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Research Article

Study Effect of Extreme Wind Direction Change on 3-Bladed Horizontal Axis Wind Turbine

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ABSTRACT. The Horizontal Axis Wind Turbines (HAWT) are used very popular in the world. They were installed mainly on land. However, on the land, the wind regime change is very complex such as high turbulence and constantly changing wind direction. In the International Electrotechnical Commission (IEC) 61400-1 standard, the wind regime is devided into the normal wind conditions and the extreme wind conditions. This study will focus on the extreme wind direction change and estimate the aerodynamic forces acting on a 3-bladed HAWT under this condition. Because the extreme wind direction change may cause extreme loads and it will affect the lifetime of HAWTs. This issue is experimented in the wind tunnel in Mie University, Japan to understand these effects. The wind turbine model is the 3-bladed HAWT type and using Avistar airfoil for making blades. A 6-component balance is used to measure the forces and the moments acting on the entire wind turbine in the three directions of *x*, *y* and *z*-axes. This study estimates the load fluctuation of the 3-bladed wind turbine under extreme wind direction change. The results show that the yaw moment and the pitch moment under the extreme wind direction change fluctuate larger than the normal wind condition. Specifically, before the sudden wind direction change happened, the averaged maximum pitch moment M_X is -1.78 Nm, and after that M_X is 4.45 Nm at inrush azimuth of 0°.

Keywords: Wind tunnel; extreme wind direction change; load; 3-bladed horizontal axis wind turbine;

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1. Introduction

In recent years, the movement to promote clean energy has been activated from the viewpoint of global warming prevention and energy security. The natural and sustainable renewable energy such as solar energy, wind power, biomass, geothermal energy, wave power and tidal power attract attention. Among them, wind power generation has been noticed all over the world because the cost of the power generation is relatively low and the power generation efficiency is high. Installed capacity of wind power has obtained 51 GW on the worldwide on 2018 including nearly 47 GW onshore and 4.5 GW offshore. This was fifth consecutive year which annual addition capacity exceeds 50 GW, but also the third year of decline following the peak in 2015 (Arthouros Zervosv 2019)

In addition, due to the global warming and climate change, many storms occured with more frequency and stronger intensity. Therefore, the wind regime change is complex. The extreme wind events are presented in the International Wind Turbine Design Standard IEC61400-1 (IEC 2005). The extreme wind events can lead to very large loads causing fatigue or damage to some turbine components. Wind is usually unsteady with high levels of turbulence in the short time, resulting in air flows characterized by rapid changes in the speed and direction (Burton et al., 2001; Alpman, 2015; Li et al., 2016a).

The wind turbine is divided into 2 types: horizontal axis wind turbines (HAWTs) and vertical axiswind turbines (VAWTs) depending on the axis of rotation. HAWTs have high energy conversion efficiency during the high wind speed, but VAWTs are advantageous in low speed wind regime and rapidly changing direction (Pope et al., 2010; Sutherland et al., 2012). For VAWTs, the aerodynamics of three-bladed VAWTs with straight, curved and helically-twisted blades under sinusoidal wind conditions is analysiced (Scheurich 2013). The transient amplitude fluctuations of the wind velocity in an urban environment decreases the high solidity H-type VAWT, while the fluctuations in the wind direction do not have an effect (Kooiman and Tullis 2010, Danao et al., 2013, 2014); Wekesa et al., 2015).

For HAWTs, the 3-bladed horizontal axis wind turbines have been used for the almost wind farms in the world. So, in this study, the behaviour of the 3-bladed wind turbine under the extreme wind condition is analysed.

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Variations in wind speed and direction were modelled using technique such as synthetic turbulence generation where an inverse Fourier transform method is used to generate a set of turbulent fluctuations with a specified shear, length scale, and intensity (J. Mann 1998). This technique has been successfully implemented in a large eddy simulation (LES) with a modelled 3-D gust structure (Norris et. al. 2010, 2012). In addition, the structural failure analysis of wind turbines impacted by super typhoon Usagi (Xiao Chen et, al. 2016). It proposed to modify the current IEC design standard and a few potential future directions of study to reduce the risk of wind turbine failure under extreme wind conditions such as typhoon and hurricane.

In addition, the magnitudes of gust event was defined by a simultaneously wind velocity and direction change. The wind velocity gust amplitude indicated a good agreement with the recommended ECD value of 15 m/s when it occurred simultaneously with a wind direction change (Hansen et al., 2007). The problem of extreme gust wind and direction change recognition and extreme event control, based on the structural dynamic system were presented. They can prevent the rotor speed from exceeding the over-speed limit by the fast collective blade pitching (Kanev et al., 2010). Asymptotic statistical models on closed form, the result indicated a rational and consistent calibration of four extreme external conditions defined in the IEC 61400-1 standard (i.e. extreme operating gust, extreme wind shear, extreme coherent gust with direction change and extreme wind direction change) (Larsen et al., 2008)

The fatigue and extreme loads of wind turbine components were analysed under some conditions such as the normal and extreme turbulence, the extreme gust events, and the direction changes according to the certification specifications (Lars O.Bernhammer et, al. 2016). The comprehensive modelling research framework was finally outlined, which can help understand and model the impact of extreme weather on power systems and they can be prevented or mitigated in the future (M. Panteli el, at. 2015). Furthermore, the effect of the turbulence intensity and wind shear on the power characteristic of a horizontal axis wind turbine was estimated (Li el, at. 2016a).

Therefore, in order to understand clearly the effect of sudden wind direction change on load of the 3-bladed wind turbine, this paper will show the experimental data to estimate that effect. Thence, the paper will show the experimental results of the effect of the extreme wind direction change on the load of 3-blade horizontal axis wind turbine. Yaw moment and pitching moment are 2 objectives which are used to estimate the fluctuation of load on wind turbine under the extreme wind direction change.

2. Experimental Apparatus and Method

2.1 Wind tunnel and 3-bladed wind turbine

The wind tunnel is used to experiment the effect of the extreme wind direction change on wind turbine. The wind tunnel is an open wind tunnel with an outlet diameter of 3.6 m and an air collector size of 4.5 m × 4.5 m as shown in Figure 1. The mainstream wind velocity can be adjusted in the range from 0 to 30m/s (Maeda el, at. 2014). A 3-bladed horizontal axis wind turbine (HAWT) model is used in this experiment. It has a blade length of 0.8m. The blade is made by the Avistar airfoil. The rotor rotational speed is adjusted by a variable speed generator. The rated rotational speed is 880 rpm and it is possible to set up to a maximum of 1200 rpm (L.Q. Sang el, at. 2017).

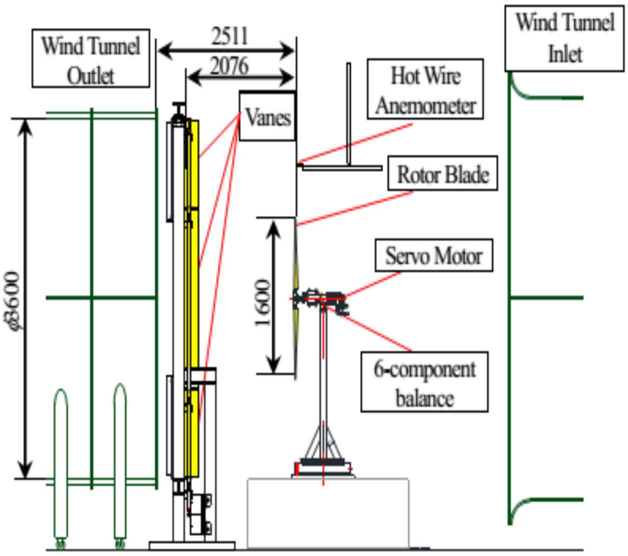

Fig. 1 Experimental apparatus and louver equipment

A six-component balance system is used to measure the forces and moments applied to the entire wind turbine in the three directions of *x*, *y* and *z*-axes,

2.2 Louver vanes

The Louver vanes system was set up at the air passage outlet of the wind tunnel as shown in Figure 1. The aim of this system is to make the change of the wind direction. The vanes are connected to two servo motors and a variable vane array of 16 columns divided into three stages of upper, middle and lower.

The cross-sectional shape of the Louver vane row is a NACA0012 airfoil with the chord length of 0.3 m. The variable cascade of 16 columns is connected to a link mechanism and can be set to any angle by those servo motors.

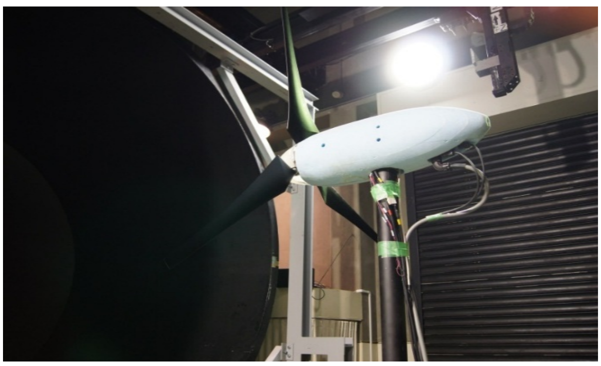

Fig. 2 3-bladed horizontal axis wind turbine

2.3 Experimental method

Load analysis of wind turbine are discussed under the extreme wind direction change in the wind tunnel.

The sudden wind direction change condition in experiment is the same the Extreme Direction Change (EDC) of IEC614001 standard. Changes over time of the wind direction from the EDC model $\theta(t)$ is defined by the following equations (1) and (2).

$$\theta_e = \pm 4 \arctan\left\{\frac{\sigma_1}{V_{hub}\left(1+0.1D/\Lambda_1\right)}\right\} \tag{1}$$

$$\theta(t) = \begin{bmatrix} 0° & for & t<0 \\ \pm 0.5\theta_e\left\{1-\cos\left(\pi t/T\right)\right\} & for & 0 \le t \le T \\ \theta_e & for & t>T \end{bmatrix} \tag{2}$$

Here, θ_e is the wind direction change angle, T is the sudden wind direction change time, σ_1 is the standard deviation of the mainstream wind velocity, V_{hub} is the hub height wind velocity, D is the rotor diameter, and Λ_1 is the turbulence scale parameter, respectively.

The 10 MW wind turbine is assumed in this study. The wind turbine has the rotor diameter of 200 m, the hub height wind velocity is 11 m/s, the turbulence scale parameter is 91 m and the wind direction change angle is $\theta_e = \pm 28.2$ °.

The experimental condition of the 3-blade wind turbine is assumed as follow:

- Wind velocity : 8 m/s
- Pitch angle : 0°
- Inlet wind angle : -15.1°
- Tip speed ratio : 6
- Rotational speed : 580 rpm

The pitch moment M_x and the yaw moment M_z are used to evaluate wind turbine load fluctuation due to the suddenly change of wind direction. In the case of oblique inflow conditions, the wind turbine generates a moment due to the difference in fluid force generated with respect to the azimuth angle. Therefore, we focus on the pitch moment M_x and the yaw moment M_z in order to evaluate the wind turbine behavior at the time of wind direction change.

3. Results and Discussion

3.1 Sudden direction change condition in wind tunnel experiments

Table 1
Five positions when looking at the wind turbine from the upstream

Position	$(x/R, z/R)$
Center	(0,0)
Right end	(1,0)
Left end	(-1,0)
Top end	(0,1)
Lower end	(0,-1)

The five positions represented on the rotor surface are summarized in Table 1. Figure 3 shows the comparison of the wind direction fluctuation at five points on the rotor surface. The horizontal axis represents time t from the trigger timing (hereinafter referred to as "trigger reference time"), and the vertical axis is the wind direction θ_{WD}.

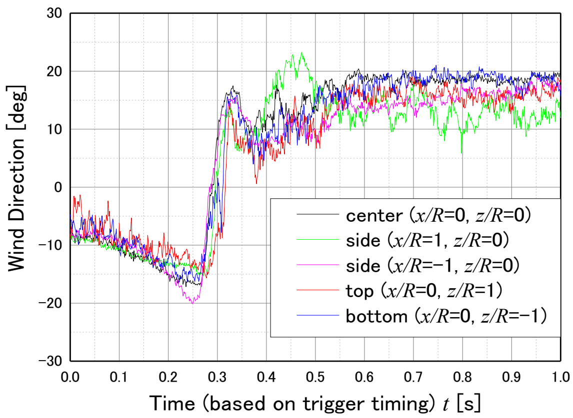

Fig. 3 Comparison of wind direction variations at 5 points in the rotor surface

The color of each point corresponds to that of the legend in Figure 3. Figure 4 shows the wind direction variation of the 5-points average in the rotor surface for the EDC model of the IEC standard. The axes are the same as in Figure 3. As can be seen from Figure 4, the sudden change in wind direction simulated in the wind tunnel is relatively consistent with the EDC model of the IEC standard.

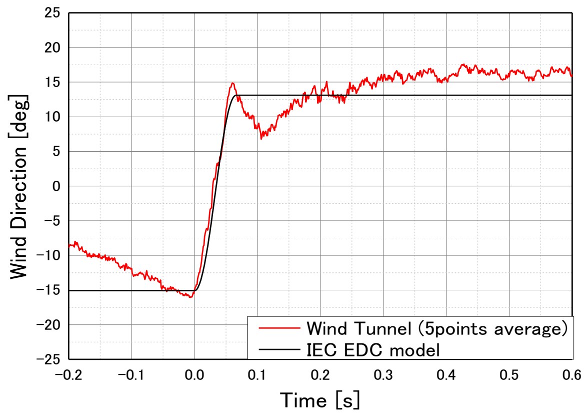

Fig. 4 Wind direction change of the 5-points average for EDC model of IEC standard

3.2 Data arrangement method

The moment load is evaluated under the sudden changing inflow correspond to the wind azimuth angle (hereinafter referred to as "inrush azimuth angle"). However, for the convenience of the program, what can be set as an experimental condition is the azimuth angle when the trigger signal is output. Therefore, use equation (3) to calculate the rush azimuth angle:

$$\Psi_{in} = \Psi_{tr} + t_{lag} \times \omega \tag{3}$$

Here, Ψ_{in} is the rush azimuth angle, Ψ_{tr} is the azimuth angle when the trigger signal is output, t_{lag} is the time lag from the start of the rapid change of the wind direction to the rotor surface inflow, and ω is the rotor angular velocity. The lag time from the start of the wind direction change device to the rotor surface inflow was 0.267 [sec] from Figure 4.

3.3 Variation of pitch moment at sudden wind direction change relative

Figure 5 shows the variation of the pitch moment at the time of sudden change of wind direction with respect to the trigger reference time when the inrush azimuth angle of 3-blade wind turbine changes. The axes are shown as in Figure 5. Since the 3-bladed wind turbine is targeted at 120° with respect to the azimuth angle, the representative inrush azimuth angle is 0°, 40°, 80°.

From this figure, when the sudden wind direction change impact to the rotor surface, the pitch moment was fluctuated larger. It is proof that before the sudden wind direction change happened, the averaged maximum pitch moment M_X is -1.78 Nm, and then M_X is 4.45 Nm at inrush azimuth of 0°. In addition, the three-bladed wind turbine showed three cycles of amplitude to the inrush azimuth.

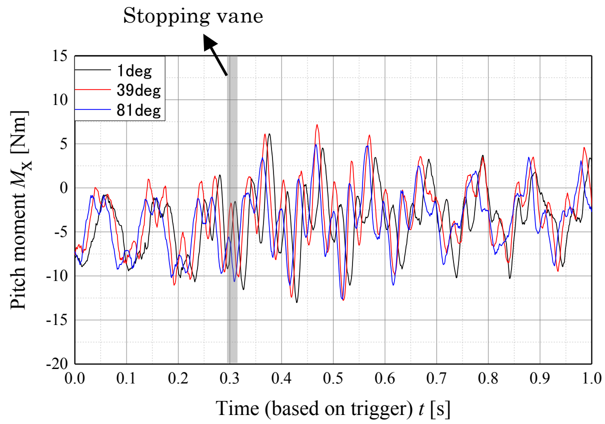

Fig. 5 Variation of pitch moment at sudden change of wind direction with respect to trigger reference time when inrush azimuth angle of 3-bladed wind turbine changes

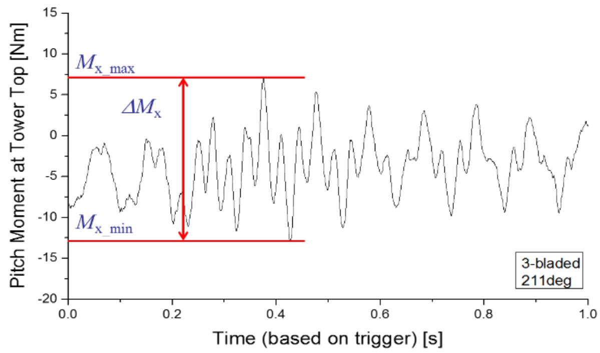

Fig. 6 Maximum pitch moment value M_x_max, minimum value M_x_min, and amplitude ΔM_x

Figure 6 shows the variation of the pitch moment at the time of sudden change of wind direction with respect to trigger reference time when the inrush azimuth angle of the 3-blade wind turbine changes. The horizontal axis is time and the vertical axis present the pitch moment at the tower top. When the sudden wind direction change occured, the maximum value of the pitch moment is 6.14 Nm, the minimum value is -13.02 Nm.

3.4 Wind turbine yaw moment fluctuation due to sudden change in wind direction

Figure 7 indecates the change of the yaw moment under the sudden change of the wind direction with respect to the trigger reference time when the inrush azimuth angle of the 3-bladed wind turbine changes. Since the 3-bladed wind turbine is targeted at 120° with respect to the azimuth angle, the representative inrush azimuth angle is 0°, 40° and 80°. From this figure, after the sudden wind direction change occured, the yaw moment is more fluctuated.

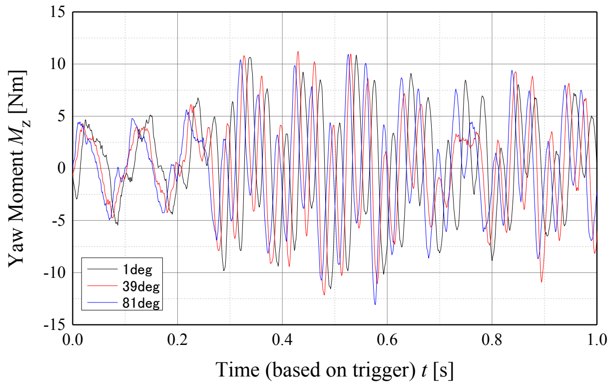

Fig. 7 Fluctuation of yaw moment at sudden change of wind direction with respect to trigger reference time

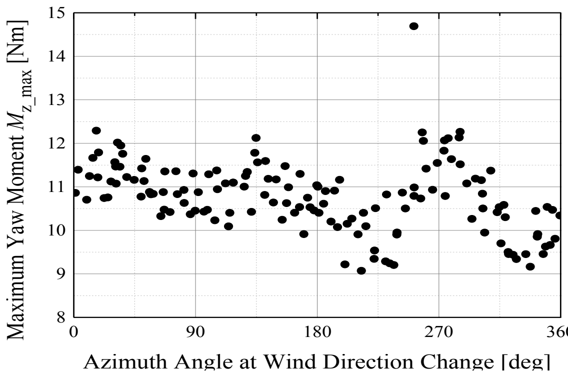

Fig. 8 Maximum value of yaw moment for rush azimuth angle

Figure 8 and 9 exhibit the maximum and minimum yaw moment with respect to the inrush azimuth angle. The horizontal axis represents the inrush azimuth angle, and the vertical axis represents the amplitude of the yaw moment. From these figures show that the 3 cycles was observed for the inrush azimuth. For the maximum yaw moment has 3 peak at 45^0, 135^0 and 270^0. For minimum yaw moment also has 3 peak at 120^0, 230^0 and 360^0. It means that when the extreme wind direction change accused, the yaw moment was affected and more fluctuated as shown figure 7.

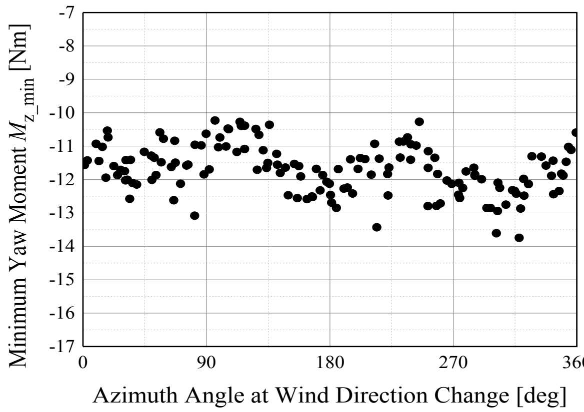

Fig. 9 Minimum value of yaw moment for rush azimuth angle

Figure 10 shows the fluctuation amplitude of the yaw moment of the 3-bladed wind turbine. From this figure shows that the 3 cycles was also observed for the inrush azimuth.

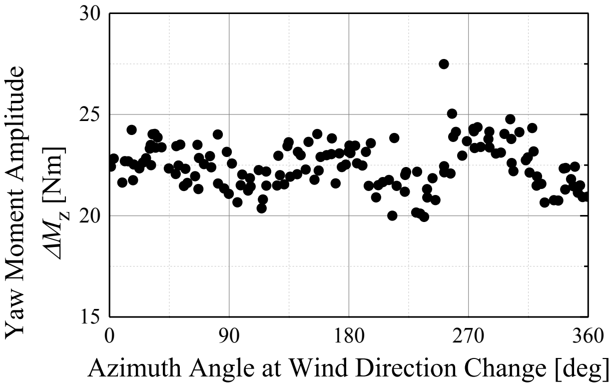

Fig. 10 Amplitude of yaw moment to rush azimuth angle of 3-bladed wind turbine

4. Conclusion

In this study, one of the extreme wind conditions of the IEC standard was performed in the wind tunnel of Mie University, Japan. The effect of the sudden wind direction change on load of the wind turbine was observed. Some results are shown as:

- For the pitch moment amplitude, the behavior of the 3-bladed wind turbine was showed three cycles. After the wind direction change occured suddenly, the fluctuation of the pitch moment is larger. It is presented that before the sudden wind direction change happened, the averaged maximum pitch moment M_X is -1.78 Nm, and then M_X is 4.45 Nm at inrush azimuth of 0°.

- With regard to the yaw moment amplitude, the amplitude of 3 cycles was observed for the inrush azimuth of the 3-bladed wind turbine. The 3-bladed wind turbine in terms of the averaged value of the pitch moment amplitude. The same the pitch moment, the yaw moment also is more fluctuation after the sudden wind direction change.

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