WAVE-INDUCED IMPACT ON MONOPILE-TYPE OFFSHORE WIND TURBINE RESPONSE

Hiroaki Kashima, Port and Airport Research Institute, kashima-h2w7@p.mpat.go.jp
Haruo Yoneyama, Port and Airport Research Institute, yoneyama@p.mpat.go.jp

INTRODUCTION

The offshore wind turbine industry has been actively working toward the goal of carbon neutrality by 2050. Technological advancements in large-scale fixed-bottom offshore wind turbines (OWTs) have significantly improved power generation and economic efficiency. However, the dynamic response characteristics of these turbines in coastal waters, especially in the presence of waves, remain largely unknown. In this study, we conducted a series of numerical simulations using a wind-wave load coupled analysis method to investigate the impact of waves on the dynamic response of a 15MW monopile-type OWT in wind and waves.

OUTLINE OF METHOD

We selected a 15 MW monopile-type OWT model [Gaertner et al., 2020], which was adopted for analysis code comparison and validation within the framework of the International Energy Agency Wind Technology Cooperation Program (IEA Wind TCP) as shown in Figure 1. This OWT model is a three-bladed upwind type with a variable-speed wind turbine featuring pitch control. Its operational wind speeds include cut-in at 3 m/s, rated at 10.6 m/s, and cut-out at 25 m/s. In our study, we assumed that the OWT model is situated in coastal waters at a water depth of 20 m. The analyses were conducted using OpenFAST, a time-domain solver developed by the National Renewable Energy Laboratory (NREL) in the U.S., which serves as a wind turbine load analysis code [NREL, 2021]. This code is a comprehensive coupled wind-wave-structure analysis code, encompassing aerodynamic analysis based on blade elementary momentum theory, hydrodynamic analysis employing the modified Morison equation, and structural analysis for both the wind turbine tower section based on the modal method and the monopile section based on the finite element method. It is important to note that, In the hydrodynamic analysis, wave breaking forces were not considered; only drag and inertia forces were considered to calculate wave forces. Therefore, our focus in this study was on understanding the impact of non-breaking waves on the dynamic response of the OWT. For our input data, we characterized fluctuating winds using a Kaimal spectrum (mean wind speed at the hub height ranging from 4 to 24 m/s, wind direction at 0 deg), and uni-directional irregular waves using a JONSWAP-type spectrum (wave height ranging from 2 to 8 m, period from 6 to 16 s, wave direction at 0 deg). The data was sampled at a frequency of 20 Hz, and the analysis spanned a period of 600 s.

RESULTS AND DISCUSSION

Figure 2 shows the relationship between the hub-height mean wind speed u_{mean} and the time-maximum bending moment M_{max} at three different altitudes: mudline (z = -20 m, represented in red, tower base (z = 15 m, represented in blue) and tower top (z = 144.5 m, represented in green).

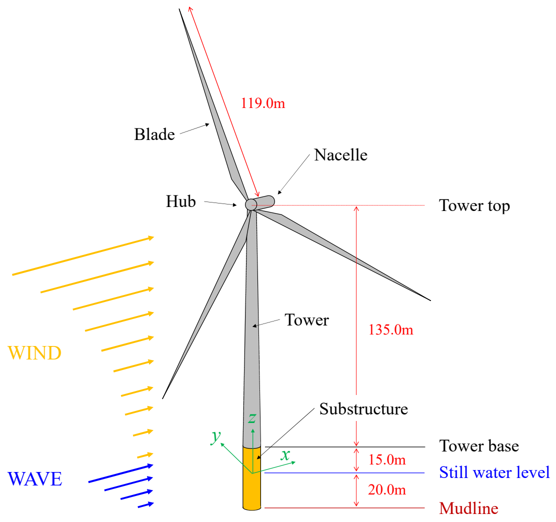


Figure 1 - Schematic view of the 15MW monopile-type OWT

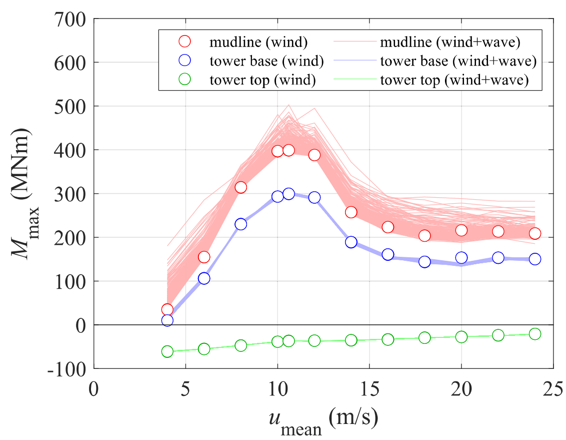


Figure 2 - Relationship between the hub-height mean wind speed and the bending moment at the three altitudes

The marks indicate the time-maximum bending moments under fluctuating wind loads only, and solid lines indicate the time-maximum bending moments under both fluctuating wind and wave loads. In the case of fluctuating wind loads only, the bending moment at the top of the tower is the largest at the cut-out wind speed, while at the mudline and the base of the tower, the bending moment increases with increasing wind speed, reaching a peak around the rated wind speed, and decreasing towards the cut-out wind speed. These results are consistent with previous study, such as that by Yamaguchi et al. [2014]. This is due to the difference in the source of the bending moment acting on the OWT. At the top of the tower, the predominant moment stems from the rotor surface of the OWT, remaining consistent in the vertical direction and

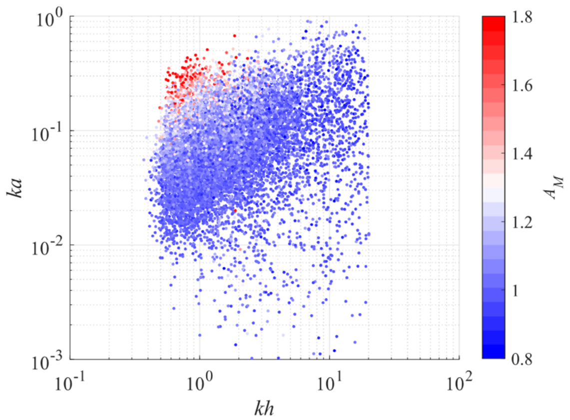


Figure 3 - Relationship between the wave steepness, relative water depth, and amplification ratio of bending moment due to wave loadings for the case of u_{mean} = 6 m/s.

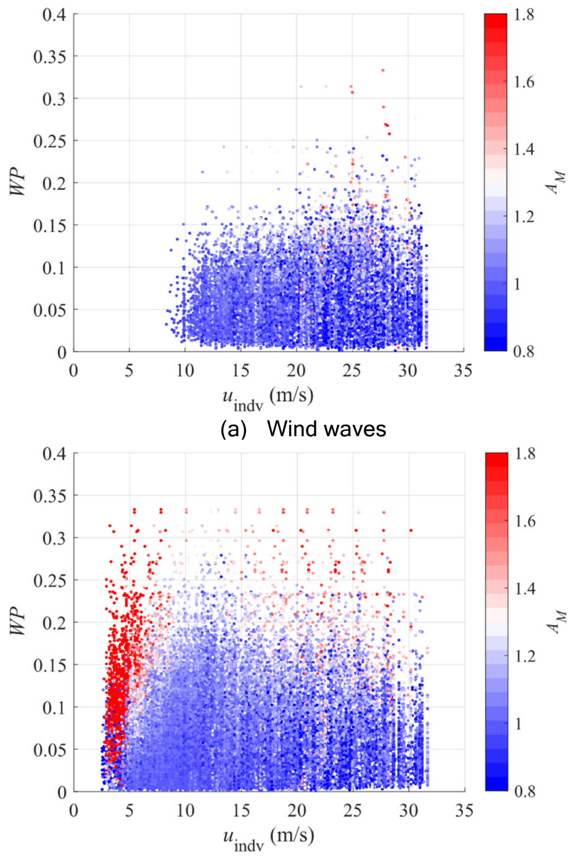
peaking at the cut-out wind speed. In contrast, at the tower's base and the mudline, the primary moment is generated by the thrust force acting on the OWT's rotor surface. This force increases towards the tower's base, reaching its maximum near the rated wind speed. Moreover, it can be seen that wave loading substantially enhances the bending moment at the mudline in comparison to the bending moment at the tower's base and top. Depending on the wind speed, the bending moments can be more than twice as large. Therefore, these results emphasize the significant influence of wave loading on the dynamic response characteristics of the OWT at the mudline.

Figure 3 shows the relationship between wave steepness *ka*, relative water depth *kh*, and the amplification ratio of bending moment due to wave loading A_M. A_M is defined as the ratio of the bending moment corresponding to each individual wave in wind and waves to the bending moment in wind only. The response of the OWT can be amplified due to wave action, wave by wave, and this amplification effect is particularly pronounced in shallow water wave conditions when the relative water depth is small, and the wave steepness is large. Therefore, when constructing monopile-type OWTs in coastal waters, it is essential to thoroughly understand the impact of wave loads on wind turbine responses.

To investigate the impact of swell on the dynamic response of the OWT, we separated the wave field into wind wave and swell using the wave age [Tamura et al., 2020], and evaluated the wind turbine response to each type of wave event. Figure 4 shows the relationship between wind, waves, and bending moments for wind wave and swell events. The horizontal axis is the wind speed at hub height corresponding to each individual wave u_{indv}, and the vertical axis is a wave characteristics parameter derived from the wave steepness and relative water depth, given by the following equation.

$$WP = \frac{ka}{kh}\tanh\left[1-\frac{\cosh(kh)-1}{kh\sinh(kh)}\right] \quad (1)$$

Figure 4 shows a comparison of the dynamic response of monopile-type OWT to wind waves and swell. These suggest that bending moments can be locally amplified due to wind waves and swell under specific conditions



(a) Wind waves

(b) Swell

Figure 4 - Difference in dynamic response of OWT to wind waves and swell.

during strong winds and high waves, such as in typhoons and strong low-pressure systems (u_{indv} > 20 m/s and *WP* > 0.2). Similarly, swell can lead to bending moment amplification under weak wind conditions (u_{indv} < 10 m/s). The detailed dynamic response characteristics of monopile-type OWT under wind and wave loads in coastal waters will be presented at the conference.

REFERENCES

Gaertner, E., Rinker, J., Sethuraman, L., Zahle, F., Anderson, B., Barter, G., Abbas, N., Meng, F., Bortolotti, P., Skrzypinski, W., Scott, G., Feil, R., Bredmose, H., Dykes, K., Shields, M., Allen, C., & Viselli, A. (2020): Definition of the IEA wind 15-megawatt offshore reference wind turbine, *Technical Report NREL/TP-5000-75698*, NREL.

NREL (2021): OpenFAST documentation release v3.0.0., https://github.com/OpenFAST/openfast.

Tamura, H., Kawaguchi, K. and Fujiki, T. (2020): Phase-coherent amplification of ocean swells over submarine, Journal of Geophysical Research: Oceans, 125(2).

Yamaguchi, A., Sarli, P. W. and Ishihara, T. (2014): Load estimation of a wind turbine support structure during operation and validation by measurement, Proceedings of the 25th National Symposium on Wind Engineering, Vol. 23, pp. 133-138.