SEPARATION CONTROL BY ALTERNATING TANGENTIAL BLOWING/SUCTION AT MULTIPLE SLOTS

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Abstract

A method of separation-control using alternating tangential blowing/suction at small speeds on multiple slots was proposed and the properties of this method were studied by applying it to the flow-control of a thick airfoil. The method of numerically solving the Reynolds averaged Navier-Stokes equations was employed for the study. Using alternating tangential blowing/suction with small speeds, in the blowing phase, the boundary layer velocity profiles downstream of the slot are made fuller and more separation resistant and in the suction phase, the boundary-layer velocity profiles both up and downstream of the slot are made fuller and more separation resistant. For the airfoil considered in the paper (which is of 40 percent thickness and has ten slots), with a peak velocity of about $1.5U_{\infty}$ *of blowing/suction, the separation is suppressed. Since the suction is more effective than the blowing in controlling separation, when all the slots operate in-phase* $(f=0)$*, the global flow field varies with time periodically and the aerodynamic forces oscillate with large amplitude. If there is a phase difference* $(f \neq 0)$ *between operations of slots, then suction effect is always present in the flow, which results in very small variation of force coefficients and flow field remains virtually unchanged at various time instants. However the time averaged values of force coefficients are slightly reduced for out-of-phase blowing/suction in comparison with in phase blowing/suction.*

1 INTRODUCTION

Boundary Layer separation entails great losses and limits the performance of many flow-related devices. Through separation control, flow pattern close to that given by inviscid flow theory can be obtained, leading to large lift and very small drag. The prevention of separation on airfoil and the generation of high lift are important aspects of boundary layer control. Much research has been done on this area [1~3].

It is known that if traditional methods of blowing or suction, such as using high-pressure air from the jet engine, were used for suppressing separation, very complex and large interior ducting would be needed. Due to the recent emergence of Micro fabricated Electro-mechanical systems (MEMS), the idea of alternating blowing/suction has originated. The implementation of the alternating tangential blowing/suction with small speeds at multiple slots can be made much easier due to MEMS actuators. Among the various MEMS designs, zero-mass jet actuator [5] appears to be the most suitable for the above purpose. Zero-mass jet results from oscillating a diaphragm in an enclosed rigid cavity having a small orifice. Air is drawn into the cavity by low-level suction pressure created by the diaphragm and then is expelled by the same diaphragm. The diaphragm is activated electro-statically, electro-magnetically or using piezoelectric material. The peak velocity and frequency are defining parameters of the zero-mass jet actuator. Several such actuators may be considered in the form of an array acting as a single unit. If a slot exit on an airfoil surface is replaced by an array of zero mass jet, complex air supply systems are no more needed.

Recently, first author of this paper and Sun [13] reported their study on separation control on a thick airfoil with multiple slots with alternating tangential blowing/suction at small speeds. By alternating tangential blowing/suction it's meant that at each slot exit, the blowing/suction velocity was in the tangential direction of the airfoil surface and its magnitude varied periodically with a zero mean i.e.

$$V=V_a \, Sin\,(2 \pi f t) \qquad (1)$$

Where V, V_a and f are the instantaneous velocity, peak velocity and frequency of blowing/suction respectively. There were 10 slots placed on the upper of airfoil and all the slots operated in phase.

It was seen that alternating tangential blowing/suction was very effective in controlling the separation and high values of time-averaged force coefficients were obtained however there were oscillations in the value of force coefficients due to alternating blowing/suction. The suction was found to be more effective than blowing, since during suction boundary layer profiles were fuller both upstream and downstream of the slot and hence more separation resistant. During blowing phase the boundary layer downstream of the slot was only made fuller and therefore less separation resistant as compared to suction phase. Therefore during alternating blowing/suction, the flow field and force coefficients also varied with time during one complete cycle of blowing/suction. The extent of variation of force coefficient during a cycle was found to be dependent on V_a and f. However it was found that when V_a is large enough to suppress separation $(V_a \geq 1)$ and frequency is large enough $(f \geq 1)$, then the global flow field did not vary much and the variation in force coefficients was also reduced.

The present research work is an extension of the previous research work of first author [13]. In this work, the effects of out-of-phase operation of slots are examined. The idea comes from the fact that during in-phase operation of slots, suction and the blowing phase are neatly separated during a cycle. For the case of out-of-phase operation of slots, at any instant some of the slots will be in suction mode while others in the blowing mode. This means that suction effect will always be partially present in the flow and this may result in reducing variation in force coefficients, as well as reducing variations in global flow field.

In the present paper, numerical simulations based on the Navier-Stokes equations are conducted to study the effectiveness of controlling boundary-layer separation on a thick airfoil by out-of-phase tangential blowing/suction with small speed at multiple slots.

2 COMPUTATIONAL METHOD

The governing equations are the two-dimensional, compressible and Reynolds averaged Navier-Stokes equations. The equations are expressed in strong conservation form. They are well documented in the literature [7] and will not be repeated here. The perfect gas law, Sutherland`s viscosity formula, a constant Prandtl number and an algebraic eddy viscosity model for turbulence are used with the governing equations.

The governing equations are solved using the implicit, approximate factorization algorithm of Beam and Warming [8]. The scheme is formulated using three-point-backward implicit time differencing and second-order finite difference approximation for all spatial derivatives. Constant coefficient fourth-order explicit and second-order implicit spectral damping is added to damp high frequency oscillations and enhance stability behavior [7].

The Baldwin-Lomax two-layer eddy viscosity model [9] was chosen in the present flow simulations based on its previous successes in calculating flows on airfoils without separation [10]. Ref [10] studied the validity of the Baldwin–Lomax turbulence model for the airfoil static and dynamic stalls. It was shown that for steady flow, the Baldwin-Lomax model produced an inordinate amount of leading edge suction at high α, thereby delaying stall to an angle of attack greater than observed physically. In the present work with flow control applied, the flow is practically attached; therefore, it is proper to use the Baldwin-Lomax model.

At the inflow boundary, the velocity components and temperature are specified as free stream conditions while the pressure is extrapolated from the interior. At the outflow boundary, the pressure is set equal to the free-stream static pressure and the velocity and temperature are extrapolated from the interior.

In the present calculations, the interaction between the flow of blowing/suction at a slot-exit and the surrounding fluid is simulated using a time-dependent boundary condition at the slot-exit. As perceived by an observer standing next to the slot-exit, periodic flow out of and into the slot-exit is felt. The boundary condition for the alternating blowing/suction is therefore one that represents an oscillatory velocity described by periodic function with zero mean. In this paper, at grid points located at the slot-exit, harmonically varying velocities were prescribed and caution was exercised to ensure that the calculated pressures, and hence densities, on these grid points were consistent with the prescribed time-dependent blowing/suction velocities.

Since slots are placed on the airfoil surface, the construction of a suitable body-fitted grid system becomes more difficult. To deal with these requirements a special Poisson Solver based on the method developed by Thomas [11] with modifications incorporated by Liu et al [12] is used for grid generation. This solver uses a multi-regional approach to determine the source term, resulting in better control of grid line distribution. The grid topology used in this work was an O-grid, with the grid cut line extending from the airfoil nose to the outer boundary. A portion of the grid for a thick airfoil with 10 slots is shown in Fig. 1.

3 CODE VALIDATION AND SOLUTION ACCURACY EVALUATION

The code was validated with experimental data for a variety of cases, including flow around a NACA 0012 airfoil with angle of attack below stall angle of attack [4], unsteady flow around a NACA 0012 airfoil oscillating in pitch [12], unsteady flow around a circulation control airfoil with blowing jet [12]. As with any numerical analysis, great care must be taken to insure the accuracy of the computed results. Grid of size 480×131 (480 points on the airfoil surface and 131 in the direction normal to the surface) was used in all calculations. It is the same grid used in all the calculations in Ref [13], where it was selected after extensive grid testing. The far field boundary was set at 10 chords away from the airfoil surface. The grid was sufficiently dense in the region close to the surface. The close up view of grid around slot (slot No 2) is shown in Fig 2.

4 RESULTS AND DISCUSSION

The airfoil considered in the present study was the same as that in Ref [13]. It was of 40 percent thickness, the upper and lower surfaces of which were semi-ellipses of 32 and 8 percent thickness respectively. Ten slots were equally spaced on the upper surface of the airfoil, from $0.6\ c$ to $0.97\ c$. The slot heights were $0.002\ c$. The free-stream Reynolds number was 10^6 and Mach number 0.15. All the calculations were performed at $\alpha=10^{\circ}$.

The blowing/suction velocity at a slot-exit is prescribed using a sinusoidal function of the form.

$$V=V_a \times Sin\ [2\pi f t+(n-1)f];\ n=1,2,\ldots 10 \qquad (1)$$

Here n is the number of slots V, V_a and f denote, respectively, the non-dimensional instantaneous velocity, peak velocity and frequency of the blowing/suction, t denotes the non-dimensional time. In the non-dimensionalization, free stream velocity, U_∞, airfoil chord length c and c/U_∞ are used as reference velocity, length and time respectively. The direction of V is in the tangential direction of the airfoil surface next to the slot-exit. The sinusoidal boundary condition was enforced at each grid-point on a slot-exit. Here f denote the phase difference between each successive slot.

In the previous research work by first author [13] of the paper, all the slots operated in unison i.e. $f = 0$ and was seen that when V_a >1.0 and $f \geq 1.0$ the separation was suppressed. On this basis, in the present work V_a = 1.5 and f= 1.5 are used. A preliminary calculation was performed for the uncontrolled case (i.e. V_a = 0). The flow is highly separated and unsteady (Fig 3) and small values of C_L are obtained.

4.1 In-Phase-Blowing/Suction (Case 1)

In this case, all the ten slots are performing alternating blowing/suction without any phase difference. For ease of comparison, this case (f=0) is termed as Case 1. Figure 4(a) shows the behavior of force coefficients vs. t. The code was run for all cases till the force coefficients and the flow field of successive cycles was similar. The variation in C_L (denoted by ΔC_L) is 0.26 and the time averaged value of C_L (denoted by $\overline{C_L}$) is 2.07 for this case. The variations in C_D (denoted by ΔC_D) is 0.18 and the time averaged value of C_D (denoted by $\overline{C_D}$) is 0.13. Figure 4(b) shows the flow field around the airfoil at different instants (marked on Fig 4(a)). It is seen that the flow close to the trailing edge is changing during a cycle. This causes the force coefficient to vary during a cycle i.e. $\Delta C_L = 0.26$ and $\Delta C_D =$ 0.18. In comparison with the uncontrolled case (Fig 3), it is seen that the flow control is very effective in suppressing the separation.

4.2 Out-of-Phase Blowing/Suction

We study a typical case when $f = 45^\circ$. In this case each slot operates at phase difference of 45° from the next slot. This is shown in Fig 5 for all ten slots at a particular instant at which the 1st slot is at zero velocity. The direction and size of velocity vector depict the behavior of other slots at that instant (inward arrow means suction while outward arrow means blowing). Figure 6(a) shows that the $\Delta C_L = 0.08$ and $\overline{C_L}$ = 1.96. In comparison to Case 1, the time averaged value of $\overline{C_L}$ has decreased slightly but interesting point is that ΔC_L has decreased considerably (for Case 1, $\Delta C_L =$ 0.26). Also the time averaged drag coefficient $\overline{C_D}$ =0.125 has also decreased (for Case 1, $\overline{C_D}$ = 0.13), along with ΔC_D which is only 0.045 in this case. Figure 6(b) shows the flow field at various instants. It is seen that the flow field changes very less near the trailing edge and this variation is very less than what was seen for Case1 (Fig 4(b)). Therefore in this case ($f = 45^\circ$), the variation force coefficient is very small. As mentioned previously this effect is due to the fact that suction effect is always there at some of the slots in a cycle.

Similar results are obtained with $f = 90^\circ$. Figure 7(a), (b) show force coefficients vs. t and streamline plots at various instants for this case respectively. Here ΔC_L has further reduced to 0.04 and $\overline{C_L}$ is 1.99. The streamline plot at various instants (Fig 7(b)) also shows that there is very little variation in flow at various instants. This results in very little variations of force coefficients during a cycle.

Calculations were performed for other phase difference angles and results are shown in Table 1.

f	$\overline{C_L}$	$\overline{C_D}$	ΔC_L	ΔC_D	$\frac{\overline{C_L}}{\overline{C_D}}$
0^o (Case 1)	2.07	0.13	0.26	0.18	16.2
45^o	1.96	0.12	0.08	0.04	15.9
90^o	1.99	0.12	0.04	0.04	16.7
112.5^o	1.86	0.11	0.04	0.02	16.9
135^o	1.78	0.10	0.03	0.02	17.1
180^o	1.81	0.14	0.04	0.04	12.4

Table 1 The effect of phase change on force coefficients (V_a=1.5, f=1.5, α=10^o)

It is seen that for other cases ($f = 112.5^\circ$, 135° and 180°), similar results to that of $f = 45^\circ$ and $f = 90^\circ$ are obtained i.e. ΔC_L is greatly reduced in comparison with Case 1. Also the flow pictures at various instants (not shown here) revealed that variation in flow field was very less. It is important to mention that for all the cases, separation is almost completely suppressed and large values of force coefficients are obtained.

5 CONCLUSIONS

Following are the conclusions of the present study

1. Tangential alternating blowing/suction is very effective in controlling the separation.
2. Out-of-phase blowing/suction results in very small variation of force coefficients in comparisons with in-phase blowing/suction.
3. The flow field remains virtually unchanged at various time instants for out-of-phase blowing/suction in comparison with in-phase blowing/suction.
4. Time averaged values of force coefficients for out-of-phase blowing/suction are slightly reduced in comparison with in-phase blowing/suction.

6 REFERENCES

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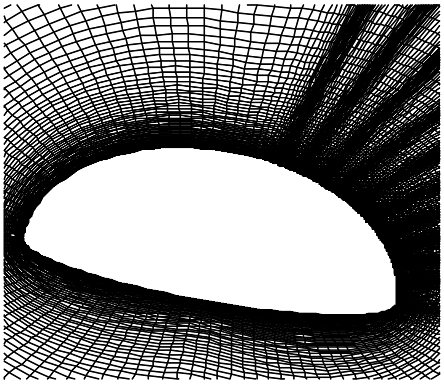


Fig 1 Grid around the airfoil

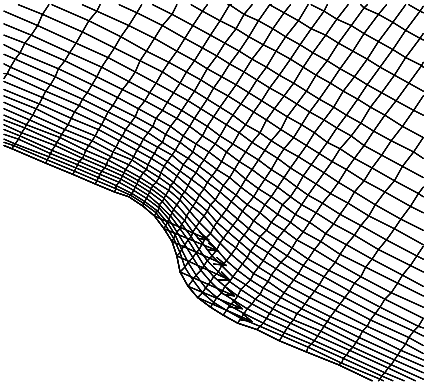


Fig 2 Grid and velocity vector plots at 2nd slot

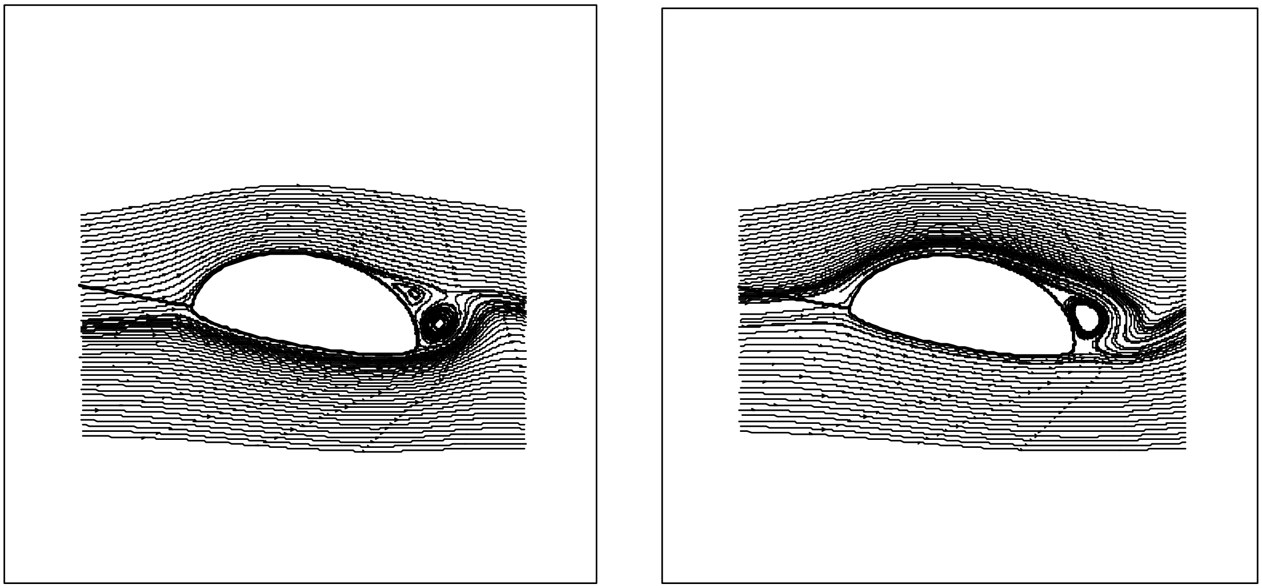
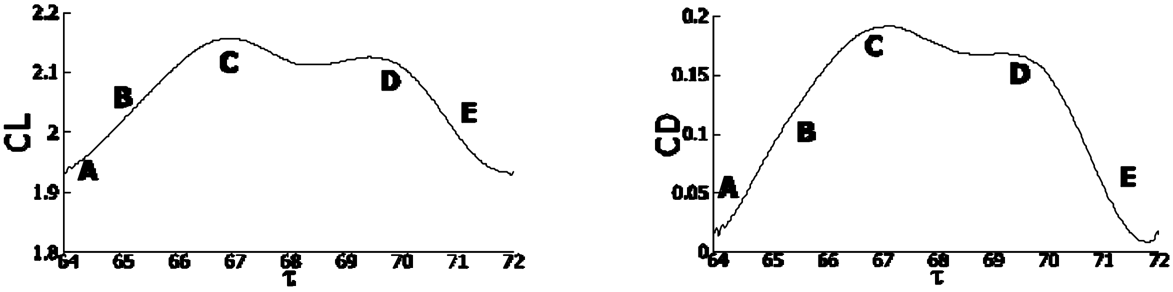
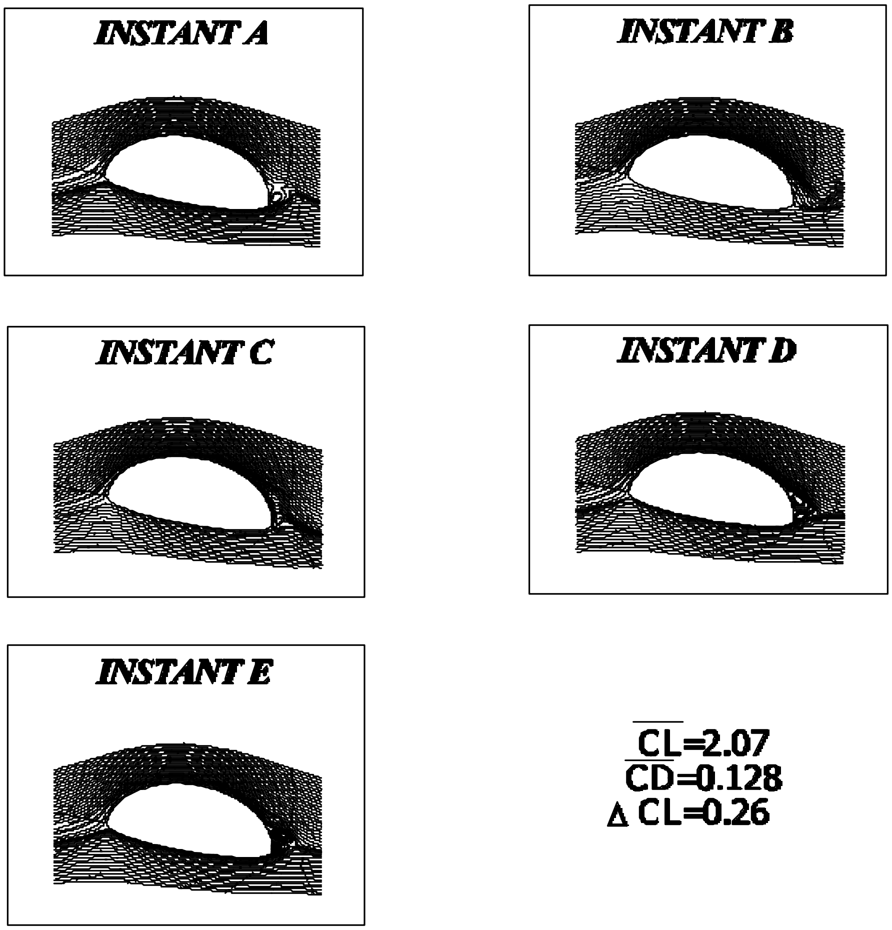


Fig 3 Streamline plots for uncontrolled case at two instants,($\alpha=10$)



(a) Force coefficient vs τ during a cycle



(b) Streamline plots at different instants

Fig 4 Force coefficients and streamline plots for Va=1.5,f=1.5,α=10 and ϕ =0

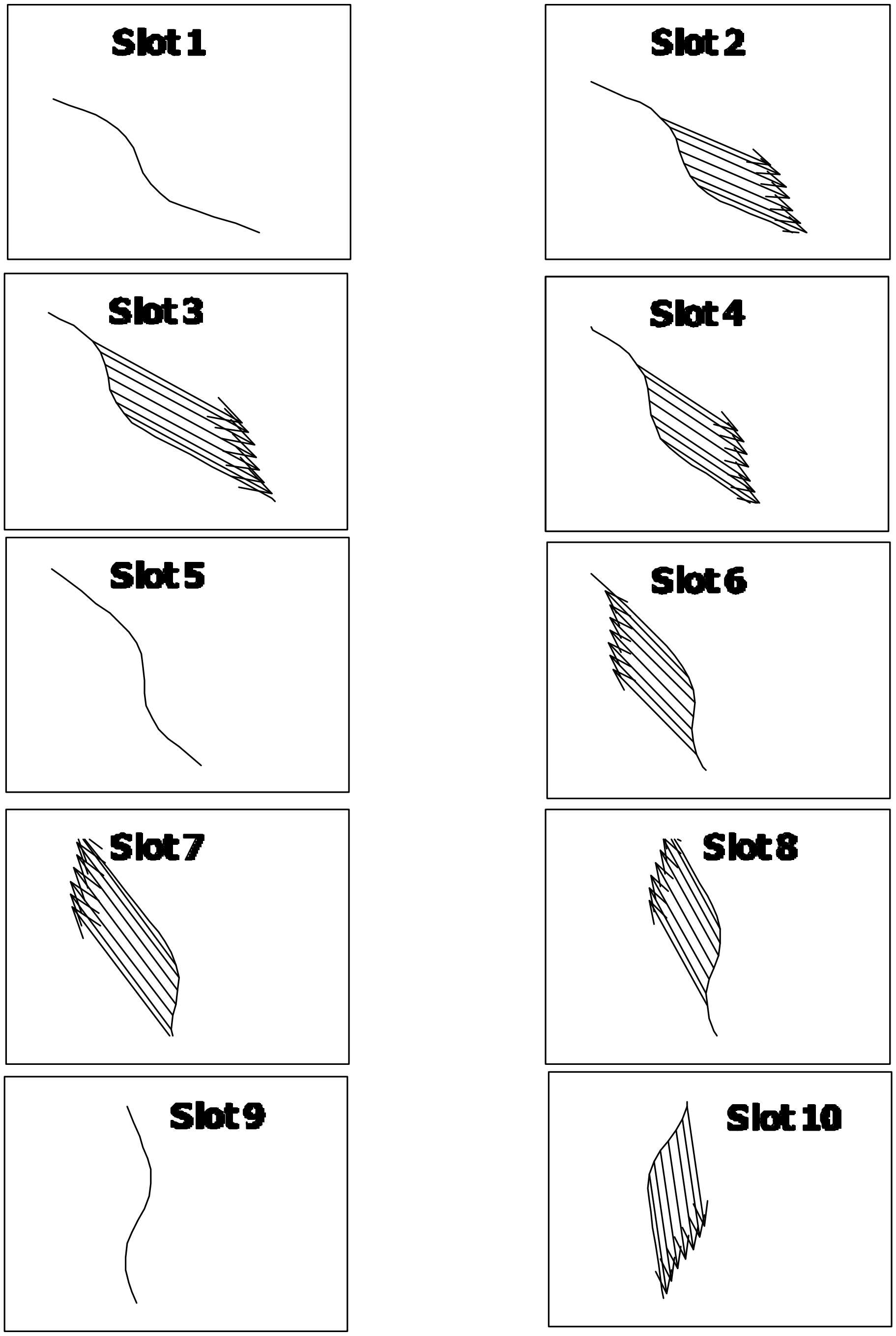
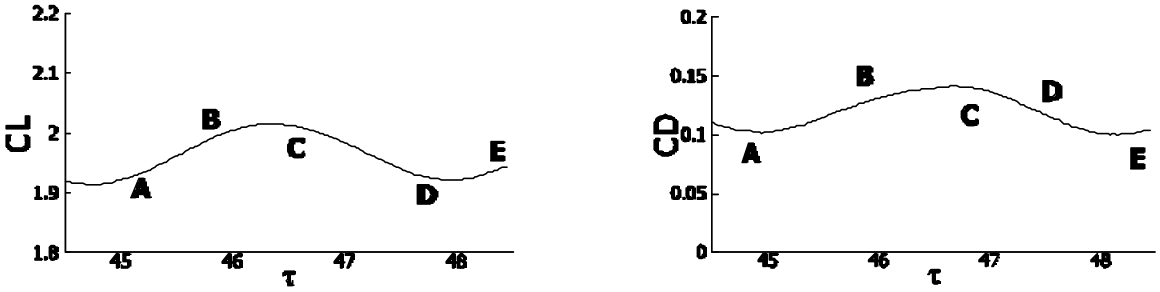
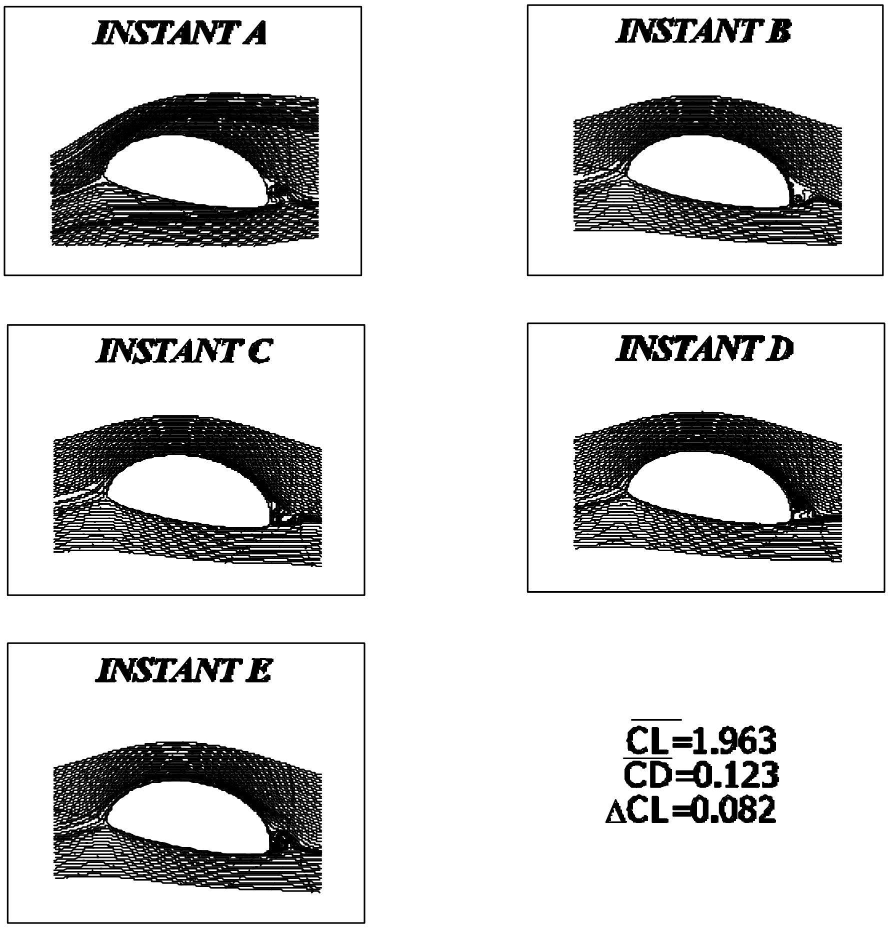


Fig 5 Velocity vector plots on all the slots at some particular instant (Va=1.5, ϕ=45)



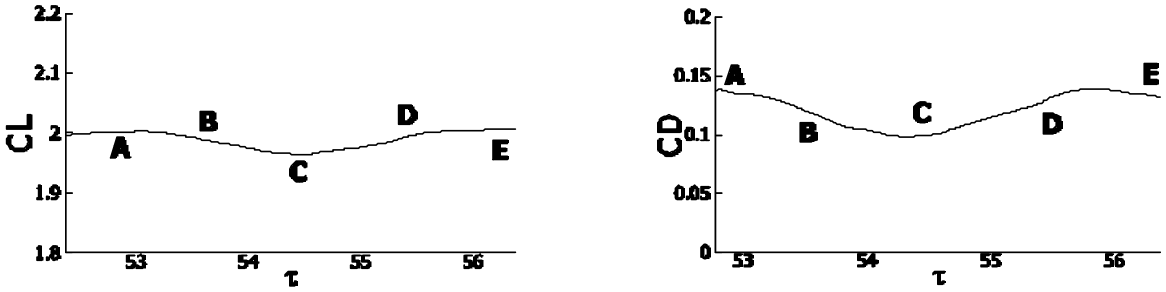
(a) Force coefficient vs τ during a cycle



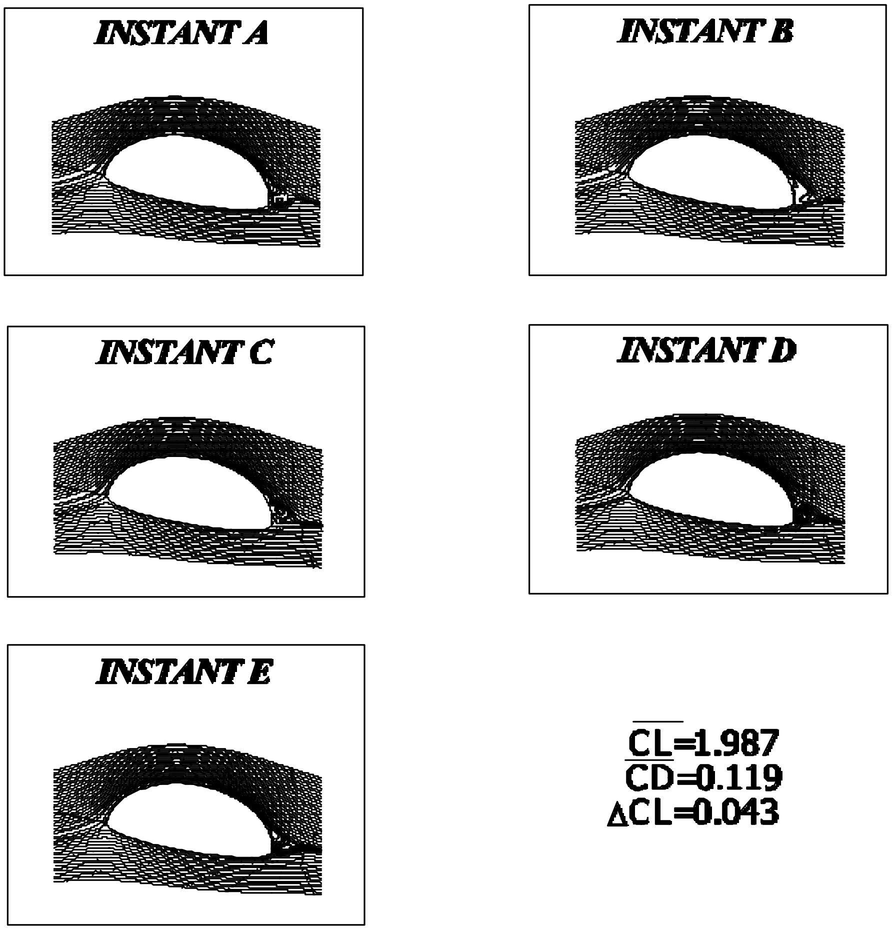
$\overline{CL}=1.963$
$\overline{CD}=0.123$
$\Delta CL=0.082$

(b) Streamline plots at different instants

Fig 6 Force coefficients and streamline plots for Va=1.5,f=1.5,α=10 and ϕ=45



(a) Force coefficient vs τ during a cycle



(b) Streamline plots at different instants

Fig 7 Force coefficients and streamline plots for Va=1.5,f=1.5, α=10 and ϕ =90