

UNSTEADY AERODYNAMICS OF OFFSHORE FLOATING WIND TURBINES IN PLATFORM PITCHING MOTION USING VORTEX LATTICE METHOD

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ABSTRACT

As flow states of offshore floating wind turbine (OFWT) is different from onshore fixed wind turbine, it is questionable whether aerodynamic load prediction of the turbine using conventional blade element momentum theory (BEMT) is accurate. The aim of this paper is to show characteristics of aerodynamic load prediction using vortex lattice method (VLM). Washizu's experimental data, which was measured under similar flow state of floating wind turbine, is used for validation. The prediction shows good results compared with experiment. To know the unsteady aerodynamics of floating wind turbine, NREL 5MW wind turbine model is used for simulation of floating wind turbine. It shows that TWS are occurred when floating wind turbine is operated in low speed inflow condition. In addition, the rotor experience TWS when floating platform is at upward pitching motion.

KEYWORDS

Floating Wind Turbine, Unsteady Aerodynamic Load, Blade Element Momentum Theory, Vortex Lattice Method

NOMENCLATURE

a	Axial induction factor
BEMT	Blade element momentum theory
TSR	Tip speed ratio
VLM	Vortex lattice method
VRS	Vortex ring state
V_z	Free stream velocity, ms^{-1}
WBS	Windmill brake state
$\theta_{0.75}$	Pitch angle of the blade measured at $0.75R$

1. INTRODUCTION

Wind energy is one of the most promising renewable energy sources. It is clean energy and at the very close to fossil price. These days, the use of offshore wind turbine has been rapidly increasing because of noise and visual problems of onshore wind turbine. Also, wind quality, which is play a significant part in driving aerodynamic power, is much better for going further offshore as there are no wind barriers. Winds are stronger, more consistent, with less turbulence intensity and smaller shear than on land. However, since water depth is also deepened in sea, fixed-bottom systems are not economically feasible. Instead, floating support systems are most competitive in deeper sea [1]. Also, the feasibility of floating platforms have been demonstrated as there has been long-term use of offshore floating substructures in oil and gas industry.

In floating state, as it is operated in complex condition, it should be analyzed differently from fixed wind turbines. Especially, while fixed wind turbine has simple flow state, the OFWT has complex flow states during floating platform motion: normal working state (NWS), turbulent wake state (TWS), vortex ring state (VRS) and windmill braking state (WBS). Figure 1 shows how various flow states occur during floating platform's pitching motion. WBS's flow is smooth and definite slipstream, which is normal condition of wind turbine. When platform starts pitching backward, the flow has a high level of turbulence. At the boundary between WBS and TWS, the flow changes abruptly from a state with a smooth slipstream to one with recirculation and turbulence as the velocity in the far wake changes direction. As platform's pitching velocity increased, definite slipstream ceased to exist and the flow near the rotor disk becomes highly unsteady and turbulent. Thomas et al. [2] shows the occurrence of breakdown of slipstream is twice as likely as for floating wind turbines than monopiles under low wind speed condition.

The aerodynamic modeling of wind turbines is consist of three categories: BEMT, VLM and CFD. BEMT is very simple engineering model based on simple momentum and strip theory. Because of comprehensible assumptions of this method, it must treated using corrections, such as dynamics stall, Glauert's thrust correction, Prandtl's tip loss function, and stall delay model. In spite of the various assumptions and approximations with the BEM, it can provides a good preliminary predictions in rather simple flow states such as WBS and TWS [3]. However, it is incomplete to consider all kinds of complex flow states of OFWT. BEMT has two major weaknesses in the analysis. First, it assumes wake as frozen though the wake of floating wind turbines is highly unsteady. To supplement this condition, dynamic inflow models are developed. Generalized dynamic wake model, which is largely used as dynamic inflow model in wind turbine simulation, is not suitable in highly loaded rotors such as recirculating flows as it assumes mean induced velocity is small relative to mean inflow velocity [4]. Second, BEMT's slipstream assumption is not satisfied when axial induction factor is more than half. Although Glauert's empirical formula is applied at this condition, Glauert's empirical correction is questionable in VRS because the formula was made

by using measurement data in the TWS. Also, as platform pitching and yawing motion introduce significant effective wind shear, correction to non-axial flow is unsatisfactory. In another method, CFD, which solves the Euler or Navier-Stokes equations, provides most physically realistic simulation. However, it is not yet practical method in design process as it has huge computational cost. In other words, as an engineering model, VLM is a reasonable method as it can represent the non-uniform induced effects associated with the vertical wake trailed from the turbine. This method has flexibility to include a wide range of validated sub-component models representing various physical effects that are difficult to model from 1D momentum theory. This method has been widely developed for use in helicopter rotor analyses, dating from 1960s, but has not yet seen significant use for wind turbine applications.

Therefore, in this study, we have investigated characteristics of aerodynamics of offshore floating wind turbine in platform pitching motion using VLM to predict more physical insight about unsteady aerodynamics.

2. NUMERICAL METHOD

A more explicit treatment of the rotor wake requires a method that can represent the spatial locations and strengths of the vortex that are trailed by each blade and convected into the downstream wake. This can be satisfied using VLM, which is based on assumption and theory as below. The fluid surrounding the body is assumed to be inviscid, irrotational, and incompressible over the entire flow field, excluding the body's solid boundaries and its wakes. Hence, velocity potential, Φ , becomes Laplace equation. Using the Green's theorem, the general solution to Laplace equation can be made by a sum of source and doublet distributions placed on the boundary.

$$\Phi^* = \frac{1}{4\pi} \int_{body+wake} \gamma n \cdot \nabla \left(\frac{1}{r} \right) dS + \Phi_\infty$$

Source and doublet distributions are solved by implementing two boundary conditions. The first boundary condition requiring zero normal velocity across the body's solid boundaries is called Neumann boundary condition. The second boundary condition requires that the flow disturbances, due to the body's motion through the fluid, should diminish far from the body. Finally, Aerodynamic force generated by vortex sheet is calculated by the Kutta-Joukowski theorem. (see more details in Ref. [5]).

To consider thickness and viscous effects, nonlinear vortex correction method (NVCM) was used. This is corrected by matching up the sectional lift from the VLM with that from the two-dimensional table look-up [6]. To correct three dimensional effect of rotor blades, Du & Selig stall delay model is implemented [7].

3. RESULTS & DISCUSSION

3.1 Validation

To validate in-house numerical code in VRS, predictions are compared with Washizu's experimental data [8], which is a moving track test of a 1.1 m diameter rotor in descent for axial conditions. As this experiment is comprise all flow states, and known as representative experiment of VRS, it is appropriate for validation for floating wind turbines. The three-bladed rotor has a solidity of 0.0573 and 8.33 deg twist. RPM is 1000 rpm, chord is 0.033. The airfoil of each blade is a NACA 00012. Data for the aerodynamic coefficients for the NACA 0012 have been gathered from an experimental data [9].

The measured and predicted thrust coefficients are shown in Figure 2. The prediction shows that VLM predicts well the value near upper border of fluctuations for the complete interval of $V_z/\Omega R$. The normal vorticity fields perpendicular to the Y axis as descent velocity are can be seen cases in Figure 3. Figure 3 shows that for WBS, smooth slipstreams are can be seen clearly. For TWS, the generation of the tip vortices can be seen. The envelope of the swirly areas begins to be located above the rotor disk plane. We can also notice the presence of an area of high amplitude of vorticity at the root of blade. It is linked with the high level of local thrust. For VRS, the tip vortices are clustered at the tip of blades. The envelopes of the recirculation zones become larger and are now largely located at the rotor disk plane. Hence, validation shows that VLM can predicts well the numerical value as well as the flow-field of turbulent wake state and vortex ring state.

3.2 Simulation for floating wind turbines

The well-known NREL offshore five mega-watt wind turbine [10] was chosen, and to focus on the aerodynamics of floating wind turbine, prescribed simple harmonic platform pitch angle was used. The pitch amplitude is three meter, and period is twelve second, which is similar to barge platform's pitching motion. The simulation of operating condition is four point five meter per second and rpm is seven point six. This is low wind speed condition which is known as highly unsteady aerodynamics is occurred.

First, to verify the outbreak of unsteady flow in the floating wind turbine at low wind speed condition, we compared the flow-field of fixed wind turbine' and floating wind turbine. In the figure 5 (a), the fixed turbine shows slipstream flow at low wind speed condition. But in the figure 5 (b), floating wind turbine shows the unsteady flow field like turbulent wake state. This is because the net convection of growing tip vortex becomes low since periodic disturbances are added by floating platform motion. Hence, we could verify the occurrence of unsteady flow in the floating wind turbine. At next, we examine the cause of turbulent wake state. According to previous research,

the unsteady flow arises from platform pitching motion at downward direction. At this movement, the induction factor, which is induced velocity divided by inflow velocity, is higher than zero point five. Typically, it means high thrust coefficient and unsteady flow. The induction factor is very high at the top of the rotor plane of location three in figure 6. We could know the possibility of cause of turbulent wake state. At next, we investigated the sectional thrust at each location of floating wind turbine if the high induction factor causes high loading. As can be seen in figure 7, different from the expectation, we could found that the sectional thrust is the least at location three. And, at the location seven, the sectional thrust is the most although axial induction factor is lower than location 3's. This is because the relative wind at the rotor is very small due to backward pitching motion/ at the location three. In other words, even though the induction factor cause high thrust coefficient, thrust is low since the dynamic pressure is very low at the location three. Hence, we inspected the location seven at the next.

Figure 8 shows the normal vorticity contour and streamlines at the location 7. At the top of the rotor, the recirculating flow can be seen. This is because the relative velocity of the top of the blade is high due to platform upward pitching motion, and rpm is increasing to earn more power, this serves as increasing of tip speed ratio. In high TSR, clustering of tip vortex are growing since the convection of tip vortex is low. Therefore, different from previous research, it shows that the complex flow occur at upward platform pitching motion.

4. CONCLUSION

In this paper, we have investigates flows states of floating wind turbine in platform pitching motion using numerical method, vortex lattice method. In validation case, it shows that VLM can predict well the numerical value as well as the flow-field of turbulent wake state and vortex ring state. In simulation of floating wind turbine, we could figure out that TWS are occurred when floating wind turbine is operated in low speed inflow condition. Also, as different from previous research, it has been shown that TWS is encountered when floating platform is pitching at upwind direction. In particular, the work presented here suggests that convection of tip vortex play an important role in governing of the behavior of the rotor in the TWS.

5. ACKNOWLEDGEMENT

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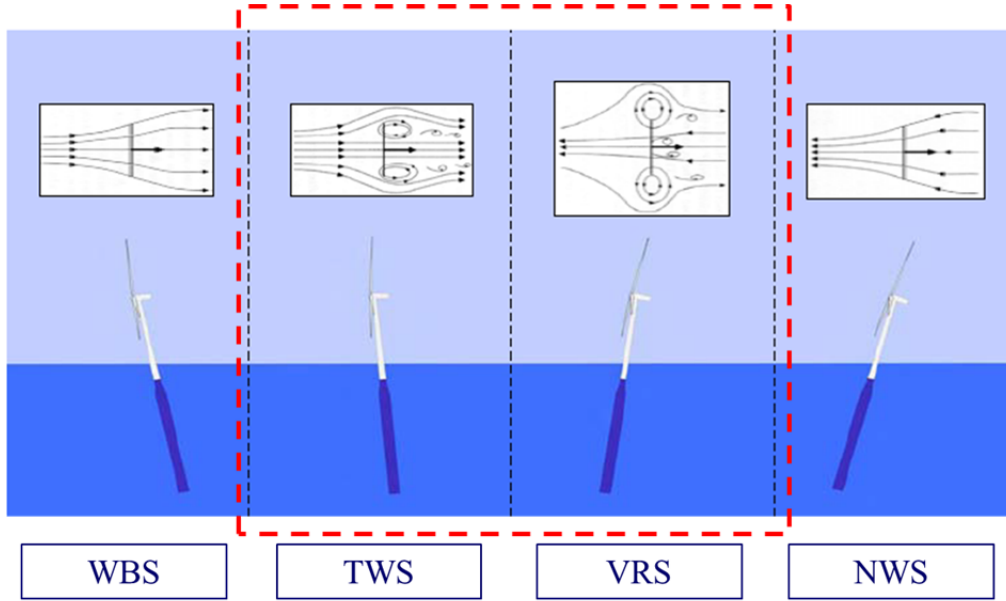


Fig. 1 Hypothetical flow states of FOWT during platform pitching motion [2].

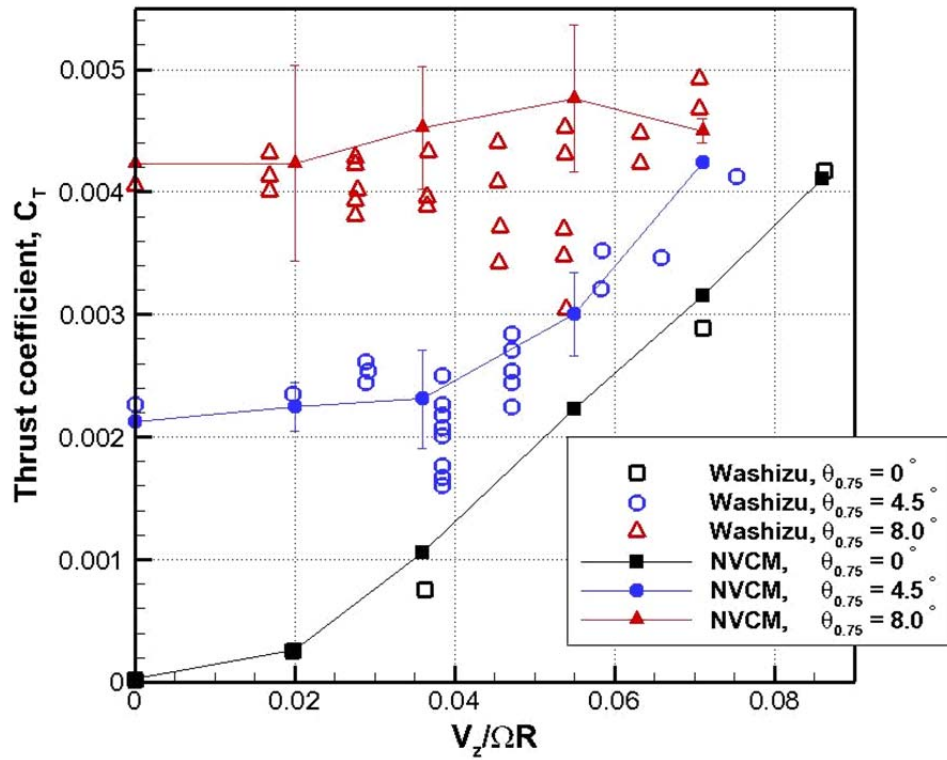


Fig. 2 Thrust coefficient versus vertical flight velocity factor for different values of the pitch angle at blade section $x=0.75$.

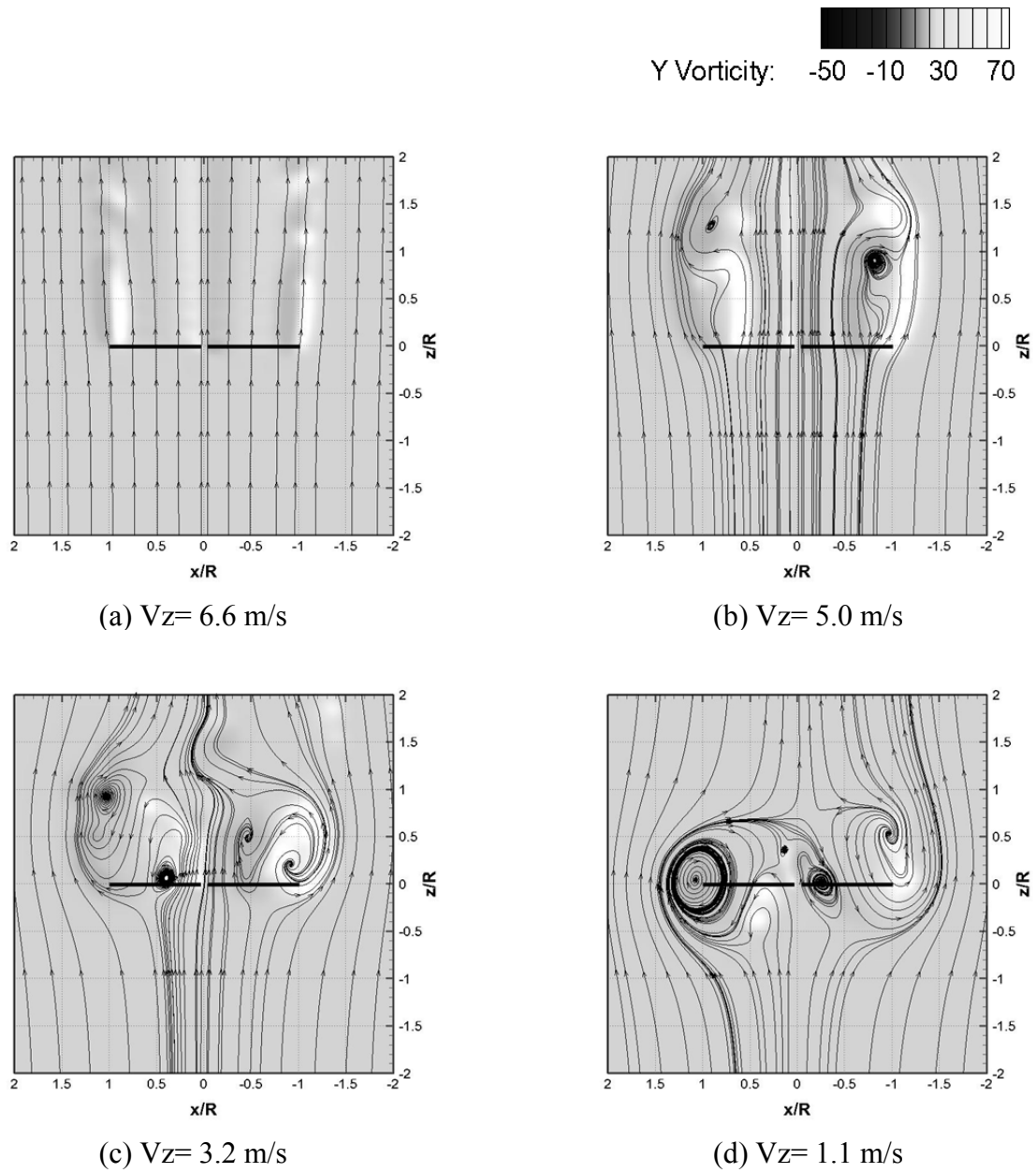


Fig 3. Normal vorticity fields and streamlines at $\theta_{0.75} = 4.5^\circ$ —
(a) $V_z = 6.6$ m/s (b) $V_z = 5.0$ m/s (c) $V_z = 3.2$ m/s (d) $V_z = 1.1$ m/s.

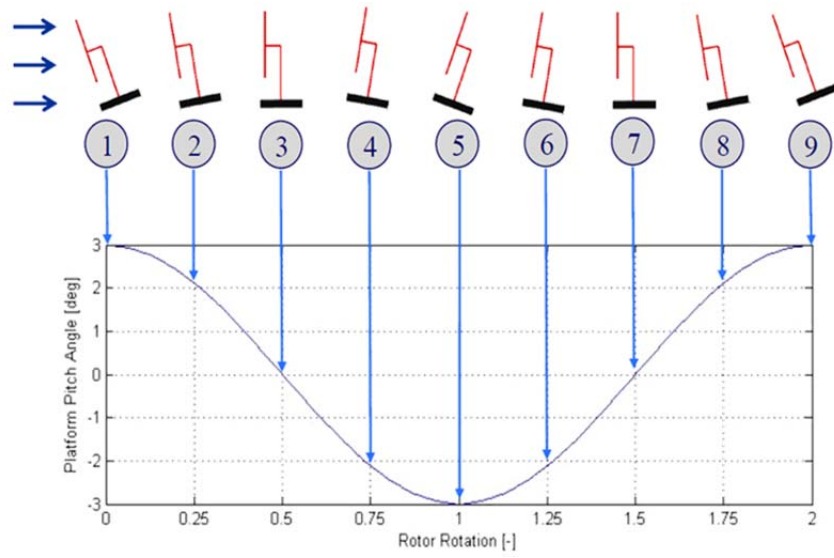
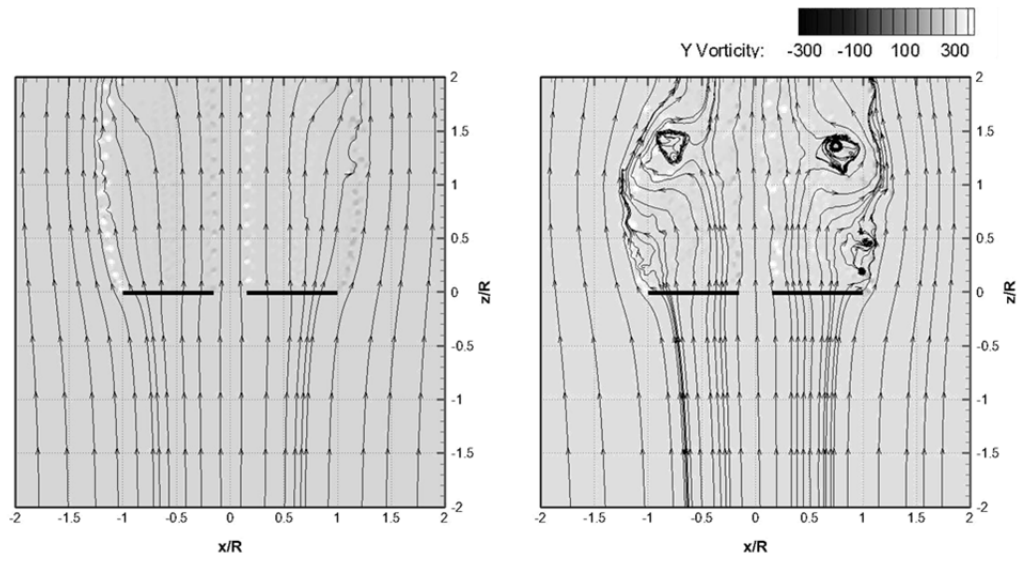


Fig 4. Floating turbine stance during pitching motion



(a) Fixed wind turbine

(b) Floating wind turbine

Fig 5. Normal vorticity fields and streamlines at $V_z = 4.5\text{m/s}$

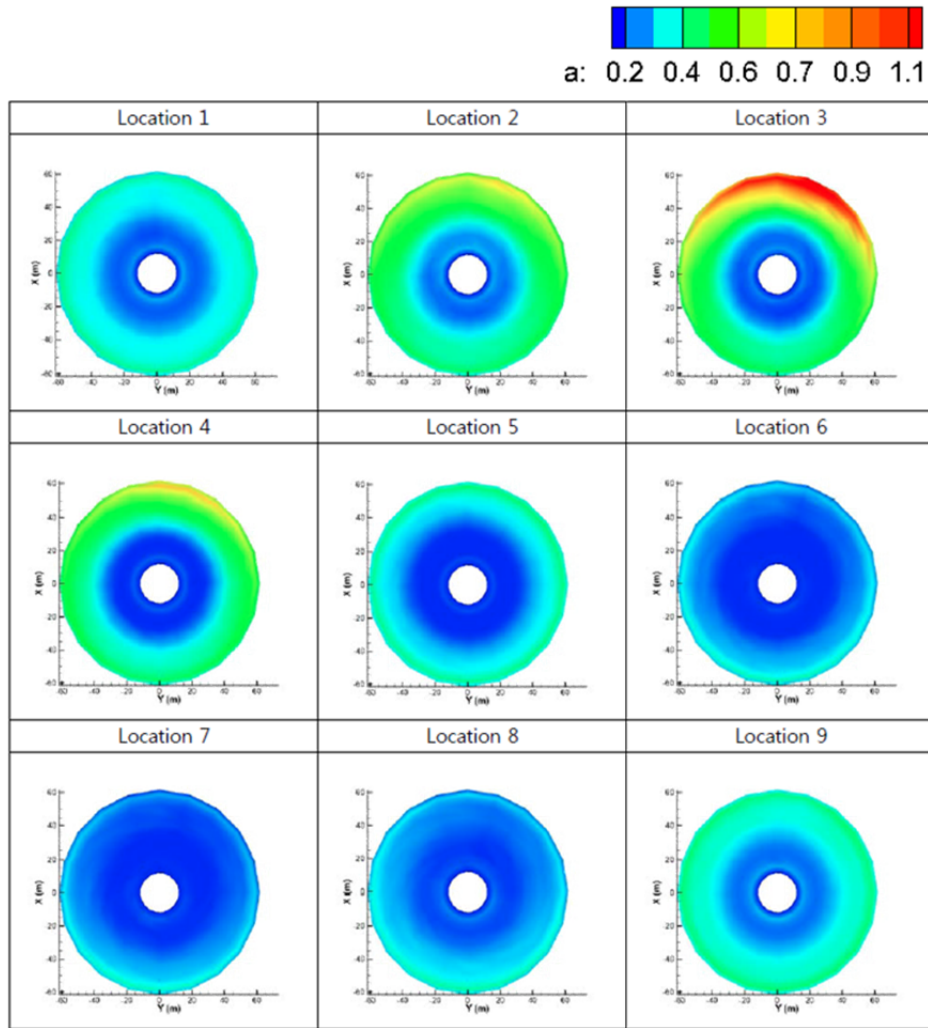


Fig 6. Local induction factor at each platform pitching location

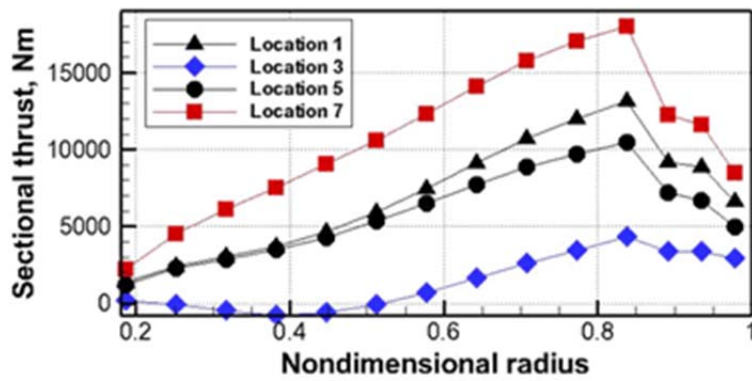


Fig 7. Local induction factor at each platform pitching location

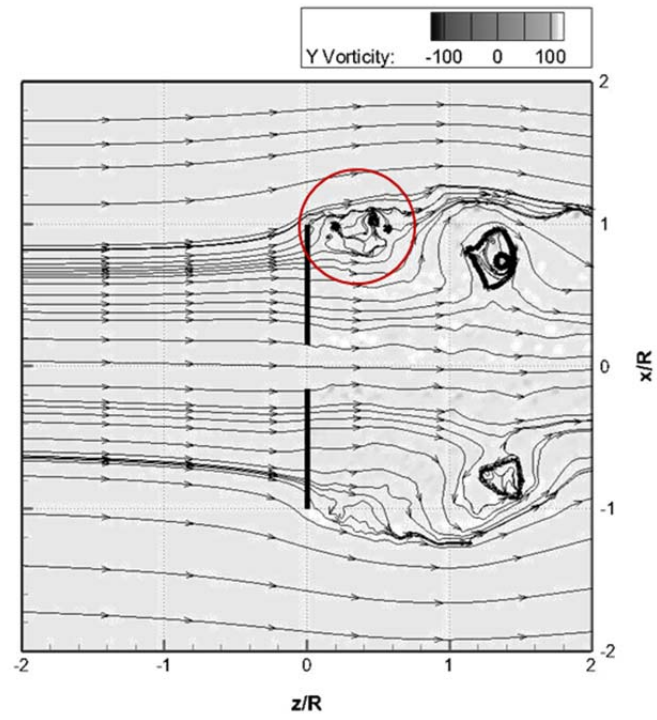


Fig 8. Normal vorticity fields and streamlines of floating wind turbine at location 7