EFFECTS OF LAMINAR-TURBULENT TRANSITION ON BUFFET ONSET AND TRANSONIC CHARACTERISTICS OF LAMINAR AIRFOIL

Wienczyslaw Stalewski*, Katarzyna Surmacz*, Janusz Sznajder*
***Institute of Aviation, Warsaw, Poland**

Abstract

Studies on shockwave-boundary-layer interaction have been conducted, aimed at evaluation of possibilities of successful application of Natural-Laminar-Flow technology in a design of transonic wing. To alleviate unfavourable effects of interaction between laminar boundary layer and a shockwave, the laminar-turbulent transition, forced by the system of micro-vanes located ahead of the shockwave has been proposed and investigated through CFD simulations.

***Keywords**: natural laminar flow, transonic flow, laminar-turbulent transition, transonic buffet*

1 Introduction

Laminar flow technology offers economic and environmental advantages of increased effectiveness and lower emissions of greenhouse gases in air transport. One of reasons limiting so far application of this technology for aircraft operating in transonic flow range is interaction of boundary layer with shockwaves in off-design conditions decreasing performance and leading to safety problems. Shockwave-boundary layer interaction (SWBLI) on laminar airfoil 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. Shockwave closing the supersonic flow region is more intensive than on turbulent airfoils and may lead to large-scale separation of the flow behind the shockwave and large increase of drag. Another phenomenon occurring in these conditions, creating safety problems, is transonic buffet – global instability and self-induced oscillations of transonic flow, being a result of positive feedback between the strong shock wave and the flow separation behind the wave. As a means of counteracting these harmful phenomena, tripping of laminar boundary layer is proposed at some distance upstream from the shockwave in order to prevent laminar boundary layer reaching the shockwave.

2 Methods and conditions of investigations

Flow analysis was conducted by solution of Unsteady Reynolds-Averaged Navier-Stokes Equations (URANS) implemented in ANSYS Fluent solver [1]. As a closure of the system of equations the four-equation Transition SST turbulence model was applied, having as unknown variables k – turbulent kinetic 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. Coupled pressure-velocity scheme and second-order spatial and temporal discretisation of URANS equations was applied. In conditions of transonic flow with shockwave on the upper surface, the tripping of laminar boundary layer was simulated as a result of application of micro-vanes – small plates perpendicular to flow and airfoil surface, generating vortices with spanwise-oriented rotation axes. The object of investigations was V2C laminar, transonic airfoil designed by Dassault Aviation especially for investigations of SWBLI.

The main focus of the investigations was defined as conditions with shockwave present on the airfoil upper surface, which, in natural laminar-turbulent transition occurs with separation of laminar boundary layer under the shockwave and, depending on the angle of attack, may oscillate along chord at reduced frequency (k=2π·C/V) of approximately 0.4, characteristic for two-dimensional transonic buffet [3]. In order to capture the onset and development of buffet two computational procedures were applied. The first one, aimed at determination of Mach number of buffet onset at constant angle of attack assuming continuous increase of free-stream Mach number from subsonic conditions through transonic flow conditions until development of intensive oscillations of shockwave on clean airfoil with frequency characteristic for transonic buffet phenomenon. The other procedure assumed fixing free-stream Mach number at a value for which transonic flow exists on the airfoil with shockwave closing the supersonic flow region, and continuous increase of angle of attack until reaching conditions of oscillating shockwave on the upper surface of airfoil. The second procedure modelled a real-life scenario of encountering vertical gust, and, as a result of increase of angle of attack, passing through the Mach - Lift Coefficient (Ma-C_L) boundary which limits operational conditions of aircraft. The same computational procedures were applied for clean airfoil case and for cases with turbulators of different size and chordwise position. As a result of the computational procedures, an/the effectiveness of the investigated turbulators in prevention of buffet could be compared for different height of the micro-vanes and their position on the airfoil. All computations were conducted in a domain simulating open-flow conditions, shown in Fig. **1**, 1 cm-wide, limited sidewise by planes with boundary conditions of periodicity and free-stream conditions applied at pressure far-field boundaries in front of the airfoil and on the upper and lower boundaries. On the outlet surface the pressure outlet boundary condition was applied. Chord (C) of the airfoil was equal to 20 cm. The geometric details of the proposed turbulators are presented in Fig. 2. It consisted of six plates of height varying from 0.15mm to 0.25mm (0.075 to 0.125% chord), with spacing of 0.7mm. Tab. 1 presents relative height of the vanes H with respect to b.l. thickness δ at Mach number Ma=0.70.

3 Natural and induced laminar-turbulent transition on V2C airfoil modelled by URANS equations

Before simulating laminar-turbulent transition forced by the turbulators, flow simulations were conducted for the clean airfoil in order to obtain reference solution corresponding to natural laminar-turbulent transition.

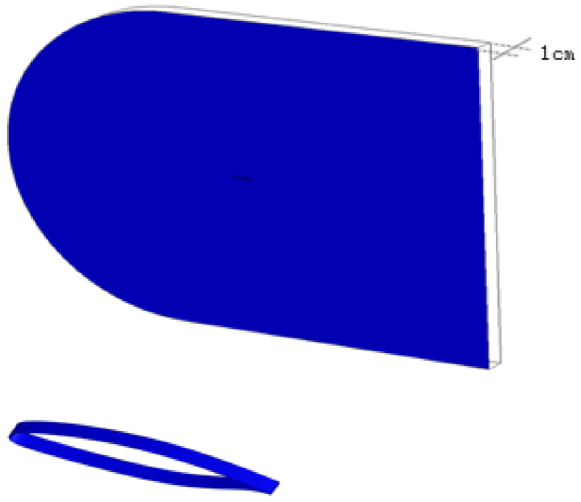

Fig. 1. View of the computational domain for the investigated airfoil.

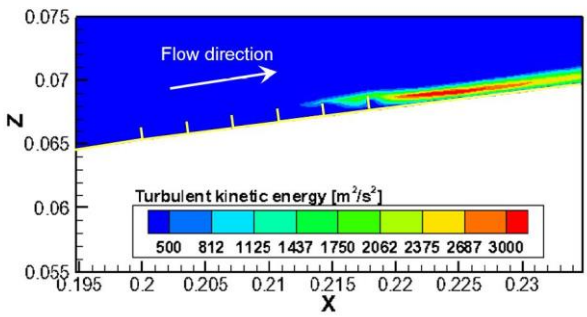

Fig. 2. Geometric details of the proposed turbulator.

Xv (%C)	**20**	**30**	**40**
H/δ, H=0.15mm	0.45	0.36	0.30
H/δ, H=0.20mm	0.61	0.48	0.40
H/δ, H=0.25mm	0.75	0.60	0.50

Tab. 1. Relative height of micro-vanes with respective to local thickness of boundary layer at Ma=0.70.

The results presented in this section were obtained for steady-flow conditions at angle of attack α=6 degrees and Mach number Ma=0.68, in absence of oscillations of shockwave. The transition is most conveniently observed as a rise of intermittency in the boundary layer and a rise of tangential stress on airfoil surface. Flow in these conditions is characterised by the presence of lambda-shaped shockwave shown in Fig. 3. In Fig. 4 it can be seen that shockwave is preceded by rise of intermittency I in the boundary layer which starts at approximately 43% chord and with intermittency finally reaching unity at the foot of the shockwave.

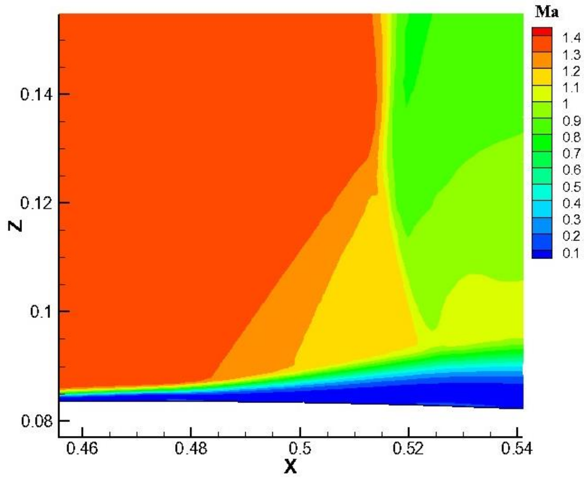

Fig. 3. Lambda-shaped shockwave at angle of attack α=6°, far-field Mach number Ma=0.68 in normalized coordinate system, based on airfoil chord.

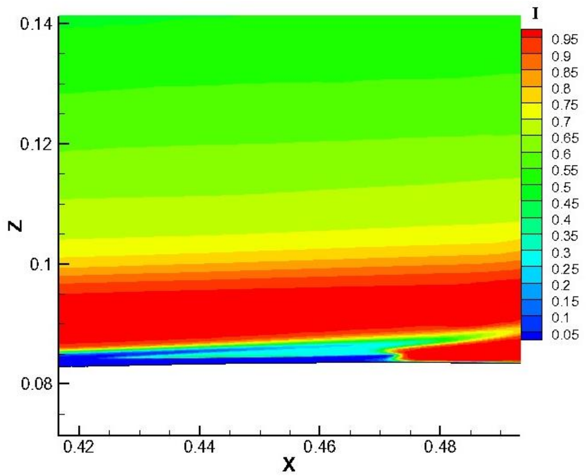

Fig. 4. Rise of intermittency in the boundary layer at α=6°, far-field Ma=0.68.

In the plot of tangential stress on airfoil surface, presented in Fig. 5 it can be seen that at 44%c starts separation of laminar boundary layer (b.l.), visible as a slightly negative segment of the tangential stress curve, which changes into large-scale separation of turbulent b.l. at 47%c, under the lambda-foot of the shockwave. Effects of tripping of laminar boundary layer with micro vanes of different height, placed in 20% chord on pressure coefficient and on surface tangential stress are shown in Fig. 6 and in Fig. 7. It can be seen that for cases with effective turbulators (H/θ>0.45), shockwave moves slightly forward and rise of pressure is more rapid, without “pressure plateau” existing in front of the shockwave in clean case, characteristic for laminar separation under the shockwave.

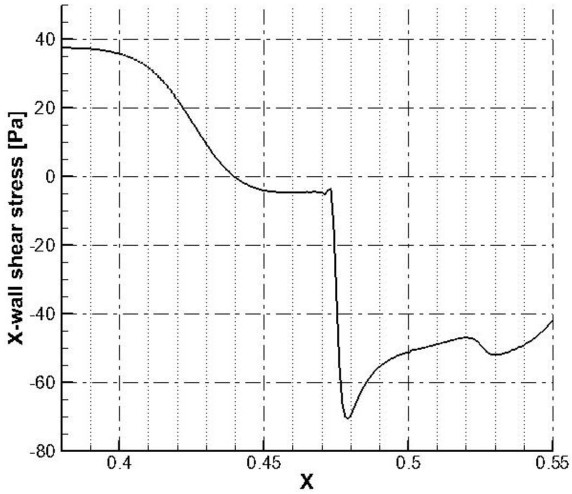

Fig. 5. Change of tangential stress on airfoil surface under shockwave at α=6°, far-field Ma=0.68.

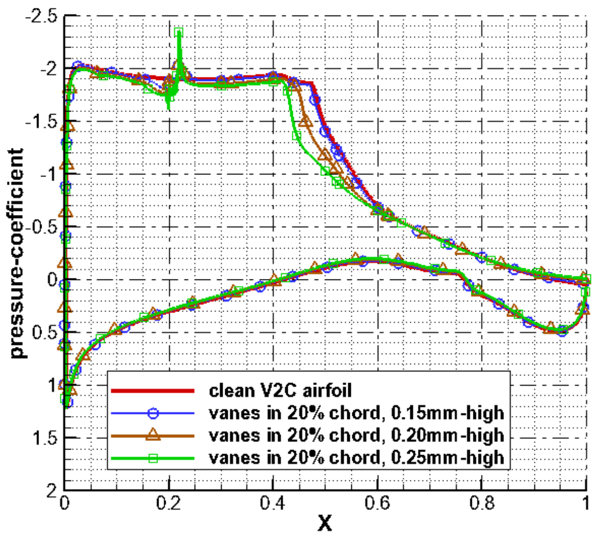

Fig. 6. Comparison of pressure coefficient for clean V2C airfoil and for cases with turbulators at α=6°, far-field Ma=0.68.

The more rapid rise of pressure is accompanied by increase of tangential stress behind the turbulators, shown in Fig. 7, which then changes sign without presence of a short, level, slightly negative line segment visible for clean airfoil, also characteristic for laminar separation. The separation of turbulent boundary layer behind shockwave then occurs over the shorter distance than for clean-airfoil case with b.l. turbulised when crossing the shockwave. Comparison of tangential stress for clean-airfoil case and for cases with turbulators of the same height, placed in different chordwise positions, presented in Fig. 8 shows, that moving turbulators upstream has the same effect on shockwave location and on size of the region of separated flow as increasing their height. On the other hand, tangential stress in the turbulised b.l increases to approximately the same level regardless of the height and position of effective turbulators.

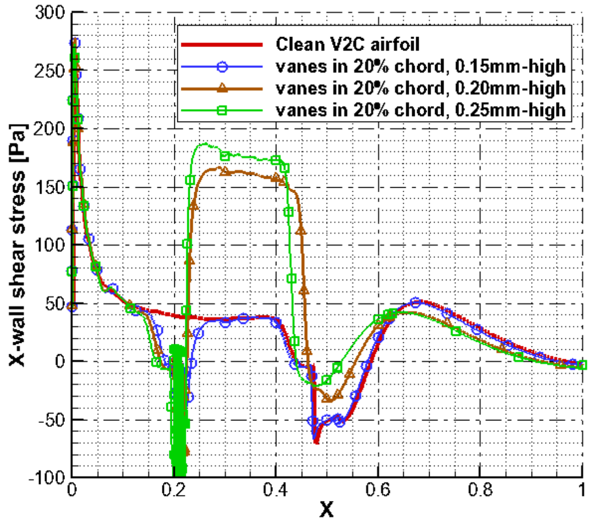

Fig. 7. Comparison of tangential stress on airfoil upper surface for clean V2C airfoil and for cases with turbulators of different height at α=6°, far-field Ma=0.68.

4 Comparison of effectiveness of buffet dumping for different height and position of turbulators

4.1 Analysis at constant angle of attack

This analysis was conducted at angle of attack of 6 degrees. It started with obtaining converged solution at Mach number of 0.65, set as the far-field boundary conditions. Next the far-field Mach number was being continuously increased by a user-defined function at a rate of 0.1 per second. This procedure allowed detecting buffet onset by inspection of pitching moment coefficient which starts to oscillate rapidly with buffet frequency as shockwave oscillates along chord (Fig. 9).

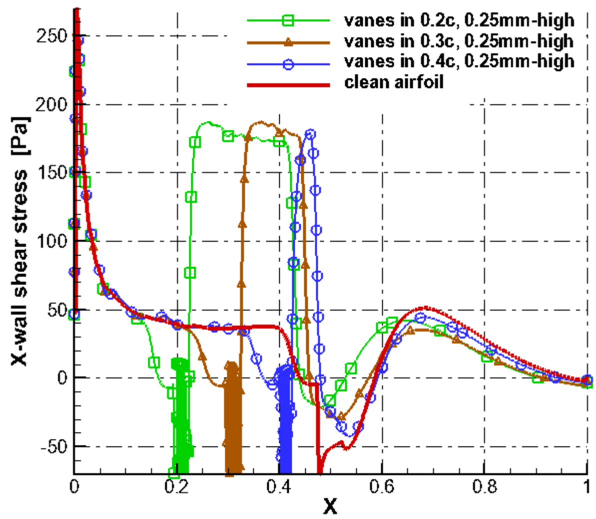

Fig. 8. Comparison of tangential stress on airfoil upper surface for clean V2C airfoil and for cases with turbulators of the same height, placed in different chordwise positions at α=6°, far-field Ma=0.68.

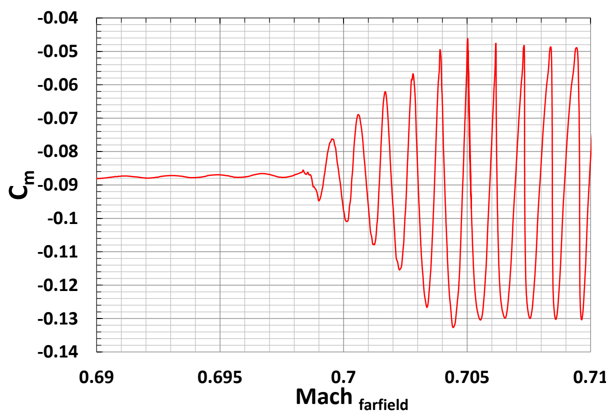

Fig. 9. Buffet onset visible as start of oscillations of pitching moment coefficient at Ma=0.689 for clean V2C airfoil.

Results of application of the above-mentioned computational procedure for several cases with turbulators of different vane height and chordwise position are presented in Figures from 10 to 16. Comparison of changes of pitching moment coefficient for turbulators of different height placed in 20% chord, presented in Fig. 10, shows that for turbulators which proved effective in tripping laminar boundary layer at far-field Mach number of 0.68 buffet phenomenon did not appear in flow conditions at which it existed on clean airfoil. It can also be seen that for turbulators of height of 0.15 mm, proved ineffective in Fig. 7, buffet phenomenon occured, but with reduced amplitude and in narrower Mach range than for clean airfoil. A likely reason for this is creation of local disturbances in distribution of upper-surface pressure which interact with the shockwave, and in effect, decrease amplitude of its oscillations. These disturbances are present in numerical Schlieren image in **Fig. 12**, emanating from extreme upstream and downstream vanes of the turbulator of 0.15mm-height, placed in 20% chord. As Fig. 11 shows, moving constant-height turbulator upstream on airfoil chord has similar effect on pitching moment coefficient to increasing its height in fixed chordwise position.

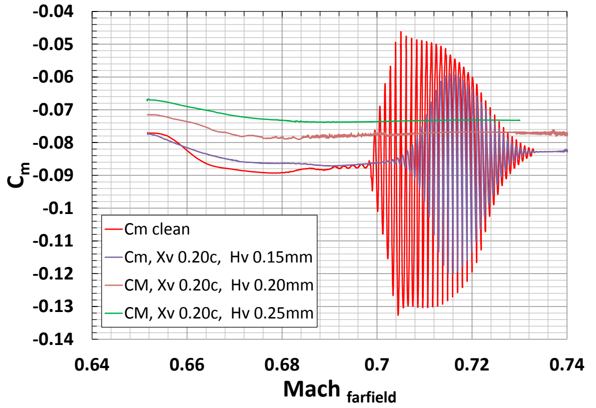

Fig. 10. Comparison of dependence of pitching moment coefficient on Mach number for clean-airfoil and for cases with turbulators of different height placed in 20% chord.

As far as lift coefficient is concerned, the most visible effects of the micro-vanes, apart from damping oscillations of shockwave is reduction of lift coefficient, the larger, the more upstream is placed the turbulator. This suggest application of this device as buffet-prevention and load-alleviation device in gust conditions which is be considered in more detail in the next sub-section, where flow simulation at increasing angle of attack is presented. Effects of application of turbulators on lift coefficient are shown in Fig. 13 and Fig. 14. It can be seen, that if damping of buffet at constant lift coefficient is sought, then turbulator should be placed close to shockwave, as result for the turbulator of the height of 0.25mm, placed in 40%c (5%c upstream of shockwave) shown in Fig. 14 suggests. If, however, an additional function is prevention of increasing lift in gust, when angle of attack grows, then it should be placed in frontal part of airfoil. Depending on the chordwise position, the turbulators may increase or reduce drag, which is shown in **Fig. 15**.

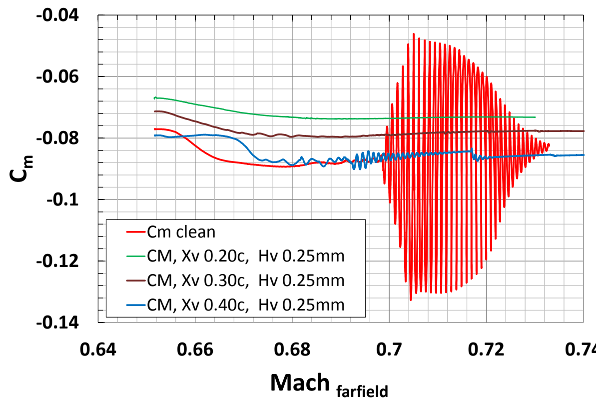

Fig. 11. Comparison of dependence of pitching moment coefficient on Mach number for clean-airfoil and for cases with turbulators of the same height placed in different chord positions.

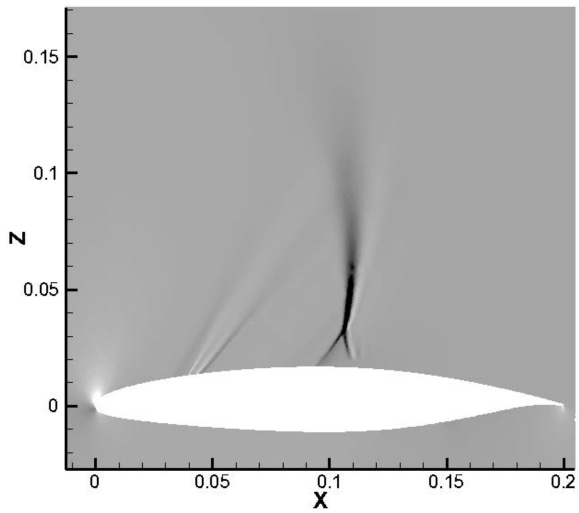

Fig. 12. Numerical Schlieren image of shockwave in presence of turbulators of 0.15mm-height in 20% chord. Ma=0.74, α=6°.

Drag reduction may be an effect of interactions of the flow disturbances produced by vanes with the shockwave, as it is largest for vanes placed in most upstream position. Effect of the turbulator on lift-to-drag ratio is the same, regardless of the position of the turbulators; L/D is decreased, as shown in Fig. 16. It is, however, worth to note, that reduction of L/D decreases with increasing Mach number.

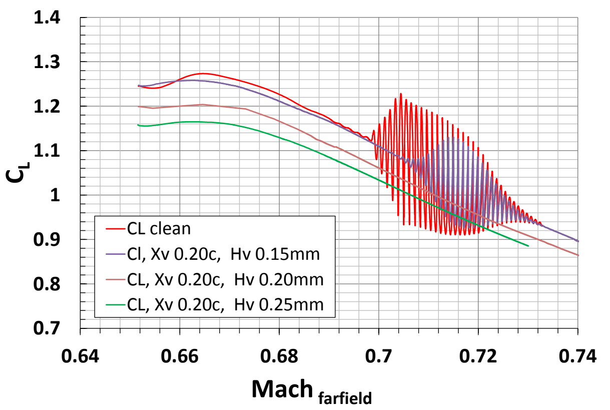

Fig. 13. Effects of changing height of the vanes placed in 20% chord on lift coefficient.

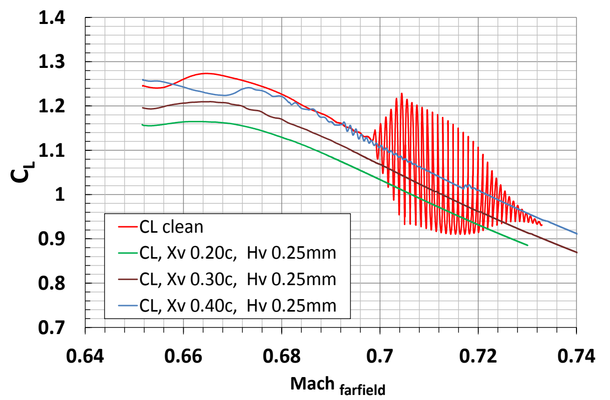

Fig. 14. Effects of changing position of vanes of 0.25mm-height on lift coefficient.

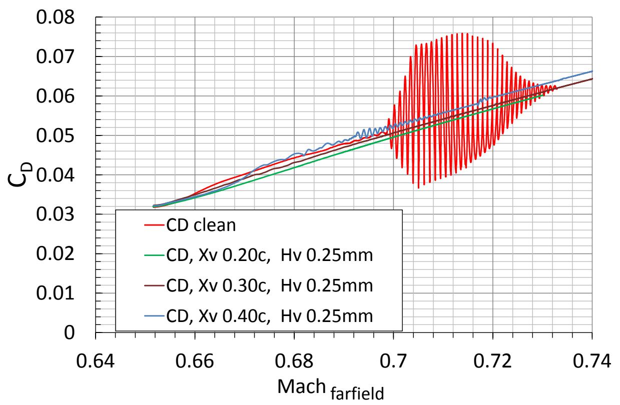

Fig. 15. Effects of changing position of vanes of 0.25mm-height on drag coefficient.

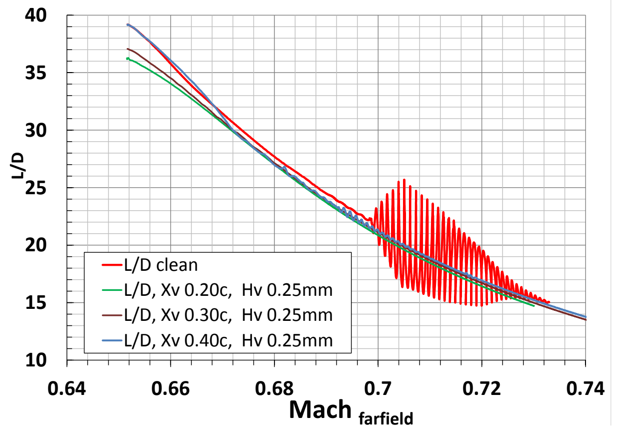

Fig. 16. Effects of changing position of vanes of 0.25mm-height on lift-to-drag ratio.

4.2 Analysis at increasing angle of attack

Reduction of lift as a result of placing the turbulator in the front part of airfoil suggests its application in prevention of crossing buffet onset boundary in conditions of gust. In order to check such a possibility a simulation of change of wing loads at continuously increasing angle of attack, and fixed far-field Mach number of Ma=0.71 was conducted. Increase of angle of attack was modelled by continuous rotation of the whole mesh, which corresponds to a ramp-type gust profile, shown in **Fig. 17**. At angle of attack of α=4.5°, in pre-buffet conditions, activation of the turbulators, placed alternatively

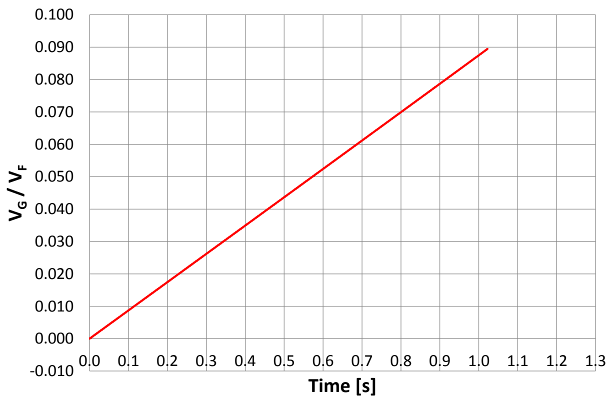

Fig. 17. Ratio of gust velocity to level flight velocity vs time.

in 20% chord and in 40% chord was simulated by change of boundary condition on their surfaces from "interior" to "wall". The analysis was conducted without solving equations of motion of aircraft which would bring about some reduction of angle of attack as a result of upward motion of wing surface and aircraft in gust, as well as without modelling of possible aero-elastic deformations of wing. Change of lift and pitching moment coefficient resulting from activation of turbulators is shown in Fig. **18** and in Fig. 19. For both configurations with turbulators elimination of oscillations of shockwave was achieved after short intermediate period of highly unsteady flow. For turbulator placed in 20% chord a 12% reduction of lift occurred in addition to damping-out of buffet and remained constant in the analysed range of angle of attack.

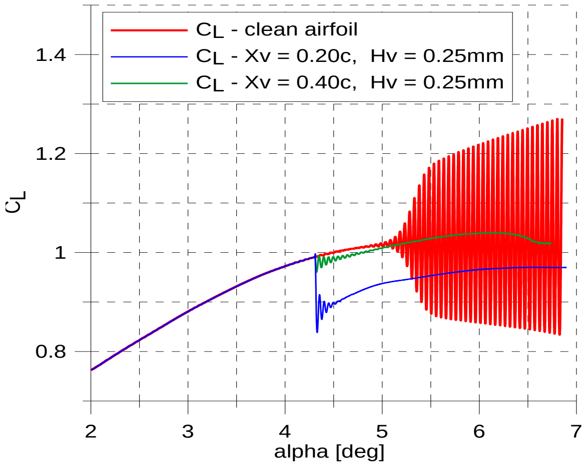

Fig. 18. Comparison of change of lift coefficient on clean airfoil and on airfoil with vanes of 0.25mm-height placed alternatively in 20% chord and 40% chord.

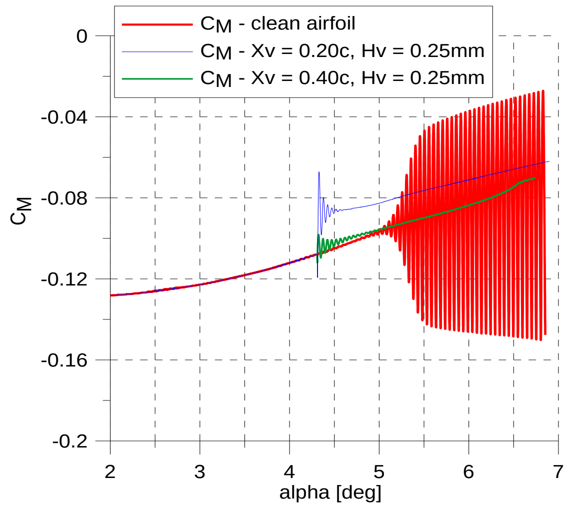

Fig. 19. Comparison of change of pitching moment coefficient on clean airfoil and on airfoil with vanes of 0.25mm-height placed alternatively in 20% chord and 40% chord.

5 Conclusions

The results of conducted flow simulations of tripping laminar boundary layer by the proposed system of micro-vanes show, that large-scale effects in wing loading, resulting in prevention of buffet and alleviation of wing load can be achieved by application of small-scale devices placed in critical regions of boundary layer. In the presented study the effective wing-load alleviation and elimination of strong oscillations of shockwave have been achieved by application of the micro-vanes of height at least 0.125% of wing chord, preferably located at 20% of wing chord.

6 Acknowledgements

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