ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1213604

IDENTIFICATION OF THE BOUNDARY LAYER SHOCK WAVE INTERACTION TYPE IN TRANSONIC FLOW REGIME[1]

Robert Placek, Wit Stryczniewicz

Institute of Aviation, Aerodynamics Department
Krakowska Avenue 110/114, 02-256 Warsaw, Poland
tel.: +48 22 8460011 int. 360, 312
e-mail: robert.placek@ilot.edu.pl, wit.stryczniewicz@ilot.edu.pl

Abstract

The paper presents various approaches to wind tunnel data analysis when identifying the shock wave boundary layer interaction type. The investigation was carried out in the transonic flow regime in the N-3 Wind Tunnel of Institute of Aviation. The Mach number was 0.7 and Reynolds number was approximate equal 2.85 million. The object of the research was a laminar airfoil in configuration without and with turbuliser device mounted on the upper model surface. In order to achieve turbulent boundary layer in front of the shock wave the carborundum strip was used. The effect of the varying angle of incidence on the flow filed was investigated. During experimental research, different means and test methods were applied (pressure measurements, Schlieren and oil visualisation, Particle Image Velocimetry (PIV), hot-film anemometry). The results were analysed in terms of the shock wave boundary interaction type. Most of results were in good agreement with theoretical models reported in the literature. The study showed that combination of various measurement techniques should be used in the shock wave boundary investigations in order to achieve more consistent and reliable conclusions. The results of the presented research can also be used for better understanding other mechanisms i.e. the boundary layer shock wave separation process in transonic flow regime.

Keywords: *transonic flow, wind tunnel techniques, shock wave, airfoil, boundary layer interaction*

1. Introduction

The interaction type between the shock wave (SW) and the boundary layer is very important for performance of aircrafts and turbomachinery, especially in the transonic flow regime. The boundary layer interaction with the shock wave may lead to the drag rise, severe shock wave separation or even high shock wave unsteadiness level called buffet phenomena. This has significant impact on the airfoils performance, which was mentioned in [15, 20, 24]. The SWBLI and SW structures description could be found in positions such as [4] and recently [1]. The development of the separation process for turbulent boundary layer connected with the SW and its type classification were detailed described by Pearcey in [16, 17]. Unsteady shock wave behaviour in transonic speed regime and connected phenomena were and are still studied. Experimental and numerical results were described i.e. in [2, 5, 8, 10, 14].

There are several experimental methods allowing for general classification of the SWBLI type on base the boundary layer (BL) character. Interaction could be laminar, (transitional) or turbulent. The most reliable method for classification of the SWBLI type (laminar or turbulent) is measuring the velocity profiles in the BL along the model surface ahead SW. The velocity profiles indicate ~~on~~ the laminar or turbulent type of the BL. The measurements can be performed for example with use of special hot wire probe, traversing pitot probe [19] or more modern and non-intrusive approach such as using Particle Image Velocimetry visualisation method (PIV) [21]. The drawbacks of first and second methods are: i) interaction of the probe with the flow and ii) requirements about flow cleanness, humidity. PIV is a non-intrusive method, nevertheless it often suffer from laser beam

[1] *The research was conducted as a part of study of Transition Location Effect on Shock Wave Boundary Layer Interaction (TFAST project in 7th EU Framework Programme).*

reflection on the model surface. This disadvantage sometimes makes the BL identification ahead the SW difficult. On the other hand, the PIV method allows recognizing the SWBLI type from the SW shape above the model surface.

The BL character can be also determined with use of Infra-Red Thermography (IRT) (i.e. in [11]) or Temperature Sensitive Paint (TSP) (i.e. in [6]). Both methods base on temperature distribution changes on non-conductive heat model surface. The character of the BL is strictly connected with shear stress. Once the transition location in the BL is detected, the interaction type could be estimated by knowing the SW position. Similarly, the transition location can be determined with oil visualisation. This method required skilfully prepared oil mixture adequate to test conditions. For instance, the oil could be replaced by a naphthalene. In turbulent region, the temperature and turbulence in the BL are higher than in laminar BL [18]. Because of increased rate of sublimation, the turbulent BL region will be covered be less dense fluid.

Other method indicating the laminar or turbulent BL character is shear stress measurement on model surface. For instance, the Preston tube can be used to measure shear stress [9]. While the laminar BL will change into turbulent, the region with rapid decrease of skin friction coefficient value could be observable.

The SWBLI could be also identified on base the shock wave structure. The stronger rear lambda foot and numerous compression waves ahead of the SW are typical for laminar BL interaction with the SW [1, 13, 20].

The experimental investigation was performed in the Institute of Aviation (IoA) [25]. During study, designed by Dassault Aviation (mentioned in work [7]), the V2C laminar airfoil was used. Basing on numerical predictions, the laminar boundary layer at M=0.7 and Re= 3.42 million should have been maintained up to angle of attack $\alpha=7^0$ for base line airfoil. During wind tunnel tests, the boundary layer character might have been changed from laminar to turbulent ~~one~~ for base-line model, what was to be examined. In case of model with required turbulent BL on its upper surface, the incipient transition was initiated by grain roughness. Its height was determined by using simplified method described in [3] and on base IoA numerical calculations.

The objective of presented work is to provide qualitative measurements of BL and SW, which could indicate on the SWBLI type over a laminar airfoil at transonic speed.

2. Experimental setup

The experimental investigation has been conducted in the IoA Trisonic Wind Tunnel N-3 [12]. 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 number can be changed in range 0.2-1.15. The test duration depends on the Mach number and for instance, for transonic Mach values last about up to 10 minutes. The test section can be equipped with (top and bottom) solid or perforated walls. During TFAST investigation, the solid walls were mounted.

The V2C airfoil model, as mentioned above, was laminar type. The airfoil model of chord 0.2 [m] and span 0.6 [m] had the relative thickness approx. 15% chord. In order to measure pressure distribution (mean value) along the airfoil chord, pressure tubes were mounted inside the model to 64 pressure taps of 0.5 [mm] diameter. Pressure tubes were connected to two 32-channel electronic scanners ESP-32HD DTC Pressure System (scan rate 333 Hz). Straight rows of static pressure measurement points were located both on the top and bottom surface of the model (Fig. 1). Besides, during WT tests the aerodynamic rake was mounted behind the model.

To investigate Schlieren photography the IoA Schlieren optical system and the 60 Hz video camera was used. The record mode was on when wind tunnel test run. From recordings reduction the movies ~~a~~nd pictures has been achieved.

The visualization and pressure tests have been made at the same time.

In order to perform oil visualisation test special mixture was used. It contained of oil acid, silicone oil and titanium white. The liquid was applied on the upper model surface by a roller. The wind tunnel run time was up to establish steady oil distribution on the model surface. Following the wind tunnel was stopped and model upper surface photographed. In order to investigate another Mach number and angle of incidence case, the model was prepared by removing oil layer from model surfaced and oil mixture was applied again before next wind tunnel run.

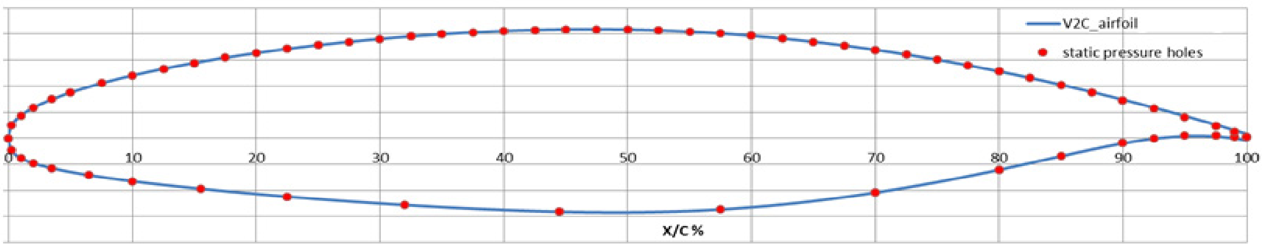

Fig. 1. The static pressure orifices location at airfoil

The PIV laser pulse laser impulse time was 8 ns and repetition of the system was 7 Hz [24]. 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 SENFLEX hot film array sensors were used for L-T transition location measurement. The sensors array was mounted in earlier prepared cavity on the top model surface, filled by resign in order to avoid thermal influence during tests.

The boundary-layer transition was triggered on the model upper surface by the use of the carborundum strip, fraction f180, of approx. 0.1 [mm] height and 4 [mm] width. The height of carborundum grain was based on a local Reynolds number derived in IoA CFD calculations. The location of the carborundum strip was at 10% of airfoil chord.

The tested model in the N-3 wind tunnel test section is presented in Fig. 2.

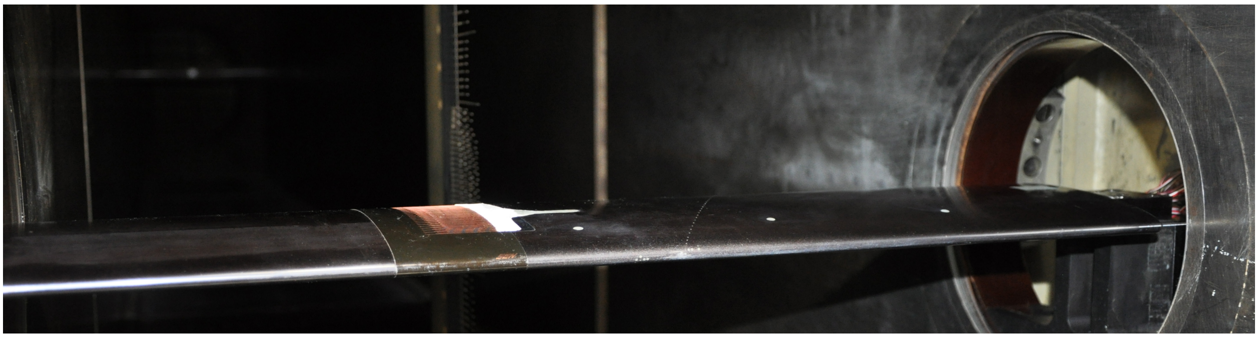

Fig. 2. The V2C airfoil in the test section of the IoA N-3 trisonic wind tunnel

3. Results and discussion

The results were compared in terms of SWBLI type identification for the model configuration with and without roughness strip. The Mach number was M=0.7 and Reynolds number was Re≈2.85 million. For presented model configurations angle of incidence was equal $\alpha_i=4^0$.

The effect of the varying angle of incidence on the flow filed was analysed by comparison of Schlieren visualisation pictures.

Pressure & Hot Film Anemometry measurements

According to [20, 24], the pressure distribution shape can indicate on different SWBLI type. The characteristic pressure inflection just ahead SW indicates on the laminar type of boundary layer interaction with SW. For turbulent BL, the pressure rise appears earlier and is more rapid. The presented pressure distributions in Fig. 3 (averaged values) confirmed that the laminar character of SWBLI for clean model and turbulent for model with rough strip.

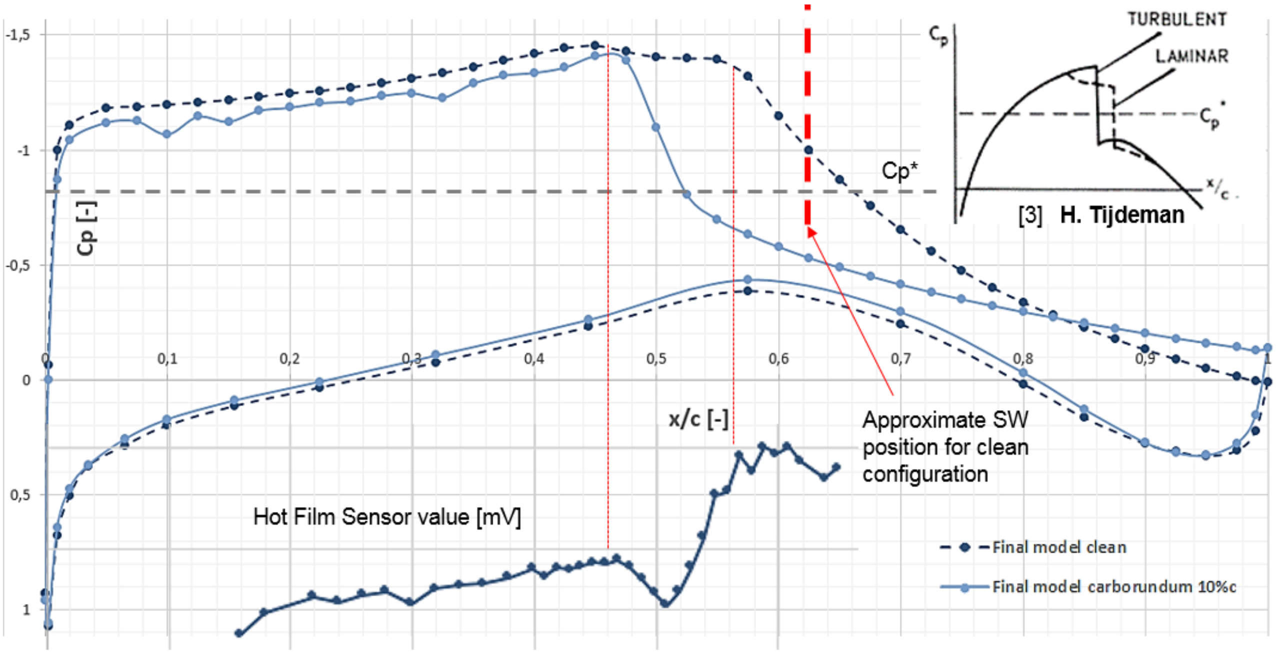

Fig. 3. The Comparison of the Cp distribution- M=0.7; Re≈2.85 million; Incidence αi=4 º. The shear stress under Cp distribution plot for clean configuration given

The shear stress distribution measurements were performed at limited distance on model chord and only for model in clean configuration. However, the hot film sensors were not calibrated, the plot created from measurement values (values were given in [mV]) revealed the characteristic change (see Fig. 3). The rapid decrease of measured value (~skin friction) corresponds to the origin of laminar BL change into turbulent one. This phenomenon occurred just in front of SW main foot, ahead of which the laminar bubble presence is considerable. The described result has similar character to the CFD calculations for the same airfoil, which were performed and described in [23].

Schlieren visualisation

The instantaneous colour Shlieren pictures of the model with and without roughness were shown in Fig. 4. There were identified two kinds of SWBLI types. The laminar /turbulent boundary layer interaction was identified by focusing on the shock wave shape features (basing on i.e. [1, 13, 20]). The laminar SWBLI characterises (clean model configuration) strong rear foot of the main SW and wide impact region of the compression waves ahead. The main SW is downstream running and nearly normal to the model surface. Additionally, because of the sensitiveness of BL in this region, main SW reflected from BL could be observed as Prandtl-Mayer expansion wave closed by compression wave (at small incidence).

In case of the turbulent SWBLI (model with roughness configuration), characteristic strong front SW foot can be observed. The λ-foot and compression waves ahead the SW is much weaker. Additionally, the SW interacting with the turbulent BL is curved, whereas at laminar case SW looks normal.

The increasing angle of incidence for both SWBLI types (both presented model configurations) made the main SW stronger. The further increase of incidence strengthens main SW even more. For clean model configuration, the reflected SW behind the main SW disappeared. This might indicate the fact, that increasing incidence cause change the laminar BL into turbulent.

Moreover, in the IoA it was found, that just below the moderate incidence $\alpha i=4^0$ the SW unsteadiness increased and SW boundary layer separation started occur. The SW location on model with roughness was closer to the leading edge (LE) (and even closer to the LE with incidence) of the airfoil, than for clean model case.

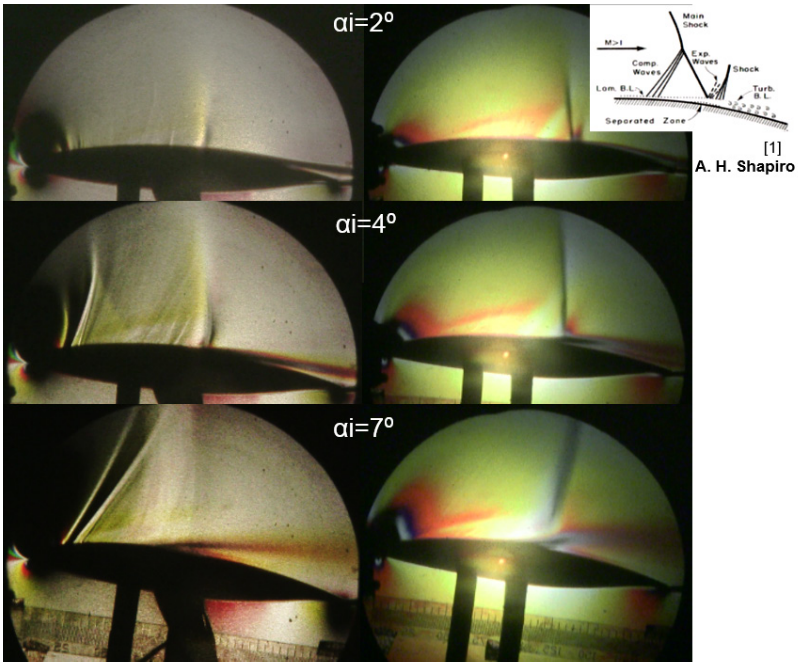

Fig. 4. The Schlieren pictures of the model with roughness (on left) and in clean configuration (on right); M=0.7, Re≈2.85 million; Incidence αi=2, 4 and 7 ^{0}

Oil visualisation

The oil visualisation pictures were shown in Fig. 5. For model with roughness, the rarefaction of the oil mixture behind the grain strip can be observed. It is maintained up to narrow stagnation region , just ahead of the SW. Less dense oil, at the location where turbulence level was higher (due to high fluid kinetic energy), is typical for turbulent BL. This kind of region could be also seen at model surface in clean configuration, but only behind turbulent wedges. The remaining area (the laminar BL) is observable denser and more uniform. This maintain up to wider stagnation area, in front of the SW foot.

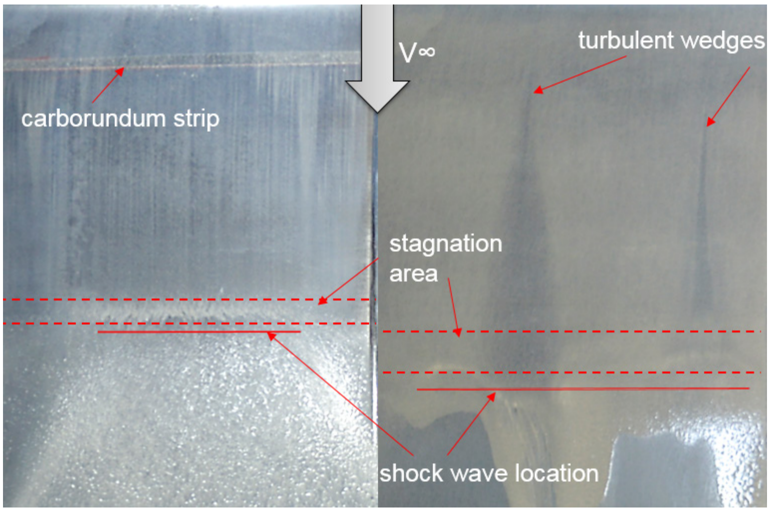

Fig. 5. The oil visualisation pictures of the model with roughness (on left) and in clean configuration (on right); M=0.7; Re≈2.85 million; Incidence αi=2, 4, and 7 ^{0}

PIV visualisation

Visualization of the flow field for angle of the incidence $\alpha i=4^0$ is presented in Fig. 6. The flow separation occurs at some distance behind the SW at about x/c ≈ 0.7. The flow between the SW and separation location reattached to model surface (as the turbulent one). Although, the main limitation of the performed PIV measurement was poor resolution of the velocity in BL, the character of the velocity distribution behind the SW might indicate on laminar (or transitional) SWBLI at this incidence. This is probable, because the experiment revealed an increased velocity magnitude region of the velocity behind the SW. This analysis could be verified by detailed velocity profile measurement in the BL.

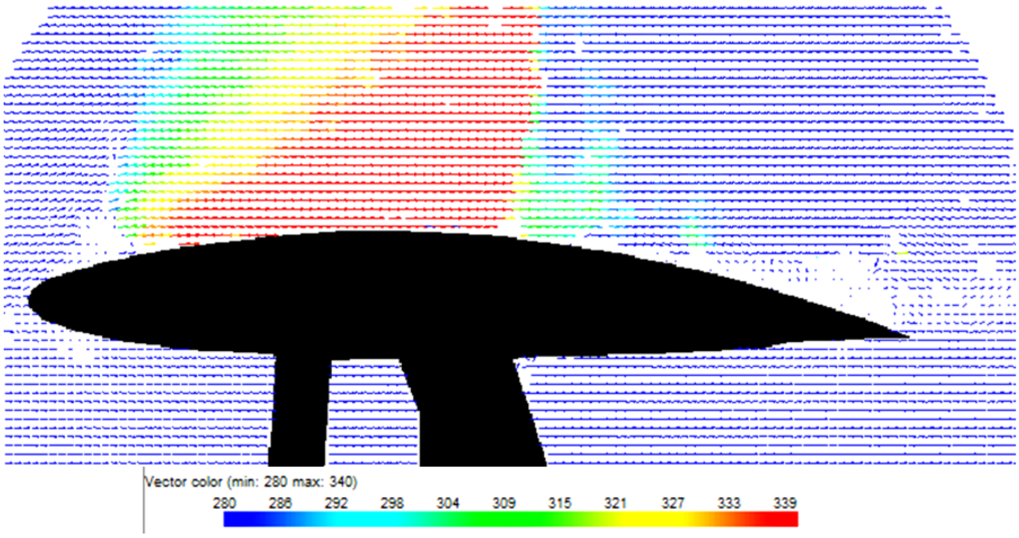

Fig. 6. Vector velocity field for freestream Mach number 0.7 and angle of incidence 4°. Scale in [m/s]

4. Conclusions

The paper presents results of application of various experimental methods for investigation of flow over laminar airfoil at transonic speed. The main goal of this paper was to characterize the SWBLI type. During investigation, different experimental approaches were applied. Some of methods were based on pressure response near the SW, others on the BL character in front of the SW or on SW shape. Most of performed measurements allowed for classification of the SWBLI type. The results given were consistent with this reported in the literature.

Presented results could be also useful for different analysis undertaking i.e. airfoils performance study for different configurations or for better understanding of the SW separation development process.

The future investigations should be performed with using of the quality-improved visualization methods and synchronized measurements. Such measurements will allow for more clarified observations. For this purpose, the issues with resolution and model surface reflections must be solved.

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.

The project was also co-financed by the Ministry of Science of Republic of Poland from the funds dedicated to scientific research in 2012-2015, agreement No. 2641/7.PR/12/2013/2 and by Institute of Aviation.

References

[1] Babinsky, H., Harvey, J. K., *Shock Wave-Boundary-Layer Interactions*, Cambridge University Press, Ch. 3, 2014.

[2] Bendiksen, O. O., *Review of unsteady transonic aerodynamics: Theory and applications,* Progress in Aerospace Sciences, 47, pp 135-167, 2011.

[3] Braslow, A. L., Knox, E. C., *Simplified method for determination of critical height of distributed roughness particles for boundary-layer transition at Mach numbers from 0 to 5,* NACA-TN-4363, 1958.

[4] Delery, J., Marvin, J. G., *Shock Wave-Boundary-Layer Interactions,* AGARD-AG-280, Ch. 2, 1986.

[5] 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.

[6] Flaszynski, P., Doerffer, P., Szwaba, R., Kaczynski P., Piotrowicz M., *Shock Wave Boundary Layer Interaction on Suction Side of Compressor Profile in Single Passage Test Section,* Journal of Thermal Science, Vol. 24, Is. 6, pp 510-515, 2015.

[7] Grossi, F., *Numerical Study of a Laminar Transonic Airfoil,* Extract from PhD Thesis, Ch. 7, pp. 122-123, 2014.

[8] Hermes, V., Klioutchnikov, I., Olivier, H. *Numerical investigation of unsteady wave phenomena for transonic airfoil flow,* Aerospace Science and Technology 25, pp 224-233, 2013.

[9] Huang, X. Z., *Transonic Buffet of a Supercritical Airfoil,* Research And Technology Organization, RTO Technical Report 26, pp. 295-339, 2000.

[10] 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.

[11] Jun Z., Zhenghong, G., Hao, Z., Junqiang, B., *A High-speed Nature Laminar Flow Airfoil and Its Experimental Study in Wind Tunnel with Nonintrusive Measurement Technique,* Chinese Journal of Aeronautics, 22, pp. 225-229, 2009.

[12] Kania, W., *Aerodynamika doświadczalna w zakresie dużych prędkości.,* Journal of Theoretical and Applied Mechanics, 21.4, pp. 611-644, 1983.

[13] Kim, H. D., Setoguchi, T., *Shock Induced Boundary Layer Separation,* 8th International Symposium on Experimental and Computational Aerothermodynamics of Internal Flows, Lyon, France 2007.

[14] Lee, B. H. K., *Self-sustained shock oscillations on airfoils at transonic speeds,* Progress in Aerospace Liepmann, H. W., *Interaction Between Boundary Layers and Shock Waves in Transonic Flow,* J. Aero Sci., Vol. 13, No. 12, pp. 623-237, 1946.

[15] Ligum, T. I., *Aerodynamics and flight dynamics of turbojet aircraft*, Ch. 1, §13, National Aeronautics And Space Administration, 1969.

[16] Pearcey, H. H., *Some Effects of Shock-induced Separation of Turbulent Boundary Layers in Transonic Flow past Aerofoils*, Aeronautical Research Council Reports And Memoranda, No. 3108, London 1959.

[17] 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, pp. 18-20, Paris, France 1968.

[18] Ren, Z. Z. 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, 2013.

[19] Seddon, J., *The Flow Produced by Interaction of a Turbulent Boundary Layer with a Normal Shock Wave of Strength Sufficient to Cause Separation,* Aeronautical Research Council Reports And Memoranda, No. 3502, London 1959.

[20] Shapiro, A. S., *The dynamics and thermodynamics of compressible fluid flow*, Ch. 22.8, 28.4, Ronald press company, 1954.

[21] Stryczniewicz, W., *Development of Particle Imagine Velocimetry Algorithm*, Problems of Mechatronics, 9, pp. 41-54, 2012.

[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] 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.

[24] Tijdeman, H., *Investigations of the transonic flow around oscillating airfoil*, Part 1, Ch. 3.4., 1977.

[25] Wiśniowski, W., *Specializations of the Institute of Aviation – review and conclusions*, Transactions of the Institute of Aviation, 235, pp. 7-16, 2014.