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Evaluating Passive Structural Control of Tidal Turbines

Song Fu*, Cameron Johnstone†and Joe Clarke‡
Energy Systems Research Unit
Department of Mechanical and Aerospace Engineering
University of Strathclyde
Glasgow, UK, G1 1XJ
*song.fu@strath.ac.uk
†cameron.johnstone@strath.ac.uk
‡joe@esru.strath.ac.uk

***Abstract*—The research focus of this project is to design a methodology to reduce fatigue and peak structural loading experienced by support structures used for tidal stream converters.**

The methodology is based on the dynamic analysis of a tower-monopile support structure for offshore wind turbines. A tuned mass damper (TMD) is implemented in the nacelle in fore-aft direction by correcting the discrete equation of motion of a fixed tidal turbine. Parameters such as added mass and viscous damping were thus incorporated in the mass and damping matrix to study the effects of using a TMD on a tidal energy converter. Both frequency and time domain analysis are presented to compare the TMD effect in different conditions. Moreover a sensitivity analysis in soil effect and different tower-monopile shape is presented.

The result shows the infuence of the TMD for a fixed tidal turbine when the structure suffers an instant impact and under unsteady continuous wave-current coupled forces.

***Keywords*—Tidal Turbine, Monopile Support, Tuned Mass Damper, Loads Reduction, Dynamics**

I. INTRODUCTION

Tidal-stream energy may make a important contribution to UK's renewable energy demand, it has been estimated that this type of energy can contribute 18 TWh per year for UK by tidal-stream energy alone [1]. Currently, there are several types of tidal turbines tested in the past 10 years. Six main types of Tidal Energy Convertors (TEC) are categotized by EMEC [2], which are horizontal axis turbine, vertical axis turbine, oscillating hydrofoil, enclosed tips (venturi), archimedes screw and tidal kite. Horizontal axis turbines are the most common type of TEC and are the primarily focused of this investigation.

The environment tidal turbines operate within is considered dynamic due to turbulent flow which are also affected by wave motion components encompassed within the bulk tidal flow. Considering unsteady wave-current coupled forces as excitations, the dynamic load experienced on a tidal turbine is a complicated physical problem which poses a challenge for engineers trying to design larger tidal turbine foundations and other floating support structures. Different structural damping strategies have been implemented in the wind industry such as tuned mass dampers and some control technologies like generator torque control and blade pitch control are also developed to reduce the fatigue and structural loading.

Even though structural damping control strategies have not been studied in the tidal energy field , strategies used by the offshore wind industry can be used as a first approximation to augment the structural life of diverse components. Passive control approaches are wildly invested for wind turbines [3, 4, 5]. The use of a tuned mass damper (TMD) on a wind turbine structure, is a simple passive structural control technique to absorb energy at one of the natural frequencies of the entire structure [6]. The aim of this project is to design a tidal turbine station keeping system with a tuned mass damper in order to reduce fatigue and peak structural loading experienced by the support structures. This may result in a reduction of mass and costs associated with the structural support and station keeping system.

II. METHODOLOGY

A. Case Study: Torr Head Tidal Array

The design of the turbine support structure investigated is based on Torr Head Tidal Energy Array project built by Tidal ventures. This project is located in the north coast of County Antrim in Northern Ireland and the maximum capacity is 100MW with 50 to 100 turbines each with a rated power output of at least 1MW. This project started its feasibility and site research in 2013 and plans to be operational in 2020, now it is at Condents and Evironmental Statement (ES) Submission stage. The Environmental Impact Assessment (EIA) report lists three types turbine support structures relevant to the project [7], which are gravity base structures including sub-sea bases, drilled monopiles and drilled pin pile tripods.

For this investigation, a drilled monopile structure for a 1MW turbine is selected and the relevant parameters are given in Table I. Most of the parameters are from the EIA report, but there is no imformation of the pile wall thickness and the top mass (rotor and nacelle weight). The thickness here is estimated from the plie diameter, material density, weight and length. Moreover, the top mass is from Alstom's 1MW tidal turbine [8]. Some parameters can be changed in order to simulate different conditions.

TABLE I
TOWER-MONOPILE SUPPORT PARAMETERS.

Materials	Steel
Height of nacelle centre	25m
Pile diameter	2.5m
Structure weight	Dry weight of 120 tonnes
Thickness	0.073m
Top mass	150 tonnes

B. Numerical Model

A model to study the application of Tune Mass Dampers (TMD) on structures used for tidal tuebines is presented in this section. This model is based on studies done for wind turbine technnologies, as presented by [9]. A wind turbine with a tower-monopile supporting structure can be modelled as an inverted pendulum, a general representation of the system is shown in Figure 1.

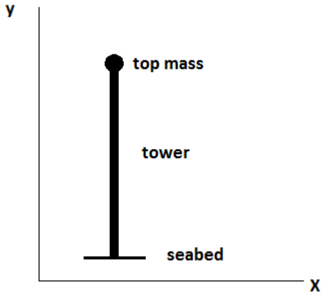

Fig. 1. Structural model of a flexible wind (tidal) turbine

The location of the Tuned Mass Damper (TMD) is in the nacelle, this model intially considers a nacelle ocillating in a horizontal fore-aft direction which is denoted by TMDx. Figure 2 shows a simple schematic of the TMDx configuration.

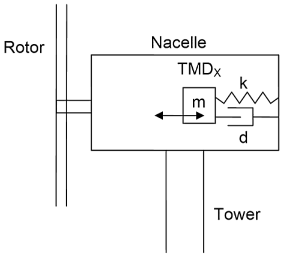

Fig. 2. Schematic of $\mathrm{TMD_X}$ in turbine nacelle [3]

The tower-monopile dynamics can be modelled as a forced response of a non-gyroscopic damped linear system, a finite element model, established for wind turbines [10] is given by:

$$\mathbf{M}\ddot{\boldsymbol{x}} + \mathbf{C}\dot{\boldsymbol{x}} + \mathbf{K}\boldsymbol{x} = \mathbf{F}(t) \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the structural mass, damping and stiffness matrices; $\ddot{\boldsymbol{x}}$, $\dot{\boldsymbol{x}}$ and $\boldsymbol{x}$ are structural nodal acceleration, velocity and displacement vectors in x-axis respectively ; $\mathbf{F}(t)$ is the applied force, which in this case is predominantly the rotor thrust applied on the top node of structure and drag forces on the tower due to the tidal current. The rotor thrust is calculated by Blade Element Momentum Theory in wave-current coupled conditions, Figure 3 shows the procedure using Nevalainen's data [11, 12] in the dynamic analysis.

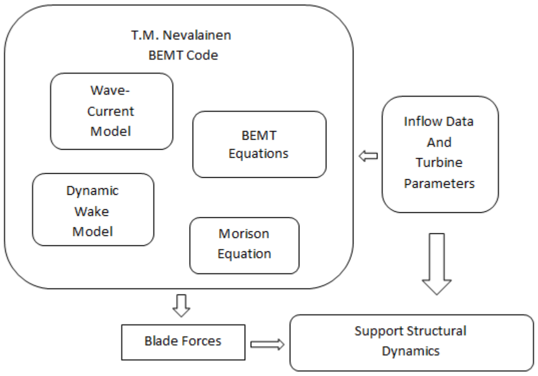

Fig. 3. Flow chart of forces input

The structural damping is related to the first tower modal frequency ω_{0t} as follows [13, 14]:

$$\mathbf{C} = 2\varsigma_t\omega_{0t}\mathbf{M} \tag{2}$$

where ς_t is structural damping ratio for steel structure which is set to 0.005 [13].

Unlike onshore and offshore wind turbines, tidal turbines are fully submerged in water, so the effect of added mass cannot be ignored. The added mass will change the natural frequecies of the structure, this will be shown in the results section. The tower is considered to be a vibrating rod in the water column in order to calculate the added mass and viscous damping [15]. So the equation of motion can be corrected as:

$$(\mathbf{M} + \mathbf{M}_\mathrm{A})\ddot{\boldsymbol{x}} + (\mathbf{C} + \mathbf{C}_\mathrm{H})\dot{\boldsymbol{x}} + \mathbf{K}\boldsymbol{x} = \mathbf{F}(t) \tag{3}$$

where $\mathbf{M}_\mathrm{A}$ is the added mass matrix and $\mathbf{C}_\mathrm{H}$ is the hydrodynamic viscous damping matrix.

The $\mathrm{TMD_X}$ is considered as an additional degree of freedom in the x-axis. Once the tower-monopile's natural frequencies have been derived, the TMD properties can be calculated as [16]

$$\omega_\mathrm{TMD} = \sqrt{\frac{k_\mathrm{TMD}}{m_\mathrm{TMD}}} \tag{4}$$

$$\varsigma_\mathrm{TMD} = \frac{c_\mathrm{TMD}}{2\sqrt{m_\mathrm{TMD}k_\mathrm{TMD}}} \tag{5}$$

where ω_TMD is the TMD natural frequency, k_TMD is the TMD spring stiffness, m_TMD is the TMD mass, c_TMD is the TMD damping constant and ς_TMD is the damping ratio. As suggested by [17], the optimal TMD natural frequency is approximately 93% of the tower natural frequency. Then the damping ratio ς_{TMD} can be estimated according to the study [18].

The TMD properties are applied to obtain the mass matrix of $\mathrm{TMD_X}$, $\mathbf{M}_{\mathrm{TMD}}$, the damping matrix, $\mathbf{C}_{\mathrm{TMD}}$, and the stiffness matrix, $\mathbf{K}_{\mathrm{TMD}}$. The discrete equation of motion defined with TMDx can be written as:

$$\begin{bmatrix} \mathbf{M}+\mathbf{M}_{\mathrm{A}} & 0 \\ 0 & \mathbf{M}_{\mathrm{TMD}} \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{x}} \\ \ddot{\boldsymbol{x}}_{\mathrm{TMD}} \end{Bmatrix} + \begin{bmatrix} \mathbf{C}+\mathbf{C}_{\mathrm{H}}+\mathbf{C}_{\mathrm{TMD}} & -\mathbf{C}_{\mathrm{TMD}} \\ \mathbf{C}_{\mathrm{TMD}} & \mathbf{C}_{\mathrm{TMD}} \end{bmatrix} \begin{Bmatrix} \dot{\boldsymbol{x}} \\ \dot{\boldsymbol{x}}_{\mathrm{TMD}} \end{Bmatrix} + \begin{bmatrix} \mathbf{K}+\mathbf{K}_{\mathrm{TMD}} & -\mathbf{K}_{\mathrm{TMD}} \\ -\mathbf{K}_{\mathrm{TMD}} & \mathbf{K}_{\mathrm{TMD}} \end{bmatrix} \begin{Bmatrix} \boldsymbol{x} \\ \boldsymbol{x}_{\mathrm{TMD}} \end{Bmatrix} = \begin{Bmatrix} \mathbf{F}(t) \\ 0 \end{Bmatrix} \tag{6}$$

set $\mathbf{K}_{\mathrm{T}} = \begin{bmatrix} \mathbf{K}+\mathbf{K}_{\mathrm{TMD}} & -\mathbf{K}_{\mathrm{TMD}} \\ -\mathbf{K}_{\mathrm{TMD}} & \mathbf{K}_{\mathrm{TMD}} \end{bmatrix}$

$$\mathbf{C}_{\mathrm{T}} = \begin{bmatrix} \mathbf{C}+\mathbf{C}_{\mathrm{H}}+\mathbf{C}_{\mathrm{TMD}} & -\mathbf{C}_{\mathrm{TMD}} \\ \mathbf{C}_{\mathrm{TMD}} & \mathbf{C}_{\mathrm{TMD}} \end{bmatrix},$$

$$\mathbf{M}_{\mathrm{T}} = \begin{bmatrix} \mathbf{M}+\mathbf{M}_{\mathrm{A}} & 0 \\ 0 & \mathbf{M}_{\mathrm{TMD}} \end{bmatrix},$$

$$\ddot{\boldsymbol{X}} = \begin{Bmatrix} \ddot{\boldsymbol{x}} \\ \ddot{\boldsymbol{x}}_{\mathrm{TMD}} \end{Bmatrix}, \dot{\boldsymbol{X}} = \begin{Bmatrix} \dot{\boldsymbol{x}} \\ \dot{\boldsymbol{x}}_{\mathrm{TMD}} \end{Bmatrix},$$

$$\boldsymbol{X} = \begin{Bmatrix} \boldsymbol{x} \\ \boldsymbol{x}_{\mathrm{TMD}} \end{Bmatrix} \text{and } \mathbf{P}(t) = \begin{Bmatrix} \mathbf{F}(t) \\ 0 \end{Bmatrix}.$$

then the equation of motion for the whole structure is as follow:

$$\mathbf{M}_{\mathrm{T}}\ddot{\boldsymbol{X}} + \mathbf{C}_{\mathrm{T}}\dot{\boldsymbol{X}} + \mathbf{K}_{\mathrm{T}}\boldsymbol{X} = \mathbf{P}(t) \tag{7}$$

C. Time Domain Solution

In order to solve the differential equation, Newmark β method is selected for wind turbines with finite element model [10]. This method is widely used in numerical evaluation of the dynamic response of structures and solids such as in finite element analysis to model dynamic systems. Equation (7) discretized in the time domain by this algorithm is presented below:

$$\mathbf{M}_{\mathrm{T}}\ddot{\boldsymbol{X}}_{t+\triangle t} + \mathbf{C}_{\mathrm{T}}\dot{\boldsymbol{X}}_{t+\triangle t} + \mathbf{K}_{\mathrm{T}}\boldsymbol{X}_{t+\triangle t} = \mathbf{P}(t+\triangle t) \tag{8}$$

$$\boldsymbol{X}_{t+\triangle t} = \boldsymbol{X}_t + \triangle t\dot{\boldsymbol{X}} + \triangle t^2[(\frac{1}{2}-\beta)\ddot{\boldsymbol{X}}_t + \beta\ddot{\boldsymbol{X}}_{t+\triangle t}] \tag{9}$$

$$\dot{\boldsymbol{X}}_{t+\triangle t} = \dot{\boldsymbol{X}}_t + \triangle t[(1-\gamma)\boldsymbol{X}_t + \gamma\boldsymbol{X}_{t+\triangle t}] \tag{10}$$

Substitution Eqn (9) (10) into Eqn (8) and rearranging to obtain the final form of the equation so that $\boldsymbol{X}_{t+\triangle t}$ can be solved:

$$\begin{aligned} [\mathbf{K}_{\mathrm{T}} + \frac{\gamma}{\beta\triangle t}\mathbf{C}_{\mathrm{T}} + \frac{1}{\beta(\triangle t)^2}\mathbf{M}_{\mathrm{T}}]\boldsymbol{X}_{t+\triangle t} &= \mathbf{P}(t+\triangle t) \\ +\mathbf{C}_{\mathrm{T}}\{\frac{\gamma}{\beta\triangle t}\boldsymbol{X}_t + (\frac{\gamma}{\beta}-1)\dot{\boldsymbol{X}}_t + \triangle t(\frac{\gamma}{2\beta}-1)\ddot{\boldsymbol{X}}_t\} \\ -\mathbf{M}_{\mathrm{T}}\{\frac{1}{\beta(\triangle t)^2}\boldsymbol{X}_t + \frac{\gamma}{\beta\triangle t}\dot{\boldsymbol{X}}_t + (\frac{\gamma}{2\beta}-1)\ddot{\boldsymbol{X}}_t\} \end{aligned} \tag{11}$$

where β and γ are set to 0.25 and 0.5 respectively in order to make the method implicit and unconditionally stable [19].

III. RESULTS

The calculation for the first natural frequency of the structure is the first step to determine the optimum TMD parameter. In this study only the fote-aft TMD system, $\mathrm{TMD_X}$, is under consideration, so the first tower bending mode is the most important [3]. According to the model, the first natural frequency for the stucture is 9.069 rads/s (1.443Hz) for the stucture support case study. This is a high value compared to a 5MW offshore wind turbine with monopile support which usually has a first nature frequency of 1.71 rads/s (0.272Hz) [16]. Based on an investigation [3], the mass of the TMD is suggested as 2% of the total mass of the monopile. This results in a final mass of 2400kg in this case study. In order to inderstand the effects of the TMD mass on the structure, a parametic study using four different masses is performed in Section 3.A.

A. TMD Parametric Study

This section illustrates a sensitivity analysis of different TMD configurations' effects on the structure. In this study, 1200kg. 2400kg, 3600kg and 4800kg $\mathrm{TMD_X}$ mass values are choosen which are related to 1%, 2%, 3% and 4% of the monopile mass respectively. Table II summarised the TMD parameters obtained.

TABLE II
TMD PARAMETERS

mass persentage	mass (kg)	k (N/m)	c (N*s/m)	ς (-)
1%	1200	85359	1233.4	0.0609
2%	2400	170720	3471.4	0.0858
3%	3600	256080	6346.4	0.1045
4%	4800	341440	9723.8	0.1201

The tower top fore-aft deflection with and without $\mathrm{TMD_X}$ are simulated over 120s, an instant load of 450kN is applied on the structure at the time step 0.4s then removed at 0.5s, Figure 4 shows the results.

The results shows that $\mathrm{TMD_X}$ has a clearly effect on the structural response when an instant load is applied on the strucure such as from a impact of an extreme wave-current coupled force on turbine or a marine mammal impact. The TMD shows a better performance in deflection reduction with higher mass ratio. However the results for the TMDs with mass

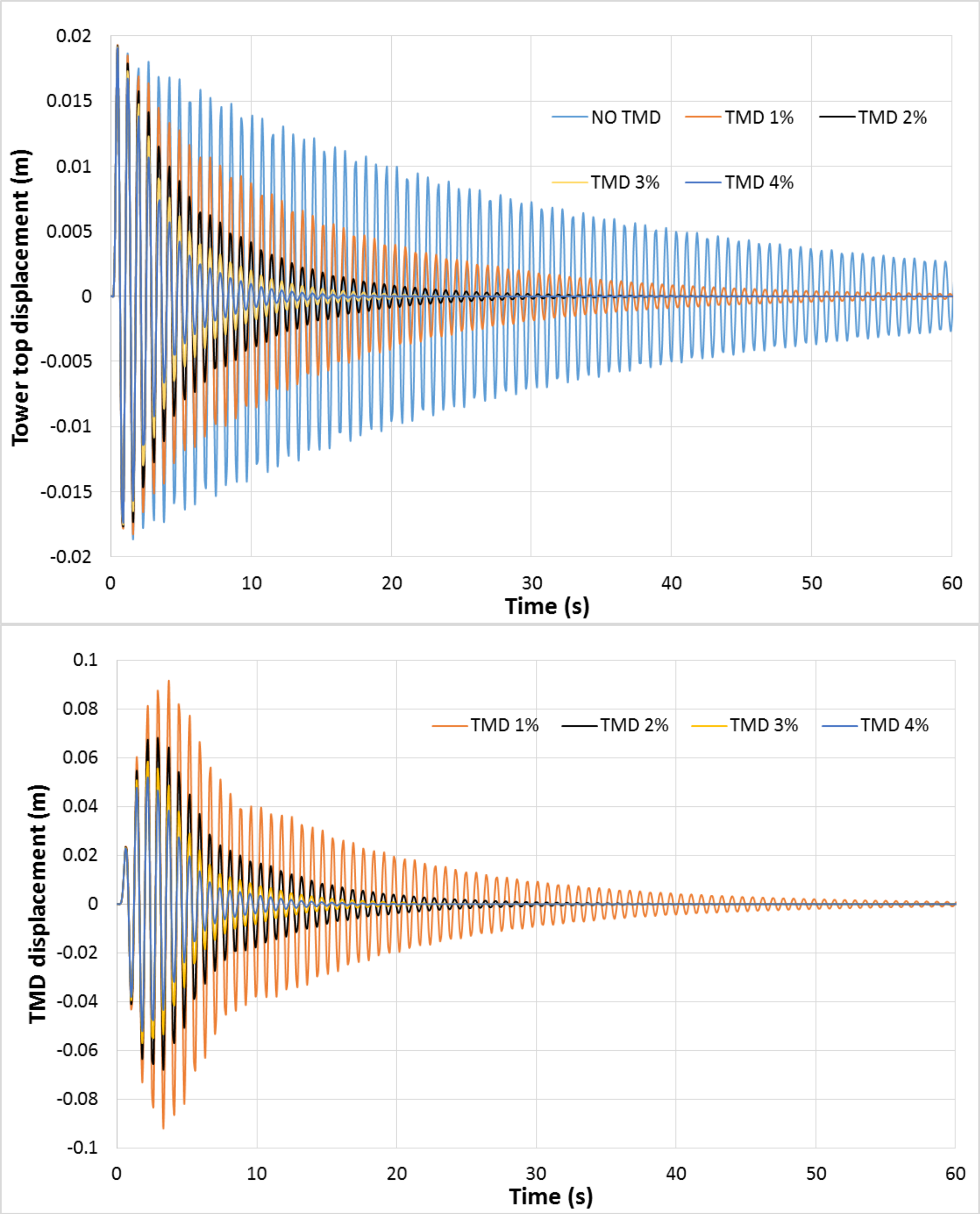

Fig. 4. Tower top displancement and TMD displacement in time series

ratio higher than 2% do not show a significant improvement in the deflection reduction. Furthermore, all the TMD_X with the mass persentage of 2%, 3% and 4% will make the system stop vibriting in 45s and the TMD displacement is also within the range of 0.2m, which is small relative to the Alstom's 1MW tidal turbine nacelle which is 22m in length. Besides, the TMD mass (mass ratio 2%) is only 1.6% of the top mass. This means that using a TMD on tidal energy applications is vailable in terms of their space requirement and ease of installation.

B. Monopile Results Including Wave-current Interactions

This study uses the unsteady wave-current coupled loads data generated from an improved Blade Element Momentum Theory [20]. The tidal current speed is 2.5m/s, significant wave height is 5.979m, average zero crossing period is 7.616s for a sea-state generated by an estimated wind speed of 25.628m/s. These data was taken from the British Oceanographic Data Centre [21], provided UK Offshore Operators Association and funded by the Institute of Oceanographic Sciences. The water depth is assumed to be 50m. A 5 minutes simulation is applied under this load condition and figure 5 shows a result of tower top displacement and fore-aft bending moment at tower base in a window of 14s .

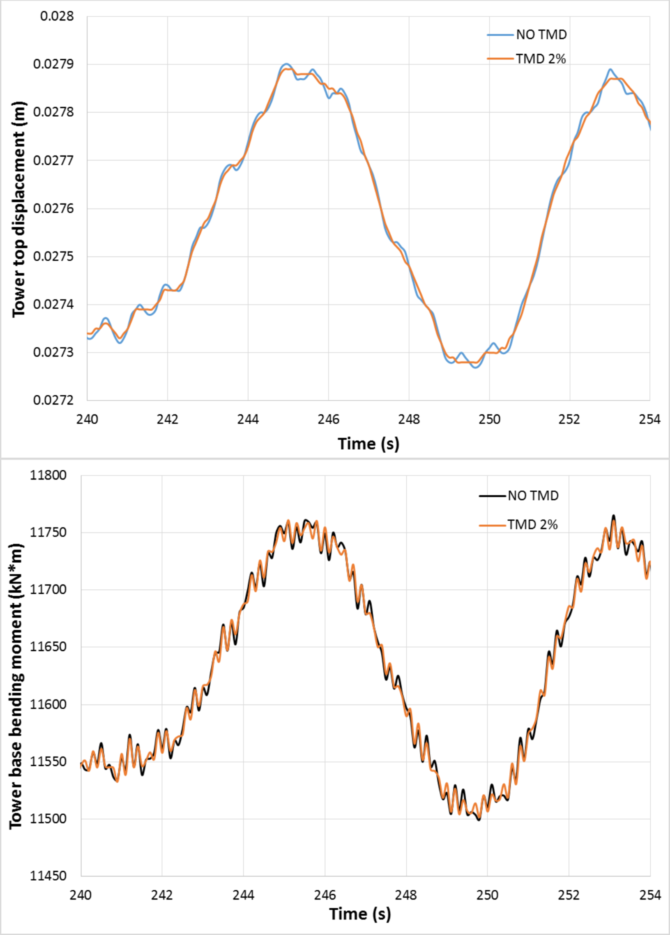

Fig. 5. Tower top displacement and base bending moment in time series

It is obvious that for a long term running the TMD effect can be almost ignored because the reduction of displacements and loads is small as the figure shows. When the structure becomes stable, a rainflow-counting algorithm [22] is applied here to do a primary fatigue evaluation for the maximum stress at tower base from 200s to 300s of the simulation. Table III and IV shows the results of the the fatigue analysis done for a monopile when not using and using TMD.

TABLE III
NUMBER OF CYCLES AT VARIOUS STRESS RANGE AND MEAN STRESS COMBINATION FOR STRUCTURE WITHOUT TMD

Stress Range (MPa)	Mean Stress (MPa)				
	216	218	220	222	224
0.97	27	110	85	120	26
2.90					
4.83			9		
6.77			1		
8.70			3		

TABLE IV
NUMBER OF CYCLES AT VARIOUS STRESS RANGE AND MEAN STRESS COMBINATION FOR STRUCTURE WITH TMD

Stress Range (MPa)	Mean Stress (MPa)				
	216	217	218	219	220
0.95	26	105	86	118	27
2.86					
4.76			9		
6.67			1		
8.57			3		

From these tables, the two factors cyclic stress ranges and the number of cycles in this range, which are more important than the mean peak stress [23], are almost same in these two conditions (less than 5% difference). By the use of S-N curves, it can be demonstrated that the smaller amplitude stress fluctuations in the case using TMD will yield a longer fatigue life (number of cycles to failure) [24]. However, it can also be seen that the effect of the TMD on the fatigue load reduction is neglegilable for long term operations of the system.

C. Frequency Domain Analysis

Frequency domain analysis is presented in this section to investigate the influence of added mass and TMD to the structure. Figure 6 shows the first 4 mode shapes of the structure. Figure 7 shows a plot of the tower base fore-aft bending moment in frequency domain with three different conditons. The first figure presents the results where no added mass effect and no TMD is considered, second one has added mass effect but no TMD, the last one has both added mass and TMD.

As Figure 7 shows, there is a peak at the first natural frequency of the structure which is mode 1, the natural frequecy will reduce slightly from 1.533Hz to 1.443Hz when considering the added mass effect. Moreover, the amplitude of reasonance in fore-aft direction decreases significantly when TMD_X is applied on the structure. Generally, the passive structural control such as tuned mass damper is an effective

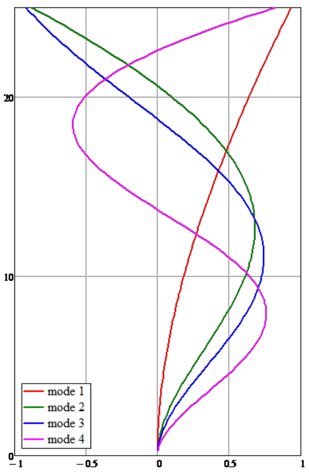

Fig. 6. Mode shapes of monopile struture

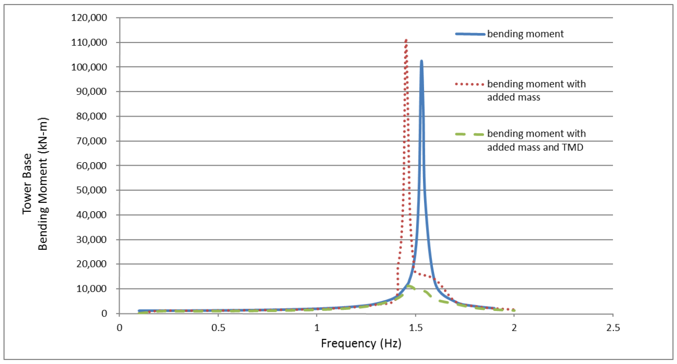

Fig. 7. Frequency domain results of structure

method to reduce the loads due to the vibration of structural modes.

D. *Sensitivity Investigation of Soil Effect*

A sensitive analysis of the soil effect on the structure is presented in this section. Usually for offshore wind turbines using monopiles, the piles are not fixed at the end, but are free to rotate and translate, so the soil reaction loads are considered as non-linear soil springs [25]. In this paper the complicated soil spring is not used and the pile is assumed fixed on the seabed. In order to investigate the soil effect, an assumption that the soil will become loose when the structure vibrates for a long period so the the monopile length, which is not fixed, will increase as Figure 8 shown.

Two different conditions are analysed here, one is the soil loosened for 5m at the end of monopile, the other is 7.5m. Figure 9 shows the mode shapes of the two cases.

In these two cases the first natural frequency reduces to 1.081Hz and 0.951Hz separately, since when the soil loosens by time the first natural fequency of the structure will reduce. As the soil has a significant effect on the structural response, it is important to avoid soil loosening on the seabed, or alternatively to reduce the structural vibrations that are brought on. As the discussion above showed, the TMD will reduce structure vibration only slightly over a long period operation (aproximately 0.7% reduction of top displacement).

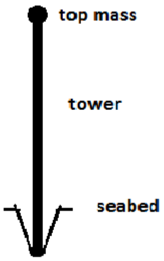

Fig. 8. Soil loosening

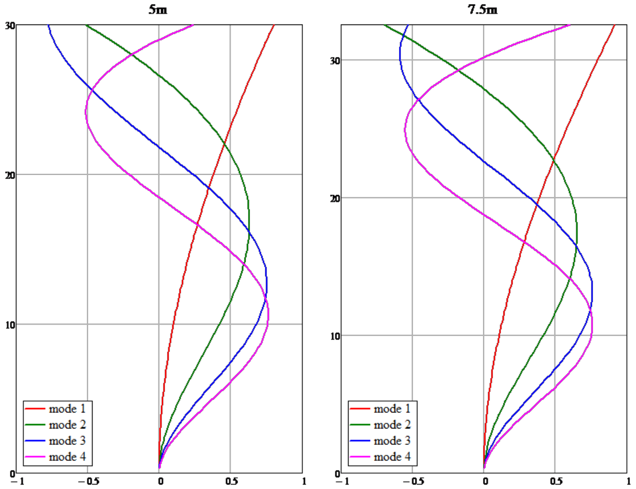

Fig. 9. Mode shapes for 5m and 7.5m loosening

E. *Different Tower-monopile Design Sensitivity Analysis*

In this section the shape of the structure is changed, different tower segments will have different diameters from 2.2m to 3m and each segment is 5m in length unlike the former one which is straight and has the same diameter. The new strucuture keeps the same total mass as the former one by changing the thickness of each segment. Figure 10 shows the skech of new structure.

The first natural frequence of the new structure is 10.903 rads/s, now for TMD_X with mass ratio 2%, the K_{TMD} is 246765 N/m, C_{TMD} is 4174N*s/m and the damping ratio ς_{TMD} is 0.08575. Figure 11 gives the mode shapes of the new structure, compared with Figure 5 the mode shapes of these two structures are almost same. However the bending moment at tower base of the new structure is more smooth than the former one in Figure 12, which means the stress fluctuations are less. Based on Amzallag's method [22], most of the small fluctuations, which are treated as residues, will not be extracted as cycles during a reconstruction procedure, so the number of cycles may not reduce a lot.

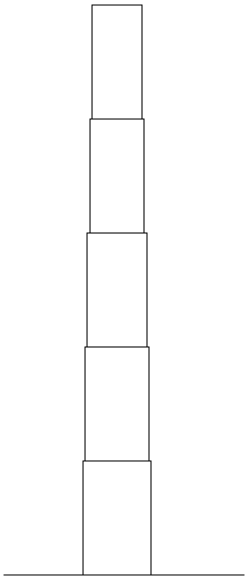

Fig. 10. New structure shape

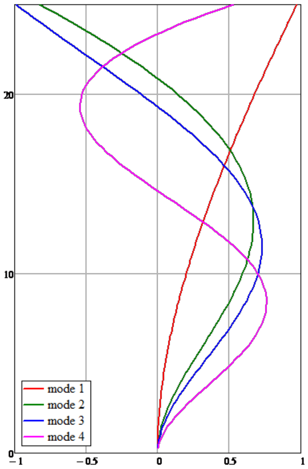

Fig. 11. Mode shapes for new structure

Table 5 gives the fatigue parameters of the new structures for the period from 200s to 300s, it is obvious that the stress range and the mean stresses are smaller due to the differences in diameter and thickness of the base segment. Moreover, the number of cycles in these stress ranges only decrease in a small amount, which matches the prediction based on rainflow-counting algorithm. Althougth it is not a great progress, the new shape of the structure still has a better fatigue performance than the former one.

IV. CONCLUSIONS AND FUTURE WORK

This paper has presented an investigation of the passive structural control technology for tidal stream turbines. The main conclusions of this paper are:

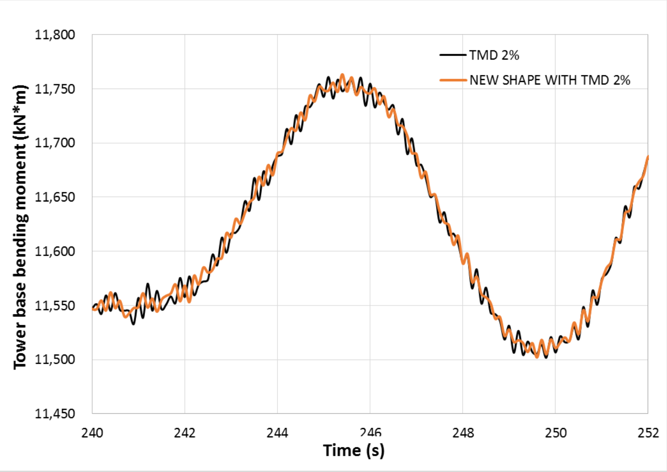

Fig. 12. Caparison for base bending moments in time series

TABLE V
NUMBER OF CYCLES AT VARIOUS STRESS RANGE AND MEAN STRESS COMBINATION FOR NEW STURCTURE WITH TMD

Stress Range (MPa)	Mean Stress (MPa)				
	150	151	153	154	155
0.65	24	98	62	89	21
1.96					
3.27			9		
4.58			1		
5.89			3		

- A simple and fast simulation code has been developed to model the monopile support structures for turbine applications and analyse their dynamics including the added mass and hydrodynamic damping effects.
- Moreover a passive structure control technique was employed in this methodology, which used a TMD on the structure to do a fully coupled dynamic analysis in time domain.
- A parametric study varing the mass of the TMD in fore-aft direction was undertaken in order to compare the effects to the structure. Following this methodology, structural designers can determine the optimum option based on the previous studies in wind turbines.
- When a TMDx was implemented in the system, it had significant effects on the resonance reduction and fore-aft fatigue load-reduction under instant impacts. However, compared to the instant fluctuating impact, TMD had an insignificant effect when modest unsteady wave-current coupled forces were applied on the structure for a long operating period. But changing the shape of tower-monopile supporting structure will make a better performance in fatigue analysis.
- Unlike most large offshore wind turbines, the tidal turbine tower-monopile systems investigated in this project showed higher first natural frequencies due to the shorter length. Furthermore, the added mass correction will make natural frequencies of the structure slightly reduced.

When the structure become longer in some specific conditions like soil loosening, the natural frequencies of structure will decrease.

Future work will be focused on:

- $\mathrm{TMD}_{\mathrm{Y}}$ will be applied on the structure which is aimed to reduce side-side loads and roll motion.
- Investigation of the application of gracity based foundations.
- Investigation of the application of hydraulic dampers.
- Investigation of floating tidal turbine models such as the CORMAT technnology [26].

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