iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 9 **Issue:** IX **Month of publication:** September 2021

DOI: https://doi.org/10.22214/ijraset.2021.38179

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 9 Issue IX Sep 2021- Available at www.ijraset.com

Analysis of Load Reduction of Floating Wind Turbines Using Passive Tuned Mass Dampers

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Abstract: An efficient method for restraining the large vibration displacements and loads of offshore floating wind turbines under harsh marine environment is proposed by putting tuned mass dampers in the cabin. A dynamics model for a barge-type offshore floating wind turbine with a fore–aft tuned mass damper is established based on Lagrange's equations; the nonlinear least squares Leven berg–Marquardt algorithm is employed to identify the parameters of the wind turbine; different parameter optimization methods are adopted to optimize tuned mass damper parameters by considering the standard deviation of the tower top longitudinal displacement as the objective function. Aiming at five typical combined wind and wave load cases under normal running state of the wind turbine, the dynamic responses of the wind turbine with/without tuned mass damper are simulated and the suppression effect of the tuned mass damper is investigated over the wide range of load cases. The results show that when the wind turbine vibrates in the state of damped free vibration, the standard deviation of the tower top longitudinal displacement is decreased approximately 60% in 100 s by the optimized tuned mass damper with the optimum tuned mass damper mass ratio 1.8%. The standard deviation suppression rates of the longitudinal displacements and loads in the tower and blades increase with the tuned mass damper mass ratio when the wind turbine vibrates under the combined wind and wave load cases. When the mass ratio changes from 0.5% to 2%, the maximum suppression rates vary from 20% to 50% correspondingly, which effectively reduce vibration responses of the offshore floating wind turbine. The results of this article preliminarily verify the feasibilities of using a tuned mass damper for restraining vibration of the barge-type offshore floating wind turbine

I. INTRODUCTION

Wind turbine is being pushed into deep sea gradually and offshore floating wind turbine has been a focus of research in the field of wind energy, due to the higher and more stable wind speed in deep sea wind farm than onshore or near-coast waters. Near-offshore wind farms in shallow water have been extensively built in recent years, but they are still often blamed for visual and noise impacts, and their foundations may also leave relatively large seabed footprints.1 In contrast, with less space constraints and more consistent wind, deep sea wind energy is more promising. Instead of fixed-bottom installations, floating foundations are generally considered to be an economical and feasible way of deployment if the water depth is between 60 and 900 m.2 At present, there are three main types of floating platform designs, which are the Energy Barge, the OC3-Hywind Spar Buoy, and the Tension eg Platform (TLP).3 The major sources of stability for the three platforms are buoyancy, ballast, and mooring line tension, respectively. One of the challenges for floating wind turbines is the wave and wind-induced platform tilt motion, which will greatly increase the displacements and loads on turbine structure due to high inertial and gravitational forces. Large tower and platform healing angle will cause great tower top displacement (TTD), which will induce severe fatigue and ultimate loads at tower bottom and blades' roots.4 According to Jonk man and Matha,5 when comparing a spar-type floating wind turbine with an onshore design, the sea-to-land ratio of fatigue damage equivalent loads (DELs) with respect to fore–aft tower base bending moments is 2.5, and the number has reached 7 for the barge-type, which can definitely lead to increased maintenance, reduced availability, more expensive components, and even structural failures. Thus, advanced structural control technique is required to reduce the loads and improve the structural response of offshore floating wind turbine. Besides, soft foundation properties of floating wind turbines will lead to low natural frequency platform motion, so that commonly used blade pitch control strategy for fixed-bottom wind turbines may cause negative damping or even large resonant motion.6 These problems have drawn a lot of attention from both academia and industry on improving the load reduction mechanisms of floating wind turbines. In literature, different methods have been proposed to effectively reduce extra loads brought by platform tilt motion, which can be classified into two different categories

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II. OBJECTIVE OF THIS STUDY

Tuned mass dampers show great promise for use in offshore wind turbines. Bothpassive and active TMDs can reduce tower and mooring line loads significantly, which leads to lighter and less expensive structures. This thesis contributes a set of optimized passive TMDs for four offshore wind turbines, as well as an analysis of an activecontroller for the barge platform.

The optimization of the passive tuned mass damper is completed for the monopile, barge, spar buoy, and tension leg platform in Chapter 3. This chapter includes the optimization of the spring and damping parameters using a genetic algorithm. The results of this genetic algorithm are then simulated in FAST-SC and compared to a baseline without a TMD. Each of the four platforms has a unique TMD configuration that results in the best load reduction.

The monopile achieves the best load reduction with both a fore-aft and a side-sideTMD in the nacelle. With this configuration, fore-aft loads are reduced by up to 10%, and side-side fatigue loading is reduced by as much as 66%. Side-side ultimate loads are effected as well, with the 95th percentile load being reduced by 32%. The barge benefits from the same TMD configuration, with a 15% fore-aft fatigue damagereduction and up to a 33% reduction in side-side fatigue loading. Even with theload reduction, the best barge fatigue damage values are approximately 4 times the baseline for the monopile.

III. LITERATURE REVIEW

A. Background

The low turbulence, high speed wind resource offshore is another benefit. Figure 2.1 shows the onshore wind resource map for the United States. The wind speeds are taken at a height of 80 meters. It can be seen from this map that most of the onshore wind resource is in the interior of the country, in areasof low population density and far from many of the major load centers on the coasts. Figure 2.2 shows the offshore wind resource. Not only are the wind speeds higher, but the high wind speeds regions are larger and more uniform. Also, the offshore wind resource is closer to the coastal population, which reduces electricity transmission distances. Offshore wind turbines also may be able to achieve more efficient designs due to a higher noise tolerance. Without the stringent noise requirements of onshore turbines, turbines can have higher tip speed ratios, which in general leads to more efficient turbine designs.

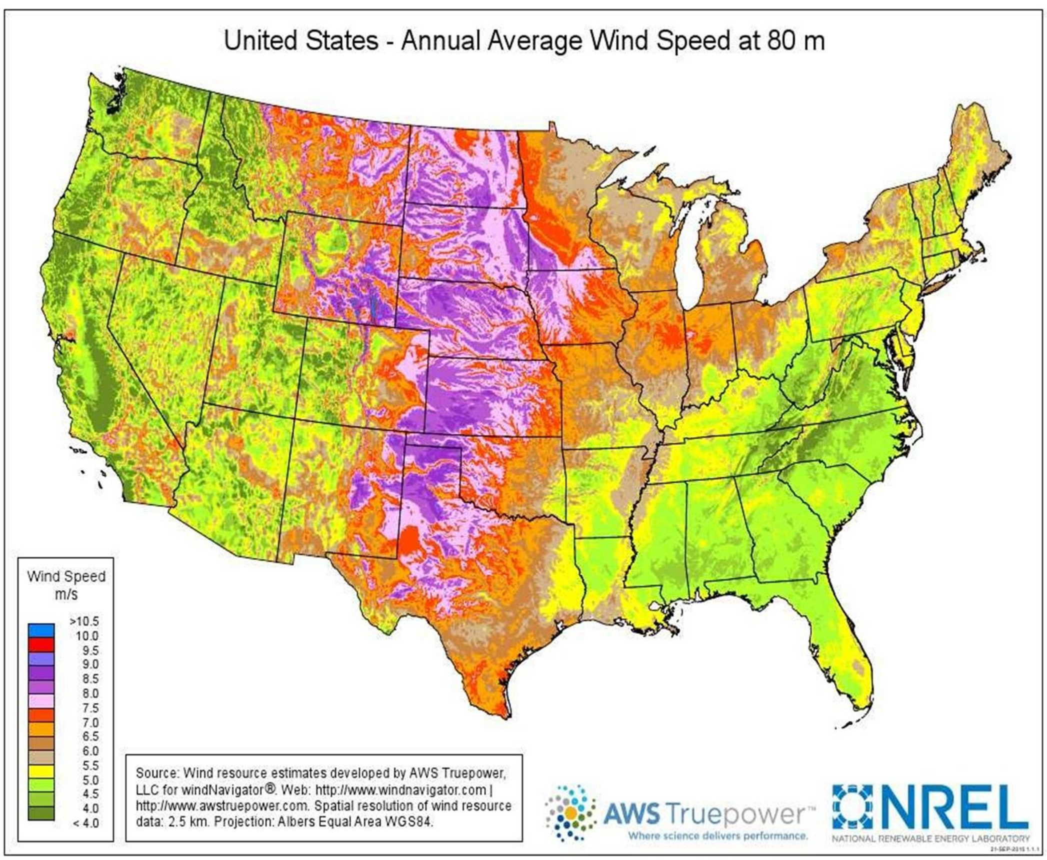

Figure 2.1. Onshore wind resource at 80m height

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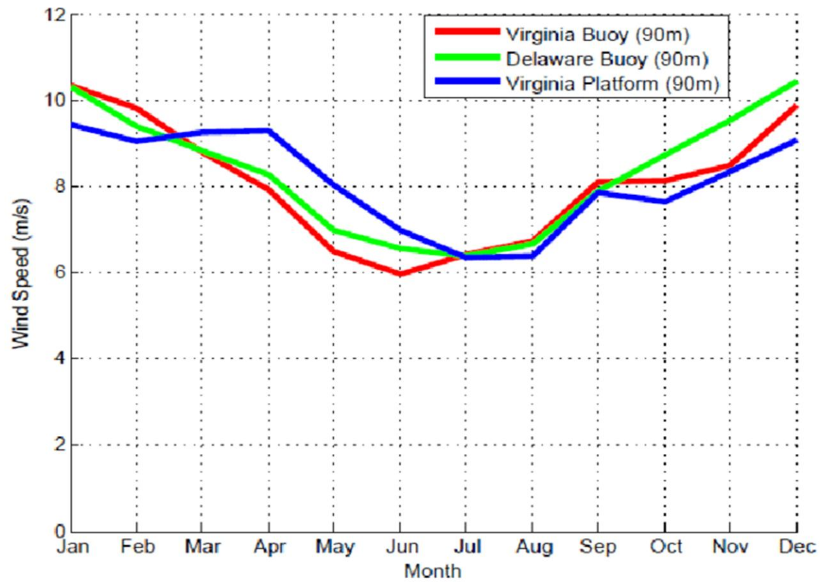
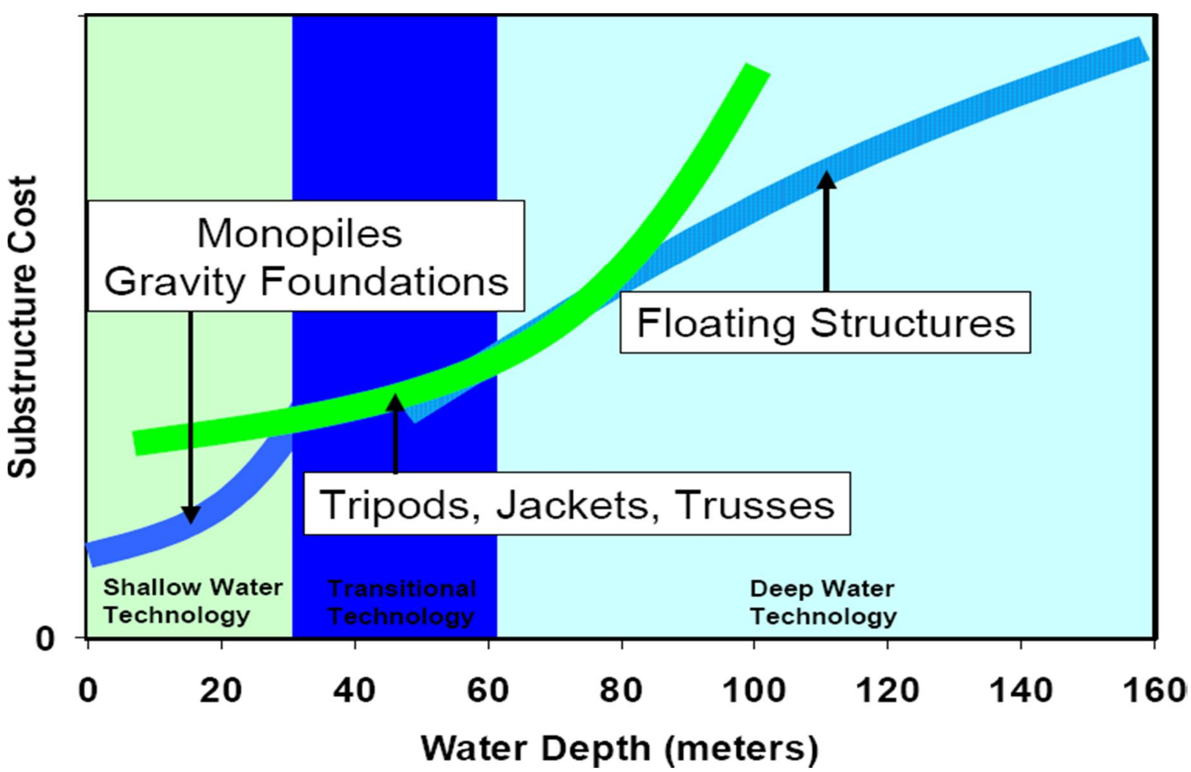


Figure 2.2. Offshore wind resource at 90m height

IV. EXPERIMENTAL DETAILS

With the addition of an actuator,the HMD gains the potential for improved performance over a passive system. Examples of installed HMDs utilizing servomotor and hydraulic actuators can be found in the literature [12]. Both the AMD and HMD can add energy to the system, thus there is a potential for instability. The HMD, however, includes a passive system, so it can still provide load reduction with no actuation power.



In practical applications of active structural control, it is critical to understand and account for the dynamics of the actuator when modeling and designing the over- all system. Control-structure interaction (CSI) refers to the dynamic interaction between the structure and the actuator in active structural control applications, and is an unavoidable result of using a real actuator for generating active control forces. Control-structure interaction exists because there is a natural feedback path between the structure and the actuator. This feedback can be seen in the block diagram in Figure2.20 [8]. Note that in addition to the effect of the actuator on the struc- ture (indicated by “f” in Figure2.20), there is also an influence on the actuator by the structure. In the past, control systems for structures neglected CSI, which can severely limit performance and robustness [4, 8].

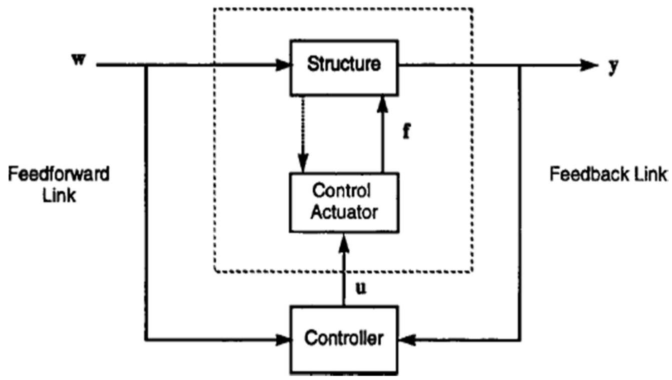


Figure 2.20. Block diagram showing CSI [8]

Research has been conducted on using passive TMDs for wind turbines, especially for offshore structures due to the larger loading [6, 7, 10, 30, 39]. Earlier studies focused on fixed bottom structures, but previous work also focused on floating struc-tures [26, 28]. This research led to the development of FAST-SC, an updated version of the NREL wind turbine aero-elastic design code, which has the capability to simu-late both passive and active tuned mass dampers. More details on the capabilities of the FAST-SC code are discussed below, and can be found in the literature [27, 28, 33].FAST is a fully coupled aero-hydro-servo-elastic code that simulates the perfor- mance of wind turbines [19]. It uses Blade Element-Momentum theory (BEM) or generalized dynamic wake theory to calculate aerodynamic loads, a linear modal rep- resentation for structural components, and a non-linear hydrodynamic subroutine that calculates wave loading on the platform for offshore applications [16]. This code is interfaced through Matlab/Simulink, and a controller can be implemented graphi-cally with Simulink.

A modification to FAST to accommodate structural control (FAST-SC) was de- veloped by Lackner and Rotea [28]. This code includes the capability to model two independent TMDs, one in the fore-aft direction and one in the side-side direction (see Figure 2.21). The TMDs can be located in the nacelle or the platform. The addition of locating the TMD in platform is mainly for the spar buoy and TLP platforms, in which it may be desired to move the TMD into the platform. This layout is attractive because there is little room in the nacelle for extraneous systems like the TMD, and since extra mass in the nacelle could create unwanted loading. It may also be feasible to use a larger TMD in the platform than in the nacelle, which could increase per- formance. In addition to the spring and damping forces, an active force provided by an actuator can be applied to the mass [27, 33]. Position constraints known as stops are imposed on the stroke of the TMDs. These constraints were introduced because the nacelle has a limited amount of space, but the stops can be set to any distance.

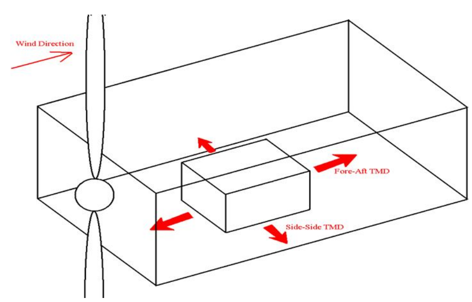


Figure 2.21. Diagram showing direction of Fore-Aft and Side-Side TMDs in anacelle.

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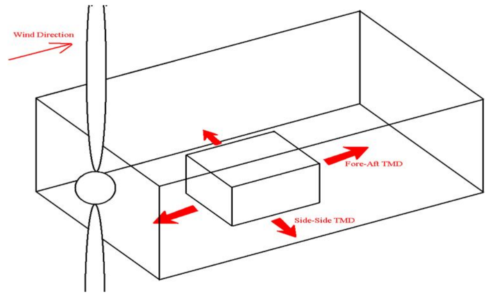

Figure 2.21. Diagram showing direction of Fore-Aft and Side-Side TMDs in anacelle.

V. RESULTS AND DISCUSSION

This article presents an investigation into the use of the TMD structural control for the offshore floating wind turbine. The major contributions and conclusions of the article are as follows: 1. The dynamic model of the barge-type offshore floating wind turbine with a TMD installed in the nacelle was established based on Lagrange's equations. Parameter identification was performed based on LM algorithm, and the proposed model was verified when comparing its simulation results with the outputs from FAST-SC. Different parameter optimization methods were adopted for TMD parameter determination. Especially, the GA provides a more efficient and accurate optimization method compared with the exhaustive search method. 2. Optimal spring and damping coefficients for different TMD mass ratios are obtained by different parameter optimization methods. There exists the optimum TMD mass ratio 1.8% when the wind turbine vibrates in the state of damped free vibration and the standard deviation of the tower top fore–aft displacement is decreased approximately 60% in 100 s by the optimized TMD. Figure 14. Suppression rates of TMD on the standard deviation of the evaluation indices: (a) tower top fore–aft displacement, (b) tower base fore–aft moment, (c) blade tip flap displacement, and (d) blade root flap moment. He et al. 313 3. Standard deviation suppression rates of the displacements and loads in the tower and blades increase with the TMD mass ratio when the wind turbine vibrates under the combined wind and wave load cases. When the mass ratio changes from 0.5% to 2%, the maximum suppression rates vary from 20% to 50% correspondingly, which effectively reduce vibration responses of the offshore floating wind turbine. 4. The traditional pitch control causes the phenomenon that the suppression rates of the displacements and loads at both the low and the high wind speeds are larger than the rated wind speed, which presents the V-shaped distribution characteristics. The proposed passive TMD structural control method shows encouraging prospects of applications in future with the significant positive impact it may have on the exploring of offshore wind energy. Further work is to consider the advanced control methods such as semi-active and active controls for this problem, and the main aim of the future study is to show how the advanced control of an offshore floating wind turbine could be successfully used for suppressing problem vibrations Due to the cost and manufacturing challengesof constructing a tuned mass damper for this application, alternative forms of mass damper systems including tuned liquid column dampers should be considered. Alter- natively, a purely active mass damper should be considered, which would eliminate the need for large displacement springs and dampers. Control-structure interaction must be taken into account when designing this system. With these recommenda- tions, tuned mass dampers could provide a cost effective means of load reduction in offshore wind turbines The monopile achieves the best load reduction with both a fore-aft and a side-sideTMD in the nacelle. With this configuration, fore-aft loads are reduced by up to 10%, and side-side fatigue loading is reduced by as much as 66%. Side-side ultimate loads are effected as well, with the 95th percentile load being reduced by 32%. The barge benefits from the same TMD configuration, with a 15% fore-aft fatigue damagereduction and up to a 33% reduction in side-side fatigue loading

VI. CONCLUSIONS AND FUTURE WORK

A design of an active control system for a mass damper in an offshorewind turbine using the barge floating platform is modified to include an actuator model. The addition of the actuator model creates a more realistic simulation, and motivates a controller redesign. When the actuator is added, the AMD uses 5-10 times more power in some cases, while reducing loads by only a few percent. In order to make an active controller viable for offshore wind turbines, actuator models must be included in future work. These load reductions for all of the platforms could have a beneficial effect on the cost of an offshore wind turbine as long as the TMD could be constructed at a reasonable cost.

Future work on this topic should consider a preliminary economic feasibility study. This study should quantify the cost associated with the load reduction and compare this to the material and construction cost of a TMD, as well as the power usage in the case of an AMD. The monopile achieves the best load reduction with both a fore-aft and a side-sideTMD in the nacelle. With this configuration, fore-aft loads are reduced by up to 10%, and side-side fatigue loading is reduced by as much as 66%. Side-side ultimate loads are effected as well, with the 95th percentile load being reduced by 32%. The barge benefits from the same TMD configuration, with a 15% fore-aft fatigue damagereduction and up to a 33% reduction in side-side fatigue loading. Even with theload reduction, the best barge fatigue damage values are approximately 4 times the baseline for the monopile. All of the studies in this thesis focused on using an ideal tuned mass damper. In practice, however, the mechanics of a tuned mass damper may be difficult to achieve. For example, with a stroke of ±8m, a spring would need to stretch 16m and a springlike this may not exist, or may prohibitively expensive. A tuned liquid column dampermay be a good alternative to the tuned mass damper for this application. The water which supplies the mass in a TLCD is essentially free for an offshore turbine, and there are no large scale springs and dampers involved. Further research should go into developing a passive TLCD for use in an offshore wind turbine.

VII. ACKNOWLEDGMENT

I am grateful to the almighty that provided me enough strength and courage to overcome all my difficulties in the completion of this challenging work. I acknowledge those who stood by me, supported and encouraged me throughout. Words fail me to express my heartiest and profound sense of gratitude to my supervisor, Mr. Puneet , under whose supervision, I have completed the thesis work. Without his hard working, erudition and helpful nature, it was not possible for me to complete the thesis. It would not have been possible for me to complete this work without the help of different scholars and resource persons. I am very thankful to the authorities of Desh Bhagat University library, Mandi Gobindgarh, Bhai Kahan Singh Nabha Library, Punjabi University, Patiala, Panjab University Punjab university library, Chandigarh, Guru Nanak Dev University Library , Amristar, tribune office and Punjab Vidhan Sabha Library, Punjab Secretariat library, Chandigarh for allowing me to consult all the relevant sources, records, books and newspapers. I am very thankful to all the authorities that very kindly provided me with all necessary facilities.

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