

Development of a PIV system for Measuring Wake Characteristics of an Offshore Floating Wind Turbine with Pitching Motion

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1. Introduction

Floating offshore wind turbines (FOWTs) are a type of wind turbine which is possible to harvest the wind energy in deep sea areas where bottom-fixed wind turbine cannot operate. However, the motion of FOWTs due to waves and wind results in more complicated wake behavior than that of fixed wind turbines. This wake can negatively influence surrounding wind turbines, such as by decreasing performance and increasing structural loads, more than the wake of a fixed wind turbine. Messmer et al. reported that wake behavior varies with the Strouhal number:

$$St = \frac{fD}{U_0} \quad (1)$$

where f is the oscillation frequency, D is the rotor diameter, and U_0 is the inlet wind speed, based on one-dimensional wake profile measurements obtained using hot wire anemometer (HWA) arranged in a straight line^[1]. Additionally, studies conducted two-dimensional wake measurements using PIV (Particle Image velocimetry) under limited oscillation conditions^[2]. In this study, PIV measurements of the wake were conducted while varying the Strouhal number of a pitching FOWT. This PIV system is newly implemented in this research. Through this approach, we explore the differences in spatial wake distribution depending on St as well as the temporal evolution of the velocity distribution, providing new insights into wake behavior under pitching oscillation conditions.

2. PIV system for FOWT's wake

PIV measurements carried out in the Thermal Stratification Wind Tunnel at the Research Institute for Applied Mechanics, Kyushu University. The wind tunnel has a cross-section of 1.1m in height and 1.5m in width, with a measurement section length of 13.5m. Fig.1 shows a schematic diagram of the PIV setup. Two measurement area were recorded separately using the same 3W semiconductor laser sheet (KATO KOKEN) and high-speed CMOS camera (WX100, Photron). Each PIV measurement area has approximately 1m in height and 2m in width. Measurements were performed at a wind speed $U_0=1\text{m/s}$, with an image capture rate of 125fps. To optimize memory usage, the image resolution was crop to 2048px×1024px to match the measurement area, allowing a maximum recording time of about 43.68s. Smoke generators (Kanomax) was used to provide seeding particles. The captured data were processed using FlowExpertII (KATO KOKEN), which applied a window deformation iterative multigrid method. In this algorithm, the interrogation window size was gradually reduced from 64px × 64px to 16px × 16px and a 50% overlap. The FOWT model used a MEL airfoil rotor with a diameter $D=0.442\text{m}$, mounted on a pitching oscillation device. The rotor Hight was set at 550mm with a maximum pitch amplitude of $\pm 5^\circ$. Wake measurements were conducted using PIV under several pitch oscillation periods, with a rotor speed $\omega=184\text{rpm}$ and tip-speed ratio $\lambda=\omega R/U_0 \approx 4.3$.

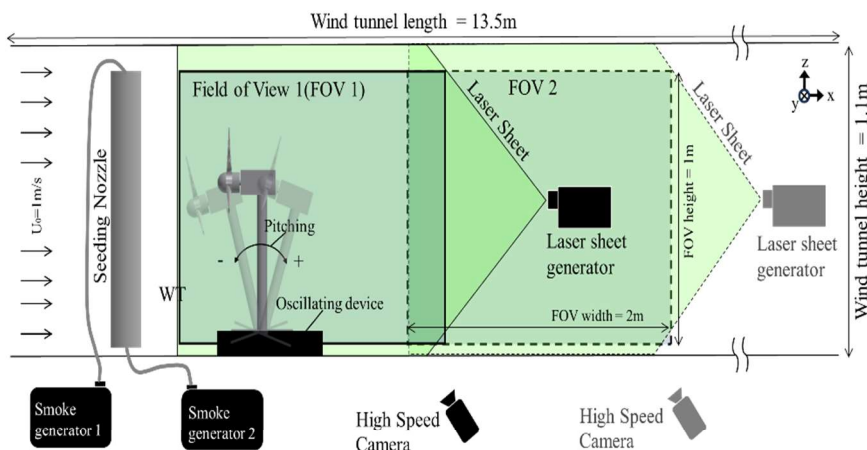


Fig.1 Overview of PIV system and FOWT model

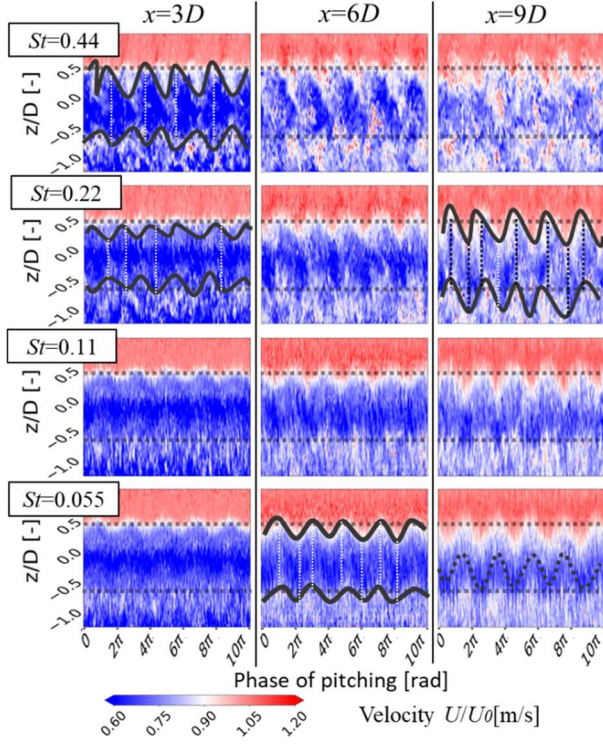


Fig.2 Contour plot of the vertical profile of velocity U/U_0 at a given location.

3 Result and discussion

Fig.2 shows time-series contour plot of vertical wake profiles of velocity U/U_0 at $x=3D$ (near wake), $x=6D$ (transition region), and $x=9D$ (far wake). The horizontal axis of each contour plot is aligned with the phase of oscillation. At $St=0.44$, the wake velocity deficit shows periodic strengthening and weakening, and this is relatively symmetric wake shape centered at $z/D=0$. Thus, this is pulsating behavior. The periodicity weakens at $x=9D$ indicating enhanced mixing and wake recovery. At $St=0.055$, the wake shows ordered meandering, characterized by continuous up-and-down motion with a stable vertical velocity distribution. For intermediate cases ($St=0.22$ and $St=0.11$), the wake transitions from pulsating behavior in the near wake to ordered meandering in the far wake.

Fig.3. Shows the result of phase averaging of velocity U/U_0 shows. This phase averaging technique can reduce the measurement noise and enhance the periodic change of wakes associated with the pitching motion period. In addition, through the identifying the phase of pitch oscillations, 2 different measurement area can be merged. For phase averaged U/U_0 at $St=0.44$, distinct V-shaped or delta-shaped pattern is observed on the wake. In contrast, the wake at $St=0.055$ exhibit long and continuous. These characteristics can be easily observed in the animation of the PPT presentation.

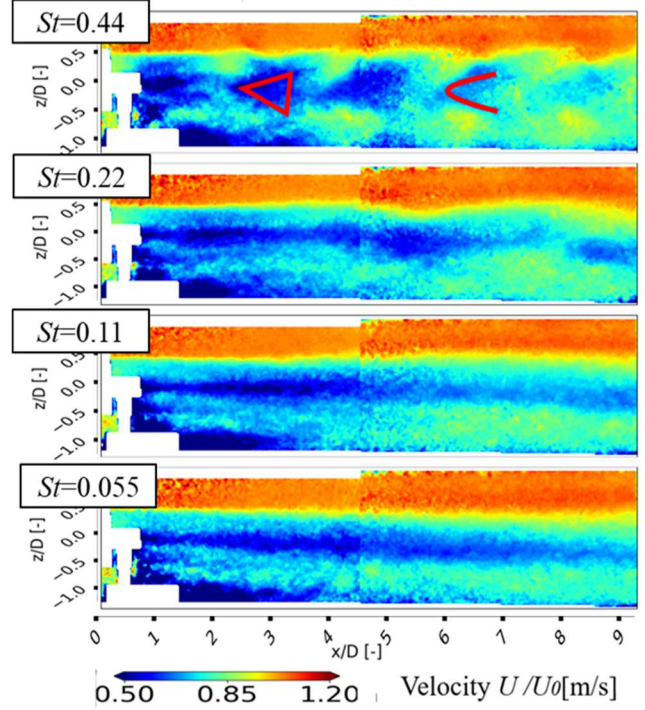


Fig.3 Contour plot of phase averaged velocity field U/U_0 .

4. Conclusion

The conclusion of findings obtained from the wake measurement of the FOWT using newly implemented PIV system is listed below:

- ✓ High St ($St>0.4$) shows pulsating wake behavior and fast wake recovery in far wake region. Low St ($St<0.1$) shows ordered meandering behavior. In the intermediate St ($0.1<St<0.4$) exhibits combination characteristics.

- ✓ Phase-averaged analysis revealed distinctive wake deficit shape in special. Especially at $St=0.44$, pulsating wake exhibited distinct delta-shaped or V-shaped velocity deficits.

5. References

- [1] Messmer et al., Enhanced recovery caused by nonlinear dynamics. J. Fluid Mech. 2024, vol. 984, A66
- [2] Fu et al., Wake and power fluctuations of a model wind turbine subjected to pitch and roll oscillation, Applied Energy 2019, 253, 113605,

Conference presentation

1. The 1st Asia Pacific Conference on Offshore Wind Technology (APCOW2024), 2024/11
2. 第 46 回風力エネルギー利用シンポジウム, 2024/11
3. The 26th Cross Straits Symposium on Energy and Environmental Science and Technology (CSS-EST 26) 2024/12, Award: *Best Oral Presentation*