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Numerical simulation on aerodynamic performance of bird-like flapping wing with slotted-tip

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Abstract

Birds are highly capable and maneuverable fliers, and some of their unique traits are still not currently shared with current small unmanned aerial vehicles. One feature of bird wings, wingtip slots, where the outer primary feathers of birds split and spread vertically, are considered a product of improving the aerodynamic performance during the evolution of birds. It is essential to draw the optimal layout of the wingtip by studying the effects of its parameters on aerodynamic characteristics of the wing and apply it to flapping-wing MAV's design process. In this paper, the Reynolds-Averaged Navier-Stokes method (RANS) is utilized to investigate the mechanism of the effects of biomimetic slotted wingtips with different geometrical parameters (number of slots) and spatial distribution parameters (dihedral) on tip vortex structure and aerodynamic performance. After grid independence verification is accomplished, parametric geometric models of the biomimetic slotted wing are established and computation meshes are calculated. Based on models established in this paper, the results show that wingtip slots can retard the chordwise pressure gradient of the wing and mitigate wing stall, thus reduce the complexity of flight control and sensitivity to flight control errors. Adding dihedral to slotted wing gets better stall mitigation, while obtains lift increase and drag reduction in the pre-stall region, thus increases the lift-to-drag ratio, which is helpful to improve gliding capabilities under the limitation of wing span. The slotted wing tip with 45° dihedral can increase lift by 2.2%, reduce drag by 7.7%, and increase the lift-to-drag ratio by 10.3%. Meanwhile, maximum achievable lift and longitudinal stability of non-planar slotted wing obtain considerable improvement.

Keywords: wingtip slots, low Reynolds number, numerical simulation, number of slots, dihedral

1. Introduction

In a long-term natural evolution, birds have gradually formed wing shape and bone structure suitable for efficient flight, they can appropriately change wing shape and flapping pattern in a variety of complex ways to achieve mission adaptability during flight, while these capabilities are not available for current MAV (micro air vehicle) [1-2]. Mohamed et al [3] evaluated various factors that prevent MAV from obtaining stable flight characteristics, including low mass, power limitations, low speed flight, and low Reynolds number conditions. Low Reynolds number may be the most significant obstacle to overcome [4-6]. At low Reynolds number, wing performance degrades: lift coefficient decreases and drag coefficient increases. In terms of comparing the aerodynamic efficiency of aircraft wings with bird wings, Withers [7] proved that their performance is similar at low Reynolds number, however, birds behave better than MAVs, especially at high angles of attack. That is to say, we can get inspiration from bird wings to improve MAVs' behavior instead of solely airfoil optimization. In the 1970s, biologists began to study the wing structure of birds. Most birds have prominent and separated feathers at wingtip called wingtip slots, as shown in Figure 1. Slotted wingtips are considered as a feature of improving flight performance after the evolution of birds [8]. Whether wingtip slots can be applied to the design process of MAVs is a pretty worthy research topic.

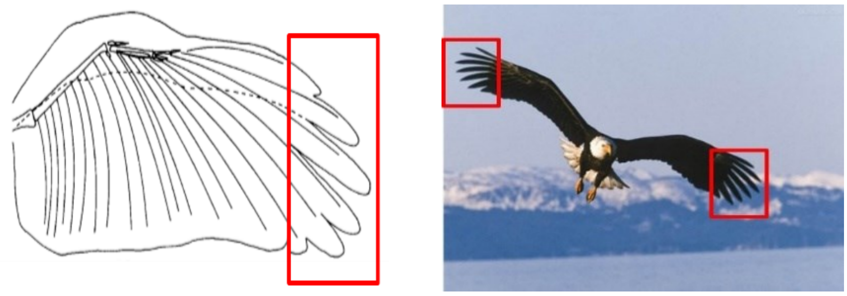


Figure 1 – Wingtip slots of birds [8].

Scholars have speculated for years about the role wingtip slots played in bird flight, besides increasing lift and decreasing drag, delaying stall, reducing noise, preventing feather wear, decreasing wing twist, controlling and stabilizing roll and yaw, improving aeroelasticity property were been suggested. They conducted targeted research on the above guesses, particularly in lift improvement, drag reduction, and yaw stabilization.

In the process of verifying the assumption that wingtip slots have the effect of increasing lift and decreasing drag, the conclusions of researchers are not consistent, even comes to some contradictions. Hence, the rationality and accuracy of the consequence need further research and verification.

Tucker [9] conducted wind tunnel experiments on wings with various types of the wingtip. At an angle of attack of 10.5^{o}, the wing with a feathered tip increased the lift-to-drag ratio from 4.9 to 10.1, and the total drag reduction was found to be 12% compared to the conventional wing with a Clark Y airfoil. To further understand the influence wingtip slots have on bird flight characteristics, Tucker [10] experimented on a Harris hawk glided freely inside a wind tunnel with clipped and unclipped wingtips. The results showed that the total drag was related to gliding speed and the number of wingtip slots. On the whole, the wing drag of Harris hawk with wingtips was smaller than that without wingtips. It was found that the bird with slotted (unclipped) wingtips had a drag reduction of about 70-90% in contrast to the clipped one. Tucker demonstrated that wingtip slots reduced the induced drag of a Harris Hawk wing by acting as nonplanar winglets and spreading the vorticity both horizontally and vertically.

Smith et al [11] examined the aerodynamic characteristics of a slotted wing with multiple configurations. When observing lift force, they found a remarkable increase of straight slotted wing than base wing with the same area. It was found that the slotted wing with appropriate dihedral and twist angle can enhance wing lift and lift-to-drag ratio.

However, the CFD results of Saiteja and Suresh [12] are not the same, they investigated the aerodynamic performance of two wings: one with wingtip slots and the other without. They concluded that there was a decrease in lift coefficient and an increase in the lift-to-drag ratio for the slotted wing as compare with the base wing.

Mitchell et al [13] investigated the influence of slot length on the aerodynamic properties of wings. Wings with various slot length were compared to a control wing to observe the variations in aerodynamic performance. Wingtip slots have a small effect on the lift of a wing. The gains and losses were rather marginal. He presumed tip slots were affected by the operating environment and design purpose and could prove beneficial in the right situations.

Siddiqui et al [14] evaluated how dihedral and flexibility affect the aerodynamic behavior of slotted wings. They aim to figure out the best-performing wingtip configuration among tested wings. The results revealed that rigid wing with curved tip had optimum aerodynamic characteristics, and flexibility has a positive impact on drag reduction and stall delay.

To understand the role wingtip slots play on wings' yaw stabilization behavior, Withers [8] compared the aerodynamic behavior of a slotted hawk wing and a single vulture feather. The results showed that slotted wingtip slightly reduced drag and increased lift, significantly increased yaw moment. He proposed that wingtip had evolved due to improving biomechanical limitations to the bending strength and reducing the propensity for the wingtip stall. Sachs and Moelyadi [15] analyzed the application of sweep wingtip to the slotted wing. They demonstrated that wingtip slots with sweep yields a stabilizing yawing moment of significant magnitude, and substantially increased with the lift coefficient.

The relevant research on wingtip slots is mainly carried out by wind tunnel test. The numerical simulation technique used in the previous research on wingtip slots is limited by the solution method of CFD and the development of computer techniques of that era. Early scholars applied the Euler equation to describe the motion of fluid in numerical simulation, however, the viscosity of the fluid is ignored in the solution of the Euler equation, and there is a big deviation in the data obtained by this method [16]. Furthermore, although Saiteja and Suresh [12] applied the NS equation which takes viscosity into account in numerical simulation, the flowfield was solved in a laminar flow state, ignoring the influence of turbulence. Therefore, the influence of turbulence should be taken into consideration with regard to choosing the solution model.

The goal of this paper is to develop a more complete understanding of how the number of slots and dihedral angle affect the aerodynamic performance of MAVs at low Reynolds numbers. Numerical simulation method will be applied to examine the aerodynamic characteristics of slotted wings. In the following sections, a bio-inspired wingtip design with varying slots number and dihedral angle is presented. The lift coefficient, drag coefficient, lift to drag ratio, and pitching moment coefficient obtained by numerical calculation on various configurations of wingtip are calculated for the range 0°< AoA < 17°. Flow details are examined to obtain further understanding of the control mechanism of wingtip slots. The final section includes a conclusion on the effect of such slotted wing configurations along with proposed future work.

2. Numerical Method

2.1 Model construction

In order to study the influence of the number of slots on the aerodynamic characteristics of wings, five different planar wing designs established in CATIA [17] were developed to allow testing of various planar wingtip planforms. A full range of tests would be performed on the wing at angles of attack ranging from 0° to 17° with each of the five styles of wingtips, as well as no wingtip attached as a control.

(1) Rectangular base wing (without extended wingtip)
(2) Base wing with elliptical tip but no slots
(3) Base wing with one slot tip (two winglets)
(4) Base wing with two slots tip (three winglets)
(5) Base wing with three slots tip (four winglets)

The wings used in these tests and outlined in Table 1 was a simple rectangular wing with a chord length of 0.45 m and span of 1.675 m for a total wing area of 0.75m^2 without wingtip (0.8m^2 with wingtip).

Table 1 – Rectangular wing specifications

Airfoil	NACA0012
Chord (c)	0.45m
Semi span (b)	1.675m
Trailing edge thickness	0.002m
Wing area	0.75m^2
Wing area with tips	0.8m^2

In nature, a bird's wingtip is not a planar configuration, its feathers bend upward in the vertical direction. Therefore, the effect of dihedral angle on the aerodynamic behavior of the wing deserves to be evaluated. Three nonplanar configurations are constructed based on the wing with three tip slots (0° dihedral), which are defined as a slotted wing with 15°, 30°and 45° dihedral angle.

For the simulations, a cuboid fluid domain is constructed. To make sure that confinement effects were negligible the domain was expanded 20c above and below the wing. Furthermore, the domain was extended far enough upstream (30c) and downstream (40c) such that the inlet and outlet boundaries did not affect the flow near the wing. One side of the calculation domain close to the wing root is taken as the symmetrical boundary, and the spanwise far-field boundary is 40c away from the wing root. Inlet and outlet boundary conditions are chosen as velocity inlet with uniform inflow and pressure outlet with zero pressure, respectively. A no-slip boundary condition was applied to the wing.

The definition of wing coordinate system is drafted in Figure 2, the origin of the fluid domain is located at the leading edge point at the root, the x-axis is along the wing chord, the y-axis is along the wing span, and the z-axis follows the right-hand rule. Dihedral is defined as the angle between the plane of wingtip and plane of the base wing.

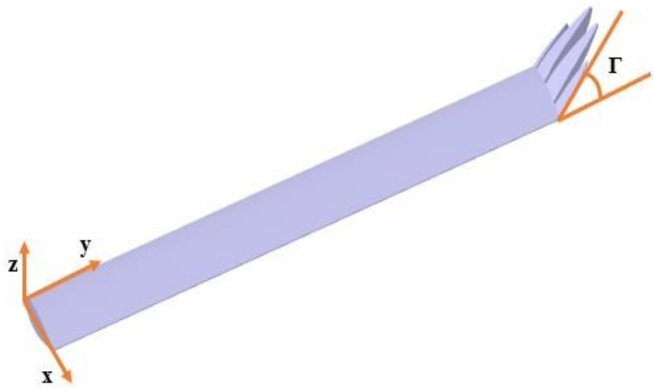


Figure 2 – Definition of wing coordinate system.

For valid comparisons, each wingtip was designed to have a matching area of $0.05m^2$ so as to not affect the overall area of the wing as they were exchanged. One wingtip was a simple rounded tip to provide a baseline for comparisons. The other wingtips were designed to resemble birds' wingtip feathers (or wing slots). In addition, in order to increase geometric constraints to eliminate the interference caused by the change of wingtip shape, the width of slots and the ratio of winglet height to width in each group of tips are the same, as can be seen in Figure 3, Figure 4, and Figure 5.

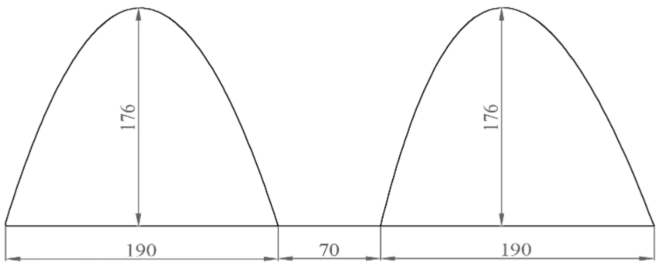


Figure 3 – Geometry size of wingtip with one slot.

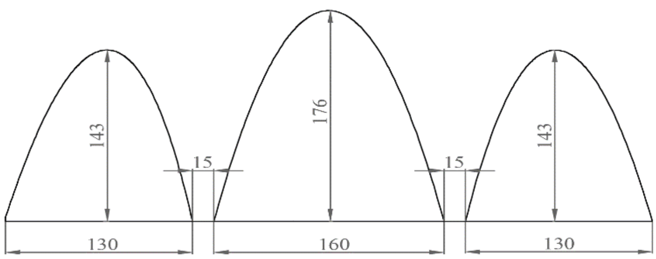


Figure 4 – Geometry size of wingtip with two slots.

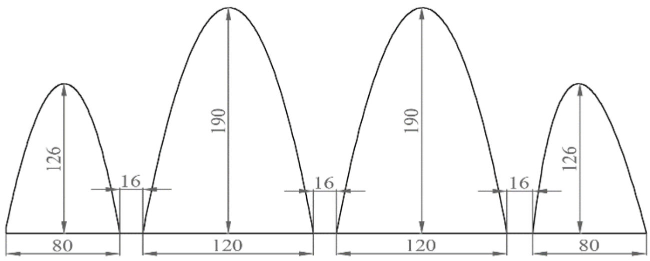


Figure 5 – Geometry size of wingtip with three slots.

2.2 Mesh generation and simulations

Computational simulations are performed by ANSYS FLUENT software [18] to examine the aerodynamic features of slotted wings and to visualize the flow distribution over wings. The steady-state Reynolds-averaged Navier-Stokes (RANS) equations under the constant property, incompressible flow assumption was solved over the computational domain. The k–ω SST turbulence model was chosen for this CFD study and implemented to capture turbulent flow around wingtips. The k–ω SST model can be used as a low Reynolds flow application without extra damping functions. SST stands for Shear Stress Transport, which helps overcome the common problem with the k–ω model that it is too sensitive to free-stream turbulence conditions at the inlet [19]. The k–ω SST model also accounts for its good behavior in adverse pressure gradients and separated flow [20]. The multi-block structured grid approach is adopted in the ICEM CFD software to generate high-quality hexahedral meshes. The upwind-biased spatial difference is used for the convective and pressure terms, and the central difference is used for the viscous terms. A globally second-order precision is retained in both space and time. Temporal sub-iterations with multigrid are employed to reduce the linearization and factorization errors.

The verification of the independence of computing mesh is firstly conducted, the mesh of computed region around the wing is shown in Figure 6, the wingtip which is the focus is implemented more accurate grid node control. The far-field boundary conditions are described as follows: V = 14 m/s, ρ = 1.225 kg/m^3, μ = 1.7894e-05 kg/(m·s), Re = 3.0×10^5, and at the atmospheric pressure of 101325 Pa. To accurately capture the gradients in the boundary layer, a great number of elements were placed near the baseline's outer surface. The first height of the near-wall is about 0.00003 m, y plus value was taken to be 1, which is consistent with the k–ω SST turbulence model.

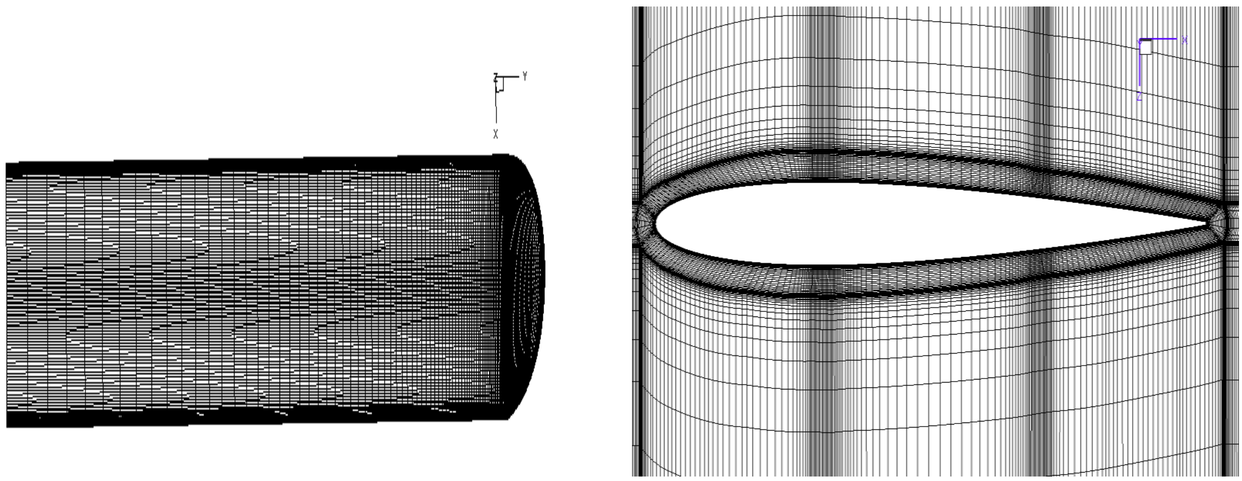


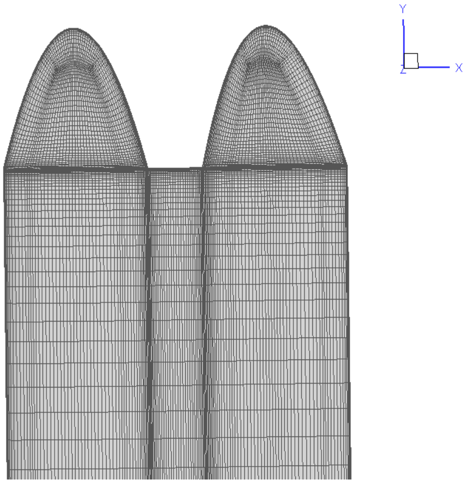
Figure 6 – Surface mesh and spanwise section mesh of wing with elliptical tip.

The three types of mesh: coarse mesh, medium mesh, and fine mesh are respectively generated to investigate the effect of mesh quantity on its lift, drag, and pitching moment characteristics at a 4° angle of attack for the elliptical wing (Table 2). The test points of the wing pitching moment in this paper are all set at the position 1 / 4 chord from the chord length of the wing root to the leading edge of the wing. Compared to coarse mesh, medium mesh offers a notable improvement in the numerical error, and medium mesh and fine mesh give almost identical lift coefficients. Hence, the medium mesh is chosen as the optimal mesh size for all simulations.

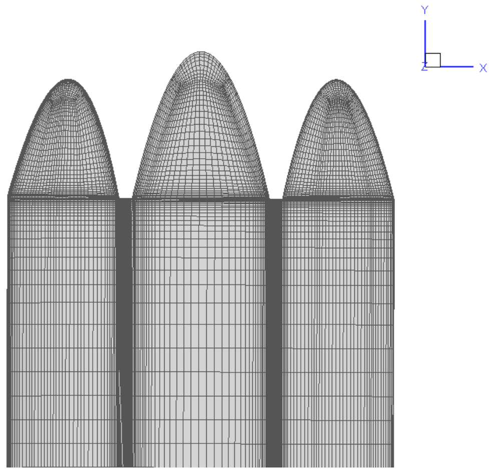
Table 2 – Lift and drag coefficient variation with mesh number

	Elements	C_L	C_D	C_M
Coarse	2×10^6	0.27714	0.01816	-0.00240
Medium	4×10^6	0.27332	0.01659	-0.00271
Fine	8×10^6	0.27323	0.01616	-0.00280

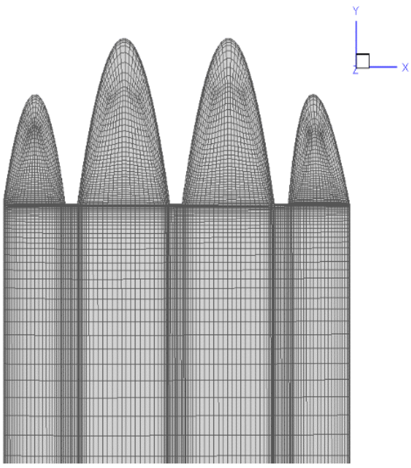
Then meshes of the other wings, as depicted in Figure 7, are constructed and some densification was carried out on the surface of the wingtip. The mesh amount and the mesh node distribution of the five sets of wings are roughly the same.



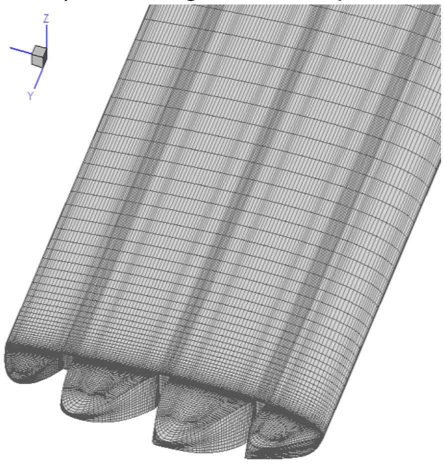
a) The wing with one tip slot



b) The wing with two tip slots



c) The wing of three tip slots



d) The slotted wing with 45° dihedral

Figure 7 – Mesh distribution of tested wings.

3. Results and discussions

In this section, results and general observation will be discussed most importantly, the non-dimensional lift coefficient, drag coefficient, L/D ratio, and pitching moment coefficient were calculated. Flow details, such as pressure contour, pressure coefficient distribution, and vorticity map are presented as supplementary to explore the aerodynamic mechanism of tip slots.

3.1 Effect of the number of slots

Figure 8 demonstrates the effect of number of slots on aerodynamic coefficients in the planar configuration. On the whole, the lift coefficients of five groups of wings increase almost linearly in the pre-stall region, while decrease rapidly after reaching the peak value due to stall. At the same time, the drag coefficients increase slowly and climb sharply around the stall angle of attack. The pitching moment coefficient breaks before the wing stall, as well.

At the smaller angle of attack (0°< AoA < 8°), the aerodynamic characteristics of five kinds of wingtip layouts are not significantly different. Then there appear different trends for five groups of wings. When the angle of attack is 15°, the wing begins to stall due to flow separation. It can be observed that adding elliptical wingtip to base wing has a nice effect of increasing lift while intensifies stall at a larger angle of attack. In analyzing the effect of slot number, it is evident that increasing the number of slots on the wingtip does not change stall angle of attack, however, lift coefficients before stall descend and drag coefficients slightly ascend in contrast to the non-slotted wing. Wingtip slots have a certain impact on reducing the propensity for the wing stall. The situation of sudden lift drop and drag rise in the post-stall region gradually relieves with the increase of tip slot number.

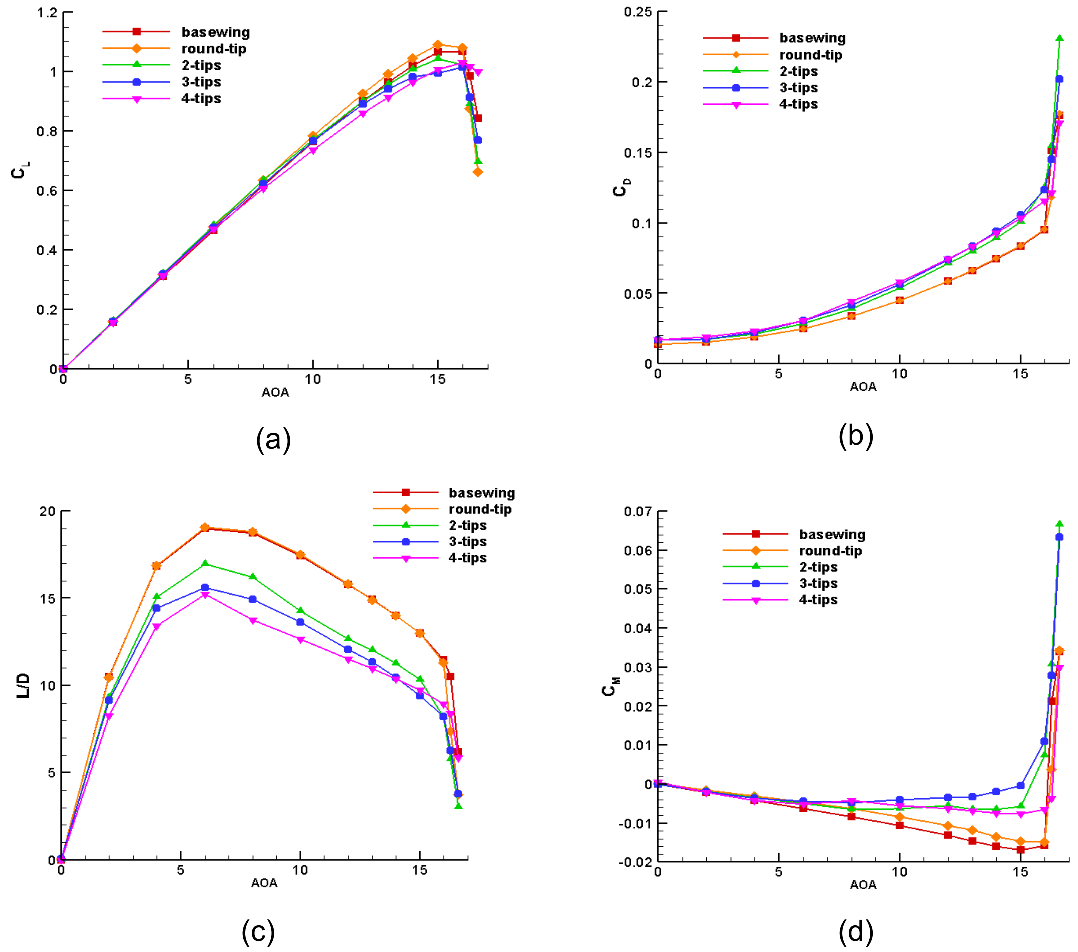


Figure 8 – Comparison of slotted wings with various tip slots on aerodynamic properties vs. angle of attack: (a) lift coefficients (b) drag coefficients (c) lift-to-drag ratio and (d) pithing moment coefficient.

From the pressure contour plots of upper surface for the angle of attack is 12° (Figure 9), it is observed that there exists an obvious low pressure area at the elliptical wingtip, while as wingtip is slotted, this low pressure area at tip part diminishes, which has a negative impact on lift improvement. The pressure at the leading edge of the wingtip grows up, hence drag rises somewhat with slot number increasing. Meanwhile, the analysis shows that increasing the number of slotted wingtips yields more viscous drag and changes the ideal elliptical distribution, which will lead to lift loss and drag goes up, thus reducing the lift-to-drag ratio.

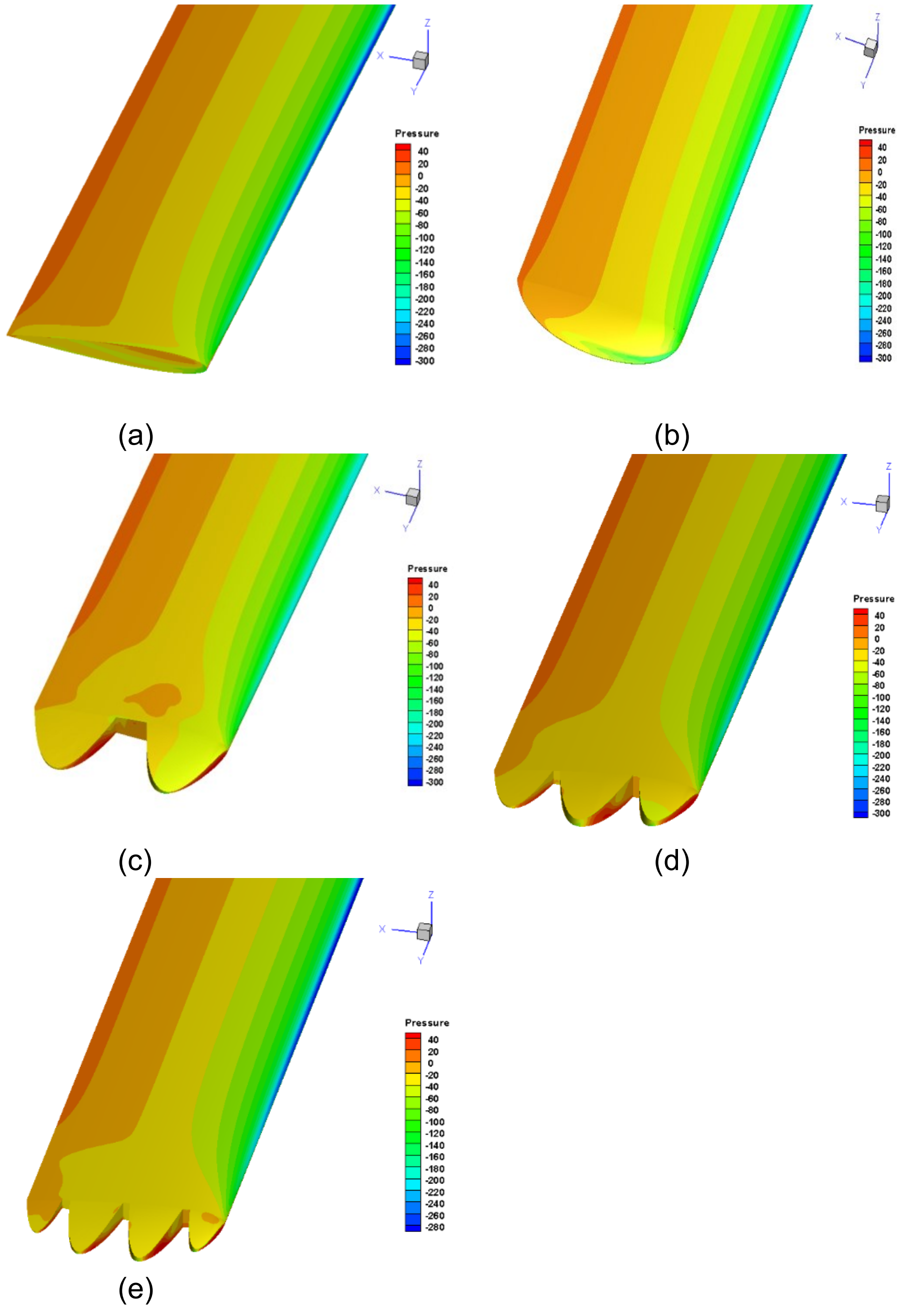


Figure 9 – Comparison of slotted wings with various tip slots on pressure contour for the angle of attack is 12°: (a) base wing (b) elliptical wing (c) wing with two winglets (d) wing with three winglets and (e) wing with four winglets.

The curves in Figure 10 illustrate the pressure coefficient distribution profile of four types of the wing at 1.6m span and 1.75m span, which represents the non-slotted base wing and slotted wingtip profile, respectively. It can be seen that each wingtip works as a single winglet due to the existence of slots, and form its own pressure distribution. This retards chord-wise pressure gradient and thus plays a part in alleviating stall.

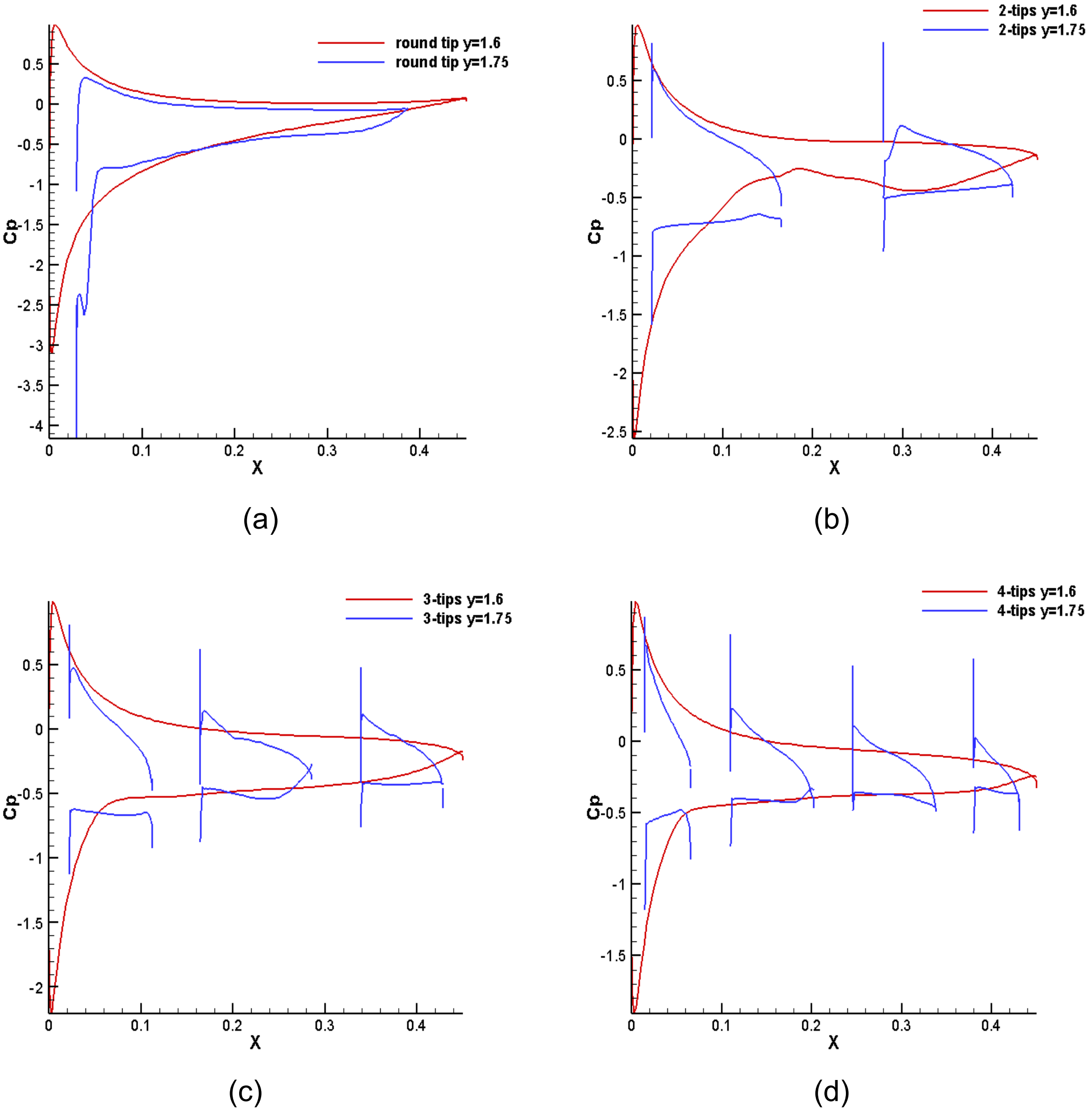


Figure 10 – Comparison of slotted wings with various tip slots on pressure coefficient distribution at 12° angle of attack: (a) elliptical wing (b) wing with two winglets (c) wing with three winglets and (d) wing with four winglets.

3.2 Effect of dihedral

To understand the effects of dihedral angle on the aerodynamic performance, Figure 11 is depicted for discussion. In view of the implicit distinction at a small angle of attack, the comparison curve for the angle of attack higher than 8° is shown here.

The results indicate that adding dihedral to the slotted wing can reduce the propensity for stall to a greater extent compared with planar configuration. The lift coefficient of the non-planar slotted wing ascends and drag coefficient descends significantly. When the angle of attack is 15°, in contrast to the planar slotted wing, the wing with a 45° dihedral can increase lift by 2.2%, reduce drag by 7.4%, and improve the lift-to-drag ratio by 10.3%.

Moreover, the maximum achievable lift of the non-planar slotted wing becomes larger with the increase of dihedral. When high maneuverability is occasionally required, it is particularly important to increase the maximum achievable lift under high wing loads. The lift-to-drag ratio is increased as the dihedral angle rises, which means that a slotted wing with dihedral can reduce fuel consumption and improve aerodynamic efficiency.

At the same time, the pitching moment coefficient decreases to a certain extent for a non-planar slotted wing, thus improving the longitudinal stability of flight. With the dihedral angle growing up, the improvement of aerodynamic properties is more obvious.

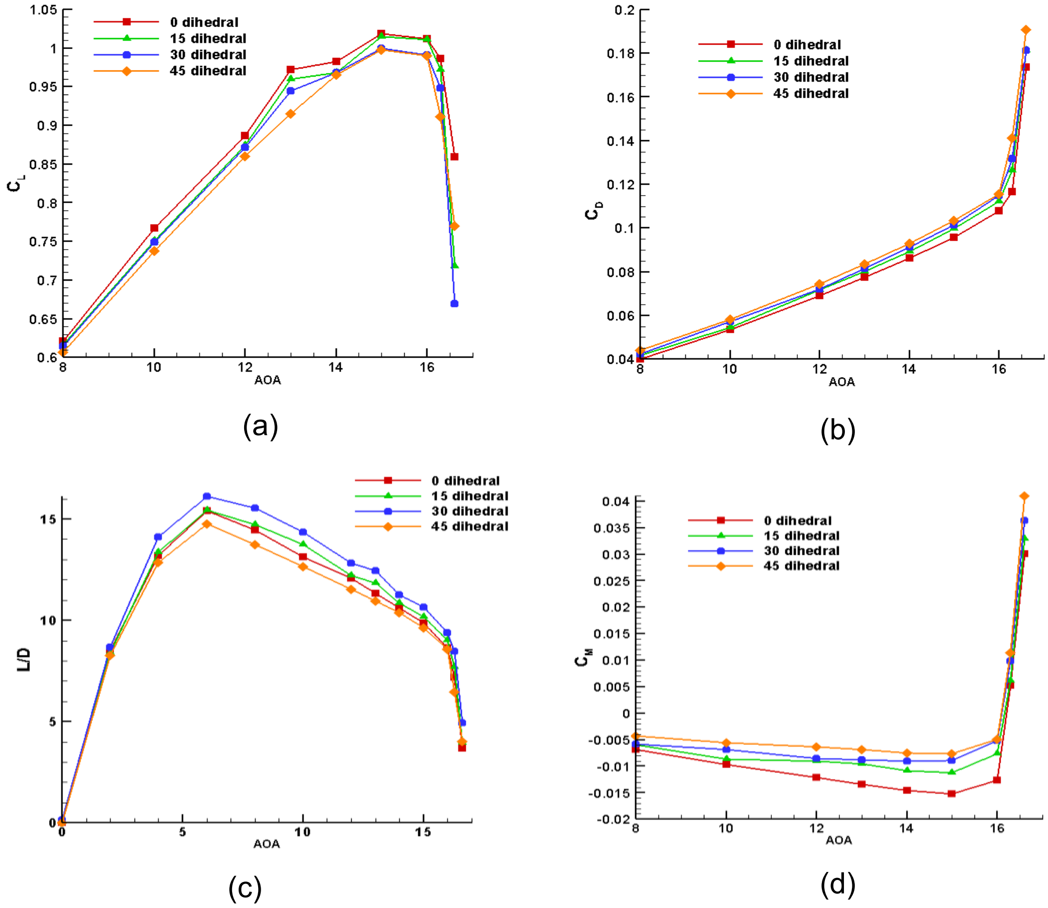
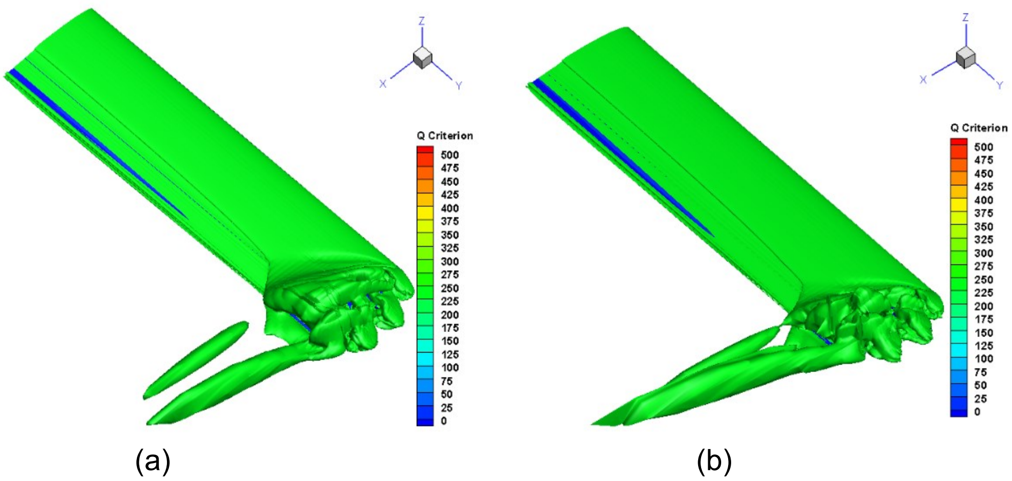
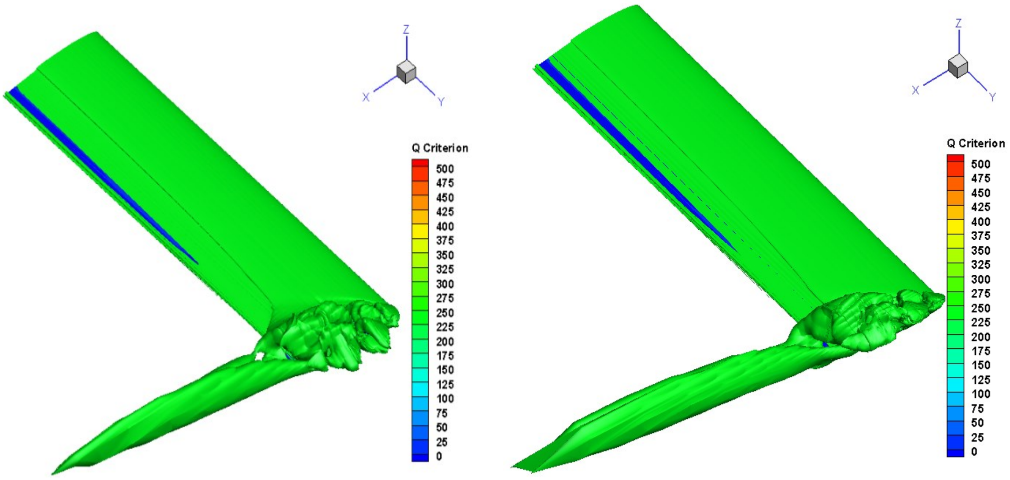


Figure 11 – Comparison of slotted wings with assorted dihedral angles on aerodynamic properties vs. angle of attack: (a) lift coefficients (b) drag coefficients (c) lift-to-drag ratio and (d) pithing moment coefficient.

The vorticity maps of slotted wings with assorted dihedral angles are presented in Figure 12, it revealed that multi winglets can diffuse the vortices, and each vortex produced around the winglet affect each other. For a planar wing layout, induced drag can be minimized by an elliptical lift distribution with a uniform downwash distribution along the span direction. Slotted wings with dihedral make them in non-planar configuration, the vorticity can spread vertically. This vertical vorticity propagation mechanism of the nonplanar structure can make the high induced flow around the wingtip more uniform, thus increasing the lift of a given span and reducing drag.





(c) (d)

Figure 12 – Comparison of slotted wings with assorted dihedral angles on vorticity map for the angle of attack is 12°: (a) 0° dihedral (b) 15° dihedral (c) 30° dihedral and (d) 45° dihedral.

4. Conclusions

The results show that there are noticeable effects when changing the design of a MAV wing to blend in with nature and mimic the wings of a bird – even despite the fact that parameters such as area stay the same. The numerical simulation of the influence of the number of horizontal wingtip slots and dihedral angle on the aerodynamic performance of the wing is carried out.

Based on models established in this paper, slotted wingtip can relieve stall to a certain extent, with the number of slots increasing, the effect of stall relief is more obvious. While adding wingtip slots will affect the streamline of wings, the potential benefit of reducing induced drag by increasing the number of slots will be reduced due to the high contribution of other drag components.

In contrast to planar slotted wing, non-planar slotted wings with dihedral not only further mitigate stall but improve lift and decrease drag in the pre-stall region, which can reduce fuel consumption, increase range and reduce take-off distance of UAVs. The reduction of pitching moment for non-planar slotted wing helps the longitudinal static stability of flight ascend. With the dihedral angle rising, the maximum achievable lift gradually increases and better meets the high maneuverability requirements of the aircraft under the high wing load. Slotted wingtips with dihedral take winglets away from the wing plane and redistribute tip vortex into multiple vortices that do not merge in the near wake, thereby reducing the effective downwash.

Further work will be focused on aerodynamic characteristics of slotted wings with various wingtip configurations in the unsteady state. The analyses are planned to continue for other geometric parameters like sweep angle, twist angle. In addition, it is a creative idea to speculate the flexibility of the wing when exploring the impact of the slotted wingtip.

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