ASSESSMENT OF FLOW AROUND FLYING MOSQUITO USING COMPUTATIONAL FLUID DYNAMICS

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ASSessment of Flow around Flying Mosquito Using Computational Fluid Dynamics

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Mosquito is one of the most dangerous animal known to humans. It spreads large number of diseases such as malaria and tops the list as the animal known for the largest number of human deaths every year. Therefore, abating/controlling the diseases spread by mosquito becomes an important topic for global health. Many new methods (as mentioned in chapter 1.1) are developed in the recent past to meet the increasing need of controlling the spread of the diseases. These new methods can be developed further and other vector-control techniques can be innovated by obtaining deeper understanding of the mosquito flight. Considering the fact that these animals rely on flight for most part of their lives (which also includes host-seeking), aerodynamic insight of the mosquito flight would provide aid in the development of flight-based mosquito traps and innovate new ones.

Importance of studying aerodynamics of mosquito flight or in general insect flight also has its application in the development of the micro aerial vehicles. The growing demand of drones and its applications has urged the current robotic engineers to study insect flight and mimic the aerodynamic mechanisms involved in insect flight. There is no doubt that insect use unsteady mechanisms (unusual to conventional aircraft flight) to generate more lift. Implementation of these mechanisms, in the modern micro aerial vehicles, can improve the flight efficiency.

Past research on mosquito is mostly focused on their interaction with host (humans) based on heat and odour of the host. Some studies were focused on studying the aerodynamics of its flight by performing experimental tests to compute mean aerodynamic forces and moments for various sub-species of mosquito. The instantaneous forces over the wings and body of a mosquito are still unknown. Furthermore, vortex dynamics and effect of wing-wing/wing-body interaction, involved in the mosquito flight, is also unknown. These topics are the focus of the current project.

The aerodynamics around mosquito wings and body is modelled using computational fluid dynamics with ReFRESCO flow solver. ReFRESCO flow solver is developed by Maritime Research Institute Netherlands (MARIN). It has been widely used in the field of ships and offshore. Its application to insect flight may be considered unusual. However, irrespective of the application, the ReFRESCO flow solver can be used to solve the governing equations which govern the fluid flow. ReFRESCO solves the incompressible, unsteady Navier Stokes equations in the computational domain. The numerical model incorporates the wing and body morphology, kinematics of the same and fluid dynamics of hovering/ slow-flying mosquito. The kinematics and morphology are inputs in this

\[^{1}\text{vector-control defined as methods to limit/eradicate an animal which transmit disease.}\]
Abstract

Three models are considered to study the effect of wing-wing and wing-body interaction. The first model (Single-Wing model) simulates the flow around the left wing, the second model (Both-Wings model) simulates the flow around both wings and the third model (Wings-Body model) simulates the flow around both wings and body. Uncertainty estimation is performed to obtain an estimate of the numerical uncertainty involved in the current results. The results are also compared with the simulation results provided by experimental zoology group of WUR. Also, the mean vertical force (per wingbeat cycle) is compared with the estimated weight of the mosquito (provided by experimental zoology group of WUR).

Considering the vortex dynamics involved in mosquito flight, a robust D-ring vortex structure comprising of the leading edge vortex (LEV), tip vortex, root vortex and shed trailing edge vortex is observed during upstroke (ventral to dorsal wing motion) motion with strong downwash in its center. A D-ring vortex structure is also observed in the downstroke motion but it is relatively weaker and dissipates in a small duration. The LEV is conical in shape with small spanwise velocities (5-10 % relative to mean wing tip velocity) and it (LEV) persists throughout translational phases of the wing motion with no signs of burst/break along the span of the wing. LEV augments the the lift force by creating larger pressure difference between top and bottom surfaces of the wings.

Majority of the mean lift (63%) is contributed by the upstroke phase whereas downstroke contributes to 37%. The mean vertical force generated by a single wing is $8.909 \pm 0.147 \times 10^{-6}$ N per wing beat cycle. Furthermore, all three models (mentioned in previous paragraphs) support the weight of the mosquito. Therefore, the mean vertical force (per wingbeat cycle) lies within the standard deviation of the weight estimate. If the average weight estimate (without standard deviation) is considered, the numerical model overestimates the weight by nearly 43%-47% depending on the model used. Thrust is produced during the upstroke and drag is produced during downstroke wing motion. The effect of the wing-wing interaction, over the aerodynamic forces, is observed to be lower than 1%. Due to wing-body interaction, the mean vertical force reduces by 2.8% and mean horizontal force reduces by 5%. These results include the numerical uncertainty. The numerical uncertainty, in the aerodynamic forces, lie below 2% in all three models. An uncertainty of 5% is obtained for vortex structures (iso-surfaces of Q criterion).

*Models simulated: Single-wing, Both-wings or Wings-body.*
Based on the results obtained, it is clear that the vortex dynamics plays an important role in the aerodynamic force production in the mosquito flight. The change in vortex dynamics conforms with the change in instantaneous forces and pressure distribution over the wing. The wing-wing and wing-body interaction is observed to be low in hovering/slow flying mosquito. Therefore, any future aerodynamic study, of hovering/slow flying mosquito, can be performed by simulating a single wing to save computation time and complexity. However, wing-wing/wing-body interaction may have significant influence with increase in forward speed. Therefore, a potential future study may consider forward flight case and change in aerodynamic properties with increase in forward speed. In addition to that, the influence of wing flexibility, addition of other body parts such as legs and proboscis and change in morphology/kinematics (fed mosquito) can be studied in future.
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INTRODUCTION

1.1. INTRODUCTION AND MOTIVATION

One of the deadliest disease known to man is malaria. A disease, that is the leading cause of mortality in Africa [2]. Out of 438,000 estimated deaths in the year 2015, 394,000 (90%) occur in Africa and rest in South-East Asia/Eastern Mediterranean regions [3]. Figure 1.1 shows the malaria cases per 1000 people for the year 2014 in the world. It is quite clear from fig 1.1 that the presence of malaria is observed in almost half of the world with major concentration in African regions. Hence, controlling the spread of malaria is an important task to save lives all over the world.

To control the spread of malaria, primary methods such as insecticides, use of nets and avoiding stagnant waters are widely used. However, an emerging resistance to insecticides [3] and mosquito bites, outside the protection of nets, call for additional intervention methods [4]. New methods, by utilizing the knowledge of mosquito flight and behaviour, are developed to prevent the spread of malaria. One such method is the laser based equipment ‘Photogenic fence’ (as shown in fig 1.2 a.) which detects the mosquito, based on its wing motion and flapping frequency, and shoots laser to exterminate the mosquito [5]. Although developers claim that it covers large areas [6], this method is widely criticized for its practicability since most of the malaria infested regions do not have stable electricity supply [7]. Another method, called the Suna trap (as shown in fig 1.2), captures mosquitoes by mimicking the human skin, odour etc. [8]. A recent study shows that the malaria prevalence is lower by 29.8% in the suna-trap intervened areas relative to non-intervened areas [4]. In order to increase the effectiveness of these methods (traps based on flight) and to innovate new prevention methods, larger understanding of mosquito flight is required. Since flight is an important part of mosquito’s life, studying the aerodynamics involved in its flight would be highly beneficial in finding new ways of vector control (based on its flight and without using insecticides [9]).
1. Introduction

Figure 1.1: World distribution of malaria 2014 [3]. Note the global spread of malaria with major concentration in African regions.

Figure 1.2: Two new methods/gadgets to control the spread of malaria. (a.) Laser based equipment Photogenic fence [5] which detects the mosquito based on its wing beat frequency and shoots a laser to exterminate it. (b.) Human mimicking system Suna trap which attracts mosquitoes by mimicking human odour/releasing $CO_2$ and traps them [8].

In general, biological flight and its aerodynamics has gained a lot of research attention from various parts of the world recently. As will be explained in the next section, insects use unusual flight mechanisms to fly [10] [11] and this has caught the curios-
1.1. Introduction and Motivation

ity of many researchers. These flight mechanisms are described in chapter 2. Wide range of insects have been studied in the past. These include locusts, hawkmoth, thrips, fruitfly, chalcid wasp, honeybee etc. Mosquito flight will be a new addition to this field of knowledge. Large aerodynamic and flight dynamic differences have been observed amongst insects and interest to study a particular specie depends on the uniqueness of its flight. Mosquito also exhibits such uniqueness. Firstly, the wing beat frequency of a flying mosquito is recorded to be one amongst the highest (600Hz) amongst insects [12] [13] and the reason for such a high number is still unknown. Secondly, when mosquito feed on human blood (only female mosquitoes feed on human blood), the size of the mosquito is observed to nearly triple. In addition to that, mosquitoes are observed to alter their wing beat frequencies and amplitudes to compensate for weight changes [14].

Another motivation to study insect flight is improve the performance of Micro Aerial Vehicles (MAVs). MAVs are used in various fields such as environmental monitoring, surveillance and reconnaissance, biochemical sensing and assessment of hostile situations [15, 16]. An example of MAV is the Delfly Micro shown in figure 1.3. It weighs 3.07 gram and it is currently the smallest flying ornithopter (10 cm wing span) with a camera mounted on board [17]. An interesting aerodynamic feature of Delfly is that it uses an unsteady mechanism called 'clap and fling' [17] which is a biological flight mechanism to generate additional lift [18]. More about the mechanism is explained in section 2.2.1. Most MAVs fly at speeds comparable with that of insects [16]. Also, MAVs size, weight and flight environments are comparable with insects [18]. Hence, study of insect flight is of large interest to the MAV community. The insect flight is considered to be a benchmark for the development of MAVs when the performance, efficiency and maneuverability are considered [19]. Understanding the aerodynamics and flight mechanism involved in insect flight will greatly help to develop advanced bio-inspired MAVs and in general, Unmanned Aerial Vehicles (UAVs). To summarize, knowledge of mosquito flight can be used in developing flight based traps, to contribute to the knowledge of the insect flight in general and to improve MAVs/UAVs.

![Figure 1.3: An illustration of an bio-inspired MAV: Delfly Micro [17]. It generates additional lift by utilizing an unsteady mechanism 'Clap and Fling' which is used by various biological flyers. Refer 2.2.1 for more information about the unsteady mechanism.](image)
1.1.1. Introduction to Biological Flight

Study of mosquito flight comes under a distinct field called insect flight which is in general, a part of biological flight. Biological flight characteristics are quite different when compared to conventional aircraft flight. Airplanes rely on the forward motion of the body (fuselage) relative to the air which produces lift force in vertical direction. The wings of an airplane are fixed, rigid and do not move with respect to the fuselage. Forward motion is accomplished by engines (propeller, jet, turbojet etc.). The control surfaces of an airplane, which change the flight directions, are also dependant on the forward motion of the airplane. On the other hand, biological flight is based on flapping of wings [15]. Like conventional aircraft flight, the wings of a biological flyer move forward relative to air. In addition to that, wings of a biological flyer also twist, turn, sweep, plunge and move relative to the body [11, 15, 18]. These wing motions are performed to maintain a proper balance of the aerodynamic forces in accordance with the flight task such as feeding, mating etc. [15]. Such wing motions make the insect flight complex when compared to conventional aircraft flight and the complexity changes with change in the flight phase like hovering, forward, gliding or flight task [10, 18].

Although, insect flight is not similar to that of conventional airplane flight, it shows some similarity with rotorcrafts such as helicopters. Rotorcrafts tilt their wing rotation plane in order to obtain a component of resultant force in forward direction giving thrust whereas biological flyers tilt their stroke plane (plane incorporating wing motion) to do the same [18]. The larger the tilting of the rotation plane of a helicopter, the faster the forward motion. Biological flyers also tilt their stroke planes to fly faster and reduce the tilt angle to slow down [18]. Although some similarities exist between insect and human flight, research into insect flight shows that the aerodynamic force generation involved in the insect flight is significantly different from human flight (more explained in the chapter 2).

Within the field of biological flyers, noticeable differences are found when the size of the flyers differs. Amongst biological flyers, the flapping pattern considerably changes from one flyer to another [20]. Figure 1.4 shows an example of the trace of wing tips of different flyers. As seen from the figure, large flyers show relatively simpler wing tip pattern than small flyers [15]. A large flyer, like an albatross, exhibits an oval wing tip path whereas locusts or fruitfly exhibits a highly curved path [18]. The change in flapping pattern results in the change of flight dynamics and hence aerodynamics. At this point, in the study of biological flyers, the differences between large flyers (birds) and small flyers (insects) are quite large [18]. In general, with an increase of the size of the flyer, the Reynolds number, defined as the ratio of inertial to viscous forces, increases. \( Re \) is proportional to the size of the flyer and flight speed. Hence, birds fly at a higher Reynolds number (\( Re \)) than insects. Figure 1.5 shows the general trend of change in characteristics of flyer based on \( Re \) and wingbeat frequency. As seen from the figure, with decrease in size of the flyer, the wing to body weight ratio tends to decrease and the wing beat frequency increases [1]. The mass of the wing contribute to nearly 10%-20% of the overall weight for birds and 1%-5% for small flyers [1]. Due to larger wing mass, the wing inertia and power requirement of flight tends to be larger for large flyers.
Based on fundamental aerodynamics, large $Re$ flight results in higher lift to drag ratio ($L/D$) [15]. For example, the lift to drag ratio for a large flyer such as albatross is nearly 19 and for a small flyer such as fruitfly is 1.8 [18]. Continuing with differences amongst large and small flyers, large flyers (with hummingbird as an exception) cannot flip their wings at the end of wing stroke unlike small flyers which is required to produce additional lift [18]. The additional lift, during wing rotation, is a result of an unsteady mechanism called 'rotational lift'. This is explained in detail in section 2.2.3.

Figure 1.4: Change in the wing tip paths for various flyers indicated by arrows: (a.) Albatross (b.) Pigeon (c.) Horseshoe bat, fast flight (d.) Horseshoe bat, slow gait (e.) Blowfly (f.) Locust (g.) June beetle (h.) Fruitfly [21].

Figure 1.5: Characteristics of biological flyers based on $Re$ and wing beat frequency [1]. With decrease in flyer size, the wing beat frequency increases with decrease in $Re$ of the flight and wing/body mass ratio.

1Wing flip is a part of supination/pronation during which the wing reverses the translation direction making the top surface the new bottom surface and the bottom surface the new top surface.
1.1.2. Methods used to study insect aerodynamics:

Aerodynamic study of the insect flight can be performed by experimental or numerical methods. For example, instantaneous forces over the insect wing or body can be measured using tethered insect flight [22] (experimental method) in which the insect is tethered to a force sensor. Or forces can be computed performing numerical simulations. Experimental methods can be performed without a lot of assumptions such as incompressibility, rigid wing, no venation (arrangement of veins in an insect wing) etc. These assumptions are usually considered in numerical methods in order to simplify the calculations, save time or due to computation limitations. Although experimental tests with insects have small number of assumptions, they involve many sources of disruptions which changes the setup expectations. The accurate quantification of the forces or motion continue to be a difficult task with the current technology [23]. To illustrate, as previously mentioned, a common experimental test used to measure the instantaneous forces and torques over insect bodies is by tethering the insects (as shown in figure 1.6 for a honeybee). Figure 1.6 shows a tethered honeybee to a force sensor which measures the aerodynamic forces [22]. This setup disrupts the insect sensory feedback mechanism by sensory organs (such as halteres) and changes the wing kinematics considerably (right image in fig. 1.6) [22]. Figure 1.6 (right image) shows the mid wing chord position in a wing beat cycle for the free and tethered flight.

As years passed and technology improved, the experimental setups also improved thereby reducing the errors. The morphology and kinematics of an insect can be obtained from the experiments with negligible errors. However, complications arise when
visualization of flow, around an insect body and wings, has to be studied. This is due to the fact that the flow around flying insects is highly unsteady which makes it difficult for experimental equipments to accurately capture the change in flow pattern [10][24]. Many researchers [23, 25] use dynamically scaled mechanical models to visualise the flow and measure forces on the wing. This provides a larger degree of control over the experiments compared to tethered flights. However, mechanical models of insect wing [25] have mechanical restrictions and cannot reproduce wing motion at large wing sweeps. As the insect wings come closer to each other, individually turn and reverse the translation direction during the end of half stroke, the servos reach their limit of rotation resulting in a physical constraint. Therefore, most experimental setups involving insect flight alter the natural flight due to physical or visual constraints [24].

Another method, used to obtain forces and visualize the flow in insect flight, involves Computational Fluid Dynamics (CFD) simulations to model the aerodynamics around the flying insect. In the initial stages of research into insect flight (early 1970s), numerical modelling was not an efficient option due to the lack of computational power and difficulty of simulating insect geometry and kinematics. In addition to that, wing motion exhibits complex movements in a short duration which requires deforming/moving mesh capabilities. This requires additional computation power since mesh data has to be saved repeatedly. With higher computational power and availability of high quality solvers in present age, further research through CFD is feasible. The advantages of using CFD are many. This includes simpler setup (softwares used to solve the flow, mesh generator, flow visualisation tool etc.), freedom to include/exclude flow properties (incompressibility, turbulence models etc.) and easier control of model kinematics and morphology.

1.2. TERMINOLOGY AND CONVENTIONS USED IN INSECT FLIGHT

A necessary part of the research project is to adopt a complete set of terminology and conventions used in insect flight. These are different from the conventional aircraft terminologies to a large extent. The conventional aircraft terminologies and corresponding differences with insect flight are not discussed here. This chapter deals with terminology and conventions, which are commonly used in the field of insect aerodynamics and used in current thesis. A representation of the terminologies and wing motion phases is shown in figure 1.7 for an insect [24].

1.2.1. GENERAL INSECT TERMINOLOGIES

The span of the wing represents the length from wing-tip to wing-tip. The wing length is calculated from wing base to wing tip of a single wing. The ‘chord’ at any section along the wing represents the distance from wing leading edge to trailing edge.

A wing beat cycle has 4 main stages. These stages are downstroke, supination, upstroke and pronation. Here, downstroke describes the dorsal to ventral motion and up-
stroke describes the ventral to dorsal motion of the wing. Supination is defined as a phase with large wing rotations around spanwise axis of the wing. It is performed during late downstroke and early upstroke. Pronation also represents a phase with large rotations about spanwise axis. However, pronation is performed during late upstroke and early downstroke. Wings of an insect go through translation, rotation and/or a combination of these motions. The downstroke and upstroke phases are dominated by translational motion whereas the supination and pronation largely involve wing rotation about spanwise axis [23].

An effective angle of attack ($\alpha'$) is defined as an angle made by the chord with respect to relative velocity at a section. The coordinate system described here is standard in this field (insect flight). All the parameters presented here are considered with an assumption of a rigid wing/body. An overview of the terminology adopted in the current project is given in figure 1.8 for fruitfly [26]. The inertial reference frame (X,Y,Z) is earth-fixed. The wing-based reference frame (x,y,z) is located at the body with its origin at the wing-root. Angles $\beta$ and $\chi$ represent the stroke plane angle and the body angle respectively. Here, stroke plane is a plane which incorporates wing motion and stroke plane angle is an angle made by it with the body longitudinal axis. Body angle is defined as an angle made by longitudinal axis of the body axis with horizontal plane of inertial frame.
1.2. Terminology and Conventions Used in Insect Flight

1.2.2. Wing Kinematics

The wing kinematics are represented by three angles namely rotation ($\gamma$), deviation ($\theta$) and stroke angle ($\phi$). This is shown in Figure 1.8. Deviation angle is the angle made by the wing about the x-axis, stroke angle is the angle made by the wing about the z-axis and rotational angle describes the geometric angle of attack (all in wing reference frame). The wing kinematics are provided by Dr. ir. F. T. Muijres (and team) from experimental zoology group of Wageningen University and Research (WUR). This is used in the current project. A brief procedure, explaining the method to obtain the kinematics, is presented in section 3.2.2. Kinematics was obtained by fitting Fourier series through the distributions of the tracked wingbeats. Wing kinematics are represented in terms of the first $N$ terms/order of Fourier series given by equation 1.1-1.3 [18]. The coefficients
(\phi_{sn}, \phi_{cn}, \theta_{sn} etc.) in these equations are obtained from experimental tests. Here \(f\) is flapping frequency and \(t\) is time. The stroke plane angle and body angle (as shown in the figure 1.8) are also obtained from the experimental tests. The exact formulae with degree are mentioned in the appendix A.1.

\[ \phi(t) = \sum_{n=0}^{N} \left[ \phi_{cn} \cos(2n\pi ft) + \phi_{sn} \sin(2n\pi ft) \right] \quad (1.1) \]

\[ \theta(t) = \sum_{n=0}^{N} \left[ \theta_{cn} \cos(2n\pi ft) + \theta_{sn} \sin(2n\pi ft) \right] \quad (1.2) \]

\[ \gamma(t) = \sum_{n=0}^{N} \left[ \gamma_{cn} \cos(2n\pi ft) + \gamma_{sn} \sin(2n\pi ft) \right] \quad (1.3) \]

1.3. STRUCTURE OF THE REPORT

The structure of the report is as follows:

1. Chapter 2 presents the literature study performed to gain necessary understanding of the insect flight and aerodynamics. Also, the research questions and objectives for the current project are presented at the end of the chapter. Chapter 2 deals with aerodynamic unsteadiness involved in insect flight by presenting all the unsteady mechanisms used by insects to fly. This includes the unsteady mechanisms used during upstroke or downstroke (wing motion dominated by translational motion) such as delayed stall and jet-interaction and unsteady mechanisms used during stroke reversal such as wake capture, rotational lift and clap and fling. Furthermore, the unsteady mechanisms are related to the transient forces over the insect wing during the course of wing beat cycle. The chapter also presents the species and morphology of mosquito used in the current project. In addition to that, previous research on mosquito is presented.

2. Chapter 3 deals with the methodology and theoretical formulation used in the current project. It starts with explaining the general procedure used to model the simulations for the Single-Wing, Both-Wings and Wings-Body model. Then, the procedure used to obtain the kinematics, morphology and weight estimation is presented briefly. After that, the similarity parameters obtained for mosquito flight is computed, presented and discussed. This involves Reynolds number and reduced frequency. Subsequently, the fluid flow governing equations are presented. Also, theoretical and morphological assumptions, considered in the current project, are discussed. This is followed by explanation of the computational domain and meshing for all three models (Single-Wing, Both-Wings and Wings-Body model). After that, the general procedure, used by ReFRESCO solver, to solve the governing equations followed by the solver settings are discussed in detail. This also includes the deforming grid mechanism and the procedure used to implement the wing motion. Then, the uncertainty module used to estimate the numerical uncertainty
is presented in detail. Finally, the theory behind vortex visualization (Q criterion) is reported briefly.

3. Results from the simulations are presented in Chapter 4. Firstly, the grid and time sensitivity results are discussed. This is followed by far-field flow visualization. Far-field flow visualization involves the change in vortex dynamics in the wing swept region. After far-field flow visualization, near-field flow visualization is presented. This involves the inception, development and shedding of the vortices over the wing surface. This is done by visualizing the change in vortex cores and iso-surfaces representing vortex structures (Q criterion). After that, the change in instantaneous aerodynamic forces and pressure distributions, over the wing, is discussed and related to the far-field/near-field flow visualization. Along with instantaneous aerodynamic forces, mean aerodynamic forces (per wing beat cycle) are discussed. After that, the simulation results are compared with the results provided by the WUR. Subsequently, the instantaneous forces, pressure distribution and vortex structure pattern for all three models is discussed and compared with each other. Finally, the reason for an attached LEV is discussed briefly.

4. Chapter 5 presents the conclusion derived from the current study by answering the research questions. Also, recommendations for further study and improvements are reported.

5. Appendix involve explanation of the kinematics and the Fourier coefficients used in the current project. In addition to that, the user routines written in Fortran programming language are presented. Furthermore, the body radius, obtained from the experiments, is reported. Finally, a general description of the ReFRESCO flow solver, Hexpress meshing software and meshing routine, Tecplot flow visualization software is reported.
2.1. QUASI-STeady APPROACH AND FLOW UNSTEADINESS

One of the challenging tasks, during the early research into insect aerodynamics, was to develop a model which efficiently computes the forces on an insect wing/body. In the initial stages of research into the insect aerodynamics, quasi-steady approach was widely used to compute the aerodynamic lift and drag of the insect flight. This method, as it was used initially, assumed that the instantaneous forces over an insect wing are equivalent to the steady state forces at the same wing attitude and freestream velocity [11]. Based on this model, any dynamic motion can be split into static positions. The aerodynamic forces for the whole dynamic motion can then be reconstructed by the forces over static positions [24].

Although quasi-steady method was positively demonstrated [10, 27], Ellington [11] showed that this method does not compute the aerodynamic forces accurately. This was done using proof-of-contradiction in which, the maximum vertical force, in a wing-beat cycle, was compared with the minimum lift required to stay aloft. If the maximum predicted lift force from quasi steady model is lower than the weight or mean lift required to stay aloft, the model does not compute the forces properly and if it is larger than the insect weight, the model cannot be discounted [24]. Ellington [11] showed that quasi-steady theory did not calculate the required average lift for flight and proposed to revise the model to include rotational effect [24].

Sane and Dickinson [28] revised the quasi-steady model to include forces resulting from wing rotation. The results from the revised quasi-steady model showed substantial improvement from previous model which only considered the translational wing mo-
However, the results still showed considerable discrepancies between the theoretical force estimates from revised quasi-steady model and the experimental measurements. The mean lift per wing beat cycle, predicted by the revised quasi-steady model, is well predicted but it largely underestimates the mean drag as pointed out by Bos et al. [29]. Sane and Dickinson [28] concluded the discrepancies, during the stroke reversal, to be the effect of the unsteady mechanisms during wing rotation. This limitation of the revised quasi-steady model, regarding applicability on unsteady systems such as insect flight, has spurred the search for unsteady mechanisms used by insects [24, 29].

Intensity of unsteadiness, in an insect flight, can be analysed using a similarity parameter called reduced frequency \( k \), which is the ratio of flapping speed to forward speed [11] given by the equation 2.1. Here \( f \), \( L_{\text{ref}} \) and \( U_{\text{ref}} \) are the wing-beat frequency, reference length like mean aerodynamic chord and reference velocity like forward speed respectively. This value decreases with increase in forward speed and a low value of \( k \) results in spatial derivatives of the aerodynamic forces which tend to be smaller [11]. At large forward speeds, the reduced frequency is low and the flow unsteadiness is smaller when compared to quasi-steady state. At slow speed flight, the reduced frequency increases and unsteady effects become important [11]. This brings us to the limitation of the current definition of reduced frequency. For hovering, the parameter tends to infinity. As pointed out by Ellington [11], the unsteadiness effects are expected to be largest during hovering. Reduced frequency, for hovering, is calculated by using \( U_{\text{ref}} \) as wing tip velocity. Wing tip velocity is considered to be the motion scale of the wing in hovering. Considering the wing tip velocity, reduced frequency, for hovering, is given by the equation 2.1 [18, 30]. Here \( \phi \) is the full stroke amplitude of the wing. Reduced frequency compares the spatial wavelength of the flow disturbance to the chord and gives the ratio of fluid convection scale and motion time scale [1, 30]. Considering the full stroke amplitude and aspect ratio of the mosquito wing, a large value of reduced frequency is obtained for mosquito flight for hovering. Reduced frequency for *Anopheles coluzzii* is calculated and presented in the chapter 3.3.

\[
k = \frac{\pi f L_{\text{ref}}}{U_{\text{ref}}}; \quad k_{\text{hovering}} = \frac{\pi}{\phi A_R}
\]  

### 2.2. Research Related to Unsteady Mechanisms

It is quite clear that insect aerodynamics is dominated by unsteadiness. Further aerodynamic insight, obtained from various researchers [11, 23–25, 27, 28, 31], showed that multiple mechanisms are responsible for unsteady aerodynamic forces in the insect flight. Unsteady mechanisms, that are widely known in the field, are reported in the this section.
2.2.1. Clap and Fling Mechanism

The first unsteady mechanism, which was proposed by Weis-Fogh [27] is the clap and fling mechanism. This mechanism involves close encounter of both wings (left and right) called ‘clap’ and then separation of wings called ‘peel/fling’. This is shown in the figure 2.1. It involves two sub parts, the clap and the fling. During the clap phase, the left and the right wing come in close proximity such that the leading edges of both wing touch or come close to each other and gradually, complete faces come close to each other such that the trailing edges also meet. This is shown in the upper portion of the figure 2.1. The gap, created at the start of the clap between the two wings, reduces as the clap proceeds. This produces a brief increase in downward jet as the wings come closer as shown in the c. part of the clap portion of figure 2.1. As a reaction to the increased downward jet, the wings experience an upward reaction resulting in additional lift [11]. During the fling mechanism, the wings start to move away from each other about the wing trailing edge. The wing motion, representing fling, is shown in the bottom of the figure 2.1. The increasing gap in between the wings creates a fluid inhalation into the gap resulting in an attached vorticity at the leading edge of both wings [11, 24].

Clap and fling mechanism is executed during the pronation phase and it strengthens the circulation over the wings producing higher lift than usual [18]. It was later found that an angular separation of 10-12 degrees is required in order to perform this mechanism [31]. This mechanism is observed for many insects such as encarsia [11], damselflies and moths [32]. It is expected to occur for insects with wing kinematics such that the wings come close to each other. Clap and fling is not observed in several insects like bees, wasps, beetles [18, 32]. Based on the kinematics obtained for mosquito (results
from WUR), it seems highly unlikely for mosquito to use this mechanism. The angular separation, between the mosquito wings during pronation is observed to be around 130 degrees. This is significantly greater than the range needed to perform clap and fling.

2.2.2. Delayed stall

Ellington et al. [25] studied the flight of a hawkmoth (*Manduca sexta*) by performing experimental tethered tests with smoke visualization. Tests were performed with a vertical smoke rake positioned along the wind tunnel axis and the tethered hawkmoth was moved relative to the smoke to visualise the spanwise change in flow. Figure 2.2 shows the flow mid-downstroke and at mid left wing position obtained by Ellington et al. [25]. Results showed leading edge vortex (LEV) attached on top of the wings of the insect as shown in figure 2.2. The flow separates at the LE and reattaches further downstream enclosing a LEV. The occurrence of the LEV is due to the sharp leading edge (LE) as the absence of the the smooth curve separates the flow instantly [25, 33]. It was found that the presence of the LEV on top of the wing increased the lift force. The LEV augments the lift force since the LEV is a low pressure region which creates a higher pressure difference between the top and bottom surfaces of the wing [25]. Furthermore, the size of the LEV

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(a.) Leading edge vortex on top of the Wing

(b.) LEV at different forward speeds

Figure 2.2: Flow visualisation around a female hawkmoth during late downstroke [25]. (a.) The LEV is observed as the flow detaches at the LE and reattaches further downstream due to the influence of surrounding wing. (b.) LEV at different forward speeds. The flow is largely disturbed (in the wake) during slow forward flight. It is more streamlined at higher forward speeds.
is observed to increase with increase of the forward speed (see figure 2.2 (b.)) and with the advancement of downstroke.

Occurrence of LEV is observed in all the insect species studied so far. An important question, that needed to be answered, was the source of an attached LEV. One theory explaining this is that the momentum is transferred from the chordwise to the spanwise direction thereby spiraling the axial flow towards the tip of wing [24][25]. This maintains a smaller and hence a stabler LEV by restricting its growth. The influence of spanwise flow on the attachment of LEV, in insect flight, was first observed by Ellington et al. [25]. Ellington et al. [25] measured the axial velocity in the LEV along the span of the hawkmoth mechanical wing model. Figure 2.3 shows the same. As observed in figure 2.3, the axial velocity along the span of the wing increased gradually until the mid span and then decreases. This pattern of axial velocity is found to be in agreement with the circulation in the spanwise direction. The hypothesis of the spanwise momentum transfer was supported by Liu et al. [34] and Dickinson et al. [23].

Another hypothesis, which explains stable attachment of LEV, is that the downwash from the wing tip and the wake decreases the effective angle of attack thereby restricting the growth of the LEV [35]. Both these hypothesis (spanwise velocity and wake induced velocity) were tested by Birch and Dickinson using a mechanical model of fruitfly [35]. Low spanwise velocity (2-5% of average tip velocity) and a small axial flow, at the core of the LEV, were observed along the span of the wing. This led to the conclusion that the scale of magnitudes of spanwise velocities, with respect to the wing tip, differ in hawkmoth and fruitfly flight. It is large (reaching close to wing tip velocities) on hawkmoth wing and small (2-5% of wing tip velocity) on fruitfly wing. It was concluded that the net aerodynamic performance is limited by the magnitude of the LEV strength/vorticity and not by the stable attachment of LEV [35]. Furthermore, they concluded that the hypothesis of spanwise flow restricting the growth of LEV, was not observed in the fruitfly flight.
To test the second hypothesis about the influence of tip and wake vortices over the LEV growth, Birch and Dickinson [35] observed the influence of downwash over force production and effective angle of attack. The change in the forces and the effective AOA from the first stroke (standstill air) until the third stroke (when wake structure was established) was observed. The decrease in the effective angle-of-attack and aerodynamic forces implied the influence of the downwash on the LEV. The induced velocity from the downwash decreases the effective AOA which limits the growth of the LEV. The decrease of the effective AOA in the second and the third stroke (when the wake was well established) was higher than the first stroke (no developed wake). Aono et al. [26] performed numerical simulations on fruitfly flight. The influence of downwash over wing aerodynamic forces was observed. As reported by Aono et al., mean lift decreased by nearly 25% in the second stroke but this value maintained in the subsequent strokes [26]. This indicated that the simulation results differed with stroke number (initial stroke/subsequent stroke) and that the downwash structure mostly gets established by the end of first cycle in fruitfly flight. The decrease in mean lift was considered to be due to the increase in wake which increases with wing strokes/motion. Shyy and Liu [20] performed numerical simulations on hawkmoth and fruitfly models. They found that the downwash reduces the mean lift by nearly 17% for hawkmoth and 21% for fruitfly [20]. The results obtained by Ellington et al. [25] for hawkmoth and Birch and Dickinson [35] for fruitfly suggests that different mechanisms are responsible for the attachment of the LEV.

2.2.3. Rotational Lift

Results obtained by Dickinson et al. [23], using mechanical model of fruitfly wings, showed force peaks at the start and end of a half-stroke (upstroke or downstroke). This implied the existence of rotational unsteady mechanisms apart from the unsteady mechanism due to wing translation (delayed stall). To observe the influence of wing rotation on the force generation, the total aerodynamic force were subtracted with force due to wing translation. The forces due to wing translation were obtained by rotating the wing through 180 degrees at constant speed and angle of attack. Results showed that the delayed stall mechanism is dominant only during translational phase and the rest, which contributed to 35% of stroke lift, was due to unsteady stroke reversal mechanisms called rotational lift and wake capture respectively [23]. The two observed aerodynamic force peaks at the end and start of each half-stroke as shown in figure 2.4a.

Dickinson et al. [23] related the force peak at the end of the stroke to the Magnus effect. This mechanism produces additional lift due to the rotation of the wing at the end of half-stroke creating a low pressure above and a high pressure below the wing surface. Their results were supported by Trizila et al. [37]. The changes in this mechanism, due to the change of the timing of the wing rotation which can happen before/after/during the change in stroke direction, was also explained. This is shown in figure 2.5. A positive lift peak in an advanced rotation (rotation before the wing changes direction), negative lift peak in a delayed rotation (rotation after direction change) and a combination of both in a symmetrical rotation is obtained [23]. This pattern of force peaks is also in agreement with the results obtained by Sun and Tang [36].
(a) Time history of total lift, translational and rotational estimates of lift, and velocity for hovering fruitfly [23].

Figure 2.4: Force peaks obtained from different studies during the rotational phases of wing (supination/pronation). (a.) Red and blue lines indicate the total lift and translational component respectively. The black line indicates the rotational component. Purple and green lines indicate translational and rotational velocities respectively. (b.) Solid and dashed lines indicate the results obtained by performing simulations in a wake developed flow and still air respectively. $\Delta t_r$ is the time taken to complete the rotational acceleration.

(b) Aerodynamic coefficients when the wing starts in still air obtained by Sun and Tang [36].

Figure 2.5: Force plots due to wing rotation (black) obtained by Dickinson et al. [23]. Red lines indicate forces due to rotational circulation and blue due to wake capture obtained by subtracting the rotational component from the total aerodynamic forces. Advanced, symmetrical and delayed rotation represents the wing flip before, during and after reversing the wing translational direction.
Sane and Dickinson [28], also obtained the force peaks with their improved quasi-steady model (modified to include the circulation due to wing rotation). The effect of the rotational mechanisms over the aerodynamic change were the main concentration of this study. The results from Sane and Dickinson [28] suggests different reason of the force peak at the end of the translational phase (not Magnus effect). Their argument, against previously proposed rotational lift mechanism, was that the Magnus effect can only be applied to blunt objects such as cylinders/spheres and not complex thin airfoils/cross-sections [24]. Sane and Dickinson [28] hypothesized that the obtained peak, at the end of the half stroke, was a result of an additional circulation which is generated to provide a smooth tangential force to re-establish Kutta condition at TE [24]. Results from Sun and Tang [36] supported this mechanism for the force peak at the end of the half stroke.

2.2.4. WAKE CAPTURE MECHANISM

The wake capture mechanism is linked to the force peak obtained at the start of half-stroke. The timing of the force peak, observed at the start of half-stroke, was found to be independent of the timing of the wing orientation during reversal (advanced, delayed or symmetrical rotation) [23]. This can be visualised in the figure 2.5. The peak, due to rotational lift, shifts with respect to the time, for different wing orientation during stroke reversal. However, the force peak due to wake capture occurs at the same time for all wing orientation type during stroke reversal. This makes the force peak, due to wake capture, different from the rotational lift mechanism.

![Wake capture mechanism diagram](image)

Figure 2.6: Wake capture mechanism by Sane [24]. The LEV and TEV are shed during the wing flip (A-C). As the wing reverses the direction and translates in the opposite direction (D-F), it encounters the shed LEV and/or TEV. This increases/decreases the effective flow velocity over the wing resulting in an increase/decrease in the lift.

Wake capture mechanism is explained well by Sane [24] shown in figure 2.6. As the wing rotates and reverses its direction (figure 2.6 (a.)-(c.)), the TEV and LEV are shed in the wake. When the wing reverses its direction and moves into the shed vorticity (figure 2.6 (d.)-(e.)), it encounters an enhanced velocity and acceleration fields resulting in a change in circulation and hence aerodynamic forces [24]. Based on the orientation of
the wing rotation during stroke reversal (advanced, delayed, symmetrical), there is an increase/decrease in the force magnitude (not timing of the force peak) [23]. Dickinson et al. [23] called it ‘wake capture’ since the mechanism, if used effectively (based on wing rotation), can result in an increased lift by recapturing the energy lost in the wake [23]. In addition to that, they obtained wake capture force peak even when the wing was made to stop at stroke reversal suggesting that the wake from previous stroke induced velocities over the wing [23].

Trizila et al. [37] performed flow simulations on two-dimensional (2D) and three dimensional (3D) flapping flight at $Re$ of 100. The results demonstrated the difference in wake capture mechanism for 2D and 3D flight. Simulations with uniform thickness 3D wing with elliptical airfoil and aspect ratio of 4 was used. Corresponding 2D airfoil was used to perform 2D simulations. The wing motion parameters included plunging, pitching and translation motion. Figure 2.7 shows the vorticity contours obtained by Trizila et al. [37] at two time instants during stroke reversal. As seen from the figure, the wake capture mechanism is observed to change from 2D to 3D motion. The LEV, shed in previous wake is observed to physically interact with the wing after stroke reversal for 2D case. However, in 3D case, the shed vortices convect away from the wing swept region resulting in no physical interaction. The simulations performed by Trizila et al. [37] do not include wing rotation about the wing root or stroke angle rotation. Therefore, the
result may be different for insect flight, in which, the wing rotates about the wing root as stroke angle rotation.

Another theory for the force peak at the start of the half stroke was presented by Sun and Tang [36]. They used computational fluid dynamics (CFD) to analyse the flow over a fruit fly model. Conclusions from Sun and Tang [36] contradicted the wake capture mechanism. Sun and Tang [36] explained the force peak, at the start of a stroke, as a result of sudden acceleration of the wing and not wake capture. By changing the parameters which increased or decreased the acceleration of the wing rotation, an increase or decrease in the lift coefficient was observed respectively [36]. The argument against the wake capture mechanism was that the absence of the Von Karman vortex street or shed vortex will result in the absence of the wake capture mechanism [36]. Sun and Tang also performed tests with the wing rotation starting at a stand-still air and still observed the force peak, at start of the stroke, as shown in fig. 2.4b. This suggested that the rotational acceleration influenced the generation of the force peak. Sun and Wu [38] also performed CFD analysis on the forward flight of fruitfly and their results were in agreement with Sun and Tang [36]. Although the results obtained from Sun and Tang [36] were in agreement with their measured forces, noticeable discrepancies near stoke reversal and validation sections were identified [24]. However, neither of the contradicting conclusions, about the force peak at the start of the half stroke by Dickinson et al. [23] and Sung and Tang [36], can be neglected.

2.3. Aerodynamic differences based on insect size and Reynolds number

Figure 2.8: Stream traces over (a.) hawkmoth, (b.) fruitfly and (c.) thrips by Shyy and Liu [20]. The LEV burst and instability is observed to lower/negligible for fruitfly ($Re \sim 120$) and thrips ($Re \sim 10$) flight unlike hawkmoth ($Re \sim 2000$). Over the hawkmoth wings, the LEV is observed to burst around 70-80% along wing length.
Considerable aerodynamic differences are observed when the size of the insect or Re of insect flight changes. This involves the vortex dynamics in the course of the wingbeat cycle and the vortex structure pattern. To illustrate, results obtained by Ellington et al. [25] and Liu et al. [34], considering hawkmoth flight, showed an unstable LEV over hawmoth wings which breaks down at 70-80% of wing span length. Also, the LEV, over the hawmoth wings, was observed to be conical-spiral in shape along the wing length. However, Birch and Dickinson [35] obtained a stable-attached LEV without any spiral behaviour for the fruitfly flight. Also, a second LEV, from wing tip and extending towards wing root during supination, as observed in hawkmoth flight is not seen in the fruitfly flight. Birch and Dickinson [35] concluded that the flow structure over an insect flight critically depends on the Re of the flight. Re for the fruit fly is around 100-250 and hawkmoth fly at a Re higher than 2000 [35].

The difference in the LEV was related to the magnitudes of the spanwise flow, which was substantial for a hawkmoth compared to a fruitfly [25]. The tests on hawkmoth and fruitfly present a possibility of multiple aerodynamic mechanisms responsible for an attached LEV. These are the presence of a high spanwise flow for a large Re hawkmoth and the influence of the downwash over the LEV for a low Re fruitfly. Unlike hawkmoth flight, the attachment of LEV on the fruitfly wings is due to flow induced by tip vortex (TV) and wake vorticity [35]. This was also supported by Aono et al. [26].

Shyy and Liu [20], performed CFD over three different insects namely hawkmoth, fruitfly and thrips (Re ~10). The streamline pattern (shown in fig. 2.8) shows the importance of Re. The conical shaped LEV, with large spanwise flow, which breaks down around 0.75c over the hawkmoth wings (at Re ~ 6000) was not observed in the fruitfly flight. A LEV, with low axial flow in core and without any signs of break down, connecting the TV was observed in the fruitfly flight (Re ~ 120). The LEV, over the wings of thrips (Re ~ 10), was found to be connected to the TV which was in turn connected to the TEV forming a vortex ring with a cylindrical flow structure [20]. Therefore, the size of the insect has a significant influence on the flow structure around the insect wings. The difference in the vortex dynamics due to change in Re also changes the aerodynamic forces over the wings of an insect.

Differences are not just observed in the vortex structures but also the flow properties. The spanwise pressure gradient over the wings of hawkmoth and fruitfly can be seen in figure 2.9 [20]. As seen from the figure, fruitfly do not produce steep pressure gradients, along the LEV, like hawkmoth. Figure 2.10 shows the spanwise velocity vector plane at 60% wing length for hawkmoth (top) and fruitfly (bottom). As seen from this figure, a greater spanwise flow, within the LEV, over the hawkmoth wings is observed when compared to the fruitfly wings. Shyy and Liu [20] conclude that at higher Re (6000), a higher pressure gradient creates enough spanwise flow within the core of LEV resulting in a helical flow structure [20].
2.4. MOSQUITO CLASSIFICATION, MORPHOLOGY AND PAST RESEARCH

A brief summary of the literature study, related to mosquito-human interaction and its aerodynamics, is presented in this section. Before that, its classification and morphology is discussed in brief.
2.4.1. **Classification and Morphology of Mosquito**

There are 3500 species of mosquitoes known to humans which come under 41 genera (a category of classification which comes in between family and species) [39]. *Anopheles* belongs to one of these genus which is further divided into 430 species [39]. *Anopheles gambiae* complex, a group of seven morphologically indistinguishable species within the genus *Anopheles* [40], is responsible for the largest malaria transmission in sub-Saharan Africa [40, 41]. Within the *Anopheles gambiae* complex, *Anopheles coluzzii* and *Anopheles gambiae s.s.* are the dominant malaria vectors in the sub-Saharan Africa [41]. *Anopheles coluzzii* is the current focus of the project. However, the study can be generalized to *Anopheles gambiae* complex due to morphological similarity of species within the complex [40].

Figure 2.11 shows the morphology of *Anopheles coluzzii* [39]. The main body parts are the head, thorax and abdomen. The head includes eyes for sight, long segmented antennae to detect host/habitat odours and proboscis used to feed on host [39]. The thorax includes three pair of legs and a pair of wings. The abdomen is used to contain blood meal which expands noticeably when fed [39]. For the current project, an unfed mosquito kinematics and morphology are considered. Past research on the insect flight is focused on modelling the aerodynamics of wings and body of an insect. The effect of other parts (legs and other parts relevant to the insect specie) insect are assumed to have negligible influence over the aerodynamics of the flight.

![Figure 2.11: Morphology and body parts of a female Anopheles adult][39]. The whole body is divided into head, thorax and abdomen.
2.4.2. Past research on mosquitoes

Past research on mosquito flight has been quite narrow. Although, flight forms an important part of its life, very little has been investigated concerning its flight performance and aerodynamics [42]. Lot of research has been done concerning the interaction between human and mosquito which is a direct or physical cause of the spread of the disease vector. Some studies focus on mosquito's behaviour based on the odor and heat of the host/human [43][44][45][46]. The change in direction, speed and maneuverability of mosquito have been the main focus in these studies. Dickerson et al. [9] studied the flight dynamics of Anopheles freeborni mosquito in a dense-than-air gas. They concluded that proper functioning of mosquito's haltere (shown in figure 2.11), which acts as a gyroscope, is highly dependant on the properties of flight medium [9].

Ahmad et al. [47] performed tethered experimental tests on mosquitoes (A. aegyptii and C. quinquefasciatus). The aerodynamic forces and coefficients were calculated from body parameters by considering the wings of the mosquito as a harmonic oscillator [47]. This was compared with the experimental results from tethered windtunnel flights. They obtained quantified results such as flight speeds, weight, aerodynamic forces from the tests. The obtained flight speeds range around 0.9-1.2 ms$^{-1}$, mass around 4.5-6 e-05 N, lift force around 5-8 e-05 N, drag around 0.1-0.62 e-05 N, and lift to drag ratio around 9.9-15.13 for female fliers [47].

Murty et al. [48] performed experimental tests considering the mosquito (C. quinquefasciatus). The static, dynamic and aerodynamic parameters of the flyer were studied by placing it inside a tube and measuring the sound levels [48]. Murty et al. [48] recorded the sound emitted from flapping mosquito and fed the recorded sound to oscilloscope to observe the change in voltage (after converting sound to voltage signals) [48]. Wing beat frequency was measured from oscillograms (data obtained from oscilloscope. Using cathetometer, a stroke angle of around 60 deg was measured [48]. Wings made a figure of eight in vertical plane and they were observed to vibrate in the plane parallel to the body axis of the flier [48]. The wing loading and frequency of the female flier were found to be 0.075 ±0.001 and 405 ±11 [48]. The computed moment of inertia was in the range 1.228 ± 0.013 × 10$^{-3}$g cm$^2$. Babu et al. [49][50] performed similar analysis with Culex Gelidus and Culex tritaeniorhynchus mosquito species and obtained results around the same order of magnitudes.

2.5. Current focus and research questions

The study of mosquitoes has reached new levels in the recent past. This involves study of its flight behaviour considering the odour/heat of the host, weight estimations, static and dynamic properties etc. So far, the vortex dynamics and the forces produced by mosquito wing are unknown. This is an important focus of the current project. Vortex dynamics will be studied by considering the iso-surface (Q criterion) structures. Furthermore, the difference in the vortex dynamics, transient forces and pressure distribution, due to wing-wing and wing-body interaction, will be studied. Knowing if there is/isn't
significant influence of wing-wing and wing-body interaction would ease any study in the future. If there is a significant influence, any future studies with numerical simulation cannot neglect the second wing and body. If no significant influence of the second wing (body) is observed, only single wing (both-wings) can be simulated.

2.5.1. Research Objectives and Questions

This research is carried out at Maritime Research Institute, Netherlands (MARIN) in collaboration with Wageningen University and Research (WUR) as a part of MSc program under Delft University of Technology (TUD). Research objective and questions are presented here, which forms an important part of the design framework of the thesis project. The research objective of this project is as follows:

To contribute to the aerodynamic knowledge of the mosquito flight by performing CFD simulations with ReFRESCO flow solver, including solution verification, and compare the results with the experimental and CFD results obtained from WUR.

This is further divided into subgoals which are presented below:

1. Simulation of a single wing model by reproducing wing morphology and kinematics provided by WUR.
   (a) Scrutinize accuracy of the solution by performing grid and time step sensitivity analysis.
   (b) Estimate uncertainty in forces and vortex structures using in-house (MARIN) uncertainty module.
   (c) Comparing mean lift force (per wing-beat) with the weight estimation provided by WUR. Comparing the transient forces with the simulations results provided by WUR.
   (d) Analysing the vortex structure pattern, transient forces and pressure distribution over one wing model of the mosquito.

2. CFD simulation of both wings and wings-body model.
   (a) Scrutinize accuracy of the solution by performing grid and time sensitivity analysis.
   (b) Estimate the uncertainty in forces and vortex structures.
   (c) Analysing the change in flow structure over wing, due to wing-wing and wing-body interaction by comparing the iso-structures (Q criterion).
   (d) Analyze change in transient forces and pressure distribution over the wing due to wing-wing and wing-body interaction.

Based on the literature review and research objectives, following research questions and sub-questions are formulated:
1. Can the results from the adopted CFD model be successfully compared with the CFD results from WUR and what is the uncertainty in the solution?

   (a) Does the mean vertical force (per wingbeat) support the estimated weight of the mosquito?

   (b) Do the transient forces (from current simulations) match the same from WUR simulations?

   (c) Can the solution be refined in order to reduce the errors due to spatial and time step discretization and obtain a closer comparison with WUR results?

   (d) What is the uncertainty in mean aerodynamic forces and vortex structures due to numerical method?

2. What is the change in vortex dynamics, transient forces and pressure distribution, over the mosquito wing, during the wing beat cycle. Is the vortex dynamics, transient forces and pressure distribution, over the wing, influenced by wing-wing, wing-body interaction?

   (a) What is the change in the same, with respect to non-dimensional time, for a single wing?

   (b) What is the change in the same due to wing-wing and wing-body interaction?
This chapter presents the methodology used to accomplish the objectives of the project. Firstly, a general description of the procedure, used to simulate the flow over a mosquito wing, is explained. This is followed by presenting the tests which were performed to obtain the kinematics, morphology and weight of the mosquito. Furthermore, the CFD model used to simulate the flow is presented. This involves the governing equations used, assumptions made, the solver setting used, deforming grid implementation. Finally, the uncertainty model used to quantify the error due to the numerical computation is presented. Purpose of this section is to give a brief idea about the process before getting into the detailed analysis.

3.1. Overall Procedure:

A general description of the procedure, used to model the aerodynamics, is shown in the form of a flow chart presented after the text. Parts from these will be elaborated in further sections. Based on the literature study, important inputs to the model are considered and different assumptions are adopted. Model-inputs involve the wing\body morphology and the kinematics of the same. These are obtained by performing experimental tests (as explained in section 3.2). The experiments, performed to obtain the kinematics and morphology, were completed before starting the numerical modelling and were not a part of this project.

Assumptions in the numerical model involve aerodynamic (incompressibility) and non aerodynamic based. Non-aerodynamic assumptions deal with morphology such as the wing thickness, the roundness of wing edges etc. Once the assumptions and inputs
are setup, the morphology of the wing/body (obtained from experimental tests) is used to make a CAD model. During this process, a virtual model of the wing-body is made using Rhino3D CAD modelling software. Then a domain around the wing-body model is setup, the domain surrounds the wing/body and its shape, the size and boundary conditions are carefully examined for subsequent process. CAD modelling and meshing is explained in section 3.5.

After establishing the domain, the interior of the domain is meshed using a grid generating tool. The meshing tool used in this project is Hexpress 5.2-1/Hexpress 5.2-3. Apart from generating the grid, the quality of the initial mesh is checked by examining the average/minimum/maximum cell orthogonality and skewness as explained in appendix B.2. Various meshing techniques, which form a routine of the software usage, are performed to obtain a best possible quality of the mesh. The meshing routine is explained in the appendix B.2. After obtaining the meshed model, the ReFRESCO settings are chosen. This includes the schemes used to march the solution in time and in space to obtain convergence. Also, the necessary initial/boundary conditions are set up during this stage. Furthermore, different relaxation parameters are used to reach the convergence in the shortest duration. ReFRESCO model settings are explained in section 3.6.

Since the wing moves in a three dimensional (3D) space, its motion is implemented by a user routine in ReFRESCO and it will henceforth be called as Setdeform.F90 code. The velocity of the wing is prescribed by another user routine and it will called as Setphi.F90. Both user routines are written in Fortran language and they are presented in appendix A.2. The Setdeform.F90 user routine considers the kinematic angles as an input and calculates the new position of the wing at each time step (explained in section 3.6.7). The position of the rigid boundary (wing) is used to deform the internal mesh using Radial Basis Function (RBF) interpolation scheme (explained in section 3.6.7). The user routine code is written such that the kinematics of the wing are reproduced accurately. This is cross-verified by obtaining the position of a point, at every time step, based on the kinematics of the wing. The position of the point is successfully compared with the same results obtained by WUR.

After setting up the user routine and ReFRESCO settings, simulations are run and the residuals are monitored to obtain convergence. Also, an attempt is made to obtain it faster by using various solver options and relaxation methods\parameters. After obtaining the convergence successfully, the mean vertical force (per wing beat cycle) is compared with the weight of the mosquito (obtained by experimental tests) and CFD results provided by WUR. If the mean vertical force balances the weight (or if it is slightly higher than the weight) and the results match the CFD results from WUR, then the results are considered for further analysis. If not, the model is revisited to find any issues.
Begin modelling

CAD modelling

Computational domain set-up

Meshing and quality check

ReFRESCO settings/Deformation setup/Initiation

Deformation verification

Run simulations

Monitoring residuals/Checking mean vertical force

Successful general comparison with WUR results/Weight?

yes

Uncertainty Quantification

Post Processing

no

Update model

Update settings/grid deformation if needed
After successful comparison of the weight balance and simulations from WUR, uncertainty analysis is performed. Uncertainty analysis is explained in detail in section 3.7. This is done to quantify the error due to numerical simulation. Therefore, error estimation due to space and time resolution is identified. Error due to space discretization can be performed by obtaining the solution on different meshes with different grid resolution. Error due to time discretization can be estimated by considering different time step size. Multiple simulations with different grid and time spacing is used to estimate the uncertainty. After obtaining the error estimation, a suitable grid and time resolution is considered for post processing. This is done by checking which grid spacing and time step gives the least possible error estimate or numerical uncertainty. This process is first carried out for a single wing model (left wing) and then, it is performed for Both-wings model (left and right wing) and Wings-body (left and right wing with body) model.

3.2. WEIGHT, MORPHOLOGY AND KINEMATICS

The weight, morphology and kinematics of the mosquito are important parameters in this project. The weight of the mosquito is used to check the weight support from the simulation results. This procedure is similar to Ellington’s ‘Proof-by-Contradiction’ [25]. The process involves comparing the mean aerodynamic vertical force (per wing beat) with the weight of the mosquito. The morphology and kinematics are the primary inputs to the simulation. The methods used to obtain these parameters are discussed in this section. Only brief explanation of the experimental setup is presented here. The detailed explanation will be presented in the scientific papers (expected to be published in the year 2017).

3.2.1. WEIGHT ESTIMATION:

Weighing each mosquito, used to obtain kinematics of the wing, for a statistical approximation is tedious and time consuming task. To make it easier, an empirical approximation of the weight of the mosquito (*Anopheles coluzzii*), based on the size of the mosquito, was obtained. Experiments to determine the relation between the weight and size of the mosquito was carried out by Aron P. S. Kuiper at WUR as a BSc project. First, direct weight measurements of the insect were done. The tests with mosquitoes involved a simulated feeding environment based on human smell, warmth and carbon-dioxide (CO₂) since mosquitoes are attracted to these parameters and it simulates the feeding environment. The experimental setup is shown in the figure 3.1. Two cameras, focused horizontally and vertically at the cuvette, were used. The cuvette was held by a plastic holder. Light emission diodes (LEDs) were used to illuminate the background. The cameras were calibrated in order to align them with the cuvette glass walls. A relation between the pixels and the millimeter scale was derived initially. The volume of the mosquito was found with the help of the photos of unfed and fed mosquito. Therefore, the width, length and surface area of the abdomen/thorax were measured from the photographs. The measurements were done using ImageJ which is used to trace and mea-
sure the distance from photographs as shown in figure 3.2. Direct weight measurements of mosquitoes was done using a Mettler Toledo AG204 analytical balance which has an accuracy of 0.01 mg. Weight of an fed/unfed mosquito was determined by subtracting the weight of cuvette (with fed/unfed mosquito) from the empty cuvette. Here, only the results for unfed mosquito is presented. The direct weight estimation of the mosquito was found to be $1.16 \pm 0.39$ mg for an unfed mosquito.

Figure 3.1: Experimental Setup for weight estimation adopted from BSc. report of Aron P. S. Kuiper at WUR. (a.) The setup involves 2 cameras focusing at cuvette from side and bottom. Two LEDs are used to illuminate the cuvette for photographs. (b.) Bottom view of Cuvette with unfed mosquito.

Figure 3.2: Example of surface area (left) and abdomen (right) measurements of fed mosquito using ImageJ adopted from BSc. report of Aron P. S. Kuiper at WUR. Similarly, measurements were done for unfed mosquitoes.

Four models were used to approximate the abdomen of the mosquito to a cylinder, beam-shape, variable length/width shaped model. Cylinder and beam shaped model are shown in figure 3.3. Here, the length and width/height of the model is equal to length and width of the abdomen of the mosquito. The other two models are variants
3.2. WEIGHT, MORPHOLOGY AND KINEMATICS

of the cylinder in which the abdomen length and width changed along the abdomen. The size of these models were matched with the volumes obtained by direct measurements. Assumption in this test involved constant material density along the abdomen. The measured distances were compared with the weight of the mosquito to obtain an empirical relationship. The models showed clear similarity with the actual weight of the mosquitoes (with ± 15% as standard deviation) with nearly 2% difference in results in between different models. Hence, simplest model (cylinder) is used to calculate the weight of the mosquitoes which were used to obtain wing/body kinematics. The mean estimated weight of the unfed mosquitoes used to obtain kinematics is 1.23 ± 0.65 mg. This is averaged over 31 mosquitoes.

![Figure 3.3: Illustration of models used for weight-size relation adopted from BSc. report of Aron P. S. Kuiper at WUR. Left image shows the cylinder model and right image shows the beam model. All models showed similar estimation with ± 2% difference in results in between the models. Therefore, cylinder model was adopted for final weight estimation.](image)

3.2.2. WING KINEMATICS:

The wing-kinematics are described by three Euler angles: stroke angle (γ), deviation angle (θ) and rotation angle (φ). The kinematic angles are derived relative to the stroke plane. Stroke plane is parallel to horizontal inertial reference frame. A diagram of the experimental setup is shown in figure 3.4. In figure 3.4, β is the body angle which is defined as the angle made by longitudinal axis of body with horizontal inertial reference frame. 21 flying malaria mosquitoes (Anopheles coluzzii) were filmed using three high speed video cameras operating at 13500 frames per second by Sophia Chang at Berkley University (research paper expected to be published by the end of 2016/early 2017). The wing beat kinematics of hovering/low-speed flying mosquitoes were derived from the high speed video footage of 484 measured wingbeat using a machine-vision based automatic tracking algorithm. Kinematics was obtained by fitting Fourier series through the distributions of the tracked wingbeats.
The obtained wing beat pattern for mosquito is shown in figure 3.5 as a heatmap along with fruitfly kinematics (for reader's perspective). Fruitfly kinematics is taken from the paper [51, 52]. The wingbeats are separated on the peaks of the stroke angle. The exact formulae, with the degree of Fourier terms, is given in appendix A1. As seen from the figure 3.5, the pattern of kinematic angles of mosquito change significantly when compared to that of fruitfly. When the stroke angle is compared, it lies within $\pm 26$ deg for mosquito and $\pm 90$ deg for fruitfly. Amongst all three angles, stroke angle has the largest difference when the range of magnitude is considered. The range of magnitudes for rotation and deviation angle remain almost similar for both insects. Due to small magnitudes stroke angle of mosquito when compared to fruitfly, the wings of mosquito do not come closer to each other.
3.2. Weight, Morphology and Kinematics

Figure 3.5: Kinematics of mosquito (left image) and fruitfly (right image) wing obtained from the experimental tests performed by Sophia Chang at Berkeley University (research paper expected to be published by the end of 2016/early 2017). Amongst all three angles, the range of stroke angle shows considerable difference between mosquito and fruitfly kinematics.

Figure 3.6: Motion of the mosquito’s mid-wing section chord (at 0.5 times the wing length). The wing motion during upstroke differs significantly with respect to the same during downstroke.
Based on the mosquito wing kinematics, the mid-wing chord motion (0.5 × wing length) in Z-X plane is shown in figure 3.6. For now, the whole wing beat is divided into two phases for simplicity. The upstroke motion describes the wing movement from foremost motion to rearmost position (head to tail). Downstroke is the opposite wing motion. As seen in figure 3.6, the upstroke motion differs significantly when compared to the downstroke motion.

The order of rotation of the angles is in this form: rotation angle, deviation angle and stroke angle. Initial wing orientation is shown in the figure 3.7a. Here [X, Y, Z] is the inertial reference frame axis and [x, y, z] is the wing reference frame axis. The wing is first rotated by the ‘rotation angle’ about the Y/y axis. Then it is rotated by the deviation and stroke angle about x′-axis and z″-axis respectively. The rotation of the wing, with respect to three axis in three different reference frames, are also shown in figure 3.7a. The rotation in the two wing model and wing-body model remains the same. The wings are always rotated about their hinge location (wing root). The body angle and stroke plane angle have been observed to vary slightly during the whole wing beat cycle. However, to make the computations simpler, the body angle and stroke plane angle are considered to be constant throughout the wingbeat cycle. The mean of the body and stroke plane angles (per wingbeat cycles and for all mosquitoes considered in the test) are used for the CFD simulations. The stroke plane angle and body angle are maintained at zero degrees and 45 degrees with respect to the Y axis respectively.

3.2.3. Morphology:

The morphology of the mosquito body and wings were derived from the same movies from which the kinematics are extracted. The morphology was obtained for a single mosquito wing and body from the films used to obtain the kinematics. Since the video images were coarse, a quadratic interpolation was used to obtain a smoother curve. Perpendicular view, of the same, was used to derive the morphology. This is shown in figure 3.10. The feathers over/around the wing were neglected since they do not form a part of the solid wing surface. The virtual wing morphology, which is used in the current project, is shown in the figure 3.10. From this, the geometrical parameters of the wing were derived. These are presented in the table 3.1 along with the estimated mass. This table also includes the details for fruitfly taken from Shyy et al. [30]. Since fruitfly is one of the most widely studied insects, this table gives the reader, a perspective of the morphological differences between the two insects. As seen from the table, wrt fruitfly, the mean aerodynamic chord (\(c_m\)) of a mosquito is smaller and its wing span (\(b\)) is larger. Also, the surface area of the mosquito wing is lower than the surface area of the fruitfly. This results in a large aspect ratio (nearly twice that of fruitfly) for mosquito wing defined as the ratio \(\frac{b^2}{S}\).
3.2. Weight, Morphology and Kinematics

(a) Wing isometric view in initial position.

Figure 3.7: Wing orientation

(b) First rotation with rotation angle

(a) Second rotation with deviation angle

(b) Third rotation with stroke angle

Figure 3.8: Euler rotations in three reference frames. The order of rotation (b-d) and the isometric view of the initial position (a.) is shown in this figure.
Figure 3.9: Morphology of mosquito wing and body to virtual model. The high quality video films were used to obtain perpendicular images of the mosquito. From the image, using ImageJ software, morphology of the wings was obtained. The sectional radius of the body at 32 locations was also obtained.

Figure 3.10: Virtual morphology of the wing obtained from wing outline trace.
### 3.3. Similarity Parameters

To get a better understanding of the mosquito flight, similarity parameters are calculated. These parameters can be used to have a preliminary/basic understanding of the flow. These parameters are also useful when a scaled model is considered. By maintaining these parameters equal to the natural flight similarity parameters, a dynamic similarity of the flow is established. The geometric model, used in the current simulations, is unscaled/exact. Therefore, these parameters are only used to get a preliminary understanding of the flow itself. This involves the flow randomness, unsteadiness, relative influence of translation to flapping speeds etc. Two important similarity parameters, which characterize the properties of an aerodynamic system in an insect flight, are reduced frequency ($k$) and Reynolds number [18][30]. The Reynolds number is the ratio of inertial to viscous forces [18]. The reduced frequency provides a measure of the unsteadiness and it compares spatial wavelength of the flow disturbance with the chord length [30]. These are given by eqn 3.1 for hovering flight. Here $U_{ref} = U_{tip} = \Omega R$ ($\Omega = 2 \times \phi f$, where $\phi$ is the full stroke amplitude) and $L_{ref}$ is mean aerodynamic chord [30]. The $Re$ and $k$ for mosquito flight are calculated below.

$$Re = \frac{\rho U_{ref} L_{ref}}{\mu} = \frac{\rho f A_R \phi f c_m^2}{\mu} \quad k = \frac{\pi f L_{ref}}{U_{ref}} = \frac{\pi}{\phi A_R}$$ (3.1)

For mosquito and fruitfly [30], the approximate values of these parameters are given below. Here $f$, $\phi$, $\rho f$ and $\mu$ are wing-beat-frequency, full stroke amplitude, fluid density and dynamic viscosity respectively. The density and dynamic viscosity are considered to be $1.21 \text{ kg/m}^3$ and $1.81 \times 10^{-5} \text{ Ns/m}^2$ respectively. This gives a $Re$ of 110 and $k$ of 0.27 approximately. Since the Reynolds number is quite low (comparable with fruitfly), the viscous effects are expected to damp any turbulence in the flow and the turbulence is expected to be low/negligible. Therefore, the flow, at such low $Re$, is considered to be laminar. The reduced frequency is quite high when compared to that of fruitfly which indicates larger unsteadiness in the flow.

### Table 3.1: Morphology parameters of *Anopheles coluzzii* and *Drosophila melanogaster*. The mean aerodynamic chord of the mosquito is lower than fruitfly with an increase in the wing span. This results in high aspect ratio (nearly twice) of the mosquito wing when compared to fruitfly.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mosquito</th>
<th>Fruitfly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean chord length: $c_m (mm)$</td>
<td>0.5</td>
<td>0.78</td>
</tr>
<tr>
<td>Wing span: $b (mm)$</td>
<td>6.92</td>
<td>4.78</td>
</tr>
<tr>
<td>Surface Area: $A_s (mm^2)$</td>
<td>2.53</td>
<td>3.72</td>
</tr>
<tr>
<td>Aspect ratio: $A_R$</td>
<td>12.5</td>
<td>6.12</td>
</tr>
<tr>
<td>Total mass: $M (g)$</td>
<td>$1.01 \times 10^{-3}$</td>
<td>$0.96 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
3. Methodology and Theoretical Formulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mosquito (Anopheles coluzzii)</th>
<th>Fruitfly (Drosophila melanogaster)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flapping frequency: $f$ (Hz)</td>
<td>575</td>
<td>218</td>
</tr>
<tr>
<td>Flapping amplitude: $\phi$ (rad)</td>
<td>0.93</td>
<td>2.44</td>
</tr>
<tr>
<td>Reynolds number: $Re$</td>
<td>110</td>
<td>126</td>
</tr>
<tr>
<td>Reduced frequency: $k$</td>
<td>0.27</td>
<td>0.212</td>
</tr>
</tbody>
</table>

Table 3.2: Flapping, fluid and similarity parameters obtained for Anopheles coluzzii and Drosophila melanogaster. The flapping frequency of mosquito is quite high when compared to that of fruitfly fly with a small flapping amplitude resulting in higher reduced frequency. This results in an increased unsteadiness. The $Re$ for mosquito flight is in the same range as that of fruitfly flight.

3.4. Governing Equations and Assumptions

To model the aerodynamics around an object, the Navier stoke’s equations are solved. These equations govern the fluid flow and they are derived from the conservation laws for mass and momentum. The differential form of the Navier Stoke’s equations for mass and momentum conservation, in the inertial frame of reference, are given by equations 3.2-3.3. The Energy equation is decoupled when the incompressible form of the Navier Stoke’s equation are used (as will be explained later in this sections). Here, $V$ is the velocity vector in the inertial frame, $\rho$ is the density of the fluid, $p$ is pressure, $t$ is time, $T$ is stress tensor and $B$ is body force vector. The stress tensor and deformation tensor are given by equation 3.4. Here, $I$ is a unit vector and $\mu$ is dynamic viscosity.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0, \quad (3.2)$$

$$\frac{\partial \rho V}{\partial t} + \nabla \cdot (\rho VV) = \nabla T + \rho B, \quad (3.3)$$

$$T = -\left(p + \frac{2}{3} \mu \nabla V\right)I + 2\mu D, \quad D = \frac{1}{2}(\nabla V + \nabla V^T) \quad (3.4)$$

If a control volume $V$ with a surface $S$ and a unit normal $n$ is considered, based on the Gauss divergence theorem and further simplification of the stress tensor, these equations can be written in the integral form given by 3.5-3.6. Here $V_i$ represents different velocity components. The stress tensor is split into viscous (given by the the equation 3.7) and pressure terms ($\rho I$).

$$\frac{\partial}{\partial t} \int_V \rho dV + \int_S (\rho V) \cdot n dS = 0, \quad (3.5)$$

$$\frac{\partial}{\partial t} \int_V (\rho V_i) dV + \int_S (\rho V_i V) \cdot n dS = \int_S (\tau_{ij} i^j_i - p_i) \cdot n dS + \int_V \rho b_i dV, \quad (3.6)$$
3.4. Governing Equations and Assumptions

\[ \tau = \tau_{ij} = \mu \left( \frac{\partial V_i}{\partial X_j} + \frac{\partial V_j}{\partial X_i} \right) \] (3.7)

The flight phase, slow forward flight/hovering, is considered in the simulations and the speed of the mosquito in this flight phase ranges from 0-0.1 m/s. At such low speeds (below Mach number < 0.3), the flow density can be considered constant in space and time [53]. Assuming incompressibility, the density in the above equations can be taken out of the derivatives. Therefore, the equations reduce to 3.8-3.9.

\[ \int_S (V_i).n dS = 0, \] (3.8)

\[ \frac{\partial}{\partial t} \int_V (V_i) dV + \int_S (V_i) n dS = \frac{1}{\rho} \int_S (\tau_{ij} i_j - p i_i) . n dS + \int_V b_i dV, \] (3.9)

**POISSON PRESSURE EQUATION:**

Considering incompressibility and from continuity and momentum equations, Poisson pressure equation can be derived. Consider the general form of the momentum equation in conservative form given by equation 3.10.

\[ \nabla . \left( \frac{\partial \rho V}{\partial t} \right) + \nabla . [\nabla . (\rho V V)] = \nabla . [\nabla . (\tau - \rho I) + \rho B] \] (3.10)

or

\[ \nabla . \nabla p = -\nabla . \left[ \frac{\partial \rho V}{\partial t} + \nabla . (\rho V V) - \nabla . \tau - \rho B \right] \] (3.11)

Considering the continuity equation, this can be written as equation 3.12.

\[ \nabla . \nabla p = -\nabla . [\nabla . (\rho V V) - \nabla . \tau] - \nabla . (\rho B) + \frac{\partial^2 \rho}{\partial t^2} \] (3.12)

Considering incompressibility, the last term vanishes giving,

\[ \nabla . \nabla p = -\nabla . [\nabla . (\rho V V) - \nabla . \tau] - \nabla . (\rho B) \] (3.13)

The term with stress tensor can be written as,

\[ \nabla . (\nabla . \tau) = \mu \nabla . [\nabla . (\nabla V + (\nabla V)^T)] = \mu [\nabla . (\nabla^2 V) + \{\nabla . (\nabla (\nabla V)^T)\}] \] (3.14)
or

\[ \nabla.(\nabla \tau) = \mu [\nabla^2 (\nabla V)] + [\nabla. (\nabla V)]] \tag{3.15} \]

Since \( \nabla \cdot V = 0 \) from continuity equation, we get \( \nabla.(\nabla \tau) = 0 \). Therefore, the final Poisson pressure equation (from 3.13) can be obtained as:

\[ \frac{1}{\rho} \nabla.(\nabla p) = -\nabla.[ \nabla.(V V)] - \nabla B \tag{3.16} \]

3.4.1. Assumptions related to morphology and kinematics:

Apart from incompressibility, other assumptions, relating to the morphology and kinematics are made. Firstly, the body is considered to remain in the same position throughout the wing beat cycle. This means that the body angle remains constant throughout the wingbeat cycle. This is a valid assumption since, in general insect flight, the body angle is known to change considerably with flight speed and a single flight speed is considered in the current project [18, 54]. As previously mentioned (in section 3.2.2), the body angle is observed to change slightly during the whole wing beat cycle. The body angle, considered in this project, is an average of the body angles measured for 40 mosquitoes and for the whole wing beat cycle. It is observed to be at an angle 45° with the horizontal plane of inertial frame of reference. The stroke plane angle is also considered to be constant for the same reason and it is in parallel to the horizontal inertial reference plane. This is shown in figure 3.4.

The data presenting the morphology of the legs/proboscis/antenna are not yet available and hence cannot be added to the current simulation. Therefore, the current model assumes negligible influence of other body parts except body. This is considered to be a valid assumption for the initial study. In addition to that, the wing/body are considered to be rigid bodies (without flexibility) in the simulations since the structural properties of the wing are unknown.
3.5. COMPUTATION DOMAIN AND NUMERICAL GRID

3.5.1. SINGLE WING DOMAIN

The computational domain is in the form of a box surrounding the wing. The wing is in the center of the domain with an initial position such that the wing root is on the origin of the domain. Since, the body kinematics (body angle and stroke plane angle) are constant in the current flight phase, the wing reference frame is placed at the origin. Also, the wing reference frame is only considered to make the process simple on paper. The fluid governing equations are always solved in the inertial reference frame.

The domain has six faces. All these faces are considered to be external or free-stream boundary faces. The wing is considered to be a solid boundary. The size of the domain

From the experiments related to morphology, it was found that the wing thickness is negligible compared to the length/mean-aerodynamic-chord of the wing. Hence a zero wing thickness was intended to be used. However, Hexpress cannot create three dimensional meshes for objects without thickness as it cannot 'snap' to the geometry with zero thickness. Snapping is a Hexpress meshing routine which involves projecting the staircase mesh over the surface onto the surface. For this reason, a 3% thickness was considered with respect to the mean-aerodynamic-chord (mac) as also assumed in the paper by Sun and Wu [55] for flapping wing flight. The edges of the wing are considered to be sharp as shown in the figure 3.11. A set of computation was also performed with rounded edges to quantify the differences in the solution as a consequence of it. However, the flow is expected to be detached at the edges and hence, not a large factor of edge roundedness. The difference in the mean aerodynamic forces was found to be lower than 1.5% for rounded edge simulation when compared to sharp edge simulation.

Figure 3.11: Types of wing edges: (a.) Rounded (b.) Sharp. The difference in the mean aerodynamic forces, between the results obtained from the mentioned edge morphology, is lower than 1.5%. Therefore, the sharp edge is used for the simulations due to the ease of modelling/meshing.
is 50 times larger than the mean aerodynamic chord (mac). This is believed to be large enough to compute the flow physics around the wing accurately. Results with 50% larger and smaller domain size showed a difference of nearly 0.05% in the mean aerodynamic forces. Therefore, a smaller domain would have been a valid option. However, all the results presented are obtained using the original domain size since the influence of outer domain size was checked later stages of the project and most of the data set was already obtained using the original grid size.

<table>
<thead>
<tr>
<th></th>
<th>Mesh resolution</th>
<th>Initial cells (Before refinement)</th>
<th>Total no. of cells (After refinement)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single Wing</strong></td>
<td>Coarse</td>
<td>5 × 5 × 5</td>
<td>188586</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>10 × 10 × 10</td>
<td>1073000</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>15 × 15 × 15</td>
<td>3232948</td>
</tr>
<tr>
<td><strong>Two Wings</strong></td>
<td>Coarse</td>
<td>5 × 5 × 5</td>
<td>282952</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>10 × 10 × 10</td>
<td>1530112</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>15 × 15 × 15</td>
<td>4653826</td>
</tr>
<tr>
<td><strong>Wings-body</strong></td>
<td>Coarse</td>
<td>5 × 5 × 5</td>
<td>463852</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>7 × 7 × 7</td>
<td>1095026</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>10 × 10 × 10</td>
<td>2743860</td>
</tr>
</tbody>
</table>

Table 3.3: Grid specifications for the Single-wing, Both-Wings and Wings-Body model.

Three meshes were obtained (coarse, medium and fine) to do the grid sensitivity analysis. Details of the mesh are given in the table 3.3. The domain was meshed using Hexpress 5.2-1 meshing tool which produces unstructured meshes. A refinement box, which is around 7% the size of the outer domain, was used around the wing. The size of the refinement box was decided based on several computations starting with the size of 50% the size of the outer domain size to 5%. The choice of a larger refinement box restricted the number of cell refinements within it (less refinements due to practical limitations of computation cost). Apart from the number of refinements for the choice of the size of the refinement box, it was made sure that the vortex structures (with a defined Q criterion for visual analysis) were completely enclosed within the refinement box. This was done by considering the results from larger refinement boxes and systematically reducing it by making it a priority to contain the vortex structures (with a predefined Q criterion) within the refinement box. The change in the size of the refinement box, above/equal to 7% only affected the visual resolution of vortex structures with small variation in mean forces. Therefore, a small refinement box was chosen with large refinements in it. The refinement box covers the vortex structures and a smoother variation of vortex structures is observed.

All the grids were obtained using same meshing techniques/settings. Meshing routine is explained in the appendix B.2. The differences between coarse, medium and fine mesh were the initial number of cells (before cell refinement) and diffusion rate. Diffusion rate decides the cell-resolution diffusion from fine mesh to coarse mesh. A higher
diffusion rate implies more layers of transition between small and large cells. The details of the meshes are given in the table 3.3 and 3.4. The mesh over single wing surface is shown in the figure 3.12. The computational domain is shown in the figure 3.15. The fine mesh with refinement box is shown in the figure 3.13. The mesh, close to the wing and for all three meshes (coarse, medium and fine), are shown in figure 3.14.

![Meshes](image)

Figure 3.12: Fine mesh over the wing surface for Single-Wing model. The refinement of mesh is larger on the wing edges since the flow properties are expected to have a greater change along the edges such as the formation of leading edge vortex, tip vortex, trailing edge vortex and root vortex.

<table>
<thead>
<tr>
<th>Mesh resolution</th>
<th>Minimum cell length $(m)$</th>
<th>Maximum cell length $(m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Wing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse</td>
<td>1.03E-05</td>
<td>0.03</td>
</tr>
<tr>
<td>Medium</td>
<td>6.48E-06</td>
<td>0.015</td>
</tr>
<tr>
<td>Fine</td>
<td>4.63E-06</td>
<td>0.01</td>
</tr>
<tr>
<td>Two Wings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse</td>
<td>1.10E-05</td>
<td>0.03</td>
</tr>
<tr>
<td>Medium</td>
<td>6.55E-06</td>
<td>0.015</td>
</tr>
<tr>
<td>Fine</td>
<td>4.66E-06</td>
<td>0.01</td>
</tr>
<tr>
<td>Wings-body</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse</td>
<td>6.74E-06</td>
<td>0.03</td>
</tr>
<tr>
<td>Medium</td>
<td>3.96E-06</td>
<td>0.019</td>
</tr>
<tr>
<td>Fine</td>
<td>3.68E-06</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 3.4: Minimum/Maximum cell sizes in Single-wing, Both-Wings and Wings-Body model grids.
Figure 3.13: (Left) Outer domain for fine mesh with refinement box. The refinement levels, in the refinement box, is nearly 7 with respect to the initial number of cells. (Right) The close-up image of the refinement box for the fine mesh.

Figure 3.14: Single wing model. Mesh, close to the wing, for the (a.) Coarse, (b.) Medium and (c.) Fine mesh.
Figure 3.15: Fine meshed computational domain and the wing placement. In the Single wing model, the wing is at the center of the domain with its wing root at the origin (domain center). In Both-wings model, the wing roots are at a distance 0.4 mm from the origin as shown in figure. In Wings-body model, the arrangement remains same as Both-Wings model with body in between the wings.

3.5.2. BOTH-WINGS DOMAIN

The computational domain for the Both-wings model is similar to the single wing model with few small differences. Only the differences are mentioned here. The right and left wing are at a distance of +0.4 mm and -0.4 mm from the origin of the inertial reference frame. The distance 0.8 mm is the width/diameter of the body at that location. Since the wing rotates about its hinge location, the wing reference frames are located at (0,0.4,0) mm and (0,-0.4,0) mm for the right and left wing respectively. These are also the points where the wing roots rest. So the Euler angles are used to rotate both wings in their reference frames. The mesh details are shown in the table 3.3-3.4. The meshed computational domain along with the wings is shown in figure 3.15.
3.5.3. **WINGS-BODY DOMAIN**

The outer domain, refinement box and the mesh settings in the Wings-body domain remain the same as that of the Single-wing domain or Both-wings domain. The body is an additional part in the Wings-body domain when compared to the Both-wings domain. CAD model of the body is performed in the rhino3D software. Body includes head, thorax and abdomen. The cross-sectional radius of the complete body, at 34 locations, is provided by WUR. The radius at each location is listed in the appendix A.3. This is used to obtain a 3rd order spline through the points at the circumference of the 34 locations. The spline is rotated by 360 degrees and a solid object is formed. The body is rotated by 45 degrees with respect to horizontal plane since the body angle is 45 degrees. Originally, the diameter at the neck (between head and thorax) is negligible in magnitude. But due to modelling difficulty, the point at neck of the mosquito (which has a negligible radius ~0 mm), is excluded to obtain a smoother transition between thorax and head. The original neck section is shown by blue dashed lines at neck in the figure 3.16.

The wings are placed at the same location as that of the two wing model. The body is moved such that the wing roots lie on the hinge position of the body. The hinge position of the wing is shown in figure 3.16 by blue boxes. Here $L_B$, $L_H$, $L_r$ and $L_R$ are 4.186 mm, 0.5140 mm, 3.3047 and 0.4 mm respectively. With the current model, the wing root is located at the body surface which makes CAD modelling, initial mesh and mesh deformation an impossible task. Therefore, the body was offset by 0.1 mm in the Z direction. This provides a gap between the body and the wing but barely affects the results. To check the influence of the body offset, the difference in the mean aerodynamic forces for 0.1 mm and 0.2 mm offset was obtained. The difference was observed to be lower than 0.45%. This is a small value and it is assumed that the difference between ideal case and 0.1 mm is also in same order. Hence, 0.1 mm offset is used in the current simulations. The small difference is due to the fact that the body is stationary in this flight phase unlike wings, which are the only dynamic parts. The only function of body, in this flight phase, is to provide a physical obstruction in between both the wings.

![Figure 3.16: Mosquito body and hinge location.](image)

$L_B$ and $L_H$ are the thorax+abdomen and head length respectively. $L_r$ is distance between the hinge location and extreme end of abdomen. $L_R$ is the radius at the hinge location. The hinge location is at 45 degrees with respect to horizontal. The blue dashed lines, at the neck, indicates the original morphology at the neck. Due to modelling complexity, it cannot be implemented.
3.6. ReFRESCO Flow Solver Settings, Boundary Conditions and Deforming Grid

A general description of the solver is given in appendix A.2. Navier Stokes equations, mentioned in section 3.4, are solved using ReFRESCO. This section presents the solver settings and its internal structure. The procedure, used by the solver to solve the governing equations is given by the flowchart in the next page. The initial conditions (IC) are used to initiate the computation. Then the time step is incremented. The time step is used as an input to update the kinematics and mesh deformation. This is done by the Setdeform.F90, Setphi.F90 user codes and Radial Basic Function (RBF). The momentum equations are non-linear and it is linearized. Outer loop iterations are performed to restore the non-linearity of the of the system. The outer loop computation is performed until the residuals reach user defined convergence tolerance or until a maximum number or iterations are performed. Here, a convergence tolerance of 1E-06 is used. The outer loop iterations compose, within itself, inner-loop iterations which solve the momentum/pressure equations individually until the residuals reach a prescribed tolerance or until a maximum number of iterations are performed. The convergence tolerance used for inner-loop iterations is 1E-02. The momentum equation is solved in a segregated manner by using the initial pressure conditions resulting in a velocity predictor. The non-linear set of momentum equations are linearized by Picard type of linearization. The velocity field obtained from momentum equation is used to solve the Poisson pressure equation. After solving the inner loop iterations, the velocity field is updated based on pressure field and continuity equation. The non-linearity and coupling is restored with the outer loop iterations. If the velocity, obtained from momentum equation, is denoted by $\mathbf{U}$. Then the new velocity field is given by the equation 3.17. Where, $\nabla p'$ and $A_c$ are pressure field from Poisson equation and a discretization coefficient (obtained from momentum equation) respectively. Then convergence tolerance for the outer loop is checked. If the residuals are below this tolerance, the time step is updated and the solution is determined for the next time step.

$$\mathbf{U} = \mathbf{U}' - \frac{\Delta V}{A_c} \nabla p'$$ (3.17)
3.6. ReFRESCO Flow Solver Settings, Boundary Conditions and Deforming Grid

3.6.1. Space Discretization:

ReFRESCO uses finite volume approach (FVM) to discretize the equations in space. Therefore, the dependant variables are defined at the center of the control volumes and the integral form of the equations are obtained over each grid cell/control volume. Since the governing equations have volume and surface integrals, the volume integrals are considered by cell centered values as an average over the control volume. The surface integrals are obtained by interpolation of cell center value and face areas. These volume and surface integral approximations are given by equation 3.18. Here \( \phi, \phi_c, \phi_{fi}, \Delta V \) and \( S_{fi} \) are dependant variable, the cell center value of the same, face center value of the same, volume of the grid cell and face area of the grid cell respectively. The derivative/gradient terms are solved using Gauss theorem and interpolation schemes. For a dependant variable \( \phi \), the gradient of the cell center value is computed as 3.19. The discretization is set up for unstructured grids with arbitrary polyhedral shape (with arbitrary number of faces).

\[
\int_V \phi dV \approx \phi_c \Delta V, \quad \int_S \phi dS \approx \sum_{i=1}^{f} \phi_{fi} S_{fi} \tag{3.18}
\]

\[
\int_V \nabla \phi dV = \int_S \phi \cdot n dS, \quad \Rightarrow \nabla(\phi)_c \approx \frac{1}{\Delta V} \sum_{i=0}^{f} \phi_{fi} S_{fi} \tag{3.19}
\]

The convective term is discretized as equation 3.20, where \( q^\phi_{fi} \) is the flux of \( \phi \) for the cell \( i \). Here discretization of \( \phi_{fi} \) is based on second order QUICK scheme.

\[
\int_S \phi(U \cdot n) dS \approx \sum_{i=0}^{f} \phi_{fi} (U_{fi} \cdot S_{fi}) = \sum_{i=0}^{f} q^\phi_{fi} \phi_{fi} \tag{3.20}
\]

The diffusive flux is discretized as equation 3.21. Here the gradients are interpolated to cell faces as equation 3.19. All other terms, other than convective term, are discretized using second order central differencing scheme.

\[
\int_S \mu (\nabla U + \nabla U^T) \cdot n dS \approx \sum_{i=0}^{f} \mu_{fi} \left( \nabla U_{fi} \cdot S_{fi} + \nabla U^T_{fi} \cdot S_{fi} \right) \tag{3.21}
\]

3.6.2. Time Discretization and Time Loop Specifications:

Time discretization is implemented using implicit backward difference scheme (BDF). Therefore a time dependant term in the governing equation is approximated by the equation 3.22. Here, \( n \) represents the time level. Where \( c_1, c_2 \) and \( c_3 \) are coefficients and they depend on the order of discretization considered. In this project, second order
backward scheme is used and the coefficients are \( c_1 = 1.5, c_2 = -2.0, c_3 = 0.5 \). In the first time step, 1st order backward scheme is used with coefficients \( c_1 = 1.0, c_2 = -1.0, c_3 = 0.0 \).

\[
\frac{\partial}{\partial t} \int_V (\rho \phi) dV \approx \frac{c_1(\rho_c \phi_c \Delta V)^n + c_2(\rho_c \phi_c \Delta V)^{n-1} + c_3(\rho_c \phi_c \Delta V)^{n-2}}{\Delta t} \quad (3.22)
\]

In the time loop settings, the time-step size and total number of time-steps are defined. Initially, the time-step size was chosen based on trial and error method such that the differences in the mean forces for a timestep were small when compared to a smaller time-step size solution. The final time-step size (solution used to post process) was based on the time-step sensitivity analysis as explained in section of results 4.2.2. The whole wingbeat time \( \frac{1}{f} \) was divided into a definite number of steps to obtain the time-step. If 100 timesteps per wingbeat were desired, the value was obtained as \( \frac{1}{100f} \). Furthermore, if the solution for five wingbeats were desired, the total number of timesteps would be 500.

**3.6.3. Outer loop specifications:**

In the outer loop settings, the convergence/divergence tolerance, the maximum number of iterations and the residual norm have to be defined. Here the maximum number of iterations was set to 500. In practice, the convergence for each outer loop was obtained within 130 iterations. As previously mentioned, the convergence tolerance of 1E-06 was used. An infinity norm, given by equation 3.23, was used for the outer loop convergence. Here \( \Delta \phi \) and \( N_p \) are local flow change and total number of cells respectively.

The final residuals for the fine mesh (single wing model), with lowest time step size (400/WB) in the data set, is shown in figure 3.18. The figure shows residuals for 5 WB (400×5 = 2000). As seen from the image, all the residuals for \( L_\infty \) norm go below the tolerance \( 10^{-6} \). Convergence of the residuals in the outer loop, for two time steps (500th and 1500th), is shown in figure 3.19. In this figure, the \( L_\infty \) norm is plotted against the time-steps on a log scale. Note, figure 3.19 is from the same computations as that of the results shown in figure 3.18.

\[
L_\infty(\Delta \phi) = \text{MAX}(|\Delta \phi_i|) \quad f o r \quad 1 \leq i \leq N_p \quad (3.23)
\]
3.6. ReFRESCO Flow Solver Settings, Boundary Conditions and Deforming Grid

Figure 3.18: Final residuals in for all timesteps for fine mesh and 400 timesteps per WB. Figure shows residuals for 5 WB (400 x 5). Here, the $L_\infty$ norm (given by equation 3.23) is plotted against the time steps. Left image shows the same for velocities in three dimensions ($u$, $v$, $w$) and right image shows the same for pressure.

Figure 3.19: Outer loop convergence at two timesteps for fine mesh with 400 timesteps per WB. These plots represent the same simulation results as that of figure 3.18.

3.6.4. Boundary and Initial Conditions:

All the faces of the outer domain are considered to be farfield pressure condition. In these planes, the pressure in the boundary plane is defined as zero. All these boundary faces are considered fixed when mesh is being deformed. That is, the mesh faces on the boundaries do not participate in the deformation. The boundary faces of the wing are considered to be a ‘wall’ and no slip condition is applied. Therefore, the fluid velocity at the wing is equal to the velocity of the wing. The velocity of the wing is defined by the user in the Setphi.F90 as explained in section 3.6.7. The velocity on the body is considered to be zero since it is hovering flight. The initial pressure and velocity in the interior of
the domain is set to zero. A zeroth and first order extrapolation for outer domain and wing boundaries are applied respectively. With zeroth order extrapolation, the value on the boundary is equal to the value in the center of cell adjacent to the boundary. With first order extrapolation, the relation between the boundary value and the adjacent cell center value is linear based on the cell center value and gradient.

### 3.6.5. Inner Loop Specifications:

In the inner loop settings, specifications for momentum and pressure correction equations are established. For momentum equation, PETSC type iterative solver is used to solve the linear equations. Specifically, GMRES type solver with JACOBI preconditioner is used. Furthermore, an implicit-explicit type relaxation procedure was used to accelerate the convergence process. The values of the relaxation parameters were finalised by varying them systematically such that a faster convergence is obtained without fluctuations/divergence. The convective fluxes are discretized based on QUICK scheme and gradients were calculated using Guass theorem. The convergence tolerance for the inner loop were set to 1E-02 or a maximum number of iterations of 200. For Pressure correction equation, the settings are almost the same except that CG solver with BJACOBI (as preconditioner) is used.

### 3.6.6. Material Properties:

Standard flow properties are considered for the simulation. The flow properties used for the interior fluid are given in the table 3.5:

<table>
<thead>
<tr>
<th>Property</th>
<th>Type/parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material type:</td>
<td>Air</td>
</tr>
<tr>
<td>Dynamic/Absolute viscosity:</td>
<td>$1.81 \times 10^{-05} \text{ kg/m.s}$</td>
</tr>
<tr>
<td>Density:</td>
<td>$1.21 \text{ kg/m}^3$</td>
</tr>
</tbody>
</table>

Table 3.5: Fluid material properties.

### 3.6.7. Deforming Grid and Wing Motion:

In order to solve Navier Stoke’s equations on the deforming grid, Arbitrary Lagrangian-Eulerian (ALE) formulation is used. It is derived from the Reynolds transport theorem given by equation 3.24 [56] in an integral form [57]. ALE formulation enables flow computations on deforming grid by considering the moving/deforming grid motion. It was tested for Geometric Conservation Law (GCL) for ReFRESCO [57] previously and it wont be described in this report. Satisfying GCL law establishes an efficient execution of solution computation. That is, ensuring that the flow is only influenced by the change in the flow properties and due to the motion of the object and not due to the deformation of mesh. The integral form of ALE equation is given by 3.25 [57]. Here $\phi$ is a scalar field,
3.6. ReFRESCO Flow Solver Settings, Boundary Conditions and Deforming Grid

$V(t)$ is a time dependent control volume with boundary $\partial S(t)$, $u$ is fluid velocity, $\dot{u}$ is the grid velocity, $k$ is diffusion term, $n$ is unit outward normal and $q$ is source term. Considering specific values of $\phi$, $k$ and $q$, the equations of fluid motion are obtained. The integral form of ALE equations for mass and momentum conservation are given by the equations 3.26-3.27 [56].

$$\frac{d}{dt} \int_{V(t)} \phi dV = \int_{\partial S(t)} \frac{\partial \phi}{\partial t} dV + \int_{\partial S(t)} \phi \dot{u} n dS$$ (3.24)

$$\frac{d}{dt} \int_{V(t)} \phi dV + \int_{\partial S(t)} \phi(u - \dot{u}) n dS = \int_{\partial S(t)} k \phi n dS + \int_{S(t)} q dV$$ (3.25)

$$\frac{\partial}{\partial t} \int_{V(t)} \rho dV + \int_{\partial S(t)} \rho(u - \dot{u}) n dS = 0$$ (3.26)

$$\frac{\partial}{\partial t} \int_{V(t)} \rho u dV + \int_{\partial S(t)} \rho v(u - \dot{u}) n dS = \int_{V(t)} (\nabla \cdot T + \rho B) dV$$ (3.27)

The mesh deformation is performed using radial basis function (RBF) interpolation with Greedy algorithm. Re-meshing/adaptive meshing is not implemented to improve the numerical robustness [58]. Here, the prescribed boundary motion is used to calculate the internal mesh deformation. The internal mesh node deformation is given by the equation 3.28 [59]. Here, $x$ is the coordinates of the internal node, $x_{b_j}$ is the coordinates of the nodes on the boundary, $\alpha_j$ are the interpolation coefficients and $\phi$ is the basis function. The basis function is given by equation 3.29. Here, $\zeta=x/r$ with ‘r’ being support radius. The basis function is equal to 1 at origin and decays with increase in ‘x’. It is equal to zero for $x \geq r$. The interpolation coefficients are obtained by solving RBF function equations for the boundary nodes with prescribed node coordinates [59].

$$s(x) = \sum_{j=1}^{n_b} \alpha_j \phi(\|x - x_{b_j}\|)$$ (3.28)

$$\phi(\zeta) = (1 - \zeta)^4 (4 \zeta + 1), \quad 0 \leq \zeta \leq 1$$ (3.29)

In the interpolation process, the number of equations to be computed are proportional to the boundary nodes (less if Greedy algorithm is used). Greedy algorithm is implemented to make the process more efficient, robust and fast. This is described in [59, 60] and wont be dealt with here. The interpolation scheme is iterative since the deformation has to be, as close as possible, to the prescribed motion. A convergence tolerance of $1E-05$ is chosen or a maximum number of iterations of 50000 is implemented. The iterative equations are solved using GMRES solver with JACOBI preconditioner.
The motion of the boundary has to be prescribed along with its velocity in order to deform the internal mesh using RBF. In this case, it is the wing’s motion. This is implemented using kinematic angles and corresponding angular velocities. The boundary motion is prescribed in the Setdeform.F90 code and the angular velocities are defined in the Setphi.F90 code. These are written in Fortran programming language (Appendix A.3) and it is linked to ReFRESCO. In this code, Euler rotation matrices are used to obtain the wing motion. These rotations are obtained by three rotation matrices $R_{\phi}$, $R_{\theta}$ and $R_{\gamma}$ as shown below. The inertial reference frame is defined by left hand rule and the rotations are performed using right hand rule. Therefore, an anti-clockwise rotation is considered positive.

The wing coordinates are obtained by multiplying the rotation matrix with the initial coordinates given by the equation 3.30. The angular velocities ($\omega_{\phi}$, $\omega_{\theta}$, $\omega_{\gamma}$) are obtained by differentiating the Fourier kinematic expressions with time as shown in appendix A.1. In the first wing beat, a sine function ($F_{\text{sine}}$) is applied to the motion. This is done to have a smooth mesh deformation at the beginning and to reduce the errors due to deformation to minimal. The sine function is given by the equation 3.31. Its derivative $F_{\text{sine},dt}$ is used to obtain the angular velocities in the first wingbeat given by 3.32. Figure 3.20 shows the mesh deformation as a slice (in X-Z plane) in the domain on the left and corresponding zoomed images on the right for two stages in a wing beat.

$$R_{\phi} = \begin{bmatrix} \cos(\phi) & 0 & \sin(\phi) \\ 0 & 1 & 0 \\ -\sin(\phi) & 0 & \cos(\phi) \end{bmatrix}, \quad R_{\theta} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix},$$

$$R_{\gamma} = \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Therefore, the rotation matrix is obtained as given below.

$$R_{\text{rotation}} = R_{\gamma} \times R_{\theta} \times R_{\phi} = \begin{bmatrix} \cos(\gamma)\cos(\phi) - \sin(\gamma)\sin(\theta)\sin(\phi) & -\sin(\gamma)\cos(\theta) & \cos(\gamma)\sin(\phi) + \sin(\gamma)\sin(\theta)\cos(\phi) \\ \sin(\gamma)\cos(\phi) + \cos(\gamma)\sin(\theta)\sin(\phi) & \cos(\gamma)\cos(\theta) & \sin(\gamma)\sin(\phi) - \cos(\gamma)\sin(\theta)\cos(\phi) \\ -\cos(\theta)\sin(\phi) & \sin(\theta) & \cos(\theta)\cos(\phi) \end{bmatrix}$$

To save memory and to maintain the mesh quality per wing beat, the deformed mesh is reused for a wingbeat. In the deforming mesh mechanism, the mesh data points is saved at each time step. With increase in the number of time steps (per wing beat) and the total wingbeats considered, the data that needs to be saved increases significantly. Therefore, the mesh node points are copied for a wing beat and the saved mesh is imposed in the subsequent wingbeats. In the current project, the mesh in the second wing beat is copied and reused in the later wing beats. The first wingbeat cycle is not considered since sine damping is implemented in it. Therefore the wing does not represent the actual motion in the first wing beat and cannot be copied.
\[ X_{\text{new}} = R_{\text{rotation}} \times X_{\text{initial}} \]  

(3.30)

\[ F_{\text{sine}} = 0.5 \times \left(1 + \sin \left(3 \times \frac{\pi}{2} + \pi \times \frac{dt}{T}\right) \right) \]  

(3.31)

\[ F_{\text{sine},dt} = \frac{dF_{\text{sine}}}{dt} = 0.5 \times f \times \pi \times \cos \left(3 \times \frac{\pi}{2} + \pi \times \frac{dt}{T}\right) \]  

(3.32)

The rotation angles and the angular velocities for the first wing beat are given by equation 3.33-3.35.

\[ \phi_{wb=1} = F_{\text{sine}} \times \phi ; \quad \omega_{\phi,wb=1} = F_{\text{sine},dt} \times \phi + F_{\text{sine}} \times \omega_{\phi} \]  

(3.33)

\[ \theta_{wb=1} = F_{\text{sine}} \times \theta ; \quad \omega_{\theta,wb=1} = F_{\text{sine},dt} \times \theta + F_{\text{sine}} \times \omega_{\theta} \]  

(3.34)

\[ \gamma_{wb=1} = F_{\text{sine}} \times \gamma ; \quad \omega_{\gamma,wb=1} = F_{\text{sine},dt} \times \gamma + F_{\text{sine}} \times \omega_{\gamma} \]  

(3.35)
3.7. Numerical Error and Uncertainty Estimation

An important part of numerical study is to quantify/estimate the error due to numerical method itself. The basis of numerical method involves space and time discretization which, by itself, assumes the continuous form of flow to be discrete. CFD has been used to solve the flow equations with high precision in various fields and applications. However, every new application of CFD requires a certain level of error estimation to establish confidence in the solution. This is done by verification and validation. Validation is a procedure to check the accuracy of the simulation results by comparing it with a well established results/reality such as an experimental test results (with known error). Verification refers to numerical uncertainties/error and it is further divided into two parts.
3.7. NUMERICAL ERROR AND UNCERTAINTY ESTIMATION

called solution verification and code verification. Code verification deals with verifying if the solver solves the governing equations correctly. Solution verification involves estimating the error of a given calculation for which, the exact solution is unknown [61].

Code verification for several tests, for ReFRESCO, have been carried out in the past and wont be dealt with at this stage. These publications/papers can be accessed via [62]. The code has already been verified for deforming grid mechanism and presented in [57, 59]. Solution verification, in this project, is based on the paper by Eca and Hoekstra [61]. Only the important equations in the general method is explained here. A detailed description is found in the paper [61]. As mentioned in this paper, the exact/true error requires the knowledge of the exact solution. However, numerical uncertainty defines an interval, with some confidence, within which the exact solution exists.

3.7.1. SOURCES OF ERRORS IN NUMERICAL SIMULATIONS

The errors in CFD can be divided into three components namely iteration, discretization and round off. Iteration errors are a result of the non-linearity of the governing equations. Iterations, which are performed to obtain the convergence of each governing equation, gives rise to this error. Currently an order of convergence for $L_\infty$ of $1E-06$ is used in the outer loop. A lower convergence criteria, for fine mesh, ($1E-08$) showed no difference in the solution ($1E-4$ % difference). Therefore, iterative error, for the present simulations, is assumed to be several orders of magnitude lower than discretization errors and can be neglected. Round off errors are a result of the finite precision of the computers [61]. Round off errors are considered to be negligible when double precision is used in the computations [61, 63] which is also the case for current simulations. Discretization errors are a result of the approximations such as finite element/finite volume/finite differences. Since iterative and round off errors are negligible, discretization error is the only dominant source of numerical error in this project.

In CFD, the computational domain is assumed to be discretized in the form of mesh composed of control volumes (finite volume method). The size of these control volumes can be changed by changing the grid spacing/cell size. The smaller the control volumes get, the accurate the solution since the governing equations are derived for an infinitesimal element. Also, a smaller control volume captures the flow changes that happen at an equivalent small scale. Similarly, the time step size plays an important role in CFD. With an increase in flow unsteadiness, the changes in the flow with time increases. Therefore, a smaller time step size should be considered to simulate the flow unsteadiness with higher accuracy. Although, a smaller grid and time step size give better results, with decrease in these sizes, the computational time grows significantly. Therefore, the choice of an appropriate grid/time-step size should be made such that it is acceptable by the user (in terms of computation duration) with a small trade-off of the accuracy of the solution.
3. Methodology and Theoretical Formulation

3.7.2. Assumptions Involved

The assumptions involved in the estimation of the error are the following:

- The data/solution set should lie in the asymptotic range. Which means the change in solution with a change in grid/timestep should not be large or oscillatory.

- The grid/timestep resolution should be geometrically similar. The grid refinement ratio, geometrical properties (cell orthogonality/skewness) shouldn’t change from one grid to another.

Since, no large changes or oscillatory behaviour was observed in the mean forces with the current data set, the first assumption is considered to be met. However, the second assumption is more of an exception when unstructured grids are considered [61]. With structured grids, the similarity between different grids can easily be maintained [61]. However, the same cannot be said for unstructured grids. Hexpress meshing tool optimizes the grid cells automatically to maintain the quality of the final mesh. This may change the cell orientation, orthogonality, skewness etc. close to the body surface. Therefore, geometric similarity is roughly not met even if the same settings have been used to obtain different grid resolution. Furthermore, with deforming grid, the mesh quality changes at each timestep. This makes it even more difficult to meet the second assumption. Therefore, the second assumption is considered to be an exception in this case. A recent study by Eça and Hoekstra [64] shows that the geometric similar grids are necessary to obtain the correct order of accuracy but not the error estimate [64]. The consequence of the geometrically dissimilar grids produces scatter in the data. However, least squares fit with an estimated order of convergence (obtained from uncertainty module) produces the uncertainty efficiently.

3.7.3. Uncertainty Module

The error estimation due to discretization, based on power series expansion, is obtained by the equation 3.36 for steady cases and 3.37 for unsteady cases [65]. Here $\phi_i$ and $\phi_0$ are flow values for grid index ‘i’ and exact solution grid (with subscript ’0’) respectively. $r_i$ and $\tau_i$ are the typical cell size and time step size respectively. $\alpha_x/\alpha_i$ are constants of expansion and $p_x/p_1$ are the observed order of accuracy. For unsteady (steady) case, there are five (three) unknowns in this equation. Therefore at least five (three) solutions with different grid/timestep resolutions are needed to solve the equation by least squares fit. Furthermore, redundancy and possibility of quality check of $p_x/p_1$ can be improved if more data set is considered [61]. Therefore, nine (3 grid refinements $\times$ 3 time step refinements) solutions are considered in the current project.

$$\delta_{RE} = \phi_i - \phi_0 = \alpha_x r_i^{p_x}$$  (3.36)
\[
\delta_{RE} = \phi_i - \phi_0 = \alpha_x r_i^{P_x} + \alpha_t \tau_i^{P_t}
\] (3.37)

A well setup model, which calculates the numerical error and uncertainty, for Re-FRESCO is used. It is based on the method by Eca and Hoekstra [61]. The inputs to the module are grid and time refinement ratios and the data set. The grid and time refinement ratios are given by equation 3.38. Here \(h_1\) and \(t_1\) are typical cell size and time step size of the finest grid. The same parameters, with 'i', subscript represent typical cell size and time step size for the grid considered (coarse, medium or fine). Time step size is user defined and straightforward input to uncertainty module. However, the grid step size cannot be obtained easily for unstructured grids since the grid similarity changes. Method to calculate the grid refinement ratio is adopted by Eça et al.[66].

\[
\begin{align*}
 r_i &= \frac{h_i}{h_1} \quad \tau_i = \frac{t_i}{t_1}
\end{align*}
\] (3.38)

Three methods are used to compute the typical cell size \(h_i\) [66]. These are given below:

1. The inverse of number of cells (INC):

\[
h_i = \frac{1}{N_{\text{cells}}} \n^\frac{1}{n}
\] (3.39)

Here, \(N_{\text{cells}}\) is the number of cells in the complete domain and \(n\) is the space dimension (3 for three dimensional).

2. Average cell size (ACS):

\[
h_i = \sum_{n=1}^{N_{\text{cells}}} \frac{V_i^{1/n}}{N_{\text{cells}}}
\] (3.40)

here \(V_i\) is volume of \(i^{th}\) cell.

3. General method used for structured grids (GM)

\[
h_i = \frac{1}{N_2}
\] (3.41)

Here, \(N_2\) is the number of cells in any direction. Initial number of cells (before cell refinement) is considered in the current project.

Two more methods, tested by Eça et al.[66], consider the root mean square and statistical treatment of cell volumes. These methods are not used since they give the same
value of cell refinement ratio and hence error estimation [66]. Amongst the above three methods, the first two are adopted by Eça et al. [66] and the third method is used to compute the refinement ratio for structured grids. The above formulas are used to compute the typical grid cell size and these are presented in the table 3.6 for all three models. As seen from the table, the refinement ratios obtained from INC and GM (for unstructured grids) are same. This gives same uncertainty from both the results. The values obtained from INC and ACS are different from the GM (conventional method used for structured grids). The uncertainty based on two methods ACS and GM are presented in the table 3.7. The uncertainty from GM is also presented for readers understanding of the difference between both methods.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mesh resolution</th>
<th>Computed typical cell size ((h_i))</th>
<th>Grid refinement ratio ((r_i))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Method used:</td>
<td>INC</td>
<td>ACS</td>
</tr>
<tr>
<td>Single-Wing</td>
<td>Coarse</td>
<td>0.01744</td>
<td>0.00262</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.00977</td>
<td>0.00147</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>0.00676</td>
<td>0.00101</td>
</tr>
<tr>
<td>Both-wings</td>
<td>Coarse</td>
<td>0.01523</td>
<td>0.00229</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.00868</td>
<td>0.00130</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>0.00599</td>
<td>0.000898</td>
</tr>
<tr>
<td>Wings-body</td>
<td>Coarse</td>
<td>0.01292</td>
<td>0.001938</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.01210</td>
<td>0.001455</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>0.00808</td>
<td>0.001214</td>
</tr>
</tbody>
</table>

Table 3.6: Grid refinement ratios from different grid refinement methods for single wing model.

Inputs to uncertainty module include refinement ratios and data set \((\phi_i)\). It solves equation 3.36 with least squares sense by minimizing the function given by 3.42. Here \(w_i\) is weight used and its choice depends on the standard deviation of the fit. Weight estimators are given in the paper by Eca and Hoekstra [61]. \(N_g\) is the number of grids plus time steps included in the data set.

\[
S(\phi_0, \alpha_x, p_x, \alpha_t, p_t) = \sum_{n=1}^{N_g} w_i \left(\phi_i - (\phi_0 \alpha_x \tau_i^{p_x} + \alpha_t \tau_i^{p_t})\right)^2 \quad (3.42)
\]

If the estimated values of \(p_x/p_t\) are within acceptable range, the discretization error for a \(r_i\) and \(\tau_i\) is obtained from equation 3.37 based on the values of coefficients and order of convergence obtained by the fit. The accepted range should be closer to the theoretical order of convergence (second order in the current model). The accepted range is empirically defined as \(0.5 < p_x/p_t < 2\) [61]. If \((p_x/p_t)\) does not lie in this range, several other power series equations are solved along with equation 3.37. These equations are not discussed since the data set for the current simulations lies within this range.
In the uncertainty estimation, the goal is to estimate, with 95% confidence, the interval within which the numerically exact solution lies (given by 3.43 [65]). Where, $U(\phi_i)$ is the uncertainty for the solution $\phi_i$. Based on the solution, if the obtained $p$ ($p_x$ or $p_t$) is greater than 0, monotonic convergence is obtained. If it is less than 0, monotonic divergence is obtained. If the value of $p$ cannot be obtained from the data fit, an oscillatory convergence/divergence is expected.

\[ \phi_i - U(\phi_i) \leq \phi_0 \leq \phi_i + U(\phi_i) \]  

(3.43)

Computation of uncertainty is based on three factors given below. The uncertainty is given by equation 3.44.

1. Estimation of discretization error $\delta_{RE}$,
2. Safety factor $F_s$ adopted from grid convergence index [19] and
3. Scatter in data $\delta_n$ is quantified based on the standard deviation ($U_{std}$) of the fit and the difference between data point and the value obtained from the fit ($e_i$).

\[ U_\phi = F_s|\delta_{RE}| + \delta_n \]  

(3.44)

The in-house (MARIN) uncertainty module considers a parameter (for example vertical force) and outputs the uncertainty for the mesh and time step chosen. In this project, the uncertainty was obtained for the fine mesh with lowest timestep (400 time steps per wing beat) for Single-wing model, Both-Wings model and Wings-body model. The uncertainty was computed for mean lift and drag forces and instantaneous peak forces. In addition to that, the uncertainty for the vortex structures was determined since flow visualization is carried out during post-processing. Since, forces are directly obtained from the simulations, the input to uncertainty for forces was straightforward. It is however, not straightforward to quantify the uncertainty in vortex structures. To quantify the vortex structures, the volume of the vortex structure, which is assumed to be equal to the volume of cells enclosed by the vortex structure, was considered.

The procedure used to obtain the volume of vortex structures is as follows. The time steps, corresponding to largest force peaks, were considered. To visualize vortex structure, Q criterion is considered (theory explained in section 3.8). After deciding on a Q criterion suitable for flow visualization, the cell which correspond to Q criterion lower than the value chosen for visualization, are blanked using blanking tool in Tecplot software. Then the value of the cell volume is computed and integrated over the domain. The cell volume obtained from the calculation are input into the uncertainty module to estimate the uncertainty.
3.7.4. Uncertainty Computations

The uncertainty, computed for various parameters, for all models are given in the table 3.7. As seen from the results, uncertainty obtained from the GM method gives a lower range of magnitudes of uncertainty in most of the cases. The difference between the INC and GM method is due to geometric dissimilarity.

As seen from the table 3.7, the uncertainty for all the force parameters are below 3%. The uncertainty for vortex structures is observed to be below 5%.

<table>
<thead>
<tr>
<th>Simulation Model</th>
<th>Parameters</th>
<th>Grid spacing identification methods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>INC</td>
</tr>
<tr>
<td>Single Wing</td>
<td>Average Lift force</td>
<td>1.645%</td>
</tr>
<tr>
<td></td>
<td>Average Drag force</td>
<td>1.585%</td>
</tr>
<tr>
<td></td>
<td>Lift peak during upstroke</td>
<td>1.515%</td>
</tr>
<tr>
<td></td>
<td>Lift peak during downstroke</td>
<td>1.772%</td>
</tr>
<tr>
<td></td>
<td>Vortex structure</td>
<td>4.45%</td>
</tr>
<tr>
<td>Both Wings</td>
<td>Average Lift force</td>
<td>1.773 %</td>
</tr>
<tr>
<td></td>
<td>Average Drag force</td>
<td>1.843%</td>
</tr>
<tr>
<td></td>
<td>Lift peak during upstroke</td>
<td>1.330%</td>
</tr>
<tr>
<td></td>
<td>Lift peak during downstroke</td>
<td>1.499 %</td>
</tr>
<tr>
<td></td>
<td>Vortex structure</td>
<td>2.5 %</td>
</tr>
<tr>
<td>Wings-body</td>
<td>Average Lift force</td>
<td>1.744%</td>
</tr>
<tr>
<td></td>
<td>Average Drag force</td>
<td>2.501%</td>
</tr>
<tr>
<td></td>
<td>Lift peak during upstroke</td>
<td>2.873%</td>
</tr>
<tr>
<td></td>
<td>Lift peak during downstroke</td>
<td>1.254%</td>
</tr>
<tr>
<td></td>
<td>Vortex structure</td>
<td>5.064%</td>
</tr>
</tbody>
</table>

Table 3.7: Uncertainty estimates for the fine grid with fine timestep in the models considered.

3.8. Visualisation of Vortex Structures

After obtaining the solution for the whole beat, flow visualisation is carried out. Based on the literature study, it is quite clear that the flight around insect flight is dominated by vortex structures. To visualise/identify this, coherent structures representing the vortices, are required to be extracted from the flow field. To accomplish this, velocity gradient vector is central (VGT) [67]. The VGT, in three dimensional form, is given below for velocity field $u$.

\[
\nabla u = \begin{bmatrix}
\frac{\partial u}{\partial x} & \frac{\partial v}{\partial x} & \frac{\partial w}{\partial x} \\
\frac{\partial u}{\partial y} & \frac{\partial v}{\partial y} & \frac{\partial w}{\partial y} \\
\frac{\partial u}{\partial z} & \frac{\partial v}{\partial z} & \frac{\partial w}{\partial z}
\end{bmatrix}
\]
This is used to derive the vortex identification techniques. VGT can be split into the strain rate tensor \( S \) and the rotation rate tensor \( \Omega \) given by equation 3.45 [67]. Where the strain rate tensor and rotation rate tensor are given by equation 3.46-3.47 [67].

\[
\nabla u = S_{ij} + \Omega_{ij} \tag{3.45}
\]

\[
S_{ij} = \frac{1}{2} \left( \nabla u + (\nabla u)^T \right) = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \tag{3.46}
\]

\[
\Omega_{ij} = \frac{1}{2} \left( \nabla u - (\nabla u)^T \right) = \frac{1}{2} \left( \frac{\partial u_j}{\partial x_i} - \frac{\partial u_i}{\partial x_j} \right) \tag{3.47}
\]

Eigen decomposition of the VGT gives Q-criterion (parameter ‘Q’ as per MARIN terminologies). This represents the dominance of rotation over strain in the flow [67]. For an incompressible flow, this is given by the equation 3.48. Iso-surfaces of Q-criterion is used to identify and visualize the vortex dynamics regions around the wing.

\[
Q = \frac{\partial u_i}{\partial x_i} \frac{\partial u_j}{\partial x_j} = \frac{1}{2} \left( \Omega_{ij} \Omega_{ij} - S_{ij} S_{ij} \right) > 0 \tag{3.48}
\]
The results obtained from different models are presented here. To begin with, the results due to the influence of initial condition, time and grid sensitivity analysis are presented. This is done for the single wing simulations. Then the flow visualization, forces and pressure contours are discussed for the Single-wing model. Subsequently, the results for the Both-wings and Wings-body model are compared with the Single-wing model.

4.1. Influence of Initial Condition

The simulations are supposed to run until the effect of initial conditions (standstill air) is no longer observed. This implies a stable state solution with respect to wingbeat (WB) cycles. This is done by considering a WB which does not show significant change in the results with respect to subsequent WBs. Figure 4.1 (a.) shows the vertical force plot for 12 WBs. All the force plots are normalised with half of the weight of the mosquito ($-5.78 \times 10^{-6}$ N). As seen from the plot, only first and second cycles show difference in the results. The difference in the mean aerodynamic forces for the 5th WB with respect to the 4th WB is observed to be around 0.4% and 0.5% for $F_z$ (vertical force) and $F_x$ (horizontal force) respectively. The numerical stability is reached around fifth cycle. However, the influence of wake exists long after that. The mean vertical force is observed to decrease gradually until around 80 cycles (as shown in fig 4.1 (b.)). This is considered to be the effect of the developing wake over the aerodynamic forces. Around the 80th cycle, the forces are observed to stabilize and reach a constant value. Although, a gradual decrease is observed in the forces, the change is quite small in magnitude. For this reason and due to practical limitations of simulation time, the 12th cycle is considered for the analysis. Assuming that the 80th cycle is the flow stable solution (with respect to WBs), a difference of 7% is obtained with respect to the mean weight support (for 12th cycle).


Figure 4.1: (a.) Vertical force obtained for 12 wingbeats for fine mesh and 400 time steps per WB. (b.) Mean vertical force for 80 wingbeats. (c.) Percentage difference of mean Fz wrt 80th cycle (green line) and previous cycle (blue line). The difference in the mean aerodynamic forces between first and second WB is nearly 50%. However, this reduces to nearly 0.4% when fourth and fifth WB are compared and it decreases further with subsequent WBs. Although, difference in the aerodynamic forces between WBs reduces to low values after 3rd WB, the mean aerodynamic force continues to decrease for a large number of cycles as observed in (b.). This is considered to be the effect of the developing wake with the advancement of WB cycles.

4.2. Time and Grid Sensitivity

Forces in X (Fx), Y (Fy) and Z (Fz) direction are obtained in the inertial reference frame for the 12th wingbeat (WB). The solution for three time steps and three grid sizes are computed and presented next. The table 4.1 shows the grid and time spacing considered in the data set.
### Grid Number of Time-steps per Wingbeat (t/WB) Timestep (seconds)

<table>
<thead>
<tr>
<th>Grid</th>
<th>100</th>
<th>200</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse grid</td>
<td>1.737108 × 10⁻⁵</td>
<td>8.6855 × 10⁻⁶</td>
<td>4.3428 × 10⁻⁶</td>
</tr>
<tr>
<td>Medium grid</td>
<td>1.737108 × 10⁻⁵</td>
<td>8.6855 × 10⁻⁶</td>
<td>4.3428 × 10⁻⁶</td>
</tr>
<tr>
<td>Fine grid</td>
<td>1.737108 × 10⁻⁵</td>
<td>8.6855 × 10⁻⁶</td>
<td>4.3428 × 10⁻⁶</td>
</tr>
</tbody>
</table>

Table 4.1: Grid and time steps (per wingbeat) for time/grid sensitivity analysis. Three grid spacing and time step sizes are chosen to study the grid and time step sensitivity of the numerical model.

#### 4.2.1. Grid sensitivity:

Figure 4.2, 4.3 and 4.4 show the change in forces (Fx, Fy, Fz) when the grid resolution is changed (with constant timestep 400/WB). As seen from the plots (on the left of these figures), the change in the solution is quite small implying small sensitivity with respect to grid resolution. The differences in the solution are mostly visible in the peaks and sharp curves. Some of these differences are shown on the right side of these figures, which are the zoomed portions of the regular force plots. As seen from the plots, the medium mesh solution is closer to fine mesh solution than coarser mesh solution. This implies a numerically convergent behaviour with decrease in the grid spacing. Also, since the spatial discretization is second order accurate, the solution approaches the numerically exact solution at faster rates with decrease in grid size (also observed for time step size). Since the fine mesh solution is closer to the numerically exact solution than a coarser mesh, the results obtained from fine mesh are considered for further analysis.

#### 4.2.2. Time sensitivity:

Three time steps (as shown in the table 4.1) are considered to check the time sensitivity of the solution. Figure 4.5, 4.6 and 4.7 check the change in the total aerodynamic forces with corresponding change in time step. As seen from the plots and based on the grid/time-step size considered, the total aerodynamic forces are observed to exhibit higher sensitivity towards time step size than grid spacing. This is clearly visible as the results, for change in time step, show considerable discrepancy in the solution. By decreasing the timestep size, the solution moves closer to the numerically exact solution. This can be seen from the plots as the solution obtained from 200 time steps per WB (200/WB) is closer to the solution obtained from 400/WB than 100/WB. A simulation with 600/WB was also performed and it exhibits even smaller difference such that the difference is hardly visible in zoomed image plots. Therefore, the results from 400/WB are considered for further analysis.
4.2. Time and Grid Sensitivity

Figure 4.2: Change in horizontal force for different grid resolution at 400 timesteps/WB. With the grid spacings used in this project, the solution sensitivity to grid spacing is observed to be low. Difference in the instantaneous forces are largest at peaks and wing rotational phases (supination/pronation).

Figure 4.3: Change in side force for different grid resolution at 400 timesteps/WB.
Figure 4.4: Change in vertical force for different grid resolution at 400 timesteps/WB.

Figure 4.5: Change in horizontal force for different time step with fine mesh. The solution sensitivity is observed to be higher with the change in the time step spacing unlike grid spacing (with the time-step/grid spacing considered in the data set).
4.2. Time and Grid Sensitivity

Figure 4.6: Change in side force for different time step with fine mesh.

Figure 4.7: Change in vertical force for different time step with fine mesh.
4.3. SINGLE WING FARFIELD FLOW VISUALISATION

In this section the farfield vortex dynamics and downwash is presented. Here, farfield is defined as the region swept by the wing. Results were post processed using the flow visualisation software Tecplot. Vortices are visualized by plotting the iso-surface Q-criterion (parameter 'Q' as per MARIN terminologies) around the wing. After trying different values of Q criterion, a value of 3E+07 was observed to be appropriate to visualize the flow in the swept region. The value is chosen such that the shed vortices, from the previous wing stroke (which have lower Q-criterion value and hence are weaker), aren't displayed. The flow visualisation is concentrated in the wing swept region. Apart from the Q-criterion iso-surface, the downward velocity (Z velocity), in three planes, are plotted. The planes are in parallel (Z slice) and perpendicular (X and Y slice) to the stroke plane as shown in figure 4.8. The parallel plane (Z slice) is at a distance 0.0015m below the wing root/origin, the perpendicular plane (Y slice) is 0.0019 m from the origin (in positive Y direction) and another perpendicular plane (X slice) is at the wing root.

Figure 4.8: Slices used to visualize flow around the wing. Downward velocity (along Z axis in the inertial frame) contour is plotted in these planes in the subsequent figures. Since the stroke plane is parallel to the horizontal plane of the inertial frame, the X-slice and Y-slice are perpendicular to the stroke plane whereas the Z-slice is parallel to the stroke plane.
There is no particular time step at which a wing-motion phase (translational/rotational) starts or ends. However, to make the flow visualisation simpler, these were defined based on the wing kinematic angles. The rotation angle is used to describe the supination and pronation. The stroke angle is used to describe the upstroke and downstroke. This is described in figure 4.9

**Figure 4.9: Wing phase definitions.** The definitions are adopted based on noticeable changes in the transient stroke angle and deviation angle. Downstroke (Upstroke) is performed during the non-dimensional time $t/T = 0-0.5$ ($t/T = 0.5-1.0$). Supination (Pronation) is performed during the time $t/T = 0.2-0.7$ ($t/T = 0.2-0.7$).

Downstroke ($t/T = 0.0-0.5$) is performed when the wing moves from rear position towards the head of the mosquito (towards positive body X axis). Upstroke ($t/T = 0.5-1.0$) is performed when the wing moves from the forward position towards the rear of...
the body (towards negative body X axis). Also, Supination phase is defined by the wing rotation from mid downstroke to mid upstroke (t/T = 0.2-0.7). Similarly, pronation is defined by the wing rotation from upstroke to downstroke (t/T = 0.2-0.7).

In the figures, the long lines with arrows represent streamlines and short lines with hollow arrow-heads represent tangential vectors in the plane. Also, the color over iso-surface structures shows downward (Z) velocity in the region. Consider figure 4.10, which shows the vortex structure mid-upstroke. As seen from the figure, a D-ring shaped vortex structure is observed. For the sake of simplicity, the vortex structures over the wing leading edge (LE), trailing edge (TE), wing tip and wing root will be called leading edge vortex (LEV), trailing edge vortex (TEV), tip vortex (TV) and root vortex (RV) respectively.

Figure 4.10: Flow structure and downward velocity contour during mid-upstroke. The long lines represent the stream traces and the small lines represent the tangential vectors in the slice. A D-ring vortex structure is observed which is also the most robust vortex structure throughout the WB cycle. It maintains its structure, with increase in size, throughout the upstroke. A strong downwash is observed through the center of the D-ring vortex structure.
Therefore, the observed D-ring structure is a combination of all four. The circular blue velocity regions, in the bottom of X slice, represents vortices from downstroke. In the complete wing beat cycle, D-ring vortex structure during upstroke, is observed to be the most stable one, which lasts throughout the upstroke. As seen from the figure, a strong downwash is observed in the middle of this structure. This is due to the circulation of bound vortex and the shed TEV which act in the opposite direction (anti-clockwise and clockwise with respect to wing translation respectively). It is shown by the streamlines/vectors, around the LEV structure, in the Y slice of figure 4.10. The effect of LEV and shed TEV is such that it results in a downward momentum or a strong air jet at the center of the vortex structure. Similarly, due the RV and TV, the air-flow is drawn into the structure from sides of the wing. Due to forward motion, the RV and TV are observed to be continuously shed into wake.

Figure 4.11: Flow structure and downward velocity contour during early pronation/late upstroke.

The downwash pool, in the center of the D-ring shaped vortex, persists throughout
the wing beat either with or without a visible D-ring vortex structure. The downwash pool is sustained throughout the wingbeat due to shed vortices. Persistence of the downwash pool was also observed by 3D flapping wing simulations performed by Trizila et al. [37] and they called it 'downward-jet'. The downwash pool is confined in the region swept by the wing and it is mostly attenuated around 1.5 times the wing length in any direction from the root. With further translation in the upstroke, the size and strength of the D-ring vortex increases. Figure 4.11 shows the vortex structure at the end of the upstroke (beginning of pronation). At this point (end of upstroke/early pronation), the size of the D-ring is observed to be the largest. As seen from the figure 4.11, the downward velocity, in between LEV and shed TEV, increases when compared to mid upstroke. Although, the downwash pool does not completely dissipate throughout the wing beat, its orientation, size and the velocity within it changes at different stages of the wingbeat. This can be seen in the figures shown next (for other stages of wingbeat cycle).

Figure 4.12: Flow structure and downward velocity contour mid-downstroke.
With further progress of wing motion during pronation (wing flip), the D-ring vortex structure is broken and shed into wake. Figure 4.12 shows the vortex structure in the mid downstroke. A TEV is shed during the start of the downstroke. However, the connection between shed TEV and TV/RV is lost as soon as the TEV is shed. As seen from the figure, no connected vortex, such as the D-ring observed during upstroke, is observed during downstroke motion. Also, the downward velocity, between LEV and shed TEV, is comparatively lower than upstroke. The downwash pool, during downstroke, is shifted such that it lies between the wing bound vortex and the shed TEV. The low downward velocity, between LEV and shed TEV, is considered to be the consequence of weaker LEV/TEV when compared to the upstroke (more explained in next section). The D-ring vortex structure also forms in the downstroke but comparatively (to upstroke D-ring structure) of lower strength. This was observed with lower value of Q criterion indicating that the structure in downstroke is significantly weaker than upstroke vortex structure. Also, the duration and size of the D-ring vortex structure, during downstroke, is smaller when compared to the upstroke. The vortex structures below the wing, in figure 4.12, indicate the shed vortices from the upstroke cycle. As seen from the figure 4.12, the strength of the shed TEV during downstroke is equivalent to shed vortices during upstroke cycle. With further wing progression, the vortices over the wing (LEV, TV, RV) breakdown and shed into the wake. Figure 4.13 shows the vortex structure at the end of supination. During this stage, the downward velocity is observed to be the lowest throughout the wing beat cycle.

Figure 4.13: Flow structure and downward velocity contour late supination.
4.4. SINGLE WING NEAR-FIELD FLOW VISUALISATION

To visualise the flow structures in the near field (over the wing), vortex cores were extracted. A Tecplot tool is used to extract the vortex core position automatically based on the gradient of velocity field or vorticity field. Tecplot algorithm, used to compute the vortex cores, is based on the velocity gradient eigen modes method [68]. The algorithm extracts a line from the flow field which lies in the center of a vortex [68]. The vortex is defined by the region in which, the second largest eigen value of the symmetric tensor $S^2 + \Omega^2$ is negative [69]. Here, $S$ and $\Omega$ are strain and rotation rate tensors (as explained in the section 3.8). Vortex core positions were obtained at every timestep for a complete wing beat cycle. Apart from that, stream traces were obtained around the vortex cores to visualize the flow around different vortices. All four phases (downstroke, supination, upstroke and pronation) in the wing beat cycle were analysed.

![Pressure over the wing surface at the start of pronation](image)

Figure 4.14: Pressure over the wing surface at the start of pronation. The extreme negative pressures represent the location of the core of the LEV. The pressure contours are discussed in detail in section 4.8.

PRONATION:

During the start of the pronation (end of upstroke), an attached LEV, a shed vortex (SV) and TV are observed. A circuit (D-ring structure shown in previous section) is established connecting all three vortices through the root vortex (RV) as shown in the top (a.) of the figure 4.15. In the figure, vortex structure is shown on the left and the vortex core is shown by blue lines on the right. As seen from the images, the flow structure is three dimensional. The LEV is located above the wing and TV/RV are located on the wing tip and root respectively. Air flows smoothly over the bottom surface of the wing with no visible vortices. The shed vortex has been detached from the wing in the early upstroke. Only few stream traces are considered around the shed vortex in this figure since shed TEV is quite large at this stage and complicates the near-field flow visualization.
4.4. SINGLE WING NEAR-FIELD FLOW VISUALISATION

Figure 4.15: Vortex structures (left image) and cores (right image) during the start (a.), middle (b.) and end (c.) of the pronation phase.
The diameter of the LEV increases slightly from the wing base towards the wing tip making it conical in shape. At the location of the LEV, a negative pressure is obtained as shown in figure 4.14, which augments the lift force. The size of the TV also changes along the curvature and it is continuously shed with wing translation. As the wing progresses such that the rotation about spanwise axis is greater than the wing translation, LEV is observed to decrease in strength and move rearward (towards the TE). As shown in the middle (b.) of the figure 4.15, the LEV weakens as the wing gradually reverses its direction. The TV is seen to detach completely and join the shed vortex. The LEV is observed to detach from the tip end and join the shed vortices.

As the wing reverses its direction, the wing flips making the top surface the new bottom surface and the bottom surface, the new top surface. This is shown in the bottom (c.) of the figure 4.15. Figure 4.16 shows the vortex cores below the wing during pronation. As the wing advances with increasing translation motion, a new TV is generated on the top surface which extends towards the wing root on the LE creating a new LEV. Also, the TV extends along the TE creating a TEV on the bottom of the wing. The growing TEV is observed to be connected to the wing root which moves towards the TE with wing motion. By the end of pronation, a new LEV is formed. Also, the TEV, below the wing, grows relatively faster than the LEV and detaches at the start of the downstroke/end of pronation.

**Downstroke:**

Vortex structure during downstroke is shown in the figure 4.17. In the initial stages of the downstroke \(t/T = 0.15\), the TEV below the wing is shed into the wake. The TEV is developed at the end of pronation and quickly shed into the wake with increase in translation motion of the wing. The attached LEV grows in size and extends toward the wing root. With further wing advancement, LEV grows in size and strength. This is shown in the top of the figure 4.17. The TV also grows with wing motion and starts to destabilize. At the end of the downstroke \(t/T=0.4\), as shown in the bottom of the figure 4.17, the LEV is large in size but does not detach from the wing. However, the TV starts to detach from the extreme end of the wing tip.
4.4. SINGLE WING NEAR-FIELD FLOW VISUALISATION

SUPINATION:

In the initial stages of this phase ($t/T = 0.4$, top of the figure 4.18), the attached LEV starts to grow weak and dissipate in a short period. The vortex core of the LEV begins to move rearward (towards TE). This movement is larger close to the wing tip. As the wing flips and reverses its direction, the LEV is dissipated in the flow and the TV is shed in the wake. LEV is no longer observed at the end of stroke reversal.

As the wing flips and reverses its direction, the LEV is no longer observed and a stopping vortex is shed due to deceleration. The stopping vortex dissipates in a very short duration and it can be observed in the figure 4.28. In parallel, a new TV is formed on the top surface (after the wing flip) and grows in size. This is shown in the bottom of

Figure 4.17: Vortex structures (left image) and cores (right image) during the start (top image) and end (bottom image) of the downstroke phase.
the figure 4.18. Figure 4.19 shows the vortex cores mid-supination. With an increase in the size of the TV, a new LEV and TEV are formed on top of the wing (after wing flip). These are connected to the TV and grow towards the wing root. The growth of TEV is noticeably faster than LEV. The TEV is initially connected to the wing root from the other end and displaces, in a short duration, such that it is aligned with the TE. At the end of the supination, TEV sheds into the wake. This can be seen at the start of the upstroke phase/end of supination (top of figure 4.20).

Figure 4.18: Vortex structures (left image) and cores (right image) during the start (top image) and end (bottom image) of the supination phase.
4.4. SINGLE WING NEAR-FIELD FLOW VISUALISATION

Figure 4.19: Vortex cores during mid-supperation.

Figure 4.20: Vortex structures (left image) and cores (right image) during the start (top image) and end (bottom image) of the upstroke phase.
Upstroke:

In the initial stage of the upstroke ($t/T=0.7$), a set of connected vortices are observed as shown in the top of figure 4.20. This involves the attached LEV, the TV, the shed TEV and the RV. This connection is maintained throughout the upstroke resulting in the D-ring vortex structure. With the advancement of the upstroke, the size and strength of the LEV and TEV increases. The TV starts to destabilize around the mid-upstroke. The bottom of the figure 4.20 shows the vortex structure during the mid upstroke. The LEV is observed to be stable throughout the upstroke (and downstroke) with no signs of breakpoints or instability along the span. Also, the LEV core is observed to follow the morphology of the wing LE during upstroke/downstroke without any sign of break/instability.

4.5. Aerodynamic forces over wing

The total aerodynamic forces (pressure + friction) obtained for a single-wing model (left wing) are shown in the figure 4.21. Plot 4.21 shows the aerodynamic forces (vertical, horizontal and side-force), in the inertial reference frame, obtained from the resultant force over the wing. $F_x$, $F_y$ and $F_z$ represent the forces in horizontal (positive towards the head of mosquito/heading direction), side and vertical direction respectively. The forces are plotted against the non-dimensional time ($t/T$). Here, $t$ is the time step and $T$ is the time taken to complete a whole wing beat.

Resultant Force:

Based on the force plots, it is clear that the resultant force ‘F’ acts backward (negative X direction) in the first half/downstroke ($t/T = 0-0.5$) and forward in the second half/upstroke ($t/T = 0.5-1$) of the wingbeat. This can be clearly seen from the $F_x$ plot. Also, it faces vertically upward in the whole wing beat as seen in the $F_z$ plot. Based on the $F_y$ plot, the resultant force faces inwards (towards the wing root) during late supination and pronation phases and outwards during early supination and pronation phases.

Horizontal force:

Consider the horizontal force plot in the figure 4.21. As seen from this plot, first half of the WB comprises of negative horizontal force and the second half comprises positive horizontal force. Therefore, the horizontal component of the resultant force (over the wing) faces backward during the first half and forward during the second half of the WB. Also, absolute magnitude of $F_x$ shows a gradual increase (with respect to $t/T$) until mid upstroke/downstroke and then, a decrease (wrt $t/T$) until the end of upstroke/downstroke. There are three force peaks observed in the first half of the wingbeat. These are located at the end of pronation ($t/T = 0.05$), mid downstroke ($t/T = 0.3$) and early supination ($t/T = 0.45$). Around the stroke reversal (supination), the horizontal force magnitude starts to increase in magnitude due to change in direction. Also, similar peaks are observed in the
second half of the WB. These are located at the late supination ($t/T = 0.6$), mid upstroke ($t/T = 0.7$) and early pronation ($t/T = 0.95$). $F_x$ gradually increases in the second half of the WB. Then, the force starts to decrease from late upstroke onwards. It is clear from the plot that first half of the WB motion largely contributes to the aerodynamic drag and the second half contributes to the thrust of the flight. The mean drag force generated in the downstroke is $-9.6 \times 10^{-06}$ N and mean thrust generated during upstroke is $1.47 \times 10^{-05}$ N. The mean horizontal force during the whole wingbeat is $2.52 \times 10^{-06}$ N. Since it is positive, it acts in the direction of motion/ positive X direction.

Figure 4.21: Normalised (with weight of the mosquito) instantaneous aerodynamic forces on the single wing. (Top left) Horizontal, (top right) side and (top left) vertical force in the inertial frame of reference. Here $t/T$ is non-dimensional time.
VERTICAL FORCE:

Consider the Fz plot. The vertical force is positive indicating complete contribution to lift force. Three force peaks are observed in the downstroke and one force peak in the upstroke of the wingbeat. In addition to that, visible changes can be observed during upstroke, at the locations where the force peaks in Fx plots were observed. During upstroke, the vertical force gradually increases (with respect to t/T) until it reaches a peak value in the mid-downstroke. Then, the lift decreases gradually until the stroke reversal (supination). After the stroke reversal, the vertical force shows a similar pattern like the first half with some changes. A force peak is obtained in the mid-upstroke which is significantly greater in magnitude than the peak force in the mid-downstroke (nearly 50% greater in magnitude). Based on the results obtained, it is clear that larger lift is produced during upstroke. From the computations, downstroke contributes to nearly 37% of the total lift force whereas second half of the WB contributes up to 63% of the total lift force. The mean lift force generated during downstroke and upstroke are $6.59 \times 10^{-6}$ N and $1.1 \times 10^{-5}$ N. The mean lift force during the whole wingbeat is $8.909 \times 10^{-6}$ N.

MEAN FORCE AND WEIGHT SUPPORT:

The weight support is performed to check if the mean vertical force per wingbeat supports the weight of the mosquito. Obtained mean vertical force for single wing is given below. This is the mean vertical force for the 12th WB cycle.

$$F_{z_m} = 8.909 \times 10^{-6} \, N$$

To obtain the total weight support, the force due to both wings are required. Hence the above value is multiplied by 2 and divided by the acceleration due to gravity (9.81 m/s) to obtain the weight support. This gives a weight support of $1.8163 \times 10^{-6}$ kg. As mentioned previously, the weight of the mosquito was found to be $1.23 \pm 0.65 \times 10^{-6}$ kg. Since the weight support computed by the current model is within range of the weight (obtained from experiments), the current model supports the weight of the mosquito. If the reduction in forces due to WB cycle (as explained in section 4.1) is considered. The computed weight support equals $1.67 \times 10^{-6}$ kg. Considering the weight of the mosquito to be $1.23$ mg, the obtained weight support overestimates the weight by 35%. If the weight support from 12th WB cycle is considered, the weight support is overestimated by 47%.

SIDE FORCE:

Considering the Fy plot, the force shows a complex pattern relative to Fx or Fz. As seen from the plot, the side force is mostly acting inward during late supination and pronation. Similarly, it acts outward during early pronation and supination. Maximum side force is obtained during the end of upstroke/ start of pronation and it is larger than the magnitude of the positive forces obtained during the end of downstroke/ start of supina-
4.6. PRESSURE AND FRICTION FORCES:

Figure 4.22: Normalised (with weight of the mosquito) instantaneous pressure and friction forces on the single wing. (Top left) Horizontal, (top right) side and (top left) vertical force in the inertial frame of reference. The contribution of mean viscous forces, to the mean aerodynamic forces, is an order of magnitude lower than the mean pressure forces.

Total aerodynamic forces can be split into friction and pressure forces. Pressure forces are a result of momentum of air molecules over the surface and act perpendicular to the surface. The net pressure force is obtained by integrating the pressure force over the en-
tire body. Friction forces are a result of the viscosity of the fluid and act tangential to the surface. It is a measure of resistance of fluid motion over the surface. The net friction force is also obtained by integrating the local friction forces over the whole body. The net pressure and friction forces, over the wing for a complete wing beat, are shown in figure 4.22. The forces are split into the three components along vertical, horizontal and side direction of the wing. As seen from the plots, the friction forces have very small contribution to the total aerodynamic force when compared to the contribution of the pressure force. The mean friction forces are lower, by an order of magnitude, when compared to the mean pressure forces.

4.7. COMPARISON WITH OPENFOAM SIMULATION RESULTS:

![Graph showing comparison of aerodynamic forces between Openfoam and ReFRESCO](image)

Figure 4.23: Comparison of normalised aerodynamic forces, obtained from the current simulations, with WUR simulation results performed by Ir. W.G. van Veen as a part of PhD. Differences between both the results are observed in the force peaks which is considered to be due to the difference in the wing thickness. Current simulations are performed with 3% mac as the wing thickness whereas OpenFoam simulations are performed with no wing thickness.

Here, the results obtained from ReFRESCO are compared with the simulation results provided by Ir. W.G. van Veen as a part of PhD at WUR. Please note, the uncertainty in the simulation results from WUR is not known. Therefore, this is a general comparison. These (from WUR) results are obtained from the simulations performed using OpenFoam solver with the same fluid properties as considered in the current project. Also,
the morphology and kinematics remain the same. The total aerodynamic force plots, for a single wing, are shown in the figure 4.23. As seen from the plots, the results obtained from the current simulations are comparable with OpenFoam results with small discrepancies in the peak. These discrepancies are considered to be due the thickness of the wing or numerical error (which is low in the current simulations as given in table 3.7. The WUR simulations are performed with zero wing thickness whereas the current simulations are performed at 3% mac thickness.

4.8. Pressure over the wing

For simplicity, the top surface of the wing during downstroke is named ‘surface1’ and the top surface of the wing during upstroke is named as ‘surface2’. Differential pressure contours over these surfaces are obtained for the whole WB and shown in figure 4.24-4.26. Since the parameter is differential pressure, it is relative to ambient pressure conditions. For ease of explanation, ‘Pressure’ instead of differential pressure will be used henceforth.

The plots are shown starting from t/T=0.15. This is when the wing motion is at the end of pronation and beginning of downstroke. At this stage, the inception of LEV is observed. Consider figure 4.24. In the most part of downstroke, surface1 is facing upward (positive Z direction). The majority of pressure over surface1 is negative and surface2 is positive which results in large pressure difference between top and bottom surface of the wing. In the initial stages of the downstroke, positive pressures are only observed close to the wing root (on surface1). The lowest negative pressure on surface1 (blue color) is observed close to the wing tip. As the wing advances, the blue region on surface1 extends towards the wing root and the positive pressure region shrinks. Since the LEV is observed to increase in size with an advancement of the downstroke, the lowest pressure region coincides with the LEV core and its growth indicates the growth of LEV. The increase in the blue region (extreme negative of pressure) is observed until mid downstroke (t/T = 0.3) when it stops, and starts to decrease again due to wing deceleration.

During the initial stages of downstroke, negative pressure region on surface2 is observed only in the middle and TE of the wing. The lowest negative pressure on surface2 is observed at the TE and represents the pressure over TEV. As observed in the near-field vortex visualisations, a TEV is shed from the bottom surface (surface2) in the initial stage (t/T =0.15-0.20) of the downstroke. This can also be observed in the figure 4.24 as the negative pressure region is confined to TE and disappears with advancement (as the shed TEV moves away from the wing). It corresponds to the dip observed in the forces at t/T ~0.15. Furthermore, the pressure on the surface2 is mostly positive near the wing tip and negative near the wing root. Also, as the wing advances, the positive pressure region enlarges, towards the wing root, with a corresponding reduction of the negative pressure region at wing root.

The collective effect of decrease and increase in pressure over surface1 and surface2 is such that a net upward pressure (positive z direction) is obtained. This results in in-
increasing the resultant force (lift and drag). This can also be observed in the force plots $(t/T = 0.15 - 0.3)$ when the absolute vertical and horizontal forces increase. As the negative pressure region on surface1 and positive pressure region on surface2 reduce (from $t/T = 0.3 - 0.4$), the absolute vertical and horizontal forces also decrease.

Consider the supination phase $(t/T = 0.25 - 0.7)$ during which, the wing flips. In the initial stages of supination $(t/T = 0.3 - 0.45)$, a localized blue region is observed on the surface1 (close to the wing root, near the TE) and a corresponding positive pressure region is observed on the surface2. The force peak, observed in the vertical and horizontal forces (as seen in figure 4.21 $t/T = 0.45$) is considered to be due to this local change in pressure at the TE. To visualize these local pressure regions properly, a magnified image with larger contour scales is shown in figure 4.27. These pressure regions are a consequence of the wing motion and explained in the next section 4.8.1.

With further advancement of the wing $(t/T = 0.45 - 0.5)$, the localized blue region on surface1 and positive pressure region on surface2 reduces. Around $t/T = 0.5 - 0.6$, a force peak is observed in $F_x$ plot and a small change is observed in the $F_z$ plot. This can be considered as the effect of a localized pressure region on surface2 (close to the wingtip). This is shown, with larger contour scales, in figure 4.27. With wing motion $(t/T = 0.6 - 0.7)$, a positive pressure on surface1 (close to wing tip) and a negative pressure region on surface2 is observed to build up. This is observed around the wing tip and extends towards the wing root with advancement of the wing. At the end of the supination $(t/T = 0.7)$, a lowest pressure region (blue) on the surface2 is established. This is concentrated on the wing tip and extends toward wing root (along LE and TE). A low pressure region (blue) is also observed on the surface1, close to the TE. This is the TEV build up as observed in the near field visualisation.

Consider the upstroke phase. In the initial stages of upstroke/ end of supination $(t/T = 0.7 - 0.75)$, the lowest pressure region (blue) on surface2 is observed to increase. As seen in the near field visualisation, a TEV is shed at the start of the upstroke. This is represented by a blue region on the surface2 (at TE). The influence of the TEV is such that negative pressure region is observed on the surface1 (at TE). These negative pressure regions decreases from $t/T = 0.75 - 0.8$ as the shed vortex moves away from the wing. This pressure region is observed to be lower in magnitude than the pressure region observed during the early downstroke, when a TEV sheds into wake. Therefore, the TEV shed during early-upstroke is stronger than the TEV shed at the start of downstroke since it creates larger pressure gradient. During the mid-upstroke $(t/T = 0.7 - 0.8)$, the negative pressure region on the LE (indicating the pressure on the LEV) on surface2 gradually increases. In parallel a positive pressure region on the bottom surface (surface1) increases. This increases the vertical and horizontal forces until a peak is reached (around $t/T = 0.8$). In the second half of the upstroke, the negative region of surface2 and positive region on surface1 reduces thereby reducing the vertical and horizontal forces. An interesting observation is that the negative pressure region in the upstroke is significantly larger than the negative pressure region in the downstroke. The observations of pressure region suggests that the LEV and shed TEV are stronger (with larger pressure gradients) during upstroke than downstroke. This is in agreement with the farfield flow visualisa-
Consider the pronation phase/ late-upstroke \((t/T = 0.75-0.15)\). At the start of the pronation \((t/T = 0.85-0.95)\), the negative pressure region on surface 2 and the positive pressure region on surface 1 shrinks. Also, a localized region of positive pressure at the TE (close to the root) develops on surface 1. This change is such that it results in a force peak, as observed around \(t/T = 0.95\) in \(F_x\) plot and a small change is observed in the \(F_z\) plot. In the second half of the pronation \((t/T = 0.0-0.15)\), this local region (around TE) of positive pressure reduces in size. Furthermore, another localized negative pressure region is observed on the surface 1. This is located at the wing tip and moves toward the TE with the wing motion. This local pressure region is largest around \(0.05-0.1\) \(t/T\) which coincides with the force peak observed in \(F_x\) and \(F_z\) plots (around the same interval). Also, a region of positive pressure on surface 2, is observed. This region (on surface 2) is concentrated on the wing tip and extends towards the wing root with wing advancement. By the end of the pronation, the top surface (surface 1) is dominated by the negative pressure region.
Figure 4.24: Pressure distribution over wing surfaces. Here the pressure is differential pressure. Hence the pressure values are relative to the ambient pressure conditions. Surface1 and Surface2 represent the top and bottom surface during downstroke respectively. The parameter \( t/T \) is non-dimensional time. The wing position describes the instantaneous mid-wing chord position at that time instant.
Figure 4.25: Pressure distribution over wing surfaces. Here the pressure is differential pressure. Hence the pressure values are relative to the ambient pressure conditions. Surface1 and Surface2 represent the top and bottom surface during downstroke respectively. The parameter t/T is non-dimensional time. The wing position describes the instantaneous mid-wing chord position at that time instant.
Figure 4.26: Pressure distribution over wing surfaces. Here the pressure is differential pressure. Hence the pressure values are relative to the ambient pressure conditions. Surface1 and Surface2 represent the top and bottom surface during downstroke respectively. The parameter $t/T$ is non-dimensional time. The wing position describes the instantaneous mid-wing chord position at that time instant.
4.8. PRESSURE OVER THE WING

4.8.1. FORCE PEAKS AND LOCALIZED PRESSURE REGION

As mentioned in the literature review chapter, the force peaks observed during the wing flip are considered to be a result of unsteady mechanisms called rotational lift and wake-capture/rapid-acceleration. Please refer section 2.2.3-2.2.4 for the theory. These force peaks, in the current study, are investigated further and commented upon in this section. The force peaks correspond to the local pressure gradients observed in the pressure contours over the wing. The force peaks, observed during supination (at t/T =0.45 and 0.55), are discussed here. Discussion remains same for the force peaks during pronation phase.

The first force peak (before wing flip at t/T = 0.45), is considered to be the effect of the rotational circulation due to establishment of the Kutta condition. As the wing rotates, the stagnation point moves away from the TE onto the surface of the wing. In order to have a smooth tangential flow and re-establish Kutta condition at the TE, additional circulation is generated by the wing (apart from circulation resulting from translation motion) named as rotational circulation [11, 24]. Based on the current study, the shift in the stagnation region occurs throughout the wing flip. The first force peak is considered to the result of the wing motion/kinematics which in turn displaces the stagnation position. A better explanation, of the force peak, is provided by Sun and Tang [36]. They suggest that the force peak is due to sudden pitch-up motion of the wing resulting in larger pressure gradients and hence change in forces. Consider the first force peak (at t/T = 0.45). As observed in the figure 4.24, during this time (t/T =0.4-0.45), the pressure gradients increase in the lower part of the wing (wing trailing edge) and then subsequently (t/T =0.45-0.5) decrease. This is in agreement with the wing rotation as the wing TE is observed to accelerate with almost constant LE position. This motion can be observed in the right of the image 4.24 shown by mid-wing chord motion. This motion results in large velocities and pressure gradients resulting in a force peak. The increase and decrease in the force results from a combination of the pitch-up rotation and deceleration of wing translation.

Consider the force peak after the wing flip. Literature review provides two possible reason for the force peak after the wing flip. This is wake capture and sudden acceleration of the wing. As mentioned in the literature review, the wake capture mechanism occurs when the wing encounters its own wake shed in the previous stroke (LEV and TEV). In the current study, the LEV is observed to dissipate at the end of the half stroke. Although the vortex core is no longer observed at the extreme wing position, LEV (from previous stroke) still has a considerable influence over the fluid flow around the wing due to negligible translational velocities. The TEV, which is shed at the beginning of the upstroke/downstroke is dissipated into the downwash pool and does not physically interact with the wing as the wing flips and reverses its direction. Therefore, the large influence (if any) of shed vortices, should be that of the LEV from the previous stroke. Figure 4.28 shows the slice of normalized Q criterion mid way along the wing span during supination. As observed in the figure 4.28, the vortices shed by TE (TEV and stopping vortex) are shed in the wake. However, the LEV is observed to dissipate with wing rotation. During the force peak (t/T= 0.55), the LEV is almost completely dissipated.
An important point is that the LEV has a counter clockwise rotation and the circulation over the wing (after wing flip) is clockwise. Therefore, any influence of the wake capture should be detrimental and not increment in the lift. This point is elaborated, in the next paragraph, based on the study of Sun and Tang [36].

Unlike Dickinson et al. [23], Sun and Tang [36] suggested that the reason for the force peak after wing flip is due to the sudden acceleration of the wing and not due to wake capturing. Although Dickinson et al. [23] provided qualitative evidences of the wake-capture mechanism, their explanation lacked the quantitative estimate of wake capture mechanism. Sun and Tang [36] performed simulations by starting the wing motion from standstill condition (without wake capture) and still observed a force peak. Sun and Tang [36] compared this result from the results obtained from regular wing rotation (with developed wake). Any differences should represent the effect of the wake-capture. As observed by Sun and Tang [36], a small detrimental effect (not increment) was observed. Sun and Tang [36] changed the acceleration of the wing rotation and found that the increase/decrease in the force peak magnitude was directly proportional to the change in wing rotation acceleration. Also, the effect of wake-capture mechanism was observed to be lower when the wing rotational accelerations were increased.

In the current study, second force peak (during supination) is observed during the time $t/T = 0.5$-$0.6$. During this time, the LE of the wing has larger displacement with almost constant TE position resulting in larger velocity and pressure gradients on the top portion of the wing. Due to this motion, a second force peak is observed at $t/T = 0.55$. Based on the previous discussion, it seems highly unlikely for the wake-capture mechanism to increment the lift. Even if there are induced velocities due to LEV from previous stroke, it should have a detrimental effect and not increment. However, based on the pressure contours and wing motion, sudden-wing accelerations provide better explanation of the force peak after wing flip.

The explanation for the force peaks during pronation remain the same. However, the intensity of the unsteady mechanisms differ. During supination, the rotational lift/pitch-up rotation results in an increment in lift ($t/T = 0.45$) and drag (relative to wing motion). Comparatively, the influence of this unsteady mechanism is lower during pronation. However, the effect of sudden acceleration is exactly opposite. It has greater influence during pronation phase than supination since the force peak, observed during pronation, is larger than supination.

Figure 4.27: Local blue pressure regions during supination.
Figure 4.28: Normalized Q criterion during supination showing the wake capture mechanism. As the wing reverses its direction, it encounters the dissipated LEV from previous stroke. However, wake capture mechanism is considered to be less significant when compared to the sudden acceleration of the wing [36]. Therefore, it is not considered to be reason for a positive force peak after the wing flip.

4.9. Wing-Wing and Wing-body interaction

4.10. Total forces and pressure distribution

Firstly, the side force on the left and right wing (for two wing model) is plotted and shown in figure 4.29 (left image). As expected, the side force on the right wing is exactly opposite in direction and equal in magnitude to that of the side force acting on the left wing. This results in zero net side force on the whole model. Also, the vertical and horizontal forces are same on the right and left wing. Therefore, only left wing results for three models (Single wing, both wings and wings-body) are discussed.

Considering that the boundary condition and initial condition are at standstill (zero velocity and pressure conditions), the influence in the two wing model is considered to be due to the presence of second wing, additional bound and shed vortices of the second wing. The observed difference in the Wings-Body model is due to the blockage effect of body in between both the wings. Also, due to wing motion and downwash pool, velocity is induced over the body resulting in the forces acting on the body. The vertical and horizontal forces over the wing and body, obtained from Wings-Body model, is shown in figure 4.29. As seen from this figure, the forces obtained over the body are negligible when compared to the forces over the wings. Please note, 4.29 only plots the forces of one wing. The mean forces over the body are observed to be two order of magnitudes lower than the mean forces over the wing. The forces over body contribute to nearly 0.2% in lift and 0.9% in drag. The mean vertical force and mean horizontal force, per
wingbeat cycle, over body is $-2.14 \times 10^{-08}$ N and $2.05 \times 10^{-08}$ N respectively. Therefore, the contribution of body, to the overall aerodynamic forces, is low. Here, the observed differences also include the numerical error and the uncertainty is given in Table 3.7.

Figure 4.29: (Left image) Total side force on left and right wing. The side force from right wing cancels the side force from left wing resulting zero net side force on the complete model. The blue line represents the sum of the side forces produced by the left and right wings. (Right image) Normalised instantaneous forces over wing and body in the Wings-body model. The mean aerodynamic forces produced by body are two orders of magnitude lower than the mean aerodynamic forces produced by wing.

Figure 4.30-4.31 shows the instantaneous aerodynamic forces, on the left wing, for all the three models. The mean aerodynamic forces, over left wing, is given in the table 4.2. As seen from the plot 4.30, these influences (wing-wing and wing-body interaction) are quite low. Consider the difference between the models Single-wing and Both-Wings. The observed differences are lower than the 1%. Based on the observed results, it is quite clear that the effect of the second wing is negligible. Consider the effect of addition of the body. The mean vertical force is reduced by nearly 2.82% and mean horizontal force is reduced by 5.32% with respect to Single-wing model. Also, the mean vertical force is reduced by nearly 2.06% and mean horizontal force is reduced by 4.84% with respect to Both-wings model. Therefore, the effect of addition of body has a larger effect on the lift generation over the wings when compared to wing-wing interaction (Both-wings model). Above discussion gives a clear understanding of the effect of the body. Although body actively generates negligible lift/drag, its presence has influence over the forces generated over the wing. Due to the body, the flow over the wings, that would exist without the body, is different and hence results in change in forces. This is elaborated considering the vortex structures and downwash in further sections. Table 4.3 shows the weight supported by the three models. As observed in the table, the weight supported by the Wings-body model is lower than the other two models due to wing-body interaction. The difference in the weight support remains almost same as the difference in the forces over single wing since the active contribution of body remains negligible.
Figure 4.32-4.33 shows the pressure contours over the wings and body, for all three models, during mid-downstroke \((t/T = 0.3)\) and mid-upstroke motion \((t/T = 0.8)\). These time instants correspond to the largest force peaks observed during the wingbeat cycle. Also, the largest differences observed between the models is at the force peaks. As seen from the pressure contours, the pressure distribution over the wing remains nearly the same. The observed change in the mean aerodynamic forces are not due to change in the particular portion of the wing but due to collective effect. That is, the flow around the wing, due to addition of body, changes resulting in a slight variation of pressure forces throughout the wing. However, by increasing the contour levels to large numbers, minor differences are observed in the wing root region due to the presence of body. In addition to the above discussion, the pressure gradient over the body, due to induced velocity from the vortices over wings and wake, is negligible when compared to the large pressure gradients over the wing. This is in agreement with the forces generated by the body. Although small contribution, the portions of the body, actively contributing to the net force generation, is the mid thorax-abdomen region.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean Fz ([\text{N}])</th>
<th>Mean Fx ([\text{N}])</th>
<th>Δ Decrease %</th>
<th>Δ Decrease %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-Wing</td>
<td>(8.909 \times 10^{-6})</td>
<td>(2.523 \times 10^{-6})</td>
<td>0.7%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Both-Wings</td>
<td>(8.847 \times 10^{-6})</td>
<td>(2.499 \times 10^{-6})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-Wing</td>
<td>(8.909 \times 10^{-6})</td>
<td>(2.523 \times 10^{-6})</td>
<td>2.82%</td>
<td>5.32%</td>
</tr>
<tr>
<td>Wings-Body</td>
<td>(8.657 \times 10^{-6})</td>
<td>(2.388 \times 10^{-6})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both Wings</td>
<td>(8.847 \times 10^{-6})</td>
<td>(2.499 \times 10^{-6})</td>
<td>2.06%</td>
<td>4.84%</td>
</tr>
<tr>
<td>Wings-Body</td>
<td>(8.664 \times 10^{-6})</td>
<td>(2.377 \times 10^{-6})</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Average aerodynamic force comparison for three models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean Fz ([\text{N}])</th>
<th>Weight support ([\text{kg}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-Wing</td>
<td>(1.7818 \times 10^{-5})</td>
<td>(1.8163 \times 10^{-6})</td>
</tr>
<tr>
<td>Wings-body</td>
<td>(1.7694 \times 10^{-5})</td>
<td>(1.8036 \times 10^{-6})</td>
</tr>
<tr>
<td>Both-Wings model</td>
<td>(1.7694 \times 10^{-5})</td>
<td>(1.8036 \times 10^{-6})</td>
</tr>
<tr>
<td>Wings-Body model</td>
<td>(1.7320 \times 10^{-5})</td>
<td>(1.7635 \times 10^{-6})</td>
</tr>
</tbody>
</table>

Table 4.3: Total mean vertical force produced by all models.
Figure 4.30: Normalised instantaneous vertical force over left wing for three models.

Figure 4.31: Normalised instantaneous horizontal force over left wing for three models.
4.10. Total Forces and Pressure Distribution

Figure 4.32: Pressure distribution over the wings and body for different models during mid downstroke ($t/T = 0.3$).

Figure 4.33: Pressure distribution over the wings and body for different models during mid-upstroke ($t/T = 0.8$).
4.11. COMPARISON OF VORTEX STRUCTURES

Figures 4.34-4.37 show the Q criterion (equal to 1E+07) iso-surfaces for 4 stages of the wing beat cycle. In these figures, top left image shows the result from Single-Wing model, top right image shows the result from Both-Wings model and bottom left image shows the result from Wings-Body model. The color on the iso-surface shows the Z (downward) velocity. The bottom right image shows orientation of the wings and the body.

As observed in the plots, the differences observed between all three models, in vortex structures, is quite small. Firstly, consider the Single wing and Both-Wings model. During the whole course of the wingbeat, there is nearly perfect match in the vortex structures. The velocities over the vortex structures also comparable. Any minor changes are attributed to the grid resolution dependency which may change for different models. This is also in agreement with the forces since the difference in mean force is observed to be below 1%.

When the Single-Wing model or Both-Wings model is compared with the Wings-Body model, slight differences are observed in the vortex structures. These differences exist in the wake (below the wings) of the flow field. Due to absence of the body, the shed root vortex and trailing edge vortex are slightly more elongated in the Both-Wings model.

Figure 4.38 shows the downward velocity in a slice mid way along the body during mid-upstroke. This figure is at t/T = 0.8. As seen in this figure, the downward velocity, below the body, is larger in the Both-Wings model when compared to the Wings-Body model. Due to the presence of the body, the air below the body attains lower velocities than without it. The higher velocities, due to the absence of body, results in elongated downwash pool when compared to Wings-body model.
Figure 4.34: Iso-surface (Q criterion) during mid upstroke. [Top left] Single Wing model, [Top right] Both-Wings model, [Bottom right] Wings-Body model and [Bottom right] Orientation of wings and body.
Figure 4.35: Iso-surface (Q criterion) during mid pronation. [Top left] Single Wing model, [Top right] Both-Wings model, [Bottom right] Wings-Body model and [Bottom right] Orientation of wings and body.
4.12. LEV AND ITS OCCURRENCE

SPANWISE FLOW:

As mentioned in the literature review, the reason for an attached LEV maybe due to the spanwise momentum inside the LEV. This restricts the growth of the LEV and hence does not let it shed [24][25]. The presence of a spanwise flow is considered to be due to the spanwise pressure gradient. To analyse this hypothesis, the spanwise velocity contour, at two positions along wing, were observed. Figure 4.39 shows the velocity in Y direction mid-stroke and mid-downstroke. At these positions, the wing is almost aligned with the inertial Y axis. Therefore, these contours are a good representation of the spanwise flow.
velocity.

Figure 4.39: Spanwise velocity contours at mid-upstroke and mid-downstroke. Top image shows the spanwise velocity mid downstroke and bottom image shows the same for upstroke at two spanwise locations (0.42c and 0.5c). The spanwise velocities are observed to lower in magnitude in the core of the LEV when compared to the spanwise velocities at the TE.

As seen from the contour, the spanwise velocity at the LE is almost negligible when compared to the spanwise velocity at the TE. This is in agreement with the results obtained by Aono et al. [26] for low Re insect flight. Aono et al. [26] observed that the spanwise velocity is negligible for low Re (~ 100) insect flight such as fruitfly. Relatively large velocities were found in the mid section and TE. The spanwise velocities observed in the fruitfly model account to nearly 2-5% of the average tip velocity [20]. For hawkmoth flight (high Re~2000), the spanwise velocities were comparable with that of the average tip velocities [25]. In mosquito flight, the spanwise flow in the core of the LEV is approximately observed to be 5-10% of the average tip velocity. This is considered to be low when compared to the velocities observed at the TE.

Effect of Downwash:

Another hypothesis, which is considered to the reason for an attached LEV is the effect of the downwash on the LEV. As suggested by Birch and Dickinson [35], the downwash may have a potent inhibitory effect on LEV by reducing the aerodynamic angle of attack and
magnitude of force production. To check this, the change in the lift force for the second, until fifth WB was computed. This is previously shown in the figure 4.1. Since the first WB is sine-damped, it cannot be considered in the analysis. A difference of 2.5% was observed in the mean lift force per WB in between second and third WB. This reduces further (with an advancement of WBs) to lower magnitudes (0.5% difference in between third and fourth) in subsequent WB. Since the initial conditions, in the computational domain, is described as static air. The changes in the aerodynamic forces are considered to be the influence of the downwash. Therefore, this analysis indicates that the downwash has an influence over the lift production resulting in a reduced lift force. However, its direct influence on the LEV cannot be commented upon.

ROSSBY NUMBER:

A more detailed study, considering the influence of rotational accelerations on the attachment of LEV, was done by Lentink and Dickinson [69]. Three parameters are considered to govern the LEV dynamics. These are centripetal ($a_{cen}$), Coriolis ($a_{cor}$) and angular accelerations ($a_{ang}$). If $a_{inert}$ is the dimensionless fluid acceleration due to aerodynamic forces, it is related to rotating frame acceleration ‘$a_{rot}$’ by equation 4.1 [69]. Here $Ro$ and $A^*$ are Rossby number and dimensionless stroke amplitude respectively. It was found that the stable attachment of the LEV is governed by the centripetal and Coriolis accelerations which are, in-turn a function of the Rossby number [69]. Low values of $Ro$ indicate large centripetal and Coriolis acceleration. Rossby number is equal to the ratio of the radius of gyration to the mean aerodynamic chord ($R_g/c$) or simply ratio of wing tip radius to mean aerodynamic chord ($R/c$) for revolving wing [69]. Therefore, the $Ro$ number is infinite for the translating wing and finite for a revolving wing. Lentink and Dickinson [69] analysed the stable attachment of the LEV when the $Ro$ was changed and found that the LEV is unstable and detaches for large $Ro$ (low centripetal and Coriolis accelerations), with infinite $Ro$ (translating wing) being the limiting case. However, it remains attached for low values of the $Ro$ (large centripetal and Coriolis accelerations). The transition is considered to occur at very large magnitudes of $Ro$ number.

$$a_{inert} = a_{rot} + (a_{ang} + a_{cen} + a_{cor}) \quad (4.1)$$

Where,

$$a_{ang} = \frac{1}{A^*} \Omega \times r \quad a_{cen} = \frac{1}{Ro} \Omega \times \Omega \times r \quad a_{cor} = \frac{1}{Ro} \cdot 2\Omega \times \mathbf{u_{rot}} \quad (4.2)$$

Based on the dimension of the mosquito wing, the $Ro$ number is calculated to be 6. Since an attached LEV is observed in the mosquito flight, $Ro$ number of 6 is considered to be low enough to obtain large centripetal and Coriolis accelerations (to obtain an attached LEV). Therefore, the attachment of the leading edge vortex is considered to be either due to the effect of downwash or large centripetal and Coriolis accelerations.
5

CONCLUSIONS AND FUTURE RECOMMENDATIONS

In this project, a computation model is used to obtain aerodynamic insight into the mosquito (Anopheles coluzzii) flight. ReFRESCO flow solver is used to perform the computations using the deforming grid mechanism. Firstly, single wing model is simulated and the near/far field flow is analyzed by visualizing the change in iso-surfaces (Q criterion). Then the transient forces, over the wing, are analyzed by considering the pressure distributions and flow visualizations. Furthermore, Both-wings and Wings-body model are simulated. The transient forces, mean forces, iso-surface (Q-criterion) and pressure distribution over the wings and body are studied for all three models. Based on the results obtained, the research questions (mentioned in 2.5.1) are answered next. Subsequently, future recommendations are provided.

5.1. CONCLUSIONS AND BRIEF DISCUSSION

QUESTION 1:

Can the adopted CFD model be successfully compared with the results from WUR and what is the estimated uncertainty?

Since the numerical uncertainty in the WUR simulation results is not known, results cannot be compared with successfully. However, general comparison (without uncertainty) is done. The current result shows good similarity with the WUR simulations. Also, the current model supports the weight of the mosquito. The answer to this question is elaborated further (by answering sub-questions) and discussed in brief.
1. Does the mean vertical force (per wingbeat) support the estimated weight of the mosquito?

The weight supported by Single-Wing model is obtained to be $1.8163 \times 10^{-6}$ kg. The estimated weight of the mosquito is $1.23 \pm 0.65 \times 10^{-6}$ kg. Based on the results obtained, the mean vertical force per wing-beat cycle lies within the standard deviation of the weight estimation of the mosquito. Hence the current model supports the weight of the mosquito. However, considering the average estimated weight, the current model overestimates the weight by 47%. The reason for overestimation may be due to the wing thickness, flexibility, influence of other body parts such as legs, proboscis or overestimation of surface area of the wing. Wing thickness is unknown and assumed to be 3%. Since simulation results from WUR (performed with 0% wing thickness) also overestimates the mean vertical force by nearly same value, the wing thickness is considered to be a negligible factor within the range considered (0%-3%).

2. Do the transient forces (from current simulations) match the same from WUR simulations?

The comparison of the transient aerodynamic forces, obtained from current simulations, is in good agreement with the simulation results provided by WUR with small discrepancies in the force peaks. The discrepancies are considered to be due to the thickness of the wing (which differs in both cases) and numerical error. Since the numerical uncertainty for the WUR results is not determined, the comparison has its limitations.

3. Can the solution be refined in order to reduce the errors due to spatial and time step discretization? What is the uncertainty in mean aerodynamic forces and vortex structures due to numerical method?

Yes, the solution can be refined in order to reduce the errors due to grid and time step spacing. Based on the results obtained, the uncertainty in the mean aerodynamic forces, for coarse mesh and time-step sizes, were observed to be higher than 10%. By decreasing the grid spacing and time step spacing, this was brought down to below 2% for fine meshes with 400 time steps per wing-beat. The numerical uncertainty can be reduced further but due to practical and time limitations, the solution for fine grid were considered for post processing. The uncertainty in the vortex structures is found to be nearly 4.5% or lower in all three models.

**Question 2:**

What is the change in vortex dynamics, transient forces and pressure distribution, over the mosquito wing, during the wing beat cycle. Is the vortex dynamics, transient forces and pressure distribution, over the wing, influenced by wing-wing, wing-body interaction?

1. What is the change in the vortex dynamics, transient forces and pressure distribution with respect to non-dimensional time for a single wing?
Considering the transient forces and the vortex dynamics, it is quite clear that the flow is highly unsteady since the forces and vortices change significantly with respect to time. From the far-field flow visualisations, a large D-ring vortex structure is observed during the upstroke. This is the most robust structure throughout the wing beat cycle with a strong downwash in the center. It connects the LEV, TV, shed TEV and RV. Similar vortex structure is also visible during the end of downstroke but it is comparatively weaker and breaks down in a small interval. The downwash pool, within the D-ring vortex structure, is observed to sustain throughout the wing beat cycle with change in its orientation and velocity inside it.

The LEV, observed over the wings of mosquito, is conical in shape with a small spanwise flow inside it. The LEV shows no signs of breakdown, along the span of the wing, during the wingbeat cycle. The presence of the LEV augments the lift and drag force by creating larger pressure difference between the top and the bottom surface.

Considering the transient forces, it can be concluded that the thrust of the flight is produced during the upstroke and drag is produced during the downstroke. The net thrust generated during the wing-beat cycle is $2.52 \pm 0.04 \times 10^{-6}$ N. The majority of the lift force is generated in the upstroke (approximately 63% of the mean lift) whereas the downstroke produces lower lift (approximately 37% of the mean lift). The net vertical force generated during the complete wingbeat cycle, by a single wing, is $8.909 \pm 0.147 \times 10^{-6}$ N.

The pressure contours over the wing surfaces show a large negative pressure region on the top surface and a positive pressure on the bottom surface (in most part of wingbeat cycle) resulting in a net upward force on the wing. The pressure contours over the wing suggest that the LEV has a direct influence on the net force generation during large translation motions and small rotational motions (about the spanwise axis). The growth of LEV due to an increase in translational velocity creates a further decrease in pressure, on the top surface of the wing, resulting in greater pressure difference.

Contrary to the translational motion, LEV does not have large influence over the aerodynamic forces during stroke reversals (large rotational motions about spanwise axis). The forces during the stroke reversal are largely dominated by rotational unsteady mechanisms. During the initial part of the stroke reversal, the pitching up motion, of the wing, results in larger pressure gradients in the lower part of the wing (near TE). During the second part of stroke reversal, the sudden acceleration of the wing results in larger pressure gradients over the top part of the wing (near LE). These wing motions result in the generation of force peaks during the stroke reversal.

2. What is the change in the vortex dynamics, transient forces and pressure distribution due to wing-wing and wing-body interaction?

The effect of wing-wing interaction is observed to be very low on the transient forces and mean aerodynamic forces (below 1%). Considering the presented uncertainty estimation (table 3.7), the low influence of wing-wing interaction cannot
be proven. The largest differences were observed in the force peaks. The change in the transient forces was observed to be higher when the body was added. A difference of nearly 2.82% in mean vertical force and 5.32% in mean horizontal force was observed. Forces over body are a consequence of induced velocities from the circulation over wing and in wake. However, Body actively contributes to 0.2% \((-2.14 \times 10^{-08} \text{ N})\) and 0.9% \((2.05 \times 10^{-08} \text{ N})\) in mean vertical and horizontal forces respectively. The active contribution of body is due to the induced flow velocities from the circulations over the wings and in the wake. Therefore, the change in the forces over the wing due to the presence of the body is greater than the active force contribution of the body. The largest pressure gradients over body is observed to be in the mid-thorax-abdomen region, caused by the large velocities in the downwash pool. However, as mentioned previously, the active contribution of body still remains small. The weight support, in between three models, is observed to change by nearly 2%.

The differences in the vortex dynamics and pressure contours, between the Single-Wing and Both-wings model, are observed to be negligible in the wing swept region. The vortex core positions, iso-surfaces of the Q-criterion and the pressure distribution over the wings showed negligible differences between the three models. However, small differences were observed in the wake (below the wings). The shed vortices are observed to be slightly elongated in the Single Wing/Both-Wings model, compared to the Wings-body model. Also, the velocities in the wake, in the absence of the body are also observed to be slightly higher.

The present study shows that the effect of wing-wing and wing-body interaction is low for a hovering/slow-speed mosquito (unfed) flight. Therefore, any further study of hovering mosquito \((Anopheles coluzzii)\) can be considered by studying the aerodynamics of a single wing. However, the results can significantly differ with change in forward speed, flight phase such as landing, take-off and sudden maneuvers.

5.2. Future work

Recommendations for the future work are as follows:

1. Influence of wing flexibility:

Insect wings are usually highly flexible. In addition, presence of large number of veins makes the wing structural properties anisotropic [1]. The variation of the flexibility and venation in spanwise and chord wise direction determine the change in the LEV stability and hence the net aerodynamic forces [1]. While some researchers [54] have obtained an increase in aerodynamic efficiency (Larger lift to drag ratio) due to wing flexibility, others [70] have obtained a negligible effect or detrimental effect. Due to the complexity involved in obtaining the directional structural properties of the wing and lack of wing/body structural data, the influence of the wing flexibility cannot be commented upon in this project. This can be
studied by obtaining material properties of the wing/body and performing simulations by including fluid-structure interaction.

2. Experimental tests of the same: Although, good confidence is established for the results generated in the current project by performing weight support check, comparing with simulation results from WUR and uncertainty estimation. Further confidence, in results, can be achieved by performing experimental tests with tethered flight or mechanical model by maintaining the same Reynolds number and reduced frequency.

3. The effect of change in morphology and kinematics:
   Since the morphology considered in the current project is taken from a single mosquito, the influence of the change in morphology such as the wing length, mean aerodynamic chord and wing thickness has to be studied further. In addition to that, the morphology (of body not wings) and kinematics (of wings and body) of the fed mosquito differs considerably with respect to unfed mosquito. Therefore, the same analysis (as done in this project) can be performed for a fed mosquito and compared with the current results.

4. Investigation of the unsteady mechanisms during wing flip:
   In the current project, various unsteady mechanisms such as rotational lift, rapid pitch up, wake-capture and sudden acceleration of the wing are briefly discussed. The quantitative study of these unsteady mechanisms has not been carried out in the current project and past research (to author’s best knowledge). The unsteady mechanisms, used by mosquito, can be studied with greater depth in the future. To illustrate, the rotational accelerations, in the wing reference frame, can be computed to study the rapid pitch-up mechanism and sudden acceleration.

5. Influence of wing-body offset:
   It is clear that the aerodynamic influence of the wing-body offset (distance between wing root and body) is negligible with the range considered in this project. The original distance can be simulated by excluding a small portion of wing root to increase the distance between the wing root and body. This may result in a larger difference than the difference observed in current implementation (1%). However, it can be studied with more detail.
BIBLIOGRAPHY


APPENDIX

A.1. **Kinematics and Coefficients**

The kinematics of the wing, given by the equations 1.1-1.3 previously, are derived from steady and mod parameters given by equations A.1-A.6. Here, the parameters with subscripts (steady,n,mod,n) are coefficients obtained by experimental tests. Final Euler angles are obtained from these parameters given by equations A.7-A.9. Here modd and fmod define the type of mosquito (fed \ unfed \ partially fed). For the current project, unfed mosquito is considered and the values for mod and fmod are 1 and 1.04652046920986 respectively.

\[
\phi_{\text{steady}}(t) = \sum_{n=0}^{7} \left[ \phi_{\text{steady},cn} \cos(2n\pi ft) + \phi_{\text{steady},sn} \sin(2n\pi ft) \right] \quad (A.1)
\]

\[
\theta_{\text{steady}}(t) = \sum_{n=0}^{7} \left[ \theta_{\text{steady},cn} \cos(2n\pi ft) + \theta_{\text{steady},sn} \sin(2n\pi ft) \right] \quad (A.2)
\]

\[
\gamma_{\text{steady}}(t) = \sum_{n=0}^{4} \left[ \gamma_{\text{steady},cn} \cos(2n\pi ft) + \gamma_{\text{steady},sn} \sin(2n\pi ft) \right] \quad (A.3)
\]

\[
\phi_{\text{mod}}(t) = \sum_{n=0}^{7} \left[ \phi_{\text{mod},cn} \cos(2n\pi ft) + \phi_{\text{mod},sn} \sin(2n\pi ft) \right] \quad (A.4)
\]

\[
\theta_{\text{mod}}(t) = \sum_{n=0}^{7} \left[ \theta_{\text{mod},cn} \cos(2n\pi ft) + \theta_{\text{mod},sn} \sin(2n\pi ft) \right] \quad (A.5)
\]

\[
\gamma_{\text{mod}}(t) = \sum_{n=0}^{7} \left[ \gamma_{\text{mod},cn} \cos(2n\pi ft) + \gamma_{\text{mod},sn} \sin(2n\pi ft) \right] \quad (A.6)
\]
\[
\phi(t) = \phi_{steady} + ((modd - f mod) \cdot \phi_{mod}) \quad (A.7)
\]
\[
\theta(t) = \theta_{steady} + ((modd - f mod) \cdot \theta_{mod}) \quad (A.8)
\]
\[
\gamma(t) = \gamma_{steady} + ((modd - f mod) \cdot \gamma_{mod}) \quad (A.9)
\]

The angular velocities, as a function of the time step, are obtained by taking the derivatives of the Fourier terms. These are given by the equation below:

\[
\omega_{\phi,steady}(t) = \sum_{n=0}^{7} [2n\pi f \left( -\phi_{steady,cn \sin(2n\pi ft)} + \phi_{steady,sn \cos(2n\pi ft)} \right)] \quad (A.10)
\]
\[
\omega_{\theta,steady}(t) = \sum_{n=0}^{7} [2n\pi f \left( -\theta_{steady,cn \sin(2n\pi ft)} + \theta_{steady,sn \cos(2n\pi ft)} \right)] \quad (A.11)
\]
\[
\omega_{\gamma,steady}(t) = \sum_{n=0}^{7} [2n\pi f \left( -\gamma_{steady,cn \sin(2n\pi ft)} + \gamma_{steady,sn \cos(2n\pi ft)} \right)] \quad (A.12)
\]
\[
\omega_{\phi,mod}(t) = \sum_{n=0}^{7} [2n\pi f \left( -\phi_{mod,cn \sin(2n\pi ft)} + \phi_{mod,sn \cos(2n\pi ft)} \right)] \quad (A.13)
\]
\[
\omega_{\theta,mod}(t) = \sum_{n=0}^{7} [2n\pi f \left( -\theta_{mod,cn \sin(2n\pi ft)} + \theta_{mod,sn \cos(2n\pi ft)} \right)] \quad (A.14)
\]
\[
\omega_{\gamma,mod}(t) = \sum_{n=0}^{7} [2n\pi f \left( -\gamma_{mod,cn \sin(2n\pi ft)} + \gamma_{mod,sn \cos(2n\pi ft)} \right)] \quad (A.15)
\]
\[
\omega_{\phi}(t) = \omega_{\phi,steady} + ((modd - f mod) \cdot \omega_{\phi,mod}) \quad (A.16)
\]
\[
\omega_{\theta}(t) = \omega_{\theta,steady} + ((modd - f mod) \cdot \omega_{\theta,mod}) \quad (A.17)
\]
\[
\omega_{\gamma}(t) = \omega_{\gamma,steady} + ((modd - f mod) \cdot \omega_{\gamma,mod}) \quad (A.18)
\]
A.2. USER CODES:

A.2.1. SETDEFORM.F90 USER ROUTINE

!* *************************************************************
!*     User−defined module for defining deforming−grid motions
!*     Maritime Research Institute of Netherlands (MARIN)
!*     ReFRESCO
!*     $Id: set_deformgrid.F90.xml 4114 2016−04−06 13:09:52Z gvaz@MARIN.LOCAL $
!*     Maintainer: Douwe Rijpkema
!*     Level: Infrastructure/User−defined−routines
!*     (c) 2005−2016 MARIN
!*     Proprietary data. Unauthorized use, distribution, or duplication is prohibited. All rights reserved.
!*<
!* *******************************************************

MODULE set_deformgrid

USE controls
USE controls_parameters
USE boundaries_controls
USE fielddata
USE geometry
USE logging
USE octrees
USE imposedmotion
USE parameters
USE parallel
USE topology
USE tracing
USE math

IMPLICIT NONE

PRIVATE

INTEGER, PRIVATE :: nAllCells, nIntCells, NBndCells, nIntFaces, nBndFaces, nfamilies, & nsubGrids, nVertices

INTEGER, POINTER :: family_f(:,), cell2_f(:)
REAL(dp), POINTER :: coord_v_3(:,,:), v_c_3(:,,:), cent_c_3(:,)
REAL(dp), ALLOCATABLE :: coordinates_at_start_v_3(:,)

PUBLIC set_deformgrid_initial,&
set_deformgrid_init3,&
set_deformgrid_init4,&
set_deformgrid_init5,&
set_deformgrid_restart,&
set_deformgrid_timestep,&
set_deformgrid_outit,&
set_deformgrid_final,&
set_deformgrid_exit!, &
! set_deformgrid_read_controls

CONTAINS

!! Use *_init5 module for all *_get_pointer statements
! ==============================================================
SUBROUTINE set_deformgrid_init5
! ==============================================================
INTEGER :: ier

CALL tracing_trace_begin (trace_set_deformgrid_init5)

CALL topology_get_size ( nAllCells = nAllCells , &
                        nIntCells = nIntCells , &
                        NBndCells = NBndCells,&
                        nIntFaces = nIntFaces,&
                        nBndFaces = nBndFaces,&
                        nsubGrids = nsubGrids,&
                        nfamilies = nfamilies,&
                        nVertices=nVertices )

CALL fielddata_get_pointer ("Velocity", Field_3 = v_c_3)

CALL topology_get_pointer(family_f = family_f ,&
                        cell2_f = cell2_f)

CALL geometry_get_pointer(coord_v_3 = coord_v_3,&
                        cent_c_3 = cent_c_3)

ALLOCATE(coordinates_at_start_v_3 (nVertices ,3) , STAT=ier)
IF ( ier/=0) CALL tracing_abort_allocate_failed
coordinates_at_start_v_3 = coord_v_3

CALL tracing_trace_end (trace_set_deformgrid_init5)

END SUBROUTINE set_deformgrid_init5

!! This routine is executed at each timestep
! ==============================================================
SUBROUTINE set_deformgrid_timestep (timestep , simultime, periodicTimestep)
! ==============================================================
INTEGER, INTENT(IN) :: timestep
REAL(dp), INTENT(IN) :: simultime
INTEGER, INTENT(OUT) :: periodicTimestep
REAL(dp) :: Mult, dt
INTEGER :: ier
INTEGER :: iVertex, iFace, nVerticesFamily, iFamily, i2
INTEGER, ALLOCATABLE :: verticesFamily(:)
REAL(dp) :: gama, gama_mod, phi, phi_mod, theta, theta_mod, frequency
REAL(dp) :: amplitude, SinDamp, SinDampDer, modd, fmod
REAL(dp) :: gama_steady, phi_steady, theta_steady
REAL(dp) :: A(3,3), B(3,3), C(3,3), ABC(3,3), origin_3(3), dx, dy, dz
REAL(dp) :: origin_3 = (/0.0d0, 0.0d0, 0.0d0/)

CALL tracing_trace_begin(trace_set_deformgrid_timestep)

frequency = 575.669135
Mult = frequency*(simultime - (simultime/timestep))
amplitude = \pi/8
modd = 1.0;
fmod = 1.04652046920986;

! deviation angle
theta\_steady = (devA(1) + devA(2)\cdot\cos(2\cdot1\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{devB}(1)\cdot\sin(2\cdot1\cdot\pi\cdot{\text{Mult}}) + devA(3)\cdot\cos(2\cdot2\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{devB}(2)\cdot\sin(2\cdot2\cdot\pi\cdot{\text{Mult}}) + devA(4)\cdot\cos(2\cdot3\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{devB}(3)\cdot\sin(2\cdot3\cdot\pi\cdot{\text{Mult}}) + devA(5)\cdot\cos(2\cdot4\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{devB}(4)\cdot\sin(2\cdot4\cdot\pi\cdot{\text{Mult}}) + devA(6)\cdot\cos(2\cdot5\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{devB}(5)\cdot\sin(2\cdot5\cdot\pi\cdot{\text{Mult}}) + devA(7)\cdot\cos(2\cdot6\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{devB}(6)\cdot\sin(2\cdot6\cdot\pi\cdot{\text{Mult}})) \cdot (\pi/180)
theta\_mod = (devA\_mod(1) + devA\_mod(2)\cdot\cos(2\cdot1\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{devB}\_mod(1)\cdot\sin(2\cdot1\cdot\pi\cdot{\text{Mult}}) + devA\_mod(3)\cdot\cos(2\cdot2\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{devB}\_mod(2)\cdot\sin(2\cdot2\cdot\pi\cdot{\text{Mult}}) + devA\_mod(4)\cdot\cos(2\cdot3\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{devB}\_mod(3)\cdot\sin(2\cdot3\cdot\pi\cdot{\text{Mult}}) + devA\_mod(5)\cdot\cos(2\cdot4\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{devB}\_mod(4)\cdot\sin(2\cdot4\cdot\pi\cdot{\text{Mult}}) + devA\_mod(6)\cdot\cos(2\cdot5\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{devB}\_mod(5)\cdot\sin(2\cdot5\cdot\pi\cdot{\text{Mult}}) + devA\_mod(7)\cdot\cos(2\cdot6\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{devB}\_mod(6)\cdot\sin(2\cdot6\cdot\pi\cdot{\text{Mult}})) \cdot (\pi/180)
theta = theta\_steady + ( (modd - fmod) \cdot theta\_mod )

! stroke/position angle
gama\_steady = (stroA(1) + stroA(2)\cdot\cos(2\cdot1\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{stroB}(1)\cdot\sin(2\cdot1\cdot\pi\cdot{\text{Mult}}) + stroA(3)\cdot\cos(2\cdot2\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{stroB}(2)\cdot\sin(2\cdot2\cdot\pi\cdot{\text{Mult}}) + stroA(4)\cdot\cos(2\cdot3\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{stroB}(3)\cdot\sin(2\cdot3\cdot\pi\cdot{\text{Mult}}) + stroA(5)\cdot\cos(2\cdot4\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{stroB}(4)\cdot\sin(2\cdot4\cdot\pi\cdot{\text{Mult}}) + stroA(6)\cdot\cos(2\cdot5\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{stroB}(5)\cdot\sin(2\cdot5\cdot\pi\cdot{\text{Mult}}) + stroA(7)\cdot\cos(2\cdot6\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{stroB}(6)\cdot\sin(2\cdot6\cdot\pi\cdot{\text{Mult}})) \cdot (\pi/180)
gama\_mod = (stroA\_mod(1) + stroA\_mod(2)\cdot\cos(2\cdot1\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{stroB}\_mod(1)\cdot\sin(2\cdot1\cdot\pi\cdot{\text{Mult}}) + stroA\_mod(3)\cdot\cos(2\cdot2\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{stroB}\_mod(2)\cdot\sin(2\cdot2\cdot\pi\cdot{\text{Mult}}) + stroA\_mod(4)\cdot\cos(2\cdot3\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{stroB}\_mod(3)\cdot\sin(2\cdot3\cdot\pi\cdot{\text{Mult}}) + stroA\_mod(5)\cdot\cos(2\cdot4\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{stroB}\_mod(4)\cdot\sin(2\cdot4\cdot\pi\cdot{\text{Mult}}) + stroA\_mod(6)\cdot\cos(2\cdot5\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{stroB}\_mod(5)\cdot\sin(2\cdot5\cdot\pi\cdot{\text{Mult}}) + stroA\_mod(7)\cdot\cos(2\cdot6\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{stroB}\_mod(6)\cdot\sin(2\cdot6\cdot\pi\cdot{\text{Mult}})) \cdot (\pi/180)
gama = gama\_steady + ((modd-fmod)\cdot gama\_mod)

! pitch, rotation
phi\_steady = (picA(1) + picA(2)\cdot\cos(2\cdot1\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{picB}(1)\cdot\sin(2\cdot1\cdot\pi\cdot{\text{Mult}}) + picA(3)\cdot\cos(2\cdot2\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{picB}(2)\cdot\sin(2\cdot2\cdot\pi\cdot{\text{Mult}}) + picA(4)\cdot\cos(2\cdot3\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{picB}(3)\cdot\sin(2\cdot3\cdot\pi\cdot{\text{Mult}}) + picA(5)\cdot\cos(2\cdot4\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{picB}(4)\cdot\sin(2\cdot4\cdot\pi\cdot{\text{Mult}}) + picA(6)\cdot\cos(2\cdot5\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{picB}(5)\cdot\sin(2\cdot5\cdot\pi\cdot{\text{Mult}}) + picA(7)\cdot\cos(2\cdot6\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{picB}(6)\cdot\sin(2\cdot6\cdot\pi\cdot{\text{Mult}})) \cdot (\pi/180)
phi\_mod = (picA\_mod(1) + picA\_mod(2)\cdot\cos(2\cdot1\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{picB}\_mod(1)\cdot\sin(2\cdot1\cdot\pi\cdot{\text{Mult}}) + picA\_mod(3)\cdot\cos(2\cdot2\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{picB}\_mod(2)\cdot\sin(2\cdot2\cdot\pi\cdot{\text{Mult}}) + picA\_mod(4)\cdot\cos(2\cdot3\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{picB}\_mod(3)\cdot\sin(2\cdot3\cdot\pi\cdot{\text{Mult}}) + picA\_mod(5)\cdot\cos(2\cdot4\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{picB}\_mod(4)\cdot\sin(2\cdot4\cdot\pi\cdot{\text{Mult}}) + picA\_mod(6)\cdot\cos(2\cdot5\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{picB}\_mod(5)\cdot\sin(2\cdot5\cdot\pi\cdot{\text{Mult}}) + picA\_mod(7)\cdot\cos(2\cdot6\cdot\pi\cdot{\text{Mult}}) + &
\quad\text{picB}\_mod(6)\cdot\sin(2\cdot6\cdot\pi\cdot{\text{Mult}})) \cdot (\pi/180)
phi = phi\_steady + ((modd-fmod)\cdot phi\_mod)

! start up, for smoother deformation at the start
A.2. USER CODES:

periodicTimestep = 0
IF (simultime < 0.999d0/frequency) THEN
  imposedMotionDeformGridRead = .FALSE.
  imposedMotionDeformGridSave = .FALSE.
  SinDamp = 0.5*(1+(SIN((3*pi/2)+(pi*simultime/0.173710893E-02))))
  SinDampDer = 0.5*frequency*pi*COS((3*pi/2)+(pi*simultime/0.173710893E-02))
ELSE IF (simultime < 1.999d0/frequency) THEN
  imposedMotionDeformGridRead = .FALSE.
  imposedMotionDeformGridSave = .TRUE.
  SinDamp = 1.d0
  SinDampDer = 0.d0
ELSE
  dt = simultime/timestep
  periodicTimestep = NINT((simultime − INT(frequency*(simultime−1/frequency+dt/10))/ & frequency)/dt)
  imposedMotionDeformGridRead = .TRUE.
  imposedMotionDeformGridSave = .FALSE.
  SinDamp = 1.d0
  SinDampDer = 0.d0
END IF

A(1,1:3) = (/ COS(phi*SinDamp), 0.0d0, SIN(phi*SinDamp) /)
A(2,1:3) = (/ 0.0d0, 1.0d0, 0.0d0 /)
A(3,1:3) = (/ −SIN(phi*SinDamp), 0.0d0, COS(phi*SinDamp) /)
B(1,1:3) = (/ COS(gama*SinDamp), −SIN(gama*SinDamp), 0.0d0 /)
B(2,1:3) = (/ SIN(gama*SinDamp), COS(gama*SinDamp), 0.0d0 /)
B(3,1:3) = (/ 0.0d0, 0.0d0, 1.0d0 /)
C(1,1:3) = (/ 1.0d0, 0.0d0, 0.0d0 /)
C(2,1:3) = (/ 0.0d0, COS(theta*SinDamp), −SIN(theta*SinDamp) /)
C(3,1:3) = (/ 0.0d0, SIN(theta*SinDamp), COS(theta*SinDamp) /)

ABC = B . times . C . times . A

! number of vertices for a family
iFamily = topology_get_ifamily("wing")
CALL topology_get_vertices_family(iFamily,nVerticesFamily)

! space for total number of vertices
ALLOCATE(verticesFamily(nVerticesFamily),STAT=ier)
IF (ier /=0) CALL tracing_abort_allocate_failed

! fill array
CALL topology_get_vertices_family(iFamily,nVerticesFamily,verticesFamily)

! Calc new coordinates
DO iVertex=1,nVerticesFamily
  dx = coordinates_at_start_v_3(verticesFamily(iVertex),1) − origin_3(1)
  dy = coordinates_at_start_v_3(verticesFamily(iVertex),2) − origin_3(2)
  dz = coordinates_at_start_v_3(verticesFamily(iVertex),3) − origin_3(3)
  coord_v_3(verticesFamily(iVertex),1) = ABC(1,1)*dx + ABC(1,2)*dy & + ABC(1,3)*dz + origin_3(1)
  coord_v_3(verticesFamily(iVertex),2) = ABC(2,1)*dx + ABC(2,2)*dy & + ABC(2,3)*dz + origin_3(2)
  coord_v_3(verticesFamily(iVertex),3) = ABC(3,1)*dx + ABC(3,2)*dy & + ABC(3,3)*dz + origin_3(3)
END DO

! remove space for total number of vertices
DEALLOCATE (verticesFamily, STAT=ier)
IF (ier /=0) CALL tracing_abort_deallocate_failed

CALL tracing_trace_end (trace_set_deformgrid_timestep)

END SUBROUTINE set_deformgrid_timestep

A.2.2. SETPHI.F90 USER ROUTINE

*******************************************************************************/
!/ User-defined module for setting up initial and boundary conditions
!/ Maritime Research Institute of Netherlands (MARIN)
!/ ReFRESCO
!/ $Id: set_phi.F90.xml 4114 2016-04-06 13:09:52Z gvaz@MARIN.LOCAL $  
!/ Maintainer: Douwe Rijpkema
!/ Level: Infrastructure/User-defined-routines
!/ (c) 2005–2016 MARIN
!/ Proprietary data. Unauthorized use, distribution, or duplication is prohibited. All rights reserved.
!/ !<
*******************************************************************************/
MODULE set_phi

USE boundaries_controls
USE controls
USE equations
USE equations_controls
USE fielddata
USE fielddata_tools
USE geometry
USE logging
USE math
USE parameters
USE topology
USE tracing
USE common_user_code
USE imposedmotion
IMPLICIT NONE

PRIVATE

INTEGER, PRIVATE :: nAllCells, nIntCells, NBndCells, nIntFaces, nBndFaces, nfamilies,&
nsubGrids, nVertices

INTEGER, POINTER :: family_f(:), cell2_f(:)
REAL(dp), POINTER :: coord_v_3(:, :), v_c_3(:, :), cent_c_3(:, :)
REAL(dp), ALLOCATABLE :: coordinates_at_start_v_3(:, :)

PUBLIC set_phi_initial,&
    set_phi_init3,&
    set_phi_init4,&
    set_phi_init5,&
    set_phi_restart,&
    set_phi_timestep,&
    set_phi_outit,&
    set_phi_final,&
    set_phi_exit, &
    set_phi_read_controls

! Use _init5 module for all *_get_pointer statements
!=====================================================================

SUBROUTINE set_phi_init5
!=====================================================================

INTEGER :: ier

CALL tracing_trace_begin(trace_set_phi_init5)

CALL topology_get_size( nAllCells = nAllCells, &
                        nIntCells = nIntCells, &
                        NBndCells = NBndCells,&
                        nIntFaces = nIntFaces,&
                        nBndFaces = nBndFaces,&
                        nfamilies = nfamilies,&
                        nVertices = nVertices)

CALL fielddata_get_pointer("Velocity",Field_3 = v_c_3)

CALL topology_get_pointer(family_f = family_f,&
                          cell2_f = cell2_f)

CALL geometry_get_pointer(coord_v_3 = coord_v_3,&
                          cent_c_3 = cent_c_3)

ALLOCATE(coordinates_at_start_v_3(nVertices, 3), STAT=ier)
IF (ier /= 0) CALL tracing_abort_allocate_failed
coordinates_at_start_v_3 = coord_v_3

CALL tracing_trace_end(trace_set_phi_init5)

END SUBROUTINE set_phi_init5

!! This routine is executed at each timestep
!====================================================================
SUBROUTINE set_phi_timestep ( timestep, simultime )
!====================================================================
INTEGER, INTENT(IN) :: timestep
REAL(dp), INTENT(IN) :: simultime
REAL(dp) :: omg_phi, omg_gama, omg_theta, Mult, dt
INTEGER :: ier
INTEGER :: iVertex, iFace, nVerticesFamily, iFamily, i2
INTEGER, ALLOCATABLE :: verticesFamily (:)
REAL(dp) :: gama,gama_mod, phi, phi_mod, theta, theta_mod, frequency, amplitude, SinDamp
REAL(dp) :: gama_steady, phi_steady, theta_steady, SinDampDer,modd, fmod
REAL(dp) :: omg_gama_steady ,omg_gama_mod, omg_phi_steady
REAL(dp) :: omg_phi_mod , omg_theta_steady , omg_theta_mod
REAL(dp) :: A(3,3),B(3,3),C(3,3),ABC(3,3), origin_3(3), BC(3,3)
REAL(dp), ALLOCATABLE :: coordFamily_v_3 (:,:)
REAL(dp), DIMENSION(7) :: devA,devA_mod, picA, picA_mod, stroA_mod
REAL(dp), DIMENSION(6) :: devB,devB_mod, picB, picB_mod, stroB_mod
REAL(dp), DIMENSION(5) :: stroA
REAL(dp), DIMENSION(4) :: stroB
REAL(dp), DIMENSION(3) :: omega,Ax,Ay,Az,Ax_2,Ay_2,Az_2

devA_mod = (/ 7.00636674487124, 7.192362354598, 1.97142801355316, &
0.0572802765167035, −0.447618074847220, −0.12356471460361, &
0.00177122491593233/)

devB_mod = (/−0.08332360748451, 1.904439262032, −0.630994239950691, &
0.0287547492368128, 0.0326898864906297, 0.0326580591574736/)
stroA_mod = (/ 1.15250516268454, 9.2416445173509, −1.38672302575132, &
−0.030751099903380, 0.062900658939178, −0.0246589204942970, &
0.0313656778216611/)
stroB_mod = (/ 2.40132707151998, −1.86625903755917, −0.193519343542198, &
0.0137595732376273, 0.0573128175641138, −0.024476391821700/)

picA_mod = (/ 14.55551832368363, −11.3817041507945, 7.46561205609220, &
−1.16851802770818, −0.908162247927480, −0.028404363232050, &
0.23503039700012/)

picB_mod = (/ 6.4609557376637, 7.77406075276894, −2.61798071394184, &
1.21021315331134, −0.712090950952092, 0.495737294445873/)

devA = (/ 12.600593239896, −1.05518801376655, 2.87685051192363, &
0.27951749139754, −0.0131297068264702, 0.045141589362862, &
0.048921251001799/)

devB = (/ 1.82769310741796, 0.761242291367827, −0.0873300532375979, &
−0.16903679787311, 0.016242614093394, −0.000671862910724079/)
stroA = (/ 4.64099540934589, 20.1133648275172, 0.26761728383553, &
A.2. USER CODES: 

\[ \text{stroB} = (\{-1.59319547414612, 0.453383511772053, -0.416351365654601, & -0.00258465457298127/\})\]

\[ \text{picA} = (\{91.8906847730657, 1.24095744080671, -0.428145158510778, & -4.05510115423453, -0.421582494380705, 0.0316851732367878, & -0.170914375937093/\})\]

\[ \text{picB} = (\{56.6143647462281, -3.99892033174505, 0.127052254030260, & -0.338401803360118, 0.809090710274975, -0.129890709745552/\})\]

CALL tracing_trace_begin (trace_set_phi_timestep)

frequency = 575.669135
Mult = frequency * (simultime - (simultime / timestep))
origin_3 = (0.0d0, 0.0d0, 0.0d0)
amplitude = pi/8
modd = 1.0;
flmod = 1.04652046920986;

!deviation angle

theta_steady = (devA(1) + devA(2)*COS(2*1*pi*Mult) + &
devB(1)*SIN(2*1*pi*Mult) + devA(3)*COS(2*2*pi*Mult) + &
devB(2)*SIN(2*2*pi*Mult) + devA(4)*COS(2*3*pi*Mult) + &
devB(3)*SIN(2*3*pi*Mult) + devA(5)*COS(2*4*pi*Mult) + &
devB(4)*SIN(2*4*pi*Mult) + devA(6)*COS(2*5*pi*Mult) + &
devB(5)*SIN(2*5*pi*Mult) + devA(7)*COS(2*6*pi*Mult) + &
devB(6)*SIN(2*6*pi*Mult)) * (pi/180)

theta_mod = (devA_mod(1) + devA_mod(2)*COS(2*1*pi*Mult) + &
devB_mod(1)*SIN(2*1*pi*Mult) + devA_mod(3)*COS(2*2*pi*Mult) + &
devB_mod(2)*SIN(2*2*pi*Mult) + devA_mod(4)*COS(2*3*pi*Mult) + &
devB_mod(3)*SIN(2*3*pi*Mult) + devA_mod(5)*COS(2*4*pi*Mult) + &
devB_mod(4)*SIN(2*4*pi*Mult) + devA_mod(6)*COS(2*5*pi*Mult) + &
devB_mod(5)*SIN(2*5*pi*Mult) + devA_mod(7)*COS(2*6*pi*Mult) + &
devB_mod(6)*SIN(2*6*pi*Mult)) * (pi/180)

theta = theta_steady + ((modd-fmod)*theta_mod)

!stroke / position angle

gama_steady = (stroA(1) + stroA(2)*COS(2*1*pi*Mult) + &
stroB(1)*SIN(2*1*pi*Mult) + stroA(3)*COS(2*2*pi*Mult) + &
stroB(2)*SIN(2*2*pi*Mult) + stroA(4)*COS(2*3*pi*Mult) + &
stroB(3)*SIN(2*3*pi*Mult) + stroA(5)*COS(2*4*pi*Mult) + &
stroB(4)*SIN(2*4*pi*Mult)) * (pi/180)

gama_mod = (stroA_mod(1) + stroA_mod(2)*COS(2*1*pi*Mult) + &
stroB_mod(1)*SIN(2*1*pi*Mult) + stroA_mod(3)*COS(2*2*pi*Mult) + &
stroB_mod(2)*SIN(2*2*pi*Mult) + stroA_mod(4)*COS(2*3*pi*Mult) + &
stroB_mod(3)*SIN(2*3*pi*Mult) + stroA_mod(5)*COS(2*4*pi*Mult) + &
stroB_mod(4)*SIN(2*4*pi*Mult) + stroA_mod(6)*COS(2*5*pi*Mult) + &
stroB_mod(5)*SIN(2*5*pi*Mult) + stroA_mod(7)*COS(2*6*pi*Mult) + &
stroB_mod(6)*SIN(2*6*pi*Mult)) * (pi/180)

gama = gama_steady + ((modd-fmod)*gama_mod)

!pitch, rotation

phi_steady = (picA(1) + picA(2)*COS(2*1*pi*Mult) + &
picB(1)*SIN(2*1*pi*Mult) + picA(3)*COS(2*2*pi*Mult) + &
**A. Appendix**

\[
\begin{align*}
\text{picB} (\pi/2) * \sin (2\pi \text{Mult}) &+ \text{picA} (4) * \cos (2\pi \text{Mult}) &+ \\
\text{picB} (3) * \sin (2\pi \text{Mult}) &+ \text{picA} (5) * \cos (2\pi \text{Mult}) &+ \\
\text{picB} (4) * \sin (2\pi \text{Mult}) &+ \text{picA} (6) * \cos (2\pi \text{Mult}) &+ \\
\text{picB} (5) * \sin (2\pi \text{Mult}) &+ \text{picA} (7) * \cos (2\pi \text{Mult}) &+ \\
\text{picB} (6) * \sin (2\pi \text{Mult}) &+ \text{picA} (8) * \cos (2\pi \text{Mult}) &+ \\
\end{align*}
\]

\[
\phi_{\text{mod}} = (\text{picA}_{\text{mod}} (1) + \text{picA}_{\text{mod}} (2) * \cos (2\pi \text{Mult}) &+ \\
\text{picB}_{\text{mod}} (1) * \sin (2\pi \text{Mult}) &+ \text{picA}_{\text{mod}} (3) * \cos (2\pi \text{Mult}) &+ \\
\text{picB}_{\text{mod}} (2) * \sin (2\pi \text{Mult}) &+ \text{picA}_{\text{mod}} (4) * \cos (2\pi \text{Mult}) &+ \\
\text{picB}_{\text{mod}} (3) * \sin (2\pi \text{Mult}) &+ \text{picA}_{\text{mod}} (5) * \cos (2\pi \text{Mult}) &+ \\
\text{picB}_{\text{mod}} (4) * \sin (2\pi \text{Mult}) &+ \text{picA}_{\text{mod}} (6) * \cos (2\pi \text{Mult}) &+ \\
\text{picB}_{\text{mod}} (5) * \sin (2\pi \text{Mult}) &+ \text{picA}_{\text{mod}} (7) * \cos (2\pi \text{Mult}) &+ \\
\text{picB}_{\text{mod}} (6) * \sin (2\pi \text{Mult}) &+ \text{picA}_{\text{mod}} (8) * \cos (2\pi \text{Mult}) &+ \\
\end{align*}
\]

\[
\phi = \phi_{\text{steady}} + \left( \left( \text{modd} - \text{fmod} \right) \times \phi_{\text{mod}} \right)
\]

**Start up, for smoother deformation at the start**

**IF** (simultime < 0.999d0/frequency) **THEN**

\[
\text{SinDamp} = 0.5 \times \left( 1 + \sin \left( 3 \pi /2 + \pi \times \text{simultime} / 0.173710893E-02 \right) \right)
\]

\[
\text{SinDampDer} = 0.5 \times \text{frequency} \times \pi \times \cos \left( 3 \pi /2 + \pi \times \text{simultime} / 0.173710893E-02 \right)
\]

**ELSE IF** (simultime < 1.999d0/frequency) **THEN**

\[
\text{SinDamp} = 1.0 \text{d0}
\]

\[
\text{SinDampDer} = 0.0 \text{d0}
\]

**ELSE**

\[
\text{dt} = \text{simultime} / \text{timestep}
\]

\[
\text{SinDamp} = 1.0 \text{d0}
\]

\[
\text{SinDampDer} = 0.0 \text{d0}
\]

**END IF**

\[
A(1,1:3) = (/ \cos (\text{phi} \times \text{SinDamp}), 0.0 \text{d0}, \sin (\text{phi} \times \text{SinDamp}) /)
\]

\[
A(2,1:3) = (/ 0.0 \text{d0}, 1.0 \text{d0}, 0.0 \text{d0} /)
\]

\[
A(3,1:3) = (/ -\sin (\text{phi} \times \text{SinDamp}), 0.0 \text{d0}, \cos (\text{phi} \times \text{SinDamp}) /)
\]

\[
B(1,1:3) = (/ \cos (\text{gama} \times \text{SinDamp}), -\sin (\text{gama} \times \text{SinDamp}), 0.0 \text{d0} /)
\]

\[
B(2,1:3) = (/ \sin (\text{gama} \times \text{SinDamp}), \cos (\text{gama} \times \text{SinDamp}), 0.0 \text{d0} /)
\]

\[
B(3,1:3) = (/ 0.0 \text{d0}, 0.0 \text{d0}, 1.0 \text{d0} /)
\]

\[
C(1,1:3) = (/ 1.0 \text{d0}, 0.0 \text{d0}, 0.0 \text{d0} /)
\]

\[
C(2,1:3) = (/ 0.0 \text{d0}, \cos (\theta \times \text{SinDamp}), -\sin (\theta \times \text{SinDamp}) /)
\]

\[
C(3,1:3) = (/ 0.0 \text{d0}, \sin (\theta \times \text{SinDamp}), \cos (\theta \times \text{SinDamp}) /)
\]

\[
\text{ABC} = B \times C \times A
\]

! number of vertices for a family

iFamily = topology_get_ifamily("wing")

**CALL** topology_get_vertices_family(iFamily, nVerticesFamily)

! Set velocity

! deviation angle velocity

\[
\text{omg}_\text{theta}_{\text{steady}} = 2 \pi \times \text{frequency} \times (-\text{devA} (2) \times 1 \times \sin (2 \pi \text{Mult}) &+ \\
\text{devB} (1) \times 1 \times \cos (2 \pi \text{Mult}) - \text{devA} (3) \times 2 \times \cos (2 \pi \text{Mult}) &+ \\
\text{devB} (2) \times 2 \times \cos (2 \pi \text{Mult}) - \text{devA} (4) \times 3 \times \sin (2 \pi \text{Mult}) &+ \\
\text{devB} (3) \times 3 \times \cos (2 \pi \text{Mult}) - \text{devA} (5) \times 4 \times \sin (2 \pi \text{Mult}) &+ \\
\text{devB} (4) \times 4 \times \cos (2 \pi \text{Mult}) - \text{devA} (6) \times 5 \times \sin (2 \pi \text{Mult}) &+ \\
\text{devB} (5) \times 5 \times \cos (2 \pi \text{Mult}) - \text{devA} (7) \times 6 \times \sin (2 \pi \text{Mult}) &+ \\
\text{devB} (6) \times 6 \times \cos (2 \pi \text{Mult}) ) \times (\pi/180)
\]

\[
\text{omg}_\text{theta}_{\text{mod}} = 2 \pi \times \text{frequency} \times (-\text{devA}_{\text{mod}} (2) \times 1 \times \sin (2 \pi \text{Mult}) &+ \\
\text{devB}_{\text{mod}} (1) \times 1 \times \cos (2 \pi \text{Mult}) - \text{devA}_{\text{mod}} (3) \times 2 \times \sin (2 \pi \text{Mult}) &+ \\
\]
A.2. USER CODES:

\[
\text{devB\_mod(2)} \cdot 2 \cdot \cos(2 \cdot 2 \cdot \pi \cdot \text{Mult}) - \text{devA\_mod(4)} \cdot 3 \cdot \sin(2 \cdot 3 \cdot \pi \cdot \text{Mult}) + \& \\
\text{devB\_mod(3)} \cdot 3 \cdot \cos(2 \cdot 3 \cdot \pi \cdot \text{Mult}) - \text{devA\_mod(5)} \cdot 4 \cdot \sin(2 \cdot 4 \cdot \pi \cdot \text{Mult}) + \& \\
\text{devB\_mod(4)} \cdot 4 \cdot \cos(2 \cdot 4 \cdot \pi \cdot \text{Mult}) - \text{devA\_mod(6)} \cdot 5 \cdot \sin(2 \cdot 5 \cdot \pi \cdot \text{Mult}) + \& \\
\text{devB\_mod(5)} \cdot 5 \cdot \cos(2 \cdot 5 \cdot \pi \cdot \text{Mult}) - \text{devA\_mod(7)} \cdot 6 \cdot \sin(2 \cdot 6 \cdot \pi \cdot \text{Mult}) + \& \\
\text{devB\_mod(6)} \cdot 6 \cdot \cos(2 \cdot 6 \cdot \pi \cdot \text{Mult})) \cdot (\pi /180) \\
\]

\[
\text{omg\_theta} = \text{omg\_theta\_steady} + ((\text{modd}\_\text{fmod}) \cdot \text{omg\_theta\_mod}) \\
\text{omg\_theta} = \sin\text{Damp} \cdot \text{omg\_theta} + \sin\text{DampDer} \cdot \text{theta} \\
\]

\[
!\text{stroke/position angle velocity} \\
\text{omg\_gama\_mod} = 2 \cdot \pi \cdot \text{frequency} \cdot (-\text{stroA}(2) \cdot 1 \cdot \sin(2 \cdot 1 \cdot \pi \cdot \text{Mult}) + \& \\
\text{stroB}(2) \cdot 2 \cdot \cos(2 \cdot 2 \cdot \pi \cdot \text{Mult}) - \text{stroA}(3) \cdot 3 \cdot \sin(2 \cdot 3 \cdot \pi \cdot \text{Mult}) + \& \\
\text{stroB}(3) \cdot 3 \cdot \cos(2 \cdot 3 \cdot \pi \cdot \text{Mult}) - \text{stroA}(4) \cdot 4 \cdot \sin(2 \cdot 4 \cdot \pi \cdot \text{Mult}) + \& \\
\text{stroB}(4) \cdot 4 \cdot \cos(2 \cdot 4 \cdot \pi \cdot \text{Mult})) \cdot (\pi /180) \\
\]

\[
\text{omg\_gama} = \text{omg\_gama\_mod} + ((\text{modd}\_\text{fmod}) \cdot \text{omg\_gama\_mod}) \\
\text{omg\_gama} = \sin\text{Damp} \cdot \text{omg\_gama} + \sin\text{DampDer} \cdot \text{gama} \\
\]

\[
!\text{pitch/rotation angle velocity} \\
\text{omg\_phi\_mod} = 2 \cdot \pi \cdot \text{frequency} \cdot (-\text{picA}(2) \cdot 1 \cdot \sin(2 \cdot 1 \cdot \pi \cdot \text{Mult}) + \& \\
\text{picB}(2) \cdot 2 \cdot \cos(2 \cdot 2 \cdot \pi \cdot \text{Mult}) - \text{picA}(3) \cdot 3 \cdot \sin(2 \cdot 3 \cdot \pi \cdot \text{Mult}) + \& \\
\text{picB}(3) \cdot 3 \cdot \cos(2 \cdot 3 \cdot \pi \cdot \text{Mult}) - \text{picA}(4) \cdot 4 \cdot \sin(2 \cdot 4 \cdot \pi \cdot \text{Mult}) + \& \\
\text{picB}(4) \cdot 4 \cdot \cos(2 \cdot 4 \cdot \pi \cdot \text{Mult}) - \text{picA}(5) \cdot 5 \cdot \sin(2 \cdot 5 \cdot \pi \cdot \text{Mult}) + \& \\
\text{picB}(5) \cdot 5 \cdot \cos(2 \cdot 5 \cdot \pi \cdot \text{Mult}) - \text{picA}(6) \cdot 6 \cdot \sin(2 \cdot 6 \cdot \pi \cdot \text{Mult}) + \& \\
\text{picB}(6) \cdot 6 \cdot \cos(2 \cdot 6 \cdot \pi \cdot \text{Mult})) \cdot (\pi /180) \\
\]

\[
\text{omg\_phi} = \text{omg\_phi\_mod} + ((\text{modd}\_\text{fmod}) \cdot \text{omg\_phi\_mod}) \\
\text{omg\_phi} = \sin\text{Damp} \cdot \text{omg\_phi} + \sin\text{DampDer} \cdot \text{phi} \\
\]

\[
\text{omega} = (/ 0.0d0, 0.0d0, 0.0d0 /) \\
\text{Ax} = (/ \text{omg\_theta}, 0.0d0, 0.0d0 /) \\
\text{Ay} = (/ 0.0d0, \text{omg\_phi}, 0.0d0 /) \\
\text{Az} = (/ 0.0d0, 0.0d0, \text{omg\_gama} /) \\
\text{BC} = \text{B} \cdot \text{times} \cdot \text{C} \\
\]

\[
\text{Ay}_2(1) = (\text{BC}(1,1) \cdot \text{Ay}(1)+\text{BC}(1,2) \cdot \text{Ay}(2)+\text{BC}(1,3) \cdot \text{Ay}(3)) \\
\text{Ay}_2(2) = (\text{BC}(2,1) \cdot \text{Ay}(1)+\text{BC}(2,2) \cdot \text{Ay}(2)+\text{BC}(2,3) \cdot \text{Ay}(3)) \\
\text{Ay}_2(3) = (\text{BC}(3,1) \cdot \text{Ay}(1)+\text{BC}(3,2) \cdot \text{Ay}(2)+\text{BC}(3,3) \cdot \text{Ay}(3)) \\
\]

\[
\text{Ax}_2(1) = (\text{B}(1,1) \cdot \text{Ax}(1)+\text{B}(1,2) \cdot \text{Ax}(2)+\text{B}(1,3) \cdot \text{Ax}(3)) \\
\text{Ax}_2(2) = (\text{B}(2,1) \cdot \text{Ax}(1)+\text{B}(2,2) \cdot \text{Ax}(2)+\text{B}(2,3) \cdot \text{Ax}(3)) \\
\text{Ax}_2(3) = (\text{B}(3,1) \cdot \text{Ax}(1)+\text{B}(3,2) \cdot \text{Ax}(2)+\text{B}(3,3) \cdot \text{Ax}(3)) \\
\]
\[ Az_2 = Az \]

\[ \omega = Ax_2 + Ay_2 + Az_2 \]

!!print *,\omega

DO iFace=nIntFaces+1,nIntFaces+nBndFaces
  IF (family_f(iFace)==iFamily) THEN
    i2 = cell2_f(iface)
    !cent_c_3(i2,:)!
    v_c_3(i2,:) = omega.x.cent_c_3(i2,:)
    !!print *, v_c_3(i2,:)
  END IF
END DO

CALL tracing_trace_end(trace_set_phi_timestep)

END SUBROUTINE set_phi_timestep

END MODULE set_phi
A.3. **Body radius:**

The cross-sectional radius, at 34 points, along the body of the mosquito is provided in the table below. The 34 points are along the body covering the abdomen, thorax and head of the mosquito. Point 1 is at the extreme tail/abdomen position and point 34 is located at extreme head position.

<table>
<thead>
<tr>
<th>Point</th>
<th>Radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.2244</td>
</tr>
<tr>
<td>3</td>
<td>0.2585</td>
</tr>
<tr>
<td>4</td>
<td>0.2738</td>
</tr>
<tr>
<td>5</td>
<td>0.2818</td>
</tr>
<tr>
<td>6</td>
<td>0.2882</td>
</tr>
<tr>
<td>7</td>
<td>0.3018</td>
</tr>
<tr>
<td>8</td>
<td>0.3155</td>
</tr>
<tr>
<td>9</td>
<td>0.3234</td>
</tr>
<tr>
<td>10</td>
<td>0.3260</td>
</tr>
<tr>
<td>11</td>
<td>0.3094</td>
</tr>
<tr>
<td>12</td>
<td>0.3028</td>
</tr>
<tr>
<td>13</td>
<td>0.3140</td>
</tr>
<tr>
<td>14</td>
<td>0.3068</td>
</tr>
<tr>
<td>15</td>
<td>0.4040</td>
</tr>
<tr>
<td>16</td>
<td>0.4924</td>
</tr>
<tr>
<td>17</td>
<td>0.4743</td>
</tr>
<tr>
<td>18</td>
<td>0.4563</td>
</tr>
<tr>
<td>19</td>
<td>0.4166</td>
</tr>
<tr>
<td>20</td>
<td>0.0000</td>
</tr>
<tr>
<td>21</td>
<td>0.1804</td>
</tr>
<tr>
<td>22</td>
<td>0.3051</td>
</tr>
<tr>
<td>23</td>
<td>0.3550</td>
</tr>
<tr>
<td>24</td>
<td>0.3825</td>
</tr>
<tr>
<td>25</td>
<td>0.3879</td>
</tr>
<tr>
<td>26</td>
<td>0.3868</td>
</tr>
<tr>
<td>27</td>
<td>0.3845</td>
</tr>
<tr>
<td>28</td>
<td>0.3809</td>
</tr>
<tr>
<td>29</td>
<td>0.3762</td>
</tr>
<tr>
<td>30</td>
<td>0.3634</td>
</tr>
<tr>
<td>31</td>
<td>0.3239</td>
</tr>
<tr>
<td>32</td>
<td>0.3618</td>
</tr>
<tr>
<td>33</td>
<td>0.1681</td>
</tr>
<tr>
<td>34</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Table A.1: Radius of body from tail (point 1) to head (point 34) at 34 equidistant locations. The length of the whole body is 4.7 mm.
ReFRESCO solver and other tools used

B.1. ReFRESCO:

ReFRESCO is a CFD solver used to compute the fluid dynamics numerically. It can be used to solve single-phase/multiphase incompressible flow based on Navier Stoke’s equations. ReFRESCO uses finite volume method (FVM) to discretize the conservation equations [37]. The conservation equations, given by Navier Stoke’s equations for mass and momentum, are solved with pressure correction using SIMPLE algorithm [37]. The unsteady simulation requires physical time-stepping which is accomplished by first or second order implicit backward scheme called BDF (implemented in ReFRESCO) [37]. Also, the equations can be solved by coupled or segregated method. The nonlinear set of equations are linearized using Picard’s method at each physical time step [37]. Elements of mesh with different number of faces like tetrahedral, hexahedral, pyramid etc. can be used since face based implementation is adopted [37]. The computation can also be performed with mesh consisting of h-refinement [37]. This allows hanging nodes in between two cells in a mesh which can be useful if the geometry is complex. Furthermore, mesh schemes such as deforming, moving, sliding, adapting can be used [37].

Various turbulence models (if needed) can be successfully implemented with ReFRESCO. The turbulence models which can be used are Spalart-Allmaras model, \(k-\varepsilon\) standard model, \(k-\varepsilon\) RNG model, \(k-\varepsilon\) original Wilcox model, \(k-\omega\) modified Wilcox model, \(k-\omega\) SST Menter model. Furthermore, cavitation models can be used if needed. The Volume-of-Fluid ased approach or Transport-Equation-Based-Model is used to implement it.
**B.2. HEXPRESS:**

Hexpress is an automatic hexahedral grid generation tool developed by Numeca Int. The version of software, used in the current project, is Hexpress 5.2. It produces 2D/3D unstructured mesh with only hexahedral elements. There are different steps involved to obtain the mesh for the simulation. These are explained here. Please note, all the magnitudes mentioned here are dimensionless.

**CAD manipulation and domain generation:**

The CAD model (with wing thickness) is imported into Hexpress. Initial step involves placing the wing at the hinge location. Therefore, wing root is placed at the origin for single wing. For two wing model, the left wing is obtained by importing the right wing model (second time) and rotating it by 180 degrees about the inertial Z axis and 180 degrees about inertial Y axis. This gives a mirror image of the right wing about the origin. Furthermore, the right (left) wing is translated such that the wing root is at the hinge location of \([0,0.0004,0]\) \((0,-0.0004,0)\). Then a cubical domain, around the wing/wings, was made. The size of the domain is \(0.15 \times 0.15 \times 0.15\) (50 × wing length). After obtaining the outer domain, the interior is meshed.

**B.2.1. Meshing routine**

The first step in the meshing process involved creating an initial number of cells in the interior of the domain. The initial number of cells is mentioned in the table 3.3. Then ‘mesh-adaptation’ procedure was performed. This is the most important part of the meshing routine and involves the largest manual involvement. During this step, the initial number of cells are split throughout various refinements. One refinement implies splitting the initial number of cells into half of their original size, two refinement implies 1/4th the original size and so on. The first refinement is done in the refinement box which was nearly 7% that of the size of outer domain. This was chosen after multiple simulations were performed starting with a refinement box of 50% (initial simulations). A smaller refinement box is used to obtain finer mesh cells around the wing by maintaining the overall number of cells in the domain. With larger refinement box, finer cells at large distances from wing are obtained with a corresponding increase in the total number of cells and hence, the computation time significantly. The refinement over the wing and inside the refinement box are limited by the cell target size which was set to zero. Therefore, the refinement level was limited by the number of refinements itself. The number of refinements in the refinement box was considered to be 7 for all the meshes (coarse, medium and fine).

The refinement on the top and bottom face of the wing were 3 times lower than the boundaries (curved face). The number of refinements considered over the top/bottom surface were 9 and boundary face (curved face) was 11. An important parameter considered during the meshing scheme was the diffusion rate. This defines the transition
between the smaller cells (close to the wing) and larger cells (outer domain cells). This was considered to be 2, 4 and 6 for coarse, medium and fine mesh respectively. The reason for increasing the diffusion rate was because cells of half the size (with respect to previous mesh) were desired close to the wing. By increasing the diffusion rate, higher number of layers (with more refinement) were obtained close to wing. A diffusion rate of 2 was used for the refinement box for all three meshes since the region in between refinement box and the outer domain boundary had relatively negligible change in properties when compared to the region inside the refinement box. After refinements and diffusion layers, the cells intersecting the geometry (wing) are removed (trimming stage). Then, ‘snapping’ is performed during which the staircase mesh, produced after trimming, is projected onto the geometry curves/vertices.

The last stage in meshing involves ‘optimization’ process. During this, a user defined/default percentage of cells with lowest quality are considered for optimization. A main goal of optimization stage is to transform twisted/concave cells to untwisted/convex cells. The optimization settings were changed such that best quality (most orthogonal/low skewness) mesh was obtained for the coarse mesh. This settings were maintained for medium/fine mesh. An attempt, to obtain better quality cells, is made. In case of negative/concave cells after optimization, the meshing routine fails and the user needs to increase refinements in the region where negative/concave cells are observed. No negative/concave cells were obtained for all three models (Single wing, Both-Wings and Wings-body). Mesh quality is checked by observing the minimum/maximum values of the cell equiangular skewness and orthogonality of the domain cells after optimization. The orthogonality of a cell is given by equation B.1. Here, \( m_{i,j,k} \) represents the centroids of the opposite faces of a hexahedral cell. An orthogonality close to 90 represents a cell close to an orthogonal cell (all angles = 90 degrees). Equiangular skewness is given by the equation B.2. Here \( A_{max} \) and \( A_{min} \) are the maximum and minimum angle of a face in a cell. \( A_e \) is an optimal angle which is equal to 90 degrees for hexahedral cells. A cell with 0 equiangular skewness is of good quality and the quality decrease with increase in the parameter until 1 (bad quality). Hexpress also has the option to display the histogram of the above mentioned parameters. The histogram along with min/max of the these parameters is shown in figure B.1 for coarse mesh of single wing model. The cell distribution more or less remains the same for other models. The final mesh is saved as a CGNS file format which is compatible with ReFRESCO.

\[
\gamma_{ijk} = m_i \cdot (m_j \wedge m_k) \quad \forall (i \neq j \neq k); \quad Orthogonality = 90 - \cos(\min(\gamma_{ijk})) \quad (B.1)
\]

\[
\text{Equiangular Skewness} = \max \left[ \frac{A_{max} - A_e}{180 - A_e}, \frac{A_e - A_{min}}{A_e} \right] \quad (B.2)
\]
Figure B.1: Mesh Quality histograms for coarse mesh of Single wing model.

B.3. Tecplot:

Tecplot is a flow visualisation software which can be used to post process data in 27 formats [71] in multiple dimensions (1D/2D/3D). It includes macro panel and debugger to perform large tasks in loops (vortex cores for every time step were obtained using a macro). Flow can be visualized using multiple frames, iso-surfaces, streamlines/streamtraces with/without controlled blanking [71]. It also includes shock layer/ vortex core extraction algorithms. In addition to that, various data can be computed considering existing data and interpolated/integrated/averaged etc. in the domain [71]. More about the software can be learnt from the website 'http://www.tecplot.com/'. 