ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1213531

PIV MEASUREMENTS OF FLOW SEPARATION OVER LAMINAR AIRFOIL AT TRANSONIC SPEEDS

Wit Stryczniewicz, Robert Placek

Institute of Aviation, Aerodynamics Department
Krakowska Avenue 110/114, 02-256 Warsaw, Poland
tel.: +48 22 8460011, ext. 312
e-mail: wit.stryczniewicz@ilot.edu.pl

Robert Szczepaniak

Air Force Academy, Aeronautics Faculty
Dywizjonu 303 Street 35, 08-521 Dęblin, Poland
tel.:+ 48 261517427
e-mail: r.szczepaniak@wsosp.pl

Abstract

The paper presents results of transonic flow field visualization over a laminar airfoil in high-speed wind tunnel. Quite recently, considerable attention has been paid to experimental investigations of an interaction between the shock and the boundary layer for aerodynamics applications. The purpose of the paper is to investigate development of the flow separation over laminar airfoil at transonic speeds. In a course of presented studies, the Particle Image Velocimetry (PIV) method was used for instantaneous velocity measurements of flow field in the test section of N-3 Institute of Aviation transonic wind tunnel. The object of the research was a laminar airfoil inclined at various angles. The effect of the varying angle of incidence on the flow filed was investigated. The freestream Mach number was 0.7. The results of the PIV measurements were analysed in order to identify the type of the separation from the measured velocity fields. Three forms of separation for low, medium and high angle of incidence was distinguished. The results are in good agreement with theoretical models reported in the literature. The study showed that application of quantitative flow visualisation technique allowed gaining new insights on the complex phenomenon of transonic flow over airfoil. The results of the presented research can be used for better understanding of the mechanism of the flow separation process in transonic flow over airfoils and fluid structure interactions.

Keywords: *shock wave, transonic flow, boundary layer separation, Particle Image Velocimetry*

1. Introduction

The structure of the interaction between the shock wave and the boundary layer plays important role in performance of wings, profiles and blades of turbines and compressors. Particularly, the shock interaction with a separated boundary layer in transonic flow may be a cause of many unsteady phenomenon like control surfaces oscillations, flow unsteadiness in engine intakes, or even flow inducted structure vibrations known as buffeting [1]. Better understanding and control of this phenomenon is crucial for the performance improvement of the airplane parts and turbomachinery equipment. The objective of presented work is to provide qualitative and quantitative measurements of separation over a laminar airfoil at transonic speeds.

In the last few years, there has been a growing interest in the investigations of shock wave boundary layer interaction (SWBLI). The unsteady effects of shock wave inducted separation were investigated in course of UFAST project [2]. The effect of laminar turbulent transition location was investigated on the structure of SWBL interaction was investigated numerically [3] and experimentally in the 7th Frame Work Programme Project TFAST project. Steady and unsteady transonic flow field with separation about airfoil was investigated experimentally in [4-6] and recently in [7]. Much research on unsteady transonic flow field above airfoil with flow separation related with buffet onset has been done numerically. Levy [8] proposed a numerical model for computations of unsteady turbulent flows with separation caused by a shock wave over an airfoil. Recently, advanced numerical simulations have been used for SWBLI in investigations of the transonic flow around airfoils [9, 10]. A comprehensive review of recent progress in shock wave/boundary layer interactions research can be found in [11] and a review of unsteady transonic aerodynamics can be found in [12].

The structure of flow separation on airfoils at transonic speeds depends on various factors, mostly on: a) the type of boundary layer (laminar, turbulent or mixed), b) the angle of incidence, c) the freestream Mach number, d) the shape and thickness of the airfoil, e) the shape and strength of the shock and f) the pressure fluctuations in the flow resulting the frequency and amplitude of shock oscillations. Therefore, various types of separation were observed and classified in the literature. Pearcey [13] proposed classification of the types of separation based on a stationary shock interacting with a turbulent boundary layer. Two models were specified: a) only rearward growth of laminar bubble and a) applicable when the rear separation is incipient or present. The alternative model b) was divided in three variants: 1) rear separation provoked by bubble, 2) rear separation provoked by shock and 3) with rear separation already present. Mundell and Mabey [14] proposed classification for the unsteady transonic flow with shock oscillations. The following classification of the flow separation with increasing incidence was proposed: a) type 1: for low angle weak shock thickens boundary layer; b) type 2: stronger shock locally separates boundary layer for higher values of angles; c) type 3: for high values of angle of incidence very strong shock separates the boundary layer to trailing edge.

The measurements of unsteady transonic flow field based on pressure fluctuations have been carried out since 1950's. Nowadays, application of new quantitative flow visualisation techniques such as Particle Image Velocimetry allows gaining new insights on the complex phenomena of transonic flow over airfoils. The PIV method was successfully applied for velocity measurements at transonic and supersonic flows [15]. Raffel [16] performed PIV measurements of unsteady transonic flow fields above a NACA 0012 airfoil. The SWBLI was investigated with PIV method by Humble [17] and recently by Giepman [18]. Hartmann [19] performed time resolved stereo PIV measurements of unsteady shock-boundary layer interaction on a supercritical airfoil.

The presented research was conducted in a course of complementary research in the TFAST project. The objective of the work was to perform qualitative and quantitative whole field velocity measurements of separation over airfoil at transonic speeds. In a course of presented studies, the PIV method was used for visualisation of flow separation over an airfoil at transonic speeds for fixed Mach number and various angles of incidence. The results showed different types of flow separation for various angles of incidence.

2. Experimental setup

The experimental investigation has been conducted in the Trisonic Wind Tunnel N-3 of the Institute of Aviation in Warsaw [20]. The N-3 wind tunnel is a closed circuit blow down type wind tunnel with partial recirculation of the flow. The test section dimensions are 0.6 x 0.6 x 1.5 m. The Mach numbers vary in range 0.2-2.3 and the test run duration for transonic speeds last about 5 minutes. In the transonic configuration the upper and bottom walls of the test section are perforated in order to simulate unconfined flow conditions. In the presented research solid walls was used in order to provide uniform conditions with CFD simulations performed in a course of different part TFAST project [3].

The airfoil model comprises the laminar type profile V2C which has been under investigation in the TFAST project. The airfoil chord length was c = 200 mm and relative thickness was 15%. The model was equipped with pressure orifices and Kulite pressure transducers not used in the presented research. Picture of the test section with the investigated airfoil is presented in Fig. 1a.

a) b)

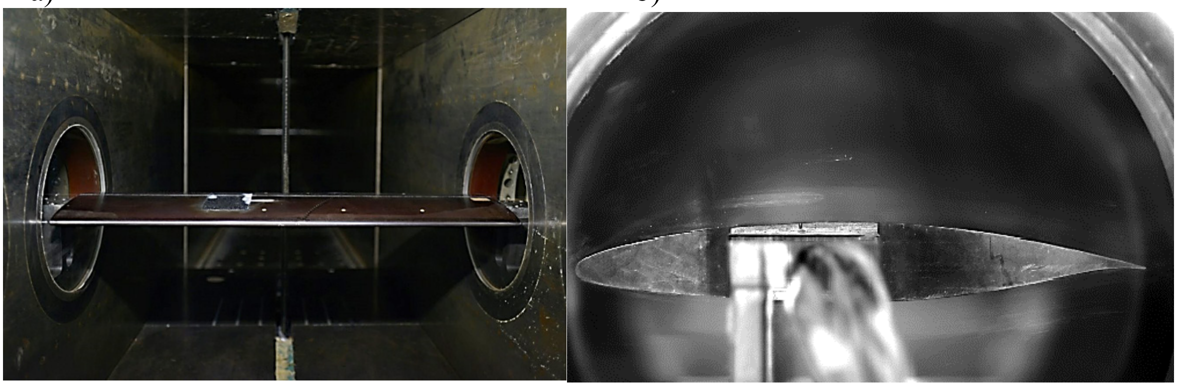

Fig. 1. View of the investigated airfoil in the test section of the IoA N-3 trisonic wind tunnel a) front view, b) view of PIV camera

The Particle Image Velocimetry setup comprised of dual-cavity solid-state (Nd:YAG) nanosecond pulse laser with a wavelength of 532 nm and digital 4 MP digital camera. The impulse time was 8 ns and repetition of the system was 7 Hz. The light sheet thickness was about 2 mm and the laser light was provided with a use of periscope system downstream of the test section. This configuration enabled positioning the light sheet parallel to the incoming flow providing good particles illumination conditions in the test section form the trailing edge of the model to approximately x/c = 0.2, where x = 0 corresponds to the leading edge. The energy of the laser impulse at the light sheet forming optics was approximately 120 mJ. The flow was seeded with a droplets of Di-Ethyl-Hexyl-Sebacat (DEHS, CAS-No. 122-62-3) with mean diameter of 2 µm according to the seeding generator specification. In order to provide uniform seeding distribution in the test section, the seeding was introduced to the flow approximately 6 m upstream of the test section. The Stokes number for the parameters of the flow and the particles was Stk = 0.02. Since Stk < 0.1 the particles should follow the streamline closely and the tracing accuracy errors are assumed to be below 1% [21]. The particles images where recorded with Dantec Dynamic HiSense camera with 2048x2048 pixel sized sensor. A 80 mm Canon 80 1:2.8 lenses was mounted to the camera. The field of view covered whole airfoil and approximately 0.125% of chord length downstream of the trailing edge. The measurement area of the PIV camera is shown in Fig. 1b. The system was calibrated with dedicated Dantec Dynamic calibration target in a form of a flat plate with dots. The standard deviation from the nominal position of the dots on the target was below 0.005 mm. The detailed description of the PIV setup can be found in [22].

3. Results and discussion

For every angle of incidence 100 image pairs was acquired. The images were analysed using Dantec DynamicStudio software. The adaptive correlation scheme was used with 3 steps of the interrogation area refinement. The final interrogation area size was 32 x 32 pixels with overlap factor of 50% [23]. For post-processing the universal outliner procedure was applied using normalized median test using surrounding vectors. Small size of the neighbourhood (5 x 5 pixels) was used in order to avoid smoothing of the velocity gradient on the shock.

Instantaneous vector velocity filed for Mach number 0.7 and angle of incidence 1° is presented in Fig. 2. An abrupt decrease of the flow velocity at the shock terminating the supersonic flow region above the airfoil surface can be observed. The flow separation is visible at the trailing edge. Unfortunately, the spatial resolution of the PIV measurements and the laser light reflections form the surface do not allow measuring the velocity in the boundary layer. For that reason, the location and size of bubble cannot be detected.

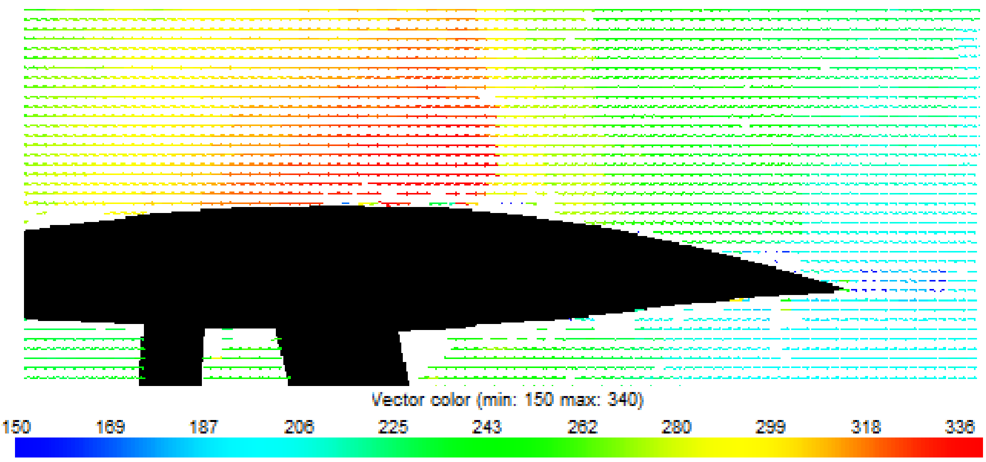

Fig. 2. Vector velocity field for freestream Mach number 0.7 and angle of incidence 1°; the field of view is cropped in order to zoom the separation region. Scale in [m/s]

Visualization of the flow field for moderate angle of the incidence is presented in Fig. 3. Stroger shock separates boundary layer. The flow separation starts closer to SW, at x/c ≈ 0.7. Vector velocity field for high angle of the incidence is presented in Fig. 4. Very strong shock separates boundary layer to the trailing edge. The flow separation starts right at the shock wave foot.

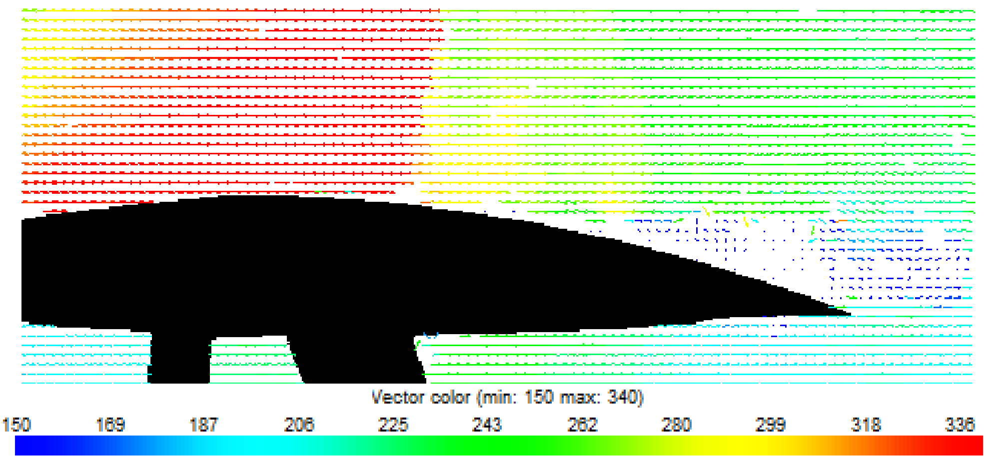

Fig. 3. Vector velocity field for freestream Mach number 0.7 and angle of incidence 4°; the field of view is cropped in order to zoom the separation region. Scale in [m/s]

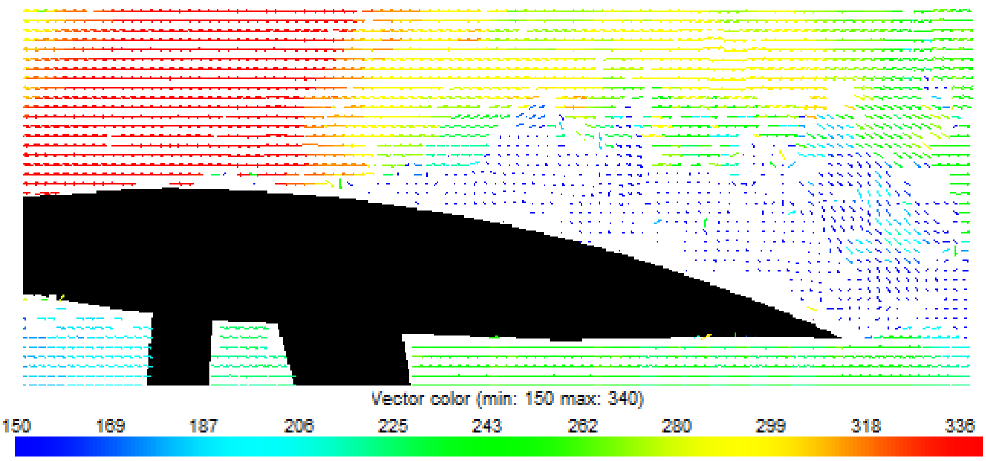

Fig. 4. Vector velocity field for freestream Mach number 0.7 and angle of incidence 7°; the field of view is cropped in order to zoom the separation region. Scale in [m/s]

The velocity magnitude in a cross section perpendicular to the main flow downstream the trailing edge for three angles of incidence is presented in Fig. 5. The investigated flow filed was very unsteady, especially for moderate and high angles of incidence. Therefore, the velocity profiles were determined from average of 100 instantaneous velocity fields. The values were extracted from line positioned at distance 0.1 *c* downstream of the trailing edge. One can notice that the velocity profiles are similar to the momentum loss profiles from aerodynamic rake measurements.

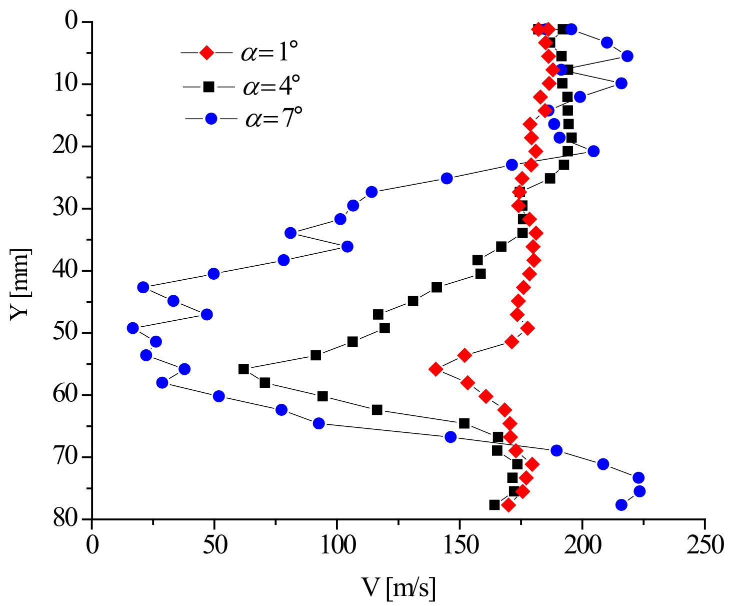

Fig. 5. Velocity profile at the line in the distance 0.1 c from the trailing edge, perpendicular to the main flow; position 0 on the Y axis corresponds to point located 55 mm above the chord line of the airfoil

For low and moderate angle of incidence, the magnitudes of the velocity are different but profiles are comparable. This might indicate that the mechanism of the separation is similar. In these cases, the shock thickens the boundary layer and for moderate angle of incidence the separation on the bubble might occur followed by reattachment. For high angle of incidence, the separation region is much thicker and there is severe loss of flow velocity due to large separation structure starting at the foot of shock (see Fig. 4).

The main limitations of the experimental results were not sufficient resolution of velocity measurement in boundary layer and low frequency of the PIV system. In order to investigate the dynamics of the investigated phenomenon the Time Resolved PIV measurement should be performed with frequency f_{PIV} > 1000 Hz. In order to perform flow visualization with the use of high magnification lenses so the field of view of the PIV system camera can be zoomed at the proximity of the surface of the airfoil.

The purpose of the presented research was to perform visualization of the flow separation over the laminar airfoil at transonic speeds in a qualitative and quantitative manner. The results presented in Fig. 2, 3 and 4 are in good agreement with types of flow separation proposed by Mundell and Mabey [14]. Particularly, the vector velocity field in Fig. 3 resembles the type 2 and Fig. 3 corresponds to the type 3 of flow separation.

4. Conclusions

The paper presents the results of flow visualization over laminar airfoil at transonic speed. The PIV method was used for qualitative and quantitative visualization of flow filed above laminar airfoil. The results of 100 instantaneous measurements for three angle of incidence were analysed. From the research that has been carried out, it is possible to conclude that there is good match between the obtained results and theoretical models reported in the literature.

In future work, high spatial resolution PIV measurements will be performed in order to characterize the type of boundary layer (laminar/turbulent) and visualize the shock/boundary layer interaction. For this purpose, the issue of laser light reflections should be also addressed.

Acknowledgements

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) within the project TFAST (Transition Location Effect on Shock Wave Boundary Layer Interaction), under grant agreement No. 265455.

References

[1] Lee, B. H. K., *Self-sustained shock oscillations on airfoils at transonic speeds,* Progress in Aerospace Sciences, 37, pp. 147-196, 2001.
[2] Doerffer, P., Hirsch, C., Dussauge, J.-P., Babinsky, H., Barakos, G. N., *Unsteady Effects of Shock Wave Inducted Separation,* Notes on Numerical Fluid Mechanics and Multidisciplinary Design, 114, Springer – Verlag Berlin Heidelberg 2010.
[3] Sznajder, J., Kwiatkowski, T., *Effects of Turbulence Induced by Micro-Vortex Generators on Shockwave – Boundary Layer Interactions*, Journal of KONES Powertrain and Transport, 22, 2015.
[4] McDevitt, J. B., Levy, L. L. Jr. and Deiwert, G. S., *Transonic Flow About a Thick Circular-Arc Airfoil*, AIAA Journal, 14, pp. 606-613, 1976.
[5] Lee, B. H. K., *Investigation of flow separation on a supercritical airfoil*, Journal of Aircraft, 26, pp. 1032-1039, 1989.
[6] Jacquin, L., Molton, P., Deck, S., Maury, B., Soulevant, D., *Experimental Study of Shock Oscillation over a Transonic Supercritical Profile*, AIAA Journal, 47, pp. 1985-1994, 2009.
[7] Zhao, Z., Ren, X., Gao, C., Xiong, J., Liu, F., Luo, S, *Experimental Study of Shock Wave Oscillation on SC(2)-0714 Airfoil*, 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Grapevine, USA 2013.
[8] Levy, L. L. Jr., *Experimental and Computational Steady and Unsteady Transonic Flows about a Thick Airfoil*, AIAA Journal, 16, pp. 564-572, 1978.
[9] Wollblad, C., Davidson, L., Eriksson L.-E., *Investigation of large scale shock movement in transonic flow*, International Journal of Heat and Fluid Flow, 31, pp. 528-535, 2010.
[10] Szubert, D., Grossi, F., Garcia, A. J., Hoarau, Y., Hunt, J. C. R., Braza, M., *Shock-vortex shear-layer interaction in the transonic flow around a supercritical airfoil at high Reynolds number in buffet conditions*, Journal of Fluids and Structures, 55, pp. 276-302, 2015.
[11] Gaitonde, D. V., *Progress in shockwave/boundary layer interactions*, Progress in Aerospace Sciences, 72, pp. 80-99, 2015.
[12] Bendiksen, O. O., *Review of unsteady transonic aerodynamics: Theory and applications*, Progress in Aerospace Sciences, 47, pp. 135-167, 2011.
[13] Pearcey, H. H., Osborne, J., Haines, A. B., *The interaction between local effects at the shock and rear separation a source of significant scale effects in wind-tunnel tests on aerofoils and wings*, AGARD, 35, Paris, France, pp. 18-20, 1968.
[14] Mundell, A. R. G., Mabey, D. G., Pressure fluctuations caused by transonic shock/boundary-layer interaction, Aeronautical Journal, 90, pp. 274-282 1986.
[15] Scarano, F., *Overview of PIV in Supersonic Flows*, In Schroeder A and Willert C E. Partcle Image Velocimetry, Springer-Verlag, 2008.
[16] Raffel, M., Kompenhaus, J., *PIV measurements of unsteady transonic flow fields above a NACA 0012 airfoil*, Laser Anemometry Advances and Applications, 2052, pp. 527-534, 1993.

[17] Humble, R. A., Scarano, F., van Oudheusden B. W., Tuinstra, M., *PIV Measurements of a Shock Wave/Turbulent Boundary Layer Interaction*, 13th Int. Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portuga 2006.
[18] Giepman, R. H. M., Schrijer, F. F. J., van Oudheusden, B. W., *High-resolution PIV measurements of a transitional shock*, Experiments in Fluids, 56, pp. 113-133, 2015.
[19] Hartmann, A., Klaas, M., Schröder, W., *Time resolved stereo PIV measurements of unsteady shock-boundary layer interaction on a supercritical airfoil*, 15th Int Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal 2010.
[20] Wiśniowski, W., *Specializations of the Institute of Aviation – review and conclusions*, Transactions of the Institute of Aviation, 235, pp. 7-16, 2014.
[21] Tropea, C., Yarin, A., Foss, J. (ed.), *Springer Handbook of Experimental Fluid Mechanics*, Springer, ISBN 978-3-540-25141-5.
[22] Stryczniewicz, W., Surmacz, K., *PIV Measurements of the Vortex Ring State of the Main Rotor of a Helicopter*, Transactions of the Institute of Aviation, 235, pp. 17-27, 2014.
[23] Stryczniewicz, W., *Development of Particle Imagine Velocimetry Algorithm*, Problems of Mechatronics, 9, pp. 41-54, 2012.