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The impact of passive tuned mass dampers and wind–wave misalignment on offshore wind turbine loads

Gordon M. Stewart, Matthew A. Lackner *

Department of Mechanical and Industrial Engineering, University of Massachusetts Amherst, 160 Governors Drive, Amherst, MA 01003, USA

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ABSTRACT

Offshore wind turbines experience complex external loading from a variety of sources, especially wind and waves. To be economical, offshore wind turbine must operate reliably under these loading conditions. The external loading is complicated by the directionality of the wind and the waves. Metocean data in Europe and the US shows that the wind and the waves are often misaligned by significant amounts. This misalignment causes large loads on the tower in the side-side direction, which has very little structural damping compared to the fore-aft direction. Recent papers have highlighted the importance of considering wind–wave misalignment when analyzing the loads of offshore wind turbines. A variety of approaches are feasible and have been investigated to mitigate loading on offshore wind turbines due to the wind and waves. Many approaches control the aerodynamic loading on the rotor, either via control of the blade pitch or other aerodynamic actuation. This paper analyzes an alternative approach using structural control, in which passive tuned mass dampers are used to absorb and dissipate structural vibrations. In particular, this study investigates the load mitigation potential of passive tuned-mass-dampers for a 5 MW offshore wind turbine supported by a monopile, and subjected to realistic external conditions that include wind–wave misalignment. A comprehensive set of operational simulations is used to demonstrate that optimally tuned passive tuned-mass-dampers are capable or reducing tower fore-aft and side-side fatigue loads by approximately 5% and 40%, respectively. A discussion of the practical feasibility of such an approach is also provided.

1. Introduction

Offshore wind turbines (OWTs) operating in the marine environment are subjected to external loading from a variety of sources including wind, waves, current, and ice [1–3]. These external loads impact the major components of the OWT and may lead to failures and costly downtime [4–7]. For offshore wind energy to be cost effective, OWTs must be able to withstand these loads and operate reliably. Reliability is particularly crucial for OWTs (in contrast to land-based) because maintenance is expensive, dangerous, and often impossible for prolonged periods when the sea states are sufficiently harsh.

While it is well-known that the loading from wind and waves may eventually cause fatigue or ultimate load failures in OWTs, the majority of simulations and analysis of OWT loads in the literature utilize conditions in which the wind and waves are aligned in the same direction, referred to here as the fore-aft direction [8–12]. Given that wind is a primary driving force for waves, the use of aligned wind and waves appears logical. Some recent studies, however, have demonstrated two important factors: (i) the percentage of time that an OWT operates with misaligned wind and waves is significant; and (ii) because OWTs have very little structural damping in the side-side direction, which is orthogonal to the aerodynamic damping provided by the rotor thrust in the fore-aft direction, misaligned waves increase the overall loading on the support structure [13,14]. For example, a wind–wave misalignment of 90° was shown to increase the side-side mud-line bending moment by a factor of 5, while the fore-aft mud-line bending moment only decreased by 30%. On an absolute scale the side-side mud-line bending moment for 90° misalignment was approximately 25% greater than the fore-aft mud-line bending moment for a standard 0° misalignment [13].

The motivation to reduce loads on OWTs and improve reliability is compelling, and numerous load mitigation approaches have been evaluated for both fixed-bottom and floating turbines, including individual pitch control [8,12,15], acceleration feedback control [16–19], active generator torque control [20,19] feed-forward control using lidars [21], and smart rotors with active aerodynamic devices [22,23]. These approaches all focus on controlling the

* Corresponding author.
E-mail addresses: gmstewar@student.umass.edu (G.M. Stewart), lackner@ecs.umass.edu (M.A. Lackner).

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aerodynamic loading on the blades. An alternative approach to reduce the loads on OWTs is structural control, which affects the response of the structure itself, and is the focus of this paper. The control of civil engineering structures has been an active research area for over two decades, with the goal of protecting structures from dynamic loading due to earthquakes, wind, waves, and other sources [24–30]. There are three major categories of control methods for structures: passive, semi-active, and active [25]. Passive structural control techniques are the most straightforward, with constant parameters and no energy input, and are the focus of this paper. A simple example of a passive system is a mass-spring-damper ("tuned mass damper" or TMD) that is tuned to absorb energy at one of the natural frequencies of the main structure [27]. A wide range of potential passive actuators exist for structural control, including tuned mass dampers, tuned sloshing dampers, tuned liquid dampers, tuned liquid column dampers, friction dampers, pendulum dampers, and more [24,31–36]. The investigations carried out in this research use a TMD, although other passive actuators can me modeled as a TMD, making the results fairly general.

Early research on structural control of OWTs, excluding that of the authors and collaborators, has focused on passive control of fixed bottom OWTs using relatively simple, limited degree of freedom models that lack detailed modeling of the metocean conditions and resulting stochastic loads on the structure [34,37–40]. In the previous work of the authors and collaborators, a much higher fidelity modeling tool was developed, FAST-SC, which is an extended version of the aero-elastic design code FAST and is discussed in more detail in Section 2 [41]. Using FAST-SC, passive and active systems were designed, optimized, and evaluated for fixed-bottom and floating OWTs under realistic stochastic external loading conditions, but with aligned wind and waves only [42–45]. For an OWT with a monopile support structure with aligned wind and waves, two passive TMDs of approximately 2% of the total system mass, with one TMD oscillating in the fore-aft direction and the other side-side, reduced fore-aft and side-side fatigue loads by 7% and 60%, respectively [44]. The minimal damping in the side-side direction is obvious from these results as the addition of a TMD that oscillates in the side-side direction produces very large load reductions. For a floating barge OWT, passive and active structural control are able to reduce fatigue loads by approximately 10% and 25%, respectively, depending on the active control authority and thus power consumption [42,43,45].

The goal of the research presented in this paper is to evaluate passive structural control applied to an OWT monopile in the presence of wind–wave misalignment. wind–wave misalignment has traditionally been ignored in OWT loads analysis, but the effect of misalignment on loads is significant, and this investigation is the first to consider the combined effects of passive structural control and wind–wave misalignment. The impact of wind–wave misalignment on the loads of a baseline 5 MW OWT monopile is determined, and then the load reductions due to passive TMDs of varying mass and orientation within the nacelle are quantified. The results demonstrate that passive TMDs are an effective load mitigation strategy for OWT monopiles, and in particular are capable of reducing side-side loads in the presence of wind–wave misalignment. While this paper does not investigate detailed design of a passive system and instead considers a generic TMD, a brief discussion of the feasibility of such a system is presented.

2. Simulation tools and turbine models

2.1. FAST with HydroDyn

FAST is a fully coupled aero-hydro-servo-elastic code, developed at the National Renewable Energy Laboratory, that simulates the loads and performance of modern wind turbines [46]. When running a simulation using FAST, the aerodynamics are calculated with the AeroDyn subroutine, which uses the well-known equilibrium Blade Element-Momentum (BEM) approach. The AeroDyn calculations include the effects of axial and tangential induction, tip and hub losses (using the Prandtl model), and the Beddoes–Leishman dynamic stall model.

The structural dynamics are calculated by modeling the blades and tower with a linear modal representation. The blades and tower are modeled as flexible bodies, with distributed mass and stiffness properties, and prescribed mode shapes. There are two flapwise and one edgewise degrees of freedom (DOF) for the blades, and two fore-aft and two side-side DOFs for the tower.

The capability for modeling an offshore floating structure is possible with the HydroDyn subroutine [47]. HydroDyn calculates the hydrodynamic loads on the platform, including hydrostatic restoring contributions of buoyancy and waterplane area, viscous drag calculated using Morisons equation, added mass and damping contributions from wave radiation, including free surface memory effects, and the incident wave excitation from scattering in regular or irregular seas [47]. The loads from the mooring system are also calculated.

FAST uses a time marching simulation to solve the non-linear equations of motion of the fully coupled model. A schematic detailing the various modules in FAST is shown in Fig. 1.

2.2. Description of FAST-SC

Previous publications describe the theoretical background and practical implementation for modeling structural control in FAST, which resulted in the "FAST-SC" code [41,42]. Details are available in these earlier publications, and a brief summary is provided here. FAST-SC can model two independent TMDs with a user-defined mass, spring stiffness, damping, and translation direction. Earlier investigations defined the TMDs as translating in the fore-aft and side-side directions exclusively, but any arbitrary rotation of the TMD translation direction about the vertical axis is possible. An example of a fore-aft oriented TMD is shown in Fig. 2. The TMDs can be located in the nacelle or the platform, which is useful in the case of floating OWTs. While this paper investigates passive control, the code can run with the FAST-Simulink interface for semi-active and active control, with the spring stiffness, damping, and external force input for each TMD commanded in Simulink.

2.3. NREL 5 MW turbine and monopile models

The wind turbine model used for the analysis in FAST is the NREL 5 MW wind turbine [49]. This turbine model is widely used by many other researchers to evaluate offshore wind turbine loads and control strategies. The main features of the NREL 5 MW model are shown in Table 1. The support structure is designed for 20 m water depth.

2.4. Tuned mass damper parameters and configurations

Previous work by the authors describes the procedure for determining optimal TMD properties for an OWT monopile [44]. Specifically, the procedure determined the optimal spring stiffness and damping values for two values of the TMD mass, 10,000 kg and 20,000 kg. The optimal parameters are shown in Table 2. The damped natural frequency of the TMDs is similar to the first natural frequency of the tower, which is 0.31 Hz for the NREL 5 MW supported by a monopile, indicating that the optimization procedure tunes the TMD to this particular structural mode. These parameters are optimal for both a fore-aft and side-side translating TMD, and a sensitivity analysis indicated that the load reductions