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Active structural control of a floating wind turbine with a stroke-limited hybrid mass damper

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ABSTRACT

Floating wind turbines are subjected to more severe structural loads than fixed-bottom wind turbines due to additional degrees of freedom (DOFs) of their floating foundations. It's a promising way of using active structural control method to improve the structural responses of floating wind turbines. This paper investigates an active vibration control strategy for a barge-type floating wind turbine by setting a stroke-limited hybrid mass damper (HMD) in the turbine's nacelle. Firstly, a contact nonlinear modeling method for the floating wind turbine with clearance between the HMD and the stroke limiters is presented based on Euler-Lagrange's equations and an active control model of the whole system is established. The structural parameters are validated for the active control model and an equivalent load coefficient method is presented for identifying the wind and wave disturbances. Then, a state-feedback linear quadratic regulator (LQR) controller is designed to reduce vibration and loads of the wind turbine, and two optimization methods are combined to optimize the weighting coefficients when considering the stroke of the HMD and the active control power consumption as constraints. Finally, the designed controllers are implemented in high fidelity simulations under five typical wind and wave conditions. The results show that active HMD control strategy is shown to be achievable and the designed controllers could further reduce more vibration and loads of the wind turbine under the constraints of stroke limitation and power consumption. "V"-shaped distribution of the TMD suppression effect is inconsistent with the Weibull distribution in practical offshore floating wind farms, and the active HMD control could overcome this shortcoming of the passive TMD.

1. Introduction

As a kind of rich and important renewable energy, wind energy has become one of the most promising energy and attracted people's increasing attention in recent years [1,2]. Currently, most wind power is still generated from land-based wind turbines which are generally installed in vast and sparsely populated lands. However, in many countries, such as China, America and others, most residents live in coastal areas where land are valuable and relatively rare while power demand is huge. Therefore, developing offshore wind energy is a good choice, as it can save more land resources and reduce

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Nomenclature

k_p, k_t, k_T the equivalent spring stiffness coefficients of the platform, the tower and the TMD
d_p, d_t, d_T the equivalent damping coefficients of the platform, the tower and the TMD
m_p, m_t, m_T the masses of the platform, the tower and the TMD
R_p, R_t, R_T the distances from the tower hinge to the mass centers of the platform, the tower and the TMD
k_{Ulim}, k_{Dlim} the equivalent spring stiffness coefficients of upwind and downwind stroke limiters
c_{Ulim}, c_{Dlim} the damping coefficients of upwind and downwind stroke limiters
x_{Ulim}, x_{Dlim} the distances of the neutral static HMD to the upwind and downwind stroke limiters
Δx_U, Δx_D the deflections of the upwind and downwind stroke limiters
x_T the displacement of the TMD relative to the z-axis
x_T^n the displacement of the TMD relative to the neutral static position in the nacelle coordinate
θ_p, θ_t the rotation angles of the platform and the tower relative to the z-axis
f_a the driving force of the actuator
f_k, f_d the stiffness restoring force and the damping force of the HMD
g gravitational acceleration
Q_{lim} the damping force of the stroke limiters
V_{lim} the potential energy of the stroke limiters
M_{wind}, M_{wave} the bending moments caused by the wind and wave loads

Acronyms and abbreviations
LM Levenberg–Marquardt
SSE sum of squared errors
TwrBsMxt side-side tower base bending moment
TwrBsMyt fore-aft tower base bending moment
TTD tower top displacement
PtfmPitch platform pitch angle
PtfmRoll platform roll angle
TTDspFA tower top fore-aft displacement
TTDspSS tower top side-side displacement
GenPwr generator power
HmdPwr HMD driving power
BldPitch1 blade pitch angle
TmdDxn TMD/HMD displacement
TmdVxn TMD/HMD velocity
LQR linear quadratic regulator
OoPDefl blade-tip out-of-plane displacement
RootMyc1 blade root out-of-plane moment
PGAc parallel genetic algorithm with constraints
STD standard deviation
RMS root mean square
Ave average

power transmission loss. More important is that offshore wind resources are known to be of higher quality than that on land [3]. Thus global wind power development has been gradually shifting to the sea. Shallow sea wind power has been developed in recent years, but they are often criticized for visual and noise pollution [4], and foundations of shallow sea wind turbines are also relatively huge and with complex structures and in high construction costs [5]. By comparison, with less space limitations and more strong and steady wind resources, deep sea wind power has great potential to be exploited.

Foundation structures of offshore wind turbines play a key role in the sea wind energy development. According to different foundation types, offshore wind turbines can be broadly categorized into two types: nearshore fixed-bottom wind turbines and deep sea floating wind turbines [6]. The first one is installed on fixed-bottom foundations, including monopile, gravity based structure, and suction bucket [5]. Currently, these foundations are the mature construction method, and they are suitable for installation in shallow sea, but not meet economic feasibility in deep sea with depth more than approximately 60 m. The second type uses floating platforms and mooring lines as the supporting structures, which are economical and feasible for deeper water up to 900 m [7]. Nonetheless, floating foundations are still at an early development stage, and many different platforms are in proof-of-concept study and they are being tested with scale model in real or laboratory conditions, including type of barge, spar, tension-leg (TLP) and semi-submersible [5,8].