Experimental Investigation of Wind Loading Acting on Wind Turbine Nacelles

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1. Introduction

Severe wind conditions like typhoon are responsible for extreme loading on wind turbine components including nacelles. There has been an incident in the southern part of Japan in which several nacelles were damaged during extreme wind condition, and the damages were attributed to the underestimation of ultimate load during the design [1]. While significant number of studies has investigated loads on blades and towers of wind turbines, little attention has been devoted to the aerodynamic load on nacelles. In this study, analysis of wind load acting on turbine nacelles through wind tunnel experiments is conducted.

Nacelle essentially being a bluff body, knowledge accumulated on bluff body aerodynamics from other engineering application e.g., low-rise building, can be crucial to improve our understanding of wind induced loading mechanism of nacelles [2]. There is also a large body of research focusing specifically on wind loading on low-rise buildings and structures [3]. Majority of those studies are based on wind pressure distribution obtained from wind tunnel or full-scale measurements. Other studies have used Proper Orthogonal Decomposition (POD) to extract dominant features related to different force components from the fluctuating pressure field data ([4]). However, there are noticeable differences between nacelles and other bluff bodies. For instance, the ground effect with high turbulence intensities due to surface roughness is important for low-rise building. But this effect can be neglected for nacelles which are usually installed on high towers. Furthermore, nacelle aerodynamics is influenced by interaction with tower and blade.

In their work, Noda and Ishihara [5] conducted a wind tunnel experiments to measure wind forces and local peak pressures on nacelles. They reported that peak pressure coefficients specified in a design code GL Guideline are smaller than those obtained from experiments. Although Zahle and Sorensen [6] presented the simulation of flow around the nacelle, they did not considered wind loading.

The aim of this work is to investigate wind loading on wind turbine nacelles focusing on nacelle roof which is more prone to structural failure. To this end, mean and peak pressure distribution for uniform and turbulent inflow is compared. Furthermore, wind induced peak forces and moments on the nacelle roof are assessed as the function of wind direction and a model is proposed to estimate peak wind load.

2. Experimental setup and inflow characteristics

The experiments are conducted in the closed-circuit type boundary layer wind tunnel. Dimensions of the test section are $\mathrm{l} \times \mathrm{w} \times \mathrm{h} = 11.8 \times 1.5 \times 1.8\ \mathrm{m}^3$. Figure 1 shows the schematic of the wind tunnel test section. As shown in the figure, combination of spires, fence and blocks are used as tripping mechanism to generate turbulence boundary layer profiles.

Measurements are carried-out for two different inflow conditions: uniform flow and turbulent boundary layer profile. Mean velocity at the hub height is set to 13.5 m/s for both the cases. Figure 2 shows the vertical profiles of mean streamwise velocity and turbulence intensity measured using hot wire anemometry. It is evident from the figure that the boundary layer height for the uniform flow is $z/z_h = 0.3$, and it is found that the turbulence intensity at the hub height was 0.4%. Mean velocity profile for the turbulent flow roughly follows the

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power law profile given by

$$U/U_o = (z/z_h)^\alpha \qquad (1)$$

with exponent $\alpha = 0.2$. Turbulence intensity for this case at the hub height is about 13%.

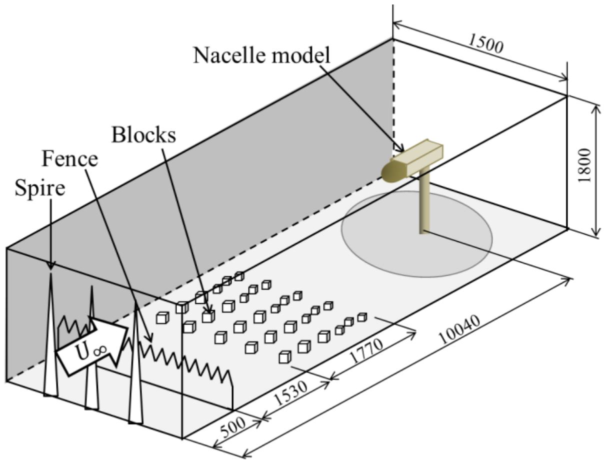
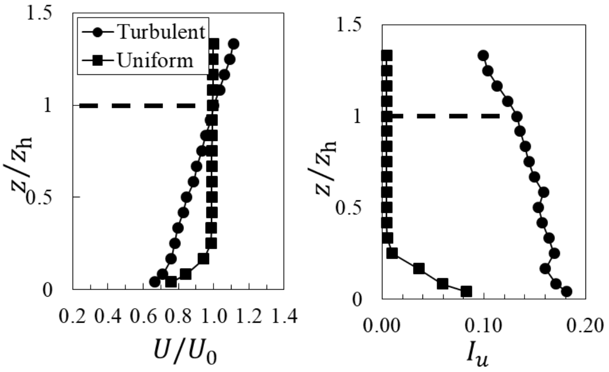


Fig. 1 Schematic of wind tunnel test section showing locations of turbulence generator and nacelle model.



(a) Mean velocity (b) Turbulence intensity

Fig. 2 Vertical profiles of mean velocity and turbulence intensity at the position of the nacelle model.

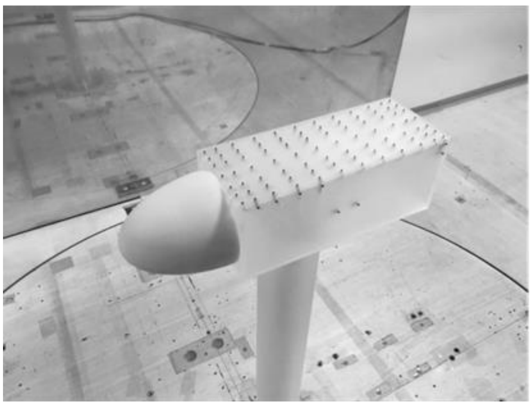


Fig. 3 Photographs of the nacelle. Pressure orifices are evenly distributed on the roof.

The wind turbine nacelle model used in this study is show in Figure 3. It has dimensions of 0.2m × 0.08m × 0.08m, with additional 0.08m for the hub, and is mounted on a tower of height 0.56 m. Pressure data are collected using 92 pressure taps most of which are evenly distributed on the roof of the nacelle. These pressure taps are connected to the transducers using 1 m long tube.

3. Results and discussions

Pressure distribution for uniform and turbulent inflow are first presented in this section. Wind induced global forces and moments estimated using the pressure information are also discussed.

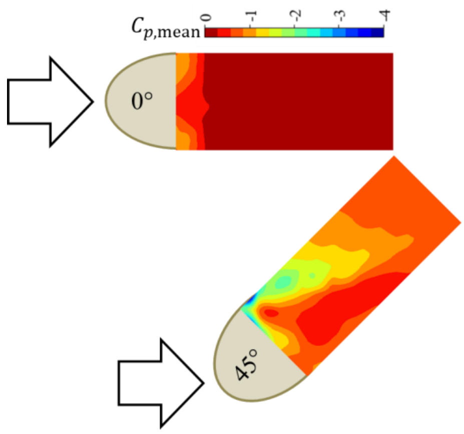
3.1 Pressure fields for uniform and turbulent flow

Time series of pressure data is collected for yaw angle from 0°to 355°at 5° interval. Here counter clockwise direction with respect to the incident wind indicates positive yaw angle. Sampling period and sampling rate are set to 64 s and 512 Hz respectively. The surface pressure data collected in this way can be expressed in the form of pressure coefficient:

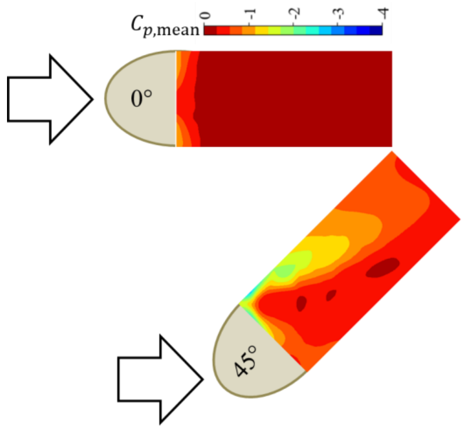
$$C_{p,i} = \frac{(p_i - p_{\mathrm{ref}})}{1/2\,\rho u_h^2} \qquad (2)$$

where p_i is the measured instantaneous pressure at the pressure tap *i*, p_{ref} is the reference static pressure outside the influence of the nacelle model, u_h is undisturbed velocity at the hub height.

In figure 4, mean pressure coefficient for uniform and turbulent boundary layer cases are compared for yaw angles 0°and 45°. Compared to 0° yaw angle, 45° has larger region with negative pressure coefficient indicating that separation region is also bigger for the later. This is because the sharp edge of the nacelle faces the incoming flow for 45°, whereas for 0°, the incoming flow greatly streamlines around the hub. Separation region is smaller for turbulent inflow case because of higher mixing and entrainment towards the nacelle surface from the free stream flow. Nevertheless, overall distribution of mean pressure coefficients for uniform and turbulent flow is similar for respective yaw angles.



(a) Uniform inflow



(b) Turbulent inflow

Fig. 4 Colormap of time-averaged pressure coefficient on the nacelle roof for 0°and 45° yaw angles.

3.2 Wind force estimation

To evaluate the overall effect of wind loading on the nacelle, force (F_L) from pressure measurement data is analyzed. To this end, point-wise pressure measurement is integrated over the nacelle surface.

$$F_L = -\int_A p\mathrm{d}A \quad = -\sum_{i=1}^{N} p_i \mathrm{d}A_i \qquad (3)$$

where p_i and $\mathrm{d}A_i$ are measured pressure and differential area of tap *i*. Coefficient of lift force is then given by:

$$C_L = \frac{F_L}{1/2\,\rho u_\mathrm{h}^2 A} \qquad (4)$$

where A is representative area. The lift (or vertical) force is investigated because of its possible damaging effect on the nacelle cover compared to the drag force which will not be significant.

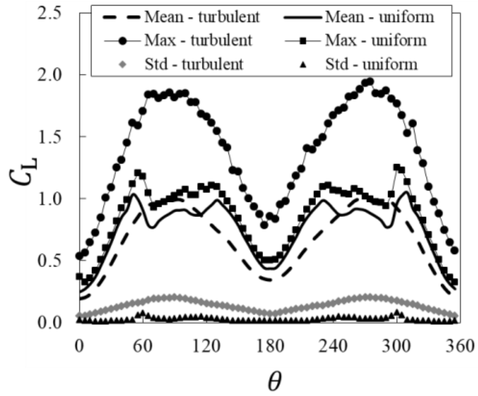


Fig. 5 Comparison of lift force coefficient for uniform and turbulent inflows.

Figure 5 shows the mean, peak and standard deviation of lift coefficient for uniform and turbulent cases. Mean and maximum values do not differ too much for uniform case, but for turbulent case, maximum C_L are significantly higher. This signifies the importance of turbulence in contribution to wind-induced loading. Two peaks –around 90° and 270°- are observed in turbulent inflow. Peaks are at 60° and 300° for uniform case, though for yaw angle between 45° and 135° and that between 225° and 315°, variation in C_L is minimal. It can be seen that the effects of uniform and turbulent flow on the nacelle aerodynamics are different.

Next a model for estimation of peak force is proposed, following the paradigm of equivalent static wind loading (ESWL). For quasi-steady assumption the peak wind-induced lift force is given by[2]:

$$\hat{F}_L = \left(1 + g\frac{\sigma_F}{\bar{F}_L}\right)\bar{F}_L \qquad (5)$$

where $\hat{F}_L$ is peak vertical force, $\bar{F}_L$ is mean vertical force, σ_F is standard deviation of the force. Peak factor g is defined as:

$$\mathrm{g} = \frac{\left(\hat{F}_L - \bar{F}_L\right)}{\sigma_F}. \qquad (6)$$

Furthermore, coefficient of variation (CoV), $\sigma_F/\bar{F}_L$ can be estimated from following relation.

$$\sigma_F/\bar{F}_L = \max(2I_h, 0.06). \qquad (7)$$

where I_h is turbulence intensity at the hub height.

Figure 6 shows the gust factor and CoV obtained from measurement and those estimated from Eqs. (7) and (8). The estimated CoV agrees well with the measured value when yaw angle is close to zero. Additionally, a relation for peak factor is proposed based on the characteristic of the measured values. It is found that cosine of twice the yaw angle shows the best fit with the measurements, i.e.,

$$g = \cos 2\theta + 5.2 \quad (8)$$

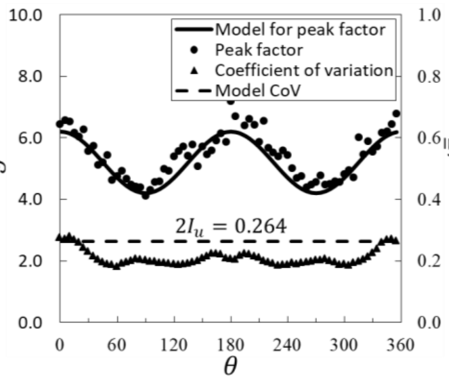
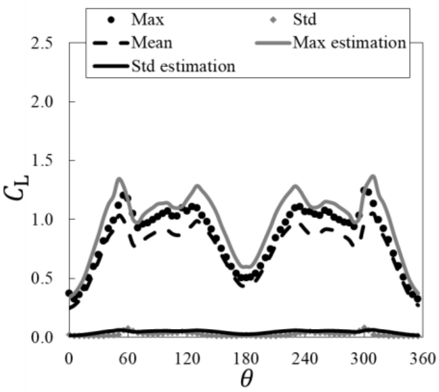
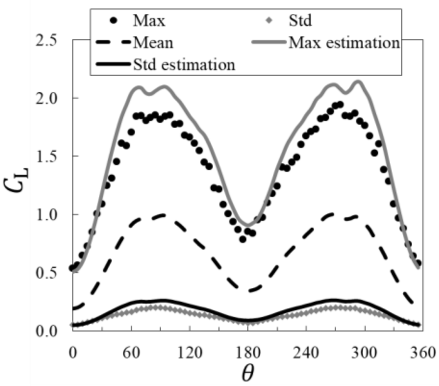


Fig.6 Comparison between predicted and measured peak factor and coefficient of variation



(a) Uniform inflow



(b) Turbulent inflow

Fig. 7 Comparison between predicted and measured lift coefficients

Fig. 6 shows comparison between predicted and measured peak factor and coefficient of variation. Figure 7 (a) and (b) compare the standard deviation and peak lift force estimated from Eqs. (7) and (5) against the measured value for uniform and turbulent inflows. It can be appreciated that both measurement and the model show similar characteristics. Maximum peak values and maximum standard deviations observed at 90° and 270° in the measurements are also reproduced by the model. Over estimation of both peak force and standard deviation can be attributed to the constant CoV model used in this study. As shown in figure 6 (a), the CoV changes with the yaw angle, and thus it is necessary to consider the effect of the yaw angle.

4. Conclusion

The current study has focused on the wind induced loading on a nacelle roof. Pressure field on the surface of scaled nacelle model was measured for uniform and turbulent inflow in wind tunnel experiments. It was found that mean pressure coefficients for uniform and turbulent flow was similar for respective yaw angles. Evaluation of the wind force showed that maximum values of C_L were significantly higher for the turbulent inflow. Finally, a model for the estimation of peak wind load is proposed. The model agrees well with the measurement.

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