# Bumblebee Aerodynamics in a Virtual Wind Tunnel

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## Abstract
Nature inspired innovation powered many engineering innovations. For example, Bird inspired flight helped us to develop intercontinental flying long range aircraft with efficiency as comparable to transcontinental migratory birds. But, short range air travel, efficiency is much lower than short range flying birds and insects. There is still a lot more we can learn from nature for cost effective and efficient short range personal transportation. One interesting short-range flight champion from the natural world is the humble bumble bee and dragonfly. Insect's flight is governed by both conventional aerodynamics and unsteady aerodynamics. Insects (Bumblebee, Dragonfly) wing structural shape, material constituent, spatial arrangement are also optimized for efficient flight. Hence, in this paper, we investigate the flight behaviour of shorts range insects. The Multiphysics CAE Model of a Bumblebee in a virtual wind tunnel is developed using COMSOL. The numerical problem is solved using Computational Fluid Dynamic (CFD) Module. We studied the aerodynamic behaviour of Bumblebee in our virtual wind tunnel. The flow and structural performance are evaluated. The unsteady aerodynamic forces acting on 3D computational Bumblebee/Dragonfly wings are studied by numerically solving the Navier-Stokes equations. The incompressible Navier-Stokes equations are discretized and solved on a specified tetrahedral grid. The objective of the present study is to investigate the influence of the different aerodynamic parameters on the flight performance. Reynolds number (Re), Drag Force, Lift Force, Drag Coefficient and Lift Coefficient. The derived parameters from a virtual wind tunnel experiment. Typical virtual wind tunnel experimental results are shown for Fluid Pressure Magnitude and Downside Fluid Velocity Magnitude as function of flapping, respectively. This model will also enable Fluid structure interaction study for aeroelastic performance. This study will benefit to develop novel lightweight personal air transporters and also drones for general purpose short haul air cargo transportation.

**Keywords**: Insect flight mechanics, virtual wind tunnel, CFD, aerodynamics, personal air transporter

## Introduction
In the last 20 years, extensive research work [1-10] on the aerodynamics and energetics of insect flight and considerable progress has been made in these areas. However, the area of insect flight dynamics for short range has received much less consideration. Hence, the focus of this paper is on mono and double wing bumblebee and dragonfly, respectively (Refer figure 1). Brief review of birds and insect flight is outlined. An overview of insect flight mechanics is given. The virtual wind tunnel setup to study the steady and unsteady aerodynamic behaviour is detailed. The virtual wind tunnel model, which is equipped to extract the lift, drag, vortex parameters of insect flight are detailed. CAD and CFD numerical modeling details of bumblebee and dragonfly are shown. Post-processed fluid velocity and pressure distribution contour plots and flight parameters at different flapping wing angles of the bumblebee and dragonfly body and wings are also shown. Mono wing bumblebee and tandem or double wing dragonfly models are evaluated in a virtual wind tunnel. The conventional flight parameters such as Lift Coefficient (Cl), Drag Coefficient (Cd) at different flapping angles are plotted at forward Flight.

## Brief Review Insect Flight Mechanics
The ‘Pterygota’ or winged insects took form about 350 million years ago. Insects have evolved as flying increases their dispersal, migration, and ability to forage for resources. The changes in the outgrowth of the body separately from the legs have led to the wings formation. Insects are the only invertebrates that attain flight. They generally have two pairs of wings. Five key aerodynamic mechanisms are identified for insect flight. These mechanisms are, added mass, rotational circulation, clap and fling, wing wake interactions, and leading-edge vortex. The leading-edge vortex mechanism is a simple solution to avoid stall for insects. The other mechanisms are not yet studied thoroughly in the context of vertebrate flight. These aerodynamic mechanisms help in explaining how the aerodynamic force is generated by the wings. Insect flight allows two modes of locomotion, indirect flight and direct flight mechanisms. Some insects attain flight via a direct action of a muscle on each wing. A set of flight muscles attached inside the wing base and the other set is attached slightly outside the wing base. When the first set of flight muscles contracts, the wing moves up. The second set of flight muscles produces the downstroke of the wing. Dragonflies, roaches, and damselflies use this mechanism to attain flight. Instead of moving the wings directly, the flight muscles distort the shape of the thorax, which in turn causes the wings to move. This indirect mechanism is seen in butterflies and bumblebees. These flight mechanisms vary depending upon how the insect’s muscles work to fly. Requirements for insect flight is more than a simple up and down

motion of the wings. The wings also rotate, move forward and back, therefore, the leading or trailing edge of the wing is pitched up or down. These complex movements help to achieve lift, reduce drag, and perform acrobatic maneuvers. In addition to shape and size, the aerodynamic performance of flying insects is highly dependent on the deformation of the wings during flight. Insects fly gracefully in the air. Seeing these insects fly, it has inspired us, humans, to create a better flight mechanism and to achieve unprecedented flight capabilities than a fixed-wing structure. Flapping flight is only studied in a few species, thus bringing challenges in understanding this form of locomotion. Flapping wings have distinct advantages which are why it is suitable for different flight modes, thus comprehending that this mechanism can be used further for complex designs. Elucidating the development of these mechanisms will aid us in forming a comprehensive model for flapping flight, but may also provide greater insight into the evolution of flight.

Figure 1 Typical Bumblebee and Dragonfly Photograph

**Types of Insect Flight**

The different kinds of insects employ different maneuvering techniques to fly. Example the maneuvering techniques of a dragonfly is different from a bumblebee. Therefore it is more important to divide the flight patterns into different physical aspects of the flight. This becomes especially useful since many insects can employ various maneuvers at varying times. The common maneuvering techniques in every insect can be divided into two types; forward flight and hovering.

**Forward Flight**

The forward flight helps insects to not only lift themselves upwards, but to move in a particular direction. This occurs when an insect's wing beats not only provide some upward thrust but a component of the force generated by the wing is in some direction not parallel with gravity. Gliding is also an action of forward flight.

**Hovering**

The hovering technique helps insects to not only lift themselves upwards, but to remain stationary in a particular height. The orientation of the insect should be in such a way that the wings not only create an upward lift force, but also counter the weight of the body. The forces must cancel each other such that the insect can remain in one position without moving forward.

Complex flight maneuvers of insects are numerically modeled using Wing element, Actuator disc and Vortex theory.

## Numerical Modeling of Virtual WindTunnel

Wind tunnels are large tubes with air moving inside. The tunnels are used to copy the actions of an object in flight. Researchers use wind tunnels to learn more about how an aircraft will fly. The wind tunnel moves air around an object, making it seem like the object is really flying. The advances in computational fluid dynamics (CFD) modelling on high-speed digital computers has reduced the demand for wind tunnel testing.

A virtual parametric model (Figure 2) of a wind tunnel is designed in COMSOL to study the insect flight mechanics. A cubical object of dimension 100 mm*100 mm*100 mm is placed at the centre of the test section as a test object. The air intake section, test section and the diffuser section is designed respectively. The cross sectional dimension of the test section is taken as 254 mm*254 mm. The length of the test section is taken as 1016 mm. Likewise the dimension of the contraction section and diffuser length is taken as 508 mm.

The virtual wind tunnel is set up to simulate for various flow conditions using Reynolds-Averaged Navier-Stokes (RANS) formulations. Also, the virtual wind tunnel is equipped to use various Turbulence fluid flow models such as, L-VEL, k-ε, k-ω, SST, v2-f and Spalart-Allmaras models. Various insect and wing shapes with Right, flexible, morphing configuration can also be modelled. The conventional flight parameters such as Lift Coefficient (Cl), Drag Coefficient (Cd) along with fluid velocity and pressure distribution contour plots can be probed.

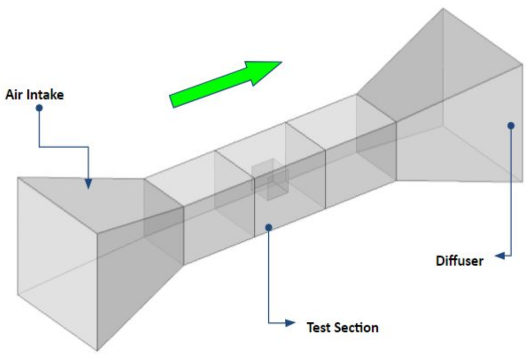


Figure 2 CAD Model of a Virtual Wind Tunnel

## Numerical Modeling of Insect Flight

Investigating the steady and unsteady aerodynamics forces generated by insect's wings is an essential step toward our understanding of interactions of flapping wings with fluids that enable insects to travel efficiently. Insect flight is a combination of physical mechanism and interacting systems that involves fluid dynamics, kinematics, morphology, and vortex dynamics, energy and power. With recent advances in numerical methods, many researchers are exploring computational methods to resolve the insect flight problem. Although the numerical techniques are more precise than analytical solutions, they require large computational power. Though there are complexities, recently several exciting CFD models of insect flight have emerged. The mathematical equations used in modeling insect flight is called the Navier-Stokes equations developed by Claude-Louis Navier and George Stokes. These equations describe the motion of fluid substances and are a result from applying Newton's second law to fluid motion.

The "simplified" model of insect flight is called a quasi-steady analysis that originated in 1925 by G.T. Walker. To find the approximate analytical solutions to the insect flight problem, scientists have developed simplified models based on the quasi-steady approximations. It makes the assumption that the instantaneous forces on a wing are determined by its current motion and is not dependent on its time history. Therefore it is possible to divide the dynamic kinematic patterns into a series of static positions. Where we can calculate the forces for each position and thus reconstruct the time history of force generation. In this method, any time dependence of the aerodynamic forces arises from time dependence of the kinematics but not that of the fluid flow itself. Therefore it would be possible to use a relatively simple set of equations to calculate aerodynamic forces on insect wings based on their kinematics.

However, for modelling complex aerodynamic manoeuvres of insects, we need to include the time varying unsteady effects of aerodynamic forces.

The Numerical Modeling of Insect Flight is set up to simulate for various flow conditions using Reynolds-Averaged Navier-Stokes (RANS) formulations.

## Numerical Modeling of Bumblebee and Dragonfly Flight

An approximate size of bumblebee and Dragonfly model (Figure 3-5) is developed using COMSOL Design Module. The bumblebee model is enclosed in a cubical fluid domain. The cubical fluid domain acts as a virtual wind tunnel where the air flows at a pre-defined inlet velocity. While one end acts as flow inlet, other acts as outlet of wind tunnel. The remaining boundaries of the cubical fluid domain act as a boundary wall in the numerical model. The boundary walls in the fluid domain restricts the flow of fluid to an open environment. The CAD model of a bumblebee with Isometric View, Front View and Top View are presented as shown below. As in thin aerofoil the bumblebee wings are naturally cambered to generate lift force. In this model the wings are approximated as a plane surface with cambered geometry. The Bumblebee and Dragonfly in a virtual wind tunnel is shown in figure 6a, 6b, respectively.

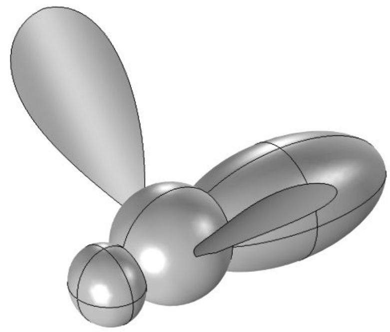

Figure 3a Bumblebee CAD Model, Isometric View

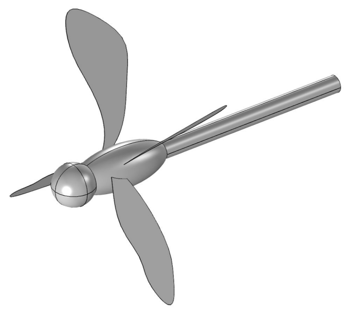

Figure 3b Dragonfly CAD Model, Isometric View

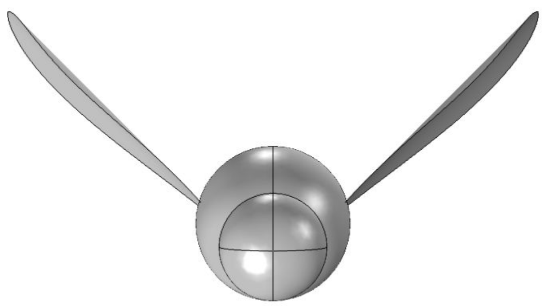

Figure 4a Bumblebee CAD Model, Front View

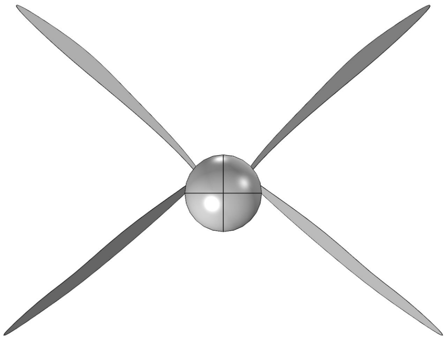

Figure 4b  Dragonfly CAD Model, Front View

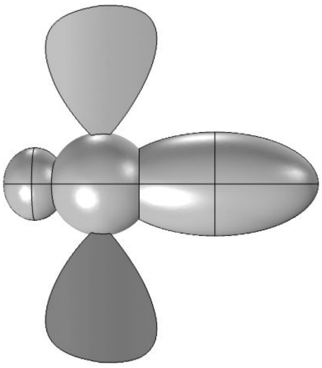

Figure 5a  Bumblebee CAD Model, Top View

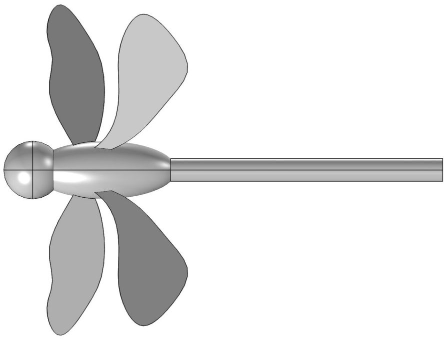

Figure 5b  Dragonfly CAD Model, Top View

## Material Properties

The inbuilt air properties COMSOL Material library is used in the numerical model. The physical properties such as Density ( $\varrho$ = 1.204 kg/m$^3$ ), Dynamic Viscosity ( $\mu$ = 1.825E-05 kg/m.s ), Heat Capacity ( Cp = 1007 J/kg.K ) and Thermal Conductivity ( K = 0.02514 W/m.K ) are taken at 20 C temperature and 1 atmospheric pressure.

## Governing Equations

The flows around birds and insects can be considered incompressible. The Mach number is typically 1/300 and the wing frequency is about 4–200 Hz. The governing equation is the Navier-Stokes equation subject to the no-slip boundary condition. The numerical model of a bumblebee and dragonfly in a virtual wind tunnel is developed using COMSOL. The numerical problem is solved using Computational Fluid Dynamic (CFD) Module. The governing equations are mentioned below.

### Fluid Dynamics

The Turbulent Flow k-ε (spf) interface is used for simulating single-phase flows at high Reynolds numbers. The physics interface is suitable for compressible flows and incompressible flows at low mach numbers.

$$\frac{u}{t} + u.\nabla u = -\frac{\nabla P}{\rho} + \nabla^2 u$$

$$\nabla .u = 0$$

$$u_{bd} = u_s$$

Where **u** is the flow velocity vector, **P** the pressure, **ρ** the fluid density, **v** the kinematic viscosity, $\nabla^2$ is the Laplacian operator $\mathbf{u_{bd}}$ the velocity at the boundary, and $\mathbf{u_s}$ the velocity of the solid.

### Boundary and Physics Definition

The in-compressible fluid flow in the bumblebee and dragonfly model is solved using the Navier-Stokes equation in comsol. The inlet fluid velocity of 1 m/s is applied at the inlet boundary and an appropriate outlet pressure is applied to the outlet boundary. The interior boundary condition is applied to the bumblebee and dragonfly wings. The materials for the fluid domain are defined as air.

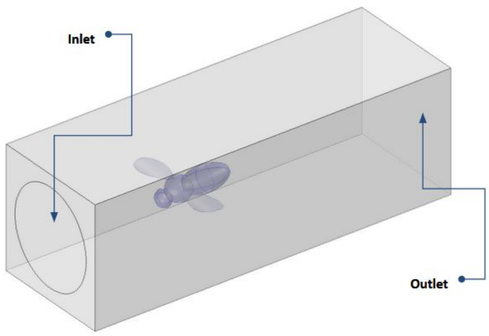


Figure 6a  Bumblebee Boundary Definition

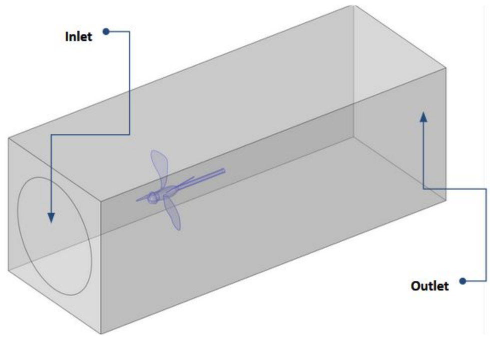


Figure 6b  Dragonfly Boundary Definition

## COMSOL Solver

An iterative, parametric, stationery study is implemented to the Bumblebee model to predict the aerodynamic forces. The stroke angle (alpha) parameters are set as range(45,-10,-45). In the case of the dragonfly model there are two stroke angle parameters one is alpha for front wings and another is beta for back wings. The stroke angle (alpha) parameters are set as range(40,-10,-40) while beta as range(-40,10,40). The wing stroke mechanism in dragonfly acts counterclockwise. While the front wings are in down stroke (alpha = 40 degree), the back wings are in upstroke (beta = -40 degree). The numerical model computed the different fluid dynamics parameters such as Velocity, Pressure at different wing angles. The Integration feature is applied to the wing surface as a Variable to compute the derived forces such as Lift force and Drag force. The lift Coefficient (Cl) and Drag coefficient (Cd) are then calculated from known Lift and Drag forces.

## Result and discussion

The fluid velocity and pressure distribution contour plots around the insect body and wings are plotted as shown in figure 7-12 and 16-21. The derived Upside Velocity, Downside Velocity, Upside Pressure and Downside Pressure are presented respectively. The fluid velocity magnitude at body surfaces of bumblebee is presented in Figure 7. The fluid velocity magnitude at the upside of the bumblebee model is plotted in Figure 8. The fluid velocity magnitude at the downside of the bumblebee model is plotted in Figure 9. The fluid pressure magnitude at body surfaces of bumblebee is presented in Figure 10. The fluid pressure magnitude at the upside of the bumblebee model is plotted in Figure 11. The fluid pressure magnitude at the downside of the bumblebee model is plotted in Figure 12.

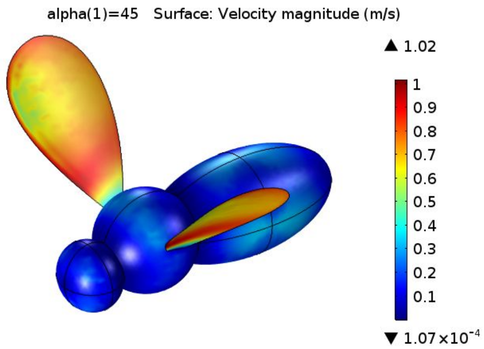


Figure 7 Surface Fluid Velocity Magnitude

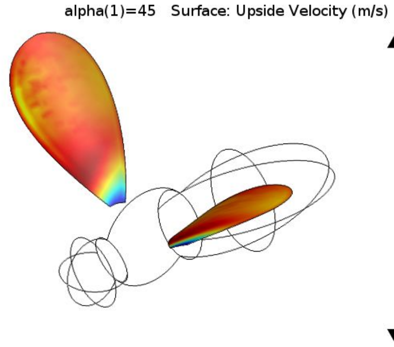


Figure 8 Upside Fluid Velocity Magnitude

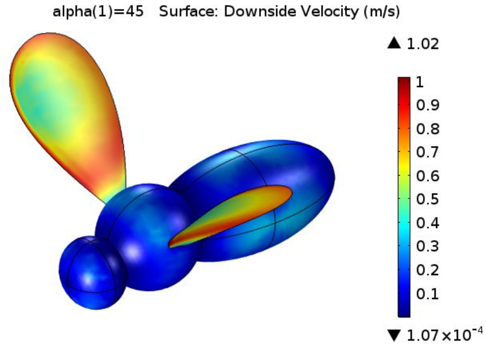


Figure 9 Downside Fluid Velocity Magnitude

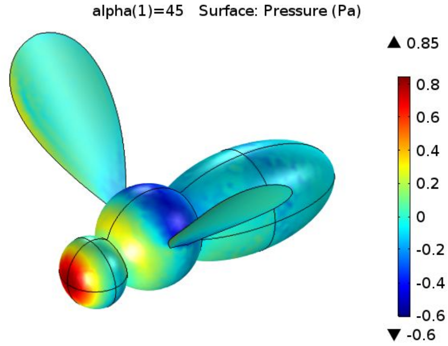


Figure 10 Fluid Pressure Magnitude

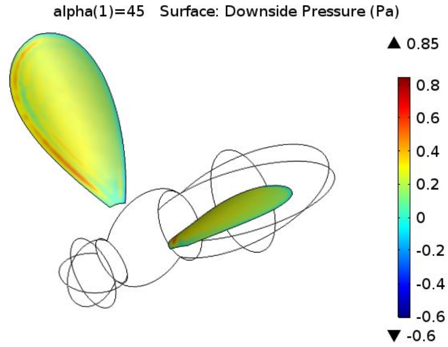


Figure 11 Upside Fluid Pressure Magnitude

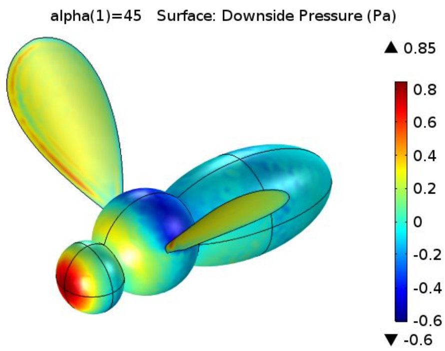


Figure 12 Downside Fluid Pressure Magnitude

The aerodynamics parameters such as Lift Coefficient (Cl), Drag Coefficient (Cd) at different stroke angles are plotted in graph figure 13-15 and 22-24. The lift coefficient (Cl) values with respect to flapping wing angle or stroke angle is represented graphically in Figure 13. The drag coefficient (Cd) values with respect to flapping wing angle or stroke angle is represented graphically in Figure 14. The comparison of lift coefficient (Cl) curve and drag coefficient (Cd) curve of bumblebee wings are plotted graphically with respect to flapping wing angle or stroke angle in Figure 15.

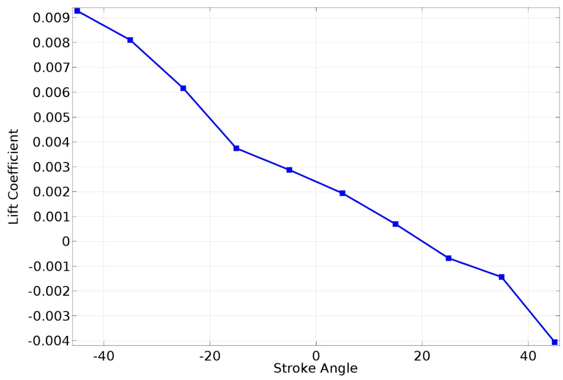


Figure 13 Lift Curve


Figure 14 Drag Curve

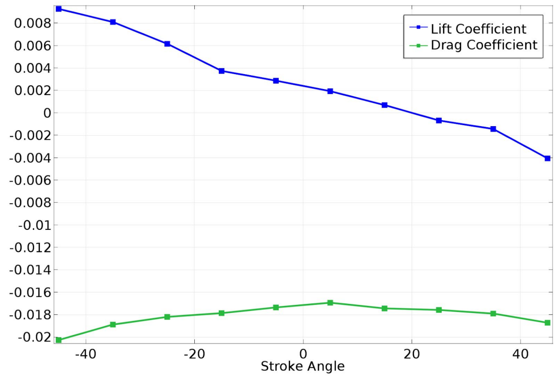


Figure 15 Cl, Cd vs Stroke Angles

Similarly the fluid velocity and pressure distribution contour plots around the dragonfly body and wings are plotted as shown in below figures. The derived Upside Velocity, Downside Velocity, Upside Pressure and Downside Pressure are presented respectively. The fluid velocity magnitude at body surfaces of dragonfly is presented in Figure 16. The fluid velocity magnitude at the upside of the dragonfly model is plotted in Figure 17. The fluid velocity magnitude at the downside of the dragonfly model is plotted in Figure 18. The fluid pressure magnitude at body surfaces of dragonfly is presented in Figure 19. The fluid pressure magnitude at the upside of the dragonfly model is plotted in Figure 20. The fluid pressure magnitude at the downside of the dragonfly model is plotted in Figure 21.

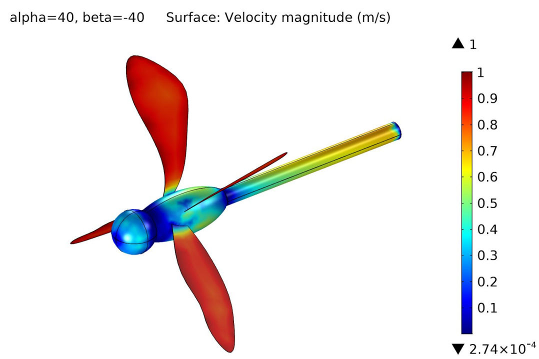


Figure 16 Surface Fluid Velocity Magnitude

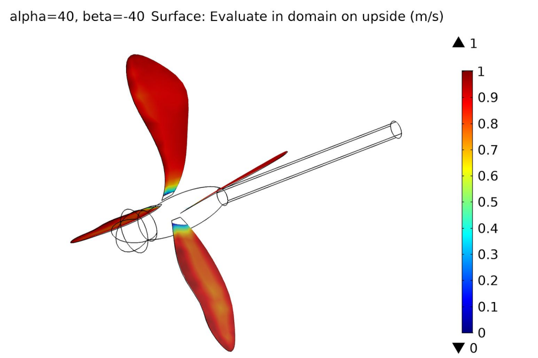


Figure 17 Upside Fluid Velocity Magnitude

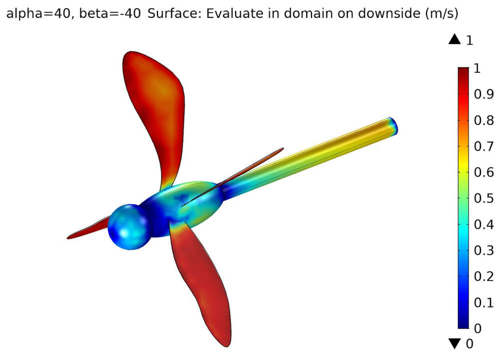


Figure 18  Downside Fluid Velocity Magnitude

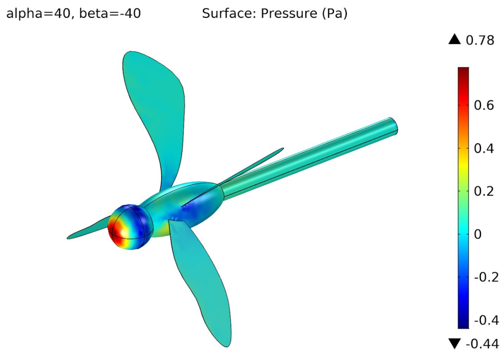


Figure 19  Surface Fluid Pressure Magnitude

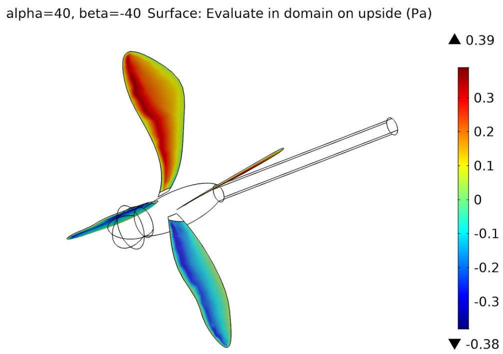


Figure 20  Upside Fluid Pressure Magnitude

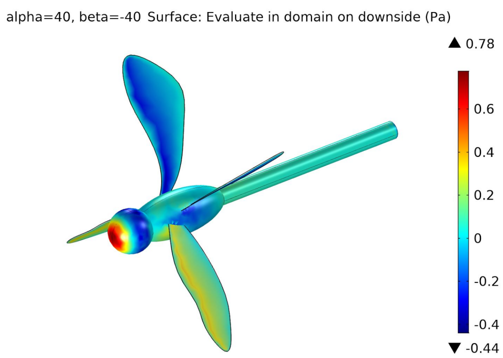


Figure 21  Downside Fluid Pressure Magnitude

The aerodynamics parameters such as Lift Coefficient (Cl), Drag Coefficient (Cd) at different stroke angles are plotted in graphical manner. The lift coefficient (Cl) values with respect to flapping wing angle or stroke angle is represented graphically in Figure 22. The drag coefficient (Cd) values with respect to flapping wing angle or stroke angle is represented graphically in Figure 23. The comparison of lift coefficient (Cl) curve and drag coefficient (Cd) curve of dragonfly wings are plotted graphically with respect to flapping wing angle or stroke angle in Figure 24.

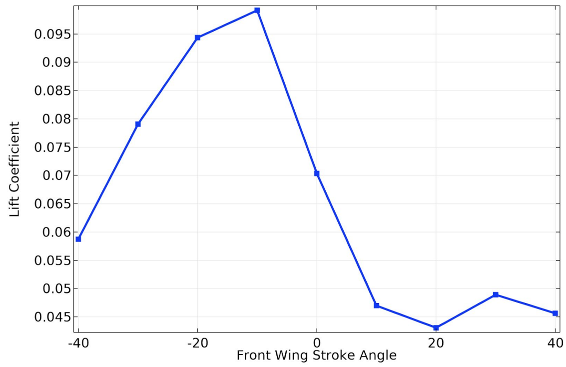


Figure 22  Lift Curve

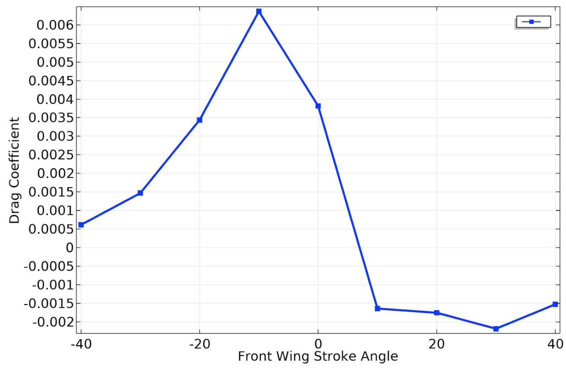


Figure 23  Drag Curve

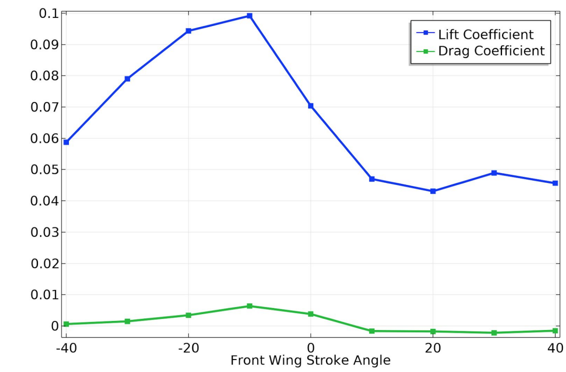


Figure 24  Cl, Cd vs Stroke Angles

The aerodynamics parameters, the Lift Coefficient (Cl), Drag Coefficient (Cd) at different stroke angles help us assess the flight performance of the insects at forward flight, where the contour plot helps to investigate the flight mechanics in detail. The quasi steady state results are enclosed in this paper, the unsteady effects will be reported in the future reports. The computational design investigation and research outcome will be used to design novel personal air transport and short haul air cargo transportation.

## Conclusion

Brief review of birds and insect flight was outlined with an overview of insect flight mechanics. The virtual wind tunnel setup to study the steady and unsteady aerodynamic behaviour were detailed. The virtual wind tunnel model, CAD and CFD numerical modeling detail of bumblebee and dragonfly were expounded. Post-processed fluid velocity and pressure distribution contour plots and flight parameters at different flapping wing angles of the bumblebee body and wings were used to study the flight performance. The insects model in the virtual wind tunnel can be scaled up to study bioinspired lightweight personal air transporters and also drones for general purpose short haul air cargo transportation.

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## Acknowledgement:-

This research was supported by the Research & Innovation Department of ATOA Scientific Technologies Pvt Ltd, Bengaluru, India. The author would like to thank the technical team, who provided insight and expertise that greatly assisted the research.