The turbulence structure of 3D separation (Stall Cells) over an airfoil

Marinos Manolesos[1], Spyros Voutsinas[1]
[1]*Laboratory of Aerodynamics, National Technical University of Athens, Greece*

Abstract The flow over airfoils that experience separation of the trailing edge type becomes three-dimensional at angles of attack around maximum lift and Stall Cells (SCs) form. SCs are large scale coherent structures of separated flow that consist of two counter-rotating vortices. In the present study the turbulence structure of a SC over a rectangular wing is investigated using Stereo PIV measurements. It is found that the turbulence characteristics of the flow are highly anisotropic and that the Boussinesq approximation is invalid. High values of normal Reynolds stresses in the SC vortices and the separation shear layer region indicates a wandering motion of the former and a flapping motion of the latter. Based on the available data the relation between Reynolds stresses, their production terms and the mean flow gradients is examined. It is found that at the centre of the SC, between the two vortices, the flow characteristics resemble those of a double shear layer while at the vortex region the effect of the vortices leads to double peaks in production terms.

Introduction

Three-dimensional separation of the Stall Cell (SC) type was first mentioned more than four decades ago [1], however, details of the SC flow structure remain unclear today. A recent link between SCs and separated flow on wind turbine blades at standstill [2, 3] has led to renewed interest in the SC flow [4-7]. The objective of the present study is to analyse the turbulence characteristics of the flow inside a SC in order to enhance our understanding of the phenomenon.

Experimental Set up

The experiments were performed in the 1.4×1.8m (height × width) test section of the National Technical University of Athens wind tunnel and concerned an 18% thick airfoil optimized for use on variable pitch and variable speed multi MW blades [8]. A schematic view of the test set up is given in Figure 1. The wing spanned the test section vertically and fences were used in order to minimize the effect of the wind tunnel wall boundary layer. A 0.4mm high zigzag tape was used at the centre of the wing span as a stabilizing disturbance to stabilize the inherently unstable SC (see [7] for details).

The green lines in Figure 1 indicate the three measurement planes normal to the flow at chordwise locations $x = 0.6c$ (plane A), $x = 0.8c$ (plane B), and $x = 1.06c$ (plane C). Planes α to ε (normal to the wing span), are given by the red lines in Figure 1 and were at $z = 0$, $z = \pm 0.067S$ and $z = \pm 0.133S$, where S is the wing span and $-0.5 \leq z/S \leq 0.5$. For each plane 2000 snapshots were taken. All data in the present study refer to a wing of AR = 2.0 at $\alpha = 10°$ and $Re = 0.87\times10^6$.

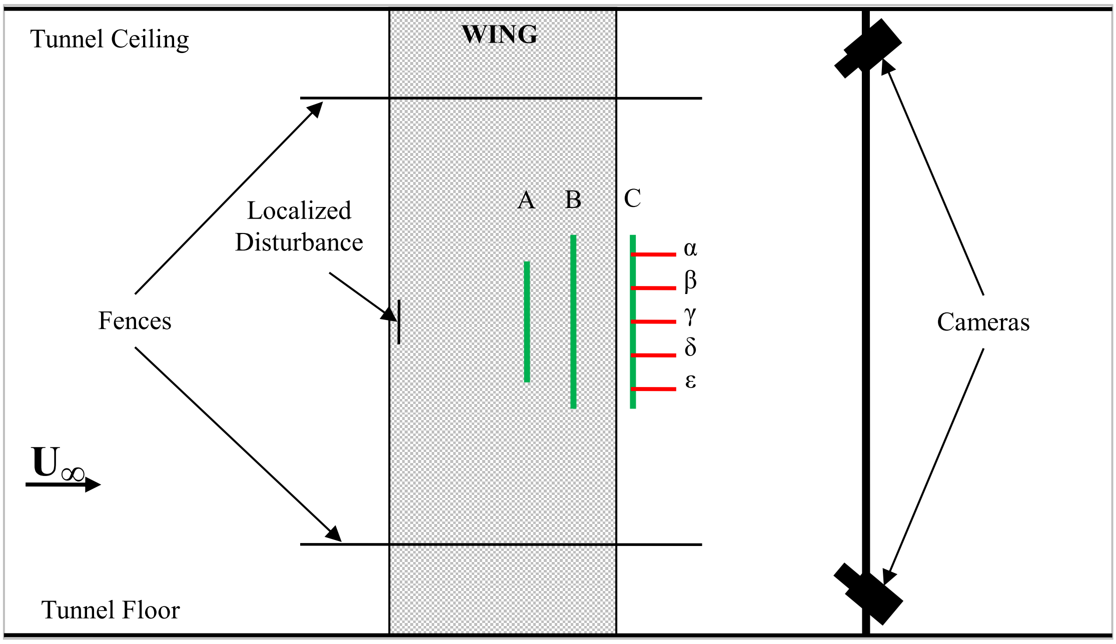

Figure 1. Schematic planform view of the test set up showing the wing, the fences, the stabilizing disturbance and the Stereo PIV cameras along with the measurement planes. Planes normal to the flow (A, B and C) are indicated by vertical green lines, while planes normal to the wing span (α, β, γ, δ and ε) are shown with red horizontal lines.

Results

Indicative results are presented in this report. Figure 2 shows contours of the $\overline{u'u'}/U_\infty^2$ and $\overline{u'v'}/U_\infty^2$ Reynolds stresses while Figure 3 shows the variation of mean flow and turbulence quantities along a line that passes through the centre of the SC vortex.

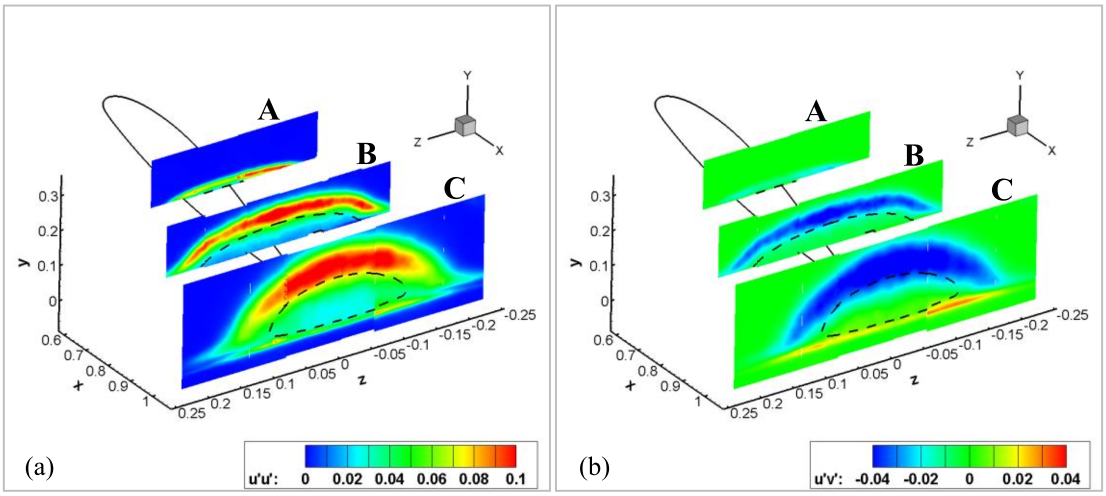

Figure 2. Contours of (a) $\overline{u'u'}/U_\infty^2$ Reynolds Stress; (b) $\overline{u'v'}/U_\infty^2$ Reynolds Stress on planes A, B and C.

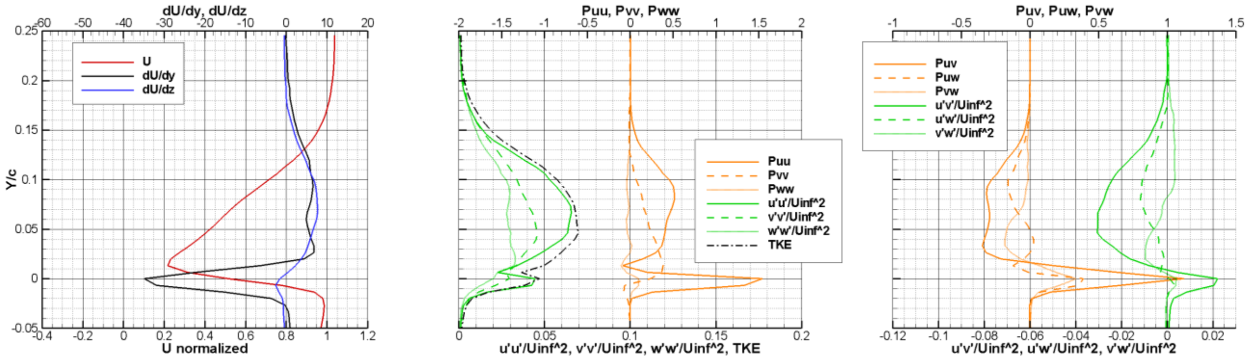

Figure 3. Variation of (a) U, ∂U/∂y and ∂U/∂z; (b) TKE, normal Reynolds stresses and production terms; (c) shear Reynolds stresses and production terms.

Conclusions

Results show that the turbulence inside a SC is highly anisotropic and that the Boussinesq approximation is invalid. The Reynolds stress distributions indicate shear layer flapping and SC vortex wandering. The turbulence characteristics between the two SC vortices resemble those of a double shear layer. However, the presence of the two vortices affects both the mean flow and the turbulence structure. Throughout the measurement planes production terms are strongly correlated to mean flow gradients. Areas where Reynolds stress production terms tend to zero, but Reynolds stress values are high indicate areas where convection/redistribution terms are significant.

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