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Effect of loading conditions on the natural frequency of offshore wind turbines using centrifuge model test

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ABSTRACT: The vibration-based scour monitoring has received significant attention recently in Structural Health Monitoring (SHM). Specifically, natural frequency monitoring techniques for the Offshore Wind Turbines (OWTs) had successful application at European wind farm sites. However, it has been shown that the variation of natural frequency was influenced by factors other than scour, such as environmental conditions. To address this, we carried out centrifuge model tests on a reduced-scale 4.2 MW OWT model subjected to different loading conditions. For realistic application of the dynamic loading, the voltage signals were generated and sent to the piezoelectric actuator via amplifier to produce forced vibration loading. The time-series of the acceleration response were recorded at different heights. Then, the natural frequency of the system was identified using the SSI-COV algorithm. The results of this study confirmed that the natural frequency of the OWT could be obtained from vibrations measured during centrifuge testing using piezoelectric actuators and accelerometers. Furthermore, this approach suggests the potential to predict scour through observed changes in the natural frequency by incorporating soil–structure interaction.

Keywords: natural frequency; offshore wind turbine; piezoelectric actuator; tripod bucket foundation

1 INTRODUCTION

For all bottom-founded offshore structures, erosion is inevitable. Deploying scuba divers to measure scour depth beneath an offshore wind turbine (OWT) is the standard method used to assess its structural health. However, conventional method can be costly and require scheduled intervention.

Recently, the use of sensors, such as accelerometers, to monitor the dynamic properties of offshore structures has been gaining attention as a means to address this issue. In principle, changes in modal properties can be correlated with structural integrity degradation, indicating whether Operation & Maintenance (O&M) is necessary.

Previous studies have emphasized the sensitivity of natural frequency to various factors, such as foundation stiffness and environmental conditions. For instance, Prendergast et al. (2015) demonstrated that the natural frequency of an OWT was strongly dependent on scour depth. It was also reported that after three months of installation, a reduction in natural frequency was observed for the Hornsea Met Mast, suggesting the effect of scour on natural frequency (Bhattacharya, 2019).

Moreover, Weijtjens et al. (2016) carried out a full-scale case study on 3-MW Vestas V90 turbines and found a drop in natural frequency due to scour for both monopile- and tripod-supported structures. They argued that the variability of the natural frequency was correlated with environmental and operational conditions, such as tidal level, wind speed, and yaw angle. Cheynet et al. (2017) and Daraemaeker et al. (2008) noted that changes in modal frequency can be obscured by environmental factors, such as temperature.

The foundation system has important implications for the dynamic behaviour of an OWT. Skau et al. (2018) highlighted the importance of the foundation in the overall dynamic behaviour of the OWT system, noting that the natural frequency was significantly correlated with the relative foundation-to-tower stiffness. Recently, Arany et al. (2016) and Jalbi and Bhattacharya (2018) also provided insights into estimating the natural frequency considering SSI effects. More recently, Suryasentana et al. (2022) emphasized the importance of the dynamic characteristics of suction bucket foundations for wind turbine applications.

Substantial evidence indicates that variations in natural frequency can serve as an indicator for the structural health monitoring of OWTs. To verify this applicability, the present study examined the effect of loading on the natural frequency of OWTs by conducting centrifuge model tests.

The objectives of this study are as follows. First, a piezoelectric actuator was developed to reliably reproduce dynamic loading conditions in the centrifuge experiments. Next, the process for obtaining the natural frequency from measured acceleration responses was verified. Finally, the effect of different vibration loading conditions on the OWT's natural frequency was examined. Ultimately, this study evaluated the potential of using the developed OWT model to investigate the effects of scour with soil-structure interaction of OWTs through a series of centrifuge experiments at KAIST.

2 TEST PROGRAM

A series of 70-g centrifuge model tests in silica sand were carried out at the KOCED Geotechnical Centrifuge Center at KAIST. Details of the testing facility were reported by Kim et al. (2013). The purpose of these tests was not only to investigate the effects of loading conditions but also to verify the performance of the developed piezo-actuator. A reduced-scale offshore wind turbine model with a tripod bucket foundation was manufactured using actual design drawings and the structural calculation report provided by KEPCO. The relative density of the silica sand was varied from loose to dense by adjusting the control parameters of the automatic sand pluviator at KAIST. Table 1 shows the scale laws connecting the model and the prototype.

Table 1. Centrifuge scale laws (Bhattacharya, 2019)

Parameter	Model/Prototype	Units
Acceleration	N	g
Length	$1/N$	m
Mass	$1/N^3$	kg
Stress	1	Nm^{-2}
Strain	1	-
Time	$1/N$	s
Frequency	N	s^{-1}
Flexural rigidity	$1/N^4$	Nm^2

2.1 Details of the wind turbine and the site

The target OWT was a 4.2-MW model located in the Yellow Sea, off the coast of Gunsan Port in South Korea. Along with tripod suction bucket foundations, it was installed in 2020 by KEPCO to verify and demonstrate the novel installation process proposed by Ryu et al. (2022) using the All-In-One-Installation (A.I.O.I) and the Multi-Purpose Mobile Base (MMB). Further details can be found in Ryu et al. (2019).

The turbine was supported by a tripod substructure with suction bucket foundations measuring 8.0 m in diameter and 9.3 m in length, embedded in a stratified seabed consisting of three layers: an upper silty sand layer, a clay layer, and a lower sand layer. Soil properties at the site were described in a report by KAIST (2015).

The Meteorological and Oceanographic Special Research Unit (HeMOSU)-2 provided 10-minute averaged time series of wave, tidal elevation, and wind data. The water depth and the mean sea level (MSL) are approximately 8 m and 3.6 m, respectively. Perpendicular biaxial accelerometers were installed at three different heights along the tower—below the transition piece, at mid-tower, and below the main yaw bearing. Seo et al. (2020) conducted a comprehensive field monitoring campaign encompassing four constructions and testing phases of an offshore wind turbine system (OWCS) supported by tripod suction buckets, with particular emphasis on the final stage wherein the fully assembled structure exhibited a measured natural frequency of 0.318 Hz. Accelerometers installed on the transition piece recorded structural responses effectively excited by ambient wind and wave loads, as confirmed by spectral analysis revealing a clear peak corresponding to the natural frequency.

2.2 Test setup

The soil box, measuring 1.522 m × 0.772 m × 0.520 m (width × length × height), was fabricated by machining thick aluminum blocks. As shown in Fig. 1, all inner walls of the soil box were covered with a thin layer of duxseal to mitigate boundary effects by regulating vibrations at the enclosure's edges. Also, the OWT model was positioned at least twice the suction bucket foundation's diameter away from the walls to minimize boundary influences. The OWT model with a tripod bucket foundation was manufactured from stainless steel, accounting for mass density and uniform thickness of the actual structural components, as reported by KEPRI (2020). All structural components were joined by a laser welding method to minimize imperfections in roundness and thickness variations resulting from the manufacturing process.

Important tower properties—such as equivalent thickness, lateral stiffness, and cross-sectional area—were calculated following Bhattacharya (2019). The equivalent thickness of the tapered tower section was computed using a weighted average of the top and bottom diameters of all sections. The additional mass from paint and other structural elements was neglected for simplification.

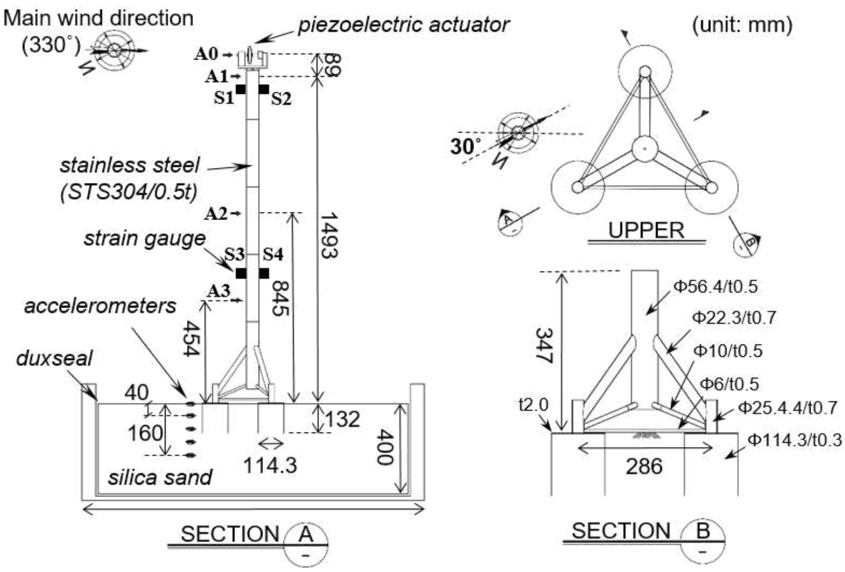

Figure 1. Geotechnical centrifuge test setup along with instrumentation plan and details of the tripod foundation model

2.3 Instrumentation

A row of uniaxial MEMS accelerometers was attached at several locations along the tower to measure the acceleration response. Considering the need for a high acceleration range and low noise with a wide bandwidth, analog output ADXL1003 series accelerometers were selected, following Kariyawasam et al. (2020). These sensors have a maximum acceleration range of 200 g. The analog output type was chosen because digital sensors could introduce data transformation issues and memory storage limitations.

To apply dynamic loading, a piezoelectric actuator was developed based on the recommendations of Cabrera et al. (2012). In this study, the amplified piezoelectric actuator APA440MML (Cedrat, 2015) was utilized, as demonstrated by Futai et al. (2018). The piezoelectric actuator was connected to an amplifier, and a dynamic load cell was mounted on one end of the actuator, while the other end featured a rolling bearing fitted with an accelerometer. Voltage signals were generated using MATLAB and sent through a Data acquisition (DAQ) system connected to the amplifier to control the actuator's behaviour. The sampling rate was set to 19.2 kHz for all sensors. For forced vibration testing, a Gaussian-type sinusoidal pulse was generated using the *gauspuls* function in MATLAB (see Fig. 2).

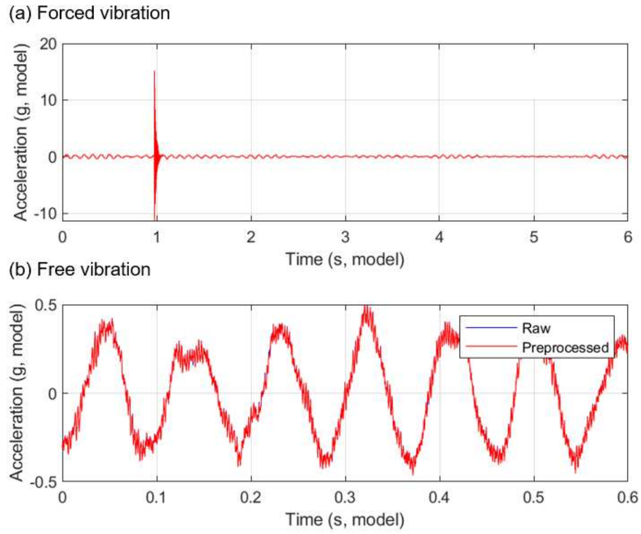

Figure 2. Example of a time-series acceleration signal (A0) for forced and free vibration at the model scale

2.4 Soil specimen and ground preparation

The ground model was prepared using silica sand, which has been widely used in various centrifuge testing centers worldwide for test repeatability. The grain size distribution and the geotechnical properties are summarized in Figure 3 and Table 2, respectively. The grain size distribution of the Saemangeum sand and the silty sand in the Southwest Sea (KEPRI, 2016) was also shown for a direct comparison. It was shown that the silica sand was similar compared with the sample obtained from the site (KOWP, 2021). The soil used in this study was a uniform silica sand, characterized by a relative density of approximately 73%, with key geotechnical parameter such as unit weight of 15.67 kN/m^3, aligned with dense sand conditions of typical offshore seabed environment.

Table 2. Index properties of silica sand used in this study

Item	Silica Sand
Unified soil classification USCS	SP
Specific gravity (-)	2.65
Max. dry density (kN/m^3)	17.17
Min. dry density (kN/m^3)	12.65
Mean grain size d_{50} (mm)	0.21
Coefficient of curvature	0.70
Uniformity coefficient	2.04

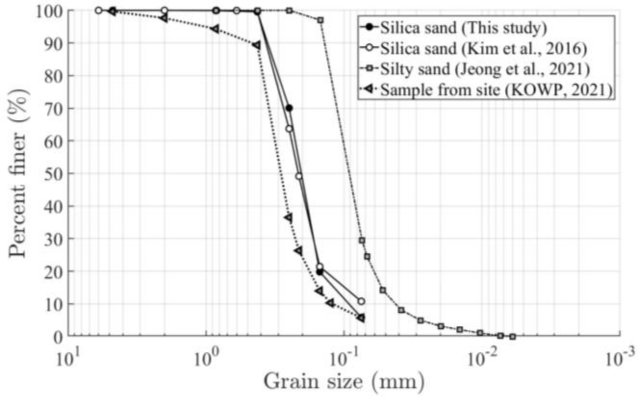

Figure 3. Grain size distribution curve for the silica sand used, along with curve from soil sample from the offshore field site for comparison

The model ground was prepared using an automatic pluviation apparatus in the KOCED geotechnical centrifuge testing center at KAIST. To achieve uniform and homogeneous ground conditions, the pluviator's control parameters were varied. Because the diffuser tank speed, drop height, and opening size all influence the soil layer's density, a series of pluviation tests was conducted to verify the apparatus's performance. Optimal control parameters were determined through a systematic trial-and-error approach by varying pluviation parameters, specifically nozzle size (3.0–6.0 mm), height (90.6–146.2 cm), and speed (30%–100%). The change in poured sand height was measured with a laser sensor during each pluviation, and the drop height was adjusted accordingly. To achieve a target relative density of approximately 73%, the pluviation parameters were set as follows: a nozzle size of 3.0 mm, a drop height of 146.2 cm, and a hopper velocity of 30%. The outcomes of multiple pluviation trials demonstrated that this particular combination of nozzle aperture, drop height, and hopper velocity yielded a consistent and uniform soil density.

2.5 Identification of the natural frequency

The SSI-COV (Stochastic Subspace Identification with Covariance) method was used to identify the natural frequency with stabilization diagrams. The approach to determining the OWT's modal properties was inspired by Devriendt et al. (2014) and Bel-Hadj et al. (2024). The MATLAB code used in this study was adopted from Cheynet (2020). In 2017, data from a suspension bridge confirmed the accuracy of this algorithm in visualizing the evolution of natural frequencies with temperature (Cheynet et al., 2017). The discrete form is represented as follows (Magalhães et al., 2009):

$$x_{k+1} = Ax_k + w_k$$
$$y_k = Cx_k + v_k \tag{1}$$

where x_k is the state vector at time k, y_k is the sampled output vector, A is state matrix, and C is output matrix, w_k and v_k are vectors representing white noise due to disturbances and inaccuracy.

The SSI-COV method analyses the time-series of the measured response with the covariance matrices defined by (2):

$$R_i = \frac{1}{N-i}\sum_{k=0}^{N-i-1} y_{k+1} \cdot y_k^T \tag{2}$$

where N is the number of points in the time-series response, and T denotes the transpose operation.

Figure 4 provides an example of applying the SSI-COV algorithm to a 5-second signal window. Automatic identification of the natural frequency was performed using real poles in the first mode range.

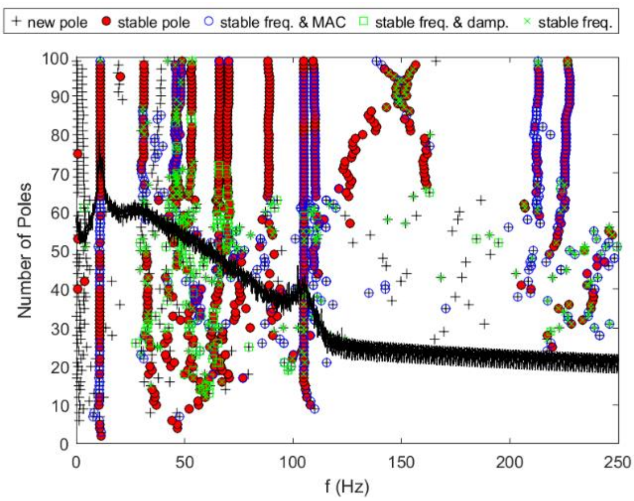

Figure 4. Example of automatic modal parameter identification using the SSI-COV method (model scale)

3 RESULT

3.1 Effect of Loading

A total monitoring duration of 800 s was used in this study. Each measurement corresponds to the result of the SSI-COV algorithm applied to one time-series window. An example of the applied vibration signals was shown in Fig. 2 of Sec. 2. Figure 5 illustrates the minor differences in frequency behaviour between Forced and Free Vibration conditions across the sample window. The window duration was set to 5.0 s, determined by trial-and-error method. The measured natural frequency ranged from 9 Hz to 12 Hz, with values clustered in the range between 10.5 Hz and 11 Hz for both Forced and Free Vibration conditions.

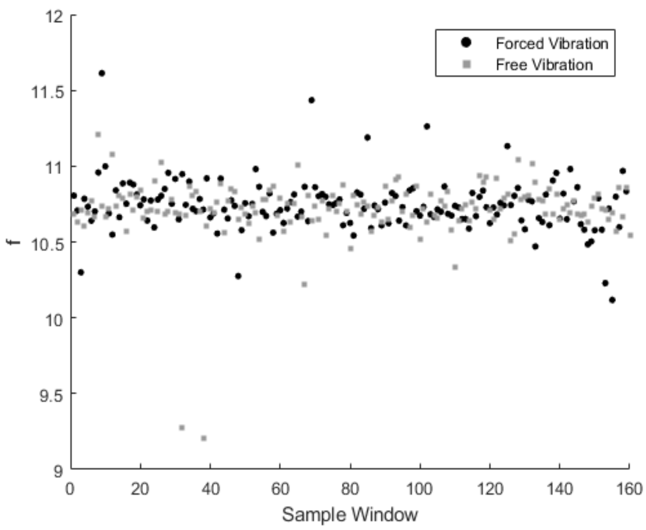

Figure 5. Tracked natural frequency values for both forced and free vibration tests

4 CONCLUSION

The vibration-based monitoring technique was applied in a geotechnical centrifuge test to a model referencing an actual 4.2-MW offshore wind turbine supported by tripod suction bucket foundations installed in Gunsan, South Korea. To apply vibration loading, a piezoelectric actuator was developed to generate dynamic loading in the centrifuge setting by controlling voltage signals with an amplifier. Acceleration response time series recorded at different locations were used to obtain the system's modal parameters using the SSI-COV algorithm.

The main outcome of this study can be summarized as follows:

- Despite moderate data variability, the results indicated that the natural frequency remained relatively stable under both forced and free vibration conditions, confirming the reliability of using acceleration time-series signals in centrifuge testing to determine the natural frequency. Moreover, this finding suggests the potential to further investigate the effects of scour by incorporating soil–structure interaction in future analyses.
- The SSI-COV algorithm was successfully implemented to determine the natural frequency values from a series of acceleration time-series measurements. The reliable extraction of natural frequency data using the SSI-COV algorithm established a strong foundation for further studies.
- The performance of the developed piezoelectric actuator was validated by adjusting its input voltage and frequency range to achieve controlled vibrations under in-flight centrifuge conditions at a 70 g-level.

AUTHOR CONTRIBUTION STATEMENT

Kyeong-Sun Kim: Conceptualization, Software, Formal Analysis, Writing- Original Draft, **Jun-Woo Kim**: Data Curation, Methodology **Seung-Won Oh**: Methodology, Writing- Reviewing and Editing, **Sung-Ryul Kim**: Supervision, Funding Acquisition, Writing- Reviewing and Editing

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