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Load mitigation for a barge-type floating offshore wind turbine via inerter-based passive structural control

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ABSTRACT

This paper investigates the application of inerter to a barge-type floating offshore wind turbine for the purpose of mitigating loads of the wind turbine structures induced by wind and wave. An inerter-based structural control system, consisting of a parallel connection of a spring, a damper, and an inerter-based network, is proposed. A nonlinear aeroelastic simulation tool for wind turbines called FAST-SC is employed for evaluating the performances of the inerter-based structural control system. Due to the inefficiency of implementing FAST-SC in optimizing the element parameters (spring stiffnesses, damping coefficients, inertances), a time-efficient parameter optimization method is proposed based on a simplified linear design model, where a mixed performance objective function including the tower-top fore-aft deflection and the TMD working space is minimized with respect to the element parameters. It is shown that there exists a tradeoff between the tower-top fore-aft deflection and the TMD working space. Moreover, numerical simulations based on the nonlinear FAST-SC code show that the overall performance can be improved by using an inerter, except the tower-top fore-aft load and the TMD working space. The inerter-based configurations tend to demand more TMD working space than the system with no inerter. Furthermore, it is demonstrated that the overall performance can be improved while maintaining similar TMD working space as the system with no inerter.

1. Introduction

Wind energy is one of the most significant renewable energy sources with continued rapid growth worldwide [1–5]. Since the wind resources at sea possess higher quality than on land [6], offshore wind energy has been more and more important with great potential to exploit. Currently, the mature installation of offshore wind turbines are still predominately limited to fixed-bottom structures, which are only available in offshore areas of shallow water (typically less than 60 m) [6]. For deeper water sites, floating structures are more flexible and promising than fixed-bottom ones, as deep water areas are usually relatively far away from land and thus have more consistent wind resources. Therefore, the investigation on floating offshore wind turbines has been drawn much attention [6–8].

As the floating offshore wind turbines are much easier to be excited by the insistent wind and wave, possible large tower platform tilt motions would be induced, resulting in considerable loads imposed on the wind turbines and increasing the possibility of damage, failures and the cost of maintenance. Therefore, the load mitigation problem for floating offshore wind turbines is of great significance. The traditional way of reducing the wind and wave loads is to regulate the blade pitch angle to reduce the platform and tower pitch [6]. This method has been demonstrated to be effective, but the drawback is that other main performances would be deteriorated due to the possible much more usage of blade pitch control [18]. The recent approach to load mitigation is to use the structural control techniques to directly inhibit platform or tower vibration, where an auxiliary spring mass system adhered to the primary structure is commonly used. Such a device is known as tuned mass damper (TMD) or dynamic vibration absorber (DVA). In [9], the installation of a passive TMD at the nacelle was attempted to suppress the vibration of wind turbines. In [10], a high-fidelity widely-used code FAST-SC was developed by modifying the aeroelastic simulation tool called FAST from the National Renewable Energy Laboratory (NREL) [7]. In [11], the FAST-SC code was employed to evaluate the performance of passively and actively controlled barge-type floating wind turbines. In [12], the impact of passive tuned mass dampers and the misalignment of wind and waves on offshore wind turbine loads was investigated by using FAST-SC. In [13], several parameter tuning

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methods were proposed for passive TMDs installed on various floating platforms including the monopile, the ITI energy barge, the OC3-Hywind Spar Buoy, and the NREL tension-leg platform (TLP). In [14], the modeling and parameter optimization of a passive TMD for a spar-type floating wind turbine was investigated. In [15], load mitigation for a barge-type floating wind turbine by using actively controlled TMD and generalized H_∞ control was studied. In [16], active structural control by using a stoke-limited hybrid mass damper for a barge-type floating wind turbine was investigated. Generally speaking, active structural control can provide better performance than passive control. However, passive structural control has its unique advantages such as high reliability and low cost, which is particularly important for offshore wind turbines due to their long lifespan.

Inerter is a two-terminal mechanical device with the property that the applied force at its two terminals is proportional to the relative acceleration between them [21], which is originally motivated for mechanical network synthesis [22,23] and successfully deployed in Formula One racing [24]. Inerter has been applied in various mechanical systems such as vehicle suspensions [25–27] and other vibration control systems [28–36], and its performance benefits have been well demonstrated. In [37], the property that inerter can reduce mechanical systems' natural frequencies has been demonstrated. In [38], the inerter-based DVA (or inerter-based TMD) was proposed and the performances were evaluated. As the coefficient for the conventional inerter cannot be adjusted on-line, in [39], semi-active inerter (changeable inertance or switching inertance) whose inertance can be adjusted on-line has been proposed, and the physical realization of semi-active inerter (changeable inertance or switching inertance) has been provided in [40].

This paper investigates the application of inerter to floating offshore wind turbines, where an inerter-based structural control system is proposed and a barge-type floating offshore wind turbine is considered. The FAST-SC code is employed for the numerical simulation. Due to the inefficiency of implementing FAST-SC in optimizing the element parameters, a time-efficient parameter optimization method is presented based on a simplified linear model, where a mixed performance objective function including the tower-top fore-aft deflection and the TMD working space is minimized with respect to the element parameters. Extensive numerical simulations based on the FAST-SC code are conducted to show the effectiveness of the proposed method and the performance benefits of using inerters to mitigate loads of floating wind turbines.

The main contributions of this paper can be summarized as follows. Firstly, an inerter-based passive structural control system is proposed for barge-type floating offshore wind turbines. Although inerter has been applied in various mechanical systems, the application of inerter in offshore wind turbines has not yet been reported. Moreover, the structure of the proposed inerter-based system is slightly different from the IDVA in [38] that a parallel-connected damper is used in the proposed inerter-based system. The purpose of such an arrangement is to passively improve the overall performance directly based on the traditional spring-damper TMD system for wind turbines in [9,10,13,14] (see the second paragraph of Section 2.2 for details). Secondly, the high-fidelity offshore wind turbine simulation code FAST-SC is employed to evaluate the performance of inerter, where in [38], the primary system is a rather simplified single-degree-of-freedom undamped system. Moreover, the FAST-SC is slightly modified to facilitate the simulation of the inerter-based passive control. Thirdly, a time-efficient parameter optimization method is proposed. Note that a similar method has been employed in [13,16] for the parameter identification, and the difference is that a first-order model is proposed proposed for the wind and wave loads to facilitate the parameter optimization (see the first paragraph of Section 3.2.2 for details).

The structure of this paper is organized as follows. Section 2 introduces the offshore wind turbine model and the passive structural control with inerter. In Section 3, a reduced-order linear design model is proposed, and an optimization problem for tuning parameters is formulated. In Section 4, numerical simulations using FAST-SC are conducted. Conclusions are drawn in Section 5.

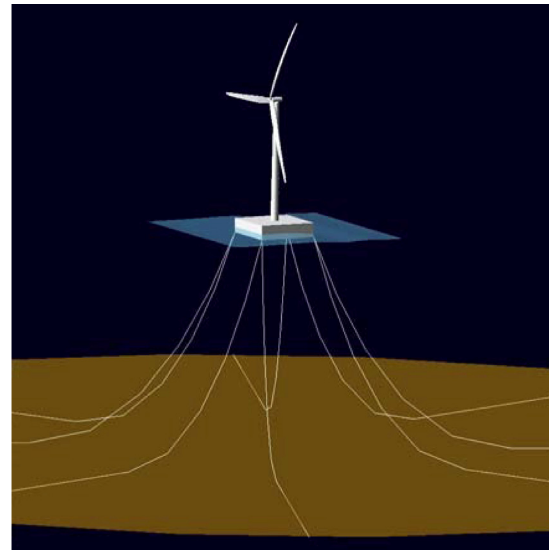

Fig. 1. NREL 5-MW floating wind turbine on the ITI energy barge [6].

2. Model description

2.1. Wind turbine model

In this paper, the NREL 5-MW baseline offshore wind turbine is adopted, which has been widely used as baseline models for offshore wind turbine design. The floating platform considered in this paper is a barge-type floating structure. The overall floating wind turbine system is illustrated in Fig. 1, and some basic parameters are given in Table 1. See [6] for detailed descriptions on this wind turbine system.

2.2. Passive structural control with inerter

In this section, the passive structural control system with inerter is described. The proposed passive structural control system is a dynamic vibration absorber (DVA) (or tuned mass damper) located at the nacelle as shown in Fig. 2, involving an auxiliary mass m_a connected to the nacelle through a parallel connection of a spring k_a, a damper c_a and a passive network $Y(s)$. The passive network $Y(s)$ consists of a finite interconnection of springs, dampers, and inerters.

Note that in [9,10,13,14], passive structural control with a parallel connection of a spring and a damper for load mitigation of wind

Table 1
Parameters of the NREL 5-MW baseline wind turbine and the ITI energy barge platform [6].

Description	Value
Rating power	5 MW
Baseline control	Variable speed, collective pitch
Drive train	High-speed multiple-stage gearbox
Rotor, hub diameter	126 m, 3 m
Hub, tower top height	90 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated rotor speed	6.9 rpm, 12.1 rpm
Rotor mass	110,000 kg
Nacelle mass	240,000 kg
Tower mass	347,460 kg
Platform mass	5,452,000 kg
Number of mooring lines	8
Anchor depth	150 m