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ANISOTROPY OF TURBULENT FLOW AROUND AN AIRFOIL

V. Uruba[*], **P. Procházka**[**], **V. Skála**[***]

Abstract: *The flow around an airfoil is analyzed from the point of view turbulence anisotropy assessment. The turbulent flow-field in the vicinity of an airfoil is populated by vortices, in some locations they tend to regularity in orientation, i.e. to anisotropy. However in the wake behind the plate as well as in the core of the boundary layer on the plate suction side the turbulence is close to isotropic state.*

Keywords: Airfoil, Turbulence, Anisotropy.

1. Introduction

The presented study is motivated by ideas about principle of flight by Hoffman and Johnson from KTH Stockholm, see Hoffman and Johnson (2010). They formulated a new hypothesis of physical mechanism of flight which relies on existence of streamwise vortical structures on the suction side of the airfoil. The vortices origin is supposed to be the instability of the boundary layer subjected to adverse pressure gradient on the airfoil pressure side (i.e. upper).

A series of experimental studies have been published recently, where the airfoil was represented by a flat plate with rounded edges and angle of attack 7 degrees. In Uruba et al. (2017) preliminary results are shown in the plane of measurement perpendicular to the flow. In Uruba, et al. (2018a) the experiments were carried out for a very high Reynolds numbers, up to 2 million. The other experiments were performed for the Reynolds number based on the airfoil chord 33 thousands only. In Uruba et al. (2018b) the boundary layer on the suction side was studied in details. In Uruba et al. (2018c) the overall flow-field has been explored. All studies have shown homogeneity of the mean flow-field along the airfoil span and existence of streamwise vorticity in the suction side of the flow. However, the vorticity appears on instantaneous basis only, vortices change theirs position and orientation both in time and space. As a result, no vortices are detectable in the time-mean flow. So, the flow-field could be considered to be fully turbulent.

In general, our knowledge of turbulent flows is still far from being satisfactory. The most theories apply only to “well developed” turbulent flow which is characterized by unrealistic features. For example the Kolmogorov theories hold for isotropic, homogeneous turbulent field characterized by turbulence Reynolds number approaching infinity. Homogeneity and isotropy are considered in statistical sense.

Any real case is characterized by some departures from that ideal case. It is essential to quantify the above mentioned features, to verify relevance of the theories for the given case.

In the presented paper we will concentrate on quantification of isotropy of the turbulence, characterized by time series of all 3 velocity component in the given point in space. The isotropy is evaluated in statistical

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[*] Prof. Ing. Václav Uruba, CSc.: Institute of Thermomechanics of the CAS, v. v. i., Dolejškova 1402/5, 182 00 Praha 8, Czech Republic, uruba@it.cas.cz, University of West Bohemia, Faculty of Mechanical Engineering, Department of Power System Engineering, Universitní 8, Plzeň, Czech Republic, uruba@kke.zcu.cz

[**] Ing. Pavel Procházka, PhD.: Institute of Thermomechanics of the CAS, v. v. i., Dolejškova 1402/5, 182 00 Praha 8, Czech Republic, prochap@it.cas.cz,

[***] Ing. Vladislav Skála: Institute of Thermomechanics of the CAS, v. v. i., Dolejškova 1402/5, 182 00 Praha 8, Czech Republic, skala@it.cas.cz

sense on the basis of variances and covariances analysis. Using this data we could evaluate the complete tensor of Reynolds stress. The subsequent (an)isotropy analysis is oriented on this kind of input information.

The anisotropy indicates presence of ordered structures (vortices) within the turbulent flow.

2. 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 plate of thickness 2 mm had rounded edges, chord $c = 100$ mm and span 300 mm. The dimensionless Cartesian coordinates are divided by the chord length c, origin is located in the middle of the trailing edge, thus the position of the leading edge is $z = -1$. The inlet velocity is equal to 5 m/s resulting in Reynolds number based on the plate chord was about 33 thousands.

The planes of measurement have been positioned perpendicular to the main flow covering the span 60mm in the plate middle position. The distances of measuring planes behind the trailing edge were $z = 0, 0.1, 0.2, \dots, 1.2$ (in green). Upstream the trailing edge the planes of measurement are split into pressure side and suction side parts respectively, the positions are $z = -0.1, -0.2, \dots, -0.7$ for both sides, light green for the suction side and light blue for the pressure side. The data from the planes of measurement are to be interpolated to the plane of evaluation (in red), which is the (yz) plane.

In Fig. 1 there is layout of the experiment. The airfoil is in dark blue, the flow is in z direction.

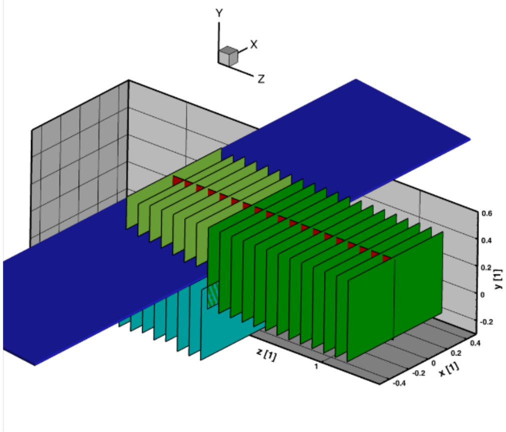


Fig. 1: Layout of the experiment.

For the experiment the stereo PIV method has been used. The raw data was evaluated using DynamicStudio software, the same software was used for the result analysis. The time-resolved stereo PIV measuring system consists of laser with cylindrical optics and two CMOS cameras with Scheinpflug mounting of lenses 60 mm focal length. Laser New Wave Pegasus Nd:YLF, double head, wavelength 527 nm, maximal frequency 10 kHz, a shot energy is 10 mJ for 1 kHz. Two cameras NanoSense MkIII, resolution 1280 x 1024 pixels and frequency 500 double-snaps per second, 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 plane of measurement. Detailed description is given e.g. in Uruba et al. (2018c).

3. Turbulence anisotropy evaluation

Dynamics and 3D structure are the basic attributes of a turbulent flow, however there are some others as range of scales, vorticity, dissipativity etc. Statistical approach to turbulence relies on the velocity field information in a single point in space, the relevant information is contained in Reynolds stress tensor.

From linear algebra it is known that any symmetrical matric could be decomposed into isotropic and anisotropic parts. Isotropy is here considered as independence on the direction in physical space described by Cartesian coordinate system. The nondimensional anisotropic part of Reynolds stress tensor, or simply anisotropy tensor, is considered to be the fundamental characteristic of the turbulence anisotropy in the given point. Of course, if this tensor is vanishing, the flow is considered to be perfectly isotropic. It could be characterized by a set of the eigenvalues and the related eigenvectors. The eigenvalues, called the principal stress are defined using Cayley-Hamilton theorem in the form of the characteristic equation.

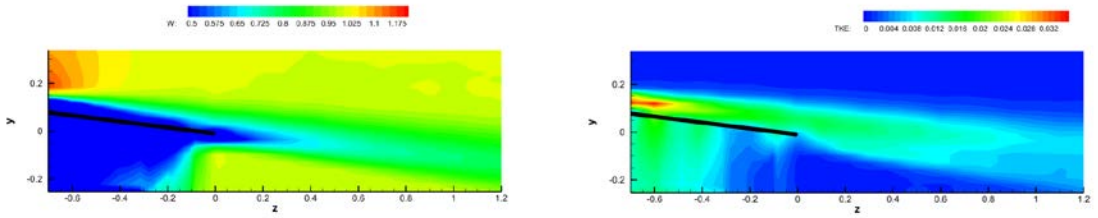
Lumley (1977) has demonstrated that all the possible states of turbulence must be found within the turbulence triangle, so called “Lumley triangle”, in invariant coordinates of the anisotropy tensor. The ordinate and the abscissa are the negative second invariant (−II) and the third invariant (III) of the anisotropy tensor, respectively. This graph is called the anisotropy invariant map (AIM).

To quantify the 3D isotropy of the turbulence Choi (2001) has introduced the anisotropic factor *F*. The *F* vanishes whenever turbulence becomes 2D, and it becomes unity when turbulence enters a 3D isotropic state.

4. Results

All results are shown in dimensionless form, the coordinates are divided by the chord length (c = 100 mm) and velocities are related to the inflow velocity (5 m/s).

In Fig. 2 the time mean streamwise velocity component W and the turbulent kinetic energy (TKE) distributions are shown.



(a) (b)

Fig. 2: The streamwise time-mean velocity component (a) *and TKE* (b) *distributions.*

The low velocity regions are located within the boundary layer on the upper suction side of the plate, in the wake and on the lower pressure side there is a huge low-velocity region. As for the TKE, maximum is located within the instable boundary layer on the suction plate side.

Now the turbulence anisotropy is evaluated, first the anisotropic factor *F*, in Fig. 3.

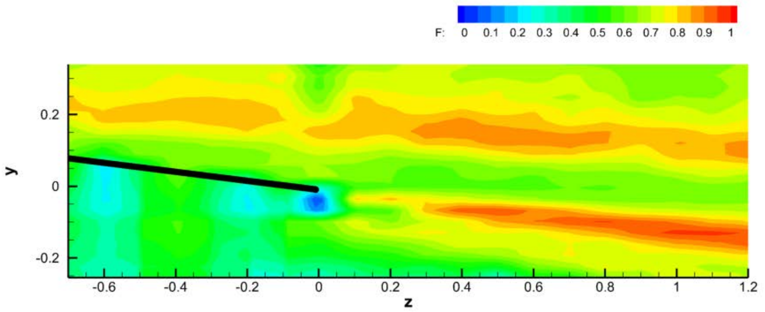
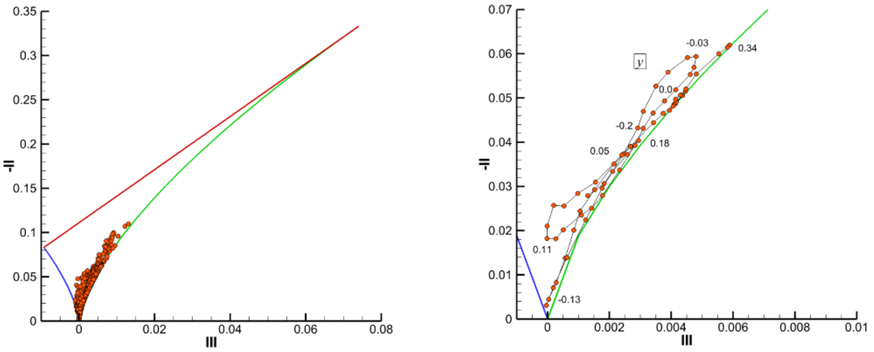


Fig. 3: The anisotropic factor F distribution.

The 2 regions of the isotropic turbulence (or close to) could be detected, red in Fig. 3. The first region is located in the wake of the plate, the second one is about 0.1 above the plate, parallel with it. In between there is region of anisotropic turbulence characterized by F = 0.5 (green in Fig. 3).

Next the anisotropy invariant map is to be shown. In Fig. 4 there are AIM with all data (a) and the detailed view on the profile z = 1.1, y position is indicated. The data is concentrated close to the green border of the graph representing the axisymmetric shape of the correlation tensor. It could be characterized by the energy ellipsoid in the shape of prolate spheroid (cigar shape) with two shorter axes of the same size, the third is longer. This situation corresponds to the presence of vortices with one preferred direction of axes.

In the wake behind the plate and in the boundary layer on the plate suction side the flow is turbulent approaching the isotropy state – red regions in Fig. 3.



(a) (b)

Fig. 4: Anisotropy invariant map for all data (a) *and for z = 1.1* (b).

5. Conclusions

The anisotropy of turbulent flow in the vicinity of an airfoil has been evaluated from existing detailed data.

The turbulent flow-field in the vicinity of an airfoil is fully turbulent. The flow in the wake behind the plate as well as in the core of boundary layer on the plate suction side the turbulence is close to isotropic state. In other parts of the flow-field slight anisotropy of turbulence appear with tendency to prolate spheroid of energy ellipsoid indicating presence of system of vortices with a preferred orientation of axes.

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