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

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Abstract. *Tripping of laminar boundary layer on V2C laminar airfoil designed by Dassault Aviation was investigated computationally using two types of turbulators: simulated array of delta-shaped, counter-rotating vurtex generators producing chordwise-oriented vortices and by vanes perpendicular to airfoil surface and to flow producing spanwise-oriented vortices. Unsteady Reynolds-Averaged Navier-Stokes equations were solved using as a closure the four-equation Transition SST turbulence model implemented in ANSYS Fluent solver. The assumed flow conditions involved strong shockwave producing flow separation at Mach number of 0.70. Both types of turbulators produced their specific effects when tripping laminar boundary layer, which varied, depending on their placement in different chordwise positions. Both solutions for tripping laminar boundary layer have reduced flow unsteadines, resulting from oscillations of shockwave. Using delta-shaped vortex generators it was possible to obtain slightly improved lift-to-drag ratio for one combination of angle of attack and Mach number and the turbulator composed of parallel perpendicular-vane turbulator has shown strong buffet-damping properties.*

1 INTRODUCTION

Interaction of laminar boundary layer with shockwave leads to occurrence of laminar separation bubble at the foot of the shockwave and of subsequent transition of the boundary layer to turbulent over the separation bubble when flow is crossing the shockwave. This phenomenon occurs for internal and external flows, with oblique and normal shockwaves. Interaction of laminar boundary layer with shockwave on aircraft wing with laminar airfoil in transonic flow may lead to separation of the flow behind shockwave, large drag increase and also to buffet phenomenon - oscillations of shockwave, resulting from pressure waves reflected from wake behind wing. In FP7 TFAST project different methods of tripping of laminar boundary layer in front of the shockwave were tested with the aim of preventing the laminar boundary layer being penetrated by shockwave. One of questions in the project is how close to shockwave tripping of laminar boundary.layer may be conducted in order to obtain turbulent shockwave-boundary layer interactions (SWBLI) . Another question, investigated by the authors of the paper is how to obtain improvement of aerodynamic characteristics of the laminar airfoil in transonic flow with shockwave terminating the supersonic region.

2 CONDITIONS AND METHODS OF INVESTIGATIONS

The object of investigations was V2C laminar airfoil designed by Dassault Aviations especially for investigatuions of SWBLI in the TFAST project. The conditions of investigations were defined as Mach number Ma=0.7 and Reynolds number Re=2.67, resulting from the chord length c=0.2m, being equal to chord of the airfoil model investigated in the transonic wind tunnel at Institute of Aviation. In these conditions, depending on the value of angle of attack the flow is either steady, with stationary shockwave, or unsteady, with low-amplitude buffet oscillations of shockwave. The flow analysis was conducted by solution of Unsteady Reynolds-Averaged Navier-Stokes Equations (URANS) using ANSYS Fluent solver [1]. As a closure of the system of equations the four-equation Transition SST turbulence model was applied having as variables k – turbulent energy, ω - specific dissipation rate of k, γ - intermittency (probability of boundary layer being turbulent) and Re_θ - Reynolds number based on boundary layer momentum thickness. Second-order spatial and temporal discretisation of URANS equations was applied. In conditions of transonic flow with shockwave on the upper surface two methods of tripping of laminar boundary layer were investigated, one involving delta-shaped vortex generators producing vortices with chordwise-oriented rotation axes and with another type of vortex generators – micro-vanes, perpendicular to flow and airfoil surface, generating vortices with spanwise-oriented rotation axes.

3 MODELLING OF TRIPPING OF LAMINAR BOUNDARY LAYER

Tripping of laminar boundary layer (b.l.) was simulated by resolving in the computational grid two technical solutions submerged in the laminar b.l., generating vortices: delta-shaped vortex generators and micro-vanes, perpendicular to airfoil surface and to flow, shown in Figure 1. The first concept is classical vortex generator inclined to flow at an angle of 14°, similar to inclination used by other researchers in transonic flow [2], [3]. Its height was chosen according to an experimentally obtained criterion for minimum Reynolds number, based on turbulator height, capable of tripping laminar boundary layer [4]. The other concept may be considered as a series of micro-Gurney tabs generating vortices in the internal locations on airfoil chord, as opposed to classical Gurney tab, which is located at airfoil trailing edge. The first concept was investigated in computational domain involving lower and upper wind-tunnel walls in order to make easier comparisons with results of wind-tunnel investigations in test section of 0.6m height. On the side walls of the computational domain, located at the distance from generators' side vertices equal 10% of the width of span fragment occupied by the device, the boundary condition of symmetry was applied. This solution was applied for modelling of an array of counter-rotating vortex generators. Inlet boundary condition was located approximately six airfoil chords in front of it, as a distance where physical inlet to test section of wind tunnel was located. On the inlet surface the pressure inlet boundary condition was imposed, and on the outlet surface, located also approximately six airfoil chords behind airfoil pressure outlet boundary condition was imposed. The values of static and dynamic pressure on inlet and outlet surfaces were chosen based on tests in the wind-tunnel. The other concept of turbulator was investigated using open-space boundary conditions, pressure far-field and pressure outlet, located approximately 50 airfoil chords in front of and behind the airfoil. This decision was taken because of the planned test case for this turbulator – buffet oscillations of shockwave which proved easier to simulate in open-space flow than in simulated conditions of solid-wall test section of wind tunnel.

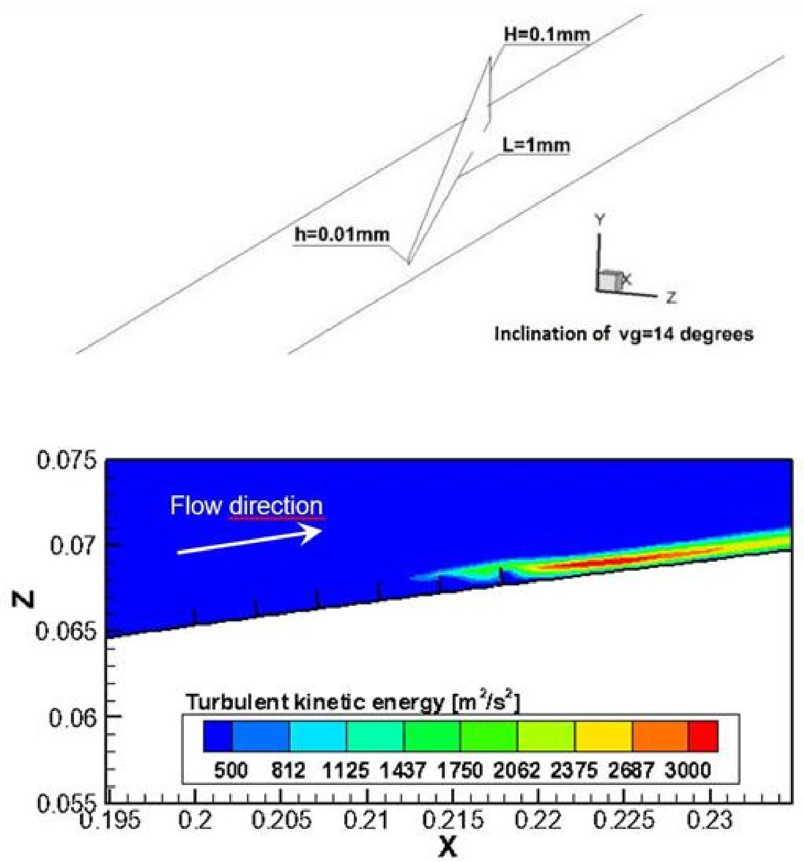

Figure 1. General ideas of concepts of proposed laminar boundary-layer tripping devices: delta-shaped vortex generators on upper part and perpendicular micro-vanes on lower part.

4 INVESTIGATED CASES

4.1 Baseline case – V2C airfoil with natural laminar-turbulent transition

Before simulating laminar-turbulent transition induced by the tripping devices, flow simulations were conducted for the clean airfoil in order to obtain numerical solution of natural transition with the applied computational methods. Figures Figure **3** - Figure **5** show the subsequent stages of laminar-turbulent transition determined by the flow solver. The transition takes place in front of the shockwave, in the region of pressure plateau at 40% – 45% chord shown in Figure 2. In Figure 3 is shown rise of intermittency in the boundary layer in this region, and in plot of tangential stress on airfoil surface in Figure 4 it can be seen that rise of intermittency is preceded by the separation of laminar boundary layer visible as change of sign of tangential stress.

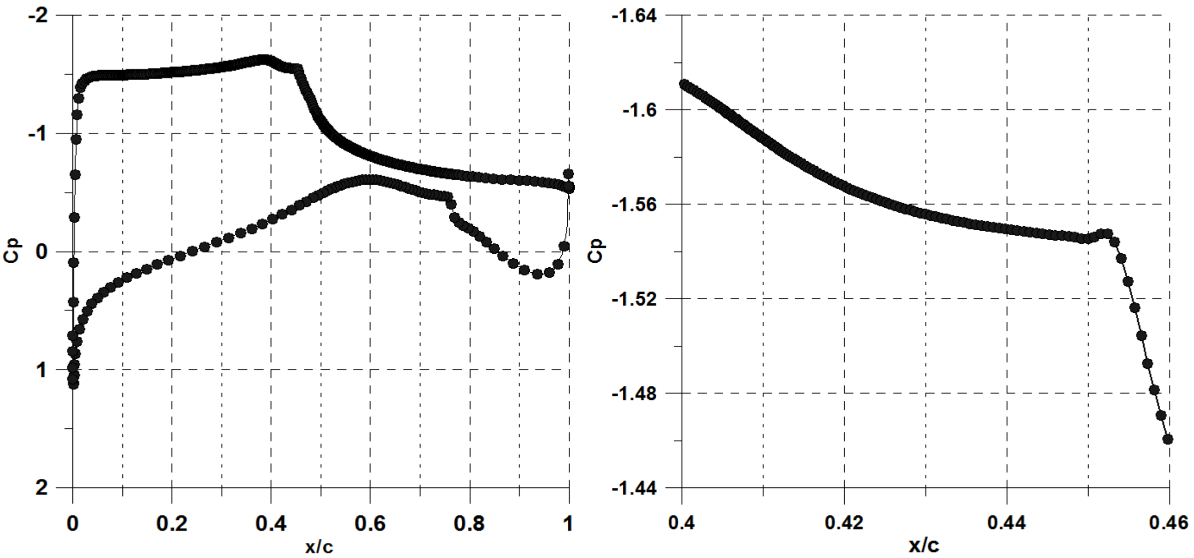

Figure 2. Plots of pressure coefficient over the complete airfoil surface (left) and for the region of plateau in front of the shockwave where laminar-turbulent transition takes place (right). α=7°, Ma=0.70, Re=2.67.

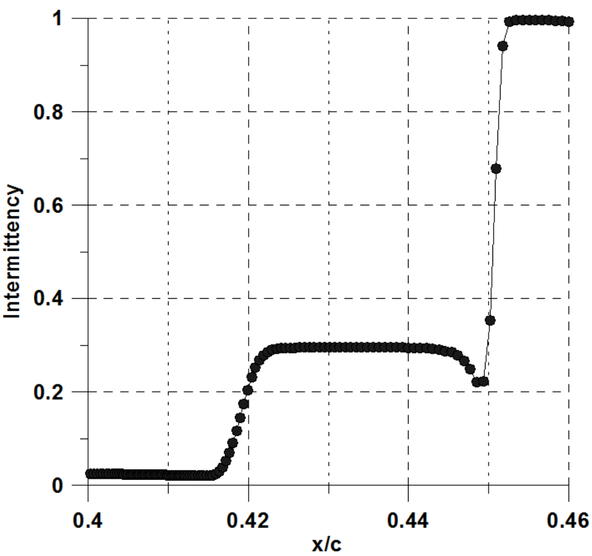

Figure 3. Plot of intermittency at control height of 0.2mm in transition region α=7°, Ma=0.70, Re=2.67.

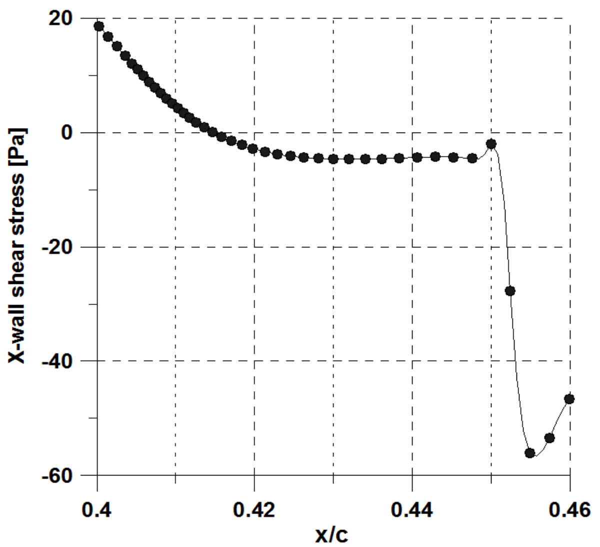

Figure 4. Plot of tangential stress on airfoil surface in transition region α=7°, Ma=0.70, Re=2.67.

In Figure 5 is presented contour of intermittency in boundary layer in the symmetry plane of the computational domain. On the left side of the contour flow in the boundary layer is laminar with intermittency approachning zero. Outside boundary layer intermittency is set to unity, in order to model flow in wind-tunnel with prescribed turbulence intensity. Start of transition is visible as increase of intermittency at a distance of approximately 0.2mm from the surface, at which height it grows to unity in a distance shown in Figure 3.

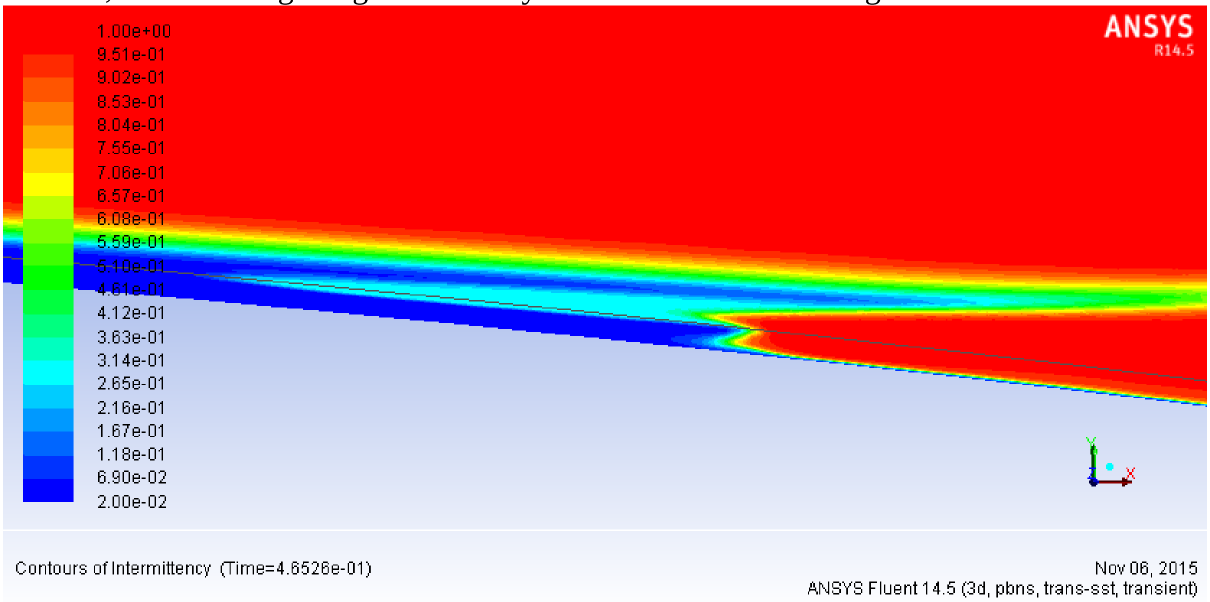

Figure 5. Contour of intermittency in the region of natural laminar-turbulent transition. Black line above airfoil surface represents the control height of 0.2mm applied in Figure 3. α=7°, Ma=0.70, Re=2.67.

4.2 Transition produced by delta-shaped vortex generators

Simulations of forced transition were conducted for two values of angle of attack: 4° and 7°. At an angle of 4° in flow with natural transition there occur low-intensity oscillation of shockwave with Strouhal number of 0.08, characteristic for buffet phenomenon. For this reason the chordwise comparisons of distributions of flow quantities such as pressure coefficient are done for median position of oscillating shockwave. In cases with tripped laminar boundary layer the flow was steady. Tripping of laminar boundary.layer was simulated for height of delta-shaped vortex-generators equal to 0.10mm. Length of the vortex.generator was equal to 1mm. For both heights of vortex generator their alternative locations in 20%c, 30%c, 40%c and 50%c (c standing for airfoil chord) were simulated. As it can be seen in Figure 6 the effects of vortex generators are very local and are visible only in the area of interaction of shockwave with boundary layer. The details of these effects, are shown in greater scale exclusively for this region in Figure 7. It can be seen that moving vortex generators closer to the shockwave extends the region of rising suction, where for clean airfoil the laminar separation formed, creating the pressure plateau shown with black line. On the other hand, for vortex generators located close to the shockwave, at 50%c, in the region of rising pressure a smaller plateau starts to form. This, as it can be seen in the plots of intermittency in Figure 8, may be linked to lower effectiveness of the vortex generators in thicker boundary layer in the central region of the airfoil. In Figure 9 is shown comparison of tangential stress on airfoil surface for the analysed cases. It can be seen that for vortex generators (vgs) located in 50%c there is no rise of tangential stress behind the vortex generator, characteristic for turbulized boundary layer. On the other hand, the increase of suction peak is the greatest of all investigated cases, which suggests that the increase of suction peak is an effect of vorticity added by the vortex generators and not the effect of tripping laminar boundary layer.

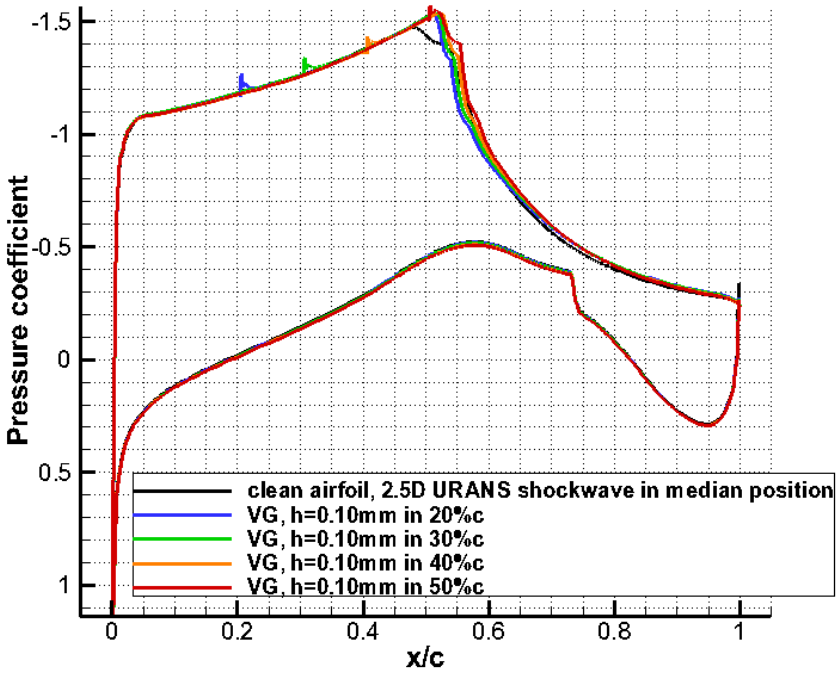

Figure 6. Comparison of distribution of pressure coefficient for clean airfoil case and for cases with simulated arrays of counter-rotating vortex generators 0.10mm-height in different positions of airfoil chord. α=4°, Ma=0.70, Re=2.67.

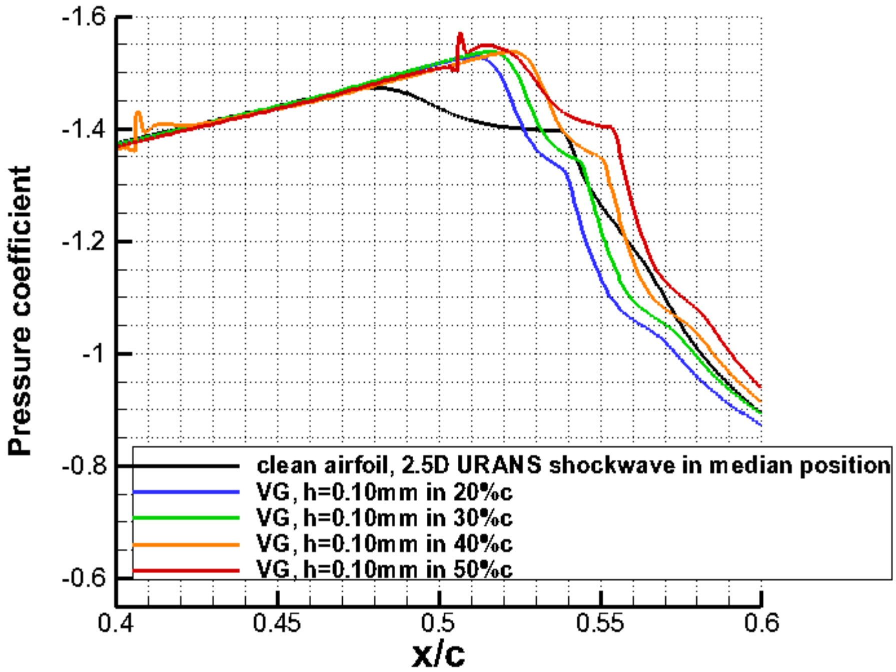

Figure 7. Details of distribution of pressure coefficient for clean airfoil and cases with vortex generators 0.10mm-height in region of shockwave-bundary layer interactions. α=4°, Ma=0.70, Re=2.67.

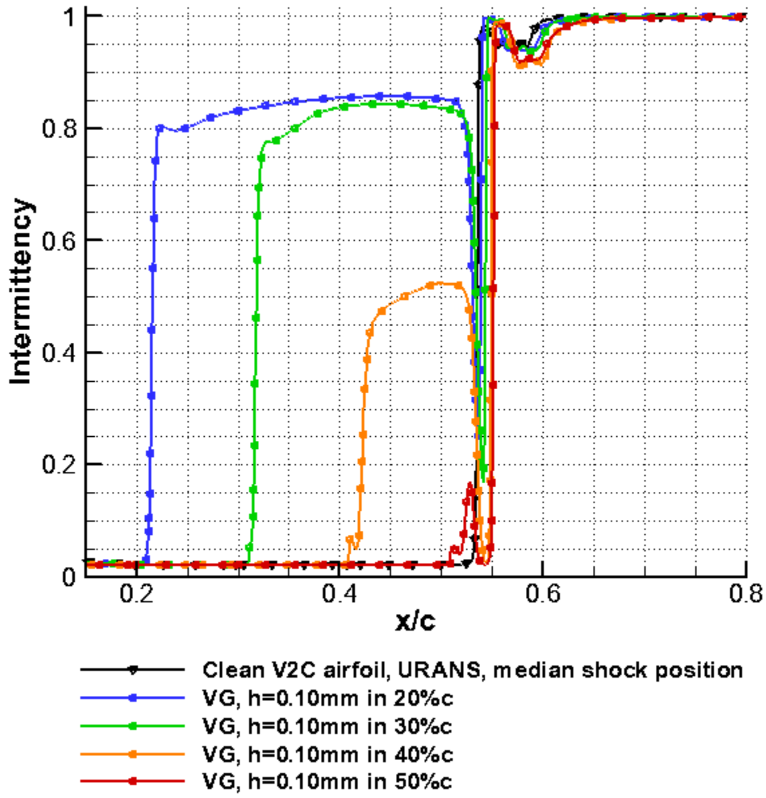

Figure 8. Comparison of distribution of intermittency in the boundary layer for clean airfoil case and for cases with simulated arrays of counter-rotating vortex generators of 0.10mm-height in different positions of airfoil chord. α=4°, Ma=0.70, Re=2.67.

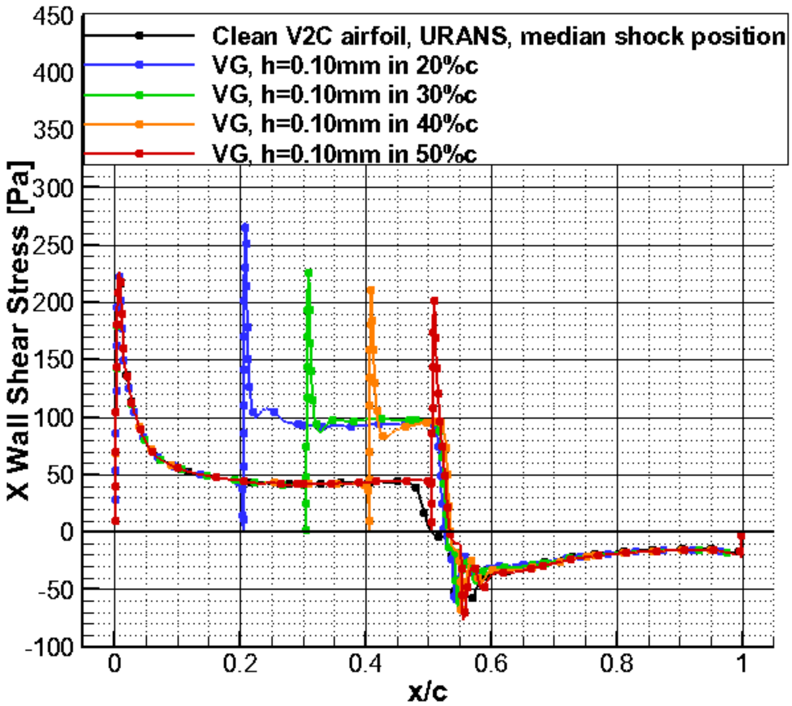

Figure 9. Comparison of distribution of tangential stress on airfoil surface for clean airfoil case and for cases with simulated arrays of counter-rotating vortex generators of 0.10mm-height in different positions of airfoil chord. α=4°, Ma=0.70, Re=2.67.

The most important effects of tripping laminar boundary layer by the delta-shaped vortex generators consist in stabilising flow, which is shown in Figure 10 to Figure 12 as solution converging to a steady-state value with stationary shockwave. Such stabilization of shock-wave was observed also in earlier work [6], where BAY methods was used for modelling of vortex generators. Other effects found at angle of attack α=4° were small increase of drag and reduction of lift-to-drag ratio, shown in Figure 11 and in Figure 12. Changes in lift depend on the chordwise position of the vgs which has influence on shape of suction peak in front of the shockwave. For vgs located in the frontal region of the airfoil, which tend to shift shockwave upstream, there occurs reduction of lift, and for the vgs located closest to the shockwave which create larger suction peak, lift slightly increases over the average value for clean airfoil. Increase of drag is also positive, and, contrary to expectations,

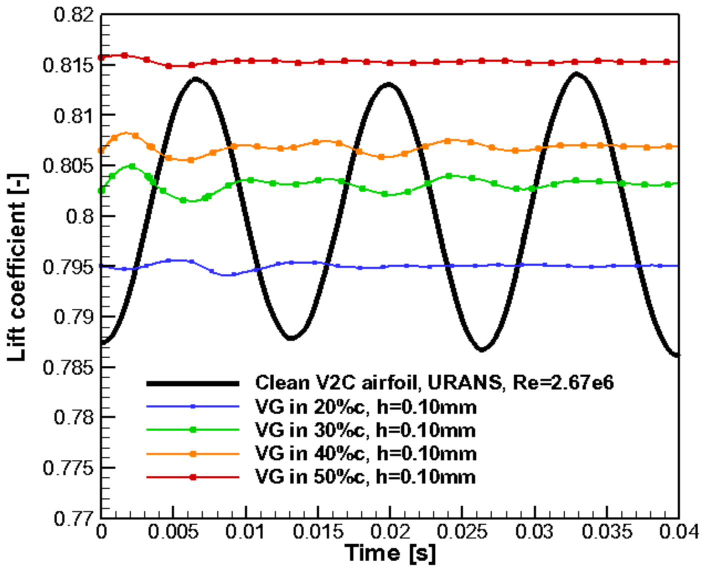

Figure 10. Effects of tripping laminar boundary layer with delta-shaped vortex generators located in 20%c, 30%c, 40%c and 50%c on lift coefficient.

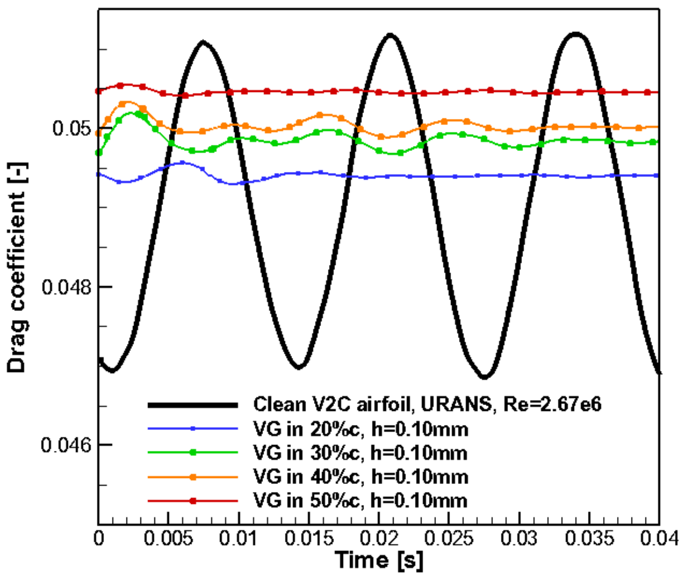

Figure 11. Effects of tripping laminar boundary layer with delta-shaped vortex generators located in 20%c, 30%c, 40%c and 50%c on drag coefficient.

drag increase is the highest for vgs located closest to the shockwave,in spite of shorter length of turbulised region with increased tangential stress.This is due to bild-up of suction peak in location behind 50%c, where negative slope of surface leads to increase of pressure drag. When analysing the changes of lift-to-drag ratio (L/D) due to presence of vortex generators it can be seen that although for all locations of vgs there occurs reduction of L/D with respect to average value for clean configuration, this reduction is the lowest for rearward-placed vortex generators. This is due to increased lift for rearward-placed vgs which compensates rising drag. This indicates that possible gains in aerodynamic characteristics may be expected when laminar boundary layer is tripped in a region close to shockwave and these gains are more likely to occur as increase of lift-to drag ratio than as reduction of drag. Reduction of drag is difficult to achieve because elimination of laminar separation bubble is done at the cost of increase of friction in the newly-formed turbulent-flow region, however short, and particularly difficult when using mechanical turbulators which themselves are an obstacle for the flow and a source of drag.

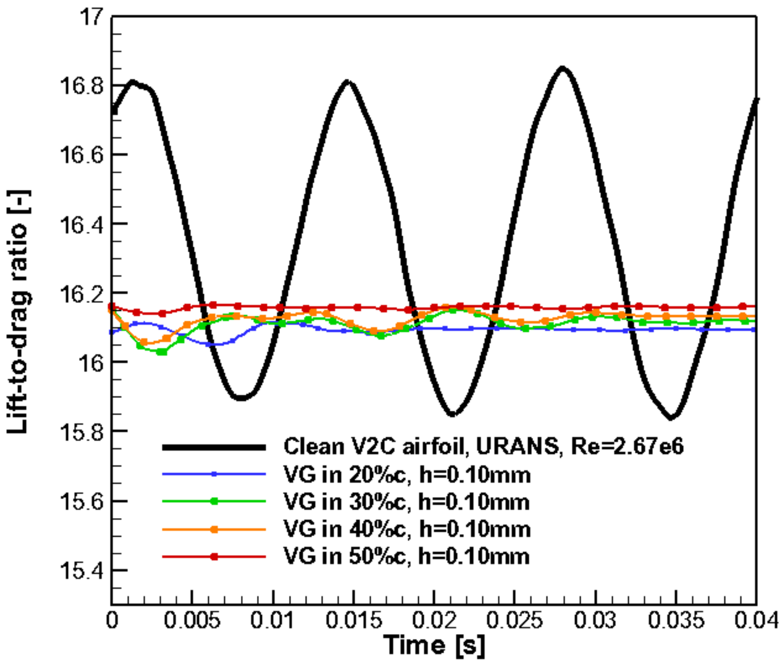

Figure 12. Effects of tripping laminar boundary layer with delta-shaped vortex generators located in 20%c, 30%c, 40%c and 50%c on lift-to-drag ratio.

A confirmation of the previously mentioned hypothesis is the case of tripping laminar boundary layer at an angle of attack of 7 degrees. The physical phenomena created by the vortex generators, as increased suction peak and elimination of separartion bubble at the foot of the shockwave, are very similar to case of flow at an angle of attack of 4 degrees.. An important difference in flow conditions is that at $\alpha=7°$ the shockwave is located closer to leading edge, at approximately 45% chord, in contrast to approximately 53%c at $\alpha=4°$. In these new flow conditions the combination of increased suction, forward shift of shockwave and lower negative surface slope lead to a very low increase of pressure drag due to increased suction on the negative-slope side of airfoil. In effect slight increase of lift-to-drag ratio over the values for clean airfoil was obtained for vortex generator located in 30% chord,, shown in Figure 14.

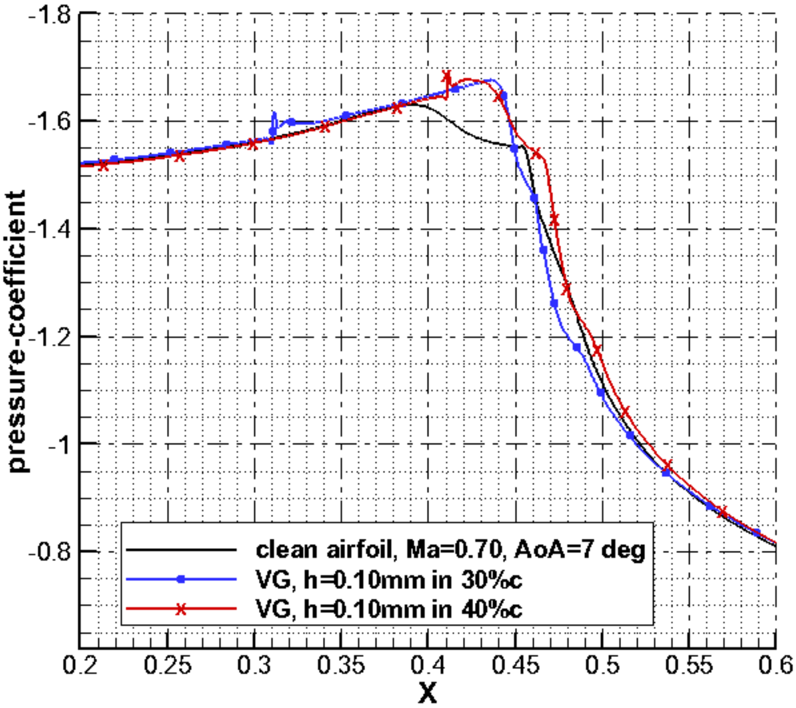

Figure 13. Comparison of distribution of pressure coefficient for clean airfoil case and for cases with simulated arreys of counter-rotating vortex generators 0.10mm-height in different positions of airfoil chord. α=7°, Ma=0.70, Re=2.67.

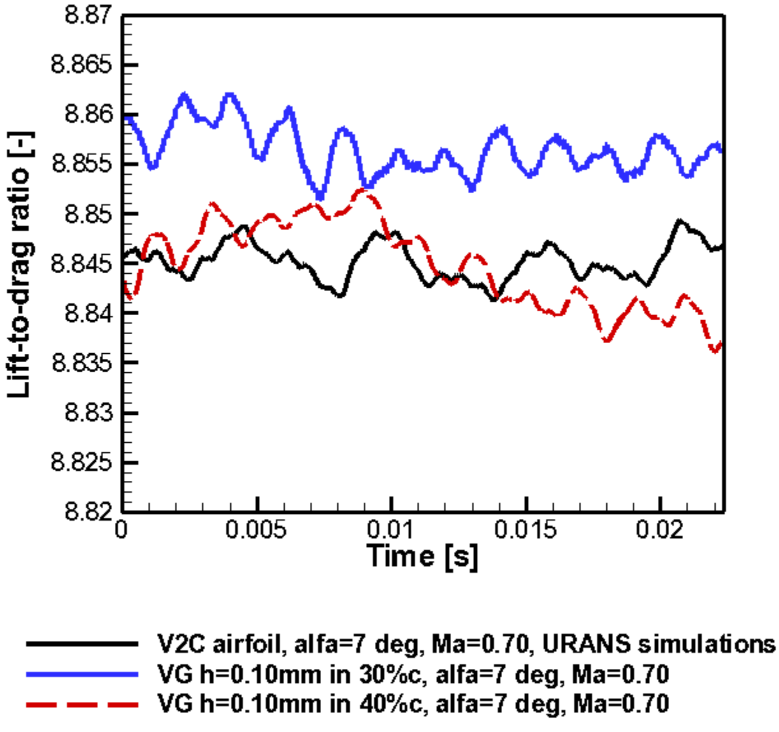

Figure 14.. Effects of tripping laminar boundary layer with delta-shaped vortex generators located in 30%c and 40%c on lift-to-drag ratio compared with results for clean V2C airfoil.

4.3 Transition produced by perpendicular micro-vanes

As it was found that effects of tripping laminar boundary layer include stabilisation of position of shockwave, this particular effect was studied further with another type of vortex generators, consisting of micro vanes, perpendicular to airfoil surface and to the flow, presented already in Figure 1. This choice was based on results of analyses showing that this turbulator was more effective at tripping laminar boundary layer then delta-shaped vgs when turbulator height was being increased [7]. The specific effects of tripping laminar boundary layer with this turbulators on distributions of intermittency in the boundary layer and tangential stress and pressure coefficient on the V2C airfoil are shown in Figure 15 and in Figure 16. In Figure 15 it can also be seen that for properly chosen height of micro-vanes intermittency rises to unity and stays constant until reaching shockwave, while increased positive tangential stress on airfoil surface is an indication of turbulised boundary layer and attached flow behind the turbulator. In Figure 16 it can be seen that in contrast to delta-shaped vortex generators which produce vortices of chordwise-oriented rotation axes, there is no increased suction in the region of pressure plateau on clean airfoil. Instead, the shockwave shifts to the front of airfoil more than for delta-shaped vortex generators and sharper rise of pressure over the shockwave, than for delta shaped vgs takes place. The sharp rise of pressure is, however, characteristic for shockwave appearing in turbulent flow region and was reported by other researchers analysing turbulent boundary layer – shockwave interactions [4]. In this respect the obtained solution is similar to that obtained for delta-shaped vgs. These features of the perpendicular-micro-vanes turbulator were taken advantage of in analysis of its effectiveness in damping buffet oscillations of shockwave. The analysis consisted in continuously increasing of free-stream Mach number from low pre-buffet value and passing through the buffet zone for clean airfoil. The results of this procedure are shown in Figure 17 where changes of moment coefficient are presented and in Figure 18 where changes of lift-to-drag ratio are presented for different values of vane height.

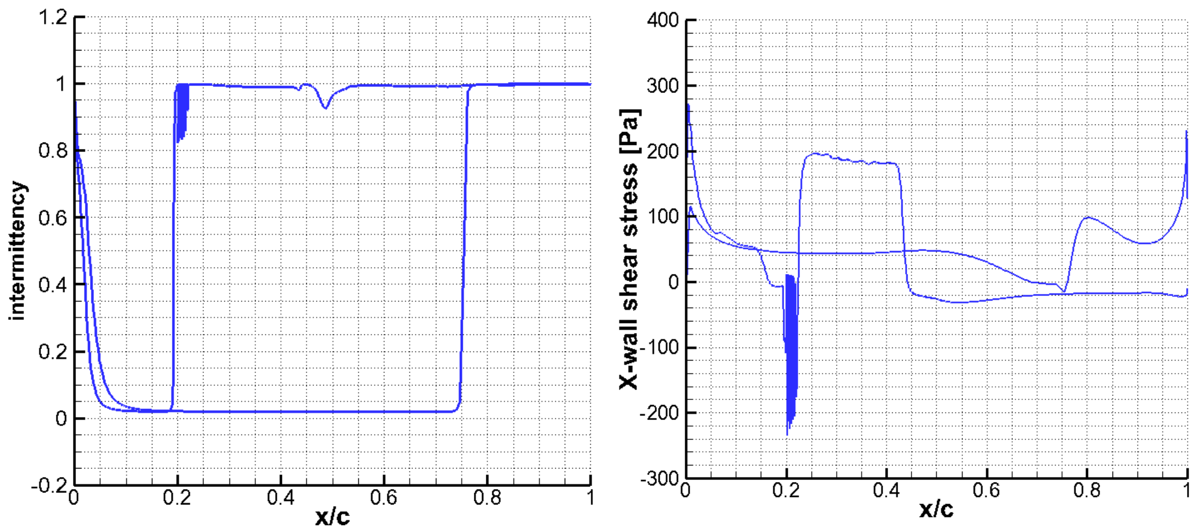

Figure 15. Intermittency at the height of 0.15mm above the airfoil surface for vanes of 0.25mm-height located in 20% chord and tangential stress in X direction on airfoil surface. Ma=0.68, α=6°.

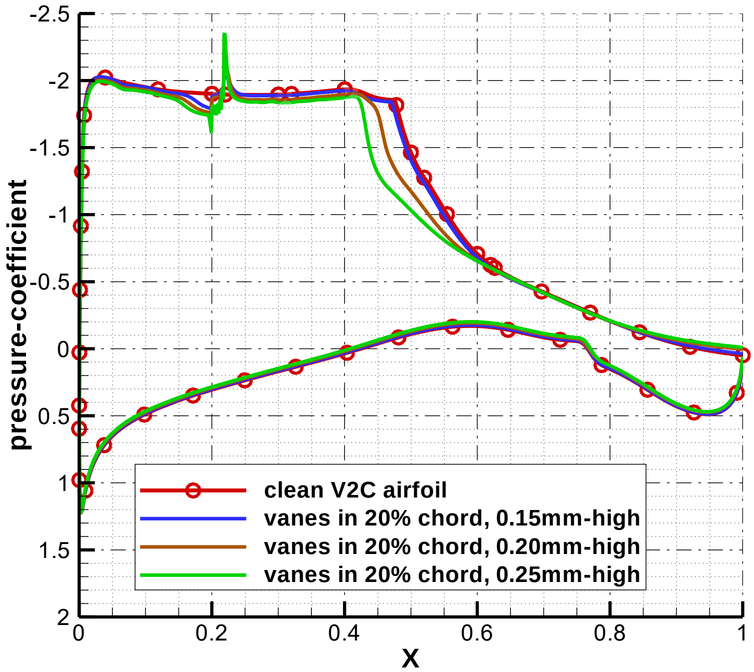

Figure 16. Comparison of distributions of pressure coefficient of clean airfoil and configurations with perpendicular vane turbulators of different height, placed in 20% airfoil chord. Ma=0.681, AoA=6°.

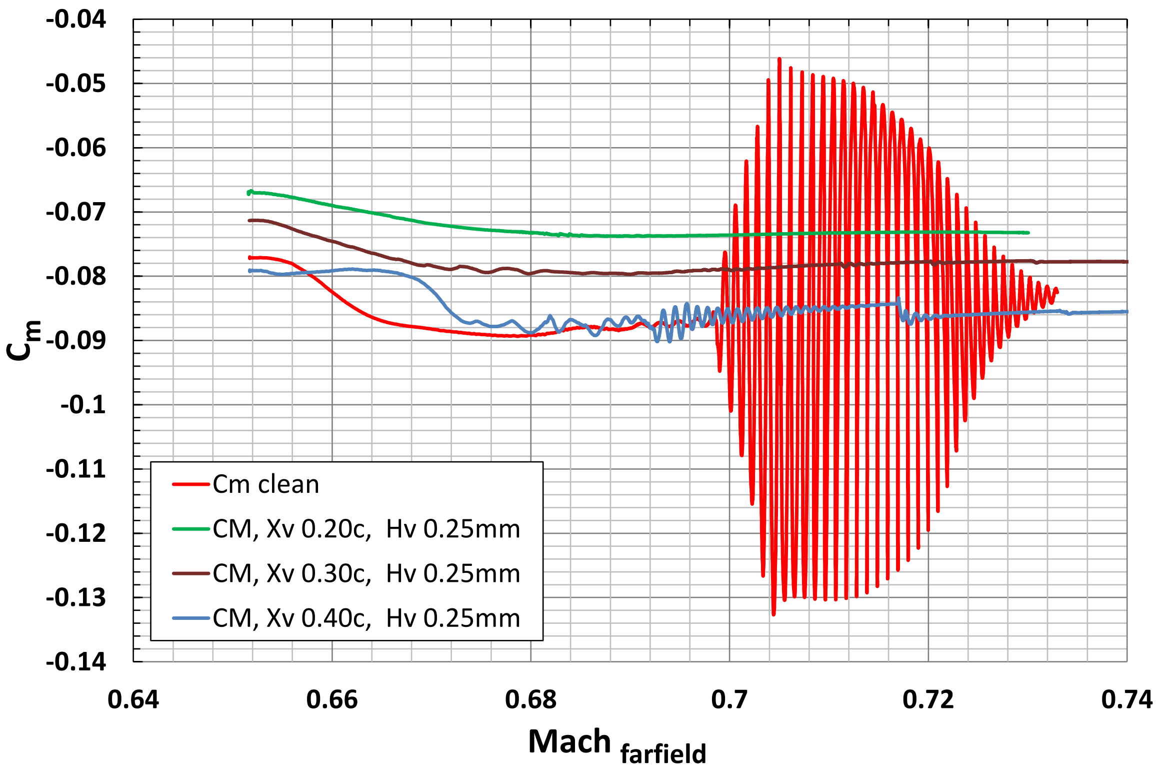

Figure 17. Effects of tripping of laminar boundary layer with perpendicular vane turbulators of different height, placed in 20% airfoil chord on pitching moment oscillations due to buffet phenomenon compared with results for clean V2C airfoil.

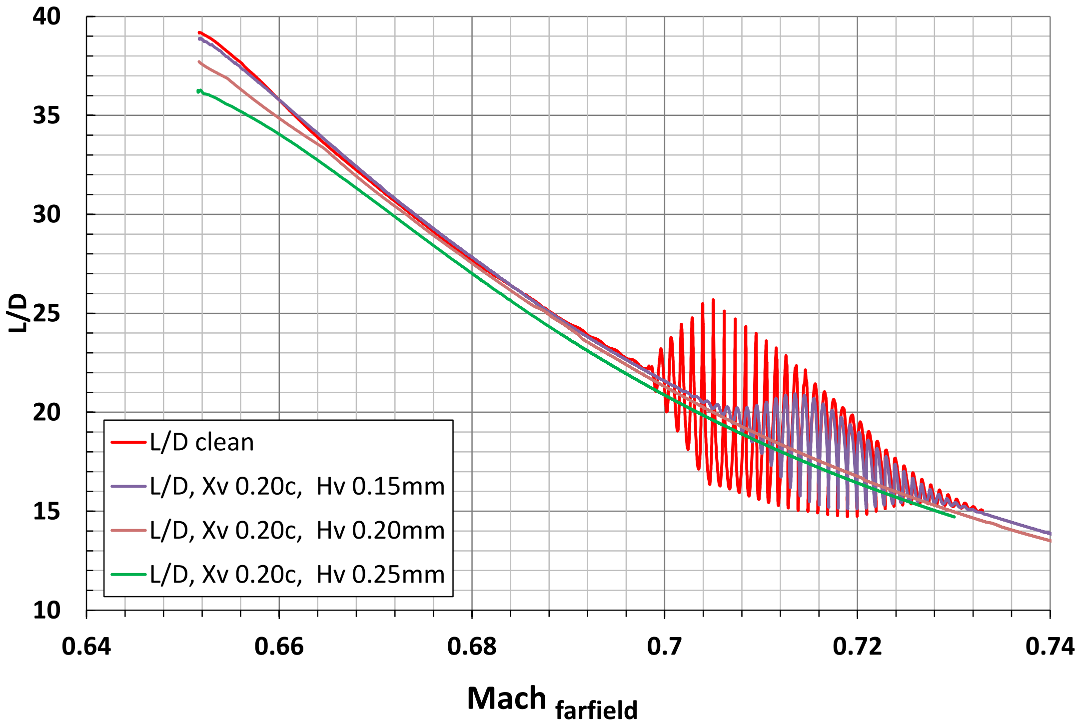

Figure 18. Effects of tripping of laminar boundary layer with perpendicular vane turbulators of different height, placed in 20% airfoil chord, on lift-to-drag ratio in transonic flow regime including buffet zone, compared with results for clean V2C airfoil.

5 CONCLUSIONS

- Improvement of aerodynamic characteristics of laminar airfoil in transonic flow with strong shockwave is more likely to occur as increase of lift-to-drag ratio, than as reduction of drag.
- Conditions when delta-shaped, counter-rotating vortex generators may improve aerodynamic characteristics of laminar airfoil in investigated conditions with strong shockwave include position of the vortex generator of height of 25% - 50% of boundary layer thickness, located approximately 5-10% of chord in front of the shockwave.
- Favourable effects of investigated delta-shaped vortex generators include, beside elimination of laminar separation at the shockwave foot, also increase of suction in front of shockwave which has positive effect on lift-to-drag ratio, compensating increased drag due to higher friction in turbulent boundary layer and due to presence of the vgs themselves.
- Both tested turbulators – the delta-shaped vortex generators and micro-vanes perpendicular to flow and to airfoil surface had positive effects on buffet phenomenon, damping oscillations of shockwave.
- The results obtained for the second type of turbulator – micro-vanes perpendicular to airfoil surface and flow have shown that for vane height equal 50% of thickness of laminar boundary layer buffet phenomenon was eliminated from Mach range where it existed on clean airfoil.

6 ACKNOWLEDGEMENTS

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