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Lift Enhancement and Drag Reduction on an Airfoil at Low Reynolds Number using Blowing and Distributed Suction

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Abstract : An active flow control technique using blowing and distributed suction on low Reynolds airfoil is investigated. Simultaneous blowing and distributed suction can recirculate the jet flow mass, and reduce the penalty to propulsion system due to avoiding dumping the jet mass flow. Energy is injected into main flow by blowing on the suction surface, and the low energy boundary flow mass is removed by distributed suction, thus the flow separation can be successfully suppressed. Aerodynamic lift to drag ratio is improved significantly using the flow control technique, and the energy consumption is quite low.

Key Words : low Reynolds number; laminar separation bubble; flow control; boundary-layer blowing; boundary-layer suction; lift enhancement ; drag reduction

1.Introduction

Aerodynamic performance of Micro-Air Vehicles (MAVs) and Unmanned Air Vehicles (UAVs) are hindered by low Reynolds number flow characteristics. Because of small size of MAV, it works at a range of 40,000 to 200,000 Reynolds number. UAV is larger but works at a very high altitude, which also leads to low Reynolds number. Typical phenomena of low-Reynolds-number, such as separation bubbles (which can be as large as 20%~30% of the chord) can significantly affect lift and drag characteristics. Therefore, it is an important aerodynamic design issue to control such separation bubbles. Many researches have been focused on separation control of low Reynolds numbers flow by using suction or blowing.

Wahidi[1] designed suction area elaaborately for LA2573a airfoil at Re=250,000. The separation bubble was controllde and airfoil performance was enhanced effectively. Zha[2] suggested using simultaneous blowing and suction, and the jet flow was powered by a pump inside the airfoil. Although experiments are quite important for getting data in blowing/suction flow control area, measurements for smaller scale flows require addition of finer instrumentation and repeating experiments for a wide range of parameters will cause expensive solutions.[3] Thus numerical experimentations are more efficient for design purposes.

In this study, blowing and suction for controlling separation bubbles on S5010 airfoil, a typical low Reynolds airfoil, is conducted at Reynolds number of

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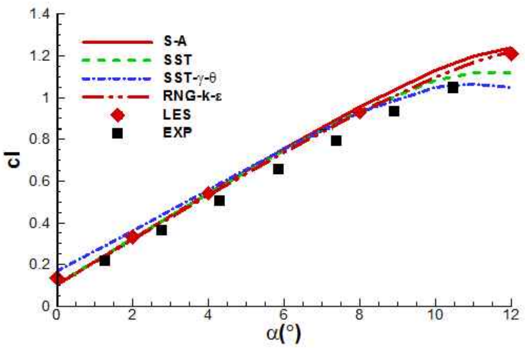
100,000. Several turbulence models have been tested for this Reynolds number. For the lack of transition prediction of turbulence models, Large Eddy Simulation (LES) was used for separation bubbles prediction. The airfoil control technique includes injection slot near leading edge and distributed suction slot near separation region. Simultaneous blowing and distributed suction are powered by pump settle inside the airfoil. The influence of parameters of suction area on controlling separation is researched. Effectiveness of this control technique is evaluated by lift enhancement, drag reduction, and power consumption. Flow characteristics of the baseline airfoil and controlled airfoil are analyzed for the reasons of the performance improvement.

2.Numerical Method

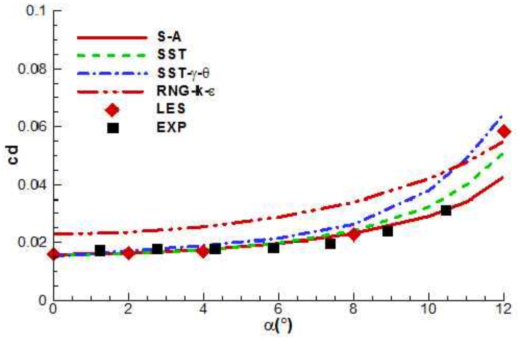
It was found that the implemented two-equation models (k-epsilon and k-omega) have difficulties in predicting the drag level at small Reynolds numbers.[4] In this study, several turbulence models ,include Spalart-Allmaras mode, SST mode, SST transition model, $-\varepsilon$ RNG model, gave been tested for the S5010 airfoil at Re=100,000

At low Reynolds numbers, however, flowfields become unsteady because of complex flow characteristics due to separation, transition, and reattachment. Thus Direct Numerical Simulation (DNS) or the Large-Eddy-Simulation (LES) is required for accurate flow structure, especially for near wall separation bubble.

Fig.1 shows a comparison of the two-dimensional simulation of the S5010 airfoil with the Spalart-Allmaras model and experimental results from Selig[5].Additionally,three-dimensionalsimulationresultswithLEShavebeenshowedinthefigure.Thetwo-equationmodelseemstooverpredictdragandpredictstallangletooearly.The Spalart-Allmaras model predicts lift and drag quit well at this Reynolds number. LES can also predict airfoil performance well, but this is highly-cost. Thus, we utilize LES to analyze some typical status for detailed flowfields characteristic



(a) Lift Coefficient of S5010 at Re=100,000



.(b) Drag Coefficient of S5010 at Re=100,000

Fig. 1 cl and cd of S5010 airfoil

3.Blowing/Suction control technique

3.1. Injection and suction effect on force

The controlled airfoil integrated with a pump system can be illustrated as in Fig. 2. There are an injection slot near leading edge and a distributed suction slot near trailing edge on the airfoil suction surface. The surface following the injection is slightly modified for geometry smooth. The low energy boundary flow mass is sucked into the cavity inside airfoil, and the same amount of mass flow with high energy is injected into the main flow tangentially. The control flow cycle is powered by the pump mounted in the airfoil.

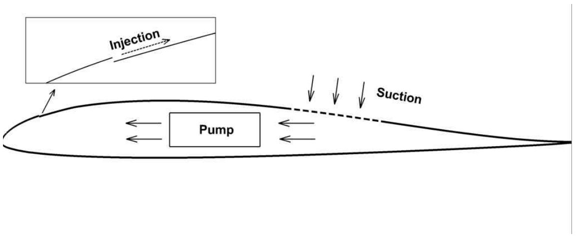


Fig.2 Sketch of a Controlled Airfoil

The total force of the controlled airfoil includes aerodynamics force as a baseline airfoil, and a reactionary force at the injection and suction slots. Using control volume analysis, the reactionary force can be calculated using the flow parameters at the injection and suction slot opening surfaces. The expressions for the force of the controlled airfoil can be given as:

$$F_{px}+F_{vx}-(\dot{m}V_1+p_1S_1)_x+(\dot{m}V_2+p_2S_2)_x \quad (1)$$

$$F_y=F_{py}+F_{vy}-(\dot{m}V_1+p_1S_1)_y+(\dot{m}V_2+p_2S_2)_y \quad (2)$$

Where the subscripts 1 and 2 stand for the injection and suction respectively. F_p and F_v are the force on the airfoil surface which caused by pressure and viscous. p, V, S represent the parameters in the injection and suction slot, which are pressure, velocity, area of slots. The reactionary force caused by pressure is $-p_1S_1$ at injection and p_2S_2 at suction. Similarly the reactionary force caused by momentum is $-\dot{m}v_1$ at injection and $\dot{m}v_2$ at suction

3.2. Jet Momentum Coefficient and power consumption

C_μ, the jet momentum coefficient, is used as a parameter for jet mass flow control. A dimensionless parameter that includes mass flow rate and jet velocity is defined as:

$$C_\mu=\frac{\dot{m}V_j}{\frac{1}{2}\rho_\infty V_\infty^2 S} \quad (3)$$

Where the $\dot{m}$ is the mass flow rate, V_j is the velocity of the injection the ρ_∞ represents the density of free stream, the V_∞ stands for velocity of free stream, and S is the area of airfoil.

The power consumption by the pump can be determined by the jet mass flow and total enthalpy change as the following:

$$P=\dot{m}(H_{t1}-H_{t2}) \quad (4)$$

The $\dot{m}$ is injection mass flow rate, and H_{t1}, H_{t2} are the total enthalpy in the injection cavity and suction cavity respectively, and Introducing the pump efficiency and total pressure ratio, the power can be expressed as :

$$P=\frac{\dot{m}C_pT_0}{\eta_p}\left(\Gamma^{\frac{y-1}{y}}-1\right) \quad (5)$$

Where, the $\Gamma=\frac{p_{01}}{p_{02}}$, and the $p_{01,}p_{02}$ are pressure at injection and suction slots. T_0 is the total temperature and $\gamma=1.4$. In this paper, we set the pump efficiency equals to 0.9.

3.3. Suction parameter effect on separation control

This section focuses on the controlling separation bubble of S5010 airfoil at AOA=2°,and Re=100,000. Suction parameters include the location on the upper surface, the mass flow rate, the slots distance, and so on. Here we focus on the suction location mainly. The suction area is determined by separation region. Fig. 3 shows the result of skin friction on the upper surface, which was obtained by LES, indicates the separation region located between 40%c~75%c. Based on this, the location of suction area is designed and listed in Table 1. The chord of baseline airfoil is 1 m. Other parameters are referenced in Wahidi[1]andZha[2]. The injection slot locates at 0.65% of the chord, and the height of the slot is 1.5mm.

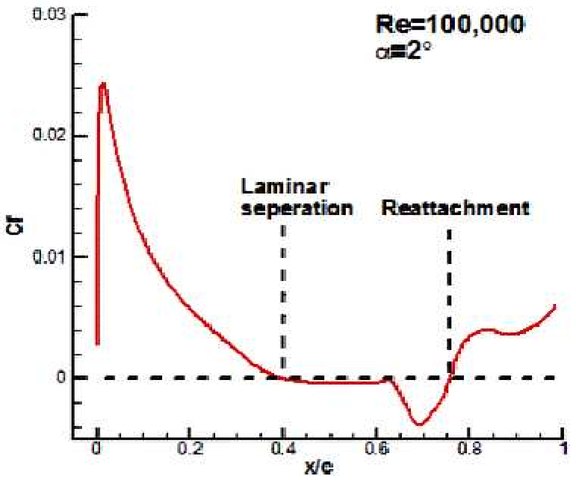


Fig.3 Friction Coefficient of S5010 on the Upper Surface

Table. 1 Parameters of Suction Locations

Location number	suction area location	the width of suction slots
1	80%~90%	5mm
2	75%~90%	5mm
3	60%~75%	5mm
4	50%~65%	5mm
5	40%~55%	5mm

Fig. 4 shows a comparison of the lift to drag ratios, affected by different suction locations. The vertical axis stands for the ratio of the controlled airfoil to the baseline airfoil. The flow control technique is effective when the value above 1. The figure indicates that the lift to drag ratios increases while the increases. Suction range of location 2 is wider than location1, thus the distance between slots is larger. But the lift to drag ratios does not have obvious difference. As the C_{μ} The performance enhancement is obvious. For example, when

keeps constant, lift to drag ratios increase until the suction area moves forward to location 4. This indicates that the most effective suction location is at the middle of the separation region.

Additionally, performance of configuration with suction only and injection only are presented in the figure. The suction area is located on the surface as the same as location 4, of which without injection. The result shows that injection only or suction only is not effective as the simultaneous blowing and suction.

Besides the aerodynamic performances, the penalty of the flow control must be considered. Considering the power expend by the pump into drag, and the equivalent drag coefficient can be calculated by aerodynamic drag coefficient adding to power coefficient. Thus an equivalent lift to drag ration is obtained. As showed in Fig. 5 the suction location 4 is the most efficient one.

The performance enhancement is obvious. For example, when C_{μ}equals to 0.011. The equivalent lift to drag ratios of controlled airfoil is about 1.14 times than baseline airfoil, and the aerodynamic lift to drag ratios is about 2.0 times than baseline airfoil.

Simultaneous blowing and suction can recirculate the jet flow mass, and reduce the penalty to propulsion system due to avoiding dumping the jet mass flow. Compared with other techniques, such as blowing jet, or suction jet, blowing in conjunction with distributed suction can inject energy for main flow on the suction surface, thus suppress the flow separation. Another advantage is that the jet can act a force on the airfoil in opposition to the drag, which reduces drag significantly. Distributed suction near separation region can eliminate the low energy boundary-layer flow and the separation bubble is suppressed effectively.

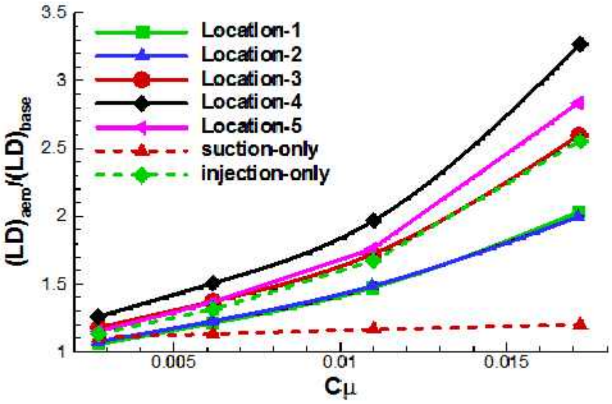


Fig. 4 Comparison of Different Suction Location Results: Aerodynamic Lift to Drag Ratios

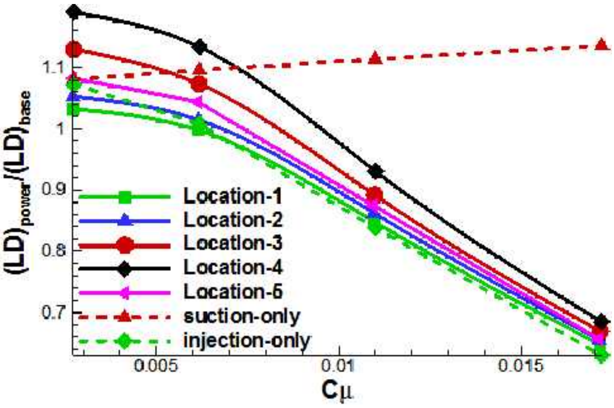
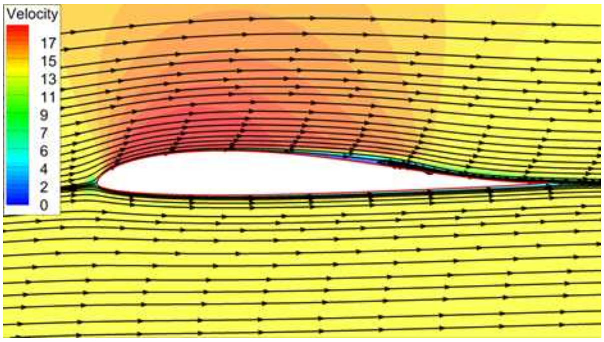
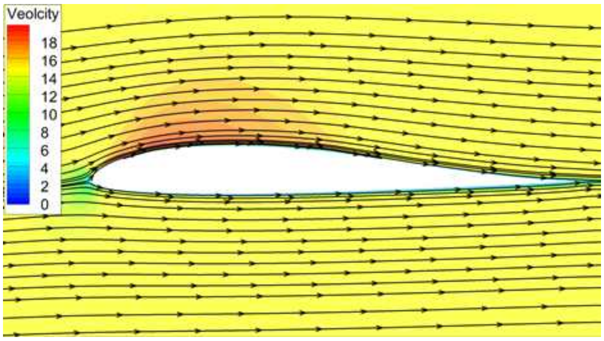


Fig. 5 Comparison of Different Suction Location Results: Equivalent Lift to Drag Ratios

Fig. 6 shows the streamline around the baseline airfoil and the controlled airfoil. The flow at AOA= ° exhibits separation and reattachment, and a separation bubbles is formed on the upper surface. Compared with this, no separation and reattachment appears on the upper surface, which indicates that the separation bubble is eliminated by blowing and suction.



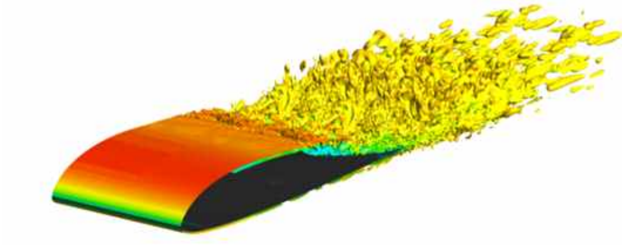
(a) Streamline Around Baseline Airfoil



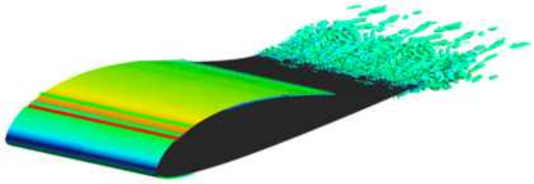
(b) Streamline Around Controlled Airfoil

Fig. 6 Velocity Distributions and Streamlines of Time-averaged Flow, AOA=2°, Re=100,000

The instantaneous flowfields around S5010 airfoil and controlled airfoil at AOA=2° are showed in Fig. 7. The Q-Isosurfaces is colored by the value of x-direction velocity. Fig. 7(a) shows that the flow separates around the position near trailing edge of S5010. The spanwise (z-direction) vortices are generated periodically. Fig. 7(b) indicates that the separation bubble on the airfoil surface is vanished, and the flow control is effective.



(a) Q-Isosurfaces of Baseline Airfoil



(b) Q-Isosurfaces of Controllde Airfoil

Fig. 7 Q-Isosurfaces of Instantaneous Flows, AOA= ° Re=100,000

4. Conclusions

As a means of flow control, simultaneous blowing and distributed suction is very effective to enhance lift and reduce drag, meanwhile, penalty to propulsion system was small. The flow control technique is easy to implement without any moving parts. These advantages give some guidelines for performance improvement for the future UAVs and MAVs.

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