Evolution of vortical structures behind an inclined flat plate

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Abstract. 2D3C TR-PIV technique was utilized to investigate streamwise-oriented vortical structures behind an inclined flat plate. The angle of attack was set to 7 deg, several fields of view in the wake were investigated. The instantaneous velocity vector fields were captured, dynamics of the flow was studied using POD method. The streamwise structures are determined by vorticity and low- and high-velocity streaks are defined. The acquired results are in a good agreement with the new hypothesis of a principle of flight.

1 Introduction

The invention of a wing is more than a hundred years old. Nevertheless, there are some doubts recently, how the lift force is actually generated. This experimental research is a reaction to the new ideas about principle of lift and flight by Hoffman and Johnson [1, 2]. This new hypothesis determine the streamwise vortical structures over and behind the airfoil as the main source of the lift force generation. This streamwise vorticity is developed as a consequence of the instabilities of the boundary layer developing under adverse pressure gradient of the suction side of the airfoil. Some experimental studies of flow instabilities and their consequences are given in [3, 4, 5].

During previous investigations the vortical structures topology within boundary layer was examined very close to the inclined plate surface [6]. Another research was focused on the wake behind the flat plate [7]. Presented study is dealing with the streamwise-oriented vortical structures and their identification using POD (Proper Orthogonal Decomposition) method from velocity vector maps located perpendicularly to the flow direction. Several parallel planes were investigated along longitudinal direction and the evolution of streamwise vorticity was observed.

2 Experiment description

A studied test airfoil is simple flat plate which is inclined at the angle of attack (AOA) 7° with respect to the incoming flow. The flow is coming from blow-down wind tunnel, cross-

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section dimension 250 x 250 mm^2, uniform flow speed 5 m/s, low turbulence intensity level (around 0,2 %). The plate has semi-cylindrical leading and trailing edges, chord length c is 100 mm, thickness of 2 mm and span dimension is 300 mm. The corresponding Reynolds number is approximately 33 000. The schematic view of the experiment arrangement can be seen in Figure 1. The coordinate system was introduced so that x- and y-axis are in the plane of measurement and z-axis is in the direction of flow. Several fields of view in streamwise direction were measured at dimensionless positions: z/c = 1, 1.3, 1.5, 1.8, 2, 2.3 and 2.5. The position z/c = 1 corresponds to trailing edge location.

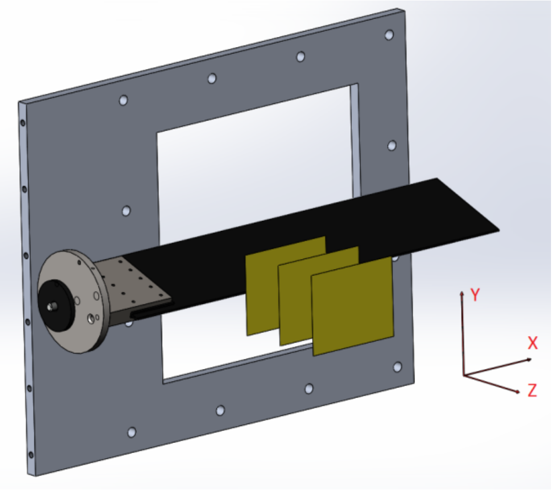


Fig. 1. The setup of inclined plate and wind tunnel orifice, coordinate system and measured planes z/c = 1.5, 2 and 2.5.

Stereo time-resolved PIV (Particle Image Velocimetry) was used to acquire the data in parallel planes, subsequent post-processing resulted in velocity vector map with all three velocity components in a distinct plane. The measuring technique is from Dantec company and consists of laser with cylindrical optics and two cameras. The laser New Wave Pegasus Nd:YLF has double head emitting light of wavelength 527 nm by maximal frequency equal to 10 kHz. A shot energy is 10 mJ for 1 kHz and corresponding power is 10 W per head. Two CMOS camera NanoSense MKIII have full resolution 1 280 x 1024 and maximal double-snap acquisition frequency is 500 Hz for full resolution. It was used half resolution in height which enabled to use double value of acquisition frequency.

Thus used camera resolution was 1 280 x 512 pixels. The field of view (FOV) dimensions were 60 x 25 mm^2. The correlation algorithm determined 68 x 29 vectors with maximal 10 % of substituted ones. Acquisition frequency was set to 100 Hz (10 sec of measurement) and to 1 000 Hz for the case of statistical quantities evaluation and for dynamical analysis, respectively. Proper Orthogonal Decomposition (POD) was applied to selected datasets. POD analysis is used here to extract deterministic structures from random turbulent flow field resulting in topological orthogonal modes. Each instantaneous PIV measurement is considered here as a snapshot. The mean flow field is calculated and it is subtracted from all snapshots – the calculation is further provided from velocity fluctuations. Further calculation (see e.g. [8]) results in series of POD modes (structures of the flow field) which are ordered according to kinetic energy content. This means that dominant structures are represent in the first modes.

3 Results

Although the investigated flow velocities were 5 and 10 m/s, the presented vector fields will be connected only with smaller velocity magnitude. Black vectors represent the velocity projected into the plane of measurement. The color represent a scalar value (velocity vector modulus, w-component of velocity, sum of velocity variances, z-vorticity). All figures are plotted in dimensionless coordinates x/c, y/c and z/c. The black dashed lines denote the position of trailing edge. Green lines are added either for z-vorticity distribution or to make visible the streamlines.

3.1 Mean flow field

Firstly, the mean flow field of the wake was evaluated. There is comparison of four distance from the trailing edge in Figure 2. The angle of attack is set to 7 and downwash effect of the inclined plate is well visible. The minimal velocities are located behind rather below the trailing edge for z/c = 1.3. With increasing distance in downstream direction, the position of local minima is shifted below and for the farthest measured plane is out of the FOV. The velocities of freestream are approximately 5 m/s. The minimal velocities were detected just behind the trailing edge for z/c = 1 (not plotted here). However, no streamwise-oriented vortical structures can be seen from time-mean images. The location of enhanced dynamical activity can reveal the distribution of velocity variances. The Figure 3a, b plotted for z/c = 1.3 and 1.5 imply that maximal values are located rather above the profile.

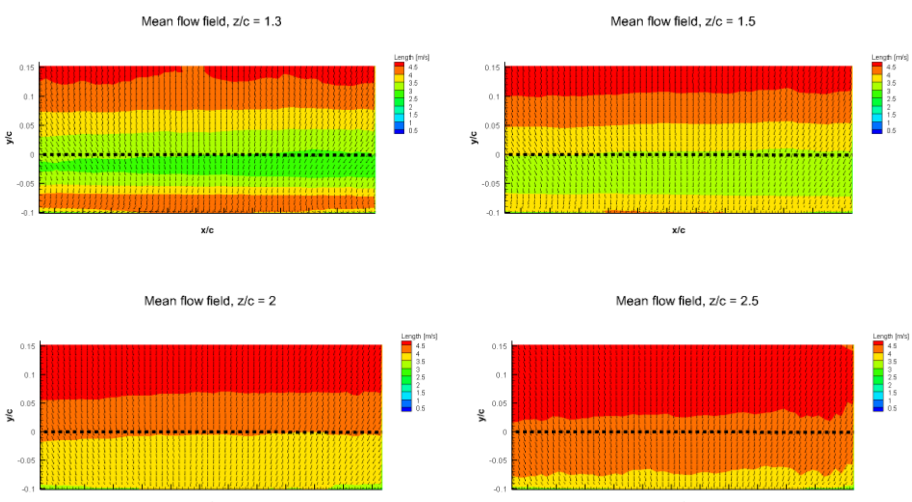


Fig. 2. a, b, c, d. Mean flow field for planes z/c = 1.3, 1.5, 2 and 2.5; distribution of velocity modulus.

3.2 Instantaneous flow field

The topology of instantaneous flow field is completely different. The irregular and perturbed wake behind the inclined plate is visible at four distinct positions at Figure 4. The extension of the wake is decreasing and its position is shifted below with longitudinal coordinate. From the vorticity distribution as well as from streamlines one can see that the

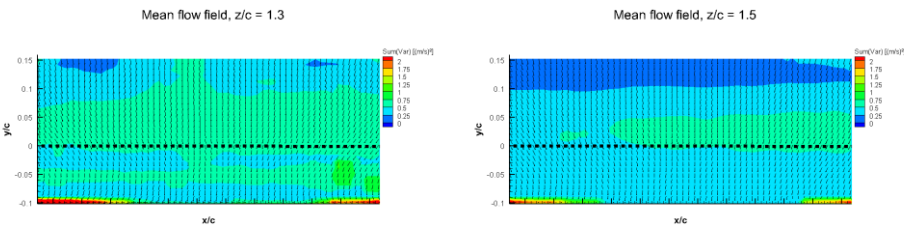
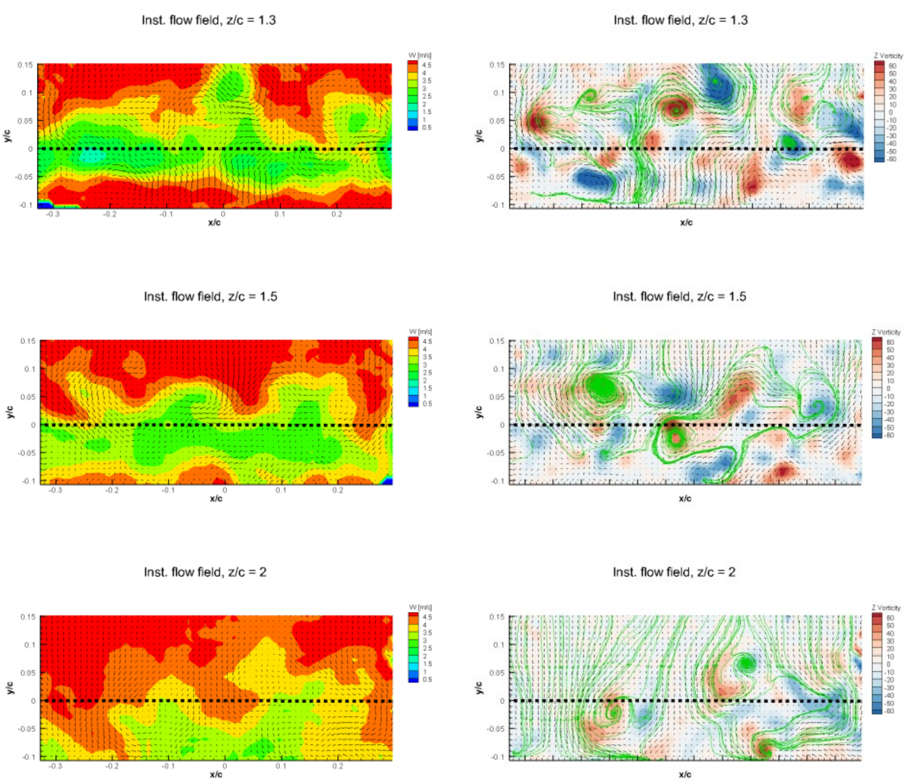


Fig. 3. a, b. Fluctuation activity for planes z/c = 1.3, 1.5; distribution of sum of vel. variances.

streamwise-oriented vortical structures gradually disappear. The last investigated plane (150 mm downstream the trailing edge) has negligible amount of vortical structures compared to the first mentioned measured plane. Flow patterns are distributed rather in the upper side of the profile. However with increasing distance in downstream direction, they are homogenously distributed throughout the FOV. The downwash effect is rather detectable in the farthest measured planes. The topology of flow field is obviously very dynamical and therefore the POD analysis was utilized to detect the deterministic structure from the random flow field.



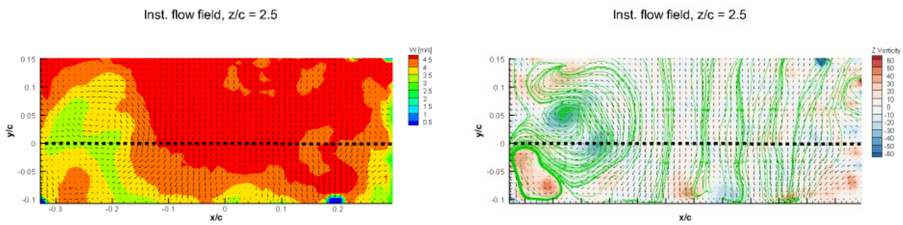


Fig. 4. a, b, c, d, e, f, g, h. Instantaneous velocity vector map for planes z/c = 1.3, 1.5, 2 and 2.5; distribution of streamwise velocity and z-vorticity with streamlines.

3.3 POD modes

As it was mentioned previously, the first POD modes are dominant concerning relative kinetic energy content which means that they consists of the biggest flow structures. The relative kinetic energy of the 30 POD lowest order modes is plotted in Figure 5. Only about 10 POD modes have relative kinetic energy higher than 2 % (the kinetic energy is calculated from velocity fluctuations). The kinetic energy of low-ordered mode is increasing with the streamwise distance. The blue line plotted for z/c = 1 implies that the flow field here consists of larger amount structures with lower energy contribution. On the contrary, the farthest plane z/c = 2.5 consists of rather bigger structures created by merging. The Figure 5b reveals that low-ordered POD modes contain bigger and more energetic structures for lower velocity 5 m/s compared to the double value.

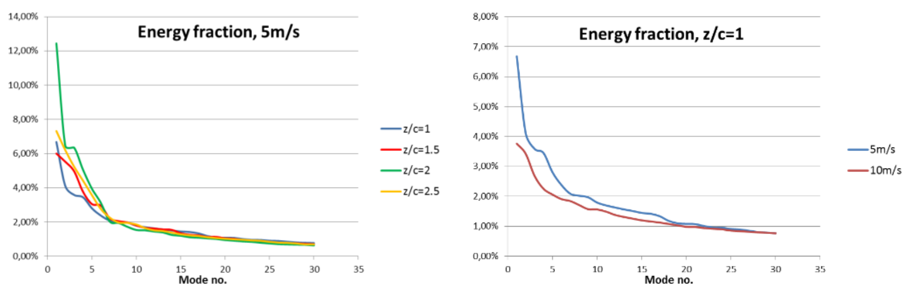


Fig. 5. a, b. The relative kinetic energy content of first 30 POD modes.

The topology of each POD mode will be given by vector distribution patterns in the plane of measurement. Color will denote the w-component of velocity in streamwise direction. Red color is used for positive velocity differences and hence high velocity region and blue color for negative velocity differences and low velocity region. Each individual vortex is identified by streamwise vorticity component isolines. In this case, the z-vorticity is calculated from velocity components in the plane of measurement. However, vorticity cannot distinguish between the swirling motion and shear but here no distinct shear regions are expected. The vortex core is located in the center of isolines and more isolines means more powerful swirling motion. Please note, that the vortices are of alternate orientation – vorticity is positive and negative.

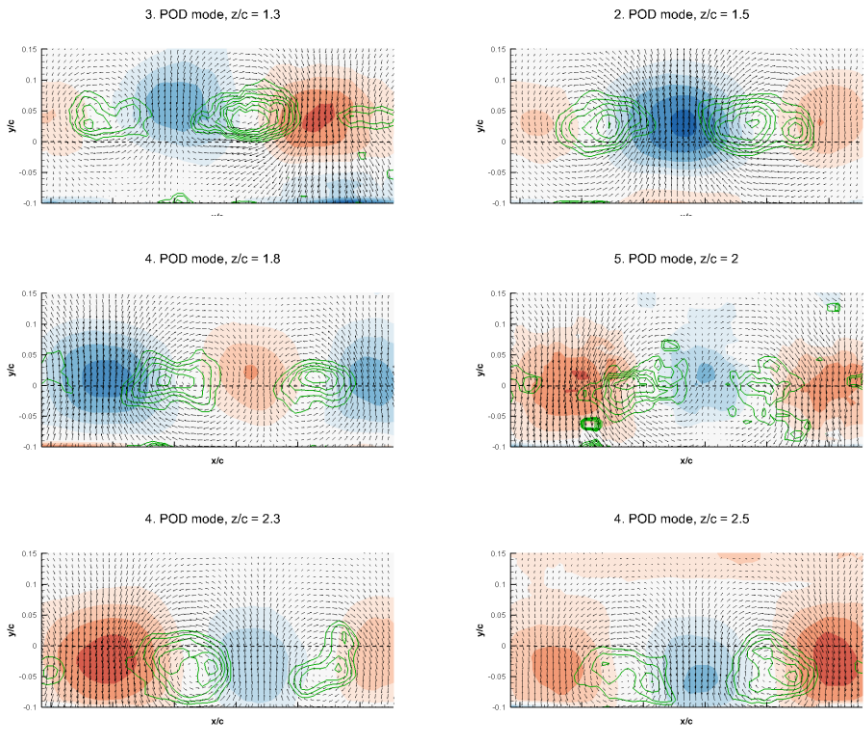


Fig. 6. a, b, c, d, e, f. POD modes of one pair of vortices for planes z/c = 1.3, 1.5, 1.8, 2, 2.3 and 2.5; distribution of fluctuation of streamwise velocity, isolines of vorticity.

There are several examples of the interesting POD modes in Figure 6-8 plotted for various planes. Again the position of trailing edges is marked by black dashed line. Note that for planes close to the trailing edge (z/c = 1.3 or 1.5) the dominant flow structures are situated above the profile in suction side. Due to downwash effect these structures are traversed rather below in more distant planes.

A large number of POD modes was detected. We focus here only on low-order modes containing interesting coherent structure. The topology of each mode consists of one pairs of counter-rotating vortices along the profile chord (Figure 6). It is visible the evolution of this pair in longitudinal direction. Although this structures was detected for distinct plane in another mode number (2nd, 3rd, 4th or 5th) it is obvious that it dominates as one of the most important. The region between streamwise vortices is created by the fluid of either high or low streamwise velocity. This distribution could indicate the existence of the streaks. Size of the vortical structures or streak region detected in these modes is not dependent on longitudinal direction in the studied range.

There is also no dependency on z-coordinates for other POD modes (Figure 7) which are characterized by two pairs of counter-rotating vortices. The size of these structures is significantly smaller and therefore they are connected with lower energy contribution to the mean flow (POD modes no. 6 and 7). The space between two adjacent vortices is again periodically filed with high or low streamwise velocity.

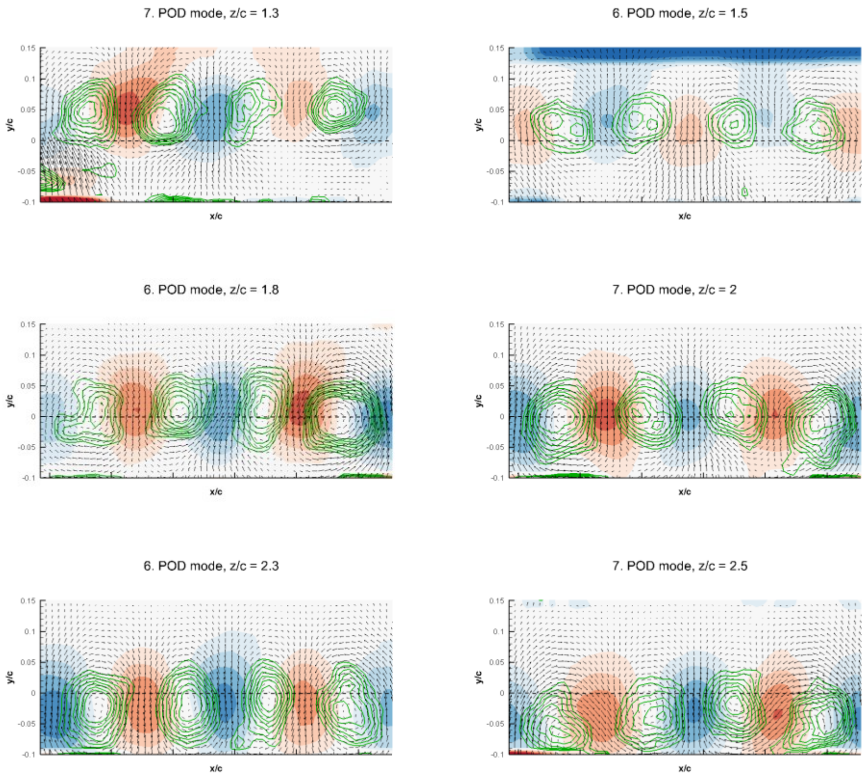


Fig. 7. a, b, c, d, e, f. POD modes of two pairs of vortices for planes z/c = 1.3, 1.5, 1.8, 2, 2.3 and 2.5; distribution of fluctuation of streamwise velocity, isolines of vorticity.

Generally it can be said that the lowest order POD modes contain long streamwise structures and positive or negative streak regions. With decreasing amount of kinetic energy of each mode the mode topology is more structured and complex (Figure 8). The existence of streamwise structures is apparent up to the farthest distance z/c = 2.5. However the role of streamwise vorticity is decreasing gradually with the longitudinal direction and there was not detected the boundary where this vorticity can be declared as negligible.

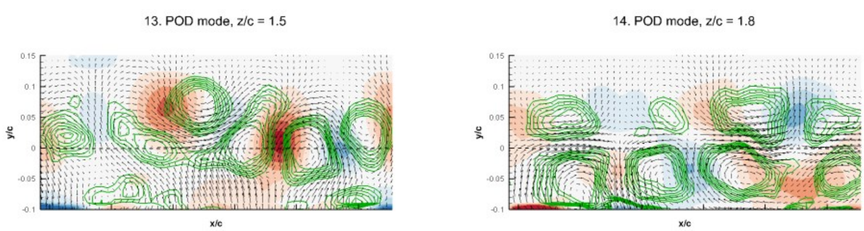


Fig. 8. a, b. POD modes of more complex topology for planes z/c = 1.5 and 1.8; distribution of fluctuation of streamwise velocity, isolines of vorticity.

4 Conclusions

This article was dealing with preliminary results of evolution of flow structures behind the inclined plate obtained using time-resolved stereo PIV technique. There is no information about streamwise vorticity from the mean flow field. However instantaneous vector maps and several POD modes have revealed the existence of streamwise vortices and probably streaks in the boundary layer region and in the wake behind a simple profile. Downwash effect of the inclined profile was presented. It was shown that low ordered modes are characterized by the existence of pairs of streamwise vortices. The topology of other modes with low energy content is more complex. The behaviour of the flow is fully dynamic. The instantaneous images have revealed that firstly smaller structures just behind the trailing edge merge into larger structures along longitudinal direction. More investigated planes should be incorporated in the future research to get more detailed information about streamwise vorticity evolution.

This experimental research created another piece that fully supports a new theory of flight and lift generation.

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