STRUCTURE OF THE WAKE BEHIND AN AIRFOIL

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Abstract

The wake behind an inclined plate simulating airfoil is to be studied experimentally. The vortical structures are identified eventually. Theirs topology and dynamical behaviour is to be studied in details using the Proper Orthogonal Decomposition method. The stereo time-resolved Particle Image Velocimetry technique is used for the experimental research. The vortex trains with oblique orientation and chequered topology have been detected.

Keywords: airfoil, boundary layer, wake, instability

1 Introduction

The flow structure in the wake behind an inclined plate simulating airfoil is to be subjected to experimental study. The main aim of the study is description of the 3D topology of the unsteady structures within the wake. The simplest airfoil represented by an inclined flat plate will be considered in this paper.

The flow-field around a prismatic airfoil in regular inflow is usually considered to be 2D, as the boundary conditions are also 2D, homogeneous along the airfoil span. This precondition is physically justified only in the case of laminar flow, for the turbulent flow it could be applied only on distributions of velocity statistics as mean values and variances, but definitely not on instantaneous situations.

In our preceding studies occurrence of streamwise vorticity within the turbulent boundary layer on the suction side of simple airfoil was proved experimentally, see [3,4,8-12]. However the vorticity appears randomly both in space and time. This is indication that similar vortical structures arise in various positions in streamwise direction. Existence of streamwise vortices in the boundary layer on an airfoil suction side is predicted by [1] and forms the basic idea of the “new theory of flight”. The physical mechanism of the boundary stability lost is addressed e.g. in [2]. This theory assumes the existence of streamwise oriented vortices also in the wake behind the airfoil. To prove or disprove existence of the vortices in the wake we prepared the new experiment. Stereo PIV measurements are carried out in the plane parallel to the plate in the wake.

We are about to indicate presence, shape of the axis and orientation of possible vortices laying in the measurement plane using the following strategy. In Figure 1 there is measurement plane (xy) in green.

Let us consider existence of a vortex with axis laying in the measurement plane oriented in x direction, its vorticity is oriented in the same direction and thus not detectable in the measurement plane velocity field. Then we could indicate positive out-of-plane velocity component w along the vortex axis on the left (red) and negative on the right (blue) belonging to the vortex intersected by the measurement plane. The geometry of the vortex axis could be estimated, however this method does not provide the unambiguous detection of a vortex presence, and it is an important indication. Similar strategy of the vortices topology description have been used in [14] to study the vortices within the boundary layer on the plate suction side. Together with knowledge of presence vorticity component in the measurement plane, which could be learned from previous results (see e.g. [8-12]), the detection method could be considered to be reliable enough.
2 Experimental setup

Flat plate inclined with angle of attack 7 degrees has been placed in a uniform low turbulence stream of air with velocity 5 m/s. The blow-down facility produces a jet with uniform velocity distribution and low intensity of turbulence, less than 0.2 %. The plate of thickness 2 mm had rounded edges, chord 100 mm and span 300 mm.

The coordinates are non-dimensioned using the chord size $c = 100$ mm. Origin of the Cartesian coordinate system is in the middle of the leading edge, position of the trailing edge is $y = 1$. The plane of measurement is placed 1 mm above the plate, so it is defined as $(xy)$ plane $z = 0.01$ above the plate. The situation is schematically depicted in Figure 1.

![Figure 1: Schematic of the experiment](image)

In paper [13] there is description of the global flow around the plate in the plane of symmetry $(yz)$. In Figure 2 there is a detail of the plate trailing edge and mean velocity distribution in the wake. Vectors represent mean velocities, in the left-hand side bottom corner there is unity vector, colour represent the velocity modulus calculated from the two measured components ("mod"). Velocities are nondimensional using the inlet velocity. In the wake there is the mean velocity deficit. In Figure 3 the position of measurement plane (white colour) is depicted.

![Figure 2: Mean velocities modulus in the wake ([13]) and position of the plane of measurement](image)

As for the measuring technique, the time-resolved stereo Particle Image Velocimetry method (hereinafter PIV) was used for the experiments. The measuring system DANTEC consists of laser with cylindrical optics, two CMOS cameras and timer box controlled by PC. The software Dynamics Studio 6.2 was used both for measurement control and velocity-fields evaluation. Laser New Wave Pegasus is Nd:YLF, double head, wavelength 527 nm, maximal frequency 10 kHz, a shot energy is 10 mJ for 1 kHz (corresponding power 10 W per head). Two cameras NanoSense MkIII, resolution 1280 x 1024 pixels and frequency 500 double-snaps per second were used. The time-series of 1600 double-snaps were acquired in sequence corresponding to 3.2 s of the record time. Tracing particles from the smoke generator Safex were used, typical size of particles-droplets was about 1 μm. The stereo-PIV method has been used for evaluation all 3 velocity components of instantaneous velocity in the measuring plane. Random error of the velocity modulus evaluation is expected to be smaller than 3 % of its value. This...
estimate is made taking into account the used interrogation area 32 x 32 pixels and maximal shift between the snaps.

3 Results

The time-series of all 3 velocity components in measurement plane have been analysed after-hands. The standard statistical methods were applied on instantaneous velocity fields first, then more sophisticated method to evaluate topology of the flow-field dynamics has been used. All presented quantities are nondimensional, the inlet velocity $U_i = 5$ m/s has been used as reference.

3.1 Instantaneous velocity distributions

First the examples of instantaneous velocity distributions are to be shown. In Figure 4 there are two examples of velocity distributions in the measurement plane randomly chosen.

Figure 4: Example of instantaneous velocity distributions ($U$, $V$ vectors, $W$ colour)

Figure 5: Examples of instantaneous in-plane velocity fluctuations (vectors) with relevant vorticity distributions (colour)
In the bottom left-hand side corner there is the unity vector for \( u \) and \( v \) velocity components. The \( w \) velocity component is represented by the colour, red positive (upwards) and blue negative. The in-plane vectors show wavy patterns, while the \( w \) out-of-plane distribution shows oblique strips.

To see better the dynamics of the flow, the Reynolds decomposition have been applied and fluctuations were evaluated from the same instantaneous velocity fields. In Figure 5 there are fluctuations of the in-plane velocity components \( u' \) and \( v' \) only. The colour represents here the vorticity component \( \omega \) perpendicular to the plane of measurement. The vorticity is calculated with help of dimensionless instantaneous velocity and dimensionless coordinates. The positive and negative vorticity form cells with opposite vorticity around and in the centre.

### 3.2 Statistics

Statistical characteristics of velocity vectors have been evaluated: mean values and variances. In Figure 6 there is distribution of the mean \( V \) and \( W \) velocity components respectively.

![Figure 6: Mean velocity components distributions, V (a) and W (b)](image)

The Figures 6(a) and (b) the vectors represent the in-plane velocity components \( U \) and \( V \), while colour shows distribution of the respective component \( V \) for Figure 6(a) and \( W \) for Figure 6(b). It is clear, that the mean velocity components in \( x \) direction \( U \) is close to zero everywhere. The values of \( W \) are relatively small not exceeding 7% of the inlet velocity. Distributions of \( V \) and \( W \) mean velocity components are close to be homogenous (i.e. independent) in the \( x \) direction.

Then the velocity variances were evaluated. The Turbulent Kinetic Energy (hereinafter TKE) have been calculated as a half of all 3 velocity components variances sum. The resulting TKE distribution in the measurement plane is in Figure 7.

The mean quantities are distributed nearly independently on the \( x \) coordinate supporting the hypothesis about 2D structure of the flow statistics. The discrepancy is connected with the experiment setup imperfections, random error of velocity evaluation and size of the ensemble for averaging.

![Figure 7: Turbulent Kinetic Energy distribution](image)
3.3 Proper Orthogonal Decomposition analysis

The topology of dynamical structures in the region of interest is studied using the Proper Orthogonal Decomposition technique (hereinafter POD). The method is described in details e.g. in [5, 6 and 7]. The POD modes are evaluated representing the velocity field dynamics. The modes are ordered according to theirs energy, the methods optimizes the modes to cover the maximal energy of the remaining dynamics. The energy fraction in Figure 8(a) shows the fraction of the total kinetic energy covered by a given POD mode. The accumulated energy in Figure 8(b) represents sum of energies of all lower order POD modes up to a given mode.

![Energy Fraction and Accumulated Energy Distributions](image)

Figure 8: Energy Fraction (a) and Accumulated Energy (b) distributions over the POD modes

In following Figures the POD modes topologies are to be shown. The in-plane velocity components $u$ and $v$ are represented by arrows, while the third out-of-plane component $w$ is shown in colour: red positive, blue negative. The modes are dimensionless.

![POD Modes Topologies](image)

Figure 9: The 1st and 2nd POD modes topologies

The two most energetic POD modes 1 and 2 represent the train of spanwise oriented vortices, the modes differ only by phase representing the same phenomenon. They are nearly of identical energy,
mode 1 is 3.5% and mode 2 about 3.4% of the total kinetic energy respectively. The frequency of the process connected with the 2 first POD modes is about 180 Hz. In Figure 10 there are a few examples of higher order POD modes.
Figure 10: Examples of the higher order POD modes topologies

The mode 3 containing about 3.0% of the total kinetic energy is represented by synchronous pulsations of the in-plane velocity components within the region of interest. Similar features possess modes 7, 8, 11 and 13 (not shown here).

Then, there are several modes with typical chequered pattern of the out-of-plane velocity component distribution. As examples the POD modes 4, 9 and 20 are shown with energy fractions POD 4 2.4%, POD 9 1.6% and POD 20 1.0% respectively. The distribution of regions with opposite $w$ velocity component orientation is nearly the same in the $y$ direction for all those modes as for the modes 1 and 2. However the higher order of the mode, more changes in $x$ direction is present. Within the defined range $-0.2 < x < 0.2$ there is no change in the mode 1, one change in the mode 4, 2 changes in the mode 9 and 3 changes in the mode 20. These all modes represent moving train of vortices in the streamwise direction, as the complementary mode exists with similar but shifted topology – see the modes 1 and 2.

The last two examples of higher order modes 30 and 100 demonstrate growing complexity and randomness. The energy fractions are 0.7% for the POD 30 and 0.2% for the POD 100. Such a low energy of these high-order modes indicates degree of significance of the modes within the complex dynamics. However, we should keep in mind, that the first 20 POD “high energy” modes with energy higher than 1% for each, explain only 30% of the total TKE – see the Accumulated Energy in Figure 8(b). Neglecting of big number of low-energy modes of order 21 and higher means that we omit 70% of the total TKE. Due to complexity and variability of the higher order modes, their effect could be considered as random.

The similar structures have been found by Schlatter et al. [5] in DNS simulation of flow around an airfoil, however the Reynolds number was considerably higher in that case.

4 Conclusions

The wake behind an inclined plate simulating airfoil was studied experimentally. The vortical structures within the wake were identified. Theirs topology and dynamical behaviour was studied using the Proper Orthogonal Decomposition method. The stereo time-resolved Particle Image Velocimetry technique is used to acquire the experimental data on velocity distributions.

Typical topology of the vortical structures in the wake behind an inclined plate includes the vortex trains with oblique orientation. They could be decomposed into chequered patterns.

This result could not be considered as an unambiguous prove of the mathematical results presented in [1], as the “new theory of flight” supposes presence of streamwise vortices on instantaneous basis. However the observed oblique vortex patterns contain the streamwise vorticity component, no doubt. In any case, the real structure is more complex than the simple theory supposes.

The observed phenomenon is to be subjected to further studies.
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Notation

$U, V, W$ [1] Dimensionless mean velocity components
$u, v, w$ [1] Dimensionless instantaneous velocity components
$u', v'$ [1] Dimensionless velocity components fluctuations
$\text{mod}$ [1] Dimensionless
$x, y, z$ [1] Dimensionless Cartesian coordinates
$\omega$ [1] Dimensionless $z$ instantaneous vorticity component
$U_i$ [m/s] Inlet velocity (5 m/s)
$c$ [m] Plate chord (0.1 m)
TKE Turbulent Kinetic Energy
POD Proper Orthogonal Decomposition
DNS Direct Numerical Simulation

Note: The dimensionless quantities are defined using chord $c$ and inlet velocity $U_i$.

References