International Journal of Heat and Fluid Flow 54 (2015) 183–195

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

A study of the energetic turbulence structures during stall delay

Yanhua Wu [a,*], Hsiao Mun Lee [a,1], Hui Tang [b]

[a] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore
[b] Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

ARTICLE INFO

Article history:
Received 10 February 2015
Received in revised form 16 April 2015
Accepted 23 May 2015
Available online 10 June 2015

Keywords:
Turbulence structures
Stall delay
Tomographic PIV
Separated turbulent flow

ABSTRACT

This study revealed the three-dimensional instantaneous topologies of the large-scale turbulence structures in the separated flow on the suction surface of wind turbine's blade during stall delay. These structures are the major contributors to the first two POD (proper orthogonal decomposition) modes. The two kinds of instantaneous flow structures as major contributors to the first POD mode are: (1) extended regions of downwash flow with an upstream upward flow beside it and a compact vortex pair closer to the blade's leading edge; (2) a large-scale clockwise vortex with strong induced flows. The two kinds of flow structures contributing significantly to the second POD mode are: (1) large counter-rotating vortices inducing strong upward velocities and a series of small vortices; (2) strong downwash flow coming from the leading-edge shear layer with a large and strong vortex on the left side and small vortices upstream. The statistical impacts of these large-scale and energetic structures on the turbulence have also been studied. It was observed that when these turbulence structures were removed from the flow, the peak values of some statistics were significantly reduced.

1. Introduction

Stall delay is an interesting aerodynamic phenomenon on the blades of rotating machinery such as helicopter rotors and wind turbines. It was first observed by Himmelskamp (1945) in 1945 that the angle of attack (AOA) at which stall occurs for a rotating blade was larger than the static airfoil and the pressure coefficients during stall delay were much larger than those on the airfoil, too. Although stall delay was known for decades, its fluid physics is still illusive. With the current higher demands of wind energy harnessed by wind turbines, a comprehensive understanding of the underlying physics of fluids in stall delay is required in order to better predict the turbine's power outputs, as well as to devise innovative means to keep improving wind turbine's performance.

There were only a limited number of past studies targeting on discovering the fluid physics of stall delay, majority of which were using various numerical simulations and/or models (Wood, 1991; Dumitrescu and Cardos, 2004; Shen and Sorensen, 1999; Chaviaropoulos and Hansen, 2000; Hu et al., 2006; Dumitrescu and Cardos, 2009; Dumitrescu et al., 2013; Yang et al., 2009). These results indicated that when stall occurred for the blade, the rotation stabilized the vortex shedding, reduced the size of the separated flow, and even attached the flow on the blade's suction surface. There was an disagreement about the reason for the reduction of the adverse pressure gradient on the blade. Dumitrescu and Cardos (2004) attributed it to the delayed boundary layer separation by the Coriolis force produced by rotation, while Wood (1991, 2005) argued that the pressure reduction in the external flow outside the boundary layer may be another reason.

Experimental measurements of the three-dimensional flow fields on the suction surface of the rotating blade for the study of stall delay were provided by Lee and Wu (2013a,b, in press) using state-of-the-art tomographic particle image velocimetry (Tomo-PIV). They observed no reversed mean flows over the rotating blade, in contrast to the massively separated flow over the static airfoil at large AOAs. The measurements also illustrated mean spanwise flow from blade's root to tip which are stronger near the blade's suction surface and in the vicinities of the shed vortices. An analysis of the rotation induced forces revealed that, at large AOAs, Coriolis forces were larger than centrifugal forces in chordwise direction from inboard to outboard, which contributes to the reduction of the adverse pressure gradient. Their measurement supported the arguments of Wood (2005) that the external flow was indeed modified by the blade's rotation. It was also observed that the freestream turbulence levels did not change the general features of the mean flows over the blade during stall delay although they had dramatic effects on the flows over the airfoil at large AOAs.

* Corresponding author.
E-mail address: yanhuawu@ntu.edu.sg (Y. Wu).
[1] Current address: Department of Mechanical Engineering, National University of Singapore, Singapore 117576, Singapore.

http://dx.doi.org/10.1016/j.ijheatfluidflow.2015.05.013
0142-727X/

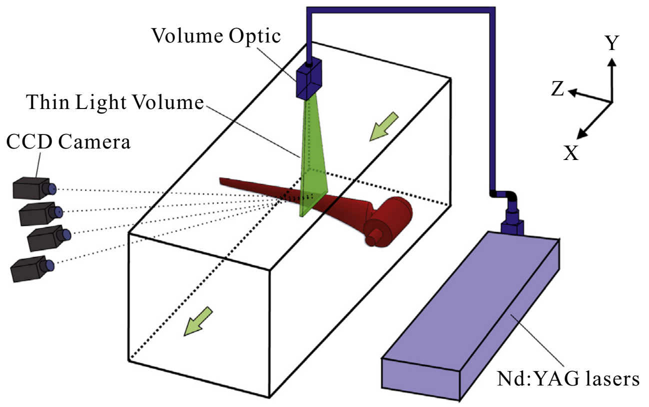

Fig. 1. Tomographic PIV setup. The single turbine blade is oscillating about ±25° in the wind tunnel's test section. The firing of the laser is phase-locked to the horizontal position of the blade when it is rotating upward. The Tomo-PIV measurements are performed at the tip speed ratio of 3. The Reynolds number, based on the relative velocity and the chord length of the blade at the center of the measurement volume of 0.25*R*, is $Re = V_r c/\nu \approx 5500$.

The experimental results of Lee and Wu (2013a,b, in press) showed the existence of turbulent flows at the inboard (close to the blade's root) section of the turbine blade when the incoming flow was separated from the blade's leading edge. It is now widely accepted that coherent turbulence structures exist in various turbulent flows (e.g Robinson, 1991; Adrian, 2007) and they are dynamically important for transporting momentum and energy. In addition, very recently, Wu (2014) used the coefficients of the proper orthogonal decomposition (POD) to establish the relationship between the POD modes and the instantaneous energetic turbulence structures and studied the effects of these structures on the turbulence characteristics of a zero-pressure-gradient turbulent boundary layer. This work is particularly motivated by this study of Wu (2014) and the objective of this work is to apply this new method to investigate the turbulence structures within the turbulent flows at the inboard section of the suction surface of a rotating blade when stall delay occurs.

There exist numerous studies on the application of POD on almost every kind of complex flows. Of particular relevance to the current study is the POD analysis on massively separated flows.

Table 1
Fractional energy contributions of the first 10 POD modes.

Mode *n*	1	2	3	4	5	6	7	8	9	10
	15.4%	7.4%	5.1%	3.9%	3.4%	2.9%	2.3%	2.1%	1.9%	1.7%

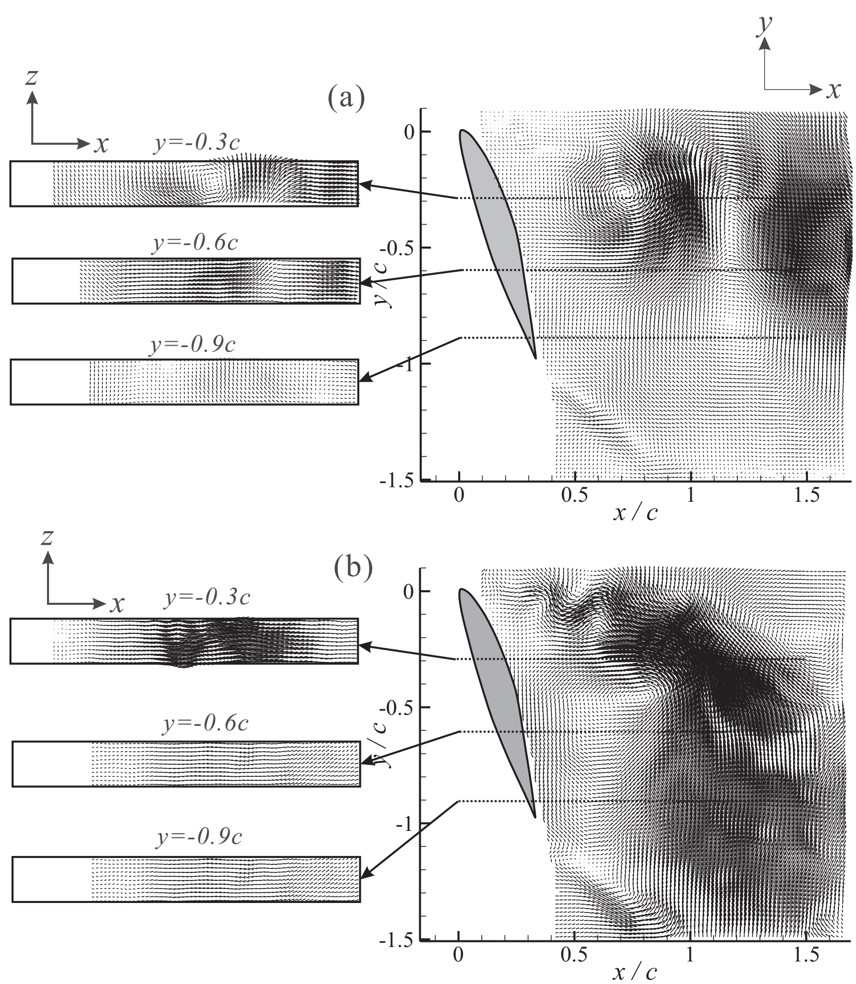

Fig. 2. Vector fields of (a) the first POD mode ϕ_1, and (b) the second POD mode ϕ_2. The vectors in the $x-y$ plane represent the u and v velocity components in the center plane of the measurement volume. The insets present the velocity vectors in the cross-sectional $x-z$ planes at three different locations, indicated by the dashed lines, along the blade's chord to illustrate the spanwise flow.