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Unsteady aerodynamics of offshore floating wind turbines in platform pitching motion using vortex lattice method

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ABSTRACT

As the flow states of an offshore floating wind turbine (OFWT) differ from those of an onshore fixed wind turbine, it is questionable as to whether the aerodynamic load prediction of a turbine using conventional blade element momentum theory (BEMT) is accurate. The aim of this paper is to show the characteristics of aerodynamic load predictions using the vortex lattice method (VLM). Washizu's experimental data, which was measured under a similar flow state of a floating wind turbine, is used for validation. The prediction shows good results compared to those of an experiment. To determine the unsteady aerodynamics of a floating wind turbine, the NREL 5 MW wind turbine model is used for the simulation of a floating wind turbine. These results show that a turbulent wake state (TWS), which is undesirable condition and cannot predicted in BEMT simulation, arises when a floating wind turbine is operated at a low-speed inflow condition. In addition, the rotor experiences a TWS when the floating platform undergoes upward pitching motion.

1. Introduction

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

In a floating state, as they are operated under complex condition, offshore wind turbines should be analyzed differently from fixed wind turbines. In particular, while a fixed wind turbine has simple flow state, the offshore floating wind turbine (OFWT) experiences complex flow states when the floating platform is in motion. These include the normal working state (NWS), the turbulent wake state (TWS), the vortex ring state (VRS) and the windmill braking state (WBS). Fig. 1 shows how various flow states occur when the floating platform undergoes pitching motion. The flow associated with the WBS is smooth and definite slipstream, which is the normal condition of a wind turbine. When the platform starts pitching backward, the flow experiences a high level of turbulence. At the boundary between the WBS and TWS, the flow state with a smooth slipstream changes abruptly to a state characterized by recirculation and turbulence, as the velocity in the far wake changes direction. As the platform's pitching velocity increases, the definite slipstream disappears and the flow near the rotor disk becomes highly unsteady and turbulent. Thomas et al. [2] show that the occurrence of a breakdown of the slipstream is twice as likely to occur with a floating wind turbine as compared to an offshore wind turbine of the monopile type under a low wind speed condition.

The aerodynamic modeling of wind turbines relies on three approaches: blade element momentum theory (BEMT), the vortex lattice method (VLM) and computational fluid dynamics (CFD). BEMT is very simple engineering model based on simple

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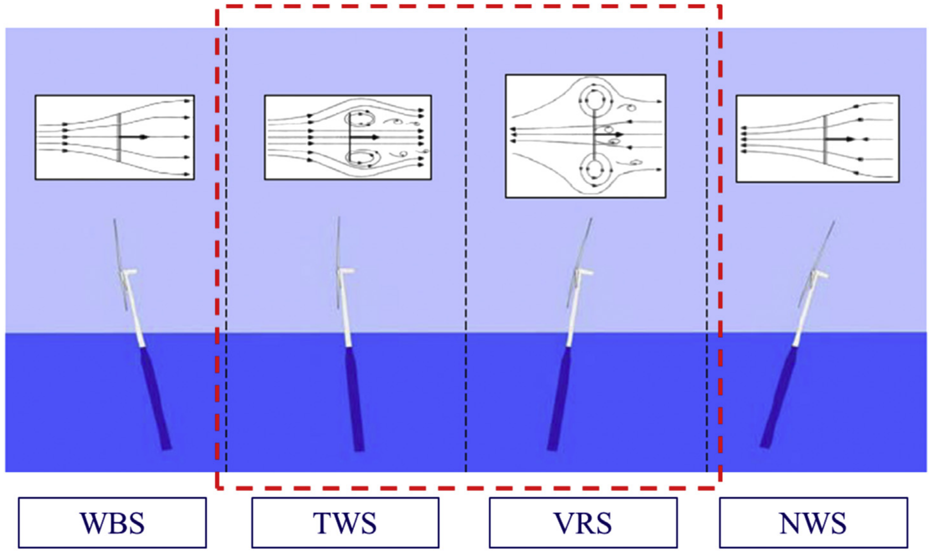

Fig. 1. Hypothetical flow states of OFWT during platform pitching motion [2].

momentum and strip theory. Owing to the comprehensible assumptions of this method, it should be used in conjunction with correction methods, such as the dynamic stall, Glauert's thrust correction, Prandtl's tip loss function, and the stall delay model. In spite of the various assumptions and approximations associated with the BEMT, it can provide good preliminary predictions in relatively simple flow states such as the WBS and TWS [3]. However, it is incomplete when used to consider all types of complex flow states that arise with an OFWT. BEMT has two major weaknesses in such an analysis. First, it assumes that the wake is frozen, though the wake of a floating wind turbine is highly unsteady. To counterbalance this condition, dynamic inflow models have been developed. A generalized dynamic wake model, which is mainly used as a dynamic inflow model during wind turbine simulations, is not suitable in highly loaded rotor conditions such as recirculating flows, as it assumes that the mean induced velocity is small relative to the mean inflow velocity [4]. Second, BEMT's slipstream assumption is not satisfied when the freestream velocity is greater twice than the induced velocity at the rotor. Although Glauert's empirical formula is applied in this condition, the feasibility of Glauert's empirical correction is questionable in VRS because the formula was created using measurement data in the TWS. Also, as platform pitching and yawing motion introduce significant effective wind shear conditions, correction as regards a non-axial flow is unsatisfactory. Another method, CFD, which solves Euler or Navier–Stokes equations, provides more physically realistic simulations; however, it is not yet a practical method in the design process because it incurs a significant computational cost. In other words, as an engineering model, VLM is a viable method as it can represent the non-uniform induced effects associated with the vertical wake trailing from the turbine. This method has the flexibility to include a wide range of validated sub-component models representing various physical effects that are difficult to model from 1D momentum theory. It has been widely developed for use in helicopter rotor analyses, dating from the 1960s, but has still yet to see significant use for wind turbine applications.

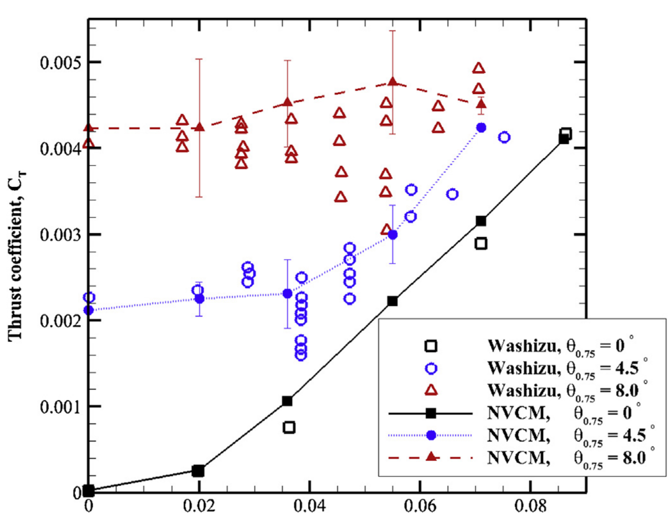

Fig. 2. Thrust coefficient versus vertical flight velocity factor for different values of the pitch angle when the blade section *x* equals 0.75.

Therefore, in this study, we investigated the characteristics of the aerodynamics of an offshore floating wind turbine undergoing platform pitching motion using VLM to provide more physical insight into 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 trailing each blade and are convected into the downstream wake. This can be satisfied using the VLM, which is based on the assumptions and theory described 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, the velocity potential, Φ, becomes the Laplace equation. Using Green's theorem, the general solution to a Laplace equation can be

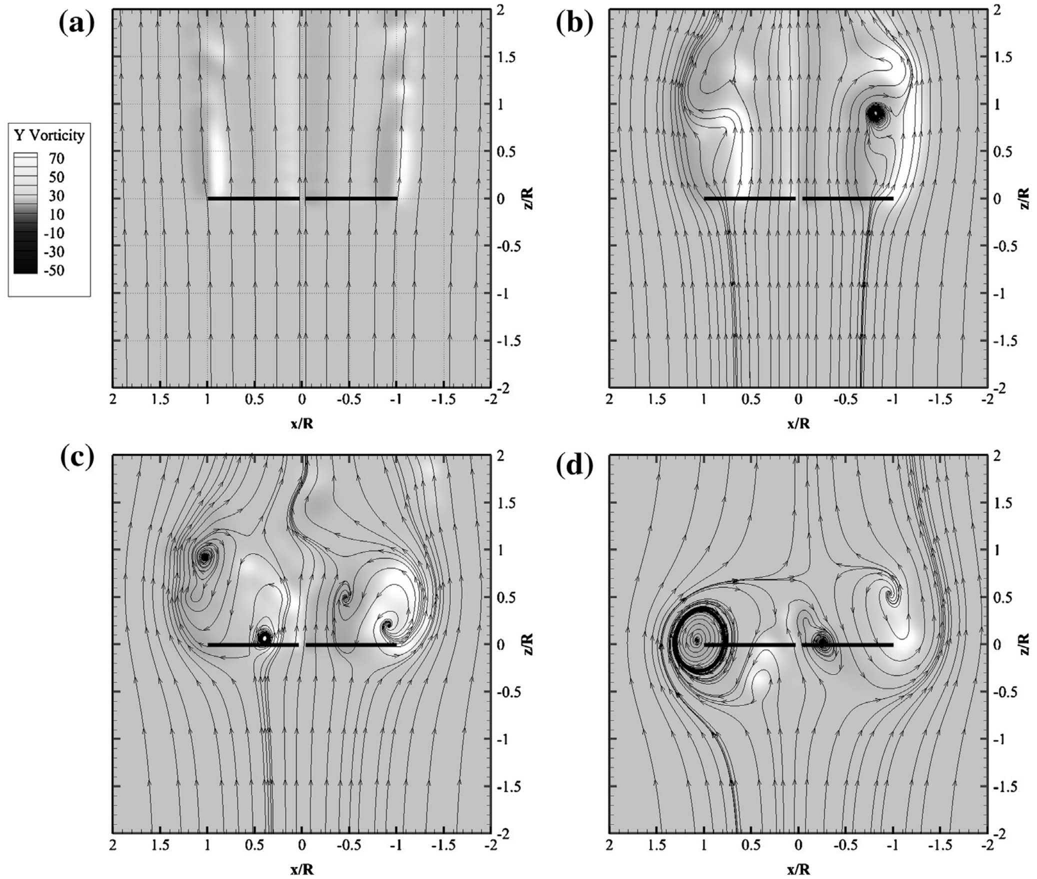

Fig. 3. Normal vorticity fields and streamlines at $\theta_{0.75} = 4.5^\circ$ – (a) Vz = 6.6 m/s, (b) Vz = 5.0 m/s, (c) Vz = 3.2 m/s, (d) Vz = 1.1 m/s.

formulated by the sum of the source and doublet distributions on the boundary.

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

Source and doublet distributions are solved by implementing two boundary conditions. The first boundary condition requiring a zero normal velocity across the body's solid boundaries is called the Neumann boundary condition. The second boundary condition requires that the flow disturbances arising due to the body's

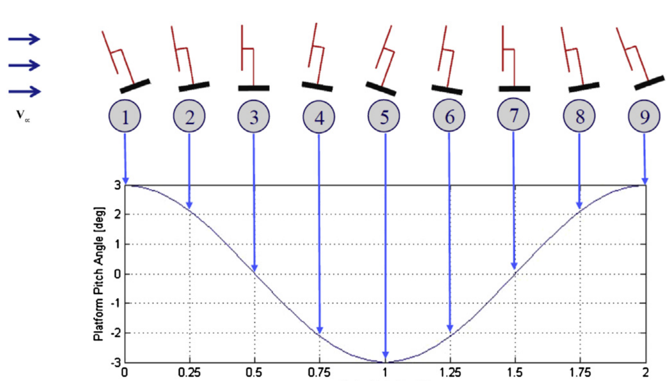

Fig. 4. Floating turbine stances during pitching motion.

motion through the fluid should diminish far from the body. Finally, aerodynamic force generated by the vortex sheet is calculated by the Kutta–Joukowski theorem (see more details in Ref. [5]).

To consider the thickness and viscous effects, a 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 the three-dimensional effects of the rotor blades, the Du and Selig stall delay model is implemented [7]. The Blade was divided into twenty-eight panels in all simulations.

The additional calculation compared to calculation of onshore wind turbine is needed as this wind turbine system is moving. So, the lattice of rotor blade is shifted in the global coordinate system. Also, relative velocity on the rotor blade by floating platform's motion is added when calculating velocity on the blade surface.

The rotor blade is assumed to be rigid. Aeroelastic effects may have been influenced accuracy of aerodynamic load. However, aeroelasticity is a little effect on the tendency of results as the change of rotor blade is small compared to floating platform's unsteady motion.

3. Results & discussion

3.1. Validation

To validate the in-house numerical code in VRS, predictions are compared with Washizu's experimental data [8], which is a

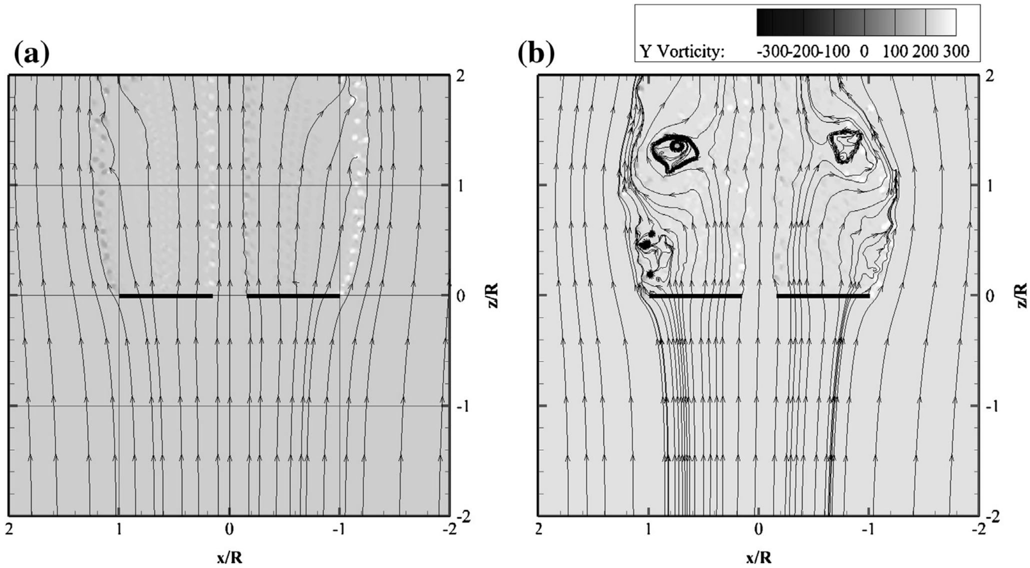

Fig. 5. Normal vorticity fields and streamlines at Vz = 4.5 m/s – (a) fixed wind turbine, (b) floating wind turbine.

moving track test of a rotor 1.1 m in diameter in descent for axial conditions. As this experiment comprises all flow states and is a typical VRS experiment, it is appropriate for the validation of a floating wind turbine. The three-bladed rotor used for the validation process has a solidity value of 0.0573 with an 8.33 deg twist. The rpm is 1000 rpm and the chord value is 0.033 m. The airfoil of each blade is a NACA 00012. Data for the aerodynamic coefficients of the NACA 0012 were sourced from experimental results [9].

The measured and predicted thrust coefficients are shown in Fig. 2. The prediction shows that VLM predicts the value near upper border of fluctuations well for a complete interval of $V_z/\Omega R$. The normal vorticity fields perpendicular to the *Y* axis as the descent velocity are shown in Fig. 3. Fig. 3 clearly shows smooth slipstreams for WBS. For a TWS, the generation of the tip vortices can be seen. The envelope of the swirly areas gradually arises above the rotor disk plane. We also noted the presence of an area of high amplitude of the vorticity at the root of the blade. It is linked to a high level of local thrust. For VRS, the tip vortices are clustered at the tip of the blades. The envelopes of the recirculation zones become larger and at this point become mainly located on the rotor disk plane. Hence, the validation shows that the VLM can feasibly predict the numerical values as well as the flow-fields of a turbulent wake state and a 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 the floating wind turbine, a prescribed simple harmonic platform pitch angle was used (Fig. 4). The pitch amplitude is 3 m, and the period is 12 s, both of which are similar to the pitching motion of a barge platform. The simulation of the operating condition is defined by a wind speed of 4.5 m/s and a rpm of 7.6. This is low wind speed condition which is known as highly unsteady aerodynamic state.

First, to verify the outbreak of an unsteady flow in the floating wind turbine under a low wind speed condition, we compared the flow-field of a fixed wind turbine and a floating wind turbine. In Fig. 5(a), the fixed turbine shows a slipstream flow at a low wind speed condition. However, in Fig. 5(b), the floating wind turbine shows an unsteady flow field, similar to a turbulent wake state. This arises because the net convection of the growing tip vortex becomes low, as periodic disturbances are added by the floating platform motion. Hence, we could verify the occurrence of an unsteady flow in the floating wind turbine. Next, we examined the cause of the turbulent wake state. According to previous research, an unsteady flow arises from platform pitching motion in the downward direction. During this movement, the induction factor, which is the induced velocity divided by the inflow velocity, is higher than 0.5. Typically, this signifies a high thrust coefficient and unsteady flow. The induction factor is very high at the top of the rotor plane at location three in Fig. 6. We could determine the possibility of a turbulent wake state. Next, we investigated the sectional thrust at each location of the floating wind turbine if a high induction factor causes high loading. As shown in Fig. 7, in contrast to expectations, we found that the sectional thrust is the lowest at location three. In addition, at location seven, the sectional thrust is the highest despite the fact that the axial induction factor is lower than it is at location three, as the relative wind at the rotor is minor due to the backward pitching motion at location three. In other words, although the induction factor causes a high thrust coefficient, the thrust is low because the dynamic pressure is very low at location three. Hence, we inspected location seven next.

Fig. 8 shows the normal vorticity contour and streamlines at location seven. At the top of the rotor, a recirculating flow can be seen, as the relative velocity of the top of the blade is high due to upward pitching motion of the platform. Moreover, the rpm increases to supply more power. This serves to increase the tip speed ratio. With a high tip speed ratio, clustering of the tip vortex increases given that the convection of the tip vortex is low. Therefore, in contrast to the hypothetical concepts [2], this shows that a complex flow can occur during the upward pitching motion of the platform.

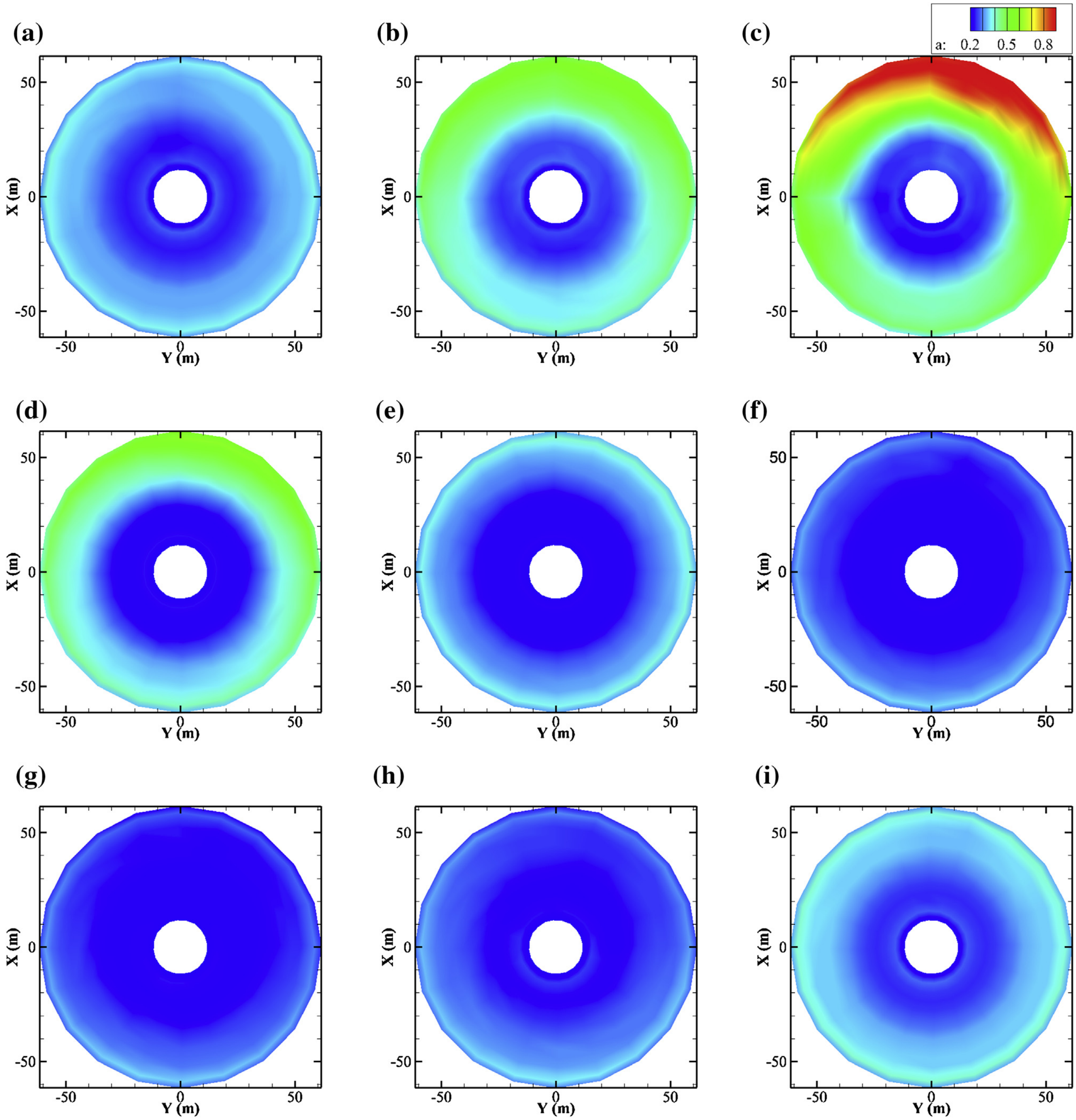

Fig. 6. Local induction factor at each platform pitching location – (a)–(i) : locations 1–9 in Fig. 4.

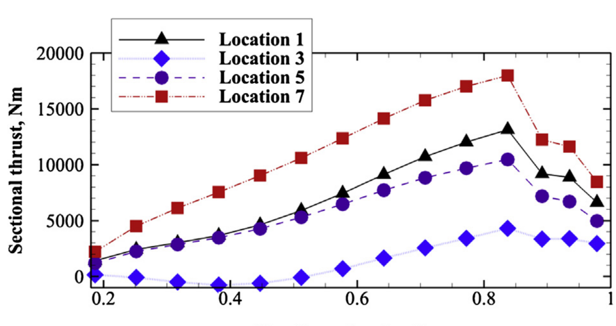

Fig. 7. Local induction factor at each platform pitching location.

4. Conclusion

In this paper, we investigated the flow states of a floating wind turbine during platform pitching motion using a numerical method, in this case the VLM. For validation, it was found that the VLM can predict well the numerical value as well as the flow-field of a TWS and a VRS. During a simulation with a floating wind turbine, we determined that a TWS, which is unwanted aerodynamic phenomena, occurs when the floating wind turbine is operated at a low-speed inflow condition. Also, in contrast to the hypothetical flow states, it was shown that a TWS arises when the floating platform is pitching in the upwind direction. In particular,

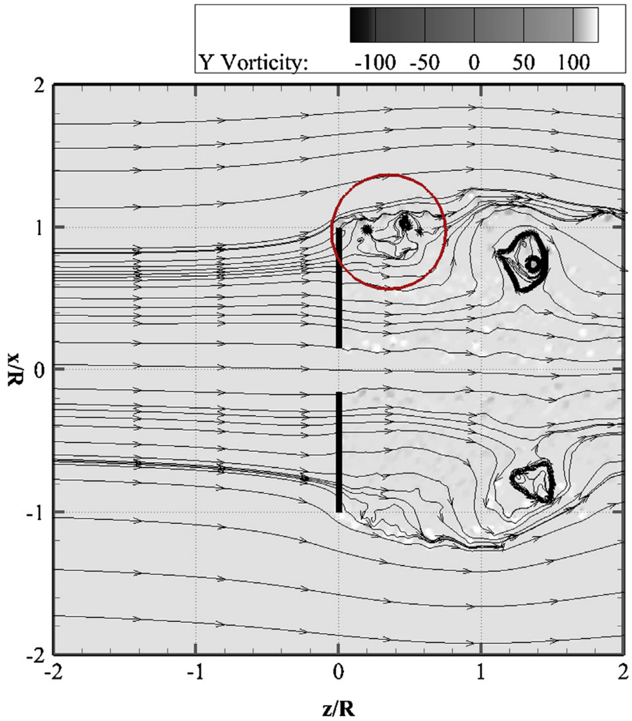

Fig. 8. Normal vorticity fields and streamlines of the floating wind turbine at location seven.

the work presented here suggests that the convection of the tip vortex plays an important role in governing of the behavior of the rotor in a TWS.

Acknowledgment

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