NUMERICAL OPTIMIZATION OF FLOW CONTROL BY TANGENTIAL JET BLOWING ON TRANSONIC AIRFOIL

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Abstract

Numerical RANS simulations are carried out to optimize airfoil aerodynamic performance and to provide a background for investigations of buffet control on transonic airfoil by tangential jet blowing. A jet of compressed air is blown from a small slot nozzle tangentially to airfoil upper surface in the region of shock location to energize the boundary layer and to reduce the shock-induced separation thus enhancing the airfoil performance. Numerical optimization is performed to determine parameters of flow control.

1 General Introduction

The most important and complicated problems of modern aerodynamics include enhancing airfoil performance which allows to achieve significant decrease in the operating costs and a fuel-burn reduction. The Mach number or angle of attack growth can lead to the flow separation due to boundary layer/shock wave interaction (SBLI) on the upper surface of the wing and buffet. 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.

There is a big variety of methods to control SBLI and thus reduce or eliminate buffet: cavity under the shock foot, bump, mechanical and fluidic vortex generators, suction, plasma actuators. Mechanical VGs were investigated in [1-2] 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 [1]. Boundary layer suction [3] and application of plasma actuators [4-5] were also examined. 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 listed below were used for buffet control. Mechanical trailing edge device (TED) which can change rear loading of an airfoil was considered in [6]. Fluidic VGs with air jets along with fluidic TED, where jet was blown on the pressure side, were studied in [7].

For fluidic TED device the parametric investigation [8] was used to assess the effect of the control-device location on aerodynamic performance, while optimization was applied to determine design and geometric characteristics of the actuator. Different objective functions were considered for the optimization process, aiming at maximizing lift and aerodynamic efficiency. The design variables were the jet orientation, the slot width, its position, and the jet intensity.

A profound review of tangential jet blowing method and corresponding investigations can be found in [9]. In numerical studies [10] it was shown that the jet blown tangentially in the region of shock location reduces the shock-induced separation. The results of calculation and experimental investigations of efficiency of application of compressed air jet tangential blowing through a slot nozzle over upper surface of a supercritical swept wing at high transonic speeds were presented in [11]. The experimental data were obtained in the TsAGI T-106 transonic wind tunnel tests of the wing-fuselage model with jet blowing over the supercritical wing. Experimental studies [12] of the flow over transonic supercritical airfoil P-184-15SR with active flow control by tangential jet blowing were carried out in the transonic wind tunnel T – 112 TsAGI. They have shown the positive impact of the tangential jet blowing on the buffet and airfoil performance.

In the present paper, the optimization of the parameters of tangential jet blowing on the upper surface of the airfoil P-184-15SR has been performed at transonic speeds. Two different objective functions were considered: maximization of lift-over-drag ratio and minimization of drag at constant lift.

2 Problem Statement

The problem was solved numerically. Numerical simulation of the flow over transonic supercritical airfoil with active flow control was carried out on the base of Reynolds averaged Navier-Stokes (RANS) equations.

2.1 Geometry, grid and solver parameters

Supercritical airfoil P-184-15SR with thickness 15% and chord length c=0.2 m was chosen for investigations (Fig.1).

The jet of compressed air was blown from a small slot nozzle tangentially to the wing upper surface. The configuration has a possibility of parametric change of location of slot nozzle position. Slot height was fixed to 0.00015 m (Fig.2).

Structured hexahedral grid was used for numerical simulations. The grid was rebuilt automatically for each slot nozzle location. Far-field boundaries were placed 40 chords away from the airfoil. Typical grid near the airfoil is shown in Fig. 3. Grid nodes are clustered normal to the surface inside the boundary layer so that $Y_{+1}<1$. The mesh of 350000 nodes was chosen for the simulations. Sensitivity of the results to grid density was checked in [10] and it shows that the volume of this grid is enough.

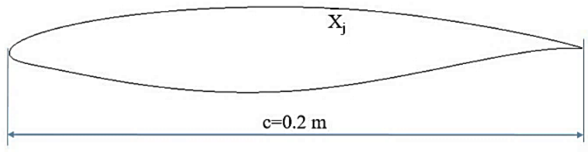

Fig. 1. P-184-15SR airfoil

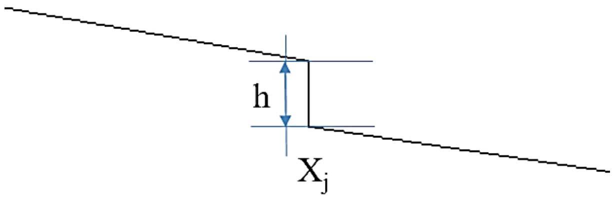

Fig. 2. Slot nozzle for tangential jet blowing

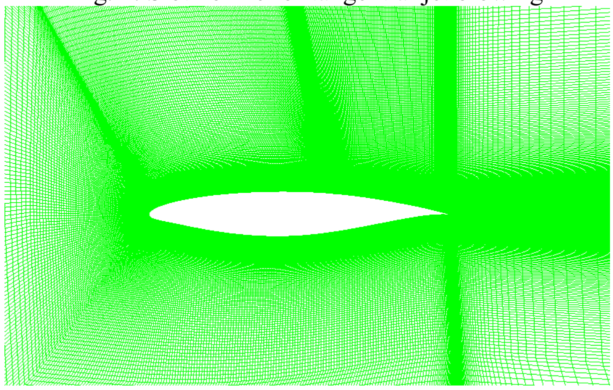
Fig. 3. Grid near the airfoil

2D RANS simulations of the flow past the airfoil were carried out for the regime with M=0.72 and Reynolds number based on free-stream parameters and chord length $Re=2.6\times10^6$. Aerodynamic performance characteristics of the airfoil with and without jet blowing were estimated. The calculations were carried out for the ideal compressible gas with laminar Prandtl number Pr=0.72. Laminar viscosity-temperature dependence was approximated by Sutherland law with Sutherland constant 110.4 K. Spalart-Allmaras (SA) turbulence model was used for simulations. The Riemann invariants were stated on the far-field boundaries. The airfoil was considered to be an adiabatic no-slip wall. The jet was simulated by boundary condition with jet stagnation pressure P_{0j} stated on the slot nozzle. One of the main jet parameters is jet momentum coefficient:

$$C\mu = \frac{\dot{m}V_j}{0.5\rho_\infty V_\infty^2 S}$$

where $\dot{m}$ is a mass flow rate through the slot nozzle, V_j is averaged jet velocity at the slot nozzle, ρ_∞ is a free-stream density, V_∞ is a free-stream velocity, S is the wing area for one meter in spanwise direction.

The numerical solutions were obtained using an implicit finite-volume method. The equations were approximated by a second-order shock-capturing scheme. The flux vector was evaluated by an upwind flux-difference splitting of Roe. Second order upwind scheme was used for spatial discretization of convective terms. The central-differencing scheme was used for diffusion terms. An Euler implicit discretization in time was used for steady-state problem. The time marching was proceeded until a steady-state solution set in.

2.2 Optimization technique description

The Adaptive Single-Objective optimization is considered in this paper. This technique consists of the Optimal Space Filling Design, Kriging response surface model and optimization algorithm MISQP (Mixed-Integer Sequential Quadratic Programming) [13].

The direct optimization is studied. At first, the Design of Experiment is built. The Optimal Space Filling design is the combination of the Latin Hypercube Sampling and maximization of the distances between the initial points. The number of initial samples depends on the number of parameters varied. After all the initial samples are calculated, the Kriging response surface is built. Then the MISQP algorithm is run. If the candidate points are not verified, the Kriging response surface is rebuilt and the algorithm is run again. If the candidate points are verified and if they are not stable the parameter domain is reduced and the procedure starts again. In each reduced parameter domain, the number of initial samples is the same. If the candidates are stable, the optimization is converged.

The following parameters were varied:

- X_j is slot nozzle position for tangential jet blowing (Figure 2);
- P_{0j} is the stagnation pressure of the jet;
- α is the angle of attack.

In this paper, the optimization was stopped and considered to be converged when the distance between the adjacent points was equal to 0.5kPa for jet intensity, 1% chord for slot location, 0.01° for angle of attack.

Two objective functions are studied:

- the maximization of lift-over-drag ratio (K);
- the minimization of the drag coefficient C_D with the constant value of the lift coefficient C_L equal to 0.51.

Preliminary computations have been performed with the different number of initial points to make sure that this number is enough to provide the verified result. Two variants were examined: 10 points – the minimum number of points for 3 varying parameters and 20 points. In these calculations the slot position X_j varied from 55% to 75% chord, P_{0j} – from 100 to 220 kPa, and α – from 1.1° to 2.2°; objective function – maximization of K. The difference in optimal results was less than 1% chord in slot positions, 0.4 kPa in jet intensity and about 0.001° in α.

3 Results of calculations

3.1 Maximization of lift-to-drag ratio

The optimization of slot location and jet intensity for the maximization of K objective function was carried out. The slot location varied from 55% to 65% chord, the jet intensity P_{0j} – from 100 to 300 kPa, the angle of attack α – from 0.9° to 2.2°. The optimization has converged after 80 calculations (Fig. 4-6). The change of plateau of cyan lines mark the zones of parameters domain reduction.

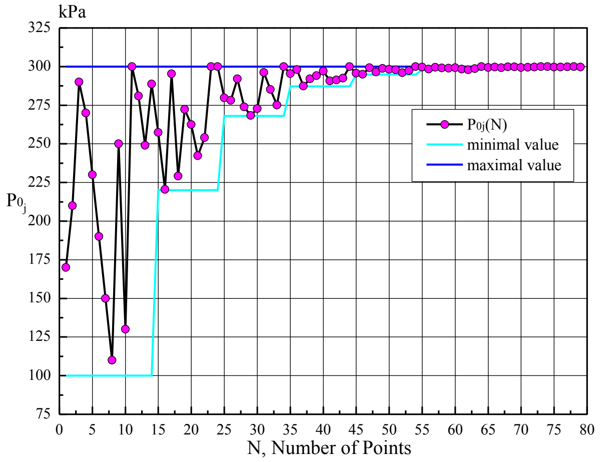

Fig. 4. Convergence history for jet intensity P_{0j}

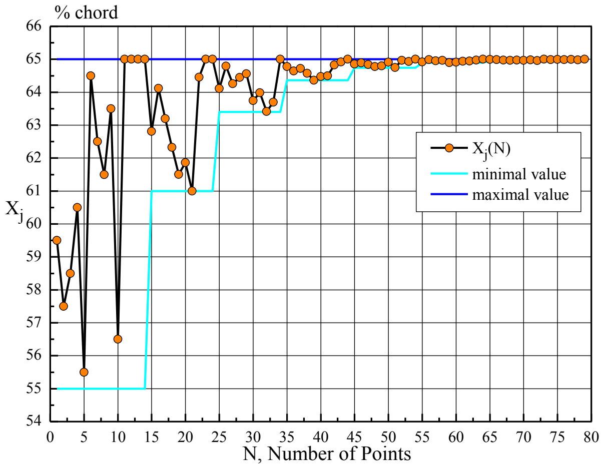

Fig. 5. Convergence history for slot location Xj

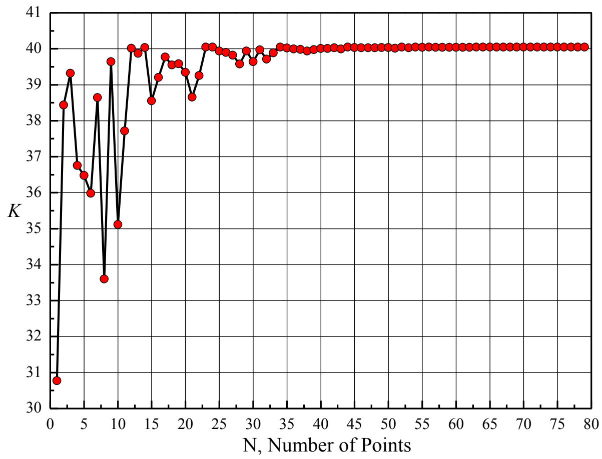

Fig. 6. Lift-over-drag ratio convergence history

The optimal result has the following parameters: X_{jopt1}=65% chord, P_{0jopt1}=300 kPa (Cμ=0.0073), α_{opt1}=1.57°. The lift-over-drag ratio is equal to K_{opt1}=40.05. These values correspond to the most downstream position of the slot in the considered domain and the most intense jet.

The same optimizations procedure was carried out for another parameters' domain: the slot location varied from 55% to 75% chord, the jet intensity P_{0j} – from 100 to 220 kPa, the angle of attack α – from 1.1° to 2.2°.

The optimal result for this case has the following parameters: X_{jopt}=75% chord, P_{0jopt}=220 kPa (Cμ=0.0055), α=1.66°. The lift-over-drag ratio is equal to K_{opt}=40.47. These values also correspond to the most downstream position of the slot in the considered domain and the most intense jet.

3.2 Minimization of C_D with constant C_L

Objective function of C_D minimization with the constant C_L=0.51 was considered. The slot location varied from 55% to 65% chord, the jet intensity P_{0j} – from 100 to 300 kPa. Two varied parameters require 6 initial samples. However, to find the point with the appropriate C_L one should perform three calculations instead of one. Two cases corresponding to the C_L~0.4 and C_L~0.6 were calculated and α for C_L~0.51 was calculated by the linear approximation. The optimization has converged after 60 iterations (Fig. 7-9).

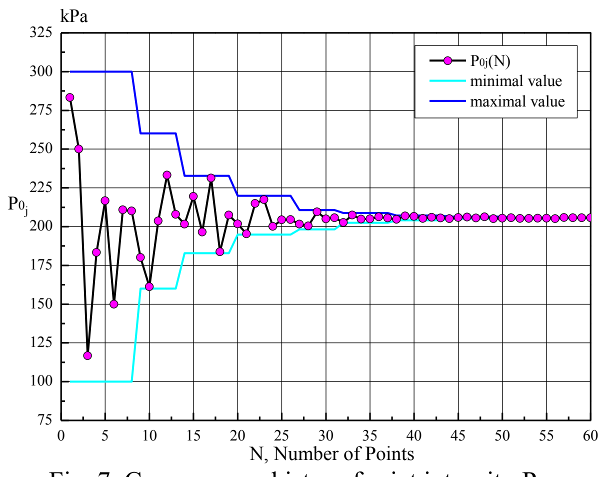

Fig. 7. Convergence history for jet intensity P_{0j}

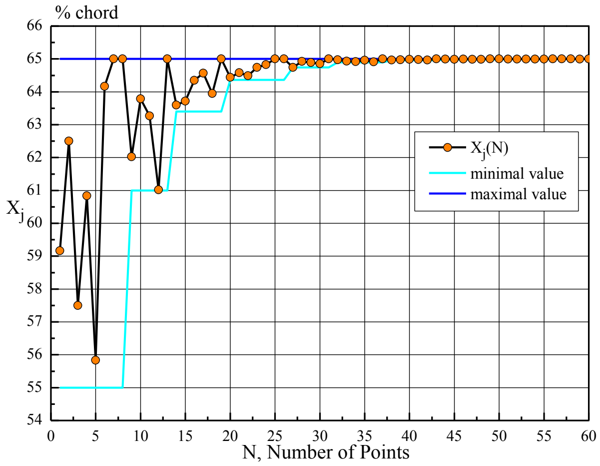

Fig. 8. Convergence history for slot location X_j

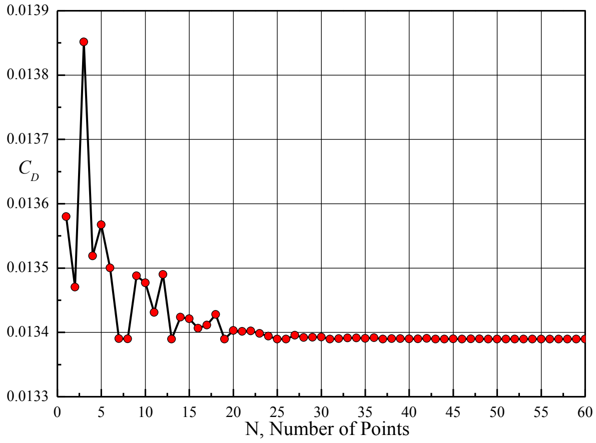

Fig. 9. Convergence history for drag coefficient

The optimal result for this objective function has the following parameters: X_{jopt2}=65% chord, P_{0jopt2}=206 kPa ($C\mu$=0.0051).

The lift coefficient is equal to C_L=0.511 and the angle of attack α=1.39°. The lift-over-drag ratio is K_{opt2}=38.15. These values correspond to the most downstream position of the slot in the considered domain, but the jet intensity is smaller than maximal value from the corresponding domain and smaller than for the one for maximization of K. However, the domain of the slot location should be extended to find the most optimal solution.

3.3 Comparison with the smooth airfoil results

The aerodynamic characteristics have also been obtained for smooth configuration (configuration without slot nozzle and without jet blowing) for the same regime as for the blowing one. The comparison with the blowing configuration is depicted in the Fig. 10-17. Blue curves correspond to the smooth configuration, red curves – for blowing at optimal parameters for the maximization of K (opt. 1): X_{jopt1}=65% chord, P_{0jopt1}=300 kPa, green curves – for blowing at optimal parameters for the minimization of C_D at constant C_L=0.511 (opt. 2): X_{jopt2}=65% chord, P_{0jopt2}=206 kPa.

According to the Fig. 10-11 one can see that the tangential jet blowing increases both lift and drag. For the case opt.1 the increase in C_L equals to 0.146 (in comparison with smooth airfoil) and for the case opt.2 this value is 0.086. The increase in C_L for linear regime leads to the increase in C_L for separation onset which should delay buffet onset.

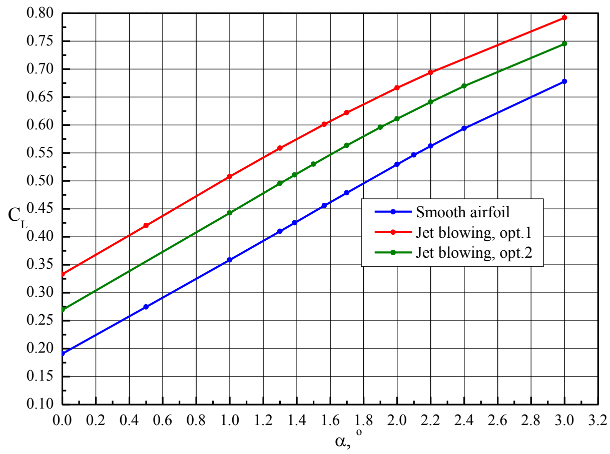

Fig. 10. Lift curve; blue curve – smooth airfoil, red – optimal solution with maximal K, green – optimal solution with minimal C_D at constant C_L

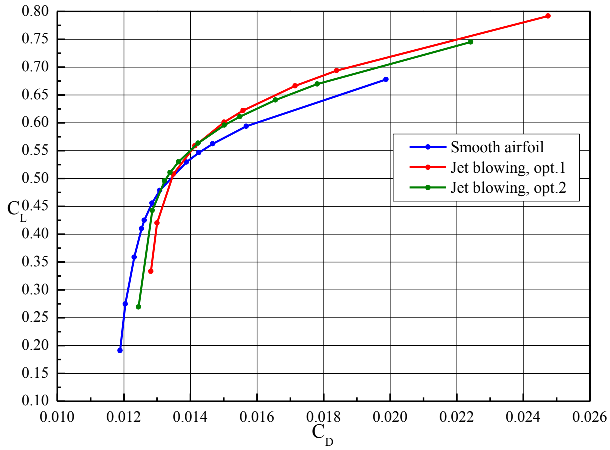

Fig. 11. Drag polar

For C_L<0.48, the polar for smooth airfoil lies left to the blowing ones and starting from C_L=0.48 it lies to the right which means that the blowing configurations are better on these regimes than smooth (Fig. 11).

Concerning the lift-over-drag ratio (Fig. 12), K_{max} is shifted to higher C_L and $\Delta K_{max1} = K_{maxopt} - K_{maxsmooth} \approx 1.7$ for the case of optimal solution with maximal K and $\Delta K_{max2} \approx 1.3$ for the case of optimal solution with minimal C_D at constant C_L. The jet shifts the K_{max} value left in the angle of attack domain (Fig. 13).

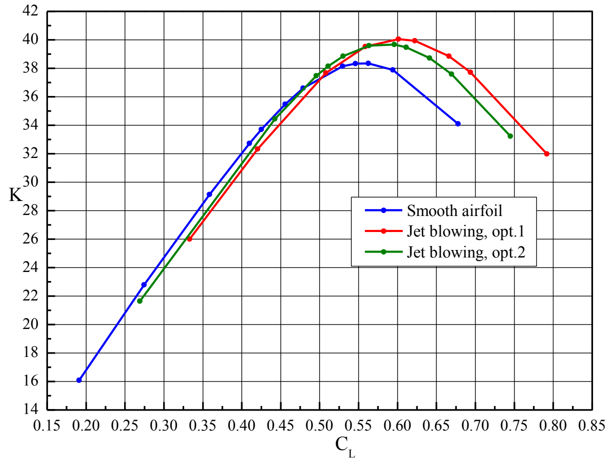

Fig. 12. Lift-over-drag ratio K on lift coefficient

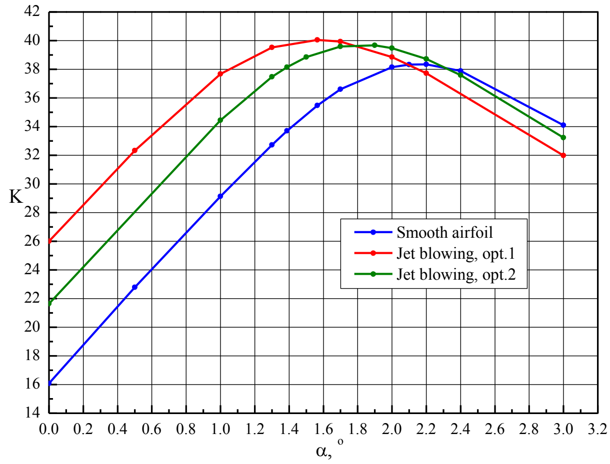

Fig. 13. Lift-over-drag ratio K on angle of attack

A comparison of pressure distributions along the airfoil chord with and without blowing (Fig. 14-15) have shown that the jet blowing leads to better pressure recovery at the wing trailing edge and to more downstream location of the shock-wave.

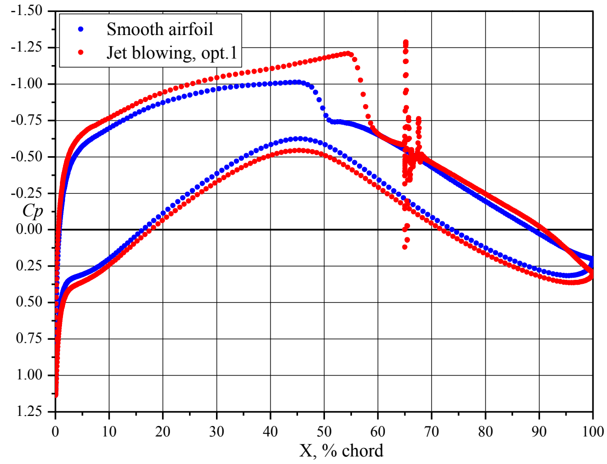

Fig. 14. Pressure coefficient distribution for opt.1 and smooth configuration at α_{opt1}=1.57°

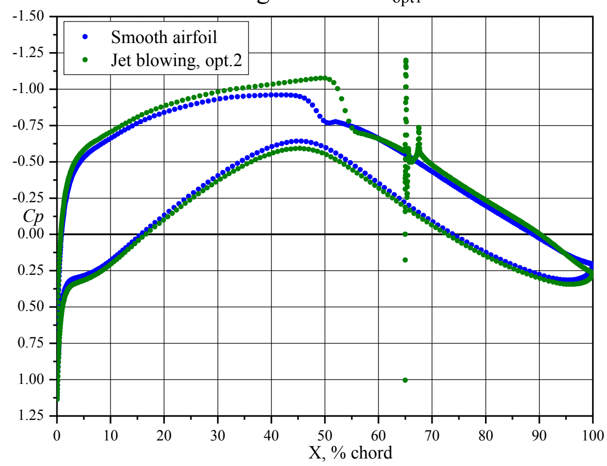

Fig. 15. Pressure coefficient distribution for opt.2 and smooth configuration at α=1.39°

As is seen in the Fig. 16-17, the friction drag increases with the blowing. The higher the jet intensity P_{0j}, the bigger this growth.

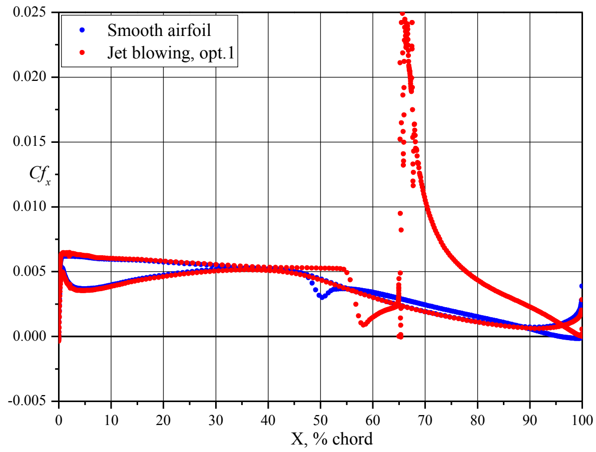

Fig. 16. X-component of wall shear stress coefficient, α_{opt1}=1.57°

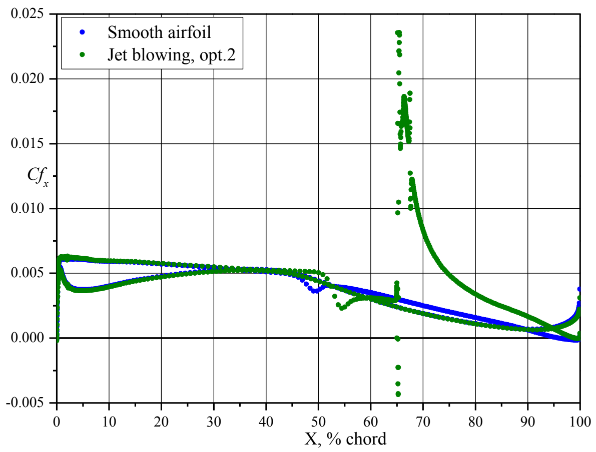

Fig. 17. X-component of wall shear stress coefficient, α=1.39°

4 Conclusions

Numerical RANS simulations have been carried out for the optimization of the parameters of tangential jet blowing on the airfoil at transonic speeds. A jet of compressed air was blown from a small slot nozzle tangentially to airfoil upper surface in the region of shock location to energize the boundary layer and to reduce the shock-induced separation thus enhancing the airfoil performance.

The optimization of tangential jet blowing parameters has shown:

- the maximization of K gives optimal result on the most downstream slot location and the most intense P_{0j} in the parameters' domain given.
- the minimization of C_D with constant C_L≈0.51 gives the optimal result with the most downstream slot location and P_{0j}=206kPa which is within the corresponding domain.
- the tangential jet blowing on the optimal regimes shifts the K_{max} value on 4.5% for the configuration with maximal lift-over-drag ratio and on 3.5% for configuration with minimal drag at constant lift. Drag decreases on 1.1%.

The future efforts will be made to estimate optimum in a wider range of slot locations. Moreover, more complex objective functions (considering penalty for jet blowing) will be investigated in the nearest future. The optimization procedures taking into account buffet characteristics will also be carried out.

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