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Technical Note

An innovative cyclic loading device to study long term performance of offshore wind turbines

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ABSTRACT

One of the major uncertainties in the design of offshore wind turbines is the prediction of long term performance of the foundation i.e. the effect of millions of cycles of cyclic and dynamic loads on the foundation. This technical note presents a simple and easily scalable loading device that is able to apply millions of cycles of cyclic as well as dynamic loading to a scaled model to evaluate the long term performance. Furthermore, the device is economic and is able to replicate complex waveforms (in terms of frequency and amplitude) and also study the wind and wave misalignment aspects. The proposed test methodology may also suffice the requirements of Technology Readiness Level (TRL) Level 3–4 i.e. Experimental Proof of Concept validation as described by European Commission. Typical long term test results from two types of foundations (monopile and twisted jacket on piles) are presented to show the effectiveness of the loading device.

1. Introduction

Offshore wind turbines are a relatively new type of structure with limited track record of long-term performance. The three main long term design issues are:

(a) Whether or not the foundation will tilt progressively under the combined action of millions of cycles of loads arising from the wind, wave and 1P (rotor frequency) and 2P/3P (blade passing frequency). It must be mentioned that if the foundation tilts more than the allowable, it may be considered failed based on Serviceability Limit State (SLS) criteria and may also lose the warranty from the turbine manufacturer. The loads acting on the foundation are typically one way cyclic and many of loads are also dynamic in nature. Further details of the loading can be found in Arany et al. [3,4].

(b) It is well known from literature that repeated cyclic or dynamic loads on a soil causes a change in the properties which in turn can alter the stiffness of foundation, see Adhikari and Bhattacharya [1,2]. A wind turbine structure derives its stiffness from the support stiffness (i.e. the foundation) and any change in natural frequency may lead to the shift from the design/target value and as a result the system may get closer to the forcing frequencies. This issue is particularly problematic for soft-stiff design (i.e. the natural or resonant frequency of the whole system is placed between upper bound of 1P and the lower bound of 3P) as any increase or decrease in natural frequency will impinge on the forcing frequencies and may lead to unplanned resonance. This may lead to loss of years of service, which is to be avoided.

(c) Predicting the long term behaviour of the turbine taking into consideration wind and wave misalignment aspects.

Limited monitoring of offshore wind turbines indicates that the dynamic characteristics of these structures may change over time and has the potential to compromise the integrity of the structure due to fatigue and resonance phenomena. For example resonance under operational condition has been reported in the German North Sea projects, see Hu et al. [11]. Change in the natural frequency of the Hornsea Met Mast structure supported on a 'Twisted Jacket' foundation is also reported by Lowe [10]. Three months after the installation the natural frequency dropped from its initial value of 1.28–1.32 Hz to 1.13–1.15 Hz. Scaled model tests carried out by Bhattacharya et al. [5–7], Yu et al. [12], Guo et al. [13], Cox et al. [8] indicated that natural frequency may change owing to dynamic soil structure interaction.

It is therefore essential to understand the mechanisms that causes the change in dynamic characteristics of the structure and if it can be predicted through analysis. An effective and economic way to study the behaviour (i.e. understanding the physics behind the real problem) is by conducting carefully and thoughtfully

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designed scaled model tests in laboratory conditions simulating (as far as realistically possible) the application of millions of cyclic lateral loading by preserving the similitude relations. Derivation of similitude relations for scaling of monopiles supporting wind turbines can be found in Bhattacharya et al. [5] and for multipod foundations in Bhattacharya et al. [7,9].

This aim of the paper is to present an innovative cyclic loading device that can be used to carry out small scale testing whereby long-term performance of offshore turbines can be studied. This device is economic, scalable to different model scales and is able to replicate complex loads acting on an offshore wind turbine. Furthermore, the wind and wave misalignment can also be simulated. The paper is structured in the following way: After a brief review of the complexity of the loads on a typical wind turbine, an innovative devise capable to simulating the loading complexity is presented. Finally, typical test results obtained from this apparatus are also shown.

2. Cyclic and dynamic loads acting on an offshore wind turbines

Offshore wind turbine installation is unique type of structure due to their geometry (i.e. mass and stiffness distribution along the height) and the cyclic/dynamic loads acting on it. There are 4 main loadings on the offshore wind turbine: wind, wave, 1P and 3P, see Fig. 1. Each of these loads has unique characteristics in terms of magnitude, frequency and number of cycles applied to the foundation. The loads imposed by the wind and the wave are random in both space (spatial) and time (temporal) and therefore they are better described statistically. Apart from the random nature, these two loads may also act in two different directions. 1P loading is caused by mass and aerodynamic imbalances of the rotor and the forcing frequency equals the rotational frequency of the rotor. On the other hand 2P/3P loading is caused by the blade shadowing effect and is simple 2 or 3 times the 1P frequency. Fig. 1 shows the typical wave forms of the 4 types of loads. On the other hand, Fig. 2 presents a schematic diagram of the main frequencies of the loads together with the natural frequency of two Vestas V90 3 MW wind turbines from two wind farms: Kentish Flats and Thanet (UK).

It is of interest to summarise to soil structure interaction issue for an offshore wind turbine. There are two main aspects related to cyclic loading conditions that have to be taken into account during design: (a) soil behaviour due to non-dynamic cyclic loading i.e. fatigue type problem and this is mainly attributable to wind loading which has a very low frequency; (b) soil behaviour due to dynamic loading which will cause dynamic amplification of the foundation response i.e. the resonance type problem. This is due mainly due to 1P and 3P loading but wave loading can also be dynamic for deeper waters and heavier turbines. A breakdown of the overall problem of soil–structure interaction into two types of soil shearing is schematically represented in Fig. 3. A model test needs to capture these behaviour.

3. Scaled model testing of offshore wind turbines and the innovative cyclic loading system

Based on the discussion in the earlier section and the soil–structure interaction, scaled model testing under repetitive cyclic loading can be divided into two categories:

a) Modelling the behaviour of foundation under cyclic loading without considering the dynamics of the system i.e. fatigue type of problem as shown in Fig. 3(a).
b) Modelling the behaviour of foundations considering the dynamics of the system i.e. studying both fatigue type and resonance type of problem as seen in Fig. 3(a) and (b).

Extensive research has been carried to study cyclic behaviour of foundation, see for example Leblanc [14], Cox et al. [8] where few hundreds to tens of thousands of cyclic loads were applied and the dynamics of the whole system has been ignored. However to realistically study, long term performance of offshore turbines, apart from dynamic loads, wind and wave misalignment must also be simulated. In addition, millions of cycles of loading to mimic the life

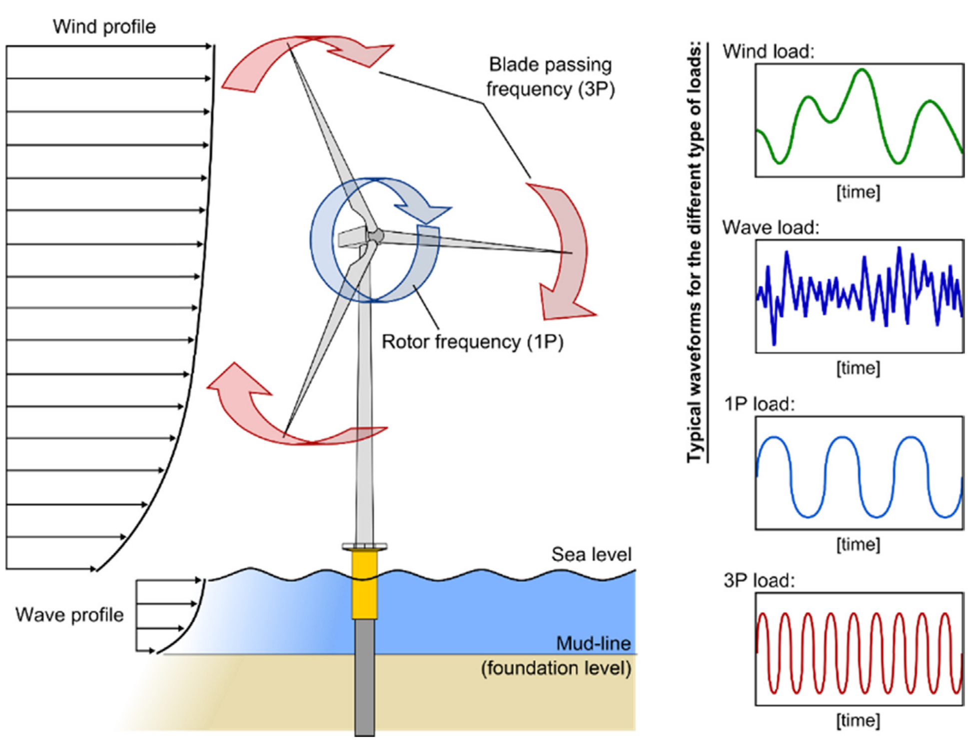

Fig. 1. External loads acting on an offshore wind turbine, along with their typical waveforms.