DYNAMICS OF A BOUNDARY LAYER SEPARATION

Václav Uruba, Martin Knob*

Dynamical behavior of a boundary layer separation is studied using both theoretical analysis and experimental approach. The dynamical nature of the phenomenon is demonstrated on a simple case of a boundary layer in adverse pressure gradient studied experimentally. The Time-Resolved PIV technique was used to study instantaneous structure of the separation region and its time development. Distinctive coherent structures and their dynamical behavior were identified using the BOD method.

Keywords: *boundary layer, separation, dynamics, triple-deck theory, Time-Resolved PIV, Bi-Orthogonal Decomposition*

1. Introduction

Flow separation or more precisely separation of a boundary layer (BL) from a wall is a very important phenomenon from the practical point of view, determining force interaction between the flow and body. The BL (boundary layer) separation is a quite vague concept. We could define it as the process that fluid elements adjacent to the wall no longer move along the wall but turn into the interior of the fluid. Separation process is characterized by local zero value of the skin friction on the wall. Recently, it has been shown that process of separation is connected with absolute instability of the fluid in the separation region (see e.g. Marquillie and Ehrenstein, 2003). Thus, the separation process itself is very sensitive to minor perturbances and it is dynamical in nature.

2. Separation – traditional approach

Classical concept of a BL separation starts from the Prandtl's theoretical concept of a BL. This concept is built for 2D cases. The necessary condition for BL separation is the increasing pressure in the streamwise direction, i.e. positive (or adverse) pressure gradient along the flow path. The necessary second determining factor is presence of viscous effects in the BL, no matter being of laminar or turbulent in nature.

The problem of a BL separation is treated even in the famous Prandtl's paper 1904, where the BL concept has been presented for the first time. The separation physical mechanism he described as follows: 'On an increase of pressure, while the free fluid transforms part of its kinetic energy into potential energy, the transition layers instead, having lost a part of their kinetic energy (due to friction), have no longer a sufficient quantity to enable them to enter a field of higher pressure, and therefore turn aside from it.'

The BL separation is generally distinguished into 2 categories – steady and unsteady. Unsteady flow in the BL may arise from boundaries moving in time or from fluctuations in

* doc. Ing. V. Uruba, CSc., Ing. M. Knob, Institute of Thermomechanics, AS CR, v.v.i., Praha

the mainstream. However, the flow separation itself causes unsteadiness, and the unsteady separation is, in general, self-excited.

The phenomenon of a BL separation is of a stability nature, so it is very sensitive to any variations of boundary conditions. This could be represented by velocity or pressure fluctuations coming from mainstream or other parts of the BL. As an example we could refer to the well known unsteady separation on a bluff-body forming pseudo-periodical vortex street.

The separation point could be fixed in a sharp edge position if present, otherwise the term 'zone of separation' is more appropriate then 'separation point'.

3. Triple-deck theory

The most significant advance in the BL theory after Prandtl's original formulation was the simultaneous discovery of so called Triple-Deck Theory by Messiter (1970), Neiland (1969) and Stewartson (1969). This theory applies to disturbances that change 'rapidly' in the downstream direction that is on a length scale short compared with that over which the underlying BL varies, though still long compared with the boundary-layer thickness. This relatively rapid change means that viscous effects associated with the disturbances are confined to a thin sublayer close to the wall (the 'lower deck III'), while the bulk of the underlying BL adjusts through an inviscid, rotational displacement (the 'middle deck II'). The fluid ejected from the middle deck induces a flow in an 'upper deck I' above the BL that is inviscid and irrotational. In turn this irrotational flow induces a dynamically significant pressure gradient in the lower deck. There is thus a feedback look whereby fluid motion in the lower deck can change the pressure gradient felt in the lower deck (albeit indirectly by means of the flow generated in the upper deck). In contrast, in classical BL theory the pressure gradient is fixed by the slip velocity and is not influenced by induced motions in the BL. Finally we note that while the pressure gradient in transversal direction is supposed to be zero in the lower and middle decks, it is non-zero in the upper deck. The topology is schematically shown in Fig. 1.

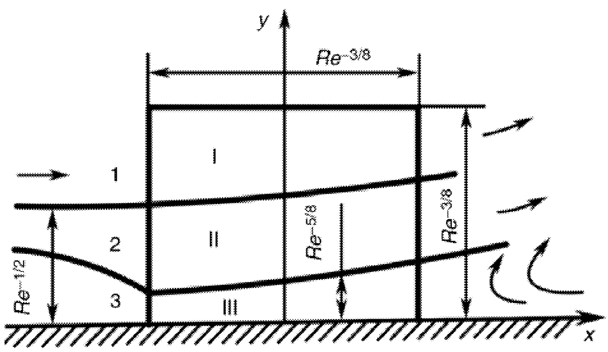


Fig.1: Triple-deck structure and its scales (Sychev et al., 1998)

4. Dynamical Aspects

To study a BL separation dynamics we could evaluate the indicator function time evolution of a BL separation region on the flat plate in adverse pressure gradient (detailed

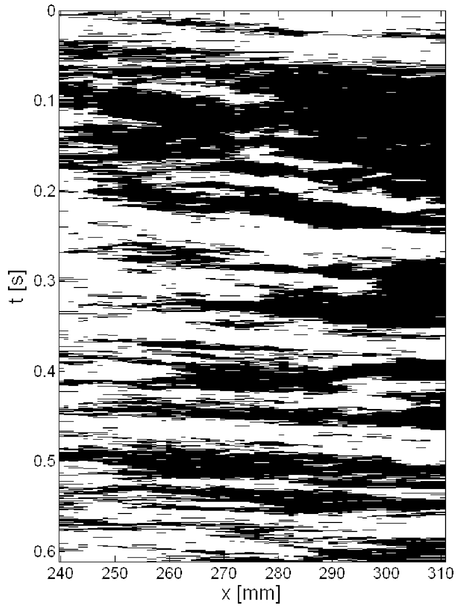


Fig.2: Flow direction in the separation region; forward = white, backward = black (Uruba and Knob, 2007a)

description of the experiment could be find in Uruba & Knob, 2007a). This function indicates sign of instantaneous value of skin friction τ_w. In Fig. 2 the x position within the separation region is on the horizontal axis, while vertical axis represents time t in seconds. White color indicates forward velocity orientation, while black indicates backward oriented flow. The dynamical behavior of instantaneous separation and reattachment points is evident in the plot. A system of instantaneous separation bubbles is detected.

Generally, above a certain critical Reynolds number, the flow-field is shown to undergo self-sustained two-dimensional low-frequency fluctuations in the upstream region of the separation, evolving into aperiodic vortex shedding further downstream. Low-frequency fluctuations, also called ‘flapping’, have been shown to be a characteristic feature of separated layers in general (Cherry et al., 1984; Dovgal et al., 1994). It has been argued that they are due to a global instability manifested in the reattachment region (Theofilis et al., 2000; Haggmark et al., 2000), triggered by topological flow changes generating secondary recirculation zones (Dallmann et al., 1995).

For steady free-stream separating turbulent BLs, a set of quantitative definitions on the detachment state near the wall has been proposed, with the definitions based on the fraction of time that the flow moves downstream, the forward-flow-fraction coefficient γ_p has been defined e.g. in Uruba et al. (2007).

Simpson (1996) suggested a BL separation zone structure with the small mean backflow defining several significant points, as shown in Fig. 3b. The *Incipient Detachment* (ID) occurs with instantaneous backflow 1 % of the time ($\gamma_\mathrm{p} = 0.99$); *Intermittent Transitory Detachment* (ITD) occurs with instantaneous backflow 20 % of the time ($\gamma_\mathrm{p} = 0.80$); *Transitory Detachment* (TD) occurs with instantaneous backflow 50 % of the time ($\gamma_\mathrm{p} = 0.50$) and Detachment (D) occurs where the time-averaged wall shear stress $\tau_\mathrm{w} = 0$. Simpson states that TD and D are at the same x-location according to available data.

Incipient Detachment was observed in old experiments when flow markers such as a dye filament injected into liquids at the wall or a tuft mounted on the surface would move upstream occasionally. In the past this location has been loosely called incipient separation. Just downstream of incipient detachment the displacement thickness of the BL begins to increase rapidly.

Intermittent Transitory Detachment was observed in old experiments when tufts or dye filaments moved upstream at a noticeably greater fraction of time than 'occasionally'. This location corresponds to the location of 'turbulent separation' or 'intermittent separation', the velocity profile at this position is labeled as 'unrelaxed'.

Transitory Detachment and Detachment correspond to the same location if the streamwise velocity probability distribution at that location is symmetric about zero velocity, which is likely for zero mean wall-shearing stress. Detachment was called the location of 'steady' separation, the velocity profile at this location is 'relaxed'.

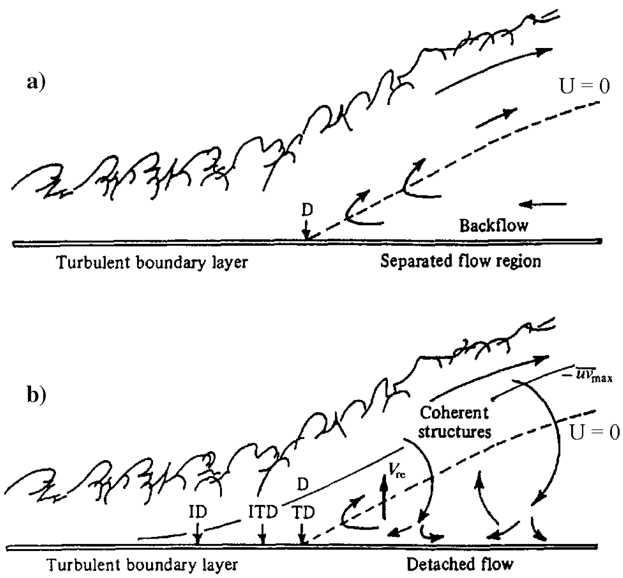


Fig.3: a) traditional view of turbulent BL separation with the mean backflow coming from far downstream; b) a flow model with the turbulent structures supplying the small mean backflow (Simpson, 1996)

Until recently many investigations were concerned only with the location of D, ignoring the fact that the turbulent separation process starts upstream of this location in all but singular cases where ID and D are at the same location. The length of the region between the ID, ITD, TD and D points will depend on the geometry and the flow, but the definitions of these points are the same (see Fig. 3b). The γ_p is not a sufficient variable to describe the flow behavior since it only represents the fraction of a streamwise velocity probability distribution that is positive.

In Fig. 3 the dashed line denotes 0 value of the mean longitudinal velocity U locations; the solid line denotes maximum turbulent shear locations; V_{re} denotes the mean re-entrainment velocity along $U = 0$.

5. Structure of flow in separation region

We have performed experiments on a flat plate BL in presence of adverse pressure gradient (see e.g. Uruba & Knob, 2007a). The flow-field near the wall in the separation region was studied in details using the Time-Resolved PIV technique.

To distinguish the TD and D points defined above the longitudinal mean velocity component U and of forward-flow-fraction coefficient γ_p distributions were evaluated. The results are plotted in Fig. 4 for x and y coordinates in millimeters, $y = 0$ corresponds to the wall level. There are also courses of U_0 and $\gamma_{\mathrm{p}0}$ as functions of evaluated near the wall (precisely for $y = 0.7$ mm). The TD point could be evaluated as a position where the forward-flow-fraction coefficient near the wall reaches the value 0.50, while for D the mean longitudinal velocity component near the wall is zero. In our experiment the x-positions of points TD and D differ slightly, for TD we obtained 260 mm while for D about 265 mm.

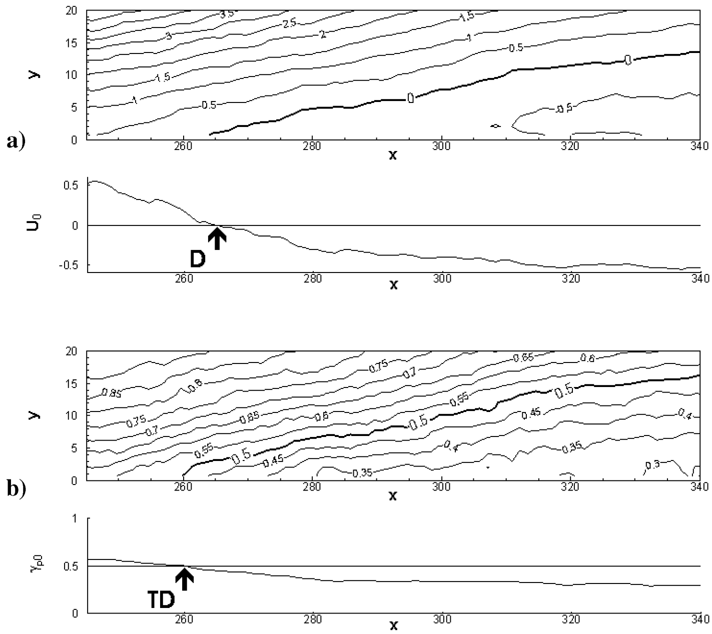


Fig.4: Distributions of a) mean longitudinal velocity component and b) forward-flow-fraction coefficient γ_p; Courses of a) U_0 and b) $\gamma_{\mathrm{p}0}$ near the wall

However, the instantaneous flow-fields differ from the mean picture substantially. To show qualitatively variability of the flow-field, a few examples are in Fig. 5 showing velocity vector fields with vector lines and corresponding skin friction. The figure shows near-wall flow structure in various situations: fully attached BL, intermediate situation and fully detached BL, respectively. The fully attached BL flow-field Fig. 5a could be described as a slightly perturbed forward flow in the whole region in question. The intermediate case Fig. 5b exhibits even more complicated structure with several vortical structures, the streamlines are oriented predominantly in the y-direction perpendicular to the wall, while the x velocity component changes in sign along the wall. The fully detached BL flow-field Fig. 5c is characterized by a strong vortex with negative (clockwise) direction and with core sitting near the position [280; 20].

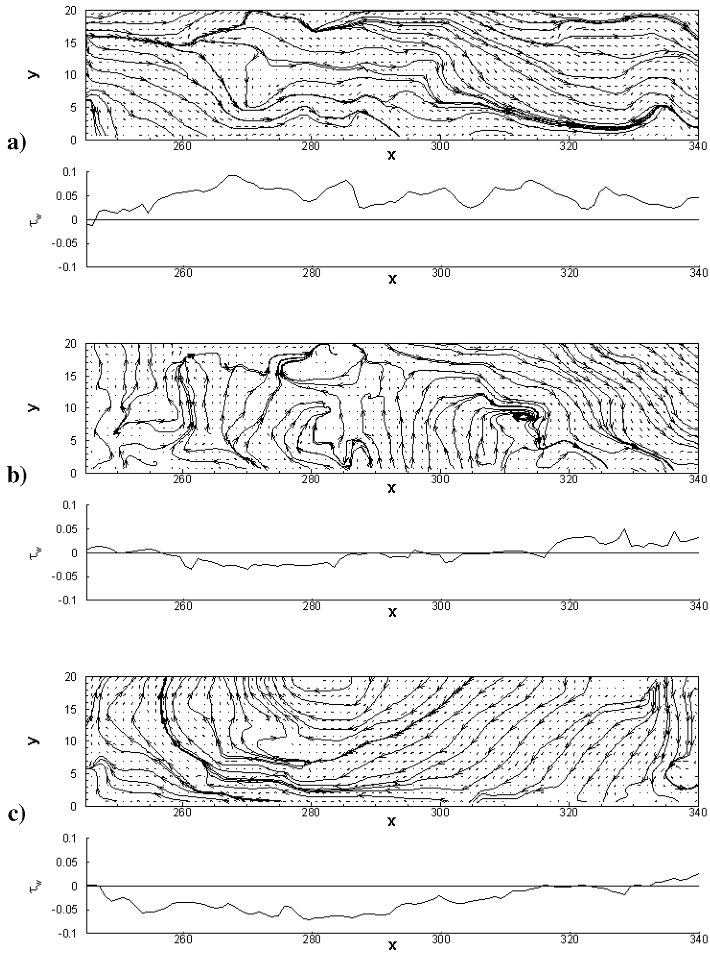
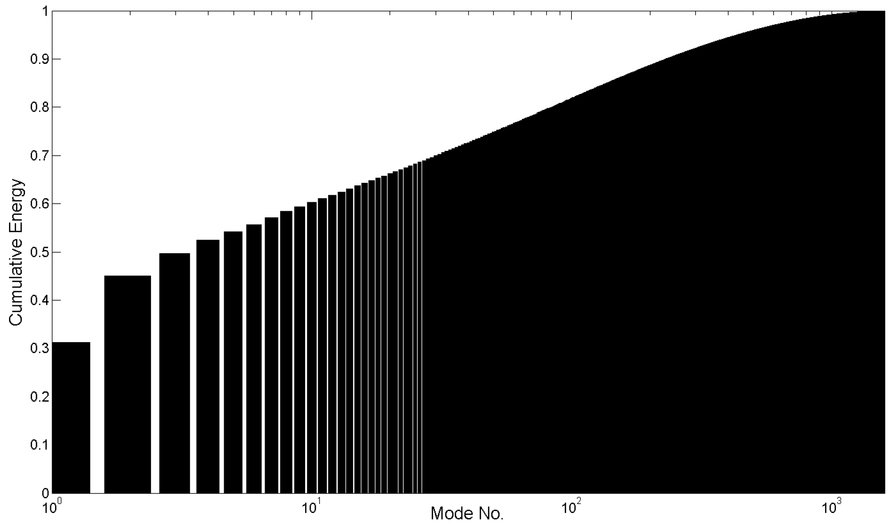


Fig.5: Example of the near-wall flow structure (velocity vector fields and vector-lines) a) fully attached BL, b) intermediate state, c) fully detached BL

To study the flow-field dynamics, the Bi-Orthogonal Decomposition (BOD) method proposed by Aubry et al. (1991) was used. This method is an extension of the well-known Proper Orthogonal Decomposition method proposed by Lumley (1967) for detection and definition so called 'coherent structures' in a turbulent flow. The BOD method offers representation of dynamically evolving vector field using energetic space and time modes called Topos and Chronos each of them (details see e.g. Uruba & Knob, 2007b).

The BOD modes are arranged according to the energy fraction which is contained in the individual modes in descending order. In Fig. 6 cumulative energies and relative energy fractions for individual modes are shown. The relative energy fraction represents non-dimensional fraction of the total kinetic energy which contains the mode in question, while cumulative energy is sum of energy of all modes with the order lower or equal to a given mode. The total energy is in both cases equal to 1. So, from the Fig. 6a we could state, that the first 10 modes contain approx. 60 % of the total kinetic energy, for example.

In Fig. 7 a few examples of low order Topoi are given. We could distinguish several features of the modes which are considered by Lumley (1969) as 'coherent structures' in-a)



b)

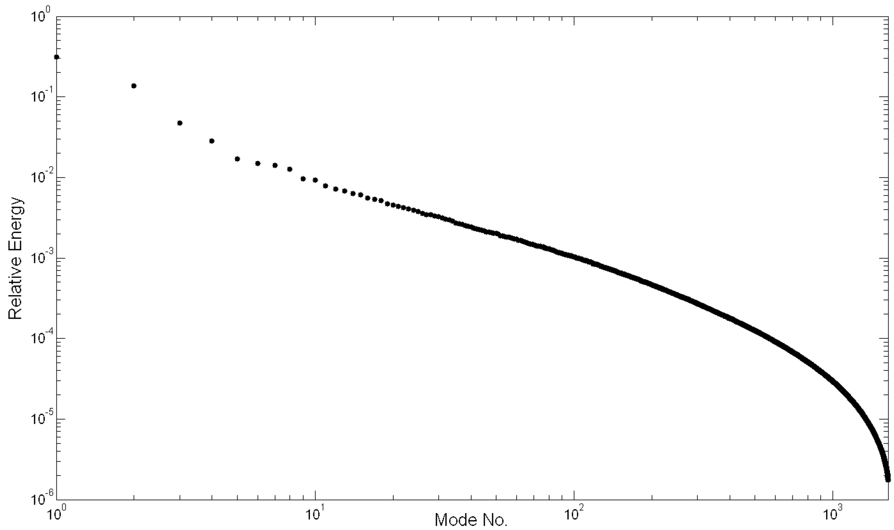


Fig.6: a) cumulative energy; b) relative energy fraction

volving in the flow dynamics. The Topos 1 (containing 31 % of total kinetic energy) is very similar to the mean flow pattern (see Fig. 4a) with exception that position of the point of zero longitudinal velocity near the wall is shifted significantly in the downstream direction. Then, the Topos 2 (14 % total energy) could be interpreted as an oblique and very strong jet pointing a little bit upstream the separation point D ($x = 250$ mm). Note that orientation of the vector field could be both positive and negative – so the jet could be in various instants oriented to the wall or away from it, depending on the sign of the Chronos 2. The same applies to all modes. Next, the Topos 3 (4.7 % total energy) is represented by a strong vortex with its centre in the point [290; 20] forming the weak jet pointing to the $x = 320$ mm on the wall (compare with the Fig. 5c). The Topos 4 (2.8 % total energy) is characterized by the vortex with core in [265; 20] and the saddle point [313; 15]. The Topos 5 (1.7 % total energy) is defined by a broad jet pointing to the wall at $x = 280$ mm in connection with two counter-rotating vortices near the wall. Character of higher mode Topoi is very similar to ones described above. Generally, the higher Topos mode order, the more complex and complicated its topology. For example the Topos 7 (1.4 % total energy) is characterized by 3 vortices near the wall and Topos 11 (0.78 % total energy) is formed by 4 vortices grouped in the two pairs of counter-rotating vortices. The Topoi 12 (0.72 % total energy) and 14 (0.64 % total energy) exhibit even more complicated structure. The demonstration in Fig. 7 ends-up by the Topos 24 (0.41 % total energy) represented by 3 vortex pairs, however the tendency continues to higher modes.

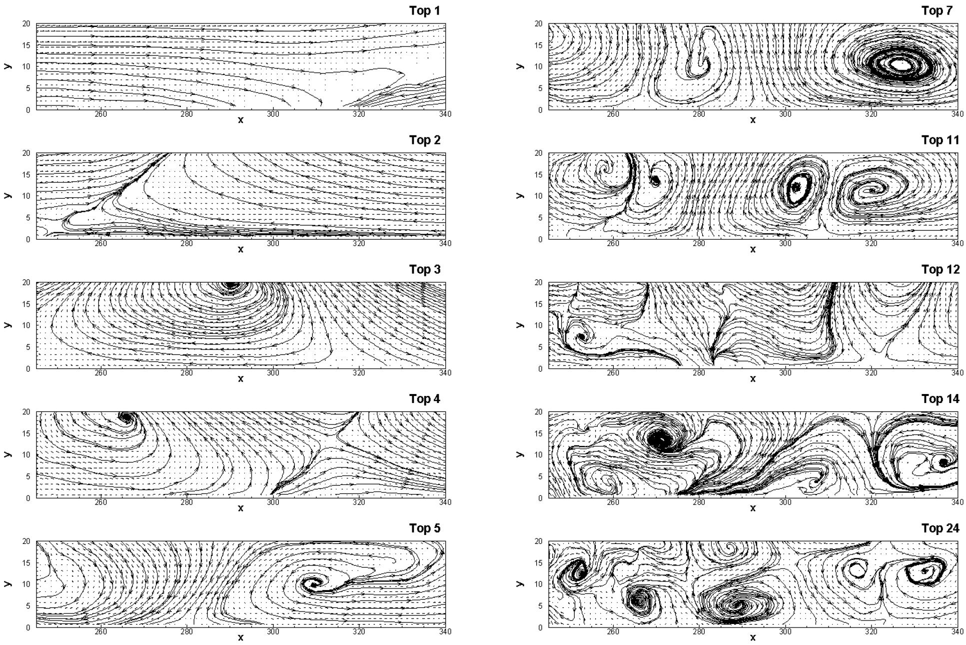


Fig.7: Topoi examples

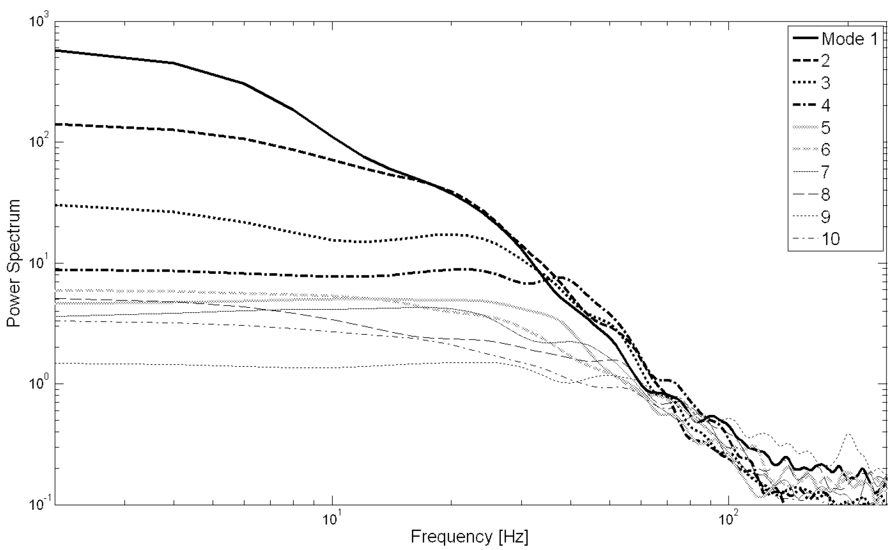


Fig.8: Spectra of low-order mode Chronoses

Then, the spectra of Chronoses were evaluated. In Fig. 8 the first 10 Chronos spectra are shown. The energy content is definitely more important for low frequencies up to 60 Hz and then all spectra decay in more or less the same form. The lower mode order, the higher energy content and the higher spectra for low frequencies. The low frequency energy corresponds to flapping of a BL separation. This tendency is remarkable for the first 4 modes and then this becomes less evident.

6. Conclusion

A boundary layer separation is definitely highly dynamical process, which could not be fully described by classical theories based on Prandtl's approach or Triple-Deck Theory. The new dynamical approach is needed.

The presented paper offers dynamical approach to a boundary layer separation based on ideas presented by Simpson (1996). In contrast to traditional view of turbulent BL separation with the mean backflow coming from far downstream the flow model with the turbulent structures supplying the small mean backflow is suggested. The time-space structure of separation zone was studied using Bi-Orthogonal Decomposition method. Dynamical behavior of the separation zone was described with help of energetic modes – Topoi and Chronoses.

Topoi in the separation zone are characterized by system of vortices, jets and saddle points, topology is specific for a given boundary conditions. In general, complexity of the topology is increasing with the mode order. Chronoses are characterized by flat maximum for low frequencies, which is more distinct for low-order modes, being related to vortex flapping in separation zone, while higher frequency spectra are very similar for nearly all low-order modes.

Acknowledgement

The authors gratefully acknowledge financial support of the Grant Agency of the Academy of Sciences of the Czech Republic, project No. IAA2076403 and the Grant Agency of the Czech Republic, project No. 101/08/1112.

References

[1] Aubry N., Guyonnet R., Lima R.: Spatiotemporal Analysis of Complex Signals: Theory and Applications, Journal of Statistical Physics, vol. 64, Nos. 2/3, 1991, pp. 683–739

[2] Dallmann U., Herberg Th., Gebing H., Su W.-H., Zhang H.-Q.: Flow field diagnostics: topological flow changes and spatio-temporal flow structure, AIAA Paper 95-0791, 1995

[3] Dovgal A.V., Kozlov V.V., Michalke A.: Laminar boundary layer separation : instability and associated phenomena, Prog. Aerospace Sci., 30, 1994, pp. 61–94

[4] Chang P.K.: Separation of Flow, 1970, Pergamon Press

[5] Cherry N. J., Hillier R., Latour M.P.: Unsteady measurements in a separated and reattaching flow, J. Fluid Mech., 144, 1984, pp. 13–46

[6] Haggmark C.P., Bakchinov A.A., Alfredsson P.H.: Experiments on a two-dimensional laminar separation bubble, Phil. Trans. R. Soc. Lond. A 358, 2000, pp. 3193–3205

[7] Lumley J.L.: The structure of inhomogenous turbulent flows, Atm. Turb. and Radio Wave Prop., Yaglom and Tatarsky eds., Nauka, Moskva, 1967, pp. 166–178

[8] Marquillie M., Ehrenstein U.: On the onset of nonlinear oscillations in a separating boundary-layer flow, J. Fluid Mech., 490, 2003, pp. 169–188

[9] Messiter A.F.: Boundary-layer flow near the trailing edge of a flat plate, SIAM J. Appl. Math., 18, 1970, pp. 241–257

[10] Neiland V.Ya.: Towards a theory of separation of the laminar boundary layer in a supersonic stream, Izv. Akad. Nauk SSSR, Mekh. Zhidk. i Gaza (4), 1969, pp. 53–57

[11] Prandtl L.: Uber Flussigkeits bewegung bei sehr kleiner Reibung, Verhaldlg III Int. Math. Kong. (Heidelberg: Teubner), 1904, pp. 484–491; Also available in translation as: Motion of fluids with very little viscosity, NACA TM 452 (March 1928)

[12] Simpson R.L.: Aspects of turbulent boundary-layer separation, Prog.Aerospace Sci, vol. 32, 1996, pp. 457–521

[13] Stewartson K.: On the flow near the trailing edge of a flat plate, Part II, Mathematika 16, 1969, pp. 106–121

[14] Sychev V.V., Rubin A.I., Sychev Vic.V., Korolev G.L.: Asymptotic Theory of Separated Flows, Cambridge University Press, 1998, Cambridge

[15] Theofilis V., Hein S., Dallmann U.: On the origins of unsteadiness and three-dimensionality in a laminar separation bubble, Phil. Trans. R. Soc. Lond. A 358, 2000, pp. 3229–3246

[16] Uruba V., Jonáš P., Mazur O.: Control of a channel-flow behind a backward-facing step by suction/blowing, International Journal of Heat and Fluid Flow, Vol. 28, Issue 4, 2007, pp. 665–672

[17] Uruba V., Knob M.: Dynamics of Controlled Boundary Layer Separation, Colloquium FLUID DYNAMICS 2007, Praha, ÚT AV ČR, v.v.i., 2007, (Eds.: Jonáš P.; Uruba V.), pp. 95–96, (a)

[18] Uruba V., Knob M.: Spatiotemporal Analysis of a Synthetic Jet Flow-Field, Conference TOPICAL PROBLEMS OF FLUID MECHANICS 2007, Praha, ÚT AV ČR, v.v.i., 2007, (Eds.: Příhoda J.; Kozel K.), pp. 185–188, (b)

[19] Uruba V.: Boundary Layer Separation Dynamics, Conference TOPICAL PROBLEMS OF FLUID MECHANICS 2008, Praha, ÚT AV ČR, v.v.i., 2007, (Eds.: Příhoda J.; Kozel K.), pp. 125–128

Received in editor's office: May 6, 2008
Approved for publishing: August 27, 2008

Note: The paper is an extended version of the contribution presented at the conference *Topical Problems of Fluid Dynamics 2008, Prague, 2008.*