

NUMERICAL SIMULATION OF THE MICRO-JET CONTROL OF THE DELTA WING

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Abstract

Increasing the maneuverability of the micro aero-vehicles (MAVs) flying at the low Reynolds numbers is the common problem of many research centers nowadays. Conventional flaps and control surfaces are not effective as, at low velocities, they should be relatively large. Large control surfaces result in the increase of the inertia and the decrease of the maneuverability of the MAV. That is why micro-actuators, such as micro-flaps, micro-membranes, acoustic micro-speakers, micro-jets or micro-heaters located at the leading-edge, are supposed to take place of the conventional control flaps. Micro-actuators can be used to manipulate the flow around the airfoil, generating the required forces and torques and controlling the flight of the MAV.

Micro-jets are the examples of the so called active micro-actuators, i.e. the actuators that require the external supply sources. The article presents the results of the numerical calculations of the finite element model (FEM) of the Bell 540 airfoil equipped with the micro-jets located near the leading edge. The Bell 540 airfoil is the slight modification of the standard NACA 0012 airfoil and it is used in the presented flying delta wing. The location of the jets, the fluxes velocities, and their influence on the aerodynamic characteristics of the airfoil are investigated. The results obtained confirm the potential of the presented method to efficiently control the flight of the MAV using the micro-jets.

Introduction

Micro-actuators have several advantages when compared with traditional flaps and ailerons: they are lighter, less power consuming and can be integrated in the so called micro-electro-mechanical systems (MEMS).

Lee et al. [9, 10] proposed micro-flaps to actively control the flow around a delta wing. Micro-jets were investigated by Mitchell et al. [11]. When compared with micro-flaps, micro-jets are more robust for possible damages that can occur as a result of higher forces affecting the flaps during sudden maneuvers or in case of turbulent flows. Small air fluxes generated by micro-jets can be used to control the location of the spiral vortices originating from the leading edge of the delta wing [8, 11]. Micro-jets can be also used to actively control the flow or its separation in the boundary layer at the under-pressure region of the traditional airfoils [6, 7, 12]. By blowing some additional air fluxes into the boundary layer micro-jets increase the flow energy and transform the laminar flow into the turbulent one. Godard et al. investigated boundary layer vortices generated by slotted [6] and round [7] jets. They found that the round jets are more efficient for the boundary layer control than the slotted ones, having smaller dimensions and weights than traditional flaps and ailerons at the same time.

Coe et al. [2, 3] described micro-jets integrated into MEMS. Having the dimensions of several microns, micro-electro-mechanical systems (MEMS) are produced using the technologies

known from the semiconductor device manufacturing. The majority of MEMS are fabricated by etching of silicon using photolithography. Other materials, such as polymers and metals, and technologies, such as embossing, stereolithography, electroplating, evaporation, etc. can also be used. As it is possible to integrate several sensors, actuators and controllers into a single micro-electro-mechanical system, it can be seen as a complete microscopic control system. Due to their small dimensions such systems are characterized by short time constants and no delays, what makes it possible to use them to efficiently control the flight of the MAV.

The present article discusses the results of the numerical analysis of the wing airfoil of the Bullit micro aero-vehicle produced by the Czech factory Topmodel Cz [13]. The MAV is presented in Fig. 1. As we can see, it is the flying delta wing. The airfoil is Bell 540, which is the slightly modified version of the standard NACA 0012.



Fig. 1. Bullit micro aero-vehicle [13]

The purpose of the numerical analysis was to determine the basic aerodynamic characteristics (drag coefficient C_d and lift coefficient C_l) of the Bell 540 airfoil equipped with micro-jets located near the leading edge. The calculations were conducted in Fluent resulting in pressure and velocity fields and characteristics $C_d(\alpha)$, $C_l(\alpha)$, where α is the angle of attack. The flows around the airfoil with and without micro-jets were evaluated. The aerodynamic characteristics of the airfoil without the jets calculated with Fluent were compared with the characteristics obtained with Xfoil [14]. The location of the jets, fluxes velocities, and their influence on the aerodynamic characteristics of the airfoil were investigated.

2. Modeling the geometry of the Bell 540 airfoil with micro-jets

The geometry model of the Bell 540 airfoil along with the surrounding air region was prepared with Gambit. Gambit is the preprocessor to Fluent used to create the geometry, generate the mesh and define the so called active zones (faces and edges) [5]. The coordinates of the airfoil were calculated with Xfoil [14], given the chord length $L_c = 0,5775$ m, obtained by measuring the dimensions of the Bullit micro aero-vehicle. Xfoil is the tested and reliable program applying the panel methods. It can be used to calculate the geometry and aerodynamic characteristics of various airfoils. In the present paper the aerodynamic characteristics obtained with Xfoil are treated as the templates with which the characteristics obtained with Fluent are compared. Of course, Xfoil can only calculate the airfoils without any jets.

Bell 540 airfoil with the edges modeling the micro-jets is shown in Fig. 2. Three different jets, denoted as jet1, jet2, and jet3, located at different places of the airfoil were considered. The first jet was located at the neighborhood of the leading edge, the second at the under-pressure region, and the third at the high-pressure region.

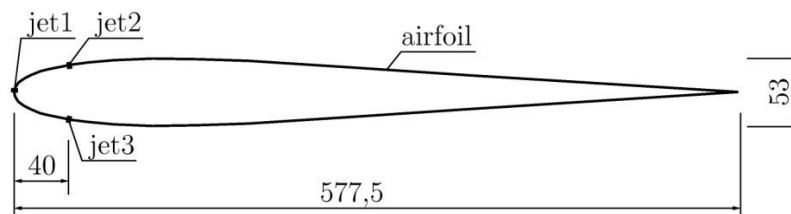


Fig. 2. Bell 540 airfoil with edges modeling micro-jets

The models of the airfoil, of the surrounding air, and of the generated finite element mesh are shown in Fig. 3. The mesh consists of 14310 elements, while the dimensions of the smallest elements near the leading edge do not exceed 1 mm. The region of the air surrounding the airfoil is bordered with a semicircle located at the left and a rectangle at the right. The airfoil is located at the middle of the region, where the mesh is extremely fine. It can be seen that the quadratic mesh is applied, resulting in a smaller number of finite elements, higher accuracy and the possibility to model the boundary layer. In order to eliminate the influence of the boundary edges on the velocity distribution inside the region, the diameter of the semicircle, as well as the lengths of the rectangle edges are assumed about 20 times higher than the chord length of the tested airfoil. The left edge of the semicircle was defined as an active zone named *farfield1*, the lower and the upper edges of the rectangle as zone *farfield2*, and the right edge – as *farfield3*. These edges play the roles of the inlets and outlets by which the air flows into/from the tested region, while the airfoil is unmovable. The boundary conditions defined at *farfield1* and *farfield2* edges are the type of Velocity Inlet, while at *farfield3* – of Pressure Outlet. All airfoil edges are modeled as Stationary Walls, except for the three modeling the micro-jets. Edges *jet1*, *jet2*, and *jet3* are modeled as Velocity Inlets or in case of no air flow from the jet – as Stationary Walls.

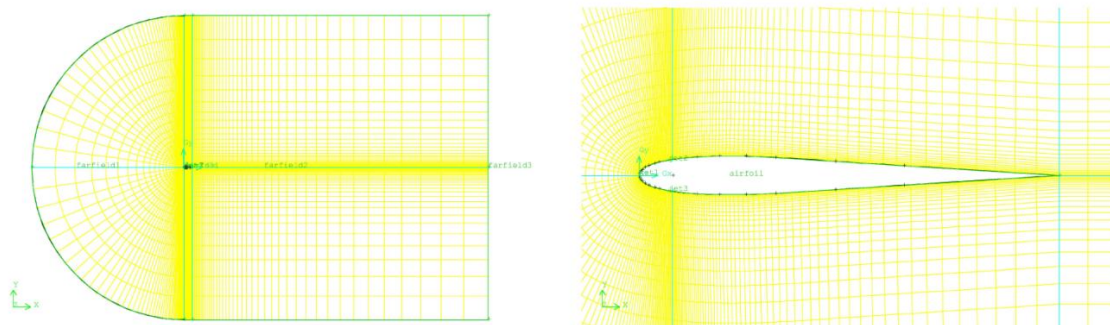


Fig. 3. The model of the Bell 540 airfoil, of the surrounding air region, and of the finite element mesh generated with Gambit

3. Modeling the flow around the Bell 540 airfoil

The calculations in Fluent were conducted with the Steady Solver and with the Spalart-Allmaras model of the turbulent flow using its standard settings [4]. The Spalart-Allmaras model is described by one transport equation, including the kinematic viscosity of the rotary motion and it is especially well-suited for the aerodynamics of low Reynolds numbers. The

fluid was defined as the air of the constant density. The flow and the modified turbulent viscosity equations were solved using the PISO (Pressure-Implicit with Splitting Operations) and PRESTO (PREssure STaggering Option) algorithms. During the calculations velocity fields around the airfoil and the values of drag C_d and lift C_l coefficients for different angles of attack α and for different jet-flux velocities v_d were determined.

During the modeling process the following values of the parameters were assumed:

- chord length $L_c = 0.5775$ m,
- angle of attack α varied from -4° to 18° by 2° (in the range from -2° to 2° by 0.5°),
- free-stream velocity module $V = 10$ m/s,
- air density $\rho = 1.225$ kg/m³,
- air dynamic viscosity $\mu = 1.71 \times 10^{-5}$ Pas,
- air temperature $T = 293.15$ K,
- velocity of the air flowing from the micro-jets $v_d = 30$ m/s or $v_d = 90$ m/s,
- jet diameter $d_d = 1$ mm.

Reynolds Re and Mach Ma numbers, where:

$$Re = \frac{\rho V L_c}{\mu}, \quad Ma = \frac{V}{a}$$

calculated for the above given parameters and for the sound velocity of $a = 343.5$ m/s are: $Re = 413706$ and $Ma = 0.029$. These values were used during the calculations of the aerodynamic characteristics of the NACA 0012 airfoil with Xfoil.

4. The results

The results for the air flow around the Bell 540 airfoil obtained with Fluent are given below. Figures present velocity fields around the airfoil for the angles of attack of $\alpha = 4^\circ$ and $\alpha = 12^\circ$, and drag C_d and lift C_l characteristics in dependency of α . The results were obtained for the following combinations of the air flows from the micro-jets:

- no outflow from any jet (Figs. 4 and 5),
- outflow from jet1 with velocity of $v_d = 30$ m/s (Figs. 6 and 7),
- outflow from jet1 with velocity of $v_d = 90$ m/s (Figs. 8 and 9),
- outflow from jet2 with velocity of $v_d = 30$ m/s (Figs. 10 and 11),
- outflow from jet2 with velocity of $v_d = 90$ m/s (Figs. 12 and 13),
- outflow from jet3 with velocity of $v_d = 30$ m/s (Figs. 14 and 15),
- outflow from jet3 with velocity of $v_d = 90$ m/s (Figs. 16 and 17).

a)

b)

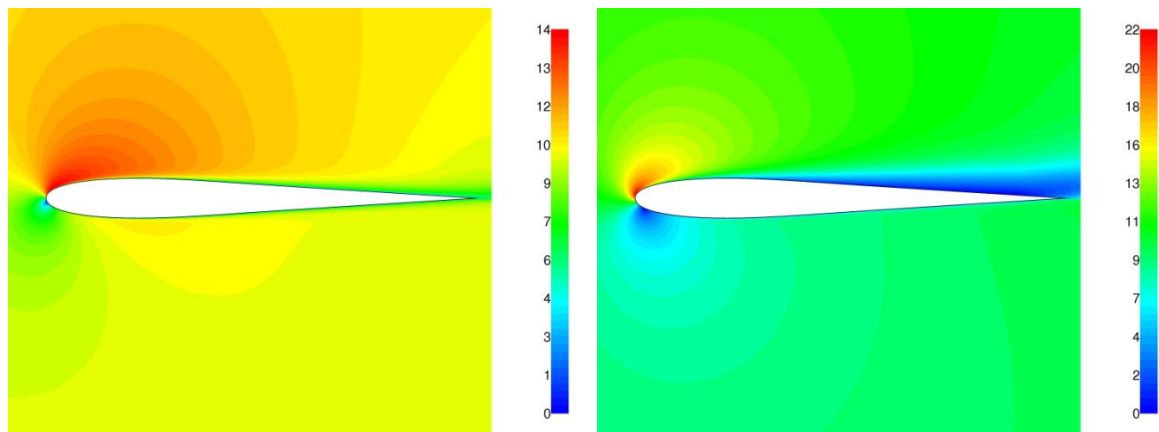


Fig. 4. Velocity field around Bell 540 airfoil;
no outflow from any micro-jet: a) for $\alpha = 4^\circ$, b) for $\alpha = 12^\circ$

Fig. 5 presents the comparison between lift C_l and drag C_d characteristics in dependency of angle of attack α for no outflow from any jet obtained with Xfoil and with Fluent. It can be seen that the values of the drag coefficient calculated with Fluent are slightly higher than the corresponding values obtained with Xfoil. This may result from the inaccuracy of the boundary layer flow model. On the other hand the values of the lift coefficient are almost the same. Furthermore a great agreement between the values of the stall angle ($\alpha = 15^\circ$) are observed. The characteristics calculated with Fluent and with Xfoil were compared with the experimental results for different airfoils presented in [1]. Taking into account the chord length, a very good agreement between the simulated and experimental characteristics can be noticed. This confirms the correctness of the flow model assumed with Fluent.

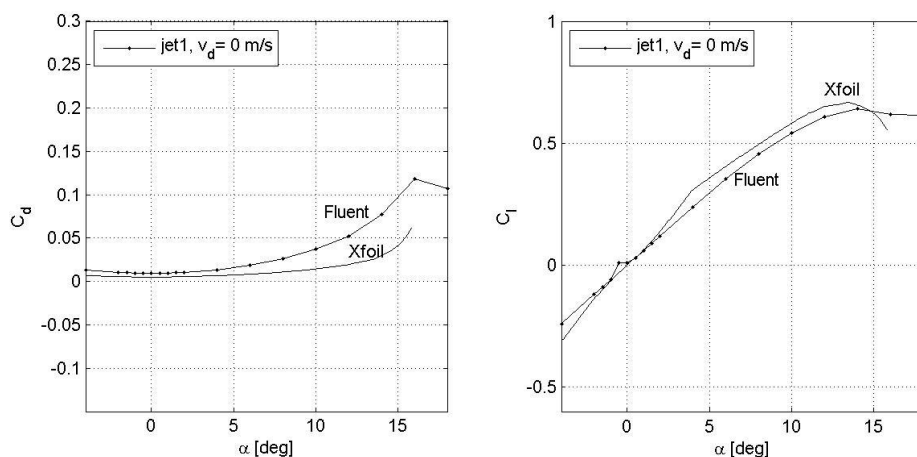


Fig. 5. Bell 540 lift $C_l = f(\alpha)$ and drag $C_d = f(\alpha)$ characteristics; no outflow from any micro-jet

a)

b)

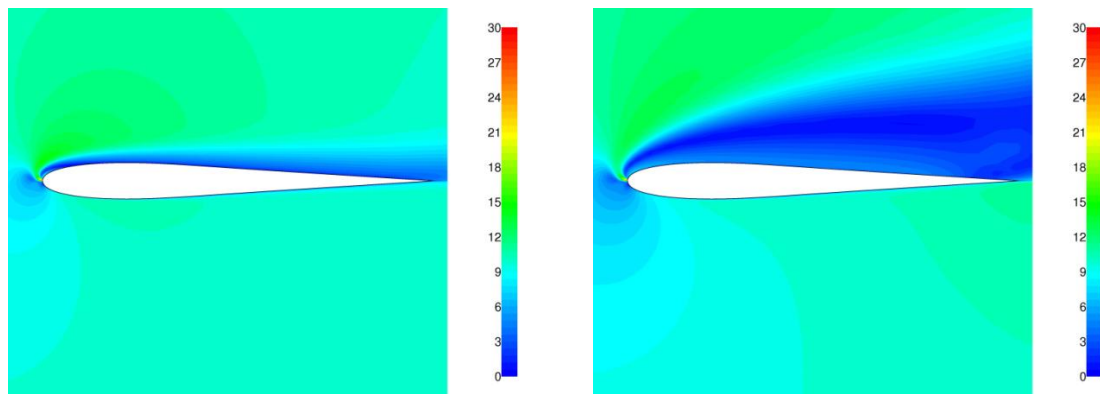


Fig. 6. Velocity field around Bell 540 airfoil;
outflow from jet1 with velocity $v_d = 30$ m/s: a) for $\alpha = 4^\circ$, b) for $\alpha = 12^\circ$

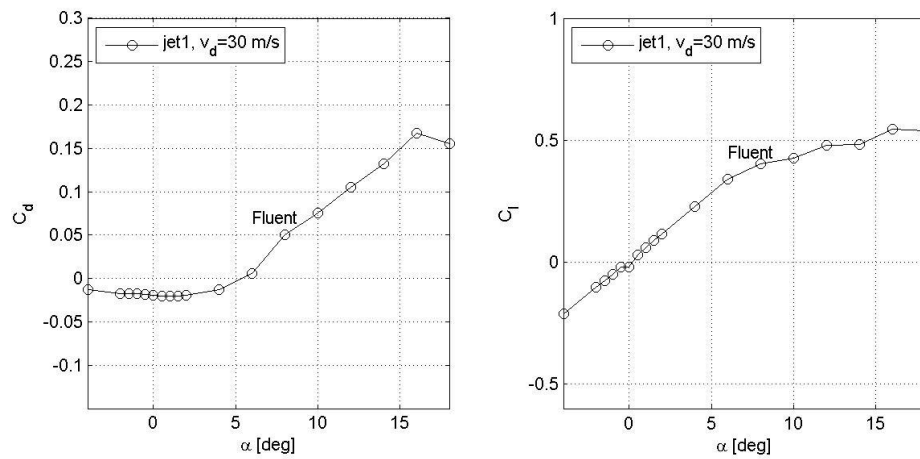


Fig. 7. Bell 540 lift $C_l = f(\alpha)$ and drag $C_d = f(\alpha)$ characteristics;
outflow from jet1 with velocity $v_d = 30$ m/s

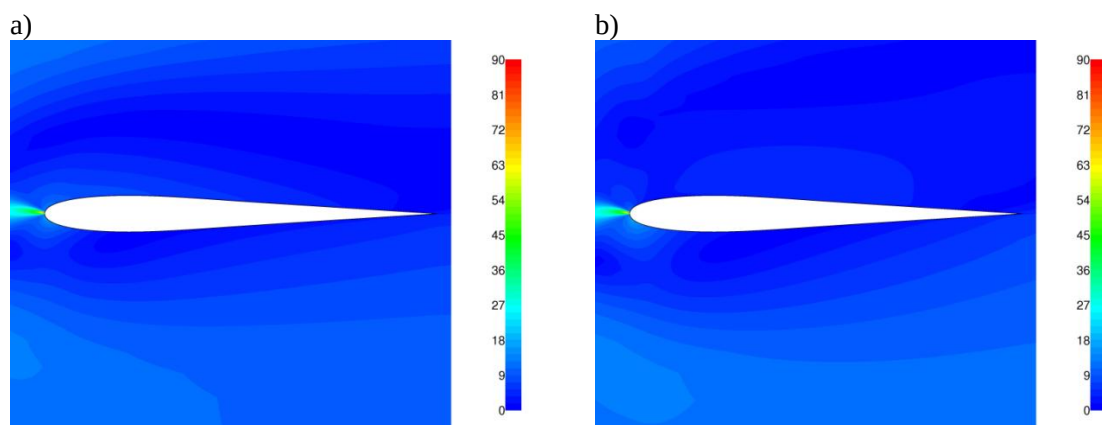


Fig. 8. Velocity field around Bell 540 airfoil;
outflow from jet1 with velocity $v_d = 90$ m/s: a) for $\alpha = 4^\circ$, b) for $\alpha = 12^\circ$

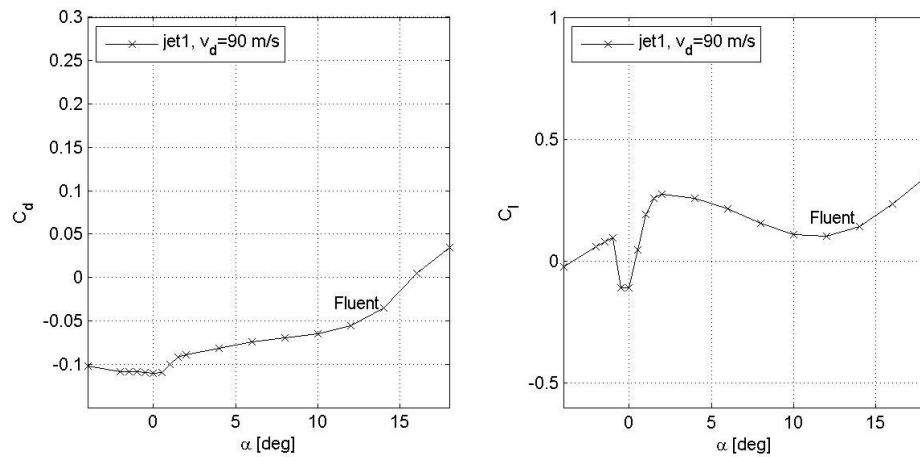


Fig. 9. Bell 540 lift $C_l = f(\alpha)$ and drag $C_d = f(\alpha)$ characteristics; outflow from jet1 with velocity $v_d = 90$ m/s

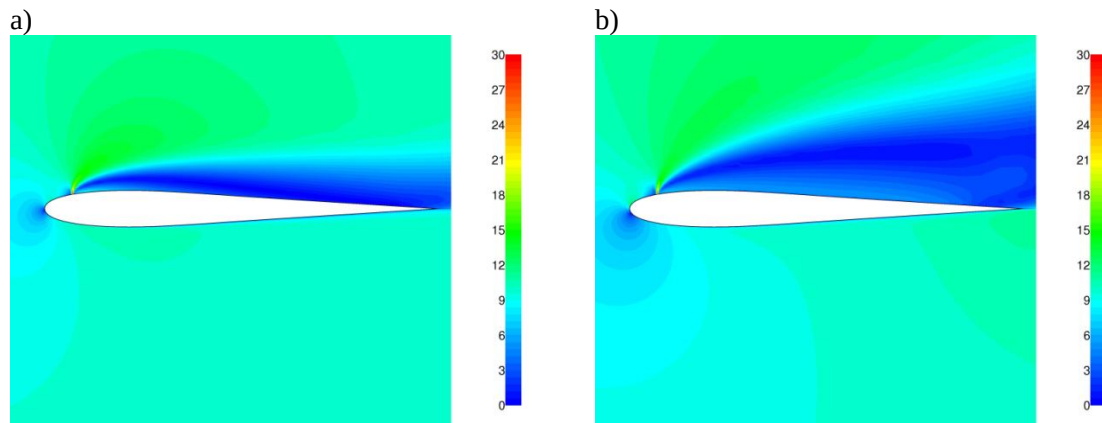


Fig. 10. Velocity field around Bell 540 airfoil; outflow from jet2 with velocity $v_d = 30$ m/s: a) for $\alpha = 4^\circ$, b) for $\alpha = 12^\circ$

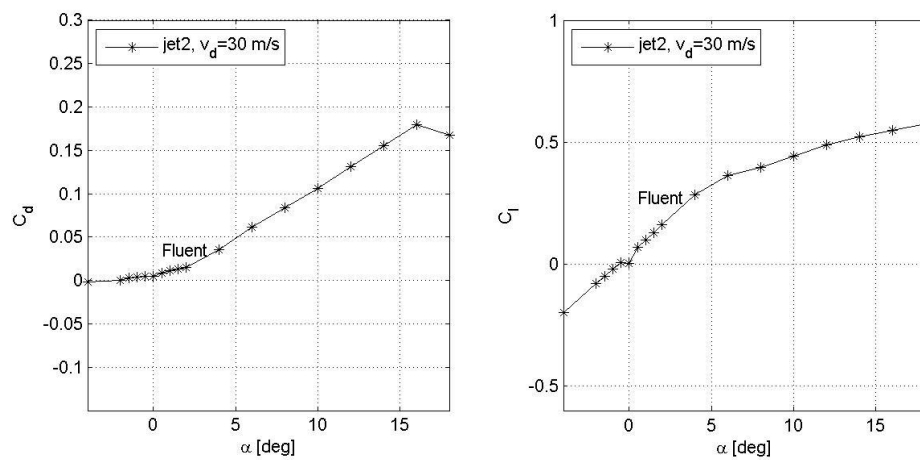


Fig. 11. Bell 540 lift $C_l = f(\alpha)$ and drag $C_d = f(\alpha)$ characteristics; outflow from jet2 with velocity $v_d = 30$ m/s

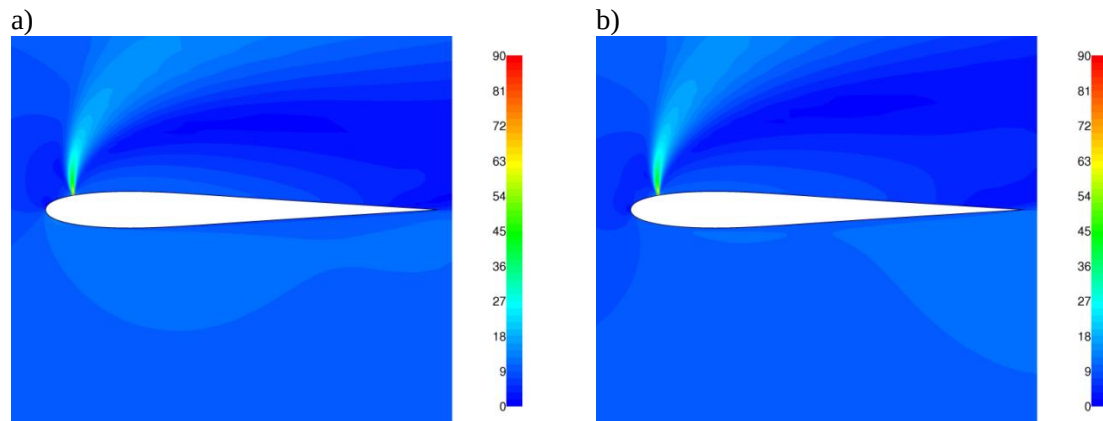


Fig. 12. Velocity field around Bell 540 airfoil;
outflow from jet2 with velocity $v_d = 90$ m/s: a) for $\alpha = 4^\circ$, b) for $\alpha = 12^\circ$

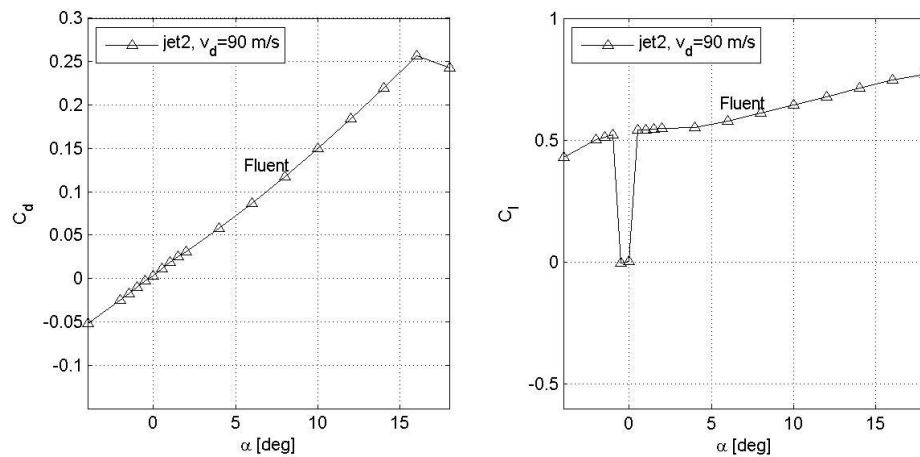


Fig. 13. Bell 540 lift $C_l = f(\alpha)$ and drag $C_d = f(\alpha)$ characteristics;
outflow from jet2 with velocity $v_d = 90$ m/s

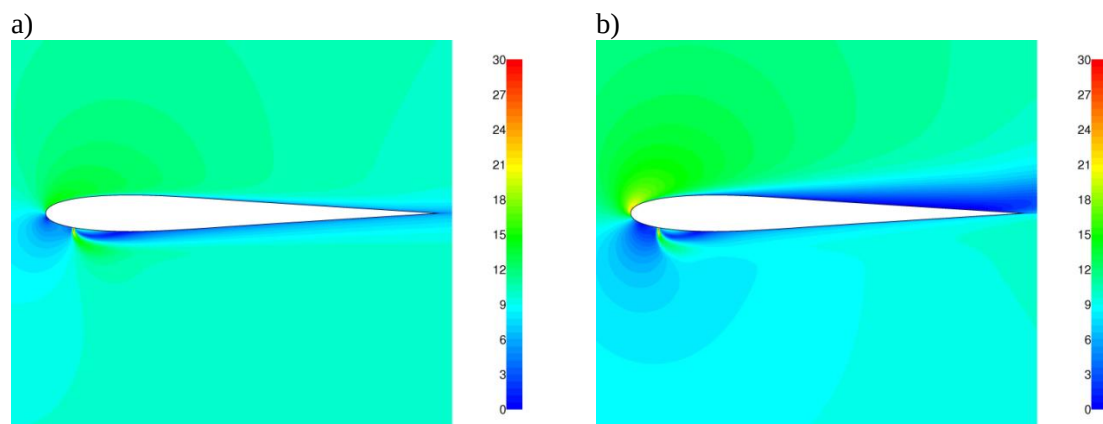


Fig. 14. Velocity field around Bell 540 airfoil;

outflow from jet3 with velocity $v_d = 30$ m/s: a) for $\alpha = 4^\circ$, b) for $\alpha = 12^\circ$

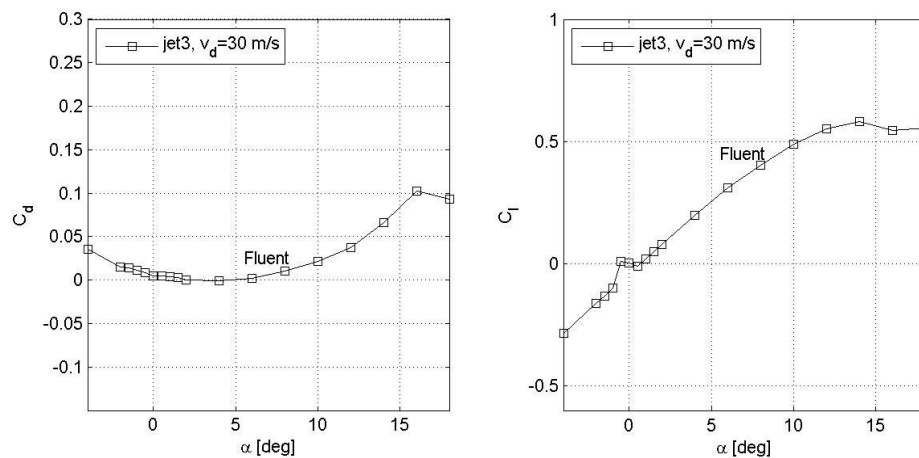


Fig. 15. Bell 540 lift $C_l = f(\alpha)$ and drag $C_d = f(\alpha)$ characteristics;
outflow from jet3 with velocity $v_d = 30$ m/s

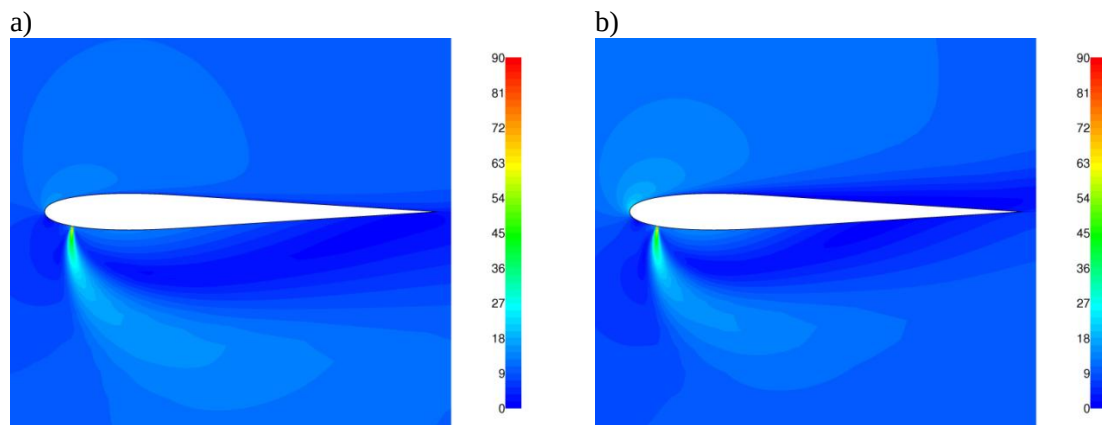


Fig. 16. Velocity field around Bell 540 airfoil;
outflow from jet3 with velocity $v_d = 90$ m/s: a) for $\alpha = 4^\circ$, b) for $\alpha = 12^\circ$

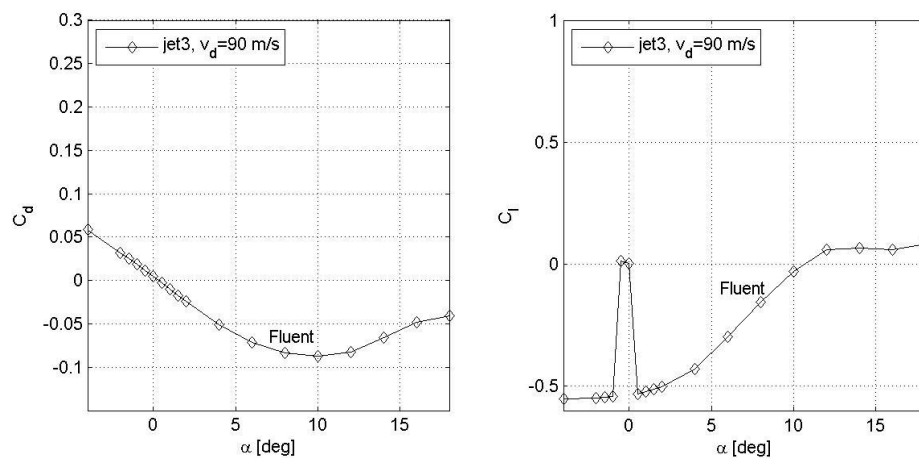


Fig. 17. Bell 540 lift $C_l = f(\alpha)$ and drag $C_d = f(\alpha)$ characteristics;

outflow from jet3 with velocity $v_d = 90$ m/s

5. The comparison

Figures 18 and 19 present the drag and lift characteristics for different angles of attack for all tested micro-jets and air outflow velocities. The highest increase in the lift force is observed when jet2 with the outflow velocity of 90 m/s is applied. However this is so only for higher angles of attack. Near zero the lift force suddenly disappears. What is interesting, for negative angles of attack a rather high lift force is observed. Unfortunately for jet2 with the outflow velocity of 90 m/s the drag force also increases.

On the other hand significant decrease and change in sign of the lift force is observed for jet3 with the outflow velocity of 90 m/s. Similarly as for jet2 it is true only for higher angles of attack. Again near zero the lift force is almost zero. For jet3 with the outflow velocity of 90 m/s the drag force decreases a lot, achieving negative values for positive angles.

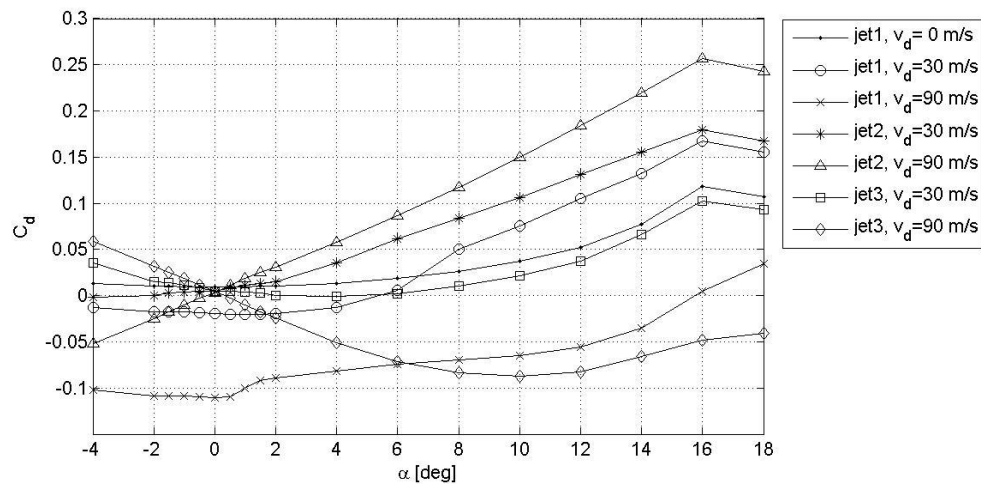


Fig. 18. The comparison of the drag characteristics $C_d = f(\alpha)$ for different outflow velocities v_d

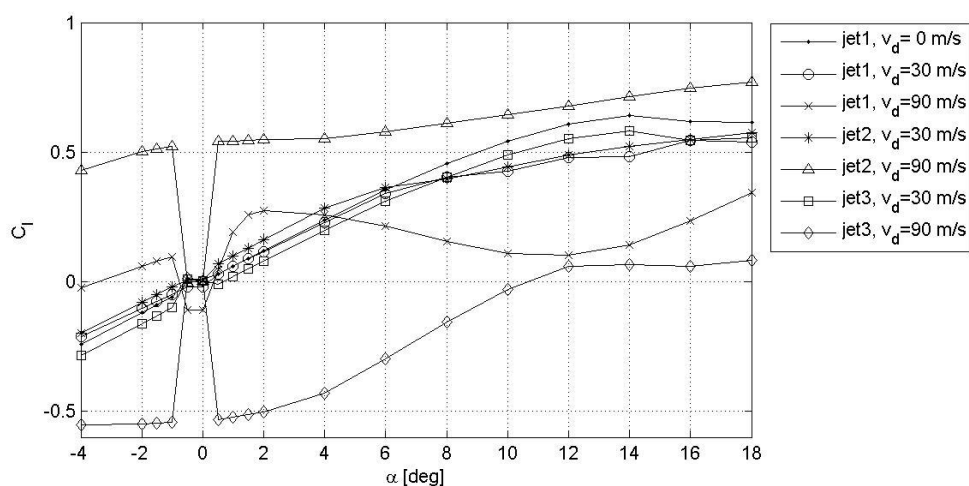


Fig. 19. The comparison of the lift characteristics $C_l = f(\alpha)$ for different outflow velocities v_d

6. Conclusion

1. The results in the form of characteristics $C_l = f(\alpha)$ and $C_d = f(\alpha)$ with no outflow from any micro-jet obtained with Xfoil and with Fluent are almost the same. They also agree with the experimental results for NACA 0012 airfoil given in [1]. This confirms the correctness of the assumed Fluent model of the flow around the airfoil.
2. It is extremely important to properly locate the micro-jets on the airfoil's surface. As can be seen in Fig. 19 the outflow from jet1 has hardly no influence on the value of the lift force. Considerable increase/decrease of the lift force is observed for the outflow from jet2/jet3 with the velocity of 90 m/s.
3. It is supposed that for the properly located micro-jets, the described changes in the lift force can be used to control the flight of the micro aero-vehicle.
4. The presented numerical results can be considered only approximately. They only confirm that the outflow from the micro-jets results in a very clear increase or decrease of the lift force. In order to quantitatively test the proposed micro-actuators the calculations for the full, 3D model of the wing should be conducted.
5. The best verification of the results presented here will be the experimental tests of the MAV in the wind tunnel or during the flight in the real atmosphere.

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