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Research Article

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Computational Analysis of Morphing Geometry Inspired From Butterfly Wings in the Application Micro Aerial Vehicles

S Kishore Kumar[1*], Srinivas Pendyala[2]

[1,2]Department of Mechanical Engineering, GITAM School of Technology, Hyderabad, 502329, INDIA

[*]Corresponding author
S Kishore Kumar, Department of Mechanical Engineering, GITAM School of Technology, Hyderabad, 502329, INDIA.

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Abstract
This paper presents a numerical analysis aerodynamic performance of a morphed geometry and observations with regard to MAV development and flight behavior of butterfly wings. The performance of the morphed wing structure is analyzed using numerical simulations. At different angles of attack, we measured the L/D ratios of the morphed wings at 2, 4 and 6 ms−1. In order to get a better grasp of the flow patterns over these wings using (CFD), we have performed wind tunnel simulations, with a focus on geometry of the biggest wing chords and maximum spans, to determine the flow parameters. In relation to their gliding performance, we compare the shapes of the wing of four butterfly species. In this study, experiments are conducted to understand how different wing shapes affect aerodynamics. The in-flight measurements reported in the biology literature are correlated with wing orientation and flight speed. A MAV design benchmark can also be used to assess the performance of these shapes in terms of gliding performance.

Keywords: MAV, Butterfly wing, Lift to Drag Ratio, CFD Analysis

Introduction

The bionic study of insect flight has lasted for a long time, and common characteristics of insect flight have been mentioned in many studies, such as elastic and thin wings and high flapping frequency (10–500 Hz). Common insects, such as bees, dragonflies, and flies, all conform to these characteristics, while butterflies' wing-flapping frequency is approximately 10 Hz, which is much lower than many other insects. Moreover, the butterfly has a larger wing area and a lower aspect ratio compared with other insects. The flight-related structures of insects are mainly concentrated on the wing-thoracic segment. The muscle groups control the wings to twist and oscillate, thereby generating sufficient lift and thrust. Furthermore, the wings are crisscrossed with wing veins, which support and reinforce the wings similar to a skeleton, as well as can be twisted to change the direction of flight. To adjust the velocity, direction, and attitude of flight, some insects change the movement mode of wings, while others changing the relative motion of various parts of themselves. Take a dragonfly as an example. Its abdominal segment has a certain effect on flight control because its long abdomen can bend or even curl [1]. The butterfly's flight state seems to be unstable, but it can complete the flight target, which is a unique phenomenon in insect flight.

Revealed the effect of LEV on the high lift of insects [2]. With the development of high-speed photography technology, Wing-motion of hovering small fly or artificial flapping wings have even been measured and flows of the wings calculated numerically. Butterfly wings flap downward when they generate lift force and upward when they generate thrust force. The phenomenon of high lift in insect flight was analyzed qualitatively through experimental fluid methods. "Rotational circulation", "wake capture", "dynamic stall or the delayed stall", and "Clap and fling" mechanisms were discovered and studied successively. The kinematics of the wings and body were measured by Sunada et al. via a high-speed video camera during the take-off of a butterfly. A vortex method was devised to calculate the aerodynamic force generated by flapping wings. The results indicate that the two wings' opening motion generated the first peak of lift-off.

In terms of bio morphological features, the butterfly is mainly composed of the five parts wing, head, thorax, abdomen, and foot, and its flight behavior is relatively complicated. Current research indicates that a butterfly's flight has the following kinematic characteristics: (1) The flapping angle has low frequency and large amplitude during wing flapping. (2) Lead-lag angle: In the downstroke, "lead-lag motion" occurs with the forewings flapping. In other words, the forewings sweep forward along the axis which is longitudinal to the body to reduce the overlapping area of the fore and hind wings. The results are reversed in upstroke. (3) Feathering angle: The twist angle of the wing is considerable. Furthermore, these characteristics have a certain relationship with the flying ability of the butterfly. At present, the aerodynamic study on butterfly flight is less than that of flies, bees, moths, etc., Simultaneously, as the wings of the butterfly grow in the position of thorax, the flapping wing motion will cause the thorax to produce the pitch oscillation with the same frequency. In most flight states the abdomen will swing actively with the body's pitch oscillation to stabilize its longitudinal attitude and even influence its maneuvering flight. Compared with most birds and insects with a high aspect ratio, the flight behavior of butterflies is more complicated, and the research on its flight mechanism is challenging.

In previous experiments, the constraint of the rope has a huge impact on the insect's flight, and the measurement errors of the observation results cannot be ignored. Besides, the measurement has limitations due to living insects' use as experimental subjects in the experiment. For example, it is impossible to measure the force applied to the wings' roots, and it is hard to confirm the impact of various vibration modes of the wings on the lift. Some scholars have proposed quasi-steady aerodynamic methods to estimate the aerodynamic forces and moments of butterflies flying forward or other insects hovering. The lift and thrust mechanism generated by the flapping wing has been analyzed partially, which is influenced by the swinging effect of the butterfly's abdomen during its flight. Furthermore, it requires more detailed observation and analysis.

Based on the previous studies, our goal is to analyze aerodynamic performance and kinematics of a butterfly wing inspired geometry. The flapping flights of relatively large-size butterflies are chosen to be observed and analyzed. High-speed cameras are arranged to capture the high-definition forward flight images of butterflies and track the spatial trajectory of the feature points on the butterfly. The butterfly's kinematic model with wing-body coupling is established to quantify the flight parameters. Based on these results, a three-dimensional multi-rigid butterfly model based on real butterfly dimensions is established. The lift and thrust characteristics of the butterfly are simulated and analyzed by computational fluid dynamics (CFD) methods. Bilateral and symmetrical flapping in forward flight is numerically simulated to clarify the longitudinal flight mechanism of the butterfly. The detailed structure of vortices and their dynamic behavior are elucidated, and their relations to force generation mechanisms are evaluated.

Literature Review

The examined small wind turbine blades in this paper in order to determine how effective they can be when modified [6]. We explored two modifications inspired by nature: spanwise corrugations on the blades that mimic the shape of dragonflies' wings, as well as flexible blades that mimic shape-morphing of bird and insect wings. A wind tunnel test was conducted on two kinds of corrugation with the result that the corrugated nature delayed stall by 4° while reducing post-stall drawbacks. A corrugated skin also displayed similar performance to the control aerofoil, but with a 7.3% reduction in lift to drag. With QBlade simulation tool, we compared the Young's modulus between a rigid turbine blade and semi-flexible and fully flexible blade. There was a reduction in peak stresses in the flexible blade despite the high spanwise deflection. This study is still preliminary, but it shows that design options that are easy to manufacture and maintain can be exploited to improve the performance of turbines. In addition to delaying stall, corrugated aerofoils were found to have similar lift-to-drag characteristics to smooth aerofoils, thus making them a better choice for wind turbine blades.

Even remote areas where local alternatives cannot be sourced can source flexible materials such as bamboo laminates. Fiberglass pieces are difficult to recycle at the end of their useful lives, so flexible blades provide an alternative that has been demonstrated here to provide similar performance and increased design lifetime. Fiberglass pieces are difficult to recycle at the end of their useful lives, so flexible blades provide an alternative that has been demonstrated here to provide similar performance and increased design lifetime. A turbine rotor could passively adapt to its operating conditions based on some promising underlying aerodynamic processes identified by this research. Initially, the two new ideas were tested independently, but after proof of concept is reviewed, increased computation is needed to combine the two ideas into one system and analyze using coupled fluid-structure interactions (FSI). In this way, we can fully optimize the flexibility and corrugations for a small wind turbine system and validate it with a physical test.

Examined the aerodynamics of the corrugated dragonfly airfoil as a means of determining its possible application in micro\MAVs in comparison to a smooth-surfaced airfoil (NACA 2408 airfoil) taking advantage of the chord Re "Reynolds number" 4x103 [7]. Our numerical calculations were performed with two different problem settings. For the analysis of aerodynamic characteristics and hydrodynamic moment, airfoil was consistently angled at a static AoA. Further, a change in the AoA is used to assess attitude stability using fluid force. A numerical solver has been validated against published numerical data for an unsteady rotating airfoil flow field. Corrugated airfoils performed quite well (with respect to CL/CD ratio) under the same conditions as the profiled NACA2408 airfoil in the lower AoA range 0° - 6°, and they performed as well as the profiled NACA2408 airfoil at the AoA of 6° and more.

When a high AoA is used for the numerical calculations, the lift and drag show strong fluctuation. In corrugated airfoils with fluctuations, lift and drag results were minimum than those obtained from simulations in 2D. In spite of high AoA, morphed wing geometry was able to suppress lift fluctuations and to promote three-dimensional flow. Numerical calculations were performed with two problem settings. Constant AoA was used for the analysis of smooth-surfaced and corrugated airfoils. The dynamic behavior of CL and CD was analyzed especially. We examined the attitude stability of airfoils by considering the force exerting on surface of an airfoil by passively changing the AoA. By comparing the current numerical solver with data from Kaneko et al., the current solver was validated with respect to an airfoil that is rotating unsteadily produces an unsteady flow field. The results have been satisfactory [8].

A nonlinear time-periodic flapping wing structure is studied to gain a broader understanding of its stability properties. A pair of bio-system models is developed for this purpose. They are Hummingbird (6DOF) and Hawkmoth (3DOF). Floquet's theory of kinetic energy and phase portrait technique along with kinetic energy integration indicate a instability in hover flight for the Hummingbird model. In this work, we investigate Kinetic Energy Integration on the Hawkmoth model in order to uncover the attraction, stability have to be increased through variations in design parameters, and find the domain of attraction. A steady hovering trim condition is achieved by adjusting the hinge location, the amplitude, the frequency, and the mean angle of attack of the wing. Using the results, a hovering control system will be designed that has been widely studied and has no clear solution based on linear analysis and average theory.

Using linearization theory and eigen values to achieve dynamic stability, the mean angle of attack can also be determined from the pitch angle by using an average theory and linearization technique. In order to determine the primary cause of lack of stability, sensitivity analysis is performed on the equivalent dynamics, using phase portraits and energy approaches. Using Floquet analysis, we observe the formation of a strange attractor in 3-D phase space when a non-autonomous dynamics is applied. The aim of this study is to provide a thorough analysis of wing flapping model in a nonlinear time-periodic mode in terms of stability properties. Various models, such as Hummingbirds (6DOF) and Hawkmoths (3DOF), have been examined extensively to achieve this goal. Floquet theory and kinetic energy integration are applied to decide on the best approach. As well as this, a variety of approaches have been implemented to improve accuracy and to carry out validation assessments. The objective has been achieved by tuning the parameters of the system to the desired region in this way, resulting in an improvement of the system's basis level of stability. Such improvements are necessary for the controller design process. In that regard, this study offers a distinct advantage over previous ones. Used a force field measurement and motion of clap-and-fling analysis to investigate the performance of aerodynamic of a micro air vehicle (MAV) with flapping wings from X-Wing inspired by bio-inspired wings [9]. Testing was conducted in the wind tunnel first to determine current MAV's operational region. A six-component miniature force transducer enables us to study the effects of wings' flexibility and flap frequency on force generation and power generation. PIV was employed to visualize flow in the wings. Results revealed the wings shed momentum from the vertical structures during clap-and-fling motion. To better understand aerodynamic characteristics of micro aircraft with flapping wings, we also examine the in-ground effect during takeoff and landing. Researchers have investigated the aerodynamics of a MAV wing model inspired by bio-inspired flapping wings in this study.

By combining force measurements with PIV visualizations of the flow field behind the flapping wing of the MAV, we conducted the experiments. As a part of this experiment, we investigated the effect of “flapping frequency”, AR “aspect ratio” etc., on force. It is observed that both thrust peaks occur in each flapping cycle, with one taking place during the instroke and the other during the outstroke. In relation to flapping frequency, the thrust increased linearly. As the span is increased, it will add to thrust generation, but it will decrease power loading (i.e., propelling efficiency). Aerodynamic performance is improved with a clean wing (without stiffeners) over stiffened wings. The trailing edge vortex sheds its weight in a visual representation of the flow field around the flapping wing.

Experimental methods

Deng et al The selected bionic inspired wing is adopted from the butterfly which shows a distinct flapping and gliding flight behaviour. In the study was focused on migrating monarch butterflies (Nymphalidae: Danainae: Danainae), which can glide for about 75 percent of their flight time over long distances and flap for only about 25 percent. The morphing structure based on wing shapes was tested, as shown in figure 1. To isolate its impact from all other factors, like the wing's flexibility, camber, topography of the surface, we simulate the wings with smooth rigid flat plates, instead of simulating them with flexible flat plates. Wing edges' geometry can greatly influence their aerodynamic performance. The wings are scaled to a 1000 mm2 area for normalization.

Methodology

Morphological parameters of the butterfly Danaus plexippu are summarized in Table 1. including the total mass (m), the thoracic mass (mt), the abdominal mass (ma), the thoracic length (Lt), the thoracic width (wt), the abdominal length (La), the abdominal width (wa), the wings mass (mw), the wing-tip length (Ltip), the wing area (2Sw), the wing loading (mg/(2Sw)). The mass of the butterfly is approximately 0.35 g. The wingspan (S) is about 8.29 cm, and its chord length is about 3.55 cm. The aspect ratio is expressed as AR = S/c.

Figure 1: Monarch Butterfly *"Danaus plexippus"*

Butterfly wing prototype Modeling

There are a hind wing and fore wing on each side of the butterfly body. To further simplify the model, the fore wing and hind wing are modeled as a unified wing. Figure 1 shows that the experimental butterflies used to model the morphed wing that consist of four parts, namely thorax, abdomen, and one pair of thin flat wings. The thorax and left wing are connected by a joint with three DOFs, as are the thorax and right wing. The parameters of the real butterfly are used as the dimensions of the simulation model for CFD. The wingspan and chord length of the simulation model is set to 9 and 4 cm. The positions of trailing and leading edge are shown in Figure 2(a). Based on the two-dimensional images of a real butterfly, a simplified butterfly wing model is created. All parameters defining butterfly simulation model geometry shown in table below.

Table 1: Parameters of simulation model

Part t	Value
Thickness of wing	1.5×10^{-4}
Span of wing	9×10^{-2}
Length of Chord	4×10^{-4}
Length of Thorax	1.5×10^{-4}
Length of abdomen	2×10^{-4}

The bio morphological characteristics of the butterfly are obviously different from other insects such as cockroaches, hawk moths, and bee flies. Compared with other flying insects, the butterfly has a larger physical size. The flight velocity of the butterfly is high, and the frequency range of flapping motion is generally 12 Hz.

Wing MAV Model for Butterfly

Flapping wing for an aerial vehicle model that may characterize the flight of a butterfly is presented in this section. This study assumes that the head and the thorax are coagulated into a single rigid body, which is referred to as body. Also, we assume that hindwings move in unison with forewings. Here we present a mathematical description of the proposed rigid body model for right and left wing. FI = {ix, iy, iz }, where the third axis points downward, and the first two axes span the horizontal plane (Fig. 4). Let FR = {rx, ry, rz } for the right wing. Similarly, let FL be the frame fixed to the left wing. It can be obtained by translating FR to the root of the left wing without any rotation. More specifically, its origin is positioned at the left wing joint, where the left wing is attached to the thorax. The first two axes span the plane of the wing, where the first axis points toward the leading edge and the second axis points toward the right wing, opposite to the left wing tip.

Quasi-Steady Aerodynamics

If a flapping wing has the same instantaneous velocity and AoA as a steady wing, moment and aerodynamic force are comparable. In this section, we propose a model based on quasi-steady aerodynamics for the butterfly wing geometry flights characterized by relatively slow flapping of large wings as modeled. Without relying on the common assumption that the flapping frequency is sufficiently large, an expression for the translational forces and the rotational force is presented. These accounts the effects of the translational and rotational motion of the body, and the wind gust in the aerodynamic force.

CFD Simulation

To clarify the influence of butterfly parameters on free flight, the CFD simulations are conducted in this paper. The mainstream direction is taken as positive X; the vertical upward movement direction is positive Y; and the horizontal movement direction is positive Z. In Cartesian space, direction is represented by *ex, ey*, and *ez*. The equations governing the flow field include equations representing three-dimensional, transient, and incompressible continuity, as well as Navier-Stokes equations

∇·u=0 (1)

∂u/∂t+ (u·∇) u= (-1)/ρair ∇p + υair ∇2 u (2)

where u is flow velocity in the Cartesian coordinate system, defined as u=u0ex. p is the pressure. The fluid is 20 °C. Air property value is adopted at 20 °C: ρair = 1.205 kg/m^3 and υair = 1.5 ×10^{-5} meter square per second. V∞, incoming flow velocity.

Numerical simulations

Numerical simulations of butterflies' wings can be used to determine how the aerodynamics of tests in a wind tunnel compare. Additionally, these methods let you visualize and measure a wide range of flow parameters while minimizing the impact of invasive flow changes that might occur in a wind tunnel. Workbench 17.0 (ANSYS) was used as the simulation tool, to compute the solution and to post-process the results.

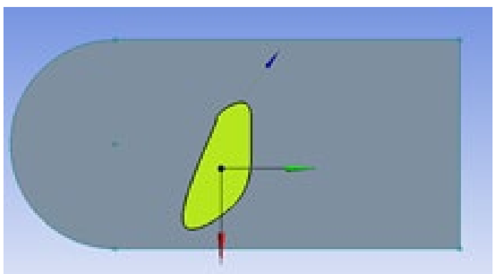

Figure 3: Simulated wing setup ANSYS

Numerical set-up

As According to the wind tunnel results, butterfly wings with fully forward forewings and a maximum wingspan yield the best glide ratios. We scaled all wing shapes to 1000 mm2 and extruded them to a thickness of 200 mm in order to achieve a similar design result as the wind tunnel models. As the flow parallels the domain, the wing geometry has been rotated so that it has an AoA of 10o. Using these angles, the inlet flow will still remain direct while creating large angles of attack. 3-D meshes were generated using ANSYS Meshing. A symmetry plane was set up at the base of the wing so that a smooth flow would result as around a gliding butterfly. Meshes comprised of the computational models have between 1.5 million and 2 million elements, with the meshes near the butterfly wings being particularly refined.

The wing surface has been improved with an eight-layer inflation layer. CL and CD results for meshes with varying elements for morphed geometry are at 10.8 degrees angle of attack. Once the desired convergence of inflation layers has been achieved, the meshes are refined until a desired convergence has been achieved. The lift to drag, lift coefficient, and coefficient of drag at different AoA, morphed geometry, and three various airspeeds were calculated based on the differences between the mesh with the most refinement and the mesh with the second most refinement. All the other geometries were simulated with similar parameters found in morphed geometries. The numerical simulations were computed using ANSYS CFX, a finite volume solution to equations of conservation of mass and momentum.

Results

Three different wing geometries were simulated at three different airspeeds. Each speed was associated with a different angle of attack. Figure 4(a) and 4(b) shows a comparison between an open wing and a closed wing when flow conditions are as given above. Results confirm that the morphed wing has the highest C_L and C_D ratio, which is 6.28, as shown in the wind tunnel test.

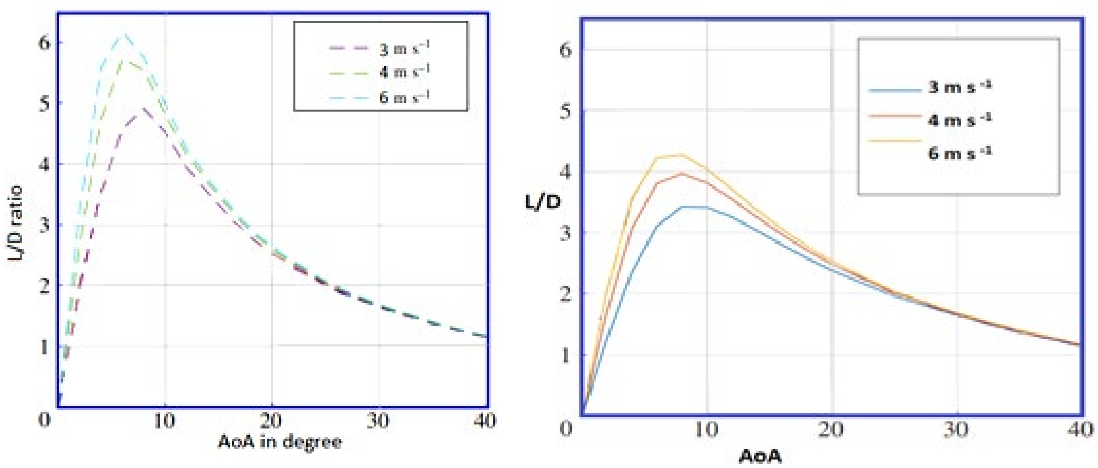

Figure 4: (a) and (b) L/D ratio as a function of AoA for Morphed closed wing and open wing

Lift-to-drag ratios are also highest at maximum airspeeds when drag is highest. In addition, when the forewing is extended to maximize the wingspan, the L/D ratio becomes 4.2, 3.9 and 3.4 for 3, 4 and 6 ms-1 respectively for AoA 6 degree to 8 degree, with the greatest improvement occurring at angles between 6.8° and 8.8°. Additionally, the experiments were successful according to these results. The variation of the CL depending on the AoA can also be seen in figure 4(b) and 4(c). A significant difference in lift coefficients of Open and closed wing is found for AoA at 6°. When compared with a fore-wing extending to maximum wingspan, the fore-wing in the forward position has a higher lift coefficient. The stall behavior is also different. As the extended forewing geometry reaches its peak lift coefficient, it gently stalls before slowly recovering. With forward forewings, however, at the AoA about 8 to 10 degree before stalling and attaining a similar lift coefficient of 7 degree for closed wing. Different fore-wing positions result in different lift generation, which explains a large portion of these effects. This design is quite different from the one with extended fore-wings, where most of the lift comes from faster air positioned parallel to the free-stream. There appears to be an increased suction in these LEVs.

Figure 5. shows vortices of the wing geometry. Despite these vortices' large energy demands, conventional lift generation mechanisms yield a lower lift-to-drag ratio. The wing geometry achieves higher lift coefficients with higher speeds. At Compared to lift to drag, the effect is slightly smaller at low angles of attack. The angle of attack and drag coefficient of figure 8 can be seen to vary. In particular, at angles of the forewing, an interesting feature can be seen. Although lower drag geometry has a lower CL/CD ratio, it has much lower lift. In other words, the lift coefficient makes the extended fore-wing geometries have a high CL/CD ratio at low AoA. A high CD results from the forward fore-wing geometry at high AoA, however, when the LEV is strong. As shown in Figure 9, the CL/CD ratio for the geometry tested is proportional to their aspect ratio. Although the geometric features differences of open and closed wing also have an impact on performance, a large part of their lift to drag ratios is explained by the different aspect ratios of their wings. At 6.8 degrees of fore-wing angle (aspect ratio 3.47), morphed wing has the maximum CL/CD ratio have the highest. Higher airspeeds generally result in a higher maximum CL/CD ratio. Considering the low Re numbers involved, it's possible that the increasing Re at a higher speed results in less pressure drag and separation.

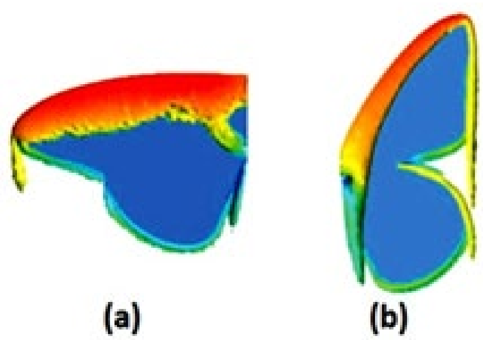

Figure 5: Vortices of (a) Closed wing (b) Open wing

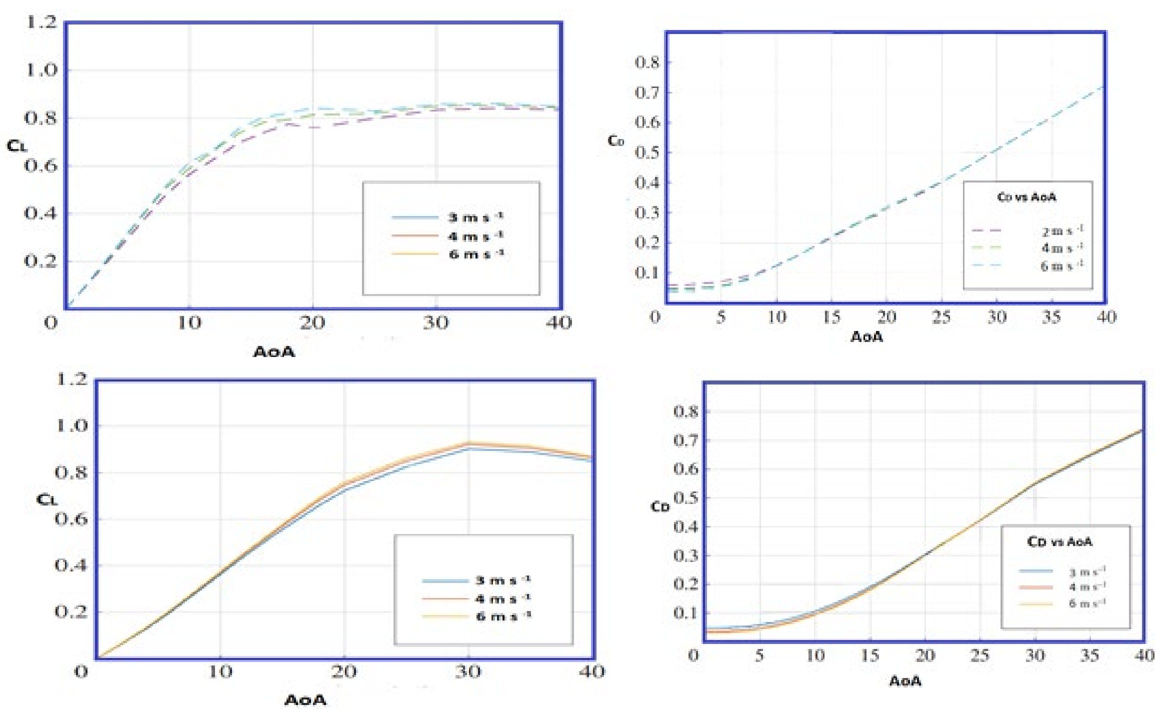

Figure 6: (a,b, c & d)Shows the CL and CD with respect AoA of the open and closed wing

Conclusion

The purpose of this paper is to improve our understanding of gliding butterfly behaviors by developing further insights into micro-robot wing design by studying aerodynamics of gliding flight for wing models of for selected butterfly in two orientations. As well as looking at the aerodynamic effects of butterfly inspired wing structure, we also study the shapes of their wings. A new low-speed wind tunnel and novel control architecture are leveraged in the study to measure at-scale lift and drag forces for millimetre- and centimetre-sized wings and to tackle the challenge of understanding the performance measured in the wind tunnel. With a gliding ratio of up to 7, the proposed structure has the best gliding performance of micro air vehicles of comparable size. The L/D ratio becomes 4.2, 3.9 and 3.4 for 3, 4 and 6 ms-1 respectively for AoA 6 degree to 8.8 degree, with the greatest improvement occurring at angles between 6.8° and 8.8°.

Additionally, the experiments were successful according to these results. The variation of the CL depending on the AoA is also analyzed. A significant difference in lift coefficients of Open and closed wing is found for AoA at 6°. In terms of increasing the glide ratio, the configuration with the widest wingspan proves to be the most advantageous. The aim of this study is to analyze the aerodynamic performance of morphing wing structure that can be applied to MAVs and can provide insight into the behavior of butterfly morphology in the futuristic unmanned micro vehicles.

Application in MAV

Using the geometries of butterfly wing at the Re we tested, we determined that the gliding ratio is maximum at higher speeds and larger wing spans. Additionally, they show the formation of similar lead-edge vortice structures to those observed in other studies. For high-performance MAVs, these factors should all be considered during the design process. Butterfly forewings inspired geometry can be oriented differently to benefit various flight regimes. The design of this wing could inspire MAVs. The fore-wings of these MAVs could be extended to increase endurance range and maximum speed, and then positioned forward to increase lift at high AoA to achieve increased aerodynamic efficiency. A flying vehicle configured this way will be able to glide at slower speeds and perform higher-g maneuvers.

Future Scope

Perhaps using flow visualization techniques and comparing them to classical wing shapes found on flying robots and planes, we could better understand the aerodynamic effects of butterfly wings. In an effort to increase the performance of the wing by influencing the boundary layer, Various hind-wing orientations and interaction between forewing and hind-wing geometrical structures will also be explored in this study, as well as the fabrication and testing of hierarchical wing surface structures. More detailed simulation, such as a direct numerical simulation or large eddy simulation, could be used to investigate flow more precisely and understand unsteady effects during flapping flight or other dynamic flight conditions. This could be achieved by studying aerodynamic three-dimensional unsteady effects at different fore-wing orientations, as in the study by Lee et al.

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