Ocean Engineering 127 (2016) 200–211

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Numerical investigations on flow structure and behavior of vortices in the dynamic stall of an oscillating pitching hydrofoil

Hamid Reza Karbasian, Kyung Chun Kim*

School of Mechanical Engineering, Pusan National University, Pusan 609-735, Republic of Korea

A R T I C L E I N F O

Keywords:
Dynamic stall
Oscillating hydrofoil
Hydrokinetic energy convertor
Marine current turbine
Post-stall

A B S T R A C T

This study numerically investigates the behavior of vortices and flow structure in a dynamic stall phenomenon, especially in post-stall where the flow is highly nonlinear. Computational fluid dynamics approaches were used to simulate unsteady flow fields. The Transition SST turbulence model was used to compute the turbulent characteristics, and second-order temporal/spatial schemes were used to reduce dissipation effects. To investigate the behavior of vortices individually, each main vortex core was targeted manually and its strength is computed. It is shown that despite the existence of coherent structures, the interaction of organized vortices is responsible for the complexity of the flow beyond the hydrofoil in post-stall. The primary LEV and primary TEV have the longest lifetime among the LEVs and TEVs, respectively. The Primary LEV loses strength quickly due to counteraction with the TEV and disruption of the energy source provided by the leading edge shear. The secondary LEV plays an important role when dynamic stall occurs and provides a lift peak in post-stall. There are time delays between the maximum circulation of main vortices and corresponding peak of the lift coefficient loop. The general interaction of counter-rotating vortices is responsible for these delays between peaks of the lift coefficient and maximum circulations.

1. Introduction

Unsteady flow around the blades of wind turbines and hydrokinetic energy convertors (i.e. marine current turbines or flapping-foil energy convertors) change the dynamic response of these systems. Therefore, loads through the blades can change dramatically and cannot be predicted in steady state mode. In the other words, the process of separation and reattachment has drastic effect on aero/hydrodynamics of foil (Leishman, 2006). One of the reasons for these unexpected dynamic responses might be the dynamic stall phenomenon (Ericsson and Reding, 1988), which occurs when series of flow separations, reattachments, and vortex core formation occur on any lifting surface or blade (Wernert et al., 1996). It should be mentioned that the vortex cores refer to those vortices which are created due to drastic shear layer in pressure gradient. These vortex cores are the main vortices that can be observed in dynamic stall phenomenon. Dynamic stall occurs when the lifting surface is subjected to a quick motion of fluid or change in its direction (Wang et al., 2010). For hydrokinetic turbine blades, any dynamic change in flow or a blade that leads to variations in angle of attack (AOA) or free stream velocity causes dynamic stall (Gupta and Leishman, 2006).

Dynamic stall may delay the static stall of a hydrofoil and increase hydrodynamic loads at higher angles than the static-stall angle of attack. In this phenomenon, the low-pressure leading edge vortex (LEV) and trailing edge vortex (TEV) interactions cause notable load variations. During dynamic stall, the LEV and TEV are involved in the production and destruction of loads, respectively. In vortex interaction, the dynamic stall proceeds initially with attached flow at low AOA. LEV formation occurs when increasing the AOA, which delays static stall (Gharali and Johnson, 2013). In the next step, TEV formation and LEV shedding from the suction side of the hydrofoil are responsible for stall, which leads to abrupt changes in hydrodynamic loads.

Ko and McCroskey (1997) and Martin et al. (1974) did preliminary studies on dynamic stall. This subject has attracted many scientists to investigate this phenomenon. Dynamic stall is considered as a big challenge in energy conversion, aerospace, and hydrodynamic propulsion systems. Many efforts have been made to improve the propulsive performance of flapping hydrofoils based on the preliminary concepts of dynamic stall at low to medium Reynolds numbers (Esfahani et al., 2015; Hoke et al., 2015; Lu et al., 2013a). The concepts have also been used to increase the power efficiency of hydrokinetic energy convertors (Karbasian et al., 2015a; Tian et al., 2014; Wu et al., 2015; Young et al., 2014). With regard to separation behavior of subsonic flow around a moving foil two distinct stall regimes can be defined. McCroskey (1982)

---

* Corresponding author.
E-mail address: kckim@pusan.ac.kr (K.C. Kim).

http://dx.doi.org/10.1016/j.oceaneng.2016.10.005
Received 19 February 2016; Received in revised form 28 July 2016; Accepted 3 October 2016

differentiated them to light and deep dynamic stall. In deep dynamic stall the massive flow separation is initiated in up-stroke phase, creating a large separated region behind the foil. The reattachment of flow may not occur until the angle of attack reaches much lower than the static angle (Tsang et al., 2008). On the other hand, in light dynamic stall case, the primary LEV is not yet fully developed before beginning of down-stroke phase. The primary LEV evolution is prematurely terminated in light dynamic stall case and then a lower strength vortex than that of deep dynamic stall might be expected (Mulleners and Raffel, 2012).

The dynamic stall phenomenon can be seen in different industrial applications with reference to the Reynolds number, which is characterized as follows:

$$\mathrm{Re} = \frac{\rho c U}{\mu} \tag{1}$$

where ρ, μ, and U are the fluid density, viscosity, and free-stream velocity, respectively. The characteristic length c can be considered as the chord length of a hydrofoil. Most recent work on numerical simulation regarding dynamic stall deals with low or high Reynolds numbers. Dynamic stall at high Reynolds number ($\mathrm{Re} > 10^6$) is considered for turbomachinery, aircraft, or helicopter rotors, while low Reynolds numbers are considered for flying birds or small turbine operations. Small to medium wind or hydrokinetic turbines operate at medium Reynolds number on the order of 10^5 (Wang et al., 2012). In this case, the flow in association with deep stall is highly nonlinear (Poirel et al., 2011). To study dynamic stall in this range, Wang et al. (Wang et al., 2010, 2012) investigated the dynamic stall of a NANCA 0012 foil at moderate Reynolds number for small to medium wind turbines. Gharali and Johnson (2015) also considered the unsteady free-stream flow field in conjunction with pitching motion to understand the unsteadiness of flow velocity in the dynamic stall process.

Almohammadi et al. (2015) assessed numerically the dynamic stall of a straight blade. They mentioned that the transition affected the overall turbine performance up to 20%. Thus, they confirmed that it is crucial to consider laminar-turbulence transition in numerical modeling of deep dynamic stall. On the other hand, Buchner et al. (2015) found that the turbulence models associated with URANS are still too dissipative in their considered case. Nevertheless, they mentioned that dynamic stall characteristics could be simulated accurately with trifle discrepancies. Wong et al. (2013a, 2013b) considered vortex strength in dynamic stall based on vortex circulations. They measured the circulation of LEV and TEV during the process and indirectly computed the hydrodynamic loads. Prangemeier et al. (2010) also investigated the LEV and TEV circulation (strength) and reported how to reduce TEV strength for an oscillating plunging foil.

Although the circulation of the main vortices has been considered for low Re, there are no findings about the overall coherent structure and behavior of vortices during dynamic stall at medium Re. To our knowledge, there are no conventional studies on the strength and lifetime of major vortices related to dynamic stall. Most research is based on the LEV and TEV. During the down-stroke, consecutive vortex creation, growth, and shedding occur. There are not many comprehensive studies on the flow structure during post-stall. The main objective of this study is to detect major vortices and study their lifetime, strength, and influence on hydrodynamic loads in dynamic stall phenomenon, especially during the post-stall. In this procedure, the vortices are targeted manually, and their strength is computed using the circulation magnitude (Stoke's circulation theorem). The lifetime and order of creation can be estimated based on the strength of vortices. A Computational Fluid Dynamics (CFD) approach was used to simulate the flow field around a two-dimensional (2D) NACA 0012 foil, and the strength of each vortex was computed in rectangular windows using scalar integration of the vorticity magnitude over the whole window.

2. Physical model and studied case

Dynamic stall can occur by different mechanisms in wind turbine and hydrokinetic energy systems. Transversal vibration of blades, pitching, yawing, variations in fluid velocity, and even dynamic behavior of the turbine (cut-in/cut-out) are responsible for dynamic stall (Gharali and Johnson, 2015; Karbasian et al., 2016). Despite the different kinematic mechanisms for dynamic stall, an oscillating pitching hydrofoil can be a good concept for dynamic stall and has been used extensively for numerical examinations (Ko and McCroskey, 1997; Leishman, 1990; Lu et al., 2013a, 2013b). However, the pitching motion of the hydrofoil introduces a sinusoidal angle of attack α as a function of time:

$$\alpha(t) = \alpha_0 + \alpha_m \sin(2\pi f t) \tag{2}$$

where α_O, α_m, f, and t are the mean angle of attack, pitch amplitude, oscillating frequency, and operating time, respectively. The oscillating frequency can be determined by the reduced frequency, k:

$$k = \frac{\pi f c}{U} \tag{3}$$

The reduced frequency represents the ratio of the convective time scale and the forced oscillation time scale (Leishman, 2006). A NACA 0012 foil was selected to oscillate with the motion pattern α=10°+15°sin($2\pi ft$), and the reduced frequency is k=0.1. The chord length is c=0.1 m, and the corresponding Reynolds number of the free-stream velocity is Re=1.35×10^5 with a turbulence intensity of 0.08%. These parameters were selected based on available experimental results for a pitching foil (Lee and Gerontakos, 2004). There have also been numerical investigations based on these experimental works (Gharali and Johnson, 2013; Wang et al., 2012).

Based on the report by Lee and Gerontakos (2004), much care has been taken during the experiments to eliminate three-dimensional (3D) flow effects on measurements of the aerodynamic loads. The hydrodynamic loads are reported based on the non-dimensional form of lift and drag coefficients:

$$C_L, C_D = \frac{[L, D]}{0.5\rho U^2} \tag{4}$$

where L and D are the lift and drag forces, respectively. The lift and drag forces are captured from both pressure and shear forces acting on the hydrofoil surface.

3. Numerical method

3.1. Solver set-up

A simulation of 2D flow over an oscillating pitching hydrofoil was carried out using the Finite Volume Method (FVM) approach. The CFD flow solver package ANSYS Fluent version 16.1 (ANSYS Fluent, Academic Research, V16.1, 2015) was used for the modeling. Unsteady Reynolds averaged Navier-Stokes (URANS) calculations were used to solve the flow pattern around the hydrofoil. The selected turbulence model is the Transition Shear Stress Transport (SST) model, which can be examined as a four-equation turbulence model (Menter et al., 2006). Two of the transport equations predict the turbulence characteristics (SST k-ω model for prediction of turbulent kinetic energy k and specific dissipation rate ω) (Menter, 1994). The other transport equations predict the intermittency and transition onset criteria (Menter et al., 2006). The SST k-ω part of this model can capture the flow field around the dynamic hydrofoil for various ranges of Reynolds numbers (Karbasian et al., 2015b, 2016; Ol et al., 2009; Wang et al., 2010). Furthermore, in the Transition SST turbulence model, some empirical coefficients should be selected as an input for the model. The transition onset can be influenced by these coefficients. In the present model, these coefficients were selected base