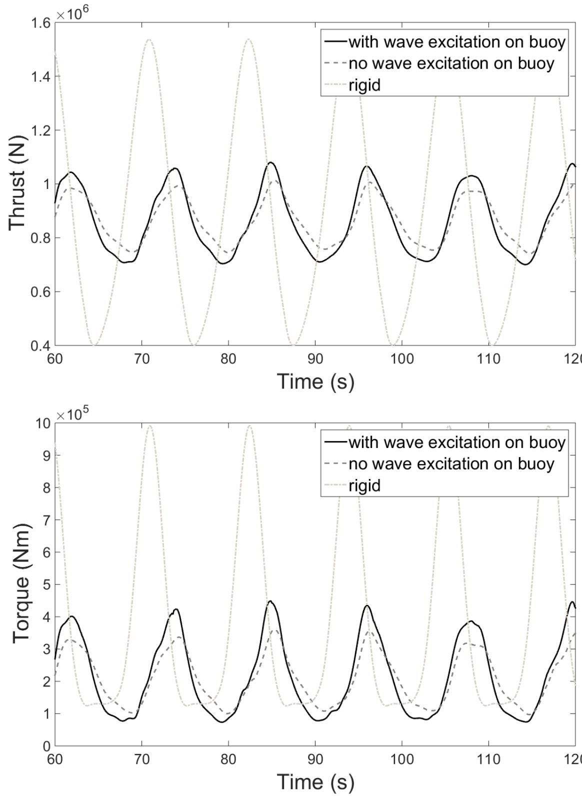

Fig. 7. Thrust and torque comparison in harsh winter sea state

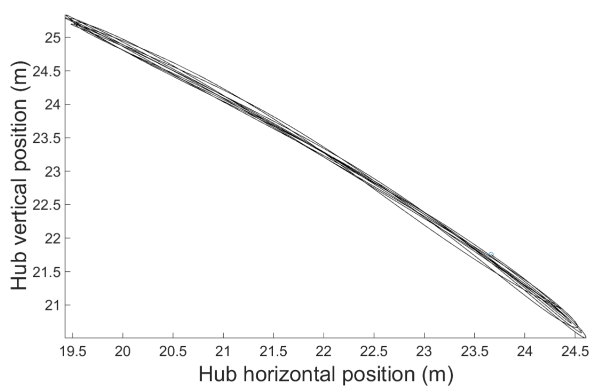

Fig. 8. Turbine displacement in harsh winter sea state

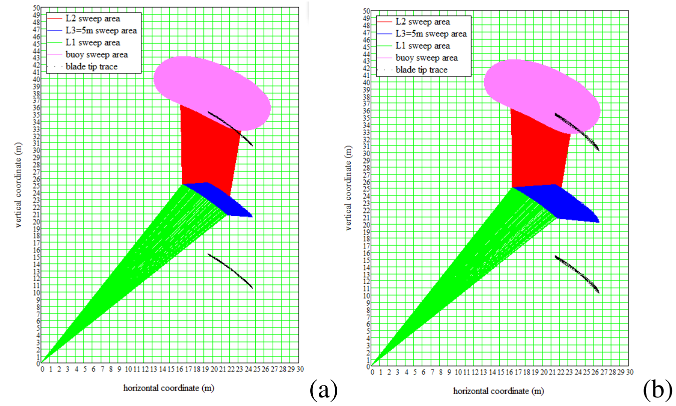

Fig. 9. System sweep area during operation (a) L3 = 3m (b) L3 = 5m

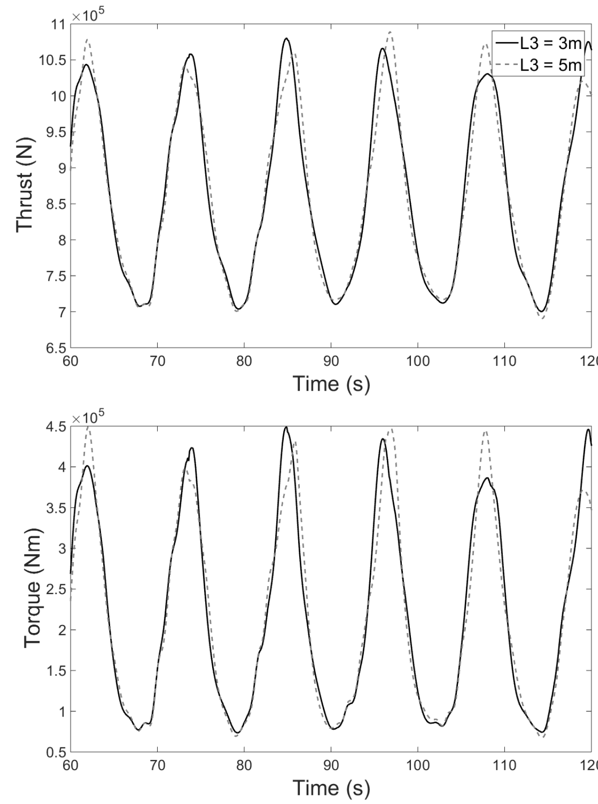

Fig. 10. Loads comparison of different L3 length in harsh winter sea state

order to avoid the risk, mooring line L3 is modified to be 5m instead of 3m, the sweep area is shown in Figure 9 (a).

When the mooring line length changes, the loads on it will also change, Figure 10 gives the comparison of thrust and torque on the turbine for different mooring line length.

It shows that in harsh winter sea state, the loads on the turbine of different L3 length is close under consideration of wave excitation on the buoy. However, the effect of L3 length shows various results in sea state 1. Figure 11 indicates that longer length of mooring line L3 results in higher peak loads on the turbine, the dispersion of thrust and torque increases from 2.1577×10^4N and 2.4258×10^4N to 2.4684×10^4Nm and 2.7832×10^4Nm respectively.

The reason is that the motion of turbine on the long mooring line is not as stable as that on the new configuration wit a short line as Figure 12 shown. The displacement for the 5 meters mooring line length is incompact but the 3 meters line follows the trajectory of an arc,

C. Swell Wave

All the discussions above are based on steep waves using approximative three step wave-current interaction model. The following investigations are focused on waves which are not steep and appropriate for linear wave theory. In sea state 2, the

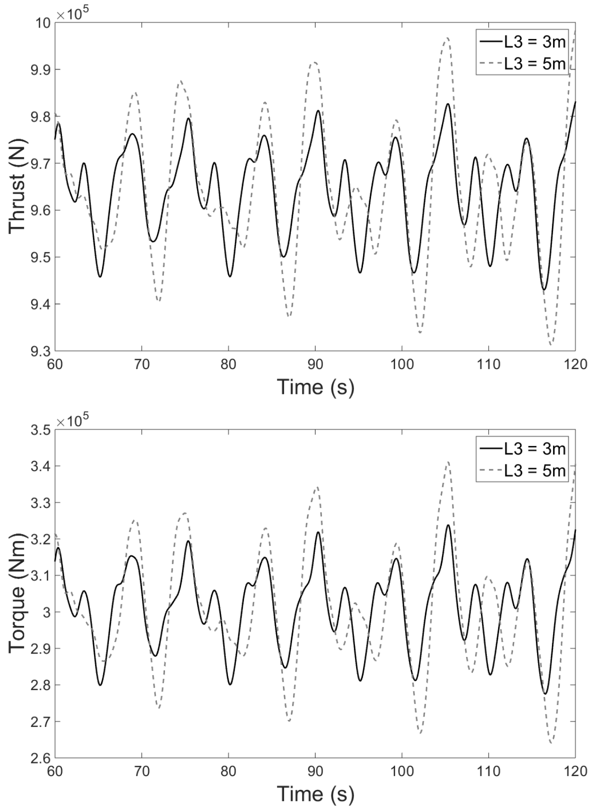

Fig. 11. Loads comparison of different L3 length in sea state 1

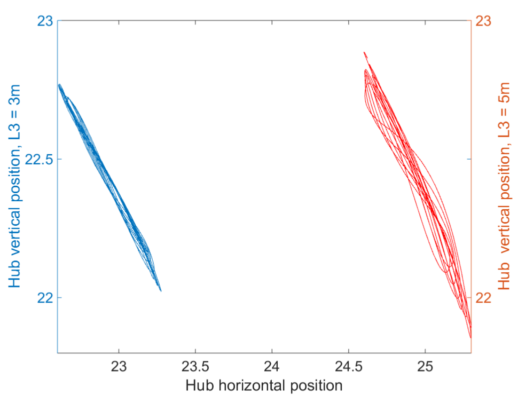

Fig. 12. Trajectories comparison of different L3 length in sea state 1

wave height is 1.07m and wave period is 11.07s, results are shown in Figure 13. It is showed that in linear wave, the wave excitation on the buoy is beneficial to the reduction of the peak loads on the turbine, this is because the superposition of the wave excitation and the buoy damper restoration effect boosts the relative velocity between the inflow and turbine. Moreover, the loads acting on the mooring lines with differernt length are similar in this sea state.

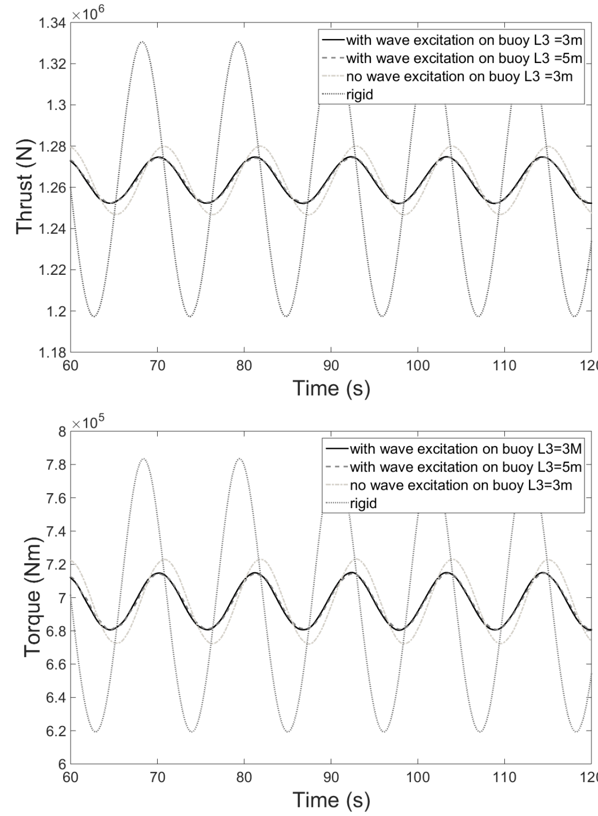

Fig. 13. Thrust and torque comparison in sea state 2

D. Random Wave

The sea state 3 is generated from significant wave height 1.07m and mean wave period 11.07s. The peak loads on the mooring supported turbine is not amplified by the wave excitation on the buoy, but the load dispersion has increased rapidly. The standard deviations of thrust with and without the wave excitation are 1.7040×10^4N and 8.8820×10^3N, the value considered wave excitation is almost twice as that without wave excitation, For the rigid supported turbine the standard deviation is 2.5750×10^4N. The toque on the turbine shows a close trend as the thrust, the standard deviations are 2.5486×10^4 Nm, 1.3563×10^4Nm and 3.3915×10^4Nm.

The sea state 4 is generated from significant wave height 2.665m and mean wave period 6.135s, the difference between results from sea state 1 and sea state 2 is obvious, in sea state 2 the wave excitation on the buoy shows a significant effect to loads on the mooring supported turbine. Compared to the resultS obtained from sea state 1 by three step wave theory, not only the load dispersion with wave excitation raises, but also the peak loads has increased. In Figure 15, the standard standard deviations of thrust for with and without wave excitation and rigid supported are 2.4231×10^4N, 1.3120×10^4N and 7.1884×10^4N. The standard standard deviations of torque are 3.5915×10^4Nm, 1.9935×10^4Nm and 7.5687×10^4Nm.

According to results two random sea states above, the performance of mooring supported turbine in peak loads reduction

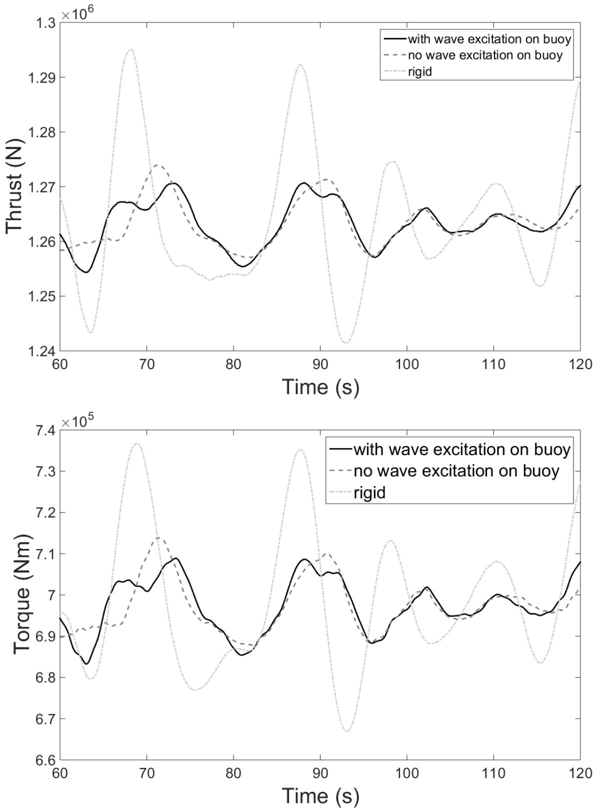

Fig. 14. Thrust and torque comparison in sea state 3

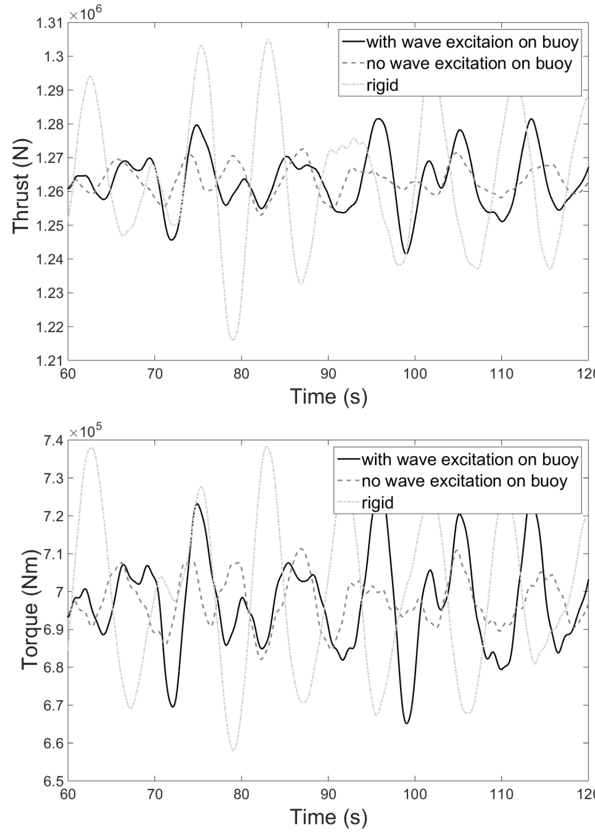

Fig. 15. Thrust and torque comparison in sea state 4

is not as favorable as its performance in fatigue analysis when the wave excitation on the buoy is considered.

IV. Conclusions

The paper shows some simulation results of different sea states for a neutrally buoyant turbine supported from a tensioned cable based mooring system. Basis on the results, the thrusts comparison reveals that forces on mooring supported turbine blades are smaller and smoother than the rigid supported, which means the fatigue performance of mooring supported turbine will be better, but the wave excitation on the buoy will make the load dispersion increase. Although the wave excitation on the buoy is not good for the device fatigue life, the mooring supported turbine still has advantages over the rigid supported turbine. The effect of wave excitation is not obvious in swell waves, however the influence will be significant when waves become steep. If consider the attitude of turbine itself, the unstable motion may result in pitch of turbine. In some condition such as the turbine suffered from very steep waves, the reduction of peak loads on the mooring supported turbine is favorable, but the pitch may lead to an impact of turbine and mooring line. So it is necessary to lengthen the mooring line connected the turbine and the tensioned mooring system if the turbine is designed to suffer from waves that have fifty year return period or a hundred year return period. Furthermore, in this paper the elasticity of the mooring lines is ignored to simplify the model, this factor should be taken into consideration in the further study of this system. In addition, it is necessary to solve the model in fractional-order [17], [18] which means the water damping term generated by the viscous force of the water should be added into the functions in order to make the model more reliable. A developed model will include the pitch of turbine, elastic mooring and water damping in the future.

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