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A study on vibration isolation for wind turbine structures

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This paper discusses the potential use of vibration isolation to reduce the dynamic response of wind turbine structures, with emphasis on structural response to seismic loading. Based on the concept of partial mass isolation, vibration isolators are proposed at the top of the turbine tower, just below the nacelle. The structural idealizations of a wind turbine including a nonlinear isolation system are presented and the responses are simulated using the finite element method. A sample turbine structure is presented and subjected to coherent wind and seismic loading in order to demonstrate the effect of isolation system parameters on the structural response. A parametric study is conducted to study the effect of isolation system parameters on the response of the turbine structure, including the blades. The responses are quantified in terms of several performance indices reflecting the trade-offs associated with implementing an isolation system on flexible structures. Results show that implementing an isolation system may be beneficial for reducing certain key parameters of the turbine's structural response, and may provide an excellent design option for the design of wind turbines in seismically active parts of the world.

1. Introduction

The increasing size and ubiquity of wind turbines for power generation has led to increased concerns regarding their structural integrity, particularly as new turbine structures become larger and more flexible. Much study has been devoted to wind turbine structures under wind loading, including research papers [3,6,11,12], books [2,7], and the development of computer codes, both public and proprietary. Standards have been established to provide design requirements and guidance, including IEC 61400-1 [8], "Wind turbines – Part 1: Design requirements". While the literature on the topic of wind effects on the structural responses of turbines is vast, the literature on seismic analysis of turbines is scarce. As wind turbines continue to be embraced in more seismically active parts of the world such as California, and the western coast of British Columbia in Canada, seismic loads are likely to govern their design. This study proposes seismic isolation to reduce the vulnerability of large wind turbines to earthquake loads, particularly near-fault earthquakes.

Wind effects on turbines, their modeling, and structural control, have been active areas of research. Murtagh et al. [11] showed that an uncoupled numerical model, in which blade and tower vibration are considered separately, may provide un-conservative results under wind loading. Dueñas-Osorio and Basu [6] studied the potential unavailability of wind turbines due to excessive wind-induced accelerations, and derived fragility curves and probabilities of unavailability of turbines. Murtagh et al. [12] proposed and detailed the behavior of a coupled structural model of a turbine with a tuned mass damper (TMD) and demonstrated that the TMD could provide significant reductions in structural response. Colwell and Basu [3] demonstrated that implementing a tuned liquid column damper for offshore wind turbines could reduce structural response and prolong fatigue life. These studies demonstrated the potential effectiveness of passive control devices for reducing structural response to wind loading and prolonging fatigue life, but did not consider seismic loading.

IEC 61400-1 provides no earthquake resistance requirements for standard class wind turbines as seismic loading is not design-driving in most regions of the world. A simplified method is provided in IEC 61400-1, in which the head mass and half the tower mass are lumped at hub height and subjected to seismic acceleration consistent with the fundamental frequency of the structure. If the structure can withstand the imposed loading, no further seismic considerations are required. Otherwise, or if seismic loading on the blades is a concern, a more detailed analysis must be undertaken consistent with local building codes. A study of a 450 kW turbine to be installed in Greece [1] found that seismic loading was not a critical concern. However, as designers work to suppress the structural actions due to wind loading using new control systems and materials, among other advances, the relative importance of seismic loading may be increased [16]. Ongoing

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research in this area includes full-scale shake table testing of wind turbines [17] as well as numerical studies of seismic response [20].

Seismic (base) isolation has been studied and shown to be an effective structural control measure to reduce the vulnerability of buildings to strong near-fault earthquakes [13]. In base isolation, a laterally flexible layer is created between the base of a structure and the ground, changing the fundamental mode of vibration from one dominated by structural deformation to one dominated by a larger displacement across the isolation layer with relatively little structural deformation [13]. There are a great variety of base isolation systems such as elastomeric bearings, lead-rubber bearings (LRBs), and friction pendulum systems (FPS), which have been deployed effectively in many building applications [13]. However, to the knowledge of the authors, there have been no studies devoted to base isolation for wind turbine structures.

This paper proposes isolation at the top of the tower structure, just below the nacelle, unlike traditional base isolation which decouples the entire structure from the ground. The proposed design is conceptually similar to partial mass isolation proposed for building applications [21], where only a part of the structure, for example the roof, is isolated from the surroundings. In partial mass isolation, under certain circumstances the amount of energy put into the structural system could be increased due to the flexibility of the structure both above and below the isolator, necessitating careful choice of isolation properties. With proper detailing and energy dissipation, the isolation system can effectively decrease structural response. In the proposed design, LRBs are used in conjunction with fluid viscous elements as the isolation system. Parametric studies are conducted to demonstrate its effectiveness, and to guide in the selection of the isolation system parameters. Response to coherent wind and seismic loading in the along-wind direction is studied using numerical simulations. The model is implemented in COMSOL Multiphysics, a finite element program which allows for explicit inclusion of the equations required to represent a vibration isolator.

2. Structure and isolation system modeling

Wind turbine towers and blades are both slender in section height compared to their length, and are typically idealized as Euler–Bernoulli beams, with response characterized by flexural deformation. A typical wind turbine is shown in Fig. 1. The naming convention used for coordinate axes in this paper is also shown in Fig. 1. The displacements are represented by u, v and w, while rotations about the axes are represented by θ with subscript representing the directional sense of the rotation.

Assuming the turbine is not in operation, the structural idealization is a linear one, which can be represented by the matrix equations of motion [5]

$$\mathbf{M}\ddot{\mathbf{d}} + \mathbf{C}\dot{\mathbf{d}} + \mathbf{K}\mathbf{d} = \mathbf{F} \tag{1}$$

where **M**, **C** and **K** are the mass, damping and stiffness matrices of the discretized structure; **d** is a vector of the structure's nodal displacements, with overdots representing time derivatives; and **F** is a vector of nodal forces. This set of equations can be solved using modal superposition, where displacements **d** are transformed into generalized coordinates whose coefficient matrices are uncoupled. Alternately, Eq. (1) can be solved directly without coordinate transformation by numerical time-stepping schemes such as Newmark's method.

The above formulation is valid for a parked turbine structure, where the geometry of the system is constant. When the turbine is in operation, the blades rotate relative to the nacelle. The effect of this rotation is modeled using a periodic rotational coupling between the rotating hub and the stationary nacelle, which can be expressed through co-ordinate transformations as [18]

$$u_n = u_r \tag{2}$$

$$v_n = v_r \cos(\omega t) - w_r \sin(\omega t) \tag{3}$$

$$w_n = w_r \cos(\omega t) + v_r \sin(\omega t) \tag{4}$$

$$\theta_{y,n} = \theta_{y,r} \cos(\omega t) - \theta_{z,r} \sin(\omega t) \tag{5}$$

$$\theta_{z,n} = \theta_{z,r} \cos(\omega t) + \theta_{y,r} \sin(\omega t) \tag{6}$$

where the subscripts "n" represent the stationary nacelle and "r" represent the rotating hub frame of reference, with displacements and rotations as shown in Fig. 1. ω represents the angular velocity of the rotor, and t represents time. Incorporating the rotation of the blades allows for the evaluation of time-varying nature of the transferred forces between the hub and the nacelle.

The tower and blades are idealized as beam elements, the nacelle is idealized as a rigid element offsetting the rotor plane from the tower, and the mass of the nacelle and hub are lumped at hub height. For this study, the isolator is located just below the nacelle, as shown in Fig. 2a. The isolator allows along-wind and across-wind motion of the nacelle with respect to the top of the tower. For modeling purposes, the multiple degree of freedom (MDOF) tower system is coupled to the blades, another MDOF system,

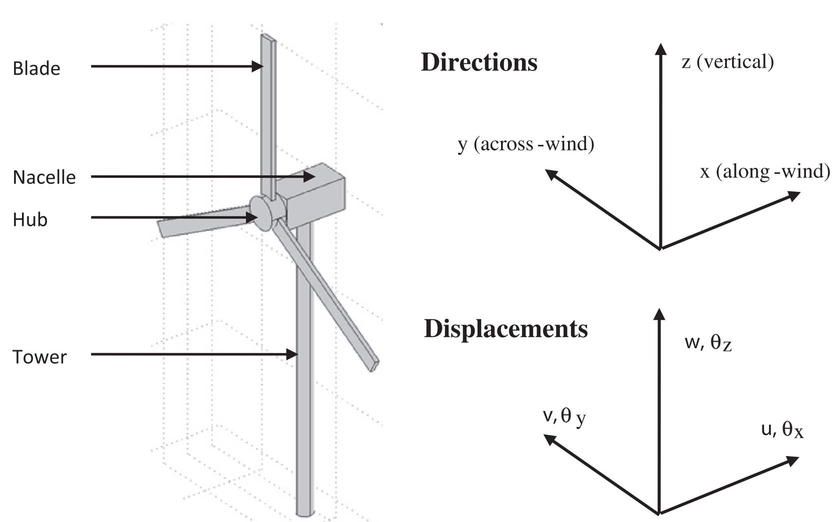

Fig. 1. Typical wind turbine and coordinate system.