Study on Trailing Edge Ramp of Supercritical Airfoil

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Abstract

Trailing edge flow control method could improve the performance of supercritical airfoil with a small modification on the original airfoil. In this paper, a ramp of 2%~7% chord length is sliced near the trailing edge to improve airfoil performance. The trailing edge ramp is adopted to create a sharp pressure recovery without flow separation. Reynolds averaged Navier-Stokes method is used to numerically study the effects of the ramp, and to investigate the influence of the ramp length and height. Results show that the ramp could increase the circulation of the airfoil and improve lift/drag ratio, and gain better buffet characteristic and some other benefits also.

Keywords: supercritical airfoil, trailing edge, ramp, flow control

Introduction

Supercritical airfoil has been widely used in modern civil airplane. It could highly increase the cruise Mach number of aircraft by delaying drag rising. Because of the importance of supercritical airfoil, many studies have been focused on flow control method of supercritical airfoil to gain better performance. Trailing edge control is a simple way to improve airfoil performance with a small change on the original airfoil, such as the Gurney flap [1] and trailing edge divergence [2]. Trailing edge control is mostly used to affect the pressure distribution, and provide better lift/drag ratio through higher suction flat or stronger aft loading on supercritical airfoil.

A trailing edge ramp is introduced in this paper. The RAE2822 supercritical airfoil is chosen as the subject of studying the effects of the ramp. There is a similar concept originally proposed by F.X Wortmann in 1974 called separation ramp, which is used for low Reynolds number(10^5~10^6) airfoils [3]. A separation ramp likely method is also used in Honda jet and other subsonic NLFs [3, 4]. Their studies mainly focus on either a higher maximum lift coefficient [5, 6] or a better pitching moment [6] of NLF airfoils other than supercritical airfoil. The separation ramp improves the characteristics of airfoils through a separation bubble near the trailing edge. However, the present CFD result shows that it seems a pressure ramp without separation gains better characteristic for supercritical airfoil. The non-separation ramp could not only increase the lift without inducing additional drag, but also improve the stall behaviour. As a result, the non-separation ramp could increase the thickness of airfoil, which benefits wing structure and aerodynamic efficiency.

Trailing Edge Ramp Shape and CFD Method

Trailing edge ramp is sliced on an airfoil with a non-zero trailing edge thickness. As shown in Fig. 1(a), considering the requirement of slicing a ramp, a new trailing edge thickness t is built through linear interpolation along the chord direction based on the original RAE2822 airfoil, which will thicken the airfoil. The interpolation is implemented as shown in Eqn. 1. This modification could assure the airfoil camber is unchanged and the airfoil surface is smooth.

$$y_{new} = y_{original} \pm \frac{x}{2} \cdot t \qquad \text{Eqn. 1}$$

Considering the demand of actual manufacture, a ramp is sliced above the thickened airfoil; meanwhile a new trailing edge t' is generated. The shape of the trailing edge ramp is defined by two parameters: t and s, as shown

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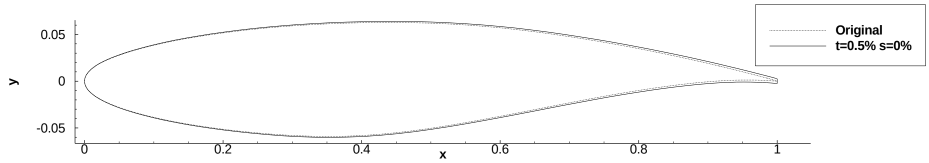
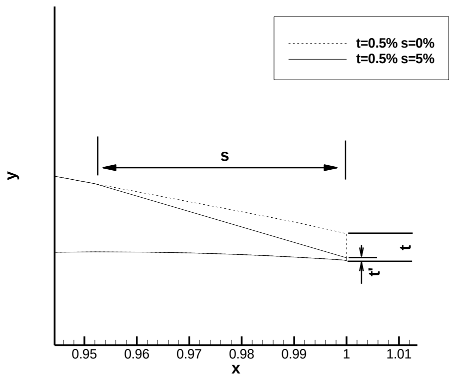
in Fig. 1(b), which are the trailing edge thickness of the baseline blunt trailing edge airfoil (*t*=0.0%~0.8% chord length) and the horizontal length of the ramp (*s*=2%~7% chord length), respectively. The dotted line in Fig. 1(b) shows the thickened airfoil before slicing a ramp. After slicing the ramp, the new trailing edge thickness *t*´ equals 0.05%.



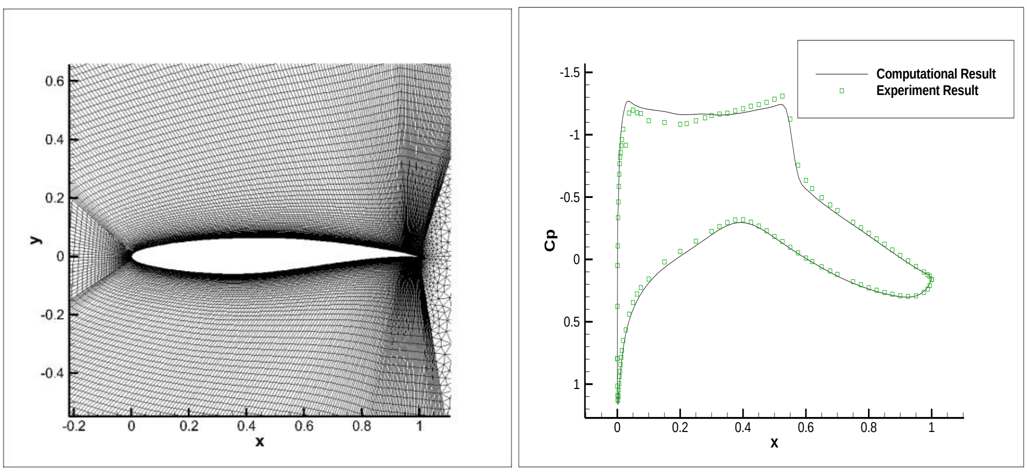
(a) Original airfoil and thickened airfoil (no ramp, s=0%)



(b) Ramp and the new trailing edge

Fig. 1: Sketch of the RAE2822 airfoil and trailing edge ramp

Unstructured solver ANSYS CFX is used to compute the aerodynamic coefficients of the airfoil. Four meshes with 40000, 49000, 60000, 72000 cells are adopted to test grid convergence. Fig. 2(a) shows the mesh of 60000 cells. High-resolution scheme in CFX is employed as the spatial discretization methods. Turbulence quantities are computed by the shear stress transport turbulence model. Fig. 2(b) shows the comparison between computation and experiment. The free stream Mach number is 0.73, Reynolds number is 6.2E6, and the AOA (angle of attack) is 3.19°. Results of different meshes are shown in Fig. 3. The flow condition is Ma=0.71 and Re=6.5E6, which represents a typical cruise condition of RAE 2822 airfoil. The results are well converged for different meshes. In the following sections, the mesh with 49000 cells is used as the baseline mesh to study the effects of trailing edge ramp.



(a) Computational grid *(b) Cp comparison of computation and experiment*

Fig. 2: Grid and computational result

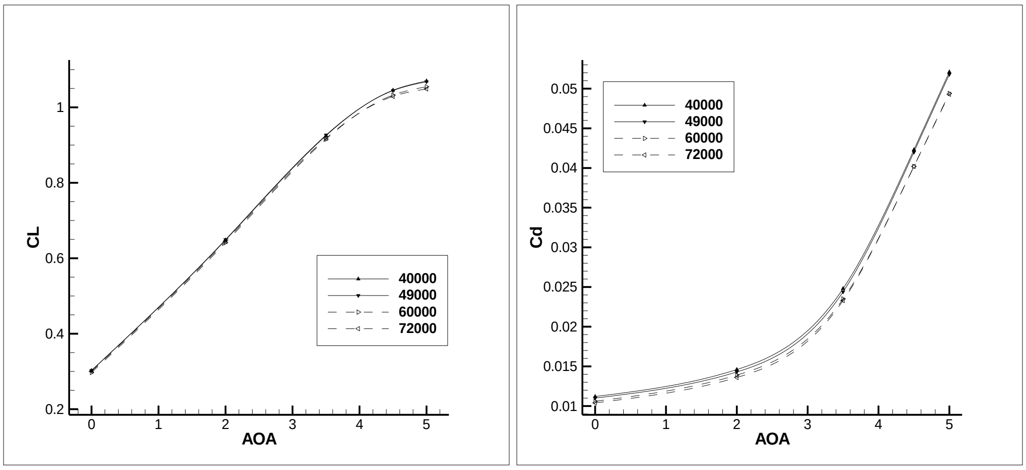


Fig. 3: Lift and drag coefficients of different meshes

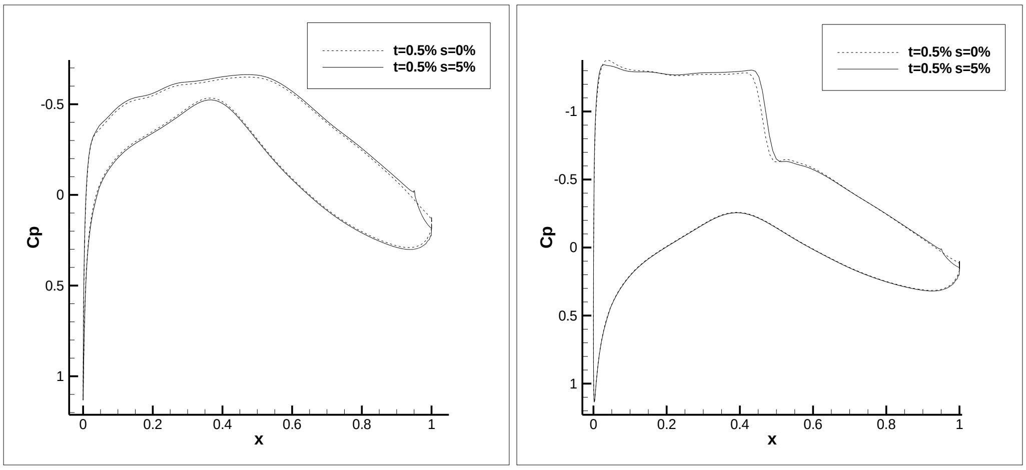
Effects of the Trailing Edge Ramp

In order to study the effect of the trailing edge ramp, pressure distributions of the airfoils with and without the ramp are computed. The free stream Mach number is 0.71 and Reynolds number is 6.5E6. First, the difference of airfoils without and with ramp is discussed at the same AOA; then the pressure distributions of the airfoils with the same lift coefficient are compared. Fig. 4 shows the same AOA case. The two figures in Fig. 4 are two AOAs without and with shock wave, respectively.

In the following sections, the original RAE2822 airfoil with a 0.5% trailing edge thickness is marked as *t*=0.5%, *s*=0% airfoil for convenience. Fig. 4 shows the ramp creates a sharper pressure recovery compared to the original airfoil. It also decreases the pressure coefficient Cp of the upper surface and has a small influence on the lower surface. It basically maintains the shape of the "supercritical" type pressure distribution, hence has very little interference to the off-design performance of the original design. On the other hand, the ramp can push the shock wave move backward at the same angle of attack, thus enhances the suction flat and increases the lift coefficient. Fig. 5 shows the pressure distribution of airfoils with the same lift coefficient. It shows that the ramp can weaken the shock wave of the original airfoil, which will reduce the wave drag and increase the lift/drag ratio. Table 1 shows the aerodynamic coefficients of the cases. The results demonstrate that the ramp could increase the lift and lift/drag ratio in a certain AOA range.

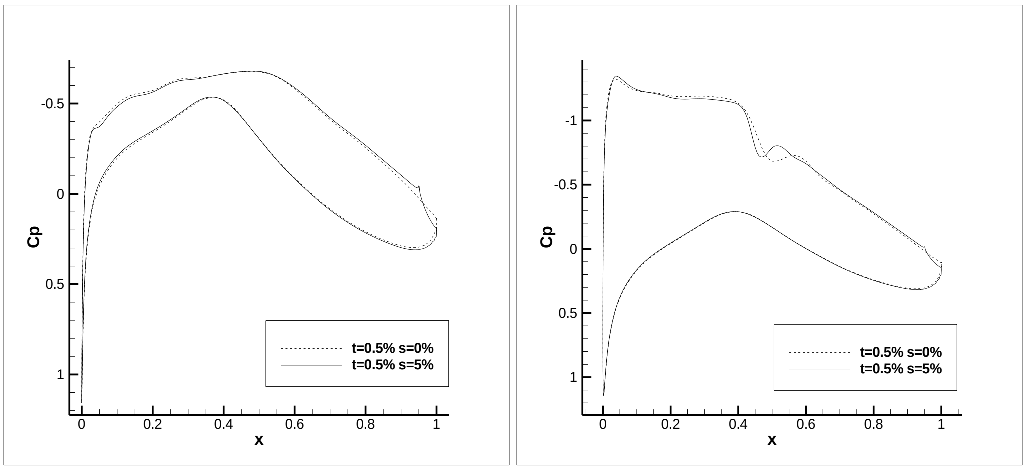
Table. 1: Aerodynamic coefficients of the cases in Fig. 4 and Fig. 5

	Fixed AOA case						Fixed lift case			
	AOA=0.0			AOA=3.0			CL=0.33		CL=0.79	
	C_L	C_d	L/D	C_L	C_d	L/D	C_d	L/D	C_d	L/D
t=0.5% *s*=0% (Original airfoil)	0.2988	0.0103	29.01	0.7948	0.0179	44.40	0.0104	31.73	0.0179	44.13
t=0.5% *s*=5% (With ramp)	0.3301	0.0103	32.05	0.8161	0.0181	45.09	0.0103	32.04	0.0172	45.93



(a) AOA=0.0 *(b) AOA=3.0*

Fig. 4: Pressure distributions of the airfoils at the same AOA



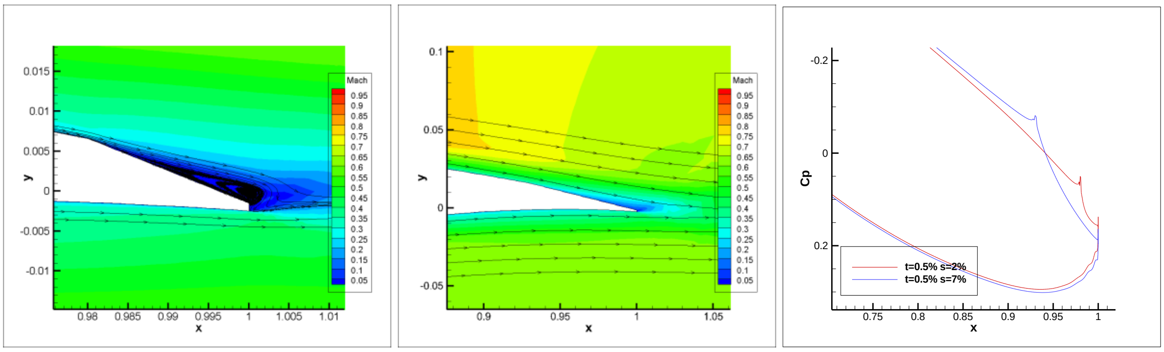
(a) C_L*=0.30* *(b)* C_L*=0.79*

Fig. 5: Pressure distributions of the airfoils with the same lift coefficient

Influence of the length of the ramp

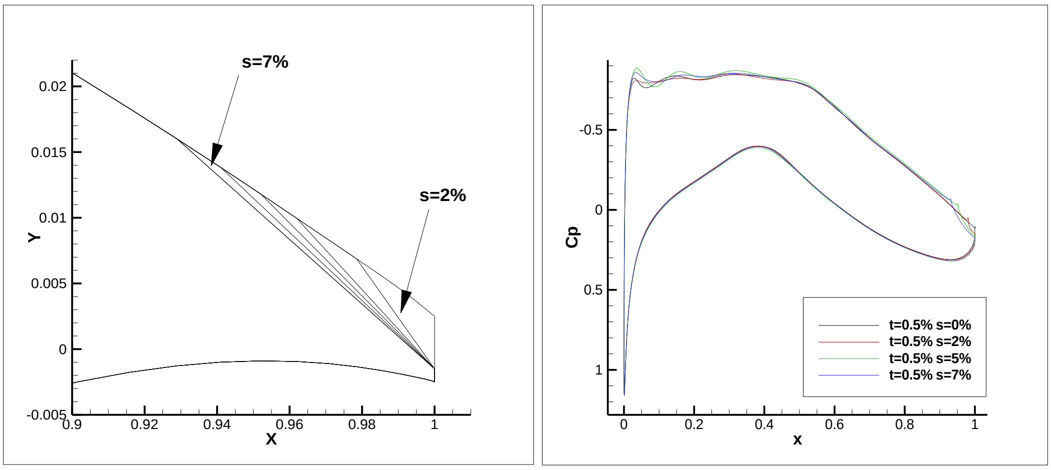
The slope of the ramp is determined by horizontal length *s* and trailing edge thickness *t* together. The pressure recovery slope caused by the ramp is directly related to the ramp slope, and the length of the recovery is determined by the ramp length. In this section, the influence of ramp length is studied.

For a certain airfoil, with the same trailing edge thickness *t*, the change of *s* will not only effect on the slope of the pressure recovery, but also influence the recovery length. A smaller *s* will gain a sharper recovery and a better chance to get a large lift coefficient, however it will also increase the possibility of flow separation. As shown in Fig. 6, the *t*=0.5% *s*=2% airfoil has obvious flow separation on the ramp, while the flow on the *t*=0.5% *s*=7% airfoil is attached. Sharper recovery is also showed in Fig. 6(c). Fig. 7 shows the shapes of airfoils and pressure distributions of different ramp lengths *s*.



(a) t=0.5% s=2% ramp *(b) t=0.5% s=7% ramp* *(c) Cp near trailing edge*

Fig. 6: Flow fields and pressure distributions near the trailing edges of two airfoil (AOA=0.0 Ma =0.71 Re=6.5E6)

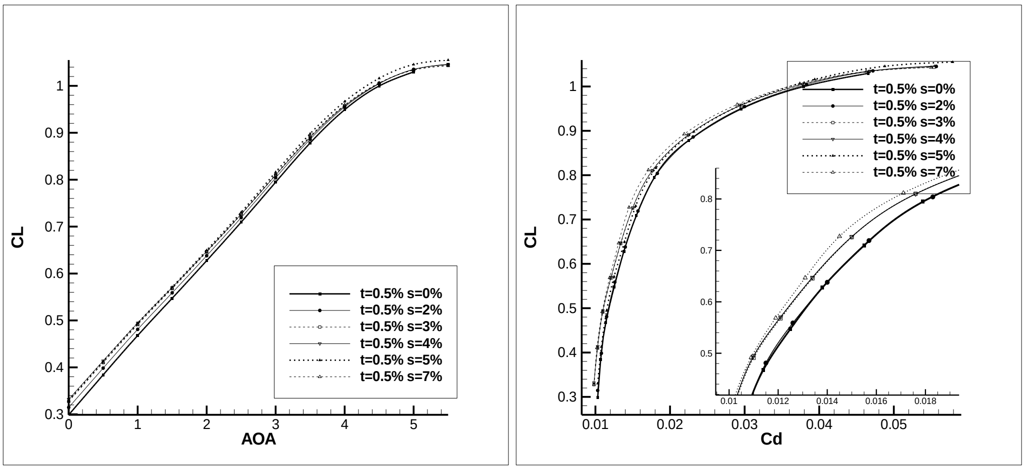


(a) *(b)*

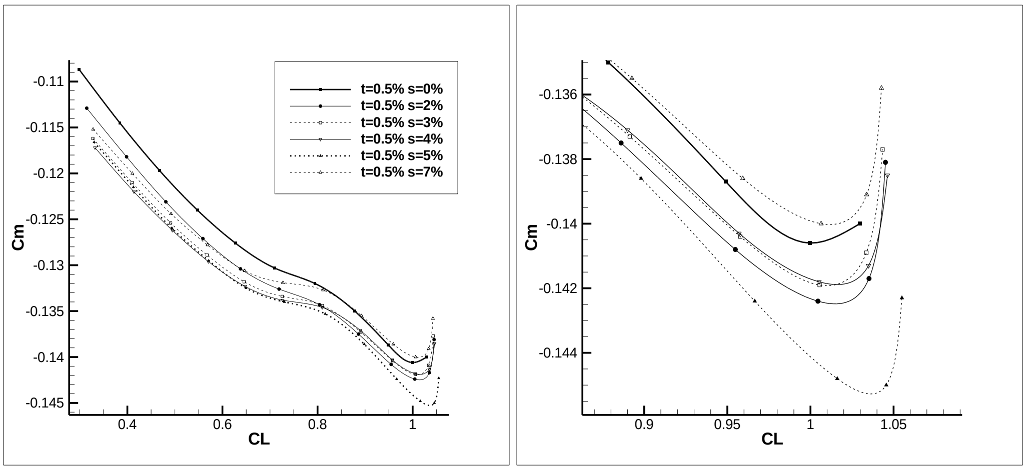
Fig. 7: Airfoils and pressure distributions with different ramp lengths s

When the trailing edge does not have a separation bubble, the pressure distribution is almost linear on the ramp (Fig. 6(b) (c)). The slope of pressure coefficient increases when the ramp length *s* decreases, as shown in Fig. 7(b). On the other hand, when flow separation occurs, the pressure in the separation bubble is almost the same, as shown in Fig. 6(a) (c), which causes the effective airfoil camber shrinks. A longer ramp could generally avoid flow separation to obtain a longer pressure recovery, then significantly increase the effective airfoil camber, hence gains a larger lift and better performance.

The aerodynamic coefficient curves are shown in Fig. 8. The results show that *s*=7% is the best case to increase the lift/drag ratio, and *s*=5% case can gain a better stall characteristic and a larger maximum lift coefficient. Meanwhile, according to Fig. 8(c), the pitching moment curve inflection point of case *s*=5% has a larger C_L than original airfoil (case *s*=0%), hence case *s*=5% could also gain a better buffet characteristic with increasing the lift coefficient by 0.03~0.04. However, the pitching moment is increased with the trailing edge ramp. It is understandable that the trailing edge camber is increased and aft loading is enhanced. Trim drag will increase with the increase of pitching moment. Quantified estimation of the benefit of lift/drag ratio and penalty of trim drag is ongoing studied.



(a) C_L-AOA *(b) Lift-drag polar curves*



(c) Pitching moment - AOA curves

Fig. 8: Aerodynamic force coefficients of airfoils with different ramp length

Effects of the trailing edge thickness

In this section, the influence of tailing edge thickness is studied. The airfoils with different *t* and *s* are shown in Fig. 9. The *t*=0.5% and 0.7% airfoil is chosen to find out the effect of trailing edge thickness. The results are shown in Fig. 10. A larger *t* can gain a larger slope with the same *s*, or a longer effective length with the same slope, which would further reduce the upper surface pressure and increase the lift coefficient without causing flow separation.

As shown in Fig. 10(b), results of the two trailing edge thicknesses indicate that the ramp could further increase the lift/drag ratio with a larger trailing edge thickness. The case of *t*=0.7% *s*=7% could gain better performance than *t*=0.5%, and it can also increases the buffet lift coefficient by 0.04~0.06. With a thicker trailing edge, the ramp could not only improve the aerodynamic performance, but also increase the airfoil thickness, which is good for reducing wing structure weight.

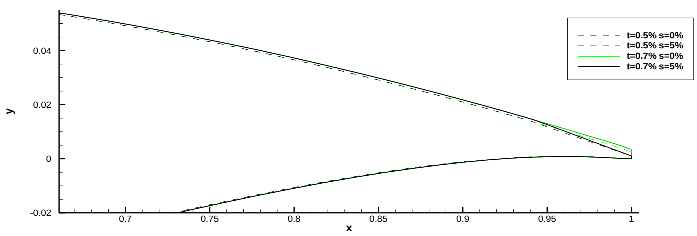
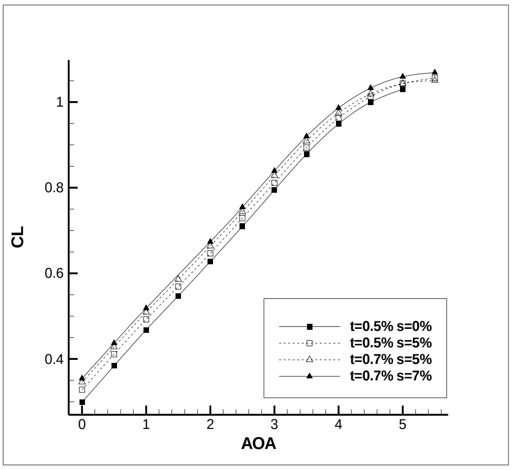
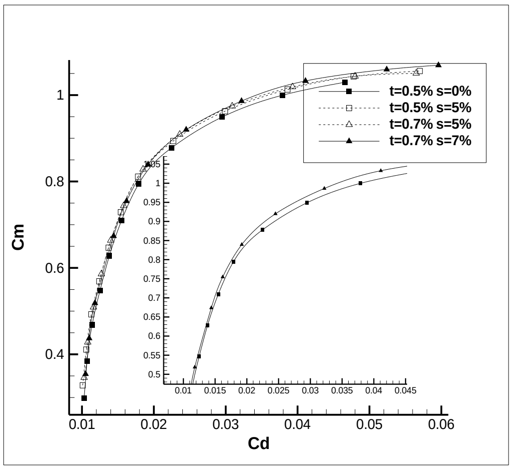
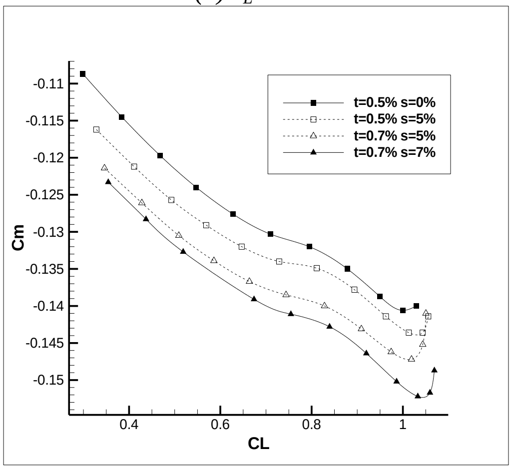


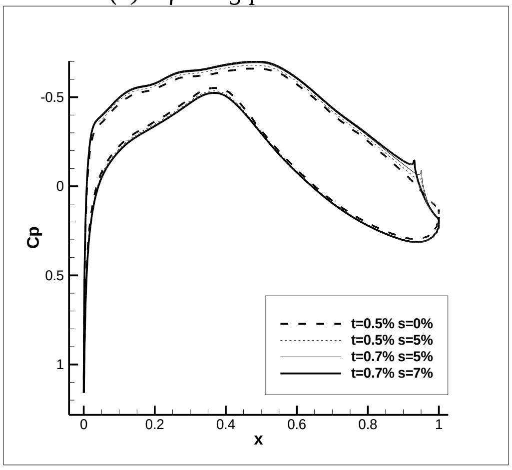
Fig. 9: Airfoils with different trailing edge thicknesses and ramp lengths





(a)C_L-AOA *(b) Lift-drag polar curves*





(c) Pitching moment curves *(d) Pressure distribution*

Fig. 10: Aerodynamic force curves of airfoils with different trailing edge thicknesses and ramp lengths

Results of different ramp lengths (Fig. 8) and ramp thicknesses (Fig. 10) are also summarised in Table 2. The drag coefficients of the airfoils at CL=0.79 are interpolated from the lift/drag polar curves. The length of linear region of the CL - Cm curve is important for buffet characteristics. The lift coefficients at the inflection point of the pitching moments are shown in the table. All airfoils with ramps have better lift/drag ratios and better buffet characteristics than the original airfoil.

Table. 2: Aerodynamic coefficients of the different airfoils

	Fixed C_L=0.79			C_L at the Cm inflection point
	Coefficient	Cd	L/D	
Original airfoil	*t*=0.5% *s*=0%	0.0179	44.13	1.00
Different ramp length s	*t*=0.5% *s*=5%	0.0170	46.47	1.04
	t=0.5% *s*=7%	0.0162	48.77	1.01
Different ramp thickness t	*t*=0.7% *s*=5%	0.0171	46.20	1.02
	t=0.7% *s*=7%	0.0173	45.66	1.05

Conclusion

In this paper, a simple trailing edge ramp is introduced to improve the performance of supercritical airfoil. The work can be summarized as:

(1)The trailing edge ramp changes the airfoil's local camber, causes an increase of the circulation like a flap, then increases the lift and improves the stall characteristic.

(2)Differs from separation ramp proposed by Wortmann, non-separation ramp can gain a larger lift/drag ratio without the additional drag caused by flow separation; furthermore, it could increase the airfoil thickness through a thicker airfoil trailing edge.

(3)The effects of ramp length and trailing edge thickness are studied. Smaller ramp length tends to cause flow separation, while larger ramp length without flow separation is good for performance. However, a main drawback of trailing edge ramp is increasing the nose-down pitching moment, which would increase trim drag. The ramp control method is going to be further investigated to estimate the overall performance.

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