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Qualitative Investigation of the Dynamics of a Leading Edge Control Surfaces for MAV Applications

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ABSTRACT

Conventional control surfaces mounted on wing trailing edges actuated with commercially available servos have not been able to achieve sufficient control authority and rapidity to keep small MAVs flying straight and level in turbulent flow. Non-conventional leading edge control surfaces are investigated as an alternative actuation solution with the potential to enhance control authority and rapidity. In this study, flow visualization of leading edge control surface revealed that higher deflection rates delayed flow separation and this is expected to enhance control forces. Higher actuation rates produced dominant leading edge vortices and hence a transient lift enhancement over the airfoil. Lift spikes from high rate actuations could be exploited to compensate for the high frequency perturbations from gusts.

1 INTRODUCTION

Small Micro Air Vehicles (MAVs) are generating high level of interests in the unmanned sector of aviation because of the diverse range of reconnaissance, surveillance and package delivery missions these lightweight systems can fulfill. However their miniature size and flight environment introduces a range of flight challenges primarily due to the relatively high levels of turbulence present at low altitudes where MAVs operate [1–6]. High frequency energy content in turbulence has the ability to rapidly accelerate and rotate these lightweight systems [7, 8]. When attempting to attenuate these deleterious effects of turbulence the actuation rate of conventional fixed wing control surfaces has been found insufficient to adequately compensate for the disturbance inputs. This is due to the relatively higher aircraft frequency response required by MAVs, coupled with the limited control authority and actuation power. Existing control surface placement and turbulence response systems do not have sufficient power and rapidity to overcome perturbations in turbulence to a level where MAVs can fly steady in urban environment [9] .

A range of passive and active methods have been explored to address this issue of poor attitude control in MAVs. Passive methods involve the aircraft's natural ability to produce the aerodynamic forces to achieve stability, through design features of the aircraft (eg., wing sweep, dihedral etc). Existing literature show that these techniques can only attenuate low frequencies of perturbations while limiting maneuverability and agility [10]. Active methods in contrast refers to the use of a control system, that goes through a Sense (detect turbulence ahead of the aircraft), Plan (consider desired control surface deflection ahead of time) and Act (aerodynamic actuation) cycle [11], see Figure 1. It is near impossible to manually fly these aircraft in turbulence [12]. Many MAVs require control input rates higher than 25 Hz [13], which is beyond the bandwidth of human operators [14]. Employment of an active attitude control system is therefore vital as a microcontroller can provide higher input control rates than human pilots.

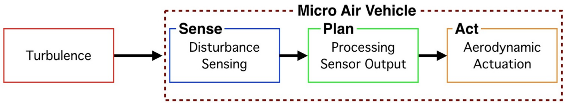

Figure 1: Control system's process for controlling MAV in turbulence, adopted from [15]

Despite active turbulence mitigation techniques such as Phased Advanced Sensing [9] and Real Time Pressure Sensing [16] showing promising results in the Sense and Plan component of the SPA cycle, it was found that conventional designs and control surfaces (i.e. mounted on the trailing edges of flying surfaces) could not achieve sufficient control authority and response to keep small unmanned craft flying straight and level in turbulence [9]. This is primarily due to the lower than required speed of mechanical actuator and small control surface of MAVs.

Potential solutions for increasing the control authority lay in the use of control surfaces that are hinged on the leading edges of wings. These provide an unstable hinge moment where the fluid is driving the actuator (forcing a passive moment), rather than resisting against it, contrary to the situation with conventional control surfaces. Concerns with the unstable nature of such Leading Edge Control Surfaces (LECS) mean that they have not been used on larger manned aircraft. However the relatively low loads on fixed wing MAV, coupled with the requirement to operate controls at much higher frequencies than manned aircraft, make them potentially

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*Email address(es): ashim.panta@rmit.edu.au useful for rapid maneuverability and turbulence rejection. As a result it might be possible for leading edge devices to be used more freely for MAV applications and could provide an insight and solutions to the controllability issues of MAVs.

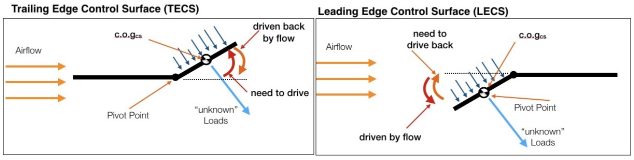


Figure 2: Free body diagram of trailing edge (left) and leading edge (right) control surfaces

Trailing Edge Control Surfaces (TECS) need power from an actuator to rotate a control surface from a neutral position to a deflected position in order to generate an aerodynamic control, see Figure 2. At this deflected position there is a restoring moment from the flow, which could be used to drive the surface back to its neutral or un-deflected position, thus potentially no actuator power is required for this part of the motion. LECS can use the flow to drive the control surface from its un-deflected position to a predetermined deflected position (i.e. there is no need for servo actuation for this part of the motion) but an actuator is needed to bring the control surface back to a neutral position and to hold it in position. So there are potential disadvantages present with the proposed solution. The complex dynamics of a LECS for low Reynolds Number (Re) ($\leq$150,000) flight is not well understood in the current body of literature. Thus the feasibility of using such system for MAV controls (to improve control authority and response) cannot be dictated without further investigation.

1.1 Low Reynolds Number Leading Edge Aerodynamics

1.1.1 Static Effects

Though the use of leading edge control surfaces for primarily control is not common, the use of leading edge devices to enhance performance is a well explored concept. Airfoil performance may be enhanced by management of boundary layer using leading surface roughness, suction or blowing. Adverse effects of separation bubbles and bubble burst (which can dominate the flows at low Re) can be overcome by various means. Transition control can be done by advancing the transition or maintaining the laminar flow both of which can suppress flow separation bubble effects [17]. At low Reynolds Numbers, flow separation occurs near the leading edge, thus it is common to employ a leading edge flow control mechanisms in order to main attached flow at high angles of attack. A thorough review of flow control mechanisms is presented by [18] to control the leading edge vortices on delta wing aircraft. Along with blowing, suction and unsteady excitation techniques the author suggested the use of leading edge control surfaces.

A study by [17] found statically deflected leading edge flaps (much like Kruger flap) enhanced aerofoil performance by augmenting lift and limiting drag at certain angle of attack. These flaps acted like a transition device preventing the formation of separation bubbles. A range of accepted flow control methods for low Re was reviewed and the most promising method was to passively design such that the (leading edge curvature, camber and thickness) severity of adverse pressure gradient forces transition to the desired location. This study was inspired by the findings of leading edge control surfaces (flaps) in natural flyers much like the study by [19]. It was found that at Re of 40000 - 120000 the addition of a leading edge flaps showed distinct performance enhancement at angle of attack ($\geq 20^0$). The leading edge flaps were found to increase the baseline airfoil's lift by up to $C_l = 0.52$. Further use of leading edge flaps as flow control mechanism can be found in [17–25].

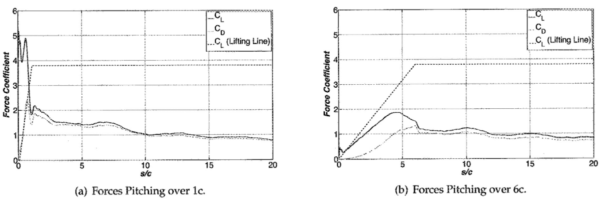
1.1.2 Dynamic Effects

MAVs must be capable of executing agile and aggressive maneuvers at highly unsteady dynamic conditions. In unsteady flow, lift generated is contributed from circulatory and non circulatory components. Circulatory components include Leading Edge Vortices (LEV) and bound circulation while non-circulatory forces are brought about the wing's acceleration and added mass. Leading edge devices are good to generate vortical structures that have significant contributions to the overall force production on an airfoil. Examples of these are observed in natural flapping flyers such as birds and insects [26]. Thus recent research in the unsteady aerodynamics associated with MAV flights has been increasingly focusing on LEVs. LEV is a physical flow phenomenon that generally occurs during a dynamic stall; i.e., when an airfoil, rapidly pitched up beyond its static stall angle generates a dynamic stall vortex, causing the lift coefficients to increase beyond its maximum value for the un-stalled case. LEVs are well studied in various aerodynamic contexts such as retreating helicopter blades or super maneuverable aircraft [27]. In the unsteady low Re regime the LEV is believed to contribute most to the lift generation [28]. As MAV flight requires rapid controls to maneuver in and around obstacles and to overcome turbulent disturbances, MAV flow physics is highly unsteady. Thus the formation of LEV have a significant influence in providing high lift coefficient for MAV applications [29]. Since rapid pitch or flapping motions occur on a smaller time scale than the development of full stall, this enhancement is exploited by small airborne creatures and is of interest for designing agile MAVs [27, 30].

A LEV generates lift increment through the low pressure region induced from the vortex core on the upper surface of the wing and provides short term enhancement of lift whilst remaining attached to the wing. LEVs are created when the adverse pressure gradient and viscous shear stresses create flow separation which causes a vortex to break away from the leading edge of the airfoil. LEVs can follow along the chord (desired) or break away from the airfoil (detrimental) [31]. At high angles of attack LEVs make significant contribution to the total lift of the wing [32]. Studies by [32] suggested the possibility of generating appreciable pitching and rolling moments for flight control. LEVs were found to shed at increasing rates for increasing Re and angle of attack in low Re [33].

1.1.3 Effects of Actuation Rates

Actuation rates also have a significant influence in unsteady force production over an airfoil. A study on a rapidly pitching flat plate wing found that the starting LEV is more pronounced at higher reduced pitch rates [34]. The lift peak was found to correlate with the maximum size of the LEV before its shedding and downstream convection [35]. A study by [36] also found that fast pitch rate enhanced the forces during the rapid pitch motions. It was found that the development and convection of LEV is linear until eruption. Attached flow from fast pitch correlates to higher force coefficients than slow pitch, where flow is quasi steady. Figure 3 from [36] shows the lift characteristics as a function of pitch rate. Furthermore investigation of a NACA 0015 airfoil pitching constantly at the mid chord by [37] measured time varying pressure drag and moment coefficients as a function of angle of attack. This study also found that higher pitch rates had dramatic positive effects on both the delay of stall and the magnitude of maximum lift coefficients, Figure 4.



(a) Forces Pitching over 1c.

(b) Forces Pitching over 6c.

Figure 3: Force coefficients for fast and slow pitch rates [36]

1.2 Objectives

The little work surrounding the low Re aerodynamics of leading edge flaps suggests that these devices improve the airfoil performance. However a comprehensive understanding of the fluid dynamics of a leading edge flap (as opposed to rapid motion of an entire airfoil) and the effects of flap deflection angles and rates on the overall force production in unsteady cases were not well established. Thus the objective of this paper is to establish qualitative perspective on the flow structures formed behind a LECS. To get an insight into the fluid mechanics associated, flow visualizations for various control surface deflection angles and airfoil angle of attack were investigated for static and dynamic deflections.

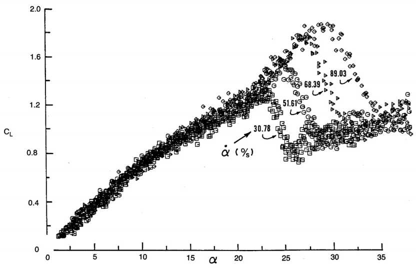


Figure 4: Coefficients of lift at various pitch rates [37]

2 EXPERIMENTAL APPARATUS

2.1 Wind Tunnel Setup

An insert box was manufactured to give nominally 2D flow across the span of a flat plate airfoil in the RMIT Aerospace Wind Tunnel. The tunnel is closed-return and has a hexagonal test section of 2.1m, 1.3m and 1.1m [LxWxH]. The insert box was fully transparent for a controlled 2D airfoil experiment while allowing video data acquisition. The insert was a Plexiglass box of 1m x 0.5m x 0.5m. The flat-plate airfoil used was 1% thick and featured a rounded leading edge and a blunt trailing edge as documented by [38, 39]. Trailing edge geometry is known not to have a strong effect on the lift and drag at low Re. The chord was 135 mm; a size typical of a fixed wing MAV. The flat-plate leading edge control surface was 30% of the chord with a similar thickness. The wing was mounted horizontally across the insert box, slotting into rotating dowels on either ends, see Figure 5. The wing was statically fixed but the leading edge control surface was free to rotate about its hinge point (at 30% of chord from the leading edge). The control surfaces were actuated by RJX 1001 servos (mounted on the wing) using an externally positioned Arduino board. Position feedback of the servo was attained from tapping the servos potentiometer.

2.1.1 Pitching Kinematics

Three different cases of control surface deflections were analyzed; a static deflections and fast and slow deflections based on reduced frequency k, [31]

$$k = \frac{\omega c}{U} \tag{1}$$

Unsteady effects increases with increased reduced frequency. ω is circular frequency (rad/s), U ref is reference velocity (m/s) and c is chord (m). The fast pitch motions were done at 1200 deg/sec (k=0.14) and slow pitch at (k=0.0017) at 15 deg/sec at Re of 30,000. Typically this involved the wing positioned at a certain angle of attack, and the control surface being accelerated at a constant rate from 0^0 to a maximum of $\pm 30^0$.

2.2 *Flow Visualization*

A 0.15 mm diameter nichrome wire was mounted vertically across the insert box in order to generate multiple smoke filaments. The wire was heated electrically (30V at 0.6 Amps) in order to vaporize a mixture of iron powder and glycerin. A Phantom Miro M310 high-speed camera was mounted from above focusing on the smoke filaments. Recordings were done at 1280 x 720 pixels with sample rate of 1000 fps.

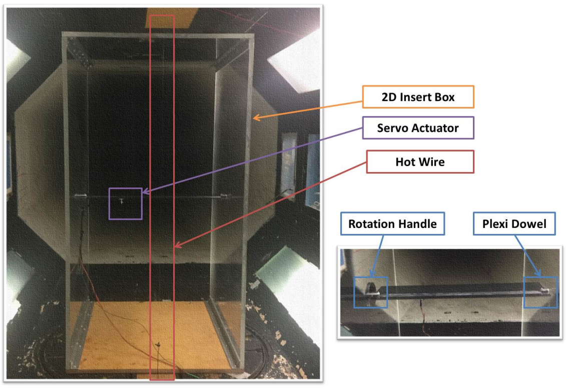


Figure 5: Wind tunnel setup for flow visualization

3 STATIC ANALYSIS

Figure 6 shows the flow over the airfoil at zero-angle of attack with controls undeflected. Flow features were found to correlate well with existing literature on flat plate airfoils at low Re, including the von Karman vortex sheet seen in Figure 6, due to the blunt trailing edge shape [38, 39].

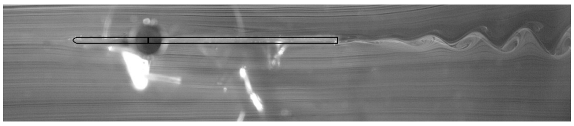


Figure 6: Flow over the wing at zero incidence

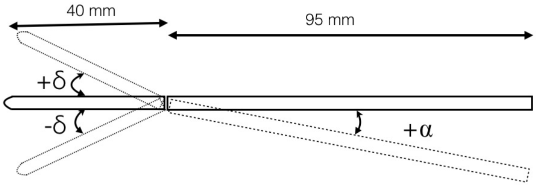


Figure 7: Sign convention, δ = flap deflection angle, α= angle of attack

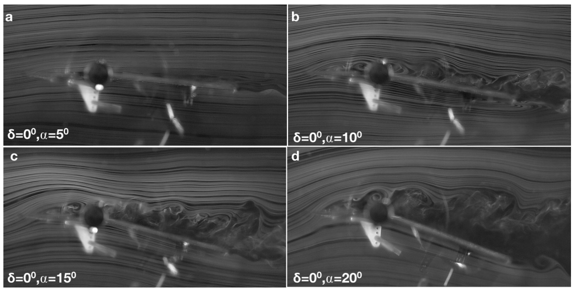


Figure 8: Flow over the wing at various incidence angles

For all positive deflections of the control surface (δ), the flow remained attached over the entire lower (pressure) surface for all angles of attack (α) tested. As expected from symmetry, all - δ deflections displayed an attached flow over the upper side for α angles up to 20 degrees. During δ deflections, the flow remained attached on the entire lower surface, up to 5^0 α. At higher incidences thin airfoils are subject to leading edge laminar separation due to the pronounced suction peak shortly downstream of the leading edge. This was clearly seen in Figures 8 b-d in which a Laminar Separation Bubble (LSB) formation is visible. The change in pressure distribution due to LSB formations generally lead to decreased lift while increasing drag [40]. LSBs seen in Figures 8 b-d are relatively small in dimension and are considered short" bubbles which do not significantly alter the pressure distribution around the airfoil [41, 42].

4 DYNAMIC ANALYSIS

Dynamic actuation of the LECS is analyzed in this section and flow patterns are compared with the static cases. A wide range of α's were tested and only the most significant variation in between static and dynamic deflections are presented. Images from the static case in Figure 8 were captured at an arbitrary time when the flow was fully developed over the airfoil. Whereas the images from the dynamic cases presented in Figures 9-12 were captured as the LECS reached the desired deflection angle.

Figure 9 shows the comparison of flow over LECS and wing for the three cases; static, slow actuation and fast actuation. For the cases of $\alpha = 0^0$ rapid actuation significantly changed the location of the stagnation line on the upper part of the control surface, promoted flow attachment on the lower surface and completely removed the flow separation on the lower surface of the airfoil. For the cases of $\alpha = 10^0$ rapid actuation promoted separation on the upper part of the control surface with a reduced region of separated flow over the upper surface of the airfoil. The flow over the upper surface was moderately attached during low δ deflections for $\alpha > 10^0$.

Beyond that, formations of dominant Leading Edge Vortices (LEV) were visible at the fastest deflection rate (Figure 9). The flow on the upper surface was found to be of complex nature and thus requires quantitative investigation of the pressure/forces on the airfoil. Thus the actuation rate of the LECS significantly influenced how the flow behaves and is expected to significantly alter the dynamic control forces on both control surface and airfoil.

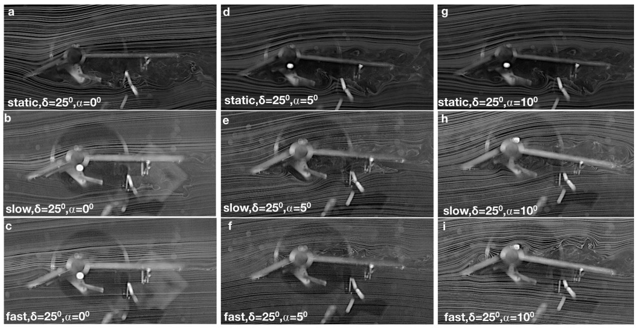


Figure 9: Comparison of flow during a static case and actuation rates of k=0.0017 (slow) and k=0.14 (fast) during negative flap deflections; a-c: increasingly actuation rate for 0^0 angle of attack (AoA) , d-f:increasingly actuation rate for 5^0 AoA, g-i:increasingly actuation rate for 10^0 AoA

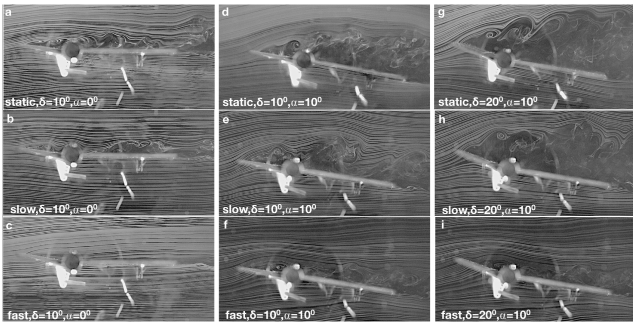


Figure 10: Comparison of flow during a static case and actuation rates of k=0.0017 (slow) and k=0.14 (fast) during positive flap deflections; a-c: increasingly actuation rate for 0^0 AoA, d-f:increasingly actuation rate for 5^0 AoA, g-i:increasingly actuation rate for 10^0 AoA

Observing both Figure 9 and 10, it is clear that both slow and fast actuation cases reduced the amount of flow separation on both the pressure and suction surfaces. The reduced flow separations on both surfaces of the airfoil were more noticeable during the fast actuation cases. An investigation of the effects of rapid actuation rates on a conventional TECS configuration by [43] also found that flow separation was delayed with faster deflection rates. Direct force measurements in a water tunnel demonstrated that the total lift coefficient responded immediately upon initiating the deflection of the control surface [43]. This implies that the attached flow found in this qualitative investigation suggests more lift production. However, these benefits reduce once the flow develops back to its common static state.

Whilst fast pitch was found to produce more dominating LEV, slow pitch was found to be largely separated and featured small LEV sheds (Figure 9). During a fast linear pitch classical LEV is formed, dominating the flow. It is hypothesized that pitch component of a shear layer aids the LEV formation. At slow pitch rates the flow was generally separated and dominance of LEV was not seen. Development of upper surface flow and LEV was strongly correlated with the kinematics of the leading edge, suggesting that local angle of attack at leading edge is of high significance in unsteady pitching motions. Investigations of the effect of pitch rate on the LEV size were done by [29, 44, 45]. In these investigations it was found that increasing the pitch rate delayed the formation of LEV on the upper surface, and made LEV more compact and stronger. While a fast pitch motion produced classical (dominant) LEV slow pitch motions lead to non dominating LEV structures where flow seemed largely separated with small LEV sheds. These findings correlate well with the qualitative results presented in this paper, Figure 9 and 10.

Results presented in this paper indicate that actuation rate of LECS have a significant influence on the flow structures, especially the LEVs, which can be related to the lift enhancement on the wing. This implies that higher deflection rates produce departures from quasi-steady response due to the lift contributions from the circulatory components, enhancing force production during the deflection phases, while slow deflection rates can be expected to be closely quasi-static. Thus it can be concluded that the flow structures are a strong function of pitch rates and that higher pitch rates means higher the angle of attack before the beginning of flow separation and more energetic suction peak. Thus higher deflection rates have significant effects on both the delay of stall momentarily and the magnitude of maximum lift coefficients.

4.1 Flow Characteristics over time

Figure 11 displays a time history of the control surface when exposed to smoke flow stream lines. Three separate angle of attack angles are shown. The time sequence displayed is post full deflection to investigate the flow mechanics directly after the leading edge deflection. The formation of LEV initiates as the control surface motion completes and remains in a deflected state. The maximum defection angle of the control surface was 30^0. In all cases the leading edge deflection activates the formation of a LEV. LEVs are seen to grow in size as they convect downstream with the flow. As the angle of attack is increased, the convection rate of the

LEV is more aggressive on the suction surface of the airfoil. The LEVs are seen to grow however this growth is disrupted when the vortex enters into the favourable pressure gradient. This occurrence is more pronounced in the higher angles of attack with the vortex almost non-existent in the final frames. LEV on the upper surface were found to traverse faster with increasing angle of attack, see Figure 11.

Experiments where performed in the same manner with actuating opposite deflection increasing the angle of attack of the airfoil (see Figure 12). In this case a LEV was only produced on the upper surface where suction pressure exists. The bottom surface did not show visible signs of LEVs due to the effect of the favorable pressure gradient. The generation of the vortex was more pronounced relative to the downward deflection presented previously. This suggests significant increases in lift generation. This increase is short lived as the vortex and surrounding flow return back to a steady flow scenario. Short lived LEVs shown here may provide a means to increase the amount of lift which exceeds what could be achieved with conventional trailing edge control surfaces. The fact that the flow is unsteady and returns to a steady state case means that this actuation may only be viable if done at high frequency and allowed to return to the non-deflected state. Further experiments are needed to evaluate this hypothesis however the strong creation of the LEV suggest that the lift gains may be significant enough for further experiments to quantify the time varying changes in lift.

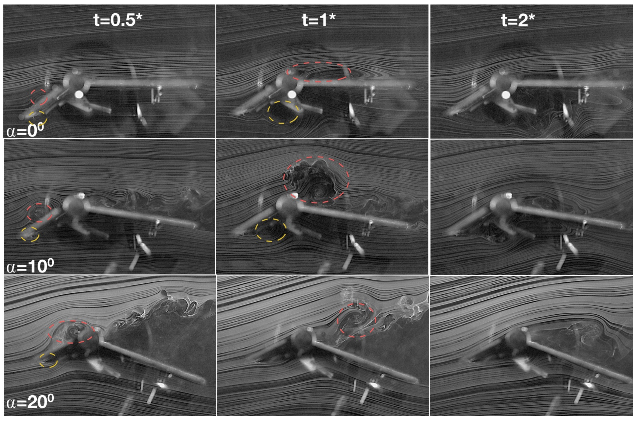


Figure 11: Flow over the wing against characteristic time during negative LECS deflection

5 CONCLUSION

Through flow visualization experiments it was found that increasing actuation rates on leading edge hinged control surfaces promoted flow attachment on the airfoil, thus could be a potential solution towards achieving high responsiveness and authority required for steady MAV flight in turbulence. The effect of leading edge flap deflection rates at varying wing angles of attack were studied. It was found that higher deflection rates produced a more dominant LEV, which grows significantly as it traverses across the chord of the airfoil. This is expected to provide a significant transient lift increment due to the presence of the low pressure vortex core on the upper surface of the airfoil. The size and development of the LEV at different deflections rates suggest correlation between quantifiable increases of incremental lift and LECS deflection rates.

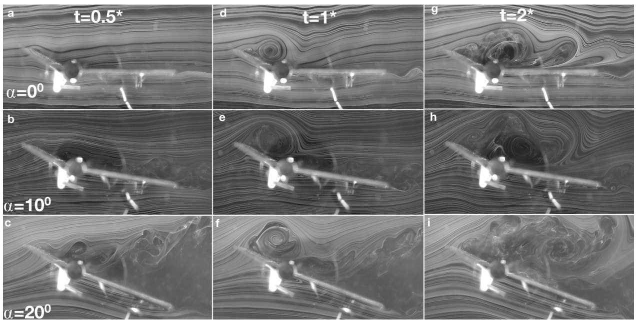


Figure 12: Flow over the wing against characteristic time during positive LECS deflection

Furthermore the study suggests that faster LECS actuation leads to greater transient lift production. The return of the LECS to its nominal position will be studied in ongoing experiments. The dynamic influence of a returning LECS (to original position) may uncover other fluid dynamic phenomena which must be accounted for in the overall system. Another quantity which must be accounted for is the effect of control surface mass and how rapid actuation causes secondary forces in line with Newtons third law. The effects of virtual mass are also assumed to have an influence on the force production when LECS are rapidly actuated. Controlling the formation of convection of LEV across the airfoil using a LECS could potentially lead to production of large control forces. It is hypothesized that LECS could hold the key in offering the high-frequency mitigation while conventional control surfaces (hinged at the trailing edge) handle the low frequency disturbances. Further work is needed to understand the generation of these transient pressures and control forces for MAV flight in turbulence. This is part of planned future research (potentially from force and pressure measurements). The potential of this control methodology could serve micro flight applications well as high-frequent response rates are needed to mitigate high frequency perturbations.

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