Load Estimation and Wind Measurement Considering Full Scale Floater Motion

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Introduction

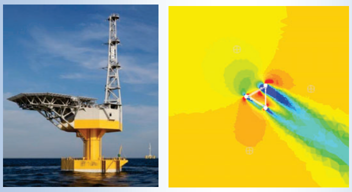
Many researches have been carried out for characteristics of the floater motion and the tower loading of the floating offshore wind turbines by using numerical simulation. Few studies discusses these issues by using full-scale measurement data. This study investigates the floater motion and tower loading characteristics by using full scale measurement data obtained at Fukushima FOWARD project.

First, floater motion measurement and tower loading measurement is discussed. Then the effect of wind speed and wave height on the tower loading is investigated. Finally, the cause of tower base moment for parked and operating wind turbine is investigated.

Measurement data

Measurement data at floating substation and 2MW turbine on semi-sub floater of Fukushima FOWARD project were used.

Floating substation



Floating substation and flow around the tower

- The floating substations are equipped with anemometers and wave measurement devices.
- Measured wind speed is corrected by using CFD simulation to consider the effect of tower.
- 3 RTK-GPS sensors, 3-axis gyro and 3-axis accelerometers are also installed on the floating substation for the floater motion measurement.

2MW turbine on semi-sub floater

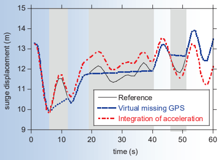
2MW wind turbine on semi-sub floater

- 1 RTK-GPS sensors, 3-axis gyro and 3-axis accelerometers are installed on the 2MW wind turbine on semi-sub floater.
- Tower moments at two different height are measured by using strain gauges.
- One year data (Jan. 2015 – Dec. 2015) are classified into operating case and parked case by using SCADA data.

Floater motion measurement

Transverse components

- Surge, sway and heave motion can be measured by using RTK-GPS sensors.
- However, RTK-GPS often fails to measure the data with RTK mode and continuous measurement is difficult.
- On the other hand, integration of the acceleration can also gives the transverse motion of the floater.
- However, integration of the acceleration causes large error, especially for low frequency component.



Comparison of floater motion in time domain

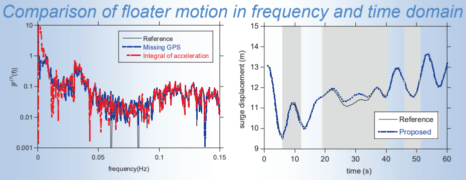
- To accurately measure the floater motion, missing GPS and integration of acceleration are combined in frequency domain.

$$F_{\mathrm{gps}}^{(j)}(f) = \mathcal{F}\left[x_{\mathrm{gps}}^{(j)}(t)\right], \qquad F_{\mathrm{acc}}^{(j)}(f) = \mathcal{F}\left[x_{\mathrm{acc}}^{(j)}(t)\right]$$

$$\Re\left[F_{\mathrm{p}}^{(j)}(f)\right] = g(f)\Re\left[F_{\mathrm{gps}}^{(j)}(f)\right] + [1-g(f)]\Re\left[F_{\mathrm{acc}}^{(j)}(f)\right]$$
$$\Im\left[F_{\mathrm{p}}^{(j)}(f)\right] = g(f)\Im\left[F_{\mathrm{gps}}^{(j)}(f)\right] + [1-g(f)]\Im\left[F_{\mathrm{acc}}^{(j)}(f)\right]$$

$$g(f) = \begin{cases} 1 & (f \le f_a) \\ \dfrac{f-f_b}{f_a-f_b} & (f_a < f \le f_b) \\ 0 & (f_b < f) \end{cases}$$
$$f_a = 0.02\mathrm{Hz}, f_b = 0.09\mathrm{Hz}$$

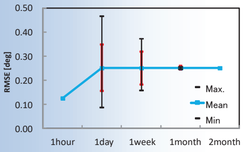
Comparison of floater motion in frequency and time domain



- Proposed method shows good agreement with reference value.

Rotation components

- Rotation components (pitch, roll and yaw) can be measured by using gyros.
- Zero-point has to be calibrated.



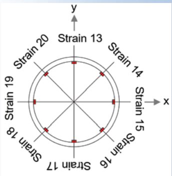
RMSE of mean pitch angle between gyro measurement and 3 GPS measurement

- Zero-point can be calibrated by using the average pitch angle of more than 1 month as zero-point.

Tower moment measurement

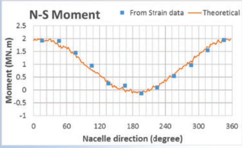
Strain gauge calibration

- 8 strain gauges are installed around the tower per one height.
- Nacelle rotation test is carried out, in which the yaw angle of the nacelle is changed from 0 to 360 degree, during calm (low wind and wave) condition.
- The calibration of the strain gauges are carried out by using the average value during nacelle rotation test.



Mean tower moment during nacelle rotation test

By using the floater motion (pitch and roll) data during nacelle rotation test, the static tower moment is calculated considering the CG of nacelle.



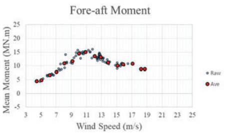
Tower base moment during nacelle rotation test

- The calculated moments show good agreement wit measurement.

Effect of wind and wave

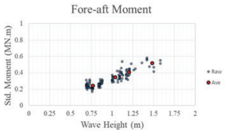
The effect of wind and wave on tower base moment is investigated.

- Mean tower base moment is only a function of wind speed and does not depend on wave characteristics.



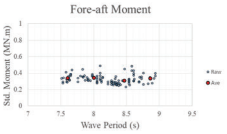
1.5m<Hs<2.0m, 7.5s<Tp<8.0s, 4%<Iref<8%, misalignment: 30deg. operating

- Standard deviation of tower base moment increases with wave height.



2.0m/s<U<4.0m/s, 7.0s<Tp<7.5s, 4%<Iref<8%, misalignment: 0deg. parked

- Standard deviation of tower base moment slightly decreases with wave period.



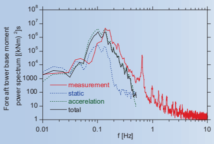
2.0m/s<U<4.0m/s, 1.0s<Hs<1.5s, 4%<Iref<8%, misalignment: 0deg. parked

The cause of tower base moment

Parked

For parked case, cause of tower base moment can be explained considering floater motion, i.e., the static (p-Δ) effect and dynamic (acceleration) effect.

$$M_{\mathrm{static}} = \sum_{k=i}^{n} m_k g \cdot x_k \qquad M_{\mathrm{dynamic}} = \sum_{k=i}^{n} m_k (h_k - h_i) a_k$$



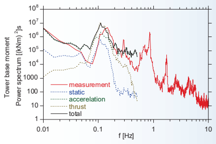
Power spectrum of the tower base moment for parked case

U=2.8m/s, I=10.9%, Hs=1.1m, Tp=7.0s, Misalignment: 147deg

- For parked case, static and dynamic effect of floater motion can explain the tower base moment.

Operating

For operating case, fluctuating thrust force from wind needs to be considered in addition to the floater motion effect.



Power spectrum of the tower base moment for operating case

U=9.9m/s, I=3.3%, Hs=1.3m, Tp=7.6s, Misalignment: 187deg

- For operating case, static and dynamic effect of floater motion, and fluctuating thrust force can explain the tower base moment.

Conclusions

1. A method to measure the transverse component of floater motion is proposed by combining the integrated acceleration and missing GPS data in frequency domain. Proposed method can accurately measure the floater motions.
2. The mean value of the tower base moment only depends on the wind speed while the fluctuating component depends on wind speed, wave height and wave period. The fluctuating component increases with the increase of wave height and slightly decreases with the increase of the wave period.
3. The fluctuating component of the tower base moment can be explained by considering the dynamic and static effect of floater motion for parked case. For operating case, fluctuating thrust force has to be considered in addition.