ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1213755

ANALYSIS OF EFFECTS OF SHAPE AND LOCATION OF MICRO-TURBULATORS ON UNSTEADY SHOCKWAVE-BOUNDARY LAYER INTERACTIONS IN TRANSONIC FLOW

Janusz Sznajder, Tomasz Kwiatkowski

Institute of Aviation
Department of Aerodynamics
Krakowska Avenue 110/114, 02-256 Warsaw, Poland
tel.: +48 22 8460011 ext. 492, fax: +48 22 8464432
e-mail: jsznaj@ilot.edu.pl, tomasz.kwiatkowski@ilot.edu.pl

Abstract

Solutions for turbulisation of a part of laminar boundary layer upstream of shockwave on laminar airfoil in transonic flow were investigated by means of solution of Unsteady Reynolds-Averagd Navier-Stokes equations using as a closure the four-variable Transition SST turbulence model of ANSYS FLUENT solver. This turbulence model has the capability of resolving laminar-turbulent transition occurring in undisturbed flow as well as under the influence of flow-control devices. The aim of the work was to investigate possibilities of improvement of aerodynamic characteristics of laminar wing of a prospective transport aircraft in adverse conditions characterised by occurrence of a shockwave over a laminar-turbulent transition region with separation of laminar flow under the shockwave. The subject is important for application of laminar flow technology, offering economic and environmental advantages due to decreased friction drag, into civil transport aviation. Natural laminar-turbulent transition in the investigated conditions takes place with occurrence of "laminar separation bubble" under the foot of a shockwave and the resulting shockwave is intensive and prone to unsteady oscillations, the "buffet" phenomenon, limiting operational range of flight parameters. In order to counteract the harmful effects of natural laminar-turbulent transition in transonic flow two types of turbulators, placed upstream of the shockwave, were investigated. One of them consisted of delta-shaped vortex generators, producing chordwise-oriented vortices. The other consisted of rectangular micro-vanes, perpendicular to flow and to airfoil surface producing vortices of rotation axes oriented spanwise. Effectiveness of both types of turbulators was investigated for varying height and their location on airfoil chord. Both types of turbulators have proved their effectiveness in tripping laminar boundary layer. The specific effects of the tutbulators, different for each type occurred in the region where laminar separation takes place on clean airfoil. As a result, the changes of lift and drag were different for each type of turbulators.

Keywords: *transonic flow control, laminar-turbulent transition, flow simulations, aircraft engineering, transport, vehicles*

1. Introduction

Economic and environmental needs for increased efficiency and lower emissions in air transport are reasons of rise of interest in application of laminar flow technology in transport aircraft. Laminar wings have been successfully applied for many years in subsonic aircraft. One of problems limiting so far application of laminar-flow wings in transonic speed range is shockwave-boundary layer interaction occurring in off-design conditions, characterized by drag rise and buffet phenomenon, consisting of intense oscillations of shockwave over wing chord. Such off-design flow conditions may appear after sudden increase of wing angle of attack due to vertical gust in turbulent atmosphere while travelling with transonic speed when region of supersonic flow exists over part of wing chord. In the TFAST project of European 7-th Framework Programme one of research subjects was the possibility of reducing unfavourable aerodynamic effects in shockwave-boundary layer interaction by inducing turbulisation of laminar boundary layer in front of the shockwave. Impact of tripping of laminar boundary layer by proposed turbulators on aerodynamic characteristics of tested airfoil was studied by solution of Unsteady Reynolds-Averaged Navier-Stokes equations with application of the four-equation Transition SST turbulence model in three-dimensional flow [1, 2].

2. Modelling of laminar-turbulent transition of boundary layer interacting with shockwave on test-case airfoil

The test case for the investigations was V2C transonic laminar airfoil designed by Dassault Aviation. Flow conditions of interest in the project were defined by Mach number of 0.70 and range of angle of attack from 1 to 9 degrees. In the lower part of this range of angle of attack, the flow was unsteady with oscillating shockwave while for angles of attack closer to upper limit the flow was steady. The phenomena corresponding to natural laminar-turbulent transition can be most conveniently presented on steady-flow case at Mach number Ma = 0.70 and angle of attack $\alpha = 7°$. In Figs. 1-2 are presented in sequence: plot of intermittency (probability of boundary layer being turbulent) along a control line 0.3 mm above the airfoil surface, plot of Mach number at the same height and plot of tangential stress on airfoil surface. The plots are prepared for a fragment of airfoil chord, from 40 to 46%, where laminar-turbulent transition takes place. It can be seen, that start of transition – rise of intermittency from near-zero values – occurs in approximately 42% chord, where Mach number decreases from supersonic values to unity. The rise of intermittency is accompanied by change of sign of tangential stress on airfoil surface shown in Fig. 2, which is an

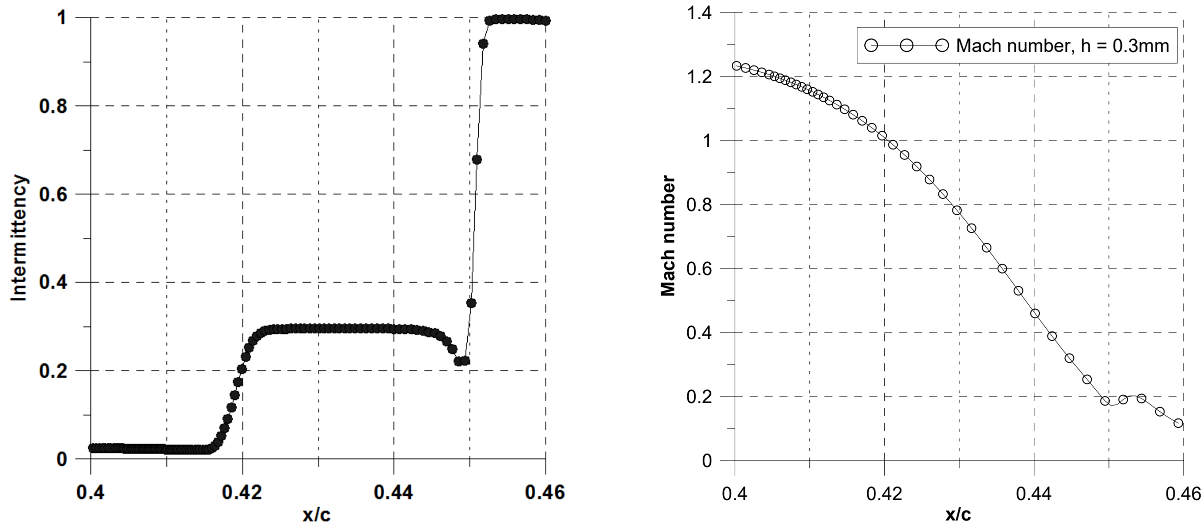

Fig. 1. Plot of intermittency and Mach number at control height of 0.3 mm in transition region at $\alpha = 7°$, Ma = 0.70, Re = 2.67

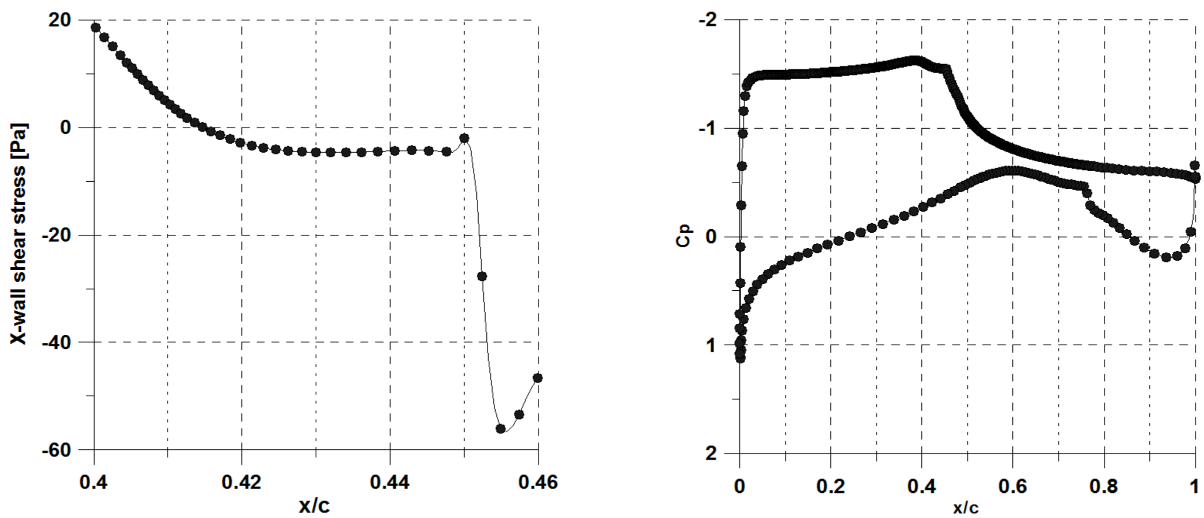

Fig. 2. Plot of tangential stress and pressure coefficient on airfoil surface in transition region at $\alpha = 7°$, Ma = 0.70, Re = 2.67

indication of laminar separation underneath the shockwave. The final rise of intermittency to unity, the indication that boundary layer (b.l.) is fully turbulent, occurs in the region of strong separation behind the shockwave which is seen in Fig. 2 as rise of pressure (steep slope of negative pressure coefficient behind 45% of airfoil chord. Thus, it may be concluded that natural laminar-turbulent transition occurs over the region of 42-45% of airfoil chord and it is accompanied by separation of laminar boundary layer, resolved in the obtained solution.

3. Effects of turbulators on laminar-turbulent transition and on aerodynamic characteristics of the investigated airfoil

The first aim of turbulisation of the laminar boundary layer was elimination of the laminar separation region, underneath shockwave, visible in Fig. 2 between 41.5 and 45% of airfoil chord. It was expected, that producing turbulent, attached boundary layer in front of shockwave would minimize harmful effects of laminar shockwave-boundary layer interactions such as drag rise due to flow separation or unsteadiness leading to oscillations of shockwave. The latter effect was observed already in modelling of effects of vortex generator using BAY method [3]. In the present work, the turbulators were not modelled by any method approximating their effects, but resolved in the computational grid in order to obtain as precisely as possible their influence on aerodynamic characteristics, including drag force, which is sensitive to small geometric details of the investigated object. Two types of turbulators were tested: delta-shaped micro vortex generators (VGs) shown in Fig. 3 and vanes perpendicular to airfoil surface shown in Fig. 4. The delta-shaped VGs produced vortices with rotation axes oriented chordwise and the micro vanes produced vortices with rotation axes oriented spanwise. Both solutions were tested with varying height of the devices.

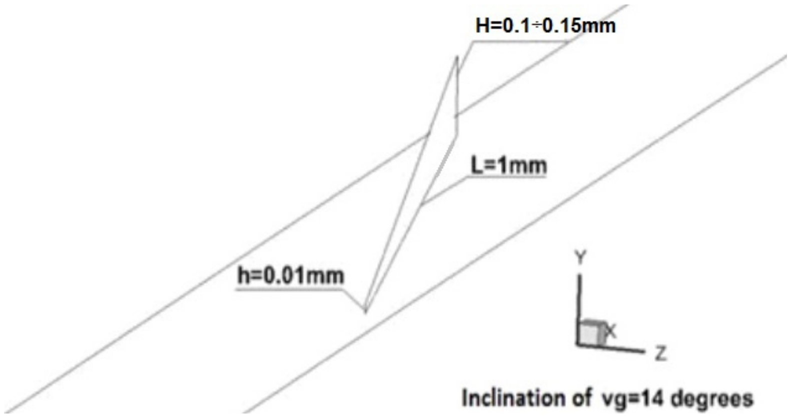

Fig. 3. Geometry of delta-shaped micro vortex generator

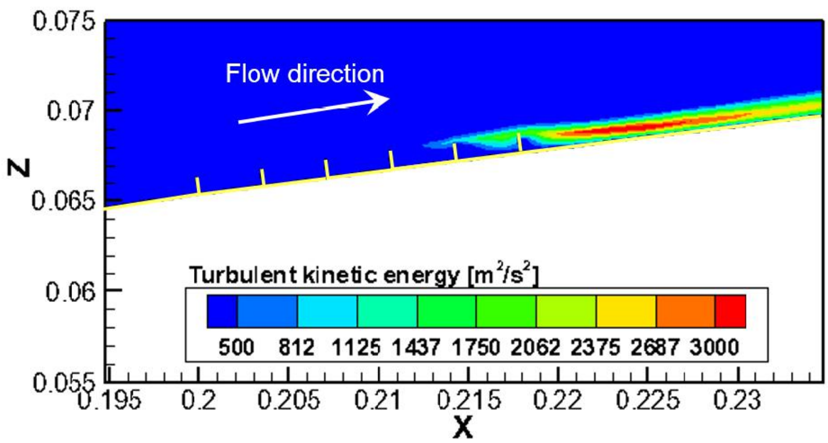

Fig. 4. Concept of rectangular micro vanes perpendicular to airfoil surface

First results are presented for delta-shaped VGs. The computations were conducted for Mach number Ma of 0.70 and angles of attack $\alpha = 4°$ and 7°. Tab. 1 presents their location on the chord and relative height with respect to local boundary layer thickness (H/θ) for $\alpha = 4°$.

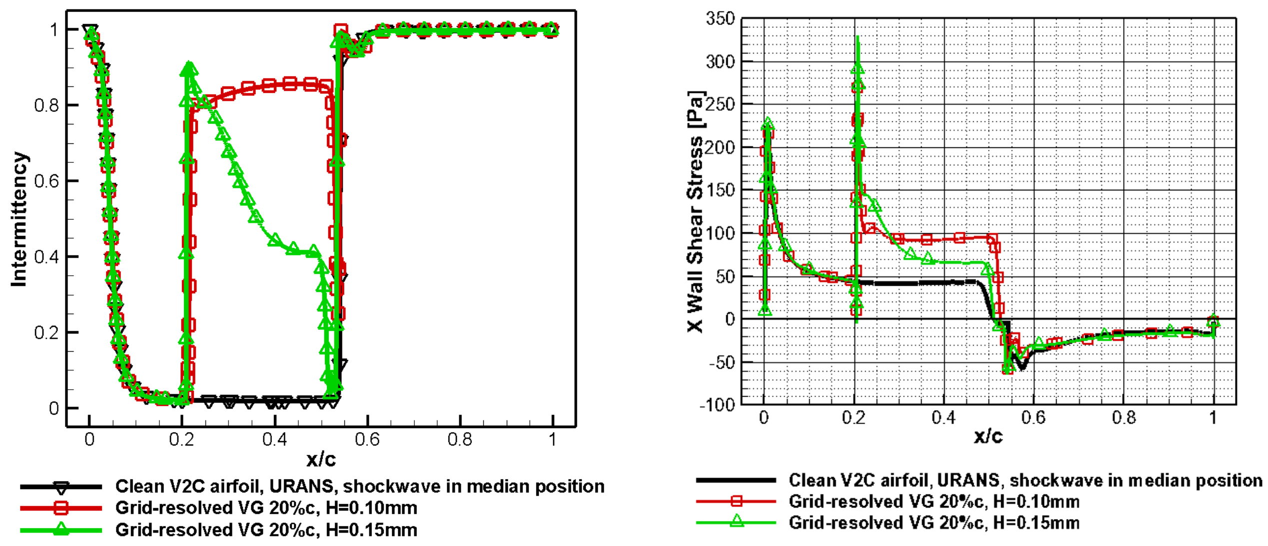

Fig. 5. Plots of intermittency at control line of 0.15 mm behind vortex generators and of surface tangential stress in X direction for VGs located in 20% chord

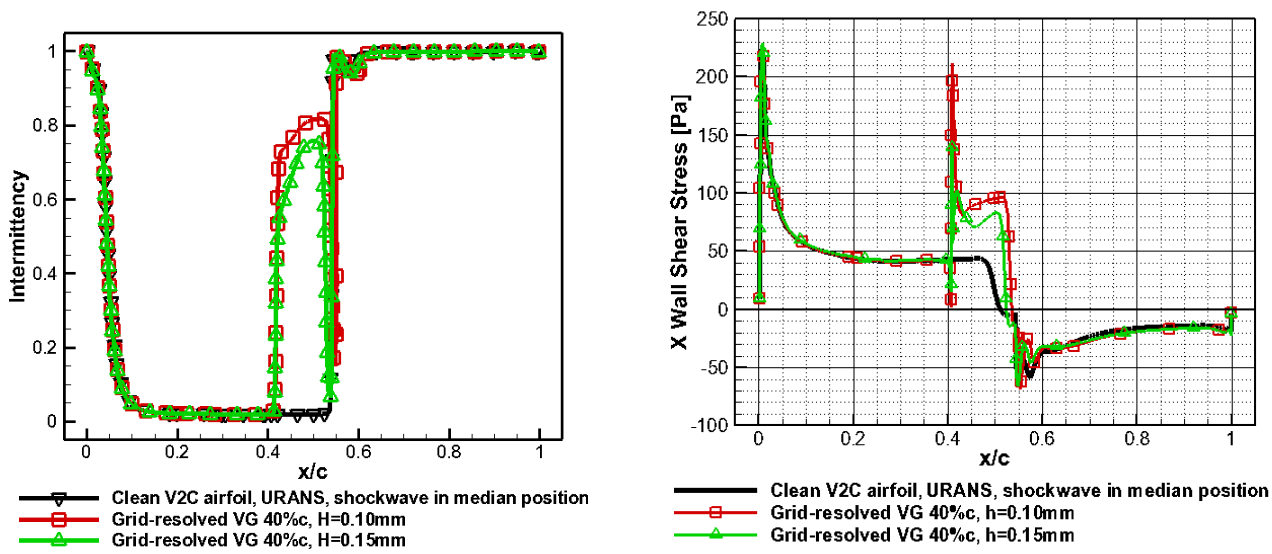

Fig. 6. Plots of intermittency at control line of 0.15 mm behind vortex generators and of surface tangential stress in X direction for VGs located in 40% chord

Tab. 1. Relative height of delta-shaped mVGs, related to local thickness of boundary layer

x/c	0.2	0.3	0.4	0.5
H/θ, H = 0.10 mm	0.30	0.24	0.21	0.05
H/θ, H = 0.15 mm	0.45	0.36	0.30	0.07

Due to large numbers of the combinations of geometric details and positions of the turbulators, only the most representative results are shown further. Figs. 7-9 present effects of varying height of delta-shaped VGs and their distance to shockwave on turbulisation of the boundary layer.

It can be seen that although boundary layer is not fully turbulent (intermittency below unity), laminar separation is eliminated and replaced by separation of turbulent b.l. slightly further downstream,

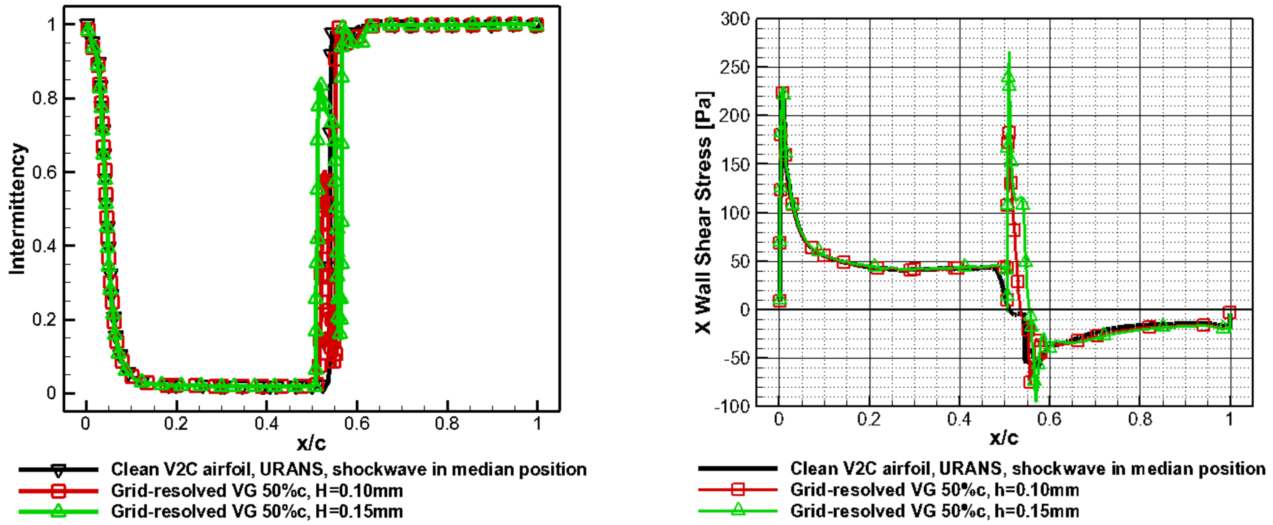

Fig. 7. Plots of intermittency at control line of 0.15 mm behind vortex generators and of surface tangential stress in X direction for VGs located in 50% chord

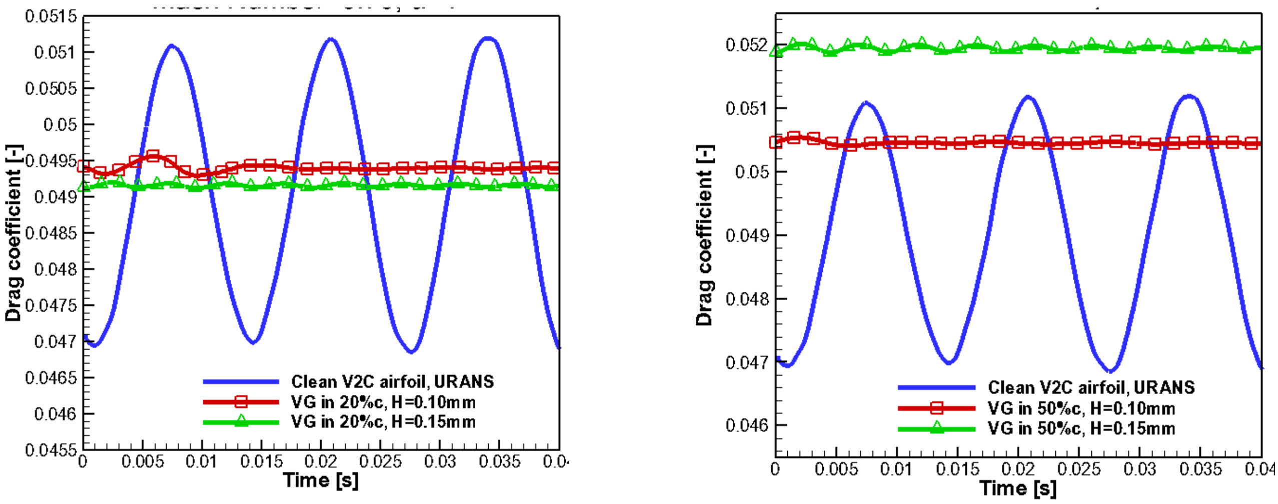

Fig. 8. Comparison of drag coefficient for clean-airfoil case and for cases with VGs located in 20% chord (left) and in 50% chord (right)

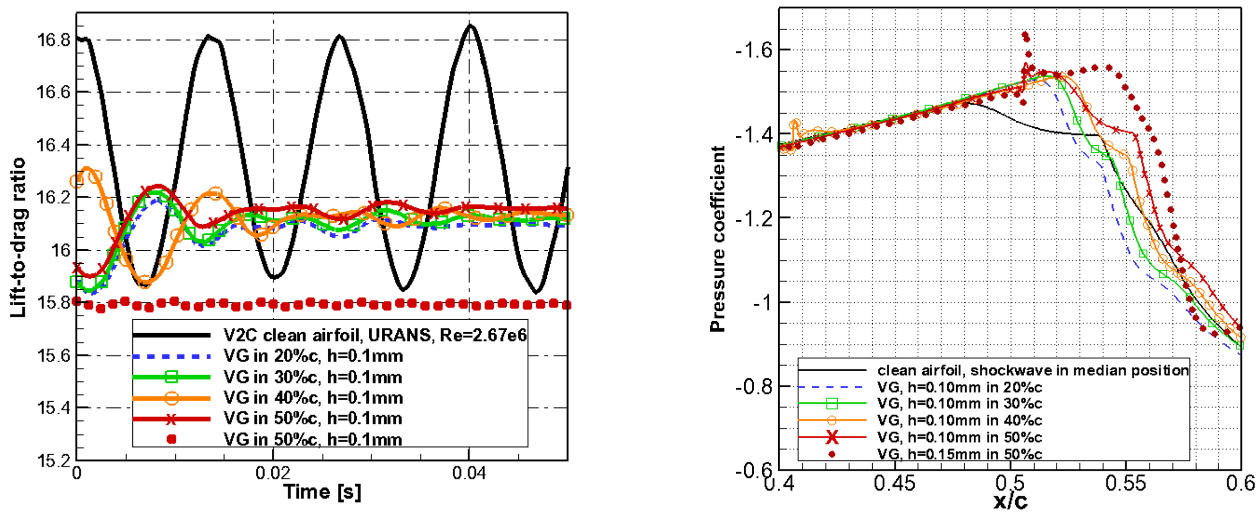

Fig. 9. Comparison of lift-to-drag ratio for clean airfoil and for configurations with turbulators and comparison of distribution of pressure coefficient in the region of shockwave for the investigated configurations

visible as almost vertical fragnent of plot of tangential stress changing sign to negative. It can also be seen that increasing height of VGs does not improve turbulisation effects, most likely because of larger surface of VGs is impeding flow. Only at 50% chord, in a thick boundary layer, the turbulisation effects of higher VGs are stronger than for lower ones. Considering aircraft performance and potential economic qualities in investigated flow conditions, most important is securing steady flow, and, ideally, decrease of drag at the same lift. If drag increase is unavoidable, lift and L/D should increase too, so that aircraft can fly at slightly lower angle of attack with lower drag. As it is shown in Figs. 10-11, the first goal was achieved, as the buffet phenomenon has been damped in turbulent flow produced by VGs. With respect to drag, contrary to expectations, at an angle of attack $\alpha = 4°$ drag was increasing as VGs were moved towards shockwave, in spite of reducing the length of the fragment of airfoil chord with increased tangential stress.

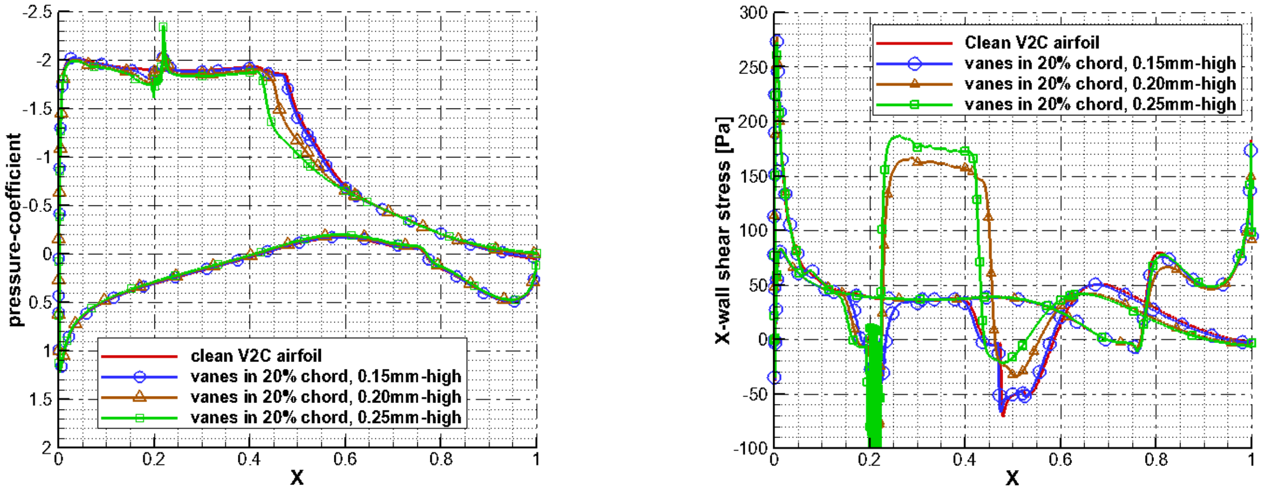

Fig. 10. Comparison of distribution of pressure coefficient (left) and of surface tangential stress (right) for clean-airfoil case and for cases with rectangular micro-vane turbulators of different height, placed in 20% of airfoil chord. $\alpha = 6°$, Ma = 0.68

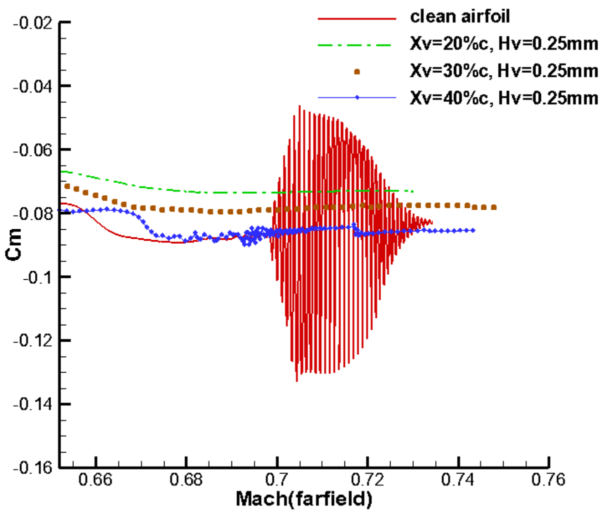

Fig. 11. Comparison of lift coefficient as a function of Mach number for clean-airfoil case and for cases with 0.25 mm-high rectangular micro-vane turbulator placed in different chord positions

As it can be seen in Fig. 12, L/D with VGs was lower than for clean configuration. The explanation of this unexpected phenomenon was found in the changes of pressure coefficient caused by VGs, shown in Fig. 12. As it is shown, the chordwise-oriented vortices increased the length of region of accelerating flow and decreasing pressure behind 50% of chord, into the region

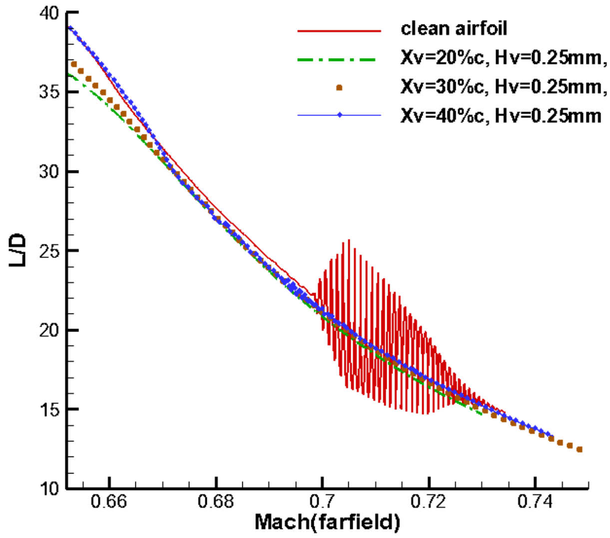

Fig. 12. Comparison of lift-to-drag ratio as a function of Mach number for clean-airfoil case and for cases with 0.25 mm-high rectangular micro-vane turbulator placed in different chord positions.

of negative slope of airfoil surface, thus increasing pressure drag. It is worth noting, that corresponding reduction of lift-to-drag ratio with respect to averaged value for clean airfoil is moderate, between 1.2 and 1.8% for VGs of 0.10 mm-height.

In comparison with the effects of delta-shaped VGs on pressure distribution, corresponding results for vanes perpendicular to airfoil surface, shown in Fig. 4, were different. As it can be seen in Fig. 10, these turbulators reduced the region of accelerating flow and also eliminated laminar separation on airfoil surface as delta-shaped VGs as well as delta-shaped VGs and produce region of increased tangential stress, consisted with turbulent b.l. These turbulators were used in the analysis of ways of eliminating of buffet phenomenon in the range of Mach numbers where it exists on clean airfoil. The methodology involved finding the height of the devices producing rise of intermittency close to unity and then obtaining a solution for unsteady flow with continuously increasing free-stream Mach number from low subsonic values into the range of transonic flow, where buffet phenomenon was found for clean airfoil. The results are shown in Fig. 11 and 12 where changes of pitching moment coefficient (most affected by oscillating shockwave) and L/D ratio are compared for clean airfoil and for configurations with different locations of turbulators on airfoil chord. It can be seen that buffet phenomenon can be eliminated in the range of Mach numbers where it occurred for clean airfoil. Comparison of L/D ratio of clean airfoil and of configurations with turbulators in Fig. 12 shows that for high Mach numbers in transonic flow, around Ma = 0.70 differences in L/D ratio between the investigated configurations are much lower than at low Mach numbers and reduction of L/D due to turbulisation with respect to clean airfoil is about 2.25% and this loss is weakly dependent on chordwise position of turbulators. This effect is due to interactions of compression waves produced by the turbulator with main shockwave, reducing wave drag, which is described in more detail in [4]. This feature makes the turbulator worth to consider as a retractable device, stowed in steady-flow conditions and deployed close to buffet boundary. Loss of L/D in these conditions is not necessarily unfavourable, as it may delay approaching buffet boundary in conditions of vertical gust – the most likely scenario of approaching buffet boundary by a transport aircraft.

4. Conclusions

Turbulisation of a fragment of laminar boundary layer in front of shockwave on laminar, transonic airfoil was simulated for two types of turbulators in order to eliminate unfavourable phenomena occurring when laminar boundary layer separates at the foot of a shockwave. Delta-shaped vortex generators immersed in the boundary layer produced enough turbulence to eliminate laminar separation of boundary layer, but chordwise-oriented vortices generated this way have produced increased suction in area behind 50% chord, which, due to negative slope of the airfoil in this area led to increased pressure drag and slightly decreased lift-to-drag ratio. The other investigated turbulator, consisting of micro-vanes producing vortices parallel to wing span has shown similar capability of eliminating the buffet oscillations in the entire Mach range where it occurred for the clean airfoil. The effect of these turbulators on aerodynamic characteristics of the airfoil consisted on moderate reduction of lift-to-drag ratio. It may also be concluded that reduction of drag or improvement of lift-to-drag ratio is difficult to achieve with a turbulator in the form of a mechanical device, being itself a source of drag in the flow. Other potential solutions for tripping laminar boundary layer worth investigating may consist of synthetic jets introducing energy to the flow.

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 Poland from the funds dedicated to scientific research in 2012-2015, agreement No. 2641/7.PR/12/2013/2 and by Institute of Aviation.

Computational support was obtained from University of Warsaw Interdisciplinary Centre for Mathematical and Computational Modelling, in the Computational Grant No. G55-7.

References

[1] Langtry, R. B., Menter, F. R., *Transition Modeling for General CFD Applications in Aeronautics*, AIAA 2005-522, 2005.

[2] *ANSYS FLUENT Theory Guide*, ANSYS, Inc., Southpointe October 2012, 275 Technology Drive, Canonsburg, PA 15317.

[3] Sznajder, J, Kwiatkowski, T., *Effects of Turbulence Induced by Micro Vortex Generators on Shockwave – Boundary Layer Interactions*, Journal of KONES Powertrain and Transport, Vol. 22, No. 2, 2015.

[4] Stalewski, W., Sznajder, J., *Load Control of Natural-Laminar-Flow Wing Via Boundary Layer Control*, Proceedings of VII European Congress on Computational Methods in Applied Sciences and Engineering, June 5-10, Crete, Greece 2016 (in print).