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Analysis of a Flapping Blade in Two-Phase Flow

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Abstract: When insects fly close to water, they sometimes fall in. They then can no longer fly, but use a different mechanism, known as hydro-foiling, to propel themselves forward in order to reach the water's edge. Hydro-foiling involves a flapping of their wings in such a way as to keep only the ventral side wetted, generating ripples on the water surface that propel them forward. A previous study provided specifics of the kinematics of hydro-foiling of honeybees and the forces associated with this motion as well as the thrust mechanism. Such motion deserves further investigation as possible mechanism for the recovery of micro-air-vehicles (MAV) when falling into water during operations. This paper details the numerical modeling of hydro-foiling by combining moving boundaries, to simulate the kinematics and volume-of-fluid (VOF) model and the evaluation of the force generation mechanisms.

Keywords: Flapping Wings, Hydro-foiling, Two-phase Flow, Thrust, OpenFOAM, Honeybee.

1 Introduction

Adapting solutions found in nature to improve technological process is a popular practice by engineers and researchers to come up with simple and robust implementations [1]. Such practices are generally given the term Biomimicry. Many insects are incredibly agile fliers demonstrating abilities to dip, dart and change directions very efficiently [2]. Honeybees are one such example of nature's best fliers. However, in addition to superior flying abilities, they are also able to propel themselves after landing in water, either accidentally or on purpose, through a mechanism called hydro-foiling, on the water surface [3]. Although this mechanism has been known for some time, it is not understood well nor has the associated kinematics been investigated and optimized. Roh and Gharib [4] were the first to study this motion in detail by observing an actual honeybee performing hydro-foiling and replicating it in an experiment to elucidate the hydrodynamics involved.

Existing literature dealing with biological propulsion have been carried out in single-phase flows mimicking either submerged swimming or flight in air. These have allowed design of flapping wing micro-air-vehicles (MAVs). Hydro-foiling, although utilizing the same range of motion as flying, differs significantly in the frequency of the motion and the specific kinematics [4]. Detailed understanding of the hydrodynamics and eventual implementation of hydro-foiling to flapping wing MAVs will expand its range of operations near to large water bodies and may have further applications for energy harvesting from waves.

The aim of this work is thus to detail a numerical approach to modeling such interface flow by combining volume-of-fluid (VOF) and moving boundaries, specifically utilizing the overset mesh method in the open-source CFD package OpenFOAM.

Data taken from Roh and Gharib's [4] initial work was digitized and used to validate the model as well as for further analyses. The digitization process inevitably generates some errors, but these are not deemed to be significant.

2 Flapping Kinematics

Flapping motion is a complex combination of translational and rotational motion. A single cycle of a flapping wing consists of two translational phases (upstroke and downstroke) and two rotational phases (pronation and supination). The downstroke is defined as the motion of the wing from the rearmost point of wing rotation (in the stroke plane) to its foremost point of wing rotation (as viewed relative to the insect body). The two rotational phases separate the downstroke and upstroke in each cycle. Pronation is defined as the transition from the upstroke to the downstroke (the ventral surface of the wing rotates to face down). Supination is defined as the transition from the downstroke to the upstroke (the ventral surface of the wing rotates to face up). These are combined in hydro-foiling and can be termed the power and recovery strokes.

The stroke plane is the plane along which the wings of the insect flap back and forth during flight. Most insects use a horizontal stroke plane for hovering flight but not necessarily the case for hydro-foiling. The stroke plane was 35 degrees in Roh and Gharib's study.

Hovering and level-forward flight are the most common flight modes of insects. Forward flight is made possible by varying the up- and downstrokes during each cycle as well as changing the stroke plane angle [7]. These different elements are also there for propulsion at an air/water interface but the combination of them will be different. In addition, during flight, the downstrokes are typically longer than the upstrokes because of the need for lift generation. It may not be the case in propulsion at the water-air interface. Although it may still be necessary to generate "upward motion" to keep more of the body of the insect above the water surface to reduce drag, it may not be as significant compared to flight.

In general, with flapping wing flight, the smaller the body of the animal or insect, the higher the wing-beat frequency [8]. Typical wing-beat frequencies are in the range of 5 – 200 Hz. In specific species though due to smaller wing area, they may increase the wingbeat frequency to compensate for this [9]. One such insect is the honeybee with a wing-beat frequency of 230 Hz. Bees also have a much smaller wing stroke amplitude when compared to most insects. In most insects the wing stroke amplitude is found to be between 145 and 165 degrees, whereas bees have a wing stroke amplitude of around 90 degrees. However, the wing stroke amplitude and frequency of the bee at the water surface is much less when compared to the wing kinematics of the bee in hovering flight [10] and in fanning mode [11].

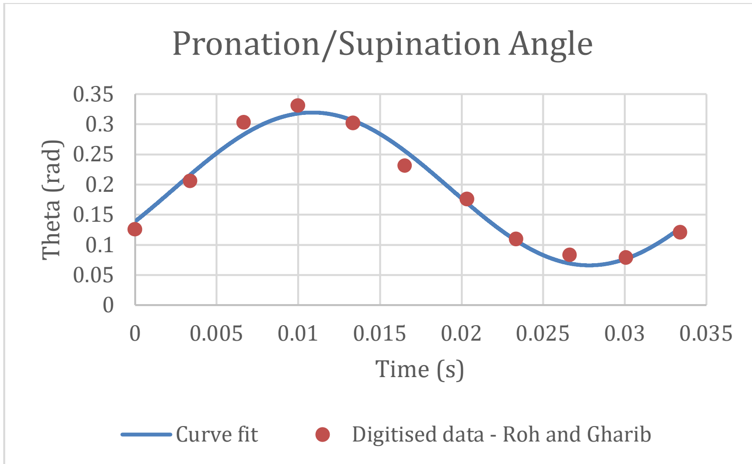
In addition to hydro foiling, there are three other mechanisms that insects use to propel themselves on the air water interface. They are surface skimming [12], water-striding [13] and drag-based propulsion [14]. In this paper, only hydro-foiling is investigated.

For the purpose of validation, the same kinematics as described in Roh and Gharib's study has been used specifically Fig 5 (A and B) in their paper. The kinematics is implemented in our model as a superposition of a pure translational motion (Fig 5A) with a pure rotational motion (Fig 5B). These two figures have been digitised and curve fitted to obtain the input kinematics into OpenFOAM.

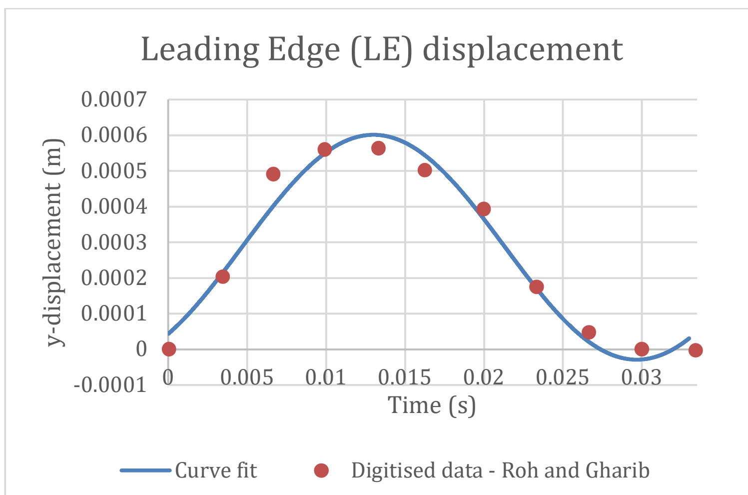
$$\boldsymbol{Y_{LE} = 0.028087 + 0.030318 \sin(2\pi \times 29.0788t + 5.5041)} \quad (1)$$

$$\boldsymbol{\theta = 11.0719 + 7.153 \sin(2\pi \times 30.013t + 5.8025)} \quad (2)$$

The curve fitted equations has the frequency at approximately 30Hz which is the same as that for the experiment. Results of the curve fit is given in Figure 1. Using more terms in the Fourier series could potentially yield a better fit but it also generates unnatural oscillations.



(a)



(b)

Figure 1: Comparison of the kinematics of the mechanical wing model (red dots) and data from experiment (continuous yellow line) for (a) the pronation/supination angle and (b) the leading-edge position

An 2D model combining the overset mesh with the volume-of-fluid (VOF) approach was set up in OpenFOAM with a rectangular background and overset mesh (for the plate). Mesh independent study was conducted with the details on the number of cells shown below. The final mesh selected for the simulations was Mesh 2 (shown in Figure 2) with a time step of 1 x 10^{-6} s. For the sake of brevity, the results from this exercise will not be presented.

Component	Mesh 1	Mesh 2	Mesh 3
Overset mesh	16173	59825	232651
Background Mesh	6197	20908	72867

Table 1: Mesh information for independence study

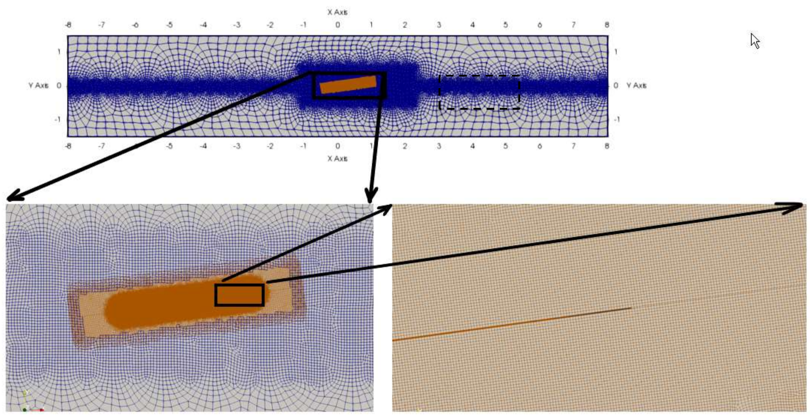


Figure 2: Illustration of the mesh used for the simulations

4 Results

Four cycles were solved for OpenFOAM and compared with the results from Roh and Gharib [4] and are presented in Figure 3. The results from Roh and Gharib [4] were obtained by digitizing their Fig S8(G) from the supplementary information document and "modified" based on instructions provided in same document to obtain thrust (F).

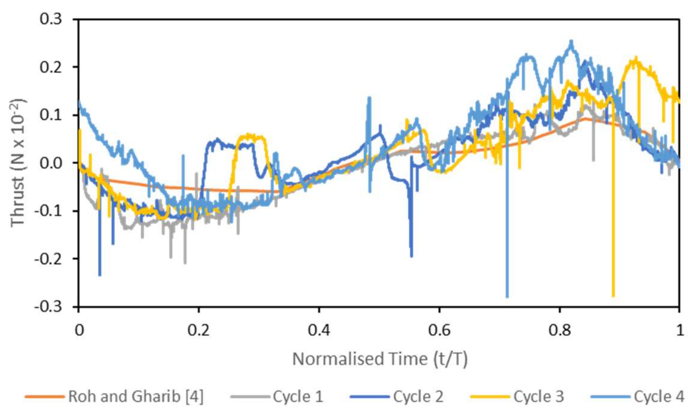


Figure 3: Comparison of simulation and literature [4]

First, it can be observed that the simulation results contain many high frequency oscillations. These are mainly temporal discontinuities that happen when there is a switching between the interpolation cells and the calculation cells and vice-versa. While this is largely insignificant, it becomes critical when the interface is in the region where the two phases of air and water overlap. Due to this, averaging the forces over one cycle will give rise to spurious results and is not investigated here.

It can be observed that generally the results compare well, with the exception of two "bumps" between t/T values of 0.2 and 0.3 that appears in some of the simulated cycles. It is not sure what is the cause of these, but it is not present in the other cycles and will not be used for the proceeding discussion. Note that these "bumps" on the recovery stroke is also present in Fig. 2C from Roh and Gharib [4] for the actual bee observation. Another thing to note is that in Figure 3, the recovery stroke precedes the power stroke whereas in actual motion, this may not be the case.

To optimize the kinematics related to this kind of motion, it is important to analyse the thrust produced with the kinematic position of the plate. This is done by combining the angular position vs time (Roh and Gharib [4] Figure 5B) kinematic information with that of thrust vs time (Roh and Gharib [4] Figure

S8G) and is presented in Figure 4 for both Roh and Gharib's data [4] and our simulations. This gives a different perspective on the data rather than just the variable vs time plots.

The power stroke is the upper half of the cycle and the recovery stroke is in the lower half. What's interesting is that a part of the recovery stroke still produces thrust. The maximum angular position which indicates the transition point between the two strokes, does not lie on the zero-thrust axis (Figure 4). This suggest that there is slight lag between when the stroke-reversal and thrust-reversal happens. This is more evident in the experimental data from Roh and Gharib [4] but is also present in our simulation data. Secondly, the production of thrust increased sharply in the first one-quarter of the power stroke and then reduces subsequently. These may be due to the portion of plate that is submerged in the water during the motion.

Detailed flow analysis will be able to shed light on this phenomenon and will form part of the proceeding work which seeks to optimize the kinematics for this kind of motion.

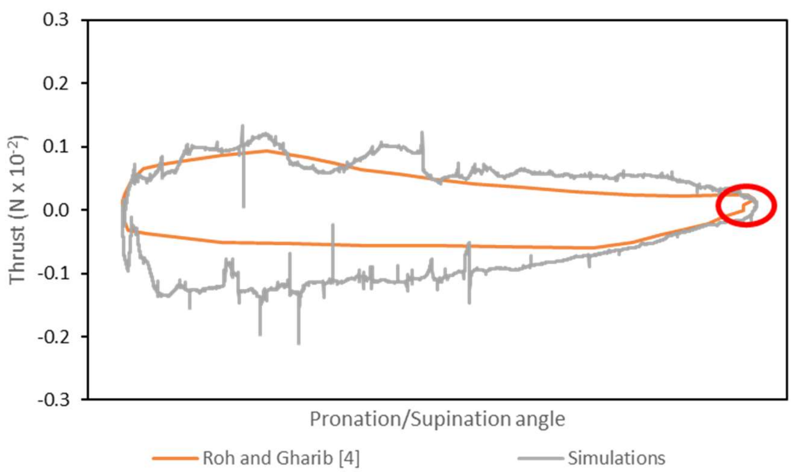


Figure 4: Thrust vs Pronation/Supination angle

5 Conclusion and Future Work

In conclusion, a CFD simulation using OpenFOAM has been performed with good qualitative comparison against existing literature. Thrust production at different parts of the kinematic cycle revealed interesting results which may have important implications in the understanding and optimization of such methods of propulsion. Future work will be focused on eliminating the noise in the simulation data to accurately evaluate the average forces but more importantly on understanding the detailed flow mechanisms and optimizing the kinematics.

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