ECCOMAS Congress 2016
VII European Congress on Computational Methods in Applied Sciences and Engineering
M. Papadrakakis, V. Papadopoulos, G. Stefanou, V. Plevris (eds.)
Crete Island, Greece, 5–10 June 2016

NUMERICAL SIMULATION OF TRANSONIC BUFFET AND ITS CONTROL USING TANGENTIAL JET BLOWING

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Keywords: buffet, URANS, flow control, tangential jet blowing, transonic flow.

Abstract. *The unsteady interaction between a shock wave and boundary layer over a transonic wing can lead to the generation of considerable separation zones and periodical shock wave motion along the airfoil chord. The phenomenon is called transonic buffet. In the present work the buffet phenomenon on a transonic airfoil is simulated numerically using second order finite-volume method. Unsteady Reynolds Averaged Navier-Stokes (URANS) equations with different turbulence models are integrated. Transonic airfoil P-184-15SR of TsAGI is used as a reference geometry with Reynolds number ~*2.6×10^6*. The buffet onset boundary is calculated for different free-stream Mach numbers. Active flow control method is proposed to alleviate the buffet onset. In this method, jet is blown tangentially near the shock wave on the upper airfoil surface. Parametric studies are performed. In all cases tangential blowing leads to significant lift growth and buffet alleviation.*

1 INTRODUCTION

Airfoils at transonic speeds are subjected to the buffet phenomenon, associated with unsteady shock-boundary layer interaction inducing self-sustained oscillations of separation zone under the shock foot on the upper surface of the wing. That leads to significant changes of the airfoil performance, i.e. lift, drag and moments. This phenomenon can further lead to structural vibrations called buffeting. Wing design standards impose margins between the buffeting onset and the cruise condition. As a consequence, a delay in buffeting onset could lead to improved aerodynamic performance characteristics that can result in the reduction of wing area and hence the friction part of drag. One of the ways of buffet alleviation is flow control.

The buffet is associated with the shock-boundary layer interaction (SBLI). Up to date a number of methods of SBLI control are developed. One of them is a passive method, in which a cavity covered with a perforated plate is placed under the shock foot [1]. Grooves and stream-wise slots are also well-known passive devices [2]. In all the methods the shock is weakened and wave drag is reduced. 2D bumps also lead to the wave drag reduction, but also result in too high penalty under off-design conditions [3]. 3D bumps are thoroughly investigated to diminish the penalty [4].

Another group of methods is based on the boundary layer energizing to prevent its separation. Among the most popular are mechanical and fluidic vortex generators (VGs). Mechanical VGs were investigated in [5-6] and proved their efficiency. The main drawback of the method is drag increase under cruise condition. Fluidic air-jet VGs and tangential jet blowing with position at 15% of the chord length to control SBLI were also considered in [5]. Boundary layer suction [7] and application of plasma actuators [8-9] were also considered. These concepts have multiple advantages, such as optional turning on during cruise regime and operation in a closed-loop strategy to optimize flow control. However, they require additional equipment resulting in a weight growth.

The concepts outlined can be used for buffet control. Mechanical trailing edge device (TED) which can change rear loading of an airfoil was considered in [10]. Fluidic VGs with air jets along with fluidic TED, where jet was blown on the pressure side, were studied in [11]. VGs are shown to be able to delay the buffet onset in the angle of attack domain by suppression of a separation zone downstream of the shock. In the case of fluidic TED, the separation was not suppressed and buffet was alleviated in the lift domain only.

In the present study buffet is simulated on the transonic supercritical airfoil P-184-15SR of TsAGI with the Reynolds number based on the chord $Re=2.6\times10^6$. Steady and unsteady Reynolds averaged Navier-Stokes equations are used with Spalart-Allmaras (SA) and shear stress transport (SST) turbulence models. The buffet onset boundary is calculated in a range of free-stream Mach numbers from 0.72 to 0.75. Flow control method based on fluidic air-jet blowing is proposed to alleviate the buffet onset. The jet is blown tangentially near the shock wave on the upper airfoil surface. Buffet alleviation is obtained for these cases.

2 PROBLEM STATEMENT

2D geometry investigated is a supercritical airfoil P-184-15SR developed at TsAGI with thickness 15% and chord length c=0.2 m. Reynolds number based on free-stream parameters and chord length is $Re=2.6\times10^6$. The baseline geometry corresponds to the smooth airfoil (figure 1).

To simulate the jet blowing, slot is added at x-coordinate X_j=60% of the chord with height h=0.15 mm (figure 2). The global mesh (figure 3) is not changed. The only grid nodes downstream of slot nozzle are added (figure 4). Computational grid consists of approximately 200 000 cells. Grid nodes are clustered normal to the surface inside the boundary layer so that

Y^+_1<1. Grid convergence study showed that the grid size is sufficient for numerical simulations [12].

Figure 1: Smooth airfoil P-184-15SR.

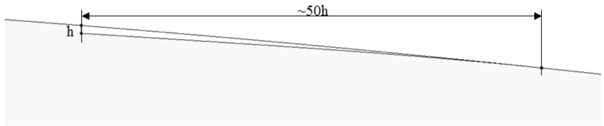


Figure 2: Slot geometry at X_j=0.6.

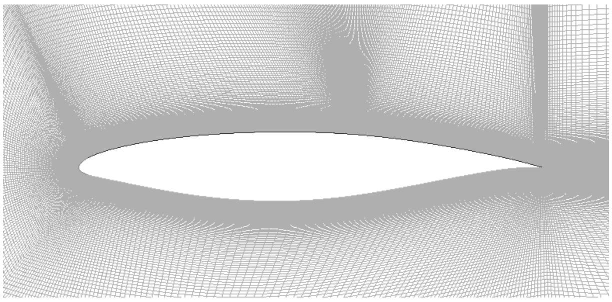


Figure 3: Grid near the airfoil.

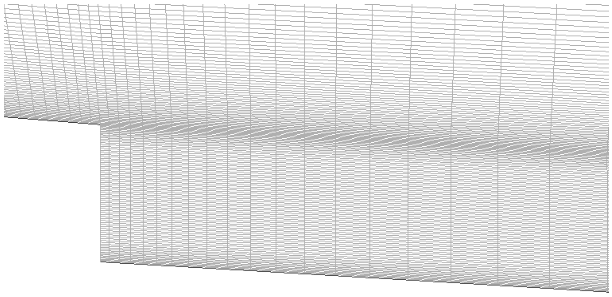


Figure 4: Grid near slot nozzle.

RANS and URANS equations are used for simulations. The calculations are carried out for the ideal compressible gas with laminar Prandtl number Pr=0.72. Laminar viscosity-temperature dependence is approximated by Sutherland law with Sutherland constant 110.4 K.

Numerical solutions are obtained using an implicit finite-volume method. The equations are approximated by a second-order shock-capturing scheme. The flux vector is evaluated by an upwind flux-difference splitting of Roe. Second order upwind scheme is used for spatial discretization of convective terms. Central-differencing scheme is used for diffusion terms. The second order time discretization is used for transient simulations. Dual time stepping scheme is used. Time step equals to $\Delta t=2\times10^{-6}$ s with internal iterations converging up to the error ~10^{-6}. Further time steps and error decreasing showed no impact on solutions.

Two turbulence models were used: Spalart-Allmaras and SST. In RANS simulations, the difference between the models for pressure coefficient C_p is relatively small (figure 5). For these simulations, free-stream Mach number is M=0.73, angle of attack AoA=4 degrees, laminar-turbulent transition was fixed at x/c=0.15. In URANS simulations, SST model showed no buffet at all considered regimes so that SA model was used for further simulations.

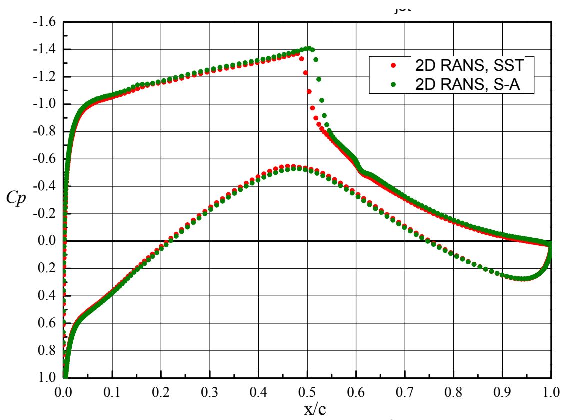


Figure 5: Cp distribution: M=0.73, AoA=4^o, geometry with a slot.

Some preliminary RANS calculations were also done to compare the flowfield over the baseline geometry and the airfoil with a slot without a jet for M=0.77 and AoA=6 deg. Slot was placed at x/c=60% and its height was of the order of magnitude less than the boundary layer thickness h=0.15 mm. The difference was small enough (figure 6).

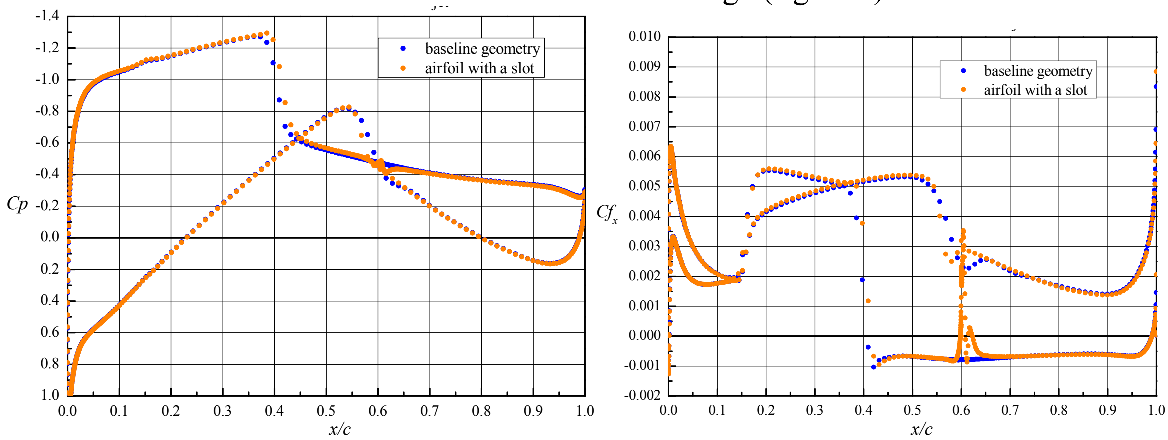


Figure 6: Cp and x-component of Cf distributions: M=0.77, AoA=6°, baseline geometry and airfoil with a slot.

3 BUFFET SIMULATION: BASELINE GEOMETRY

Buffet characterization on the P-184-15SR airfoil on the base of 2D URANS studies are carried out for the cases without jet blowing for the baseline geometry. Summary of these results on (M, α) plane is shown in Figure 7. Regimes below solid line correspond to regimes without buffet, while regimes under solid line correspond to buffet onset. Lift coefficient C_L convergence history for the case without and with buffet are shown in Figure 8. Buffet frequency was calculated using fast Fourier transformation. It varies from 99 Hz for M=0.72 and AoA=5° to 118 for M=0.74 and AoA=4.5°.

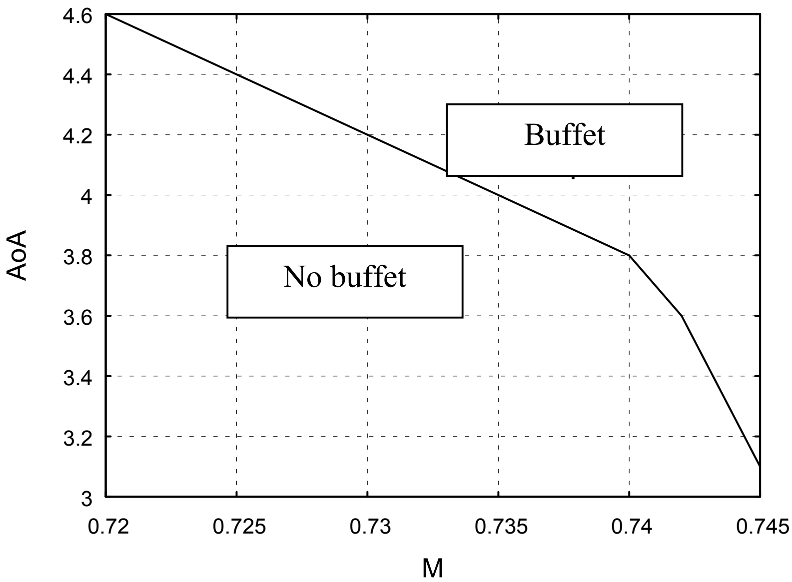
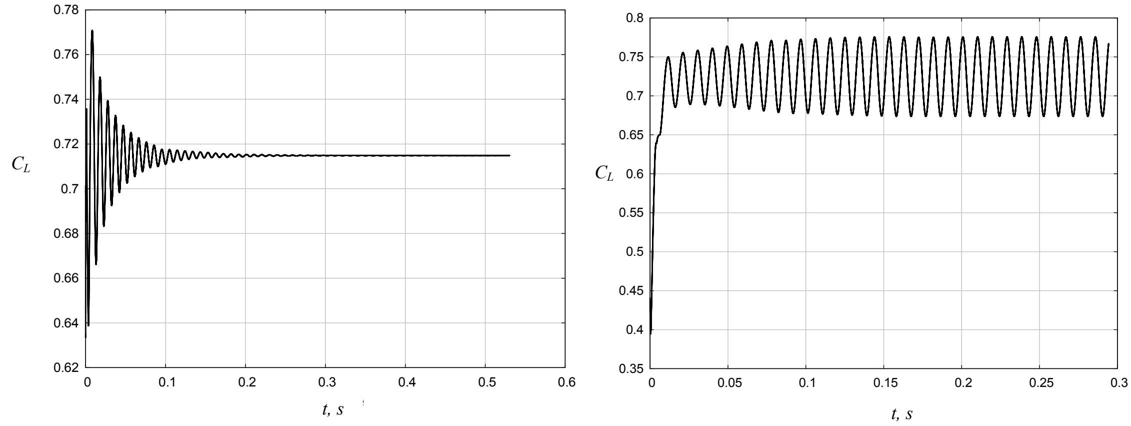


Figure 7: Buffet onset on (AoA, M) plane: baseline geometry.



a b

Figure 8: C_L convergence history for regimes without (a, M=0.73, AoA=4°) and with buffet (b, M=0.73, AoA=4.5°).

During the buffet period shock reaches its most upstream and downstream locations (figure 9). Figure 10a shows Cp distributions on airfoil surface. Blue curve corresponds to the mean C_p distribution where C_p is averaged for several periods of shock oscillation. In this case the shock is smoothed between the most upstream and downstream locations. Red curve corresponds to Cp distribution at time moment in which lift coefficient equals to the mean value. It is seen that there is a sufficient difference between these curves.

It should be noted that the shock motion also leads to the local maximum of the root mean square (RMS) of Cp in the region of shock oscillation (figure 10b).

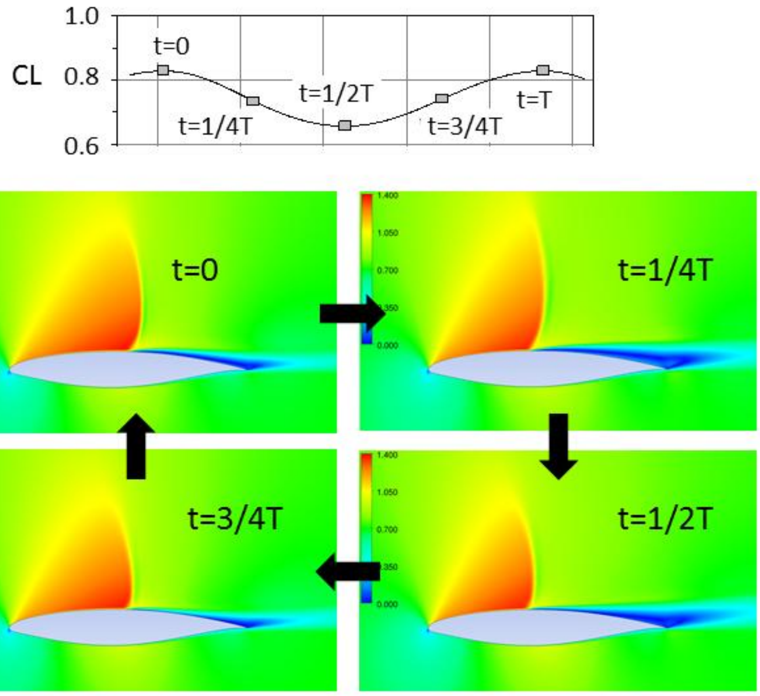
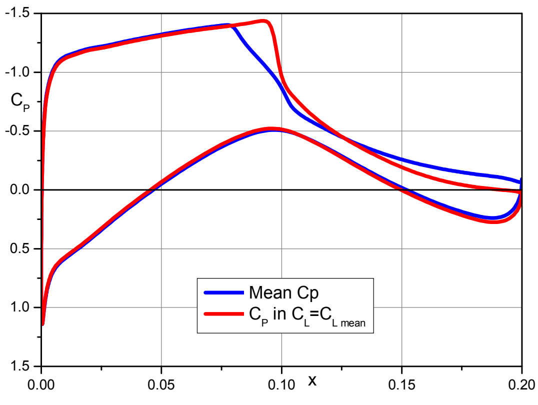
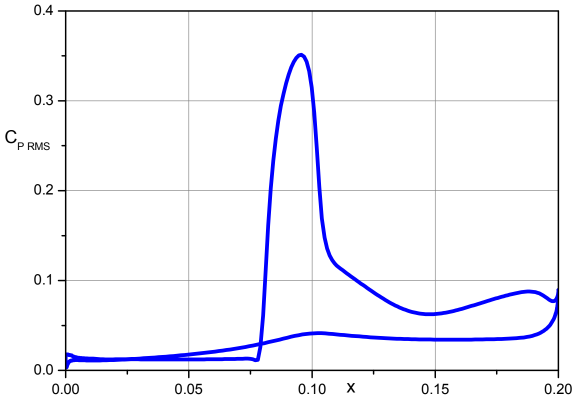


Figure 9: Mach number field evolution during the buffet period: M=0.73, AoA=5°.



a



b

Figure 10: Mean and instantaneous Cp distributions (a) and RMS of Cp (b), M=0.73, AoA=5°.

4 TANGENTIAL JET BLOWING EFFECT

To control the buffet supersonic jet is blown out of the slot (figure 11) with momentum coefficient C_μ=0.0066. The mechanism of buffet alleviation and lift increase is associated with the separation zone elimination. As seen in figure 12, longitudinal component of wall friction coefficient is above zero downstream the shock for the case with jet blowing, while being negative for the baseline geometry.

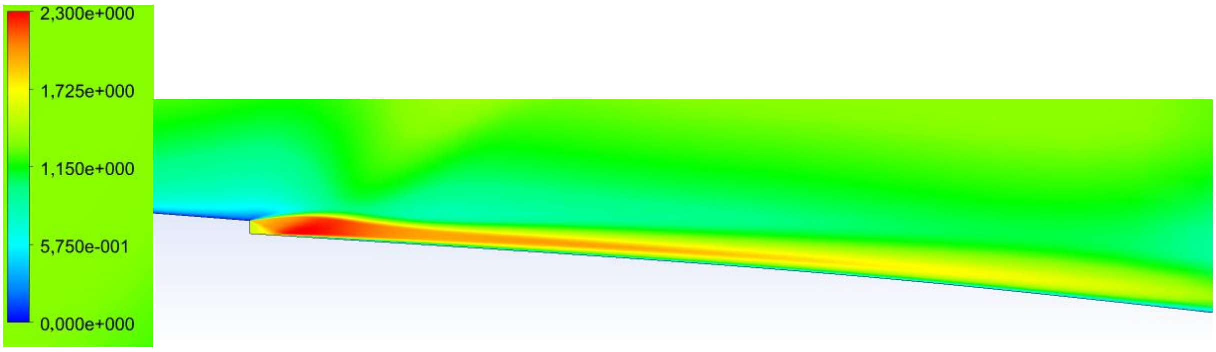


Figure 11: Mach number field near the slot nozzle, M=0.74, AoA=2°, X_j=60%, Cμ=0.0066.

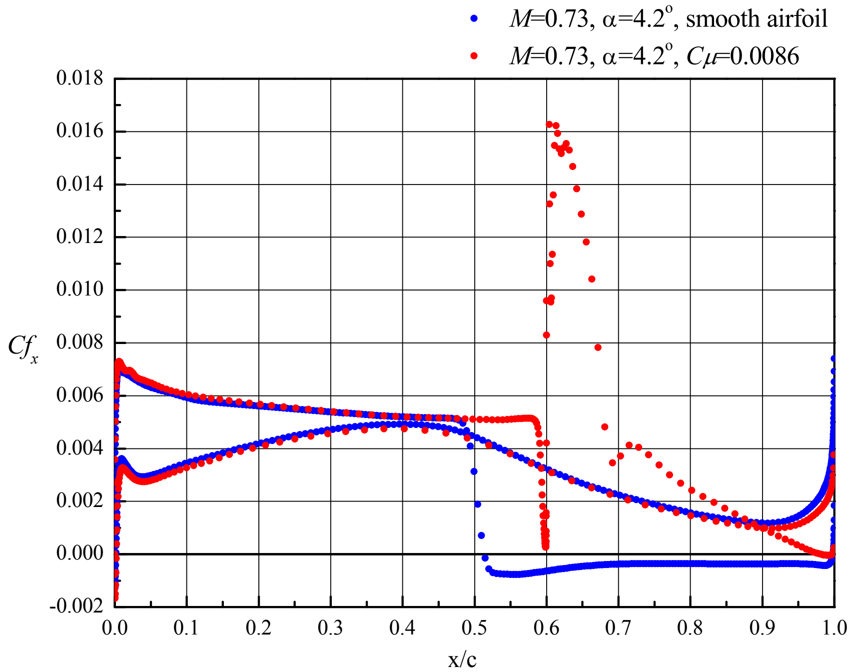


Figure 12: X-component of skin friction coefficient: smooth airfoil and airfoil with jet blowing: M=0.73, AoA=4.2°.

The mean values of C_L and standard deviations of C_L are plotted in figure 13. Both for the baseline geometry and for the jet blowing, RANS results close to URANS mean values. For the baseline case, deviation of lift curve from the linear regime is near AoA=2° while buffet onset regimes in URANS begin from AoA=4.2°. For the jet blowing with Cμ=0.0086, there is no buffet at all. The C_L increase reaches 0.2 on the linear stage and increases up to 0.4 at AoA=6°.

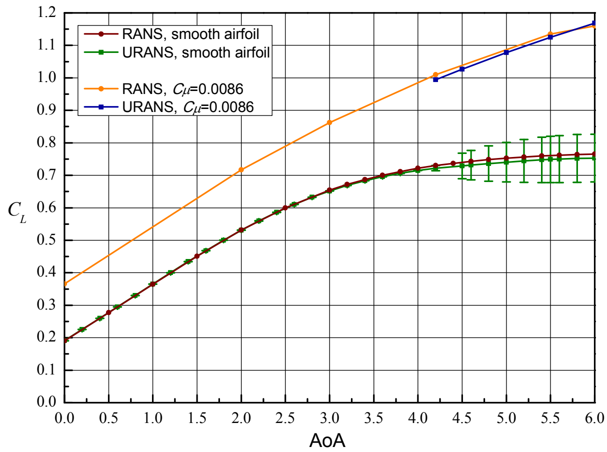


Figure 13: Lift curve for M=0.73 with and without tangential jet blowing.

Additional calculations were performed for low-momentum jet with Cμ=0.00069 (figure 14). In this case, there is no impact on C_L but AoA of buffet onset is delayed to 0.5-0.8° relative to the baseline geometry.

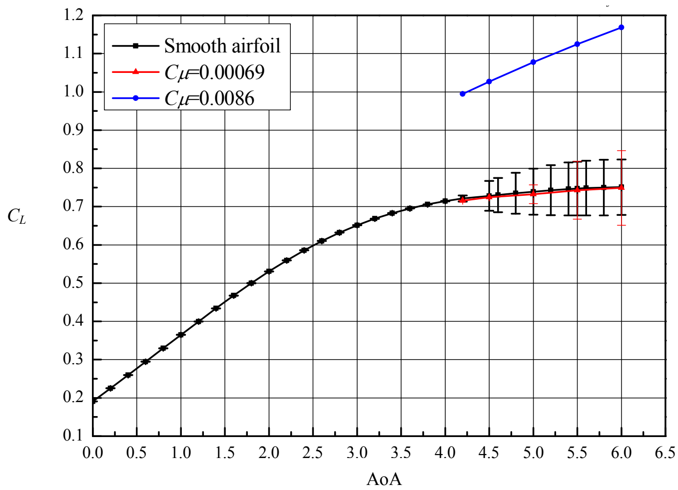


Figure 14:Lift curve for M=0.73, URANS, red curve – low momentum jet with Cμ=0.00069.

5 CONCLUSIONS

- Two-dimensional numerical simulations are carried out to characterize the buffet phenomenon on transonic supercritical airfoil P-184-15SR. The buffet boundary in AoA – Mach number is calculated.
- SST model showed no buffet while SA model was used for URANS simulations.
- Tangential jet blowing in the shock region is investigated to delay buffet. Numerical simulations showed that tangential jet blowing suppresses shock-induced separation and significantly increases lift coefficient.
- URANS results showed buffet onset delay both in the AoA and CL domain.

ACKNOWLEDGEMENTS

This work is supported by BUTERFLI Project of the 7th Framework Program of the European Commission (Grant Agreement 605605).

REFERENCES

[1] L. Bahi, J.M. Ross, T. Nagamatsu, Passive shock wave/boundary layer control for transonic airfoil drag reduction. *AIAA Paper* 1983-0137.

[2] S. Raghunathan, Passive control of shock-boundary layer interaction. *Progress in Aerospace Science*, 25: 271-296, 1988.

[3] J. Birkemeyer, H. Rosemann, E. Stanewsky, Shock Control on a Swept Wing. *Aerospace Science and Technology*, 4:147-156, 2000.

[4] H. Ogawa, H. Babinsky, M. Patzold, T. Lutz, Shock-Wave/Boundary-Layer Interaction Control Using Three-Dimensional Bumps for Transonic Wings. *AIAA Journal*, 46(6):1442-1452, 2008.

[5] H.H. Pearcey, Shock-induced separation and it's prevention by design and boundary layer control. *In: Boundary layer and flow control – it's principles and application. Ed. by Lachmann, Vol. 2, London, Pergamon Press,* 1170-1361, 1961.

[6] V.M. Gadetskiy, Ya.M. Serebriyskiy, V.M. Fomin, Investigation of the influence of vortex generators on turbulent boundary layer separation. *NASA TT* F-16056, 1974.

[7] P. Krogmann, E. Stanewsky, P. Thiede, Effects of suction on shock/boundary layer interaction and shock-induced separation. *J. Aircraft,* 22(1): 37-42, 1985.

[8] S.B. Leonov, D.A. Yarantsev, V.G. Gromov, A.P. Kuriachy, Mechanisms of Flow Control by Near-Surface Electrical Discharge Generation. *AIAA-Paper* 2005-780, 2005.

[9] A. Marino, P. Catalano, C. Marongiu, P. Peschke, C. Hollenstein, R. Donelli, Effect of High Voltage Pulsed DBD Plasma on the Aerodynamic Performances in Subsonic and Transonic Conditions. *AIAA-Paper* 2013-2752, 2013.

[10] D. Caruana, A. Mignosi, C. Robitaille, M. Correge, Separated Flow and Buffeting Control. *Flow, Turbulence and Combustion,* 71: 221-245, 2003.

[11] J. Dandois, P. Molton, A. Lepage, A. Geeraert, V. Brunet, J.-B. Dor, E. Coustols, Buffet Characterization and Control for Turbulent Wings. *Aerospace Lab Journal,* 6: AL06-01, 2013.

[12] K.A. Abramova, M.A. Brutyan, S.V. Lyapunov , A.V. Petrov, A.V. Potapchik, A.A. Ryzhov, V.G. Soudakov, Investigation of buffet control on transonic airfoil by tangential jet blowing. 6-th European Conference for Aeronautics and Space Sciences *(EUCASS), Poland, Krakow, June 25-July 3, 2015.*