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Modelling and optimization of a passive structural control design for a spar-type floating wind turbine

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ABSTRACT

Compared with fixed-bottom installation, deep water floating wind turbine has to undergo more severe structural loads due to extra degrees of freedom. Aiming for effective load reduction, this paper deals with the evaluation of a passive structural control design for a spar-type floating wind turbine, and the proposed strategy is to install a tuned mass damper (TMD) into the spar platform. Firstly, a mathematical model for wind turbine surge-heave-pitch motion is established based on the D'Alembert's principle of inertial forces. Then, parameter estimation is performed by comparing the outputs from the proposed model and the state-of-the-art simulator. Further, different optimization methods are adopted to optimize TMD parameters when considering different performance indices. Finally, high fidelity nonlinear simulations with previous optimized TMD designs are conducted under different wind and wave conditions. Simulation results demonstrate both the effectiveness and limitation of different TMD parameter choices, providing parametric analysis and design basis for future improvement on floating wind turbine load reduction with structural control methods.

1. Introduction

Most current large wind turbines around the world are installed on land with sparse population and vast land. However, in many countries, inhabitants are concentrated in places along coastlines where land is scarce while power is in high demand. Therefore, utilizing offshore wind resources is more beneficial, which will both reduce electricity transmission loss and reserve more land space for people, animals and plants. More importantly, offshore wind quality has been evaluated to be much better than that onshore. According to [1], a wind farm located offshore could experience wind speeds that are, on average, 90% greater than that over land. Therefore, global wind energy exploitation has been gradually moving to offshore areas [2]. 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 [3]. In contrast, with less space constraints and more consistent wind, deep sea wind energy is more promising for those coastal cities without enough ideal shallow water areas.

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 m and 900 m [4]. Based on decades of experience from offshore oil and gas industry, several different traditional floating platforms have been proposed to support large wind turbines in deep sea regions, including spar-buoy, tension-leg, barge, and semi-submersible [5]. In detailed design, they each correspond to the models of OC3-Hywind, MIT/NREL TLP, ITI Barge, and Principle Power WindFloat [6].

One of the challenges for floating wind turbines is the wave and wind induced platform tilt motion, which will heavily increase the loads on turbine structure due to high inertial and gravitational forces [7]. Large tower and platform healing angle will cause great tower top displacement, which will bring severe fatigue and ultimate loading on tower and blades, disturb the lubrication distribution of gearbox, alter yaw bearing loading, etc. According to [8], when comparing a spar-type floating wind turbine with an onshore design, the sea-to-land ratio of fatigue damage equivalent loads (DEL) with respect to fore-aft tower base bending moments is 2.5, and the number has reached 7 for the barge-type, thus special mechanical design or advanced control technique is required to improve wind turbine reliability. Besides, soft foundation properties of floating wind turbines will lead to low natural frequency platform motion, so that commonly used blade pitch control

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Nomenclature

$\mathbf{a}_i^k$	component k of acceleration vector for mass particle i
A_i^j	generalized added mass for DOF i with regard to DOF j
D_i^j	equivalent damping coefficient for DOF i with regard to DOF j
F_i^j	generalized force for DOF i due to effect or DOF j
g	gravitational acceleration
I_i^j	generalized inertia tensor for DOF i with regard to DOF j
J_u^X	inertia tensor for u with regard to point X
K_i^j	equivalent spring coefficient for DOF i with regard to DOF j
L_u	length of part u
m_u	mass of part u
M_i^j	generalized mass for DOF i with regard to DOF j
x_i	displacement of DOF i
$\boldsymbol{\alpha}_i$	angular acceleration vector for mass particle i
θ_i	rotation angle of DOF i
τ_i^j	generalized torque for DOF i due to effect or DOF j

Acronyms and abbreviations

am	added mass effect
Anch1Ten	tension of the first anchor
CB	center of buoyancy
CG$_u$	gravity center of part u
ctr	centripetal effect
d	misalignment between RNA mass center and tower centerline
DEL	damage equivalent load
gr	gravitational effect
hdr	hydro effect
hv	DOF of platform have motion
LM	Levenberg–Marquardt
jot	joint between platform and tower
moor	mooring lines effect
NREL	National Renewable Energy Laboratory
p	DOF of platform pitch motion
ptfm	platform
PtfmHeave	platform heave displacement
PtfmPitch	platform pitch angle
PtfmSurge	platform surge displacement
RootMyc1	flapwise bending moment at the first blade root
RMS	root mean square
RNA	rotor nacelle assembly
sg	DOF of platform surge motion
spr.damp	spring and damping effect of TMD
SA	platform symmetric axis
SCGA	simplex coding genetic algorithm
STD	standard deviation
SSE	sum of squared errors
SWL	sea water level
t	DOF of tower fore-aft bending
tmd	DOF of TMD motion
twr	tower
TmdXDxt	TMD displacement in platform frame
TwrBsMxt	side-side tower base bending moment
TwrBsMyt	fore-aft tower base bending moment
TLP	tension-leg platform
TTD	tower top displacement
TTDspFA	fore-aft tower top displacement
VA	vertical axis

strategy for fixed bottom wind turbines may cause negative damping or even large resonant motion [9]. 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.

One idea is to improve the blade pitch control strategy for load mitigation. In order to avoid negative damping, Larsen et al. developed a collective pitch control system for a spar-type floating wind turbine, ensuring the desired natural frequency of control structure is lower than the lowest critical tower frequency (platform fore-aft pitch mode) [9]. At the same time, Skaare et al. proposed an estimator based control strategy in order to avoid large resonant platform pitch motion and increase tower fatigue life [10]. Jonkman also proposed several modified collective blade pitch control strategies for a barge-type floating wind turbine, including tower top feedback and controller gain detuning [11]. Besides, in [12,13], Namik et al. proposed an advanced individual blade pitch control for floating wind turbines, which would achieve remarkable platform motion inhibition and tower load reduction, but requiring more blade pitch usage and more complex control strategy.

A more direct approach is to utilize structural vibration control devices, which have been successfully applied in civil engineering structures, such as skyscrapers and bridges [14]. It is also expected to be a promising solution for extending the fatigue life of floating wind turbines. In [15], Murtagh et al. investigated the use of a tuned mass damper (TMD) placed at the tower top of a simplified wind turbine model for vibration mitigation. Following the same installation idea, Colwell et al. explored the structural responses of a fixed-bottom offshore wind turbine with a tuned liquid column damper (TLCD) [16]. Later, Mensah et al. assessed the reliability of this idea [17]. Moreover, Li et al. performed an experimental study on an offshore wind turbine with a ball vibration absorber fixed on top of the nacelle [18]. However, these discussions are about vibration mitigation of fixed-bottom wind turbines, while their motion dynamics are quite different from that of floating wind turbines. Besides, these works are not based on the cutting edge high-fidelity codes for wind turbine models, which may not capture the comprehensive coupled nonlinear dynamics of wind turbines. Based on the aero-hydro-servo-elastic wind turbine numerical simulator FAST (fatigue, aerodynamics, structures, and turbulence) [19], Lackner et al. implemented a new simulation tool, called FAST-SC, for passive, semi-active, and active structural control design of wind turbines [20], which has incorporated TMDs into the nacelle or platform of wind turbines for load mitigation. Utilizing this code, Lackner et al. presented more realistic simulation results by installing a TMD in the nacelle of both a barge-type and a monopile supported wind turbines, and a simple parametric study was also performed to determine the TMD parameters [20]. It was shown more load reduction could be achieved when introducing active structural control, such as the multi-variable H_∞ control with a loop-shaping technique [21]. The actuator dynamics and control-structure interaction were also considered in [22]. Furthermore, in order to perform a more comprehensive parametric study, the authors in [23,24] established a 3-DOF dynamic model for different types of floating wind turbines based on first principles, and TMD parameters are designed under different optimization methods. This limited-DOF model has greatly facilitated parametric analysis and active control design, but the coupling between platform surge and pitch motion was not captured. This effect can be ignored for the barge model, but might be a strong mode for other platforms [13,25]. In addition, TMD was also proposed to be installed in the platform of TLP or spar-type floating