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Effect of miniature trailing edge effectors on performance of NACA 642-215 airfoils

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ABSTRACT

The effect of Miniature Trailing Edge on wing was carried out and analyzed to ascertain its aerodynamics performance and drag reduction capabilities. The use of Miniature Trailing Edge Effectors (MiTEs) as control surfaces for the wing design was also modeled and analyzed to evaluate the feasibility of this technology for adoption in the commercial aviation sector. These analyses were carried out at high speed subsonic compressible flow conditions similar to those experienced by a commercial transport aircraft. The MiTEs indicated the formation and convection of an unsteady vortex in the lower and upper surface of the airfoil. The C_L, C_d reported in the MiTEs configuration are shown linear variation over the Mach number ranging from 0.5-0.7 and then followed by stall with the sudden increased in drag.

Keywords: MiTEs, Unsteady Vortex, Kutta Condition, Adverse Pressure Gradient.

Abbreviation: MiTEs - Miniature Trailing Edge Effectors

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1. INTRODUCTION

Control surfaces of commercial aircraft employed make the use of large and heavy flaps for providing control action and augmenting lift at low speeds. These devices are heavy and possess high inertia, thus making them less effective for correcting transient aerodynamic phenomena and necessitating the use of large and complex feedback driven actuators. Alternate control systems are under study for their potential benefits in terms of size, weight, cost and control fidelity. The Miniature Trailing Edge Effector (MiTEs) concept is one such technology. MiTEs are small flaps that are usually 1-5% of the airfoil chord length which are deflected by 90^o. Computational investigation of wings with miniature trailing edge control surfaces has been investigated by Lee and Kroo (2004). Drag reductions observed with MiTEs was up to 25% and aerodynamic forces scale linearly with span wise flap length till flap AR≥2. Local flap deflection was also resulted in modification of lift forces over a large wing span. Drag reduction due to gaps between the flaps was caused due to unsteady flow effects. NACA 2412 and Selig SD 7062 airfoils with flap deflections of 0^0 to 30^0 were tested both in wind tunnel experiments and using computational simulation to study the flow characteristics. Numerical codes underestimate the effect of low Reynolds number flap deflection on the airfoil lift curve and lift slope (Lee and Kroo, 2004). Hage et al (2005) performed the experiments with trailing edge modification on Gurney flapped airfoil. From the experiment it has been concluded that the intensity of the vortices is strongly dependent on the flap height. 3D modifications (i.e. slits in the flaps) result in a large drag reduction with relatively little effect on the lift. This was done by reducing the intensity of the trailing edge vortices formed in the case without the slits and 12% drag reduction was reported by the author with the use of slits as compared to the 2D Gurney flap.

The use of a small flap on the trailing edge that oscillates sinusoidally about its hinge opposite to main airfoil oscillation reduces the maximum negative pitching moment and delays dynamic stall (Wong, 2010). A positive increment in lift coefficient and an increase in the wing maximum lift coefficient on Gurney flaps were reported by Cavanaugh et al (2007). The device also reported a drag increment that was non-linear with device height. The use of Miniature Trailing Edge Effectors (MiTEs) as control surfaces for the wing design was modeled and analyzed in CFD-Fluent to evaluate the feasibility of Miniature Trailing Edge Effectors as control surfaces technology for adoption in the commercial aviation sector.

NACA airfoils:
The NACA airfoils are airfoil shapes for aircraft wings developed by the National Advisory Committee for Aeronautics (NACA). The shape of the NACA airfoils is described using a series of digits following the word "NACA." The parameters in the numerical code can be entered into equations to precisely generate the cross-section of the airfoil and calculate its properties.

2. COMPUTATIONAL METHODS

The current problem has been solved in a computational platform using Fluent. The computation has been carried out using 2D modes. The viscous model is chosen as standard K-$\mathcal{E}$ Model. The formulation of the solver can be either segregated, in which the governing equations such as continuity, momentum, are solved sequentially i.e. segregated from one another or coupled, wherein the governing equations are solved simultaneously i.e. coupled together. The linearization of the equations can either be chosen to be explicit or implicit in time. The NACA64$_2$-215 airfoil with plain flap was used to carry out the

Table 1
Critical Mach number estimation

M_{cr}	$\frac{C_{p,0}}{\sqrt{1-M_{cr}^2}}$	$\frac{2}{\gamma M_{cr}^2}\left(\left[\frac{2+(\gamma-1)M_{cr}^2}{\gamma+1}\right]^{\frac{\gamma}{\gamma-1}}-1\right)$
0.7	-0.8402	-0.7791
0.68	-0.8183	-0.8652
0.689	-0.8279	-0.8255
0.6886	-0.8274	-0.8273
0.68858	-0.8274	-0.8274

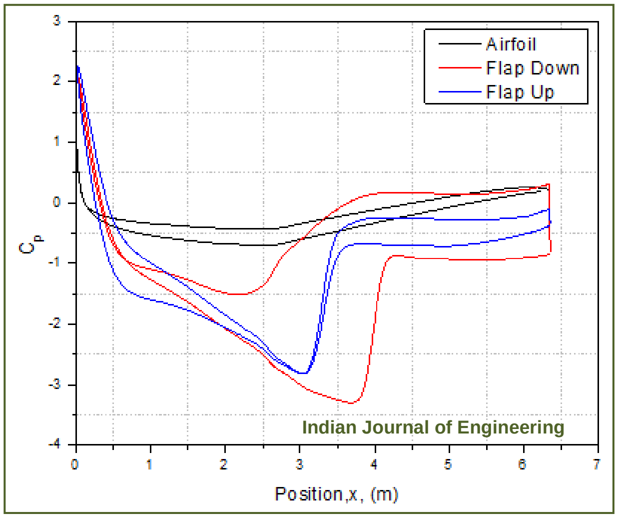

Figure 1
Pressure coefficient (C_p) variation along position

computational analysis. This airfoil is designed for operation in high speed subsonic compressible flow. It has a smooth surface and a rounded leading edge profile that favors laminar flow over a large portion of the upper surface. The 15% thick airfoil was chosen since such a thickness is representative of airfoils used in current commercial transport aircraft and is feasible from a structural standpoint. The coordinates for the NACA 64_2-215 airfoils were obtained from (Manish et al., 2007) which had a default chord length of 1 meter. These coordinates were multiplied by the required chord length to obtain the X and Y coordinate values for an airfoil with a chord of 6.35 meters. This is comparable to the chord value of industry standard commercial transport aircraft. Hence the computational analysis was carried out at a zero degree angle of attack with Mach number ranging from 0.5-0.8 to simulate cruise flight. The lift and drag coefficients from the flap deflection cases were compared with the baseline plain airfoil to analyze the effect of flap deflection on airfoil flow properties. Since the flow velocity ranges from subsonic into the transonic regime, hence the critical Mach number of the airfoil has been calculated. It has been observed from the Figure 1 that the minimum value of C_p on the airfoil surface is $\mathbf{C_{p\ min}= -0.6.}$ This value of C_p is taken at low speeds where the flow is essentially incompressible and hence to be considered that $\mathbf{C_{(p,\ 0),\ min}= -0.6.}$ The critical Mach number $\mathbf{M_{cr}}$ now be obtained by a trial and error iterative process using the following equation from (Clancy, 1986; Anderson, 1999):

$$\frac{C_{p,0}}{\sqrt{1-M_{cr}^2}} = C_p = \frac{2}{\gamma M_{cr}^2}\left(\left[\frac{2+(\gamma-1)M_{cr}^2}{\gamma+1}\right]^{\frac{\gamma}{\gamma-1}}-1\right)$$

Where $C_{p,\ 0}$ = -0.6 and γ = 1.4.

Table 1 shows that the fifth-place accuracy, when M_{cr} = 0.68858, both the left and right hand sides of equation agree, accurate to fifth-decimal place. Hence, from the analytical solution, we have: M_{cr} = 0.68858.

3. RESULTS AND DISCUSSION

3.1. Plain Airfoil Configuration

The Figure 2(a), Figure 2(b) shows the flow around the airfoil without flap deflection at a Mach number of 0.5 and 0.8. It has been observed that the flow is typical laminar throughout the region around the airfoil. The Figure 2(b) clearly shows that the stagnation point at the airfoil leading edge and the subsequent flow expansion over the top surface with its attendant pressure drop. Moreover the same analysis has been carried out for Mach number 0.6 to 0.8 and the airflow shown similar qualitatively behavior till a Mach number of 0.8. It has been reported from Figure 3 that the flow transitioned into the transonic regime. Attached shockwaves are present on both upper and lower surfaces of the airfoil. From the series of computational analysis carried out for plain airfoil configuration shows that coefficient of lift increases from Mach number 0.5 to maximum value of 0.48 then drastically decrement of C_L after Mach number of 0.7 has been reported from Figure 4. Similarly the Coefficient of drag also Increased suddenly after the Mach number 0.7. The reduction in lift and large increase in drag has been attributed to flow transition from subsonic to transonic and the transition back to subsonic flow occurs through a shock. The sudden increase in pressure after the shock caused the boundary layer to separate, with correspondingly large increases in drag and sudden decrease in lift.

3.2. Flap down and Flap up Configuration

The effect of the miniature trailing flaps has been also numerically analyzed over the Mach number ranging from 0.5 to 0.8. In the case of flap up and flap down positions, the Figure 5(a), Figure 6(a) shown that the flow is laminar throughout the region around the airfoil for the low subsonic Mach number. However as the flow exceeds the critical Mach number (0.8) strong shock wave appeared over the suction side of airfoil in case of flap down position as presented in Figure 5(b). The flap up position has been shown a similar trend of attached shockwaves on suction and pressure side as in case of airfoil without MiTEs. Similarly the same analysis has been carried out for Mach number 0.6 to 0.8 and the airflow shown similar qualitatively behavior till a Mach number of 0.8. This behavior on the pressure side of airfoil is due to presence of MiTEs which control the adverse pressure gradient in the flow direction. The measured lift and drag characteristics for the flap up and flap down configuration are presented in Figure 7. The C_L, C_d reported in the flapped configuration are shown linear variation over the Mach number ranging from 0.5-0.7 and then followed by stall with sudden increased in drag. As the flap is deflected in respected positions, the pressure gradient between the upper and lower surfaces of trailing edge of the airfoil is reduced. This result in a slight displacement of the stall and resulting in the increment of lift coefficient. The Increased C_L and C_d reported in Figure 8 for MiTEs up position are attributed to induced twin vortices at the trailing edge which alter the Kutta condition at that point and thus cause the flow to separate well before the trailing edge. This does impose an additional drag penalty, but its effect in real flight is minimal due to the small size of the flaps. Once the Mach number exceeds the critical Mach number, shock waves develop on the airfoil surface and greatly reduce flap effectiveness. The action of the MiTEs in increasing or reducing lift differs from traditional control surfaces or high lift devices. The MiTEs do not increase wing area or change the effective camber of the airfoil as is the case with conventional devices. As reported in the Figure 9 that the MiTEs indicates the formation and convection of an unsteady vortex in the lower and upper surface of the airfoil, right after MiTE deployment which alter the Kutta condition at that point and thus cause the flow to separate well before the trailing edge.

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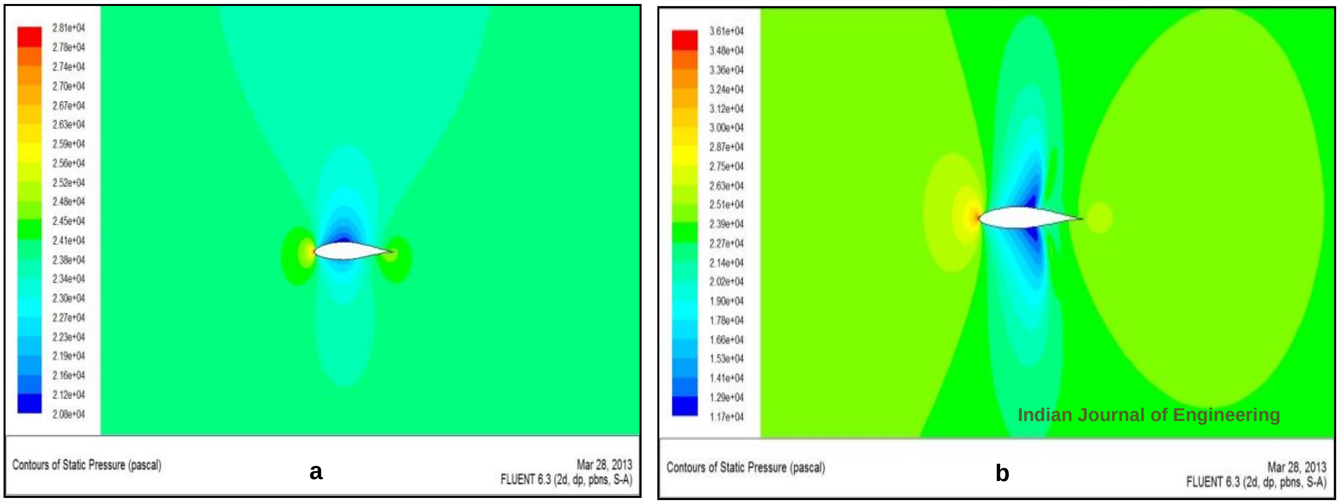

Figure 2

Contour plot of static pressure (a) Mach number =0.5, (b) Mach number=0.8

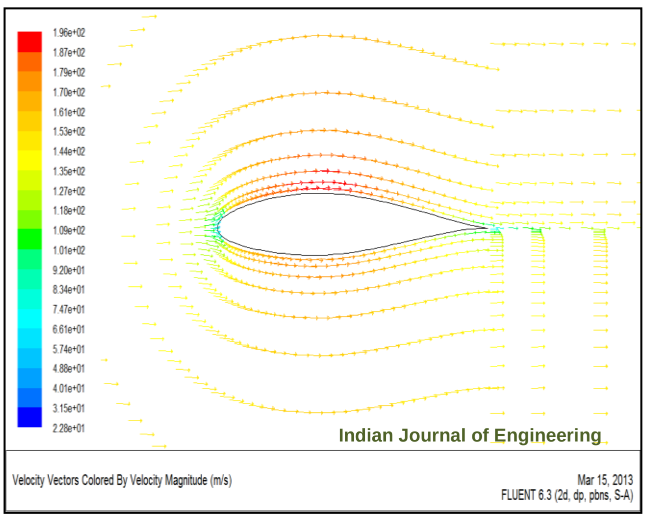

Figure 3

Vector plot of velocity at Mach number 0.5

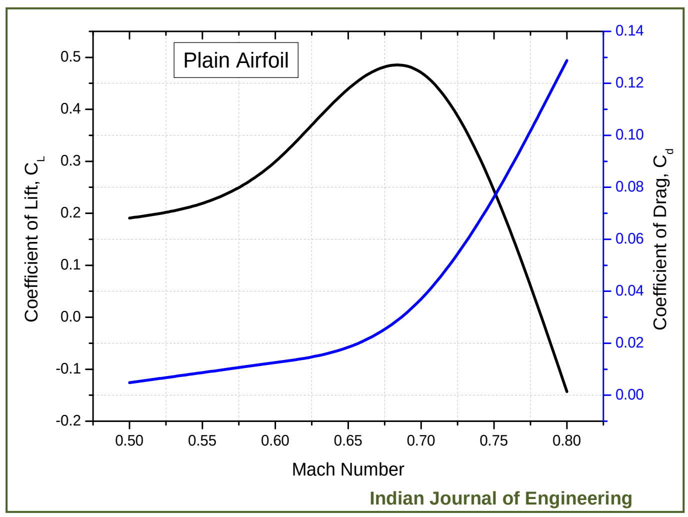

Figure 4

Variations of C_L and C_d with Mach number

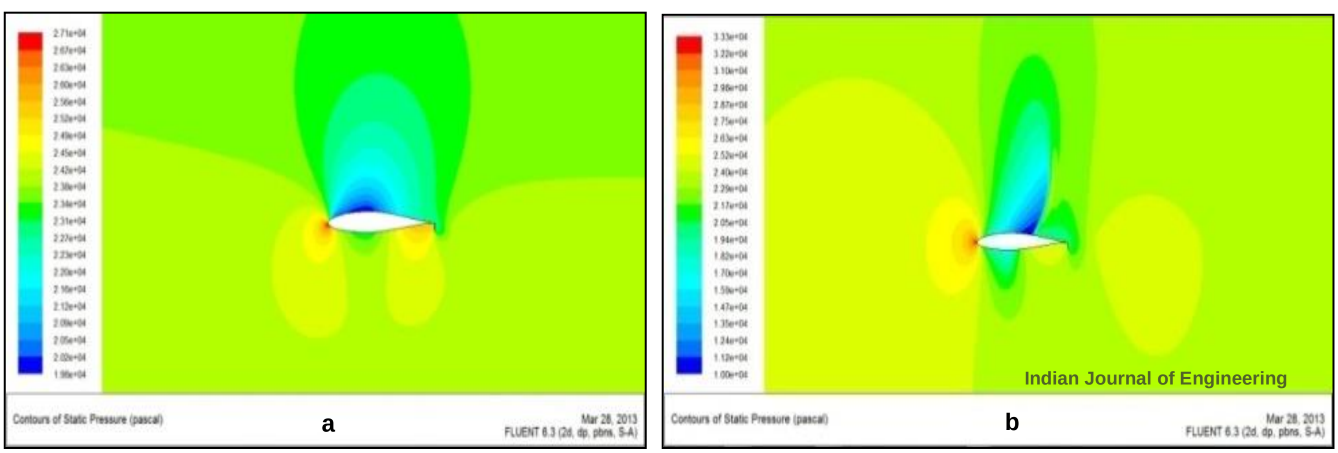

Figure 5

Contour plot of static pressure in flap down (a) Mach number =0.5, (b) Mach number=0.8

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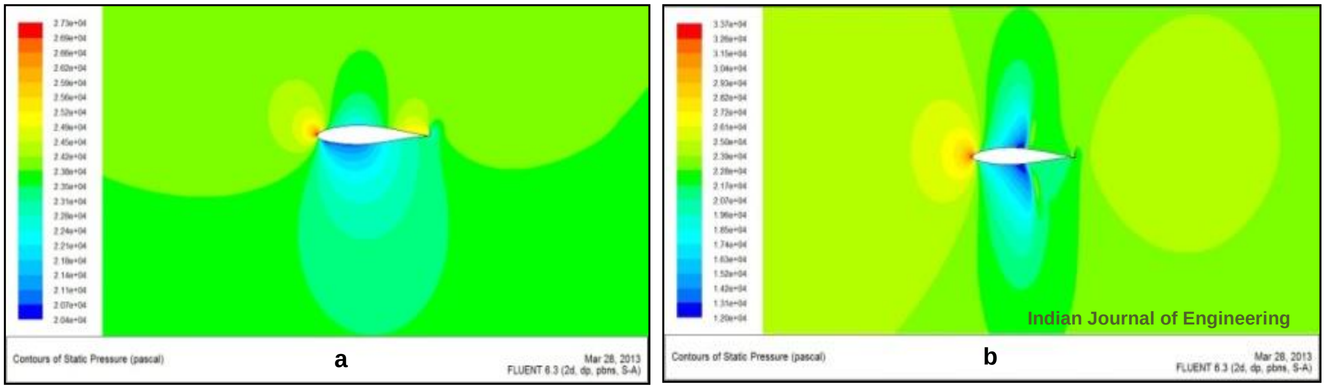

Figure 6

Contour plot of static pressure flap up (a) Mach number =0.5, (b) Mach number=0.8

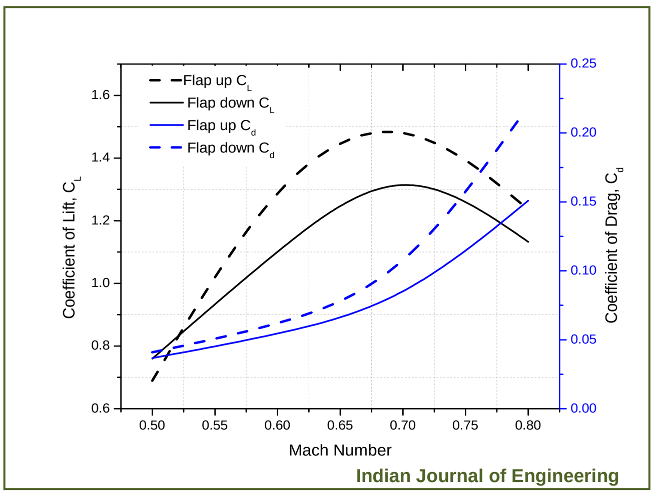

Figure 7

Variations of C_L and C_d with Mach number

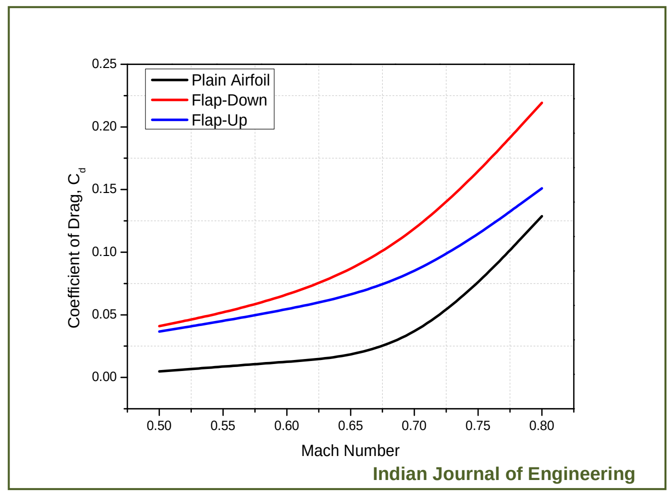

Figure 8

Variations of coefficient of drag (C_d) with Mach number

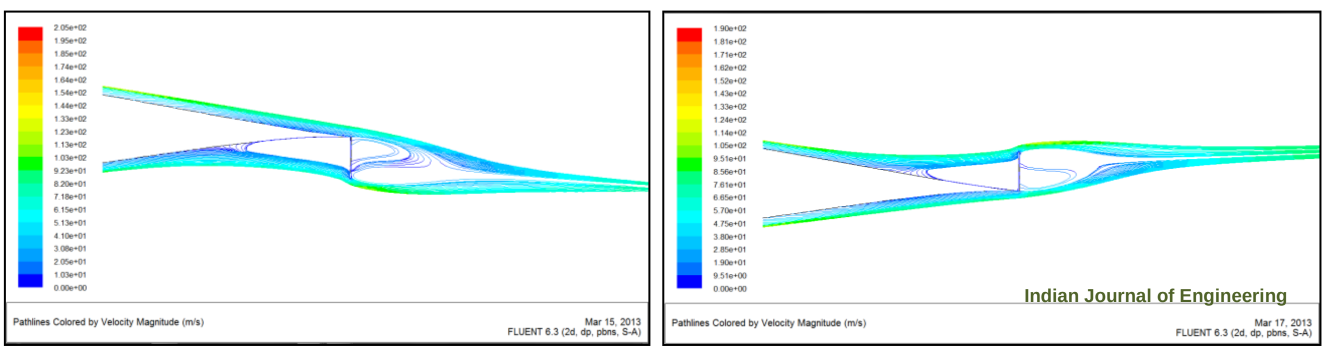

Figure 9

Vector plot of velocity for flap up and flap down position

4. CONCLUSION

The effectiveness of the MiTEs concept has been analyzed and evaluated. The use of MiTEs on commercial jet transports is viable due to the large control forces it exerts on the aircraft structure. The capability of MiTEs to act as an integrated control system and handle the functions of various components simultaneously is definitely an improvement over current control system design. The C_L, C_d reported in the flapped configuration are shown linear variation over the Mach number ranging from 0.5-0.7 and then followed by stall with sudden increased in drag. The Increased C_L and C_d reported in figure for MiTEs up position are attributed to induced twin vortices at the trailing edge which alter the Kutta condition at that point and thus cause the flow to separate well before the trailing edge. The MiTEs indicates the formation and convection of an unsteady vortex in the lower and upper surface of the airfoil.

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Lee et al. 2004:
Miniature trailing edge effectors (MiTEs) are small aps (typically 1% to 5% chord) actuated with defection angles near 90 degrees. The small size, combined with little required power and good control authority enables the device to be used for both high bandwidth control and conventional attitude control. Numerous experiments and computational simulations have been conducted for two dimensional airfoils with miniature aps. However, the three-dimensional characteristics of these devices haven't been extensively investigated. The present study examines the three dimensional aerodynamics of MiTEs using an incompressible Navier-Stokes solver. The overall change in lift induced by the aps as well as the lift distribution along the span is investigated. In addition, the efect of gaps between the aps is examined.

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