Evaluation of wind turbine natural frequency considering SFSI

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ABSTRACT: Understanding of dynamic response of large sized wind turbine structure is important to evade structural hazards by dynamic loading. Especially predicting natural frequency of structure is important to evade resonance vibration. Although natural frequency of structure is largely affected by Soil-foundation-structure interaction (SFSI), consideration of nonlinear SFSI in dynamic behavior of wind turbine is still a challenging subject for conventional analytical methods. Geotechnical centrifuge experiment can provide reliable scaled model test result to supplement and calibrate the analytic methods as it can reproduce field stress condition of soil in scaled model condition. This research is focused on evaluating natural frequency of wind turbine for monopile and monopod type foundations considering SFSI by using geotechnical centrifuge test.

1 INTRODUCTION

The size and capacity of wind turbine has been drastically increased since it was first introduced. This tendency is expected to keep on course as larger wind turbine has higher generation efficiency. As size and cost for single turbine increased, precise evaluation of wind turbine's dynamic behavior becomes important issue.

Wind turbine is sensitive against vibration due to its long, slender, and light-weighted structural characteristics. Especially resonance vibration could reduce the efficiency of generation, even cause structural damage in extreme case. Estimation of precise natural frequency of wind turbine could enables to design wind turbine to avoid resonate with dynamic loadings in targeted installation location. Especially for the offshore wind turbine which is exposed to dynamic loadings with varying frequencies.

Effect of earthquake to wind turbine is also an important issue as wind turbine's installation locations are extended to possible earthquake activity locations (Kourkoulis et al. 2014).

It is important to consider the effect of soil-foundation-structure interaction (SFSI) when evaluating dynamic properties of wind turbine such as natural frequency. But conventional analytical methods are focused mainly on structural aspect, considering foundation condition as fixed-based (van der Tempel & Molenaar, 2002) or simplified mass-spring-damper model as complex nonlinear SFSI is difficult to model. Experimental approach is needed to supplement and calibrate analytical result in well described condition of SFSI. As centrifuge can replicate field stress condition in model scale, it can produce reliable experimental result while easy to repeat compared to actual full scale experiment.

This research aims to evaluate natural frequency of wind turbine in consideration of SFSI. Research was done by using NREL 5 MW reference wind turbine with monopile, and monopod type foundations as target structure. Scaled models for wind turbine, monopile foundation, and monopod foundation were produced for this research. Natural frequency of scaled model was evaluated in fixed-based condition and SFSI condition by using geotechnical centrifuge test. Results were compared each other to observe effect of SFSI toward natural frequency of wind turbine in different foundation types. Also, change of wind turbine's natural frequency due to earthquake loading was evaluated for various strength of earthquake loadings. Natural frequency of wind turbine was evaluated before, during, and after earthquake loadings to observe changes in dynamic property due to the earthquake.

2 MODEL PRODUCTION

2.1 *Wind tower modeling*

NREL 5 MW reference wind turbine was used as target structure (Jonkman et al. 2009). Due to the limitation of the size of the centrifuge model, scaled model was produced using 1/4 scale target structure as prototype. Prototype was simplified into a model of lumped mass on hollow cylindrical shape tower, then reduced into scaled model following centrifuge scaling law as shown in Table 1.

Table 1. Centrifuge scaling law

Parameter	Scaling factor
Mass	$1/N^3$
Length	1/N
Velocity	1
Acceleration	N
Time	1/N
Frequency	N

Figure 1 shows steps for delivering scaled model. Tower is 50 cm height, 3.6 cm diameter, and 0.3 cm wall thickness. Lumped mass is 6 cm height, 5cm diameter cylindrical shape block. Total mass of model is 2.3 kg, composed of 1.2 kg tower mass and 1.1 kg lumped mass. The scaled model represents 1/4 scale NREL 5 MW offshore wind turbine when converted to prototype from 43.8 g centrifuge experiment.

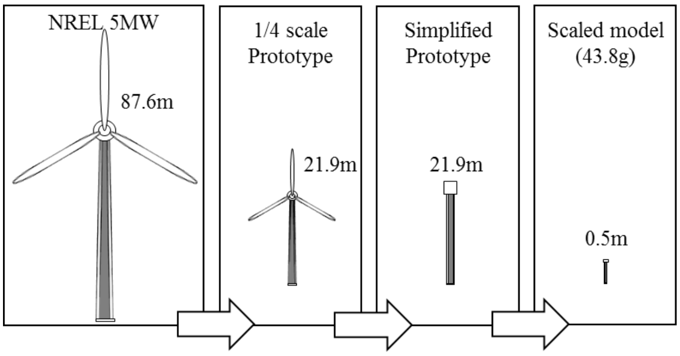


Figure 1. Scaled modeling procedure

2.2 *Foundation model*

Monopile model was produced by using NREL 5 MW class monopile as target model (Jonkman et al. 2008). Scaled model was produced using 1/4 scale target model as prototype to match with scaled model of wind tower.

Bucket part of monopod foundation was produced by referring Dong energy's 5MW bucket foundation with 16m diameter and 15m length. Monopile and monopod's substructures were designed to have same height and weight. For this, portion of monopile substructure was designed hollow with 0.15 cm wall thickness.

Fixed-based substructures were produced by using monopile and monopod foundation's substructure (above ground part) as target model. These models were designed to be bolted on an aluminum base plate to reproduce fixed-based condition of wind turbine, and they were used in evaluating wind turbine's natural frequency without considering SFSI as a comparison group. Details of substructure models are described in Figure 2.

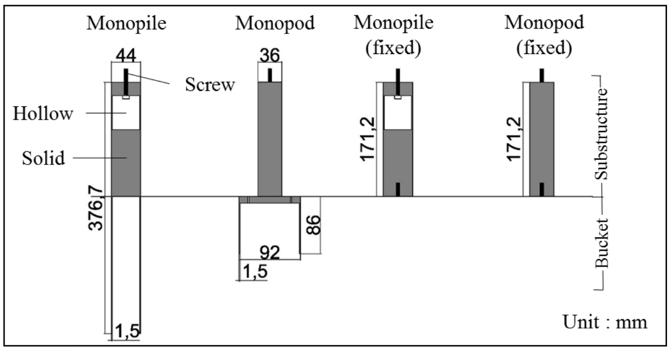


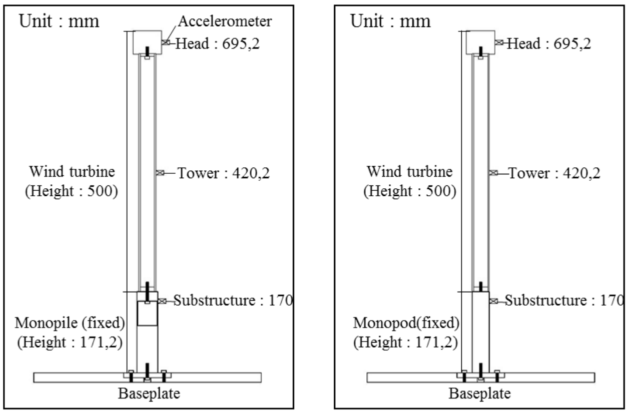
Figure 2. (a) Monopile and (b) monopod substructure model

3 EXPERIMENT PROCEDURES

3.1 *Fixed-based condition test*

1 g fixed-based condition test was conducted to evaluate wind turbine's natural frequency without considering SFSI. Produced wind turbine model was firmly connected onto fixed substructures by screw. To reproduce fixed-based condition, fixed substructures were bolted on aluminum base plate.

Natural frequency of fixed-based condition wind turbine was evaluated by fixed-free Impact hammer test. Base plate was locked firmly in the centrifuge main body to constraint oscillation, and impact was applied from the base plate. PCB model 353B17 Accelerometers were attached on the head, tower, and substructure of models to measure time-acceleration history as shown in Figure 3.



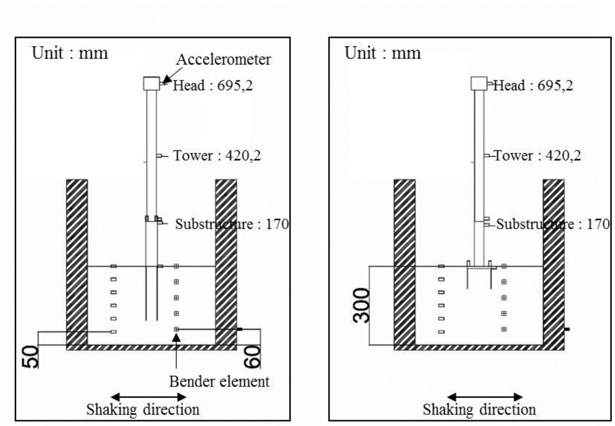
(a) Monopile fixed (b) Monopod fixed

Figure 3. Fixed-based condition test schematics

Obtained time-acceleration histories were converted into frequency-acceleration histories by using fast Fourier transformation (FFT). Natural frequency was evaluated by picking highest point in frequency-acceleration history which was measured by accelerometer attached on the head of the wind turbine.

3.2 *SFSI condition test*

SFSI condition centrifuge tests with monopile and monopod foundation were conducted in 43.8 g acceleration field to Evaluate natural frequency considering SFSI and change of natural frequency through different dynamic loading strength.



(a) Monopile SFSI (b) Monopod SFSI

Figure 4. SFSI condition test schematics

To produce SFSI condition, 30 cm silica soil layer with relative density of 85 % was produced by using sand raining. Density of produced silica soil layer was 1530 kg/m^3. Model was embedded into soil layer by hammering.

Accelerometers were installed in each 5 cm depth of soil layer to evaluate ground acceleration. 5 sets of T226-A4-X and Y bender elements from Piezo systems were installed in each 6cm depth of soil layer to measure shear wave velocity. Bender elements were fixed in parallel aluminum bars (Kim & Kim, 2010). Tip to tip distance of bender elements were 15cm. Obtained shear wave velocity profiles were used to calculate soil layer's Young's modulus using equation of $G_{max}=\rho V_s^2$ and $G_{max}=E/2(1+\nu)$. Accelerometers were also attached on the head and tower, and substructure of models to measure wind turbine's time response as shown in Figure 4.

Natural frequency of SFSI condition wind turbine was evaluated by using centrifuge-mounted shaking table (Kim et al. 2013). 3 types of dynamic loadings, 1) sweep signal, 20~300 Hz low-to-high frequency sweep signal, 2) reverse sweep signal, 300~20 Hz high-to-low frequency sweep signal, and 3) Hachinohe signal, actual earthquake time history (Fig. 5) were applied.

Each signals, which were generated by shaking table, were applied from the bottom of the model box. Time and frequency history of input signals shown in Figure 5 were measured from the bottom of the model box.

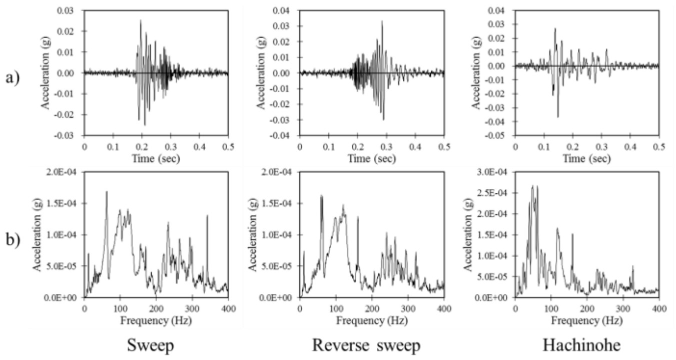


Figure 5. (a) Time, (b) frequency history of input signal

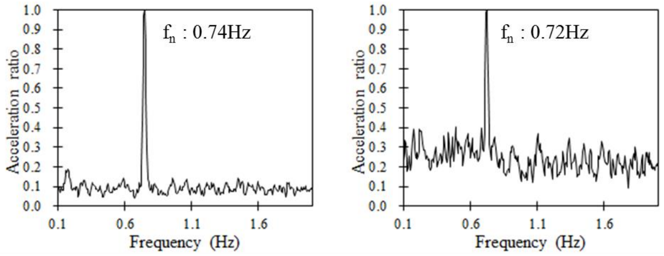
Time-acceleration histories of wind turbine were obtained by accelerometer which was attached on the head of the wind turbine. Signals were converted into frequency-acceleration history by FFT. Natural frequency was evaluated by averaging natural frequency evaluation result from 3 input signals.

To evaluate changes in dynamic property of wind turbine in different loading strength, 9 case of Hachinohe earthquake signals ranged from 0.03 g to 0.24 g in prototype scale were applied. During earthquake loadings were applied, time-acceleration histories were measured from wind turbine and soil layer. Natural frequency was evaluated before, during, and after earthquake loadings to measure changes in natural frequency of wind turbine due to the earthquake.

4 TEST RESULTS

4.1 *Fixed-based condition test*

Natural frequency was evaluated in fixed-based condition by doing FFT to time-acceleration history which was obtained from accelerometer attached on the head of the wind turbine. Scaled model, which is 1/43.8 physical model of prototype, showed clear peak point which could be considered as natural frequency of wind turbine with fixed–based substructure as shown in Figure 6. Results were converted into prototype scales by using centrifuge scaling law, and acceleration strength was normalized by peak ratio (peak point as 1).



(a) Monopile fixed (b) Monopod fixed

Figure 6. Fixed-based condition natural frequency

4.2 *SFSI condition test*

Soil characteristics, natural frequency, and earthquake behaviors were evaluated in SFSI condition monopile and monopod test which was done in 43.8 g acceleration field.

Figure 7 shows bender element test result in monopod SFSI test. Shear wave velocity profile through depth was acquired by using 3000 Hz sin wave applied by bender elements. Results were converted into prototype scale. Table 2 shows Young's modulus of soil layer calculated through depth by using shear wave velocity profile which was obtained from monopod SFSI condition test. Density of soil layer was 1530 kg/m^3, and Poisson's ratio was assumed as 0.25. This result could be used in calculating foundation stiffness in further theoretical study.

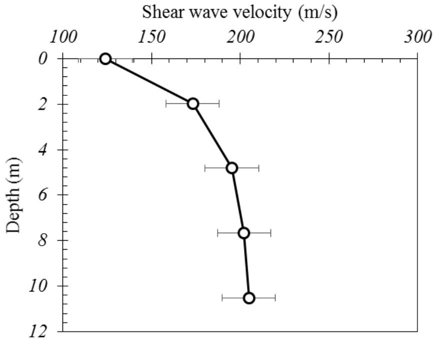


Figure 7. Shear wave velocity profile

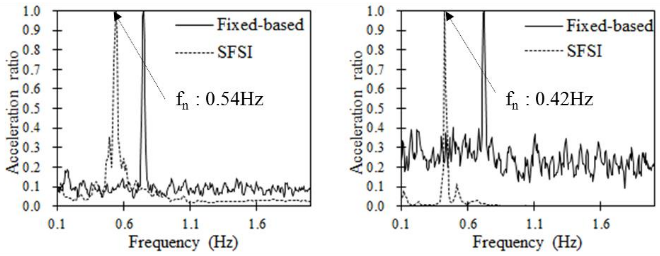
Table 2. Vs and E value for Bender elements.

Name	Depth	Shear wave velocity	Young's modulus
	m	m/s	MPa
BE1	0	123	58.8
BE2	2.0	173	114.8
BE3	4.8	195	145.9
BE4	7.7	202	156.3
BE5	10.5	205	160.6

Figure 8 shows comparison between natural frequency evaluated in fixed-based condition by using impact test, and natural frequency evaluated in SFSI condition by using sweep signal. Both results were evaluated by using time response from accelerometer attached on the head of wind turbine. Results were described in prototype scale, and acceleration strengths were normalized by peak ratio.

The result showed apparent natural frequency reduction in SFSI condition compared to the result of fixed-based condition. In monopile SFSI condition, natural frequency was decreased to 0.54 Hz, which is 27 % decrease compared with that of fixed-based condition. In monopod SFSI condition, natural frequency was decreased to 0.42 Hz, which is 42 % decrease compared with that of fixed-based condition. Results were described in prototype scale.

The result implies that monopile foundation could provide stiffer base condition against dynamic loading compared to monopod foundation.



(a) Monopile (b) Monopod

Figure 8. Natural frequency comparison

In SFSI condition centrifuge test, natural frequency was evaluated before, during, and after earthquake loading were applied. During earthquake loadings, monopile showed more apparent decrease in natural frequency. Natural frequency of wind turbine with monopile foundation was decreased from 0.54 Hz to 0.42 Hz, about 22 % in strongest earthquake. And natural frequency of wind turbine with monopod foundation was reduced from 0.42 Hz to 0.36 Hz, about 14 % in strongest earthquake as shown in Figure 9. Results were described in prototype scale.

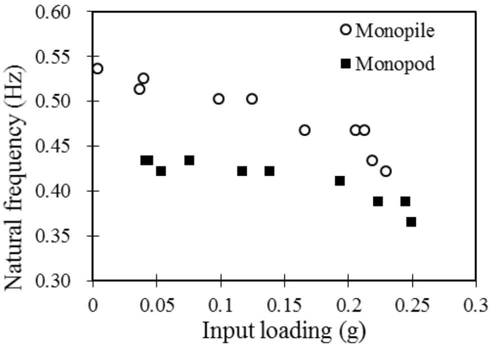
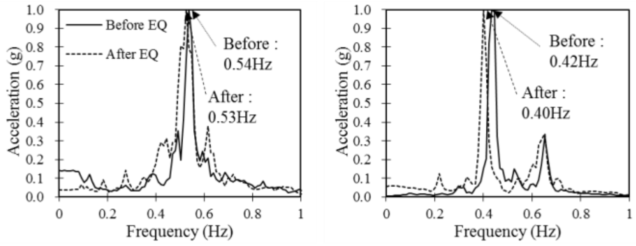


Figure 9. Natural frequency change during earthquake

Figure 10 shows natural frequency measured by using sweep signal before and after earthquakes. Natural frequency of monopile was restored to 0.53 Hz, which showed 2 % permanent decrease, and natural frequency of monopod was restored to 0.40 Hz, which showed 5 % permanent decrease. Results were described in prototype scale.



(a) Monopile (b) Monopod

Figure 10. Natural frequency before and after earthquakes

5 CONCLUSION

The objective of this research is to evaluate natural frequency of wind turbine in consideration of SFSI, and effect of earthquake to natural frequency of wind turbine. To achieve this objective, scaled model of NREL 5 MW reference wind turbine, monopile foundation, and monopod foundation was produced.

Natural frequency was evaluated in Fixed-based condition and SFSI condition, then both were compared with each other to observe the effect of SFSI to natural frequency of wind turbine for different foundation types.

Temporary and permanent change of natural frequency was evaluated before, during, and after series of earthquake loadings to evaluate nonlinear changes in dynamic properties by earthquake.

Natural frequency comparison between fixed-based, and SFSI condition wind turbine showed apparent reduction of natural frequency in SFSI condition compared to fixed-based condition. Also, monopile showed stiffer characteristics then monopod when considering SFSI.

Natural frequency was changed through different earthquake loading strengths, and permanent changes in natural frequency was occurred after earthquake. Monopile and monopod showed different nonlinear changes in natural frequency. It is interesting that monopile showed larger natural frequency reduction compared to monopod during earthquake, but showed smaller permanent natural frequency reduction after the earthquake.

These results showed potential of studying wind turbine's dynamic behavior in consideration of SFSI. Further studies are needed to provide actual parametric results which could be used in predicting precise dynamic behavior of wind turbine.

6 ACKNOWLEDGEMENTS

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