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 TRL (Technology Readiness Level) 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.

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 SLS (Serviceability Limit State) 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 (2014).
- (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 (2011, 2012). 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 (2014). Change in the natural frequency of the Hornsea Met Mast structure supported on a 'Twisted Jacket' foundation is also reported by Lowe (2012). Three months after the installation the natural frequency dropped from its initial value of 1.28-1.32Hz to 1.13-1.15Hz. Scaled model tests carried out by Bhattacharya et al (2012, 2013a, 2013b), Yu et al (2014), Guo et al (2015), Cox et al (2014) 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 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 (2012) and for multipod foundations in Bhattacharya et al (2013b).

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 device capable to simulating the loading complexity is presented. Finally, typical test results obtained from this apparatus are also shown.

2.0 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 Figure 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. Figure 1 shows the typical wave forms of the 4 types of loads. On the other hand, Figure 2 presents a schematic diagram of the main frequencies of the loads together with the natural frequency of two Vestas V90 3MW wind turbines from two wind farms: Kentish Flats and Thanet (UK).

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

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 Figure 3. A model test needs to capture these behaviour.

Figure 2: Forcing frequencies plotted against power spectra densities for Vestas V90 3MW wind turbines.

Figure 3: Breakdown of Soil-Structure Interaction of Offshore Wind Turbines into two types of problems.

3.0 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:

- Modelling the behaviour of foundation under cyclic loading without considering the dynamics of the system i.e. fatigue type of problem as shown in Figure 3 (a).
- 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 Figure 3(a) and Figure 3(b).

Extensive research has been carried to study cyclic behaviour of foundation, see for example Leblanc (2009), Cox et al (2014) 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 cycle of the wind turbine are to be applied. This paper presents an innovative device capable of applying cyclic as well dynamic loading to a wind turbine model and is described in the next section. This innovative cyclic loading system consists of two identical interlocking gears where masses can be attached, see Figure 4. The working principle of this cyclic loading device is based on the unbalanced rotation of eccentric masses and is presented schematically in Fig.5. This counter-rotating eccentric mass of equal magnitude is able to produce a unidirectional cyclic load in Y-axis only as the net force in X-axis is zero due to cancellation of the equal and opposite forces. In the case when the two masses mounted on the interlocking gears are not equal there will be a sinusoidal loading along two perpendicular directions (X and Y axis). The force resultants in X and Y axes for two cases when the masses are equal and unequal are presented in Figure 6. This loading system, along with all its components, can be seen in Figure 4.

Figure 4: Prototype cyclic loading device with all the components annotated

Figure 5: Working principle of the described loading device

It may be noted that the excitation force produced by this device is dependent on three variables: mass of the weights attached to the gears (m), the radius of the gears (r) and the angular velocity of the gears (ω). The frequency (Hz) of the cyclic loading depends mainly on the angular velocity which can be easily controlled by the voltage (V) of the power supply. In order to control the force in Y axis, the appropriate masses should be attached to the rotating gears, considering the fact that the radius remains the same. Also it is possible to change the frequency and the amplitude by just replacing the type and the diameter of the gears. Once the amplitude and the frequency of the cyclic loads are defined, the device is mounted on the tower to simulate the desired overturning moment at the level of the foundation.

In a typical offshore project, the largest contribution towards the overturning moment is due to the wind and the wave loads having different magnitude of overturning moment, frequency and also the number of cycles. A way to address this loading complexity in a scaled model tests is by attaching two of these eccentric mass actuators, one to represent each load (frequency and amplitude) and placing them at the correct height in order to produce the desired scaled bending moment at the base of the model. The result of such an arrangement would provide realistic results of the foundation's long term performance. Such a configuration is presented schematically in Figure 7, where the wind and the wave are acting along the same direction i.e. collinear. There can be loading scenarios, when the wind and the wave may not be aligned and Figure 8 shows a possible configuration that can be used for simulation.

4.0 Performance of the new apparatus in model testing

In order to assess the performance of the counter-rotating eccentric mass actuator, an extensive experimental programme was carried out where 1:100 scaled offshore wind turbine models supported on two types of foundation types: monopile and the twisted jacket (also known as IBGS: Inward Battered Guided Structure) supported on pile foundations. Further details of the testing procedure, soil container requirements, similitude/scaling relations can be found in Bhattacharya et al (2011). Up to 100,000 loading cycles were applied in the tests. The model foundations were 1:100 models scale and were made out of aluminium tubes. A rigid plastic container (1120mm x 920mm x 600mm) was used and the container was filled with Red Hill 110 Silica

soil up to a depth of 400mm with relative density of 63%. Further details on the properties of the sand and the advanced testing can be seen in Bhattacharya et al (2013). The innovative cyclic loading device was mounted on top of the tower and a pair of MEMS accelerometers were attached to the model. A non-contact laser-vibrometer was also used to independently verify the dynamic response. The test setup for the monopile foundation is presented schematically in Figure 9 and Figure 10 shows the photograph of the test setup.

A typical test procedure consists of the following: (a) Before any cyclic loading is applied, snap back test (also known as free vibration decay test) is performed to obtain the initial natural frequency and damping of the model; (b) Cyclic loading is then applied with a specified load amplitude and frequency by using the proposed device. After specified number of cycles, the actuator is switched off and snap back test is carried out. Similar methodology is carried out to study the long term performance for different types of foundations, see Bhattacharya et al (2012), Bhattacharya et al (2013). Figures 11 and 12 plots the result where 1N force was applied at a frequency of 10Hz. As mentioned, the change in natural frequency and damping is estimated after a certain number of cycles by free decay tests until 100,000 cycles are completed.

Figure 6: Force resultants in X and Y axes when the masses are equal (top) and not (bottom)

Figures 11 and 12 present the change in the frequency and damping with the number of cycles, respectively. As expected, both types of foundation exhibited an increase in natural frequency (f_n) and a decrease in damping (γ_n) with cycles of loading. Under cyclic loading, the medium dense sand densified which increased the foundation stiffness and ultimately the natural frequency. This is consistent with the results on monopile foundations, see Bhattacharya and Adkikari (2011) and also limited field observation. Further discussions on the test results are beyond the scope of this technical note.

6. Discussion and conclusions

In this paper, a new cyclic loading device is developed that has the capability to simulate many complex loading in a scaled model including the application of millions of cycles of load and the wind-wave misalignment. This loading device is economical, simple to use and scalable and therefore models of different scales can be tested. Foundations typically cost 25 to 35% of an overall offshore wind farm project and in order to reduce the LCOE (Levelised Cost of Energy) new innovative foundations are being proposed. However, before any new type of foundation can actually be used in a project, a thorough technology review is often carried out to de-risk it. European Commission defines this through TRL (Technology Readiness Level) numbering starting from 1 to 9, see Table 1 for different stages of the process. One of the early work that needs to be carried out is technology validation in the laboratory environment (TRL 4). In this context of foundations, it would mean carrying out tests to verify the long term performance. It must be realised that it is very expensive and operationally

challenging to validate in a relevant environment and therefore laboratory based evaluation has to be robust so as to justify the next stages of investment.

Table 1: Definition of TRL

TRL Level as European Commission
TRL -1: Basic principles verified
TRL-2: Technology concept formulated
TRL-3: Experimental proof of concept
TRL-4: Technology validated in lab
TRL-5 Technology validated in relevant environment
TRL-6: Technology demonstrated in relevant environment
TRL-7: System prototype demonstration in operational environment
TRL- 8: System complete and qualified
TRL -9: Actual system proven in operational environment

Figure 7: Configuration of two actuators to represent separately wind and wave loads, when these are acting along the same direction.

Figure 8: Configuration to study the wind-wave misalignment.

Figure 9: Test setup for the monopile foundation with all the instruments annotated

Fig.10: Test setup for the monopile (left) and twisted jacket (right) foundation with all the instruments annotated

Figure 11: Change in the natural frequency of the models with number of cycles

Figure 12: Change in ratio of critical damping of the models with number of cycles

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