



Semi-active control of monopile offshore wind turbines under multi-hazards



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ABSTRACT

The present paper studies the control of monopile offshore wind turbines subjected to multi-hazards consisting of wind, wave and earthquake. A Semi-active tuned mass damper (STMD) with tunable natural frequency and damping ratio is introduced to control the dynamic response. A new fully coupled analytical model of the monopile offshore wind turbine with an STMD is established. The aerodynamic, hydrodynamic and seismic loading models are derived. Soil effects and damage are considered. The National Renewable Energy Lab monopile 5 MW baseline wind turbine model is employed to examine the performance of the STMD. A passive tuned mass damper (TMD) is utilized for comparison. Through numerical simulation, it is found that before damage occurs, the wind and wave induced response is more dominant than the earthquake induced response. With damage presence in the tower and the foundation, the nacelle and the tower response is increased dramatically and the natural frequency is decreased considerably. As a result, the passive TMD with fixed parameters becomes off-tuned and loses its effectiveness. In comparison, the STMD retuned in real-time demonstrates consistent effectiveness in controlling the dynamic response of the monopile offshore wind turbines under multi-hazards and damage with a smaller stroke.

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1. Introduction

Due to environmental concerns, wind energy production and consumption has experienced a remarkable growth world-wide in the passed decade and is projected to grow more rapidly in the following decade. Under the circumstance, offshore wind plants are becoming more attractive than its onshore counterparts because of advantages including the steadier and higher wind speed, less visual impacts and less noise constraints. However, due to the combined multiple hazards including wind, wave and earthquake, excessive vibration and fatigue load will result, adversely influencing the structural integrity and service life. In this regard, structural vibration control, which has been successfully applied in civil structures, is being studied to control the offshore wind turbines.

Three basic control strategies have been developed: passive, semi-active and active [1,2]. Passive control of offshore wind turbines has been studied actively in recent years. Murtagh et al. [3] studied the control of the wind turbine along-wind vibration using a passive tuned mass damper (TMD). The authors concluded that response reduction could be achieved when the TMD was tuned to the predominant frequency. Lackner et al. [4] used dual passive TMDs placed in the nacelle to control both the fore-aft and side-side vibration. It was found that the dual TMDs can reduce the structural response of offshore wind turbines. Colwell and Basu [5] used the tuned liquid column damper to control the vibration of an offshore wind turbine.

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Research findings indicated that the tuned liquid column dampers could prolong the tower fatigue life. Although passive control techniques provide mitigation when the parameters are finely tuned, they might lose their effectiveness as a result of environmental or system variations. It was reported in [6] that most of the passive dampers deployed on highway sign structures are ineffective due to the detuning effect.

In comparison, semi-active control devices are more applicable to systems with time-variant parameters. Semi-active TMDs (STMDs) have been investigated and demonstrated effective in controlling vibration of linear and nonlinear systems subjected to stationary and non-stationary excitations [7–9]. Weber [10] utilized a semi-active vibration absorber with real-time adjusted magnetorheological damper (MR-SVA) to mitigate harmonic loading induced vibrations. It was found that the MR-SVA outperforms the passive TMD. Huang and Arrigan et al. [11,12] explored the mitigation of wind turbine blades using the STMDs retuned in real-time via a short time Fourier transform (STFT) based control algorithm. The authors found that the STMDs could mitigate the blade responses under varying operational or environmental conditions. In Refs. [7,11,12], only the frequency of the STMDs was tuned in real-time yet the damping ratio remained constant. Recently, Sun et al. [13] further advanced the control algorithm by incorporating the tuning of damping ratio. The authors examined the performance of the STMD tuned by the modified control algorithm for seismic protection and achieved improved response reduction.

In addition to passive and semi-active control, active control of vibrations have been studied and demonstrated effective under operational or environmental variations [14,15]. Staino et al. [16] used active tendons mounted inside the blade to control the edgewise vibration of wind turbine blades. The authors concluded that the proposed control scheme can significantly mitigate the response of the blade. Fitzgerald et al. [17] utilized an active tuned mass damper to control the in-plane vibration of the blades. It was found that the active TMDs can provide better reduction than the passive TMDs.

Among different types of offshore wind turbines, the monopile fixed-bottom offshore wind turbines are widely employed and under active investigation. In most existing literatures, soil effects were not considered, which is inappropriate when the soil is relatively soft. Veletsos and Verbic [18] found that flexible soil underneath the foundation can increase the damping and reduce the structural natural frequency. Furthermore, under cyclic wind, wave loading and strong earthquake strike, damage will potentially occur to the foundation [19] and the tower. The accumulated damage will change the structural natural frequency and the response magnitude. Fitzgerald et al. [20] considered soil-structure-interaction and used an active TMD to control the onshore wind turbines under wind loading. It was found that the active TMD was effective when soil structure interaction is considerable. However, the dynamic characteristics of offshore wind turbines under combined multi-hazards and potential damage have not been studied in Ref. [20] or other existing literatures.

To fill this gap, the present paper explores semi-active control of the monopile offshore wind turbines subjected to multi-hazards consisting of wind, wave and earthquake where soil effects and damage are considered. Novelty of the present study is twofold. On one hand, the dynamic characteristics of the offshore wind turbines under the combined effects of multi-hazards, soil effects and damage will be studied. On the other hand, the effectiveness of the STMD in controlling the dynamic response will be evaluated. To achieve this, a new mathematical model of the monopile offshore wind turbines coupled with the STMD is established where the dynamic interaction between the blades and the tower and the STMD is modeled. Aero-dynamic loading, wave loading, seismic loading and gravity loading are incorporated in the model. It is found that the response dominant frequency decreases as the damage develops. Significant response amplification phenomenon under the combined effects of multi-hazards and damage can be observed. When the STMD is utilized, it is shown that the STMD can provide excellent effectiveness in controlling the tower and foundation dynamic response while the passive TMD becomes off-tuned and ineffective.

2. Establishment of equations of motion

The equations of motion of a fully coupled three dimensional monopile offshore wind turbine model with and without the STMD are established using the Euler-Lagrangian equation. There are 10 degree-of-freedom (DOF) in the uncontrolled system and 11 DOF in the controlled system.

2.1. Model description

Fig. 1 illustrates the model of a monopile fixed-bottom offshore wind turbine subjected to wind, wave and seismic loadings. The global coordinate system originates at the intersection point of the tower center and the mean sea level (MSL). The left portion of Fig. 1 shows the original model and right portion shows the deformed geometry of the wind turbine under the combined loadings. Soil effect is represented by a translational spring with a stiffness coefficient k_x and a rotational spring with a stiffness coefficient k_ϕ . The damping property of the soil is represented two dash-pot with damping coefficients of c_x and c_ϕ . Parameters q_9 , q_{10} in Fig. 1 denote the translation and rotation coordinates of the foundation which will be used to establish the equations of motion in the subsequent sections.

Fig. 2(a) and (b) illustrate the coordinates of the blades(edgewise and flapwise), the nacelle and the STMD. Parameters q_1 – q_3 denote the edgewise coordinates of the three blades and q_4 – q_6 denote the flapwise coordinates. Displacement of the 1st blade is shown in Fig. 2 as a general illustration. Variables u_{1e} and u_{1f} represent the edgewise and flapwise displacements of an infinitesimal unit dr at a distance r from the blade root; variables ϕ_{1e} and ϕ_{1f} denote the edgewise and flapwise fundamental mode shape. To formulate the motion of the blade, a local coordinate system $x'y'z' - o'$ originating at the center

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