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On 3D Structure of Wake behind an Inclined Plate

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Abstract. The flow-field behind an inclined plate was investigated experimentally using stereo PIV method providing all 3 velocity vector components in the measuring plane. Flow structure in several measuring planes perpendicular to the main flow was studied. Statistical characteristics were evaluated in the measuring planes. The downwash angle was assessed as well to consider its effect on the lift generation mechanism. The dynamical behavior was studied using Proper Orthogonal Decomposition of velocity fields in measuring planes. The dominant (most energetic) structures were evaluated and presented. The detected structures are of the form of streamwise vortices combined with high- and low-velocity streaks.

INTRODUCTION

The motivation of the presented study is supporting new ideas about principle of flight by Hoffman and Johnson from KTH Stockholm, see [1]. Their hypothesis of physical mechanism of flight relies on existence of streamwise vortical structures on the suction side of the airfoil and within its wake. The vortices origin is supposed to be the instability of the boundary layer subjected to adverse pressure gradient on the airfoil suction side (i.e. upper). Some consequences and supporting experimental results of the hypothesis are given in [4,7,8].

For the present paper, the simple experiment has been carried out with the simplest airfoil possible represented by a flat plate in uniform flow and moderate angle of attack.

EXPERIMENTAL SETUP

The flat plate inclined with angle of attack 7 degrees has been placed in a uniform low turbulence stream. The blow-down facility produces a jet with uniform velocity distribution, mean velocity about 5 m/s, intensity of turbulence less than 0.2 %, mean velocity defects less than 1%. The jet has rectangular cross-section 250 x 250 mm^2. The plate of thickness 2 mm had rounded edges, chord c = 100 mm and span 300 mm.

The inlet velocity U_e is equal to 5 m/s resulting in Reynolds number based on the plate chord was about 30 thousand.

The measuring planes have been positioned perpendicular to the main flow in the distance h behind the trailing edge covering the span 60 mm in the plate middle position. The distances of measuring plane behind the trailing edge were h = 0, 0.5, 1 and 1.5 c. The situation is shown in Fig. 1.

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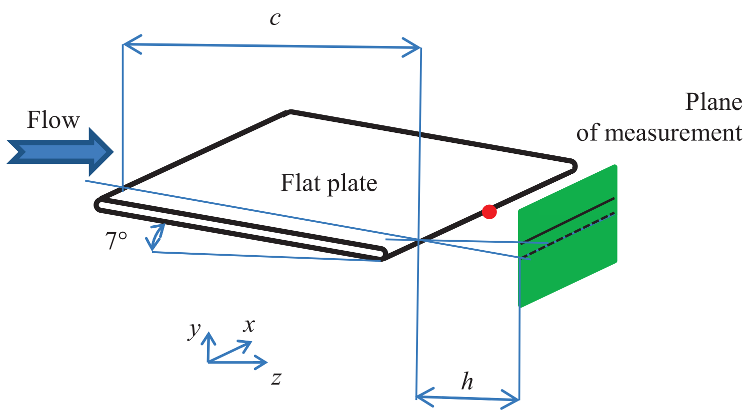

FIGURE 1. Layout of the experiment.

In Fig. 1 the Cartesian coordinate system is introduced with origin in the center of the plate's trailing edge – the red dot. The green plane *xy* is the measuring plane, incoming flow direction is in the *z*-axis. Origin of the coordinate system is located in the middle of the trailing edge. Position of the measuring plane is fixed by the *z* coordinate indicating the distance behind the trailing edge.

In the measuring plane there are two lines representing position of the plate trailing edge (upper surface). The full line is projection of the trailing edge in direction of the flow, while the broken line shows its projection in direction of the inclined plate surface. These two lines will be shown in graphical presentation of the measuring plane below.

METHODS

For the experiment the stereo PIV method has been used. The raw data was evaluated using DynamicStudio 3.4 software. The same software was used for the result analysis.

Instrumentation

The time-resolved stereo PIV measuring system was used for the experiments. The measuring system DANTEC consists of laser with cylindrical optics and two CMOS cameras with Scheinpflug mounting of lenses 60 mm focal length. The laser was New Wave Pegasus 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. The 1600 double-snaps were acquired in sequence corresponding to 3.2 s of the record time. The stereo-PIV method has been used for evaluation all 3 velocity components in the measuring plane.

The configuration of the stereo PIV system is in Figure 2.

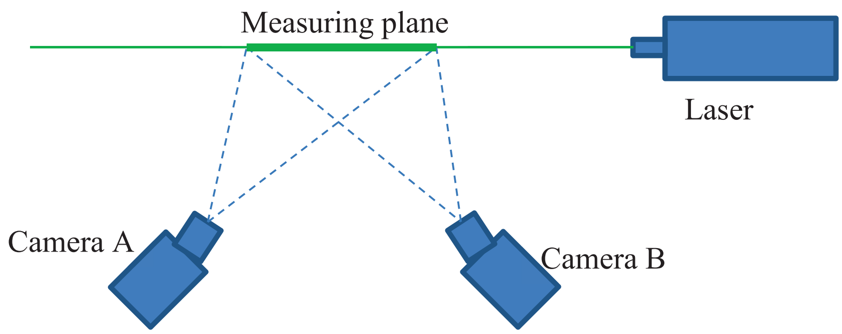

FIGURE 2. Stereo PIV layout.

The Scheinpflug mounting of lenses was used to keep the focus plane within the laser sheet. The calibration was performed using the standard dot PIV calibration target 100 x 100 mm^2, moving in the *z* direction using a precise traversing system equipped by stepper motor drive, 5 z positions are used (-2,-1, 0, 1 and 2 mm). For seeding particles, a standard SAFEX fog generator has been used.

Analysis methods

First, statistics of the vector fields is evaluated: mean values and variances. From individual velocity components variances the turbulent kinetic energy (hereinafter TKE) was evaluated.

For the analysis of fluctuation the Proper Orthogonal Decomposition (hereinafter POD) method is to be applied. Recently, the POD has been widely used in studies of turbulence. Historically, it was introduced in the context of turbulence by Lumley [2] as an objective definition of what was previously called big eddies and which is now widely known as coherent structures.

Extraction of deterministic features from a random, fine grained turbulent flow is a challenging problem. The POD provides an unbiased technique for identifying such structures. The method extracts the candidate which is best correlated, in a statistical sense, with the background velocity field. The different structures are identified with the orthogonal eigenfunctions of the decomposition theorem of probability theory. This is thus a systematic way to find organized motions in a given set of realizations of a random field.

The velocity vectors are considered and then the sum variances can be interpreted as a system fluctuating kinetic energy – TKE (to be precise twice of it). The POD method is looking for an orthonormal basis corresponding to uncorrelated (i.e. orthogonal) modes maximizing the dynamic data variance, i.e. maximizing the TKE. Implementation of the POD method is shown e.g. in [5,6].

RESULTS

The raw data represented by double snapshots produced by the TR-PIV measurement system have been processed. Results are to be presented in the form of vector and scalar distributions in the measuring planes *xy* perpendicular to the inflow direction *z*. The vector fields represent the in-plane velocity vector component *U* and *V*, while the streamwise velocity component *W* is represented by color.

All results are shown in non-dimensional form, the coordinates are divided by the chord length (c = 100 mm) and velocities are related to the inflow velocity (5 m/s). The lines representing position of the plate trailing edge are presented in all results.

For the presented paper the 4 measuring planes were selected z = 0, 0.5, 1 and 1.5 respectively. The first measuring plane touches the plate trailing edge, the last one is located 1.5 *c* (150 mm) behind the trailing edge.

Please note that the experimental setup is close to 2D configuration as for the time mean characteristics. This means that within the measuring planes the quantities evolve in *y* direction, while along the plate span *x* the mean values of all relevant quantities are more or less constant. However the instantaneous fields are highly 3D, this means that the fluctuations are of 3D nature.

Mean values

An overview of the presented results is in Fig. 3, where the 4 measuring planes in the coordinate system are shows together with evaluated mean velocity vectors (please note that the coordinate system origin is located within the $z = 0$ plane). The plate is depicted in green color.

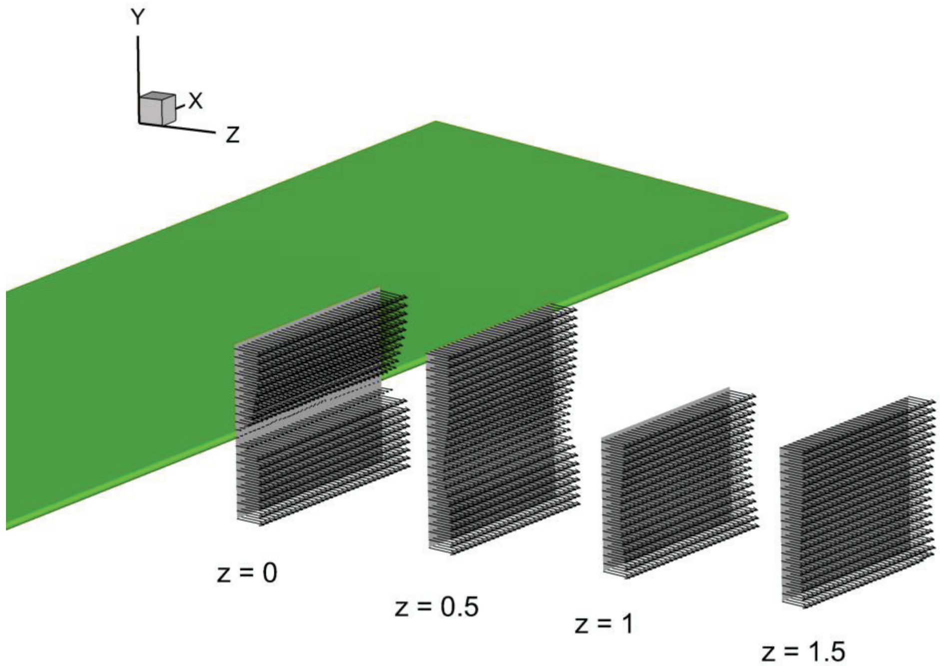

FIGURE 3. Measuring planes

In Fig. 3 the measuring areas distribution is schematically shown, the time mean velocity vectors are in *z*-axis direction approximately. The sizes and positions of the measuring areas are adopted to capture the predominant dynamical behavior.

In Fig. 4 there are the 4 measuring planes with mean velocity vectors distributions, the *z* value is given in left-upper corner. The two in-plane velocity vector components are represented by vectors, the out-of-plane velocity component (W, *z*-direction) is shown in color (blue small, green $\frac{1}{2}U_e$, red close to U_e). The color legend is in the right-upper corner and reference vector 10% of inflow velocity in the left-bottom corner in the first picture for $z = 0$ only. The projection of the trailing edge in *z*-direction corresponds to $y = 0$, *x* and y coordinates are non-dimensioned using the chord *c*.

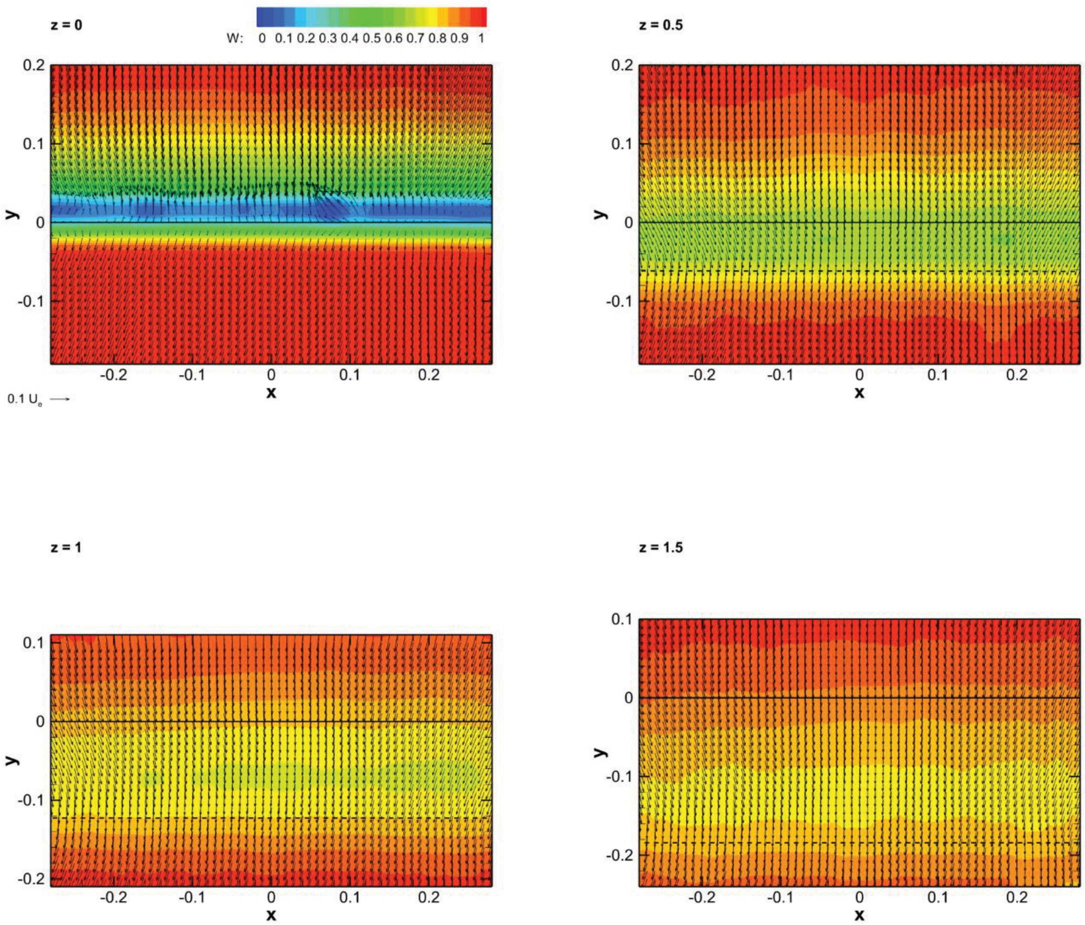

FIGURE 4. Mean velocity distributions

The trailing edge projection in the inflow direction represented by full pink line is located in the $y = 0$ position. The plate direction projection is shown as broken line and it is located below the full line except the $z = 0$ measuring plane position, where the two projections merge as the measuring plane intersects the trailing edge.

First observation, the mean velocity distribution is nearly independent on *x* coordinate, this means that the mean flow-field is close to 2D topology. However this is true only for the time-mean and it is not true for instantaneous velocity fields, as they are fully turbulent and thus 3D.

Next, the wake as the low-velocity flow region is located between the trailing edge projections and above it.

In Fig. 5 there is distribution of the down-wash angle, which is the angle of mean velocity vector departure from *z*-direction measured in *yz* plane.

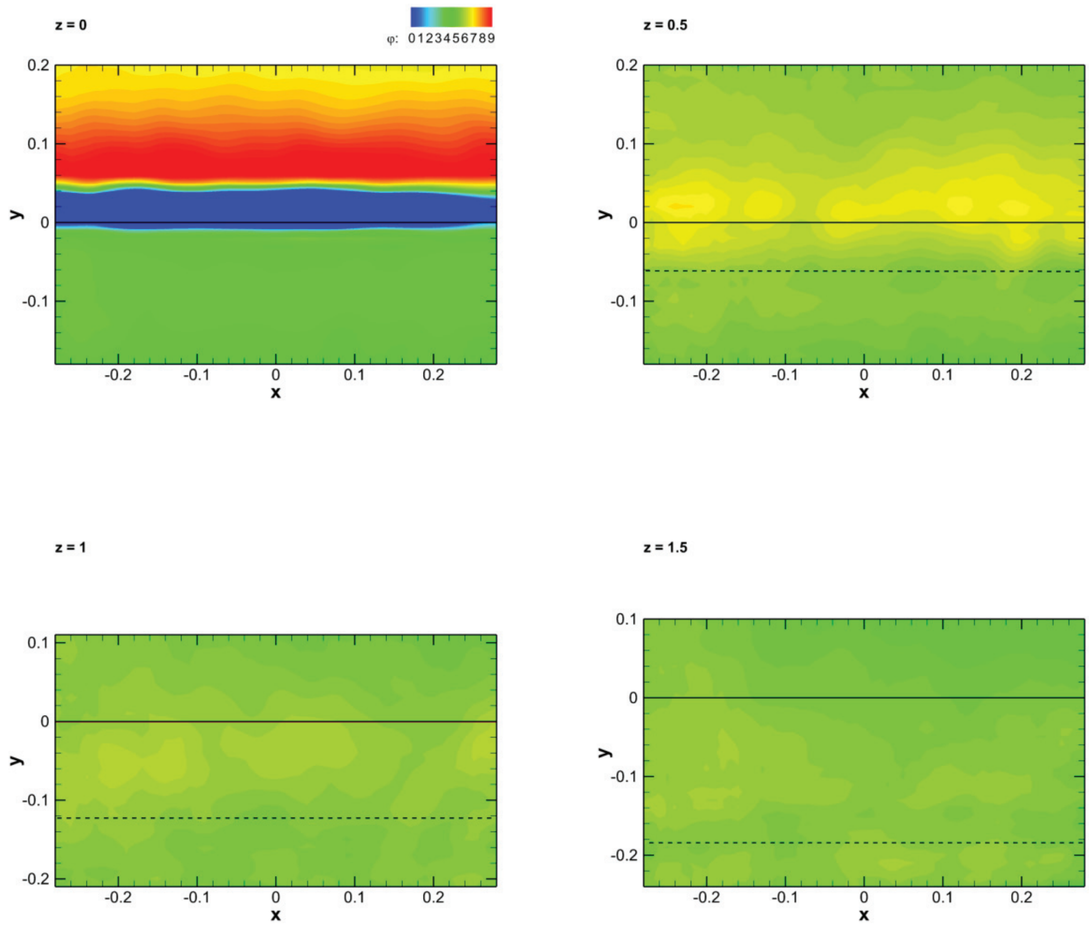

FIGURE 5. Downwash angle distributions

The down-wash angle value is expected to be close to the angle of attack 7° (yellow color). It is true for position close to the full line trailing edge projection in $z = 0.5$, for larger distance behind the trailing edge the downwash angle is close to 6° between the trailing edge projection lines, while outside is of about 0.5° smaller. The most complicated situation is for $z = 0$ measuring plane. Here close to the projection line the value of down-wash angle is undefined, as velocity is very small. Just above, close to the surface the down-wash angle is even bigger than the angle of attack of the plate, it exceeds 9°. Bellow the plate in the pressure region the down-wash angle is barely 5° in the trailing edge measuring plane and is pretty constant in the whole pressure region. The nominal value 7° is reached in the suction region, in position y about 0.2.

To estimate the dynamic activity regions the TKE distribution is evaluated. The distributions of TKE are given in Fig. 6. The values of TKE are non-dimensional, the real values are divided by U_e^2.

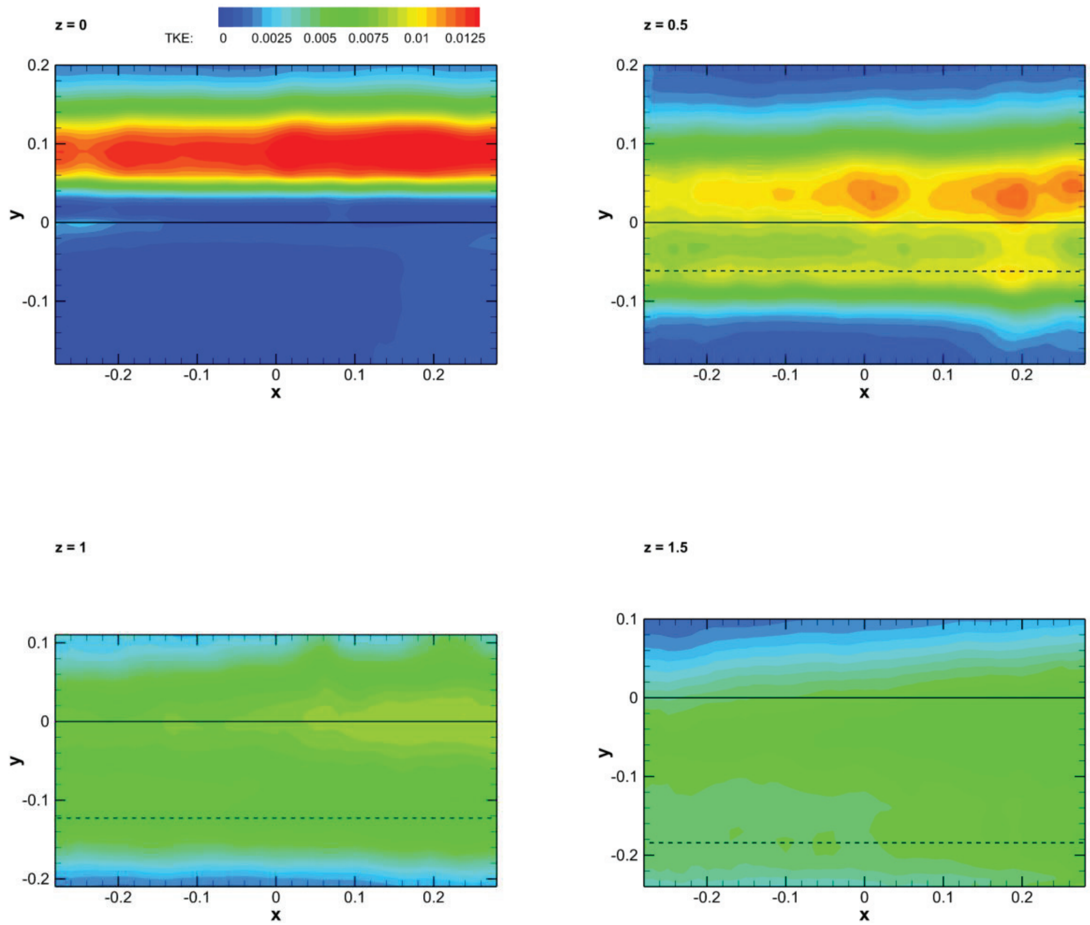

FIGURE 6. Turbulence kinetic energy distributions

In the trailing edge z-position the absolute maximum TKE is located in the suction region above the plate at $y = 0.09$, bellow the plate in the pressure region the fluctuating activity is negligible. In $z = 0.5$ the maximum is shifted downwards to $y = 0.04$, the second, smaller maximum is located close to the trailing edge projection in direction of the inclined plate surface (broken line). Outside the region $y = +\text{-}0.1$ the turbulence activity is negligible. For the $z = 1$ the TKE maximum is shifted to the position of trailing edge projection and for $z = 1.5$ is located slightly below. The maximum value of TKE decreases rapidly with distance from trailing edge z.

Dynamics

The topology of dynamical patterns in the flow-field is studied using the POD method. For the presented paper only the POD mode no. 1 with the most energy is evaluated for all 4 measuring planes.

The POD modes represent fluctuations which are superimposed on the time-mean velocity field. The modes are normalized, the amplitude of their appearance in real case depends on the associated kinetic energy. In Tab. 1 there are average (spatial) TKEs of the flow in a given measuring plane, relative energy fraction of the first POD mode and absolute value (however non-dimensional) of the first POD mode.

TABLE 1. The first POD mode relative energies.

Meas. plane pos. z [1]	Average TKE [10^{-3}]	POD1 rel. energy [%]	TKE of the POD1 [10^{-4}]
0	3.58	6.13	2.20
0.5	4.83	6.59	3.19
1	5.63	7.47	4.21
1.5	4.45	7.98	3.55

Next, the topology of the first POD mode will be shown in Fig. 7 for all 4 measuring planes.

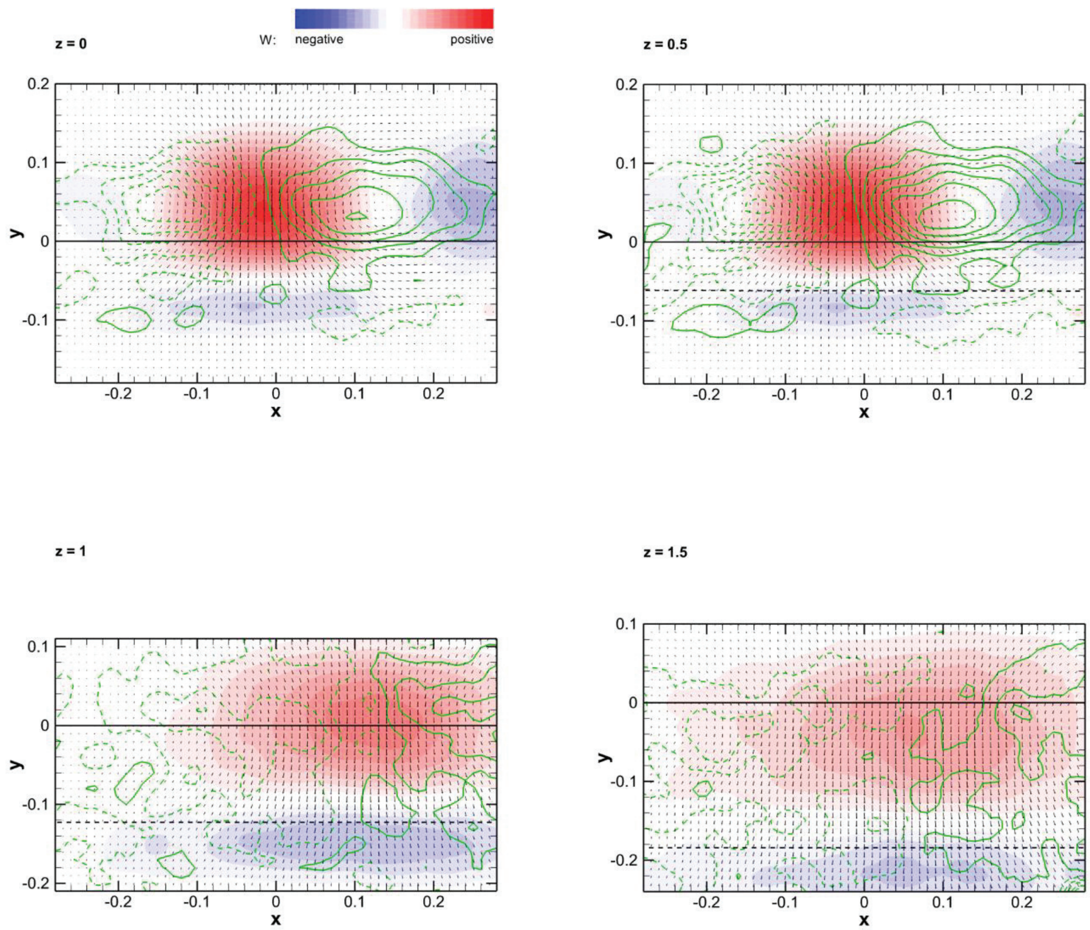

FIGURE 7. The first POD mode topologies

The most energetic POD modes show in all 4 measuring plane very similar pattern. It consists of the two streamwise vortices with centers well above the trailing edge projection in direction of the inclined plate surface (broken line). Between them there is a big region of streamwise velocity fluctuation (in red). Below the line there is smaller region of the streamwise velocity component fluctuation in opposite direction, both of them represent the streamwise streaks of high/low velocity. All the structure mentioned above are more pronounced close to the trailing edge, loosing coherence in streamwise direction. However both total TKE and energy of the first POD mode grow in streamwise direction up to z = 1, than its fall down.

CONCLUSIONS

3D structure of the flow behind an inclined plate was studied. Mean velocity field, downwash angle and TKE distributions are evaluated in the 4 measuring planes. The first POD mode development in the streamwise direction was studied as well.

Notwithstanding that the experimental results are of a qualitative nature only, they reveal existence of streamwise vortices above the plate without any doubt. The results support the new theory of flight [1].

ACKNOWLEDGMENTS

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