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An Investigation into the Effect of Long-Term Cyclic Loading on the Natural Frequency of Offshore Wind Turbines

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This paper presents a numerical study of the natural frequency of a monopile-supported offshore wind turbine in sand subjected to long-term cyclic loading. The numerical model is based on the characteristics of the soil–monopile interaction under long-term cyclic lateral loading observed in well-designed laboratory model tests, and the free vibration method was adopted to estimate the natural frequency. The study shows that the simulation, without taking into account the effect of long-term cyclic loading, yielded a natural frequency that is 8.39% greater than the measured value. A parametric study was then conducted to evaluate the effects of several key design parameters on the natural frequency. Results indicate that Young's modulus and the depth of subsidence of the soil around the monopile have a significant influence on the natural frequency of the wind turbine. An important implication of the parametric study is that the current practice of accounting for ±10% variation in the natural frequency may not be suitable for offshore wind turbines.

INTRODUCTION

Offshore wind turbines account for a higher proportion of wind energy generation capacity due to the abundance of wind potential and the open space for installation (Koh and Ng, 2016; Wang et al., 2018). Currently, most offshore wind turbines have been installed in shallow water on bottom-mounted substructures, and monopiles are often used as foundations (Damgaard, Bayat, et al., 2014). For a monopile-supported offshore wind turbine with three blades, there are three design approaches, as illustrated in Fig. 1 (Damgaard, Zania, et al., 2014; Myers et al., 2015):

1. Soft-soft design, where the natural frequency is less than the 1P frequency range (i.e., the rotational frequency of the rotor);
2. Soft-stiff design, where the natural frequency lies between the 1P and 3P frequency ranges (i.e., blade passing frequency);
3. Stiff-stiff design, where the natural frequency is higher than the 3P frequency range.

The stiff-stiff approach requires a very stiff foundation, thus leading to an expensive design (Kühn, 2003; O'Kelly and Arshad, 2016). Although it is possible to design a flexible structure with the first natural frequency below 1P, the lower bound of the 1P range usually lies around the peak of the wave spectrum, and the natural frequency must be controlled to be very low, leading to a very soft design that is critical. Hence, for conventional offshore wind turbines, resonance avoidance is often achieved by using the soft-stiff design approach (Gupta et al., 2012; Barari et al., 2017) in which the natural frequency lies between 1P and 3P. For the

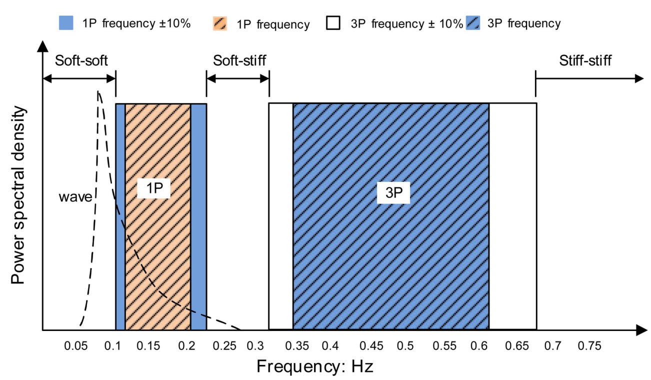

Fig. 1 Diagram showing allowable frequency range and excitation frequencies

NREL 5MW reference wind turbine shown in Fig. 1 (Jonkman et al., 2009), the cut-in and rated rotor speeds are equal to 6.9 rotations per min (rpm, 1 rpm = 1/60 Hz) and 12.1 rpm, respectively. If a 10% error is considered (DNV, 2014; Bhattacharya et al., 2013), in order to avoid resonance for this wind turbine, the soft-stiff design approach requires the first natural frequency to be within a very narrow frequency band (0.22–0.31 Hz) (Van der Tempel, 2006). If there are any changes in the foundation stiffness due to long-term cyclic loading, the natural frequency may shift closer to the 1P or 3P frequency, causing the risk of resonance and fatigue damage. Therefore, it is critical to investigate the effect of long-term cyclic loading conditions on the natural frequency of offshore wind turbines.

Offshore wind turbines are exposed to several types of external loadings, especially wind and wave actions. In its lifetime, an offshore wind turbine structure must withstand a very large number

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