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

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A B S T R A C T

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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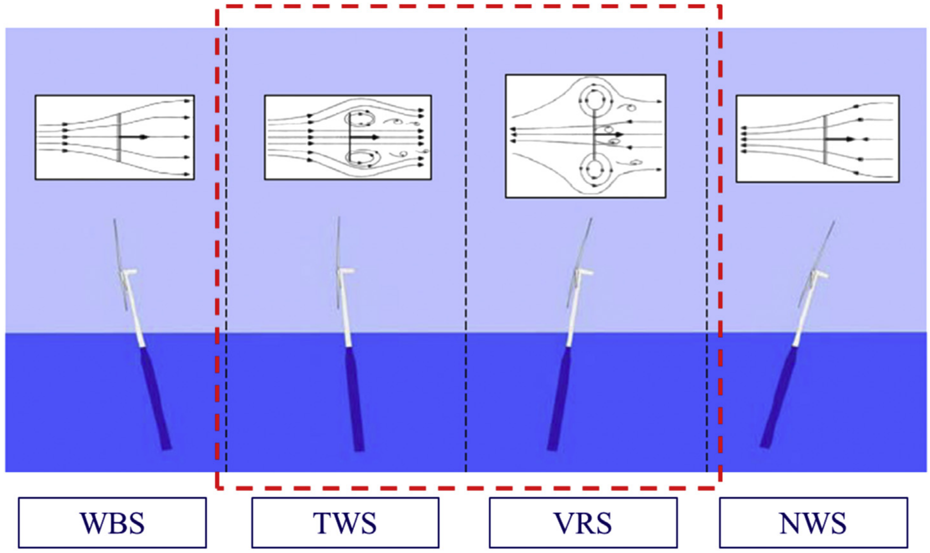

Fig. 1. Hypothetical flow states of OFWT during platform pitching motion [2].

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

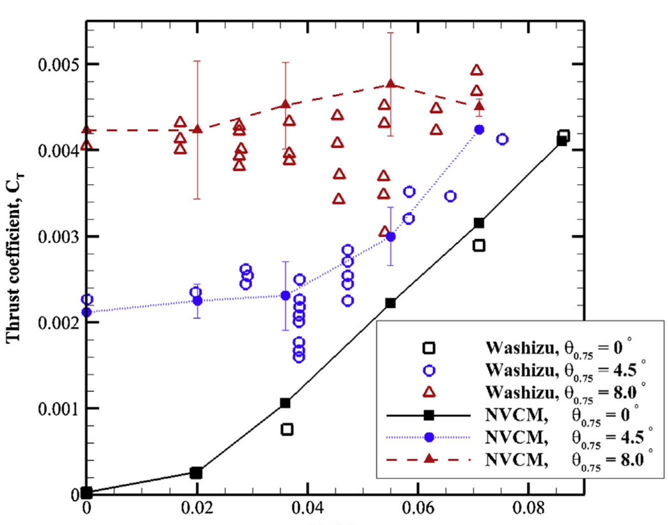

Fig. 2. Thrust coefficient versus vertical flight velocity factor for different values of the pitch angle when the blade section *x* equals 0.75.

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.

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