ESTIMATION OF FATIGUE LOAD ON FLOATING OFFSHORE WIND TURBINE AT TOWER BASE DURING POWER PRODUCTION

Danupon Subanapong[1], Atsushi Yamaguchi[2] and Takeshi Ishihara[2]

[1,2]Department of Civil Engineering, The University of Tokyo, 113-8656 Japan

Following results were obtained.

The measurement data of wind, wave and tower base moment at Fukushima Offshore site is investigated. Firstly, the analysis of full-scale measurement data is performed. Then, the Damage Equivalent Fatigue Load (DEFL) is calculated based on 1 year measurement data and used as the benchmark. The effect of direction of wind and wave, wave height and wave on fatigue load is discussed in this research. The methods to reduce number of wind and wave direction and wave height and wave period is proposed and then validated by the load calculated from measurement data.

Keywords: Damage Equivalent Fatigue Load, Wind and Wave Misalignment, Floating Offshore Wind Turbine

INTRODUCTION

For the fatigue design of offshore wind turbines, the joint probability distribution of wind speed, wave height and wave period has to be considered [1]. The combination of those parameters leads to large numbers of numerical simulations. In addition, the applicability of the approach for bottom mounted offshore wind turbine, to the floating offshore wind turbines (FOWT) are unknown.

Several studies have been carried out on the fatigue load analysis of floating offshore wind turbines wang et al. [2] studied the effect of wind and wave misalignment on the short-term fatigue damage. It is pointed out that the co-directional wind and wave gives relatively larger fatigue damage compared to other misalignment cases and it is conservative to use only co-directional condition. Roberson et al [3] concludes that to consider only the aligned wind and wave condition the side-side tower fatigue damage is underestimated by approximately 50%, and fore-aft tower fatigue is overpredicted for 5%. However, these studies only relied on simulation and there is no validation between simulation and full-scale measurement. Also, there is no conclusion on how to reduce number of computation. Therefore, a method to reduce number of considered wind and wave direction should be proposed.

Kvittem and Moan [4] pointed out the effect of wave period on fatigue damage. It is discussed that at the same wind speed and wave height condition, the smaller wave period gives larger fatigue damage. The reason is that smaller wave period causes higher frequency response which finally leads to larger number of cycle in fatigue calculation. However, this study only use simulation and there is no validation between simulation and full-scale measurement.

In this study, the effect of wind and wave misalignment is clarified and the method to reduce number of wind and wave considered in calculation is proposed. By using the tower base moment measurement data of Fukushima floating offshore wind turbines, 1-year damage equivalent fatigue load (DEFL) calculated based on proposed method is compared to the fatigue load calculated from 1-year measurement data. The effect of wave height and wave period is also discussed. The parametric study of wave height shows that the higher wave height is used, the larger fatigue damage while it is no clear tendency for wave period effect on fatigue load. Then, the method to reduce number of wave height and wave period is proposed and validated by measurement data. Finally, the combination of two proposed methods: to reduce number of wind and wave direction and to reduce number of wave height and wave period is used to compute 1-year DEFL and compared with measurement data.

ANALYSIS OF MEASUREMENT DATA

Environmental site condition

The measurement data was collected from 01/01/2015 to 12/31/2015. 10 minutes average wind speed, 10 minutes significant wave height and period, and tower base moment, and floater motion were used in this study. The number of 10 minutes data is showed in Table. 1. エラー! 参照元が見つかりません。 illustrates the wind rose and waver rose when wind turbine is in operation.

Table 1. Wind Turbine Status.

	No. of cases	Available
Operational	**34140**	**33731**
Parked	18429	15925
Total	52560	36022

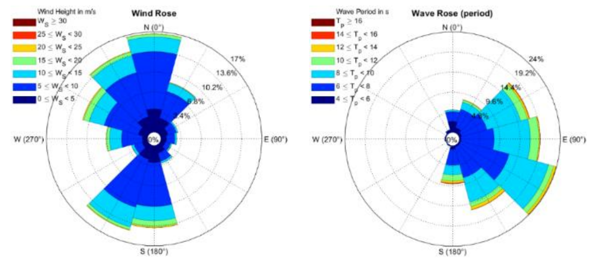


Fig. 1. Wind rose and wave rose during power production

The damage equivalent fatigue loads [5] are employed to calculate fatigue load in this study. The advantage of calculating the equivalent fatigue load instead of the regular fatigue value is that it reduces a long history of random fatigue loads into one number, which make it easier to compare different load situations. The equation for equivalent fatigue load is expressed as below.

$$DEFL = \sqrt[m]{\frac{\sum_i S_i^m n_i}{N_0}} \qquad (1)$$

where S_i is the stress range, n_i is the number of cycle in each range, N_i is the total cycle for the whole fatigue load period calculation and m is the fatigue exponential, for this case m=3 for welded steel, is used.

PROPOSED MODEL FOR WIND AND WAVE DIRECTION

Effect of wind and wave alignment on DEFL

To study the effect of wind and wave misalignment on fatigue load, the number of case for each wind and wave direction are analyzed. The same degree of misalignment is then grouped into the same color as shown in Table. 2. The damage equivalent fatigue (DEFL) for each degree of misalignment are compared in Fig. 2 for fore-aft direction and Fig. 3 for side-side direction. It can be seen that when the degree of misalignment is 0□ and 180□ the DEFL for fore-aft direction is maximum. However, there is no clear tendency for side-side moment.

Proposed method for the wind and wave direction

To reduce the number of wind and wave directions concerned for the fatigue load calculation, 4 of the most frequently occurred wind and wave direction are used: 0□, 180□, 210□, and 330□ for wind directions and 60□, 90□, 120□, 150□ for wave directions. The DEFL are calculated for each combination of wind and wave direction. The 1-year DEFL is computed by summarizing all fatigue load of each wind and wave direction by weighting the probability of their wind and wave direction. Then, the 1-year DEFL computed by proposed method is compared to the 1-year DEFL calculated from all 1-year measurement data and the conventional case (co-directional wind and wave condition) as shown in Fig. 4 and Fig. 5. It is found that the proposed method gives small underestimation about 10% for fore-aft direction and 15% for side-side direction which is acceptable while the conventional case gives relatively large overestimation about 25% for fore-aft and 20% for side-side direction. Therefore, it is concluded that this proposed method can be used to reduce number of wind and wave direction.

Table 2. Number of case for each direction

		Wind											
		0	30	60	90	120	150	180	210	240	270	300	330
Wave	0	169	28	0	0	0	0	0	0	1	135	688	761
	30	883	294	40	0	20	23	52	39	7	113	375	863
	60	1045	635	341	132	101	186	515	421	144	464	781	1043
	90	1231	691	300	272	144	194	865	744	167	375	629	831
	120	1358	539	208	430	227	341	1526	1475	163	246	495	996
	150	750	388	91	64	98	198	964	1207	233	396	428	544
	180	157	150	13	5	27	75	740	972	198	434	246	128
	210	0	0	0	0	0	0	12	11	15	39	6	0
	240	0	0	0	0	0	0	0	0	0	11	0	6
	270	0	0	0	0	0	0	0	0	1	67	11	1
	300	0	0	0	0	0	0	0	0	0	45	15	4
	330	4	0	0	0	0	0	0	0	0	60	107	64

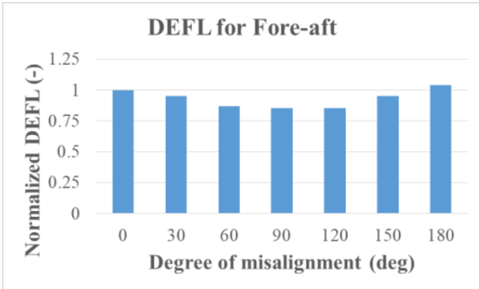


Fig. 2. Misalignment effect on DEFL for fore-aft direction

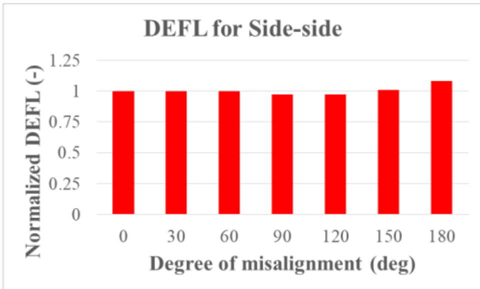


Fig. 3 Misalignment effect on DEFL for side-side direction

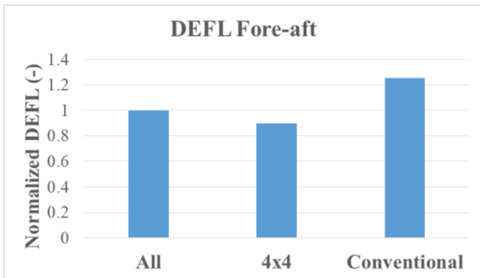


Fig. 4 1-year DEFL calculated by proposed method

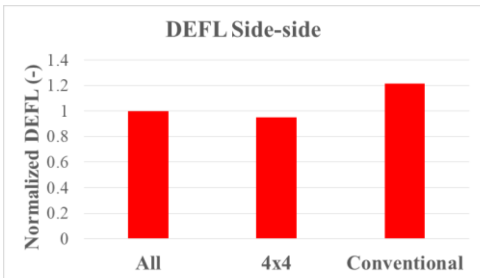


Fig. 5 1-year DEFL calculated by proposed method (side-side)

PROPOSED MODEL FOR WAVE PERIOD AND WAVE HEIGHT

Effect of wave height and wave period on DEFL

To study the effect of wave height and wave period, 210□ wind direction and 60□ wave period is selected. The probability distribution of wave height and wave period is shown in Fig. 6. The DEFL for fore-aft and side-side direction is shown in Fig. 7 and Fig. 8. Then, by comparing the DEFL for the same wave period and wind speed with different wave height the effect of wave height on fatigue load can be obtained. Fig. 9 shows the effect of the wave height on DEFL. Higher wave height causes larger fatigue load. The effect of wave period on DEFL is shown in Fig.10. As seen in Fig. 10, there is no clear tendency for the effect of wave period. Therefore, it is concluded that the effect of wave height on DEFL is important to be concerned.

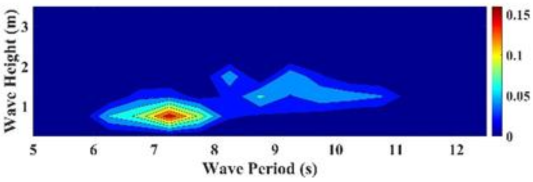


Fig. 6. Probability Distribution

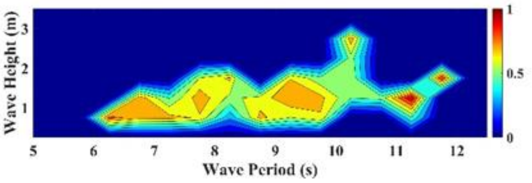


Fig. 7. Distribution of DEFL (Fore-aft)

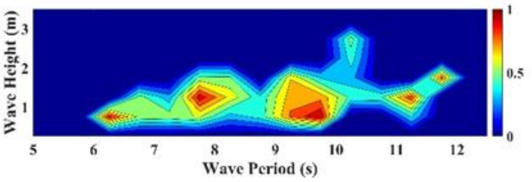


Fig.8. Distribution of DEFL (Side-side)

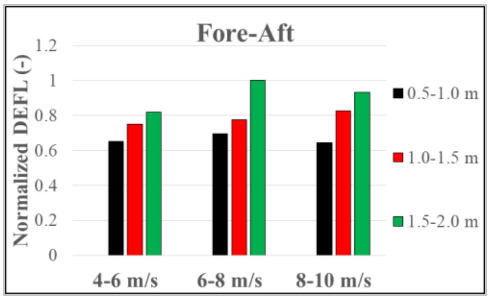


Fig. 9. Effect of wave height on DEFL

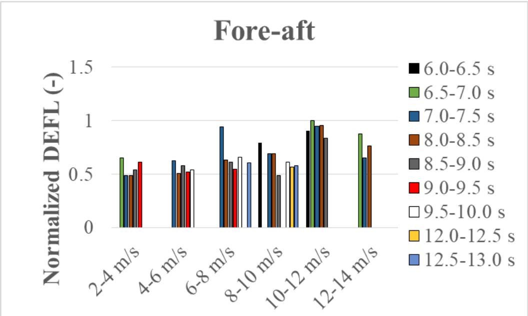


Fig. 10. Effect of wave period on DEFL

Proposed method for the wind and wave direction

As it is seen that the effect of wave height is important to be concerned. The 90 percentile of wave height is selected as the equivalent wave height. For the wave period, 25 percentile, 50 percentile, and 75 percentile of wave height are selected. To verify if this method is applicable, the DEFL at specific wind and wave direction is computed and compared with measurement data. Fig. 11 and Fig. 12 illustrate the comparison of DEFL calculated by proposed method and by using the all the measurement data in fore-aft and side-side direction. The total fatigue load is computed by summarizing DEFL of each wind speed bins by weighting the probability of their wind speeds as shown in Fig. 13. It is found that the proposed method gives very accurate prediction for both fore-aft and side-side direction. Therefore, it is concluded that the proposed method is applicable to reduced number of wave height and wave period considered in calculation.

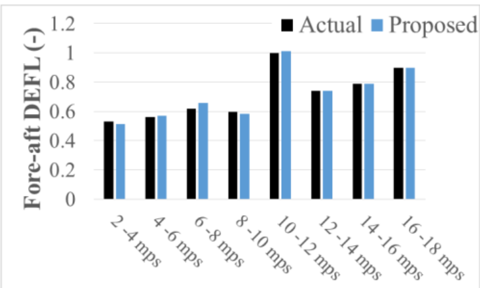
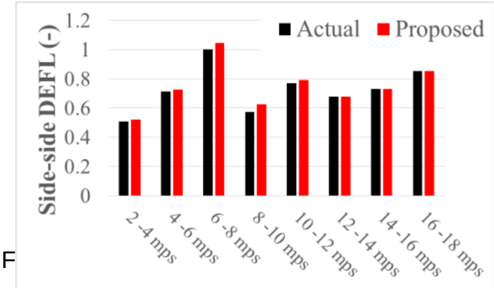


Fig. 6 DEFL of each wind speed (fore-aft)



F

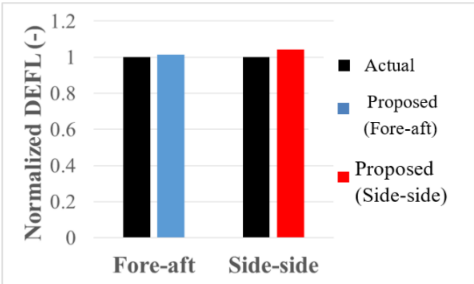


Fig. 8 Total fatigue load at specific wind/wave direction

OMBINATION OF PROPOSED METHOD FOR WIND AND WAVE DIRECTION AND WAVE HEIGHT AND WAVE PERIOD

The applicability of the combination of the proposed method for wind and wave direction, and the wave height and period, is investigated. Firstly, the wind and wave directions are selected as mentioned in the previous section: 0°, 180°, 210°, and 330° for wind directions and 60°, 90°, 120°, 150° for wave directions. Secondly, for the computation of the DEFL at each wind speed and wind and wave direction, 90 percentile of wave height is used while 25, 50 and 75 percentile of wave period are used. The total fatigue loads computed by the proposed method are compared to the load calculated from 1-year measurement data and the conventional method (co-direction of wind and wave direction) in Fig.11 and Fig.12. It is found that the conventional method gives relatively large overestimation compared to the proposed method for both fore-aft and side-side direction and the computed load by the proposed method is appropriate for the fatigue load prediction. Table.2 shows how the proposed method can significantly reduce the number of conditions required to calculate fatigue load.

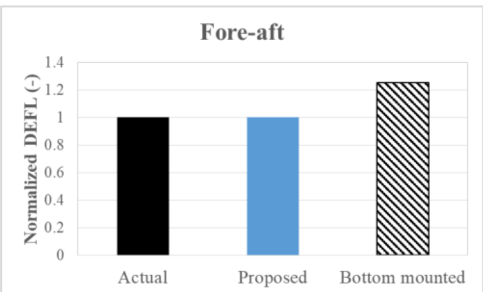


Fig. 9 Total fatigue load (fore-aft)

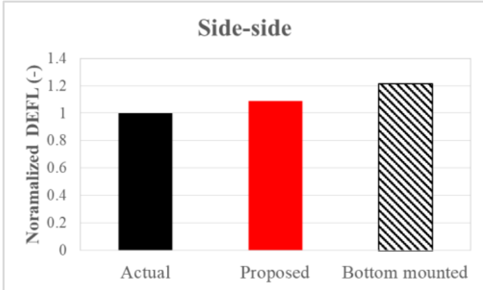


Fig. 10 Total fatigue load (side-side)

Table 3. The number of simulation cases

	Wind/wave direction	Wind speed	Wave height	Wave period	Total
All	144 (12x12)	12	6	7	7257
Conventional	12	12	6	7	6048
Propose	16 (4x4)	12	1	3	576

C

CONCLUSION

In this study, the 1 year measurement data of wind, wave and tower base moment at Fukushima Offshore site is investigated. Following results were obtained.

1) To reduce number of wind and wave direction, 4 most frequent wind directions and 4 most frequent wave directions are selected. The DEFL calculated based on 4x4 wind and wave direction gives around 10% underestimation for fore-aft direction, while it is about 5% underestimation for side-side direction.

2) To reduce number of wave height and wave period, 90 percentile of wave height with 25 , 50, 75 percentile of wave period are selected. The differences between actual DEFL and proposed method are 1.5 % and 4.2% for fore-aft and side-side direction.

3) The combination of two methods to reduce number of wind and wave direction and wave height and wave period gives accurate fatigue load calculation.

REFERENCES

[1] *IEC61400-3: Wind Turbine – Part3: Design requirements for offshore wind turbines*, 2009

[2] Wang, K., Ji, C., Xue, H. and Tang, W. (2016). Fatigue Damage Characteristics of a Semisubmersible-type Floating Offshore Wind Turbine at Tower Base. Journal of Renewable and Sustainable Energy.

[3] Robertson, A., Lackner, M., Matha, D. and Stewart, S. W. (2014). Wind/Wave Misalignment in the Loads Analysis of a Floating Offshore Wind Turbine. ResearchGate.

[4] Kvittem, M. I. and Moan, T. (2015). Time Domain Analysis Procedures for Fatigue Assessment of a Semi-submersible Wind Turbine. Marine Structures.

[5] H. B. Hendriks and B.H. Bulder (1995), Fatigue Equivalent Load Cycle Method. ECN-C-95-074