Experimental and computational study of flapping wing aerodynamics at low reynolds number

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NANYANG
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**EXPERIMENTAL AND COMPUTATIONAL STUDY
OF FLAPPING WING AERODYNAMICS AT LOW
REYNOLDS NUMBER**

CHAI WEE SERN VINCENT

**SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

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LOW REYNOLDS NUMBER**

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ABSTRACT

Recent rapid developments in micro-sized Unmanned Aerial Vehicles (UAVs) and Underwater Vehicles (UWVs) have attracted renewed research interest in flapping wings aerodynamics. Due to the limitation of the size of these vehicles, complex motions employed by the birds and fishes have to be simplified as additional actuators are needed to perform the complex motions which will significantly increase the size of these vehicles. In addition, the study of flapping wings aerodynamic is challenging as the parameters involved that affecting the performance is huge. Therefore, this thesis investigates the feasibility of flapping wings with simplified kinematic motions as the propulsion system for the micro UAV or UWV and obtains the optimizing parameters for improving the flapping wings aerodynamics performance through experimental and numerical simulation approaches. A simple analytical model for predicting the lift with moderate accuracy is also developed. In conclusion, with comprehensive works conducted, a better understanding of the physics behind the flapping wings aerodynamics allows the translation of knowledge and creates great impact to the development of flapping wings micro UAV and UWV.

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NOMENCLATURE LIST

Roman Symbols

A	Vortex Area
A	Flapping amplitude
$\hat{A}_0$	Dimensionless oscillating amplitude
D	Diameter
C_{dm}	Mean drag coefficient
C_{do}	Oscillating drag coefficient
C_{lm}	Mean lift coefficient
C_{lo}	Oscillating lift coefficient
C_L	Lift Coefficient
C_p	Power Coefficient
C_s	Smagorinsky Constant
C_d	Dynamic Constant
C_T	Thrust Coefficient
CFL	Courant Friedriches Lewy
CFD	Computational Fluid Dynamic
DNS	Direct Numerical Simulation
E	Young Modulus/ Elasticity Modulus
F_x	Forces acting at X-Axis of the load cell (Global)
F_y	Forces acting at Y-Axis of the load cell (Global)
F_z	Forces acting at Z-Axis of the load cell (Global)
I	Second moment of inertia
IB	Immersed Bounday
J	Advance Ratio
K	Bending stiffness
LES	Large Eddie Simulation
LEV	Leading Edge Vortex
P	Power generated by oscillating motion of hydrofoil

<i>Pa</i>	Pascal
<i>RANS</i>	Reynolds-Averaged Navier-stokes
<i>Re</i>	Reynolds Numbers
<i>Re_{chord}</i>	Reynolds number based on chord length of the foil
SD 7003	Hydrofoil with Selig/Donovan 7003 profile
SD 8020	Hydrofoil with Selig/Donovan 8020 profile
<i>S</i>	Surface area of the foil, m ²
<i>SGS</i>	Sub-Grid Scale
<i>S₀</i>	Area of one side of the hydrofoil
<i>St</i>	Strouhal Numbers
<i>STS</i>	Subtest stress
<i>T</i>	Time for one period
<i>TEV</i>	Trailing edge vortex
<i>T_x</i>	Torque on X-Axis of the load cell (Global)
<i>T_y</i>	Torque on Y-Axis of the load cell (Global)
<i>T_z</i>	Torque on Z-Axis of the load cell (Global)
<i>V</i>	Free stream velocity
<i>V_a</i>	Speed of advance per unit time
<i>U_∞</i>	Free stream velocity
<i>Y</i>	Maximum oscillating amplitude
<i>a</i>	Plunge amplitude
<i>c</i>	Chord Length of hydrofoil
<i>f</i>	Oscillating frequency
<i>f_x</i>	<i>Local force vector in x direction</i>
<i>f_y</i>	<i>Local force vector in y direction</i>
<i>h (t)</i>	Instantaneous heaving Amplitude
<i>k</i>	Reduced frequency
<i>t₊</i>	Dimensionless time
<i>t_{hold}</i>	Holding time
<i>u_c</i>	Combined uncertainty
<i>u_s</i>	Systematic error

s_i	Standard deviation
-------	--------------------

Greek Symbols

ν	Kinematic viscosity
Ω	Pitch rate
Ω^+	Dimensionless pitch rate
ω	Vorticity
Γ	Circulation
ρ	Density of water
η	Propulsive Efficiency
σ	Normal Stress
ε	Strain
$\alpha(t)$	Instantaneous pitching angle
ψ	Phase angle between the heave and pitch motion
μ	Dynamic viscosity
τ_{ij}	Turbulent stress tensor
ω	Rotational speed

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Chapter 1 Introduction

1-1 Background

The ability for birds to fly using flapping wings has inspired mankind to dream of flying. Over the centuries, humans have invented airplanes and rockets in order to achieve this noble dream. However, the concept of flapping wings has never been applied on big planes or any flying vehicles as the payload of these vehicles are too high.

In recent years, unmanned aerial vehicle (UAV) and unmanned underwater vehicle (UWV) in smaller scale and lower payload have seen unprecedented development in the military and civilian application. For military purpose, these vehicles are normally equipped with sensors, GPS module, camera or even weapon [1]. For civilian application, these vehicles are used mainly for security surveillance or rescuing purposes. As these vehicles can be controlled without human onboard, this greatly reduces the risk of injury or even the loss of lives. Thus, these vehicles can be sent to harsh and dangerous environment which is currently inaccessible by conventional machines controlled by human pilot.

As discussed above, for UAV or UWV to survive in harsh and dangerous environment, they have to be more agile, more maneuverable and with a higher propulsive efficiency to perform more tasks with less energy consumption. However, the propulsive efficiency of current propeller propulsion method might already reach stagnation stage. Unfortunately, most of the UAV and UWV in current days are still using conventional propeller based system for propulsion.

a) Maximum lift coefficient

b) Minimum drag coefficient

c) Maximum lift-drag ratio

Figure 1-1 Airfoil performance [2]

Apart from the factors mentioned above, the micro UAV, which needs to perform its task in a confined small room, requires to travel in low speed. As fixed wing vehicles have difficulty in travelling in low Reynolds region due to the maximum lift coefficient and the maximum lift to drag ratio deteriorated significantly at low Reynolds number (Figure 1-1), flapping wings vehicles may have the advantages over fixed wing vehicles for travelling in this slow speed regime. In addition, it does not occupied large space for containing its big wings or big rotors with the retractable wings.

Additionally, in the context of underwater vehicles, the propeller based propulsions vehicles have some critical drawbacks. Firstly, the effect of cavitations and large scale of turbulence disturbance to the surrounding of ocean lead to high wear and tear to the blades and the cavitations might generate noises and making it not suitable for reconnaissance purpose and observing deep sea marine animals. Secondly, for ocean exploration purposes, rotating propeller blades might be entangled with marine plants while the vehicle carries out missions in the deep sea.

Figure 1-2 Animals travel with flapping motion [3], [4] & [5]

Hence, by observing the nature, in particular the flapping wings of birds and the flapping tail of fishes, the flapping wings seem promising in satisfying the requirements mentioned in previous paragraph. Successful flapping propulsion might improve the performance of the micro UAV and UWV drastically over those vehicles equipped with current conventional propulsion system [6] & [7] which fuels human's interest in studying the flapping wings again.

Flapping propulsion systems might offer the following advantages: the ability to generate lift and thrust at the same time, the ability to sustain a higher lift for low Reynolds number travelling (Figure 1-1), lower noise production in water with lower flapping frequency, decreased vulnerability to entanglement marine plants under deep sea environment, and higher agility. With suitable flapping patterns and parameters, the UAV or UWV can mimic the bird (e.g. the hovering of the humming bird) or fish to propel itself in narrow or confined area which requires lower travelling speed and ease of maneuvering.

1-2 Objectives

The performance of flapping wings is determined by many aspects, such as wing shape, wing motions, wing elasticity, interaction area and et cetera. It is a great challenge for researchers to examine the factors that influence the performance of flapping wings aerodynamics which involve the complicated kinematic motions and the unsteady flow. Hence, in order to develop the micro size UAV or UWV with great performance, a good prediction tool and set of methodologies to describe flapping wings aerodynamics is clearly needed. As the complex kinematic motions require more actuators to perform the required motions and will lead to

increase the size of the micro UAV or UWV, this thesis emphasizes the study of aerodynamics of hydrofoil or flat plate which undergoes simplified kinematic motions that include: pure pitching, heaving or combined pitch and heave motion.

With recent improvement in computing power, numerical simulation has becoming a very popular engineer tool for solving engineering problems more effectively.

However, most of the conventional Computational Fluid Dynamic (CFD) solvers are difficult to simulate moving object and the preparation job for meshing the control volume with irregular geometry is tedious. Hence, this thesis evaluated the accuracy of the Large Eddy Simulation (LES) with Immersed Boundary (IB) method, as a numerical solver, for simulating the flapping wings aerodynamics.

In summary, this thesis aims to investigate the feasibility of flapping wings with simplified kinematic motion as propulsion system for micro UAV or UWV through experiment and numerical simulation, so as to develop a simple analytical model to predict the lift with moderate accuracy for saving the cost and time from the engineers to develop and optimizing the performance of the micro vehicles. The study of flapping wings aerodynamics also aims to investigate the existence of the lift and thrust enhancement mechanisms which could be utilized in the flapping wings micro vehicles for optimizing its propulsion performance.

Figure 1-3 Humming bird-like miniature UAV (left) and UWV (right) [8] & [9]

1-3 Scope

One of the main challenges in the study of flapping wings is the measurement of relatively small forces generated by the flapping wings. The main scope of this research is described as below:

1. The development and validation of an experimental setup which is capable of generating wing motions and accurately measuring the small flapping forces.
2. The validation of the computational results with the experimental results obtained in order to evaluate the suitability of the numerical solver for the flapping wings study.
3. The derivation and provision of design recommendations of flapping wings for UAVs and UWVs as propulsion system.

The flapping parameters under investigation in this study are:

1. Type of Motion : Symmetrical and non-symmetrical heaving, pitching and combined motion.
2. Speed : Heaving and pitching speed.
3. Amplitude : Heaving and pitching amplitude.

Lastly, the outline of this thesis is:

Chapter 1 provides a brief introduction and background of flapping wings aerodynamics as well as to highlight the objectives and the scopes of study.

Chapter 2 discusses the literature reviews on past researches for the study of flapping wings and the evolution of the conventional type of the propulsion system for the UAV and UWV.

Chapter 3 presents the design and development of the test rig, the selection of the tools as well as the error analysis for the equipment used throughout the study.

Chapter 4 introduces the numerical solver, the Large Eddy Simulation (LES) with the Immersed Boundary (IB) method and the discussion on the selection of turbulence models and the solver.

Chapter 5 highlights and discusses the experimental and numerical simulation results obtained from:

- Oscillating cylinder test,
- Flapping hydrofoil or flat plate with different combination of flapping parameters and Reynolds number involved,
- Study on the effect of flexibility of hydrofoil,
- Study on the lift and thrust enhancement mechanism.

Chapter 6 concludes the research conducted and contributions of the thesis. This chapter also highlights the potential areas for future studies on flapping wings aerodynamics for the development and optimization of micro UAV and UWV propulsion system.

Chapter 2 Literature Review

2-1 Conventional propulsion system for UAV and UWV

In current day, with the heavily needs of air transport, gas turbine engine has becoming very popular for airplane as propulsion system. The first patent for gas turbine development was issued to John Barber (1791) [10].

Many decades later, Hans J.P von Ohain (1935) has developed a gas turbine power plant, which consists of a multistage axial flow compressor and turbine on the same shaft with a combustion chamber and a heat exchanger for Heinkel aircraft in Germany and flied successfully [10].

During the year 1950, the development of gas turbine technology for aircrafts power plants was having vast improvement. In modern days, many new engines were developed in twentieth century by Rolls Royce, General Electric and Pratt and Whitney.

Figure 2-1 Open rotor and combustion chamber (SGT5-4000F) gas turbine (left) [10] and Global hawk UAV which uses a gas turbine engine (right) [9]

Figure 2-2 Propellers type UAV in smaller size [11]

Owing to the mature developments of gas turbine engine, it has been employed for larger UAV (Figure 2-1, right). Besides gas turbine engine, some of the smaller UAV, which does not require traveling fast and lesser payload, uses propeller type of propulsion system (Figure 2-2). However, for micro-size unmanned vehicle, fixed wing propeller type UAV has limitation in operation at low Reynolds number (Figure 1-1). Therefore, different types of propulsion system have been invented. Figure 2-3 shows micro UAVs which use flapping wings and quad-rotor propulsion system.

Figure 2-3 Micro-Unmanned aerial vehicles (MAV) [12] & [11]

The quad-rotor type UAVs (Figure 2-3, right) might have better maneuverability than fixed wings vehicle, but it requires a large space for accommodating its rotors where flapping wings type UAVs do not (Figure 2-3, left).

Similarly, for the UWV, fish liked flapping tails allow the vehicle to be further reduced in size and improve the maneuverability. Figure 2-4 shows the conventional type of underwater vehicle which is equip with conventional type of propulsion system (right) and fish-like underwater vehicle with flapping tail (left).

Figure 2-4 Fish-like micro UWV (left) and conventional Type of UWV (right) [13] & [14]

Apart from factors mentioned above, the propulsive efficiency is also noteworthy for the operation of micro UAV and UVW. According to Jamie Marie Anderson [15], the highest thrust in all propulsors is produced at low advance ratio where the efficiency is near zero; and the highest efficiency occurs when the thrust coefficient is reduced by about 50%. Hence, it is not practical to operate large propellers at low frequencies while a large motor is needed. Furthermore, according to simple actuator disk theory [15], the efficiency is trading off from the thrust coefficient as the thrust is increased. Therefore, flapping type of propulsion system can act as competitors to conventional propellers.

The advance ratio of the propeller can be defined as the following equation:

$$J = \frac{V_a}{nD} \quad (2-1)$$

where, V_a is the speed of advance per unit time, n is the propeller's rotational speed (revolutions per unit of time) and D is the propeller's diameter. [16]

2-2 Early Research on Flapping Wings

The early explanation of a bird's ability to produce thrust and lift by its flapping wings was published by Knoller (1909), followed by Vienna and Betz (1912) in Göttingen [17]. They found that, at low angles of incidence to the incoming flow, a lift force on a stationary aerofoil in free-stream almost normal to the incoming flow will be generated. If the drag on the wing is small compared to the lift, the resultant force is normal to the incident flow as well. Illustration is shown in Figure 2-5.

Figure 2-5 Illustration of forces acting on a wing [17]

As opposed to the case mentioned above, the oscillating airfoil with a heaving motion (moving up and down with a fixed angle of attack) sees an induced vertical

velocity causes an incoming velocity with an angle of incidence to the real free stream direction as shown in Figure 2-6.

Figure 2-6 Illustration of forces acting on a wing (cont.) [17]

Next, Knoller and Betz conducted further research and found that if the wing is being oscillated in a heaving motion, the lift force will be both positive and negative in a cycle. However, its thrust force would always be a non negative value even though the averaged-lift is zero. In 1922, Katzmayr conducted the first wind tunnel test on an airfoil that was mounted in an oscillating free stream and concluded that the airfoil was experiencing a thrust force.

In addition, Katzmayr concluded that the flapping wings, together with appropriate flapping parameter, can generate thrust whenever the airfoil changes its angle of attack. At the same time, the flapping airfoil can continuously shed vortices from its trailing edge, similar to jet flow pattern (Figure 2-7) which is also known as

Reverse Karman Vortex Street. In 1924, Prandtl's student, Birnbaum [17] presented a theoretical solution for the incompressible flow over flapping foils.

Apart from the pure oscillating motion, recent developments and research on flapping wing have focused on the motion of flying birds or insects and swimming fishes.

Due to the complex motion of flapping wings, besides the capability of generating thrust, in 1932, Kramer [18] first demonstrated that a wing can experience lift above the stall value when the wing is flapping from low to high angle of attacks and experience rapid wing rotation at the ends of the down-stroke and up-stroke from insect flight. This motion of flapping wings allows introducing circulation into the flow and it is known as the Kramer effect. Hence, the rapid rotation (Kramer effect), acceleration of the flapping wings (Wagner effects [19]) and the LEV - lift enhancement mechanism allows the flapping wings to enhance the lift for insect flight.

Figure 2-7 Dye flow visualization of flapping airfoil [17]

2-3 Recent researches of flapping wing through Force measurement

Throughout the flapping wings studies in recent years, most of the researchers focused on investigating the thrust or lift performance and the propulsive efficiency of the flapping wings. Before reviewing the researches done on flapping wings, some of the common parameters that were applied across the studies of flapping wings among researchers are introduced in the beginning of this section. The Strouhal number is a dimensionless value that describes the phenomenon of oscillating flow (e.g. Oscillating hydrofoil for flapping wings study):

$$St = \frac{4\pi h_0 \omega}{U} \quad (2-2)$$

where h_0 is the heave amplitude, ω is the circular frequency in rad/s and U is the velocity.

The average thrust force (x -direction) obtained from the force measurement is defined as:

$$\bar{F}_x = \frac{1}{T} \int_0^T F_x(t) dt; \quad \text{For } T \gg \frac{2\pi}{\omega} \quad (2-3)$$

The mechanical power delivered by the motors for the motion is defined as:

$$\bar{P} = \frac{1}{T} \int_0^T F_y(t) \dot{h}(t) dt + \int_0^T Q(t) \dot{\theta}(t) dt \quad (2-4)$$

where F_y is the force experienced in y -direction and $\dot{h}(t)$ is the heaving speed, $Q(t)$ is the torque in the XY plane and $\dot{\theta}(t)$ is the angular velocity in the Z axis.

The thrust and power coefficients are:

$$C_T = \frac{\bar{F}_x}{\frac{1}{2} \rho c s U^2} \quad (2-5)$$

$$C_P = \frac{\bar{P}}{\frac{1}{2}\rho csU^3} \quad (2-6)$$

Lastly, the propulsive efficiency is:

$$\eta = \frac{C_T}{C_P} \quad (2-7)$$

In recent years, due to the advancement in technology, the measurement of the thrust and lift forces that the flapping wing has becoming more feasible and more accurate. However, the actuation mechanism, force measuring sensors, the other relevant equipment and environment for conducting the experiment are still amongst the greatest challenge in the experimental setup in order to obtained more accurate results.

D.A. Read [6] conducted a series of experiments (Figure 2-8) to study the performance of the oscillating foil with simple profile (NACA 0012) with a huge carriage in a towing tank at the Reynolds number of 4000 to investigate the relationship between the oscillating simple foil (Figure 2-9) and its propulsion and maneuvering ability. The chord length of the foil is 10 cm and span-width of 60 cm. The classical oscillatory thin airfoil theory [17] states that the propulsive efficiency of a single heaving airfoil in slow oscillatory motion is only about 50%. Therefore, it requires a large airfoil to sustain the thrust value significantly. However, from the D.A. Read study, a maximum propulsive efficiency of 71.5% was archived *at $\alpha_{max} = 15^\circ$, $\psi = 90^\circ$ and $St = 0.1$.*

Figure 2-8 D.A. Read experimental test rig in the towing tank [6]

Figure 2-9 Foil trajectories for impulsive starting maneuver with 180-degree pitch change [6]

From Figure 2-10, the heave $h(t)$ and pitch $\theta(t)$ amplitude are defined as:

$$h(t) = h_0 \sin(\omega t) \quad (2-8)$$

$$\theta(t) = \theta_0 \sin(\omega t + \psi) \quad (2-9)$$

ψ is the phase angle between the heave and pitch motion and the resulting angle of attack profile are defined below (all angles are measured in radians):

$$\alpha(t) = -\arctan\left(\frac{\dot{h}(t)}{U}\right) + \theta(t) \quad (2-10)$$

Figure 2-10 Kinematic parameters of the flapping airfoil - relationship between physical pitch angle and angle of attack [6]

In 2007, Liu [20] studied the effects of oncoming flow unsteadiness on the aerodynamic characteristics of the flapping wings. When the wing altering its angle of attacks, the flow separation occurs in the vicinity of the leading edge at moderate angles of attack, however, quasi-steady aerodynamics analysis is unable to predict these phenomenons and hence, it is necessary to use the Navier stokes equation with suitable turbulence models in order to obtain accurate and quantitative results. Therefore, Liu further investigated the effects that were mentioned above by conducting a series of experiments in a towing tank. The hydrofoil was undergoing heave and pitch oscillations about the quarter-chord point. His results show that the thrust and the efficiency of the wing propulsors decreased with an increasing mean

angle of attack. Furthermore, high efficiency can be achieved for operation at angles of attack close to those of maximum lift-to-drag ratio.

In 2005, Schouveiler [21] conducted a study on the performance of aquatic propulsion system, which was inspired from the uniform swimming mode with the combination of pitching and heaving by the hydrofoil NACA0012 (Figure 2-11, chord length of 0.1m). The experiment was conducted with a fixed Reynolds number ($Re_{\text{chord}} = 40,000$). A peak efficiency of more than 70% was obtained.

Figure 2-11 (a) Kinematical parameters of the airfoil motion and (b) the definition of the angle of attack $\alpha(t)$ [21]

Heathcote [7] also conducted a series of experiments for investigating the effects of the elasticity of a flapping hydrofoil under pure heaving motion to the lift and thrust. However, conducting such experiments in the towing tank has its limitations, such as, the available travelling distance. Besides that, the size of travelling carriage is huge and complicated. Therefore, Heathcote used a water tunnel instead of the tow tank. The experimental setup is shown in Figure 2-12.

The experiments were first conducted in the water tunnel with stationary water for avoiding the disturbance from free-stream. Then, it was repeated with the incoming flow within the Reynolds number from 9000 to 27000, for investigating the effects of Reynolds to the flapping performance.

Figure 2-12 Experiment setup from Heathcote's study [7]

Figure 2-13 Schematic of a flexible airfoil plunging periodically in the vertical direction [7]

Heathcote stated that the deformation of the flexible airfoils could produce an imaginary angle of attack that varies periodically with the phase angle. The deformation of the flexible airfoils which respects to the pure heaving motion is indirectly acting as the combination of heaving and pitching motion with certain heaving amplitude and phase angle between the imaginary pitching motions. Figure 2-13 illustrates the heaving motion and the flexible section of the airfoil; the displacement of the trailing edge is denoted by $S_{TE}(t)$. The leading edge is plunged sinusoidally (S_{LE}) with plunge amplitude a , frequency f and c is the chord length. The free stream velocity is zero for the first run set of experiment, $U_{\infty} = 0$ m/s.

The three dimensionless parameters are:

$$h = a/c, \quad (2-11)$$

$$Re = f c^2/\nu, \quad (2-12)$$

$$K = I/\mu\nu c \quad (2-13)$$

Where $I = Eb^3/12$ (second moment of inertia). h is dimensionless parameter for the ratio of plunge amplitude to chord, Re is *Reynolds number*, f is the plunge frequency, μ is the dynamic viscosity, ν is the kinematic viscosity and K is the bending stiffness of the plate k .

Figure 2-14 Variation of thrust coefficient with Reynolds number [7]

Figure 2-15 Comparison of propulsive efficiency against other approaches [22]

From Figure 2-14, the very flexible hydrofoil has the highest thrust coefficient at Reynolds number of 9000, but it decreased to the least at Reynolds number of 20000. However, the very flexible hydrofoil can achieve the highest thrust to power ratio among the rest of the hydrofoil.

In addition, Figure 2-15 shows that the highest propulsive efficiency that the heaving hydrofoil can attain is at the Strouhal number of 0.1 and the propulsive efficiency is deteriorated at high Strouhal number.

Lastly, Heathcote concluded that, good control on the degree of flexibility at the trailing edge could improve the thrust performance and the propulsive efficiency. However, due to pure pitching motion can produce higher thrust as compare to pure heaving flapping motion [6] & [21], a similar test with pure pitching instead of heaving motion, with the flexible trailing edge, will be conducted for current study.

2-4 Flow visualization for Flapping Wings study on thrust and lift enhancement mechanism

As fluid flows are almost invisible to human's eyes, flow visualization needs to be performed in order to allow the flow pattern to be visible to us. The interaction between the flapping wings to the fluid and the creation and shedding of vortices from the flapping wings is important for the performance of lift and thrust generated by the flapping wing. As a result, conducting flow visualization enables us to obtain more information from flapping wings.

The most frequently used flow visualization technique is the dye flow visualization; however this technique can only provide very basic information which regarding the flow structure. With the advancement of technology, more information such as the velocity vector, magnitude and vorticity of the fluid flows can be obtained. Particle Image Velocimetry (PIV) is another new method that has been frequently utilized for fluid study in current day. Besides that, accurate CFD simulation also allows us to obtain the relevant information.

The main purpose for performing flow visualization is to reveal the hidden physics behind as well as to observe the vortices and the shedding vortex structure from flapping wings, for example thrust indicating Reversed Kármán vortex street. Its appearance can be further validated by the results obtained from the force measurement. Besides that, the interaction of the leading edge vortex to the flapping wings is also vital for optimizing flapping wings performance. The four major lift-enhancement mechanisms in flapping wings aerodynamics are [23]:

- Delayed stall due to Lead-Edge Vortices (LEV)

-
- Aerodynamic peak due to pitch-up rotation
 - Wake capture due to vortical flow and airfoil interactions
 - Weis-Fogh's clap and fling dynamics

Vortex shedding [24] occurs when pressure differences arise [25]. Figure 2-16 shows that, when the pressure at P_2 is lower than P_1 , the flow curls inwards and causes the upper and lower vortex to rotate clockwise and counter clockwise respectively. The detachment and shedding of the vortices at the downstream is normally known as the Kármán vortex street and it usually occurs if an object is experiencing drag [2].

The shedding of vortices will cause the object becomes unstable. Construction engineers should not design a building with a natural frequency which is close to its shedding frequency so as to prevent catastrophe (e.g. the collapse of Tacoma Bridge).

Figure 2-16 Illustration on the formation of Kármán Vortex Street

Figure 2-17 Flow visualization on Kármán Vortex Street left [26] & right [27]

Figures 2-17 (a) and (b) shows the Kármán vortex street with an unsteady periodic behaviour flow pattern over a bluff body. Figure 2-17 (b) shows the flow passing a cylinder with a diameter of 6.35 mm at Reynolds number of 168 (captured by the hydrogen bubble flow visualization technique). From this figure, the Kármán vortex street can be identified by its “mushroom head” which is always pointed to the upstream.

Its reverse phenomenon, the reverse Kármán vortex street, can be observed at the downstream of bird flapping wings, swimming fish and jet flow [2]. Figure 2-18 illustrates the flow interaction between the jet and the free-stream. The flow is being ejected directly from the jet, pushes the surrounding fluid away and causes the upper and bottom vortex to rotate counter-clockwise and clockwise respectively. Figure 2-19 shows the reverse Kármán vortex street which was captured from the fluorescence dye flow visualization conducted on flapping hydrofoil. The method for identifying the reverse Kármán vortex street is shown in Figure 2-19, where the direction of the “mushroom head” is pointing to the downstream.

Figure 2-18 Illustration on the formation of reversed Kármán vortex street of jet flow

Figure 2-19 Fluorescence dye flow visualization on flapping-based propulsion (top) and asymmetric wake (bottom) [28]

Apart from the force measurement which mentioned in the previous section, Heathcote [22] has also performed a series of flow visualization, with both dye flow visualization and PIV technique, for observing the flow structure pattern at the down-stream of flapping elastic wing. Figure 2-20 illustrates the flow pattern at the downstream of heaving hydrofoil; the reverse Kármán vortex street can also be clearly seen. The images sequence from Figure 2-21 was captured by the PIV

which shows the motion and the deformation of the elastic wing over a cycle. The PIV technique allows obtaining the velocity vector field around the heaving hydrofoil and the strength of vortices can be further derived. Hence, from his study, the flow structures from the heaving hydrofoil in different stiffness were distinguished.

Figure 2-20 Dye Flow visualization of vortices behind flapping hydrofoil, $Re = 1800$, $St = 0.29$; $b/c=4.23 \times 10^{-3}$; a) $t/T = 0$; b) $t/T=1$; c) $t/T=0.5$; d) $t/T=0.75$. [29]

Figure 2-21 Chord-wise flexible wing undergoes heaving motion over a cycle [22]

**Figure 2-22 Instantaneous velocity fields at $t/T = 0$ for $Re = 9000$, $St = 0.56$:
a) $b/c = 4.23 \times 10^{-3}$; (b) $b/c = 1.41 \times 10^{-3}$; (c) $b/c = 0.56 \times 10^{-3}$. [22]**

In 1997, Willmott P.A. [30] conducted an experiment on hawk moth (insect flight) to investigate the aerodynamic mechanisms (e.g. Leading Edge Vortex and etc) which is employed during the flight of the hawk moth. The experimental setup with hawk moth for flow visualization test is illustrated in the figure below:

Figure 2-23 Experimental Setup from Willmott's study [30]

A vertical streamlined smoke rake was placed on the centre line of the wind tunnel, upstream of the contraction area. A camera was used to capture the image, while illumination was provided by four strobe lamps, which was positioned to provide

maximum contrast between the smoke and the black background as shown in Figure 2-23 to capture a clear image.

The flight speed was simulated as the flow passing through the moth with the speed varying from 0.4 to 5.7m/s. The captured wake consists of an alternating series of horizontal and vertical vortex rings which were generated by the successive down and up strokes. Most importantly, it has proved the ability of down stroke for producing significantly more lift than the up stroke with the appearance of LEV.

The leading edge vortex (LEV) grew in size with increasing forward velocity and it acted as a mechanism for enhancing lift for many insects. A small jet provides some additional thrust as the trailing edges approach the end of upstroke.

Figure 2-24 Leading and Trailing edge vortex [30]

When the wings are in late supination (the action of wings rotation where the bottom part of the wings are facing upward), a leading edge bubble on the ventral surface of the wings appears in Figure 2-24b. This bubble is consistent with a flex mechanism for creation of circulation during isolated rotation and the circulation

remained attached to the wing, and therefore the lift is enhanced during the subsequent translation. The photo sequence from the conducted flow visualization is shown in Figure 2-25.

Figure 2-25 Flow structure captured at 0.4m/s free stream condition [30]

Next, F.T Muijres [23] conducted flow visualization and PIV test on the bat flight in order to investigate the effect of lift enhancement mechanisms. He found that the LEV helped to increase the lift by 40% on the bat, which is a heavier and larger animal as compared to insects.

Figure 2-26 Vortex structure and location for bat during down-stroke when wing is at horizontal with speed of 1 m/s [23]

The structures and location of various vortices are illustrated in Figure 2-26. There are two closed loops vortices where one is over the left and the other is over the right of the wing. The loop is connected to the start vortex and shed in the wake via the tip vortex and the root vortex, where the yellow-zone indicates low circulation and the red-zone constitutes high circulation. Figure 2-27 shows the LEV obtained from the DPIV conducted on the bat wing (in different chord-wise direction). Since LEV vortex is a type of lift enhancement mechanism which is proven to be existed in animal flight from the researches mentioned earlier. In this thesis, the flow visualization technique and direct force measurement were applied with synchronized timing for observing the forming and bursting of the LEV and investigating the performance of the lift by examine the hydrofoil which underwent simplified flapping motion quantitatively (focusing on the 2-D motion).

Figure 2-27 Velocity and vorticity fields by DPIV around bat wing in slow forward flight (1m/s) [23]

From the previous reviews of flow visualization on insects and flying animals, existence of LEV from the animals' flight is proven to affect the lift performance significantly. Next, the dynamic stall or delayed stall [31], which is a type of unsteady aerodynamics effect, is widely known as one of the important factors that greatly affect the performance of the unsteady lift generation. Hence, this section explained the dynamic stall effect. This effect occurs when the foil changes its angle of attack rapidly [32], forming a strong vortex which sheds from the leading edge of the aerofoil and travels to the back of the wing top. Lift is increased if this particular vortex sheet, which contains high velocity flow, travels above the airfoil; after the flow passes the trailing edge, the lift reduces abruptly and returns back to its normal stall.

The dynamic stall can normally be found in helicopters and flapping flights [33]. For a helicopter in forward flight, the angle of attack changes rapidly when the helicopter blade is in the reverse direction to the incoming flow. However, for flapping flights, such as that of an insect, it may rely on dynamic stall to produce lift if the flapping motion is fast enough [34].

As mentioned, the flow reversal above the airfoil will affect the pressure distribution after the wing rapidly exceeds the static stall angle (Point (b) of Figure 2-28). Subsequently, this reversal progresses up on the upper surface of the airfoil and forms a vortex, initially at the leading edge of the airfoil (Point (e) of Figure 2-28), but which is later enlarged and moved down to the airfoil.

When the pitching moment reaches its negative peak, both lift and pitching momentum start to drop (point h & i) and dynamic stall occurs. As the angle of

attack decreases, the vortex sheds into the wake and a fully separated flow develops on the airfoil. When the angle of attack reaches its minimum, the lift does not reach its minimum, indicating that the dynamic stall process has formed a hysteresis loop.

Figure 2-28 Illustration of dynamic stall event for NACA 0012 airfoil [34]

2-5 Theoretical and numerical methods for Flapping Wing study

Oi [35] has investigated the effect of dynamic stall through experiments, numerical simulation and dye flow visualization, to create a simple model, by modified the Theodorsen's equation with a simple attached flow model, for predicting lift in time history for a wide range of kinematics motion in order to benefit the engineering purposes with reasonable accuracy.

The modified model considered the following parameters which include the reduced frequency, flapping amplitude, Reynolds number and etc. As such, the lift coefficient from the modified Theodorsen's model can be represented by:

$$C_L(t) = 2\pi\alpha_0 + \frac{\pi c}{2} \left(\frac{\dot{\alpha}}{U_\infty} + \frac{\ddot{h}}{U_\infty^2} - \frac{c(2x_p - 1)\ddot{\alpha}}{2U_\infty^2} \right) \quad (2-14)$$
$$+ 2\pi \left(\frac{\dot{h}}{U_\infty} + \alpha - \alpha_0 + c(1.5 - 2x_p) \frac{\dot{\alpha}}{2U_\infty} \right) c(k)$$

The pitch and plunge are input as complex exponentials,

$$\alpha(t) = \alpha_0 + Ae^{i(\omega t + 2\pi\psi)} \quad (2-15)$$

$$h(t) = h_0 e^{i\omega t}$$

The phase lead of pitch to plunge, in the fraction of motion period is ψ , reduced

frequency is represented by $k = \frac{\omega c}{2U_\infty}$. The first term measures the steady lift, the

second term is the “apparent mass” or non-circulatory lift due to acceleration effect and the third term models the circulatory effect. $C(k)$ is the complex valued “Theodorsen's function” with magnitude less than one. It is a transfer function accounting for the lift amplitude and the phase lag response from its real and imaginary parts respectively. The assumption is based on the equation which

considers only on a planar wake and a trailing edge Kutta condition; therefore, it does not consider the wake rollup, vortex street, vortex shedding, convection of large separations over the airfoil, large laminar separation bubbles, leading edge and trailing edge vortices. However, Theodorsen's prediction and computation is not worsening in the deep stall (plunge only) as compared to the shallow stall (pitch-plunge). He suggested that the LEV formation and the reversed flow region above the suction side are not principal contributors to lift coefficient.

Lian [34] has conducted a numerical study on the pitching flat plate at low Reynolds number by unsteady, incompressible and laminar flow model (Figure 2-29). The investigation on the effect of pitch rate, Reynolds number, and location of pitch axis as well as the computational grid size were conducted and compared with the experimental results. He has found that increasing pitch rate allows the *LEV* to be more compact and stronger; secondly, moving the pitch position further from the leading edge will weaken the *LEV* on the top surface when the plate is pitching upward. As the pitch position passes the middle of the chord, the vortex appeared at the bottom surface, where it is believed to be caused by the effective angle of attack. The influence of the Reynolds number on the flow structure is depended on the pitch rate; the effect of Reynolds number is strong when the pitch rate is low; however, its effect is weak when the pitch rate is high. In addition, the computational grid size will also affect the results of the calculated aerodynamic forces; a smaller grid increases the lift generation value when the plate is pitched up.

Figure 2-29 Sample of overlapping grid [34]

Figure 2-30 Comparison of flow structures at different pitch rates by Dye Flow Visualization and CFD (Vorticity plot) [34]

Liu [20] stated that the quasi-static inviscid flow analysis is not accurate for modeling flapping wings aerodynamics. Hence, it is necessary to use the Navier-Stokes equation with a suitable turbulence model instead of laminar model. His statement is in contrast to Lian as the laminar model is not accurate for modeling the vortices. However, in recent year (2011), Patrick [36] has conducted a

numerical simulation for studying the hovering of rigid flapping wing aerodynamics by laminar flow model. He explained that, extensive numerical study based on complicated turbulence model is very time consuming and expensive.

Kang [37] conducted a simulation with original Menter's Shear Stress Transport (SST) turbulence model on rigid flat plate and SD7003 hydrofoil which undergoes pitching and plunging motion (2D condition). The governing equations used are RANS equations coupled with Menter's SST model and the continuity equation for incompressible flow. However, Menter's original SST turbulence model has a limit on the production term. Therefore, Kang modified the main equation in order to obtain a more accurate result. The modified equations are shown in the table below:

Table 2-1 original and modified SST equation [37]

	Original SST	Modified SST
Production term of TKE equation	$P_k = \mu_t \frac{\partial u_i}{\partial x_j} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$	$\hat{P}_k = \min(P_k, 10 \cdot \beta^* \rho k \omega)$
Eddy viscosity	$\nu_t = \frac{a_1 k}{\max(a_1 \omega, \Omega F_2)}$	$\nu_t = \frac{a_1 k}{\max(a_1 \omega, S F_2)}$

Figure 2-31 Illustration of the airfoil kinematic motion [37]

Figure 2-31 illustrates the heaving and pitching motion of the airfoil. The equations below explain the relationship between the motion, time and the free-stream condition.

$$h(t) = h_0 c \cos\left(\frac{2\pi t}{T}\right) \quad (2-16)$$

$$\alpha(t) = \alpha_0 + A \cos\left\{2\pi\left(\frac{t}{T} + \phi\right)\right\} \quad (2-17)$$

$$\begin{aligned} \alpha_e = \alpha_0 + \lambda \arctan(\pi St) \cos\{2\pi(ft + \phi)\} \\ + \arctan\{\pi St \sin 2(\pi St)\} \end{aligned} \quad (2-18)$$

h is the location of the center of rotation ($x_p / c = 0.25$) from the leading edge; h_0 is the normalized plunging amplitude, c is the chord length of the airfoil; α_0 is the mean angle of attack and A is the amplitude of the pitching motion.

The effective angle of attack is represented by α_e ; which is a linear combination of the pitching angle and the induced angle due to plunging motion. St is the Strouhal number and λ is ratio of the maximum effective angles of attack of the pitching motion to the plunging motion and $\dot{h}$ is the plunge-velocity, k is the reduced frequency.

(a) pitching and plunging, $Re = 6 \times 10^4$

(b) pure plunging, $Re = 6 \times 10^4$

(c) pitching and plunging, $Re = 1 \times 10^4$

(d) pure plunging, $Re = 1 \times 10^4$

Figure 2-32 Lift Coefficient time histories of pitching and plunging, and pure plunging on 2-D flat plate (blue line) and SD7003 (red line) at $k = 0.25$, $\lambda = 0.6$ at $Re = 1 \times 10^4$ and 6×10^4 , respectively [37]

Kang concluded that the modified SST turbulence model over-predicts the flow separation. For the simulation on flat plate, the leading edge effects overwhelmed the difference between turbulence models. Therefore, Kang concluded, for the flow over flat plate, in all numerical simulation approaches, the geometrical effect at

sharp leading edge is the dominating factor for triggering the separation from the leading edge for both pitching and plunging motion and causes the instability of the simulation. Hence, Guerrero [38] employed the overlapping grids method for tackling the problems of sharp edged geometry by overlapping the refined grid around the flapping hydrofoil.

2-6 Remarks from Literature Reviews

The above literature studies examined within this chapter have led the author to conduct further investigations on flapping wings aerodynamics as there is still a huge gap for the improvement; either in the field of numerical study or to optimize the performance of the flapping wings aerodynamics as the parameters that involved for flapping flight is very large. Apart from that, various approaches adopted by different researchers to obtain useful data which mentioned in this chapter have provided the author a clearer picture to develop the experimental test rig, the numerical model and a simple analytical model. Hence, this thesis will focus on the followings areas:

1. Experimental

The fish swimming and bird flying motion can be simplified as heaving, pitching or combined heave and pitch motions. With these simplified motions, the amount of actuators, which are needed to perform complex motions, can be reduced; hence, the size of these micro-vehicles can also be minimized. However, in order to investigate the capability of these simplified motion for producing lift and thrust, a test rig, which has the capability for conducting the above mentioned tasks with

low measurement uncertainty, has to be developed. Apart from that, size of test rig, ease of operation, repeatability, flow quality and accuracy of measuring tool are also act as important factors for building a good test rig. From the literature study, it is found that towing tank has its limitation on the travel distance; the corresponding test rig has to be movable and the design of the carriage is huge and complicated.

Hence, due to the above mentioned factors, this thesis will utilize a close-loop water tunnel with a simple test rig for conducting the force measurement and dye flow visualization. Chapter 3 discusses the details on the selection of equipment, the design and development of the test rig, as well as error analysis.

2. Numerical simulation and simple mathematical model

Some researchers stated that quasi-static stage of approximation, laminar and RANS turbulence model are not able to accurately predict the flapping aerodynamics properties due to the unsteadiness of flow involved. In order to predict the unsteady mechanism mentioned, a correct turbulence model has to be employed in order to portray the aerodynamics performance of flapping wings. However, time and cost for conducting extensive numerical simulation based on higher accuracy turbulence model or Direct Numerical Simulation (DNS) are always a factor that halting researchers to implement it. Apart from that, the conventional CFD solvers which utilized body fitted method are having difficulty on meshing complex geometry. The pre-simulation stage for moving object is also very tedious and the co-ordinate mapping is required in order to perform the

calculation. Chapter 4 discusses an alternative numerical simulation solver which might outperform the conventional numerical simulation solvers.

As mentioned, conducting extensive experiment and numerical simulation for obtaining accurate results for optimizing the performance of the flapping wing is very time consuming and expensive. Therefore, a simple mathematical model can be developed for reducing the time and cost for performing the optimization of flapping wings by filtered the parameters which cannot generate significant lift.

3. Flow structure analysis

In this Chapter, lift enhancement mechanism (the leading edge vortex) has been investigated by some researchers who conducted the flow visualization test on living bat or insects. The thrust indicating vortex street (the reversed Kármán vortex street) has also been found from swimming fishes. Hence, micro UAV or UWV could employ and utilize these mechanisms for enhancing the lift and thrust.

In order to better understand the flapping wings aerodynamics, the flow structures involved have to be studied in detail. Therefore, instead of repeating the study from the above mentioned researchers for just comparing the flow structure across different technique (experimental and numerical simulation) to prove the capability of their solver, this thesis will conduct combined study based on force measurement, numerical simulation and dye flow visualization to fully capture the hidden fact behinds the flapping wings aerodynamic.

Hence, this thesis will investigate the corresponding areas, which are summarized in the Table 2-2, in order to achieve the aims which are mentioned in previous chapter.

Table 2-2 Scope of study

Flapping Motions	Description	Approach
Symmetrical Heaving	Investigate the lift experienced by the SD8020 which undergoing symmetrical heaving	Experimental (force measurement) and numerical simulation
Symmetrical pitching	Investigate the lift experienced by the pitching flat plate in symmetrical pitching manner	Experimental (force measurement) and numerical simulation
Symmetrical pitching	Investigate the effect of flexibility to the thrust by symmetrical pitching SD 8020	Experimental (Dye flow visualization and force measurement)
Symmetrical combined heaving and pitching	Investigate the influences of the phase different to the thrust from combined pitching and heaving SD8020	Experimental (Force measurement)
Non-symmetrical pitching	Evaluate the ability of pitching SD7003 with non-symmetrical pitching motion to lift generation and investigate the effect of the lift enhancement mechanism (Leading Edge Vortex, LEV)	Experiment (Dye flow visualization and force measurement)

Chapter 3 Experimental Setup and Method

3-1 Overview

This chapter introduces the equipment used for current study. The equipment which were utilized for the force measurement and dye flow visualization include: water tunnel, force transducer, rotary DC motor, closed-loop servo stepper motor, linear guide and dye pump (Figure 3-22). The selection of force transducer and construction of experimental test rig is being discussed; error analysis for the force measurement is also presented in this chapter.

3-2 Water tunnel

A water tunnel is an essential tool to generate free-stream water flow across a submerged scaled model that enable users to investigate on the hydrodynamic effects by conducting experiments such as force measurement, dye flow visualization or Particle Image Velocimetry (PIV). As the water has a higher density than air, the resistance force exerts on the moving object with same geometrical property and travelling velocity is also higher. As a reason, the water tunnel is primarily utilized in the study. Hence, with larger interaction forces compared to air, the force measurement can be conducted with higher order of force and allows obtaining higher accuracy results as the measuring range is closer to the accuracy level of the force transducer. In addition, dye flow visualization and PIV measurements are also easier to be implemented in water tunnel.

Figure 3-1 shows the water tunnel used for this study. This particular water tunnel utilizes a centrifugal pump (with maximum pump rotational speed of 60Hz) that

generates a maximum free stream velocity of 0.2 m/s at the test section. The test section is made from high transparency tempered glass and array of screeners is used to ensure low turbulence intensity level at the test section. The contraction ratio is 4:4:1 and details dimensions of the water tunnel are shown in Figure 3-2.

3.2.1 Water Tunnel Calibration

The calibration of the water tunnel was first conducted by using a pitot tube. The calibrated free stream velocities (m/s) at the test section of the water tunnel, with the corresponding water pump rotational speed (Hz), are shown in Figure 3-5.

Figure 3-1 Water tunnel

Figure 3-2 Dimensions of water tunnel

Figure 3-3 Drawing of DRUCK pressure sensor [39]

Next, the turbulence intensity and uniformity of the water flow across the test section of the water tunnel is measured by the Dantec Mini CTA (Constant Temperature Anemometry) system [40]. The working principle of this CTA system is illustrated in Figure 3-6. A CTA probe contains a very thin wire that is being submerged into the stream. The amount of cooling on the wire by the flow provides a measure for the flow velocity. As a thermal anemometry, the temperature across the thin wire is being kept constant. As the free-stream passing across the wire, it reduces the wire's temperature and the system has to increase the current in order to maintain the preset temperature. Thus, the change in the electrical current and the heat exchanged can be cross-related in order to estimate the flow speed. The advantage of the CTA system is that the flow velocity can be measured with a very high temporal resolution which allowing the measurement of turbulent qualities.

Figure 3-6 Working Principle of Dantec mini-CTA system [40]

In this measurement, the Dantec mini-CTA uses a single wire probe made of thin tungsten wire (1 mm long and 5 μm in diameter) for one dimensional flow measurement as shown in Figure 3-7. The probe is then be heated up to 70 degree

Celsius by an electric current via a servo amplifier which is connected to one arm of the Wheatstone bridge. The data acquisition was then performed by using a National instrument (NI) Data acquisition (DAQ) card that is connected to the workstation equipped with LabView with the sampling rate of 1000Hz.

Figure 3-7 Location of the CTA probe in the water tunnel test section

As shown in Figure 3-7, the CTA probe measurement plane is located at the testing section of the water tunnel which measures 80% of the tunnel width which is the location where all the force measurements will be made. In addition, measurements were taken horizontally across the Y-axis and vertically across the Z-axis at 10 mm intervals as shown in Figure 3-8 below.

Figure 3-8 Location of calibration plane (distance between measuring points is for illustration only)

The flow speed measured by the CTA system is requires to be first calibrated with a pitot-tube. Subsequently, the collected data will be converted and reduced into the flow statistics using the following equations:

Mean velocity:

$$U_{mean} = \frac{1}{N} \sum_{i=1}^N U_i \quad (3-1)$$

Standard deviation of velocity:

$$U_{rms} = \left(\frac{1}{N-1} \sum_{i=1}^N (U_i - U_{mean})^2 \right)^{0.5} \quad (3-2)$$

Turbulence intensity:

$$Ti = \frac{U_{rms}}{U_{mean}} \quad (3-3)$$

$$Uniformity = 1 - \frac{\text{Standard deviation of velocity of each measured location}}{\text{mean velocity of each measured location}} \quad (3-4)$$

This calibration shows that the water tunnel has an averaged Turbulence Intensity (Ti) of 0.60% and a uniformity of 94.98%. The individual Ti and mean velocity, U_{mean} of each measuring location/point are plotted in Figure 3-9 and Figure 3-10.

Figure 3-9 Uniformity and Turbulence intensity across the test section

Figure 3-10 Uniformity and Turbulence intensity vertically from the surface to bottom of the test section

3-3 Force Transducers

Since the dynamic measurement of small forces for flapping wings is very demanding; it is important to select an appropriate force transducer. Thus, the following three force transducers have been tested:

1. OMEGA LC-601
2. OMEGA LC-703
3. ATI (Gamma SI-32.2.5)

In order to confirm the accuracy of the data, these force transducers were underwent the following tests:

1. Dead weight test
2. Dynamic test by oscillating cylinder (Chapter 5)

3-3-1 Force Transducer Suitability Analysis

First, the OMEGA LC-601 (1-axis) force transducer (Figure 3-11) was being calibrated and tested. This force sensor has the lowest operating load (909g) and provides the lowest full load scale error among these three force sensors. However, the sensing area of this force sensor was vibrating during the measurement. Hence, it was not selected as the vibration on the sensing area has seriously affects the accuracy of the results.

Figure 3-11 Omega LC-601 force transducer [41]

The second force transducer is the OMEGA LC-703 (1-axis). The maximum operating load of this force transducer is 5 Kilogram force (Kgf). Its dimensions are as shown in Figure 3-12 ($L = 38$ mm, $L1 = 14$ mm, $W = 14$ mm, $W1 = 9.5$ mm and $H = 19$ mm). Dead weight test on this particular force transducer was conducted in order to validate its accuracy level. Dead weights of 10g to 100g with 10g intervals were measured by the force transducer. The results from the dead weight calibration are plotted in Figure 3-13. 9000 data were collected per measurement with sampling rate of 100Hz. The tabulated mean, maximum and minimum values for each of data set from the respective measurements are shown

in Figure 3-13. Hence, the error which represents the difference between the mean measured values to the actual weight of the dead weight can be obtained.

This force transducer needs a complex mechanism to direct and convert the applied force to the measuring point as it can only measure the force in one direction (single axis, tension and compression). This particular test rig will be further elaborated in Section 3-4.

Figure 3-12 Omega LC-703 force transducer [41]

Weight (g)	10	20	30	40	50	60	70	80	90	100
Weight (N)	0.0981	0.1962	0.2943	0.3924	0.4905	0.5886	0.6867	0.7848	0.8829	0.981
Mean	0.0870	0.1804	0.2676	0.3617	0.4744	0.5640	0.6626	0.7618	0.8605	0.9797
Min	0.1156	0.1988	0.2904	0.3780	0.4933	0.5930	0.6887	0.7950	0.8773	1.0036
Max	0.0635	0.1550	0.2446	0.3393	0.4462	0.5359	0.6346	0.7339	0.8318	0.9453
Error (%)	-11.3150	-8.0530	-9.0724	-7.8236	-3.2824	-4.1794	-3.5095	-2.9307	-2.5371	-0.1325
Standard Deviation	0.00496	0.00488	0.00517	0.00525	0.00528	0.00508	0.00514	0.00526	0.00508	0.00594

Figure 3-13 OMEGA LC-703 force transducer calibration results

Figure 3-14 Force orientation vector on the ATI Force Transducer [42]

For the third force transducer (ATI forces and torques sensors), the forces and torques are recorded according to Figure 3-14. In order to reduce the hysteresis effect and increase the strength and repeatability, the beams structure inside the force transducer are machined from a solid piece of metal which allows the sensor to be in a monolithic structure [42]. Besides that, the semiconductor strain gauges are attached on three symmetrical beams inside the force transducer as sensing element.

The ATI force transducer has a response time of 7×10^{-4} seconds and the resonance frequency for axis F_x , F_y and T_z is 2KHz; F_z , T_x and T_y is of 1.4 KHz. With these conditions, this force transducer is suitable for this study as the operating frequency of the flapping foil is at the range of 10^1 Hz.

However, in order to ensure the collected data are accurate, dead weight calibration was also conducted with ranging (X-axis) from 10g to 100g. 9000 data were collected with the sampling rate of 100Hz. The calibration results in the mean, maximum and minimum of the recorded weight are plotted in Figure 3-15. A calibration report from the manufacturer is attached in Appendix III.

Weight (g)	10	20	30	40	50	60	70	80	90	100
Weight (N)	0.0981	0.1962	0.2943	0.3924	0.4905	0.5886	0.6867	0.7848	0.8829	0.981
Mean	0.0944	0.1992	0.2821	0.3748	0.4724	0.5733	0.6592	0.7516	0.8444	0.9386
Min	0.0909	0.1853	0.2786	0.3705	0.4696	0.5625	0.6561	0.7492	0.8419	0.9369
Max	0.098	0.2051	0.2854	0.379	0.4749	0.5764	0.6613	0.7535	0.8539	0.9402
Error (%)	-3.7717	1.5291	-4.1454	-4.4852	-3.6901	-2.5994	-4.0047	-4.2304	-4.3606	-4.3221
Standard Deviation	0.00118	0.00108	0.00099	0.00117	0.00073	0.00056	0.0006	0.00064	0.00234	0.00061

Figure 3-15 ATI force transducer calibration results (X-axis)

3-4 Construction of the Experimental Test Rig for Force

Measurement

This section discusses the selection of force transducer and the construction of its corresponding experimental fixture for the force measurement. For the first design, two sets of 1-axis force transducers (OMEGA LC-703) were used. A special fixture was designed in order to allow the action force to be recorded by these 1-axis force transducers (Figure 3-16).

Figure 3-16 Setups for double OMEGA LC-703 force transducer

From this particular setup, the action force ($\vec{F}$) can be obtained with the following equation:

$$\vec{F} = \vec{F}_1 + \vec{F}_2 \quad (0-5)$$

The major drawbacks of this setup is that the main frame is not strong enough to hold the force transducers, especially in dynamic mode, due to the size of the test model and the supporting bar that connected to the test model is rather large and

heavy. The whole apparatus became unstable when the oscillating frequency of the motor was increased. Therefore, this set of apparatuses was abandoned.

The second design of the experiment fixture (Figure 3-17) uses only one set of Force Transducer (OMEGA LC-703). The force transducer is mounted on a fixed frame by a bracket (brown color); hence, the forces acting on the body will be transferred by the ball bearing to the sensing axis of the force transducer. The moving mechanism indicated in Figure 3-17 is responsible for generating the rotation or linear motion for flapping hydrofoil.

Figure 3-17 Setups for single OMEGA LC-703 force transducer

Figure 3-18 Force diagrams

Figure 3-18 shows the force diagram for indicating the direction of forces in this measurement. The actual force, F_B , can be obtained by calculating the momentum balance by the following equations:

$$F_{LC}\Delta y_1 = F_B\Delta y_2 \quad (0-6)$$

$$F_B = \frac{\Delta y_1}{\Delta y_2} F_{LC} \quad (0-7)$$

F_{LC} represents the force detected by the force transducer, Δy_1 is the distance from the bearing to the force sensor, and Δy_2 is the distance from the bearing to the centre point of the submerged portion of the model. However, this setup has too many connections involved. Therefore, during high oscillating frequency test, the fixture lost its stability. In addition, from Figure 3-17, friction exists between the

blue and yellow block affects the final force reading which is cannot be ignored.
(Further illustration on Figure 3-24)

Figure 3-19 Experimental setups for force measurement by ATI force transducer

Due to the foregoing, the ATI force transducer was selected and replaced the 1-axis OMEGA force transducer; the entire fixture was redesigned (Figure 3-19) as well. The ATI force transducer was mounted to the fixed and stable frame in order to represent the Global co-ordinate system (X-axis indicate thrust or drag, Y- axis indicate lift or downward force). Thus, when the hydrofoil is moving, the forces will be detected by the force transducer directly. With this setup, the experimental structure is more sturdy and “cleaner” due to reduction of moving parts and simpler design.

3-5 Actuation Equipment

Two sets of actuating mechanisms were utilized in this study for generating the pitching, heaving (oscillating) or combined motions. The oscillating cylinder and oscillating hydrofoil (SD8020) tests used a simple rotary motor that incorporated with a linear guide for providing the linear oscillating motion (Figure 3-20).

The Cool Muscle high resolution closed loop stepper motor (CM-1, selected to 12,000 pulses per revolution) was used for the experiments on the symmetrical pitching flat plate and SD8020 hydrofoil (Figure 3-21) as well as the non-symmetrical pitching of SD 7003. An additional linear guide (THK linear guide) and linear actuator (Coupled the THK actuator with additional Cool muscle high resolution closed loop stepper motor) were used for the study of combined heave and pitch motion. The overview of experimental equipment in this thesis is shown in Figure 3-22.

Figure 3-20 Equipment and test rig for Oscillating test

Figure 3-21 Experiment setup for heaving and pitching of flat plate and hydrofoil

Figure 3-22 Overview of experiment setup and equipment

3-6 Experimental Precautions and Data Processing

During dynamic measurement, natural frequency of the structure plays an important role that influences the accuracy of data collected. Thus, it is vital to avoid conducting the experiment on the natural frequency of the test rig because operating a motor at the structural frequency will lead to serious vibration which causes destruction of the structure.

Therefore, a free vibration test on the selected experimental test rig was conducted in this study to obtain the structural frequency. An accelerometer was attached on the experiment fixture during the measurement. The free vibration test was conducted in two separate ways. First, the test was conducted on the main fixture with an attached stationary hydrofoil that hanging in the air. Second, the test was carried out on the main fixture with an attached hydrofoil that submerged in the water.

Figure 3-23a indicates that the natural frequency of the main fixture obtained from the first test (experiment setup with hanging hydrofoil in air) is 38.25 Hz. Next, Figure 3-23b shows the natural frequency of the test rig with the hydrofoil submerged in the water is 29.25 Hz. As the flapping frequency of this study does not exceed 5 Hz, it can be concluded that the structure can be used for the force measurements on the flapping hydrofoil.

Apart from the free vibration test, an experiment on flow over stationary foil was conducted by numerical simulation and experimental approach for obtaining its shedding frequency. The purpose of this test is to ensure the shedding frequency is not within the range of the natural frequency of the test rig. The lift force collected

from this test was further converted from time domain to frequency domain by Fast Fourier Transform (FFT) to determine the peak frequencies. Figure 3-23 (c) and (d) show the lift in frequency domain by simulation and experimental approach. Both methods produced the first peak frequency at 1.5Hz, which is representing the shedding frequency. However, from the experimental approach (Figure 3-23b), another peak frequency aroused at around 30 Hz. Refer to Figure 3-23 (a & b), the natural frequency of the test rig is about 20-30Hz; Thus, this particular frequency is the structural frequency of the test rig.

Figure 3-23 Natural frequency of the test rig without hydrofoil (a) and with hydrofoil submerged in the water (b) & FFT from (c) simulation and (d) experiment and structural frequency test (c) in air and (d) in water

Besides the above mentioned factors that might influence the accuracy of the measurement, the inertia of the body motion has to be eliminated for obtaining the results which is solely consists of the aerodynamic forces. Therefore, all tests were conducted separately in the air and water.

Furthermore, by Nyquist-Shannon's sampling theorem, the sampling rate has to be doubled of the operating frequency. The operating frequencies involved in all the experiments did not exceed 5 Hz. The selected sampling rate of the force transducer used (ATI) is 20000 samples per second with an averaging level of 200, resulting the final rate of sampling is 100 samples per second. Hence, this selected sampling rate is suitable for our application in order to collect the entire range of required signal.

In addition, the equipments were mounted on a fixed frame, which is isolated from the water tunnel, in order to prevent the vibration from the pump of the water tunnel to be detected by the force transducer. Furthermore, Butterworth filtering was also applied with the cut off frequency which is doubled of the operating frequency.

3-7 Experimental Error Analysis

The main sources of errors in this study can be identified from the force transducer, water tunnel and the experimental fixture. Hence, this section discusses the error analysis and identified the source of error for the force measurement tests. The definition of errors includes firstly, the bias (or systematic) error, which can be defined as the difference between the mean measured values to the true value and secondly, the precision (or random) error is the measurement of randomness found during repeated measurements [43].

Figure 3-13 reported the results from the dead weight test on the OMEGA LC-703 force transducer. The “error %” (bias error) represents the different from the measured value to the actual value of the dead weight in percent. From this set of dead weight test, the maximum bias error for this particular force transducer is around 11%.

Besides the bias error of the OMEGA force transducer, another hidden source of errors might be the friction between moving parts of the fixture and the stability of the structure of the main fixture. Figure 3-24 indicates that two pieces (arrow pointed) of the fixture are connected together by a screw. In this circumstance, the screw might be over tightened and causing these two pieces of fixture unmovable. Hence, a spacer with a diameter that is smaller than the bearing was used in order to allow the fixtures to be rotatable so that the reaction force can be transferred and recorded by the force transducer. However, for dynamic measurement, the movement of the whole test rig will cause vibration and affect the measurement

especially at high oscillating frequency. Therefore, these factors can cause a serious error in measurement and the uncertainty is hard to define.

Figure 3-24 Fixture for omega force transducer

Similarly, the dead weight test was also conducted for the ATI force transducer. From Figure 3-15, the maximum bias error is found to be 4.5%. Besides that, the dead weight test also shows that the ATI force transducer has a smaller bias error and better measurement precision than the OMEGA force transducer. Furthermore, this ATI force transducer allows the hydrofoil or the test model to be directly attached without extra fixtures needed for the force measurement; hence, the above mentioned factors of errors can be eliminated.

The uncertainties of the force transducer include the random and bias error [44], therefore, the combined standard uncertainty u_c for variable i can be defined as,

$$u_c^2 = u_s^2 + s_i^2 \quad (0-8)$$

where u_s is the systematic error and s_i is the standard deviation. The combined standard uncertainty for the OMEGA force transducer is more than 10%, and for the ATI force transducer is around 5%. Although the OMEGA force transducer

claims to have a higher accuracy by the manufacturer, the total accuracy of the force transducer combined with the required fixture results in an inferior accuracy compared to the experimental fixture with the ATI force transducer. Therefore, the final setup (Figure 3-19) with the ATI force transducer was selected.

The overall error is defined as the summation of all the possible errors from all involved instruments. Hence, the estimated total error for the force measurements that were being conducted in this thesis can be defined as:

$$\text{Error}_{\text{Total}} = \text{Error}_{\text{water tunnel}} + \text{Error}_{\text{Force Transducer}} \quad (0-9)$$

From the equation above, the error contributed by the water tunnel is 5%, and the maximum error for the ATI force balance at the measuring range is also approximately 5%. Hence, the total estimated error for the force measurement is around 10%.

Chapter 4 Computational Method

4-1 Overview

This chapter presents a short review and discussions on various approaches used for numerical simulation of flapping wings. The nature of flapping wing aerodynamics is generally characterized at low Reynolds number regimes, which is highly unsteady and transition from laminar to turbulent flow. As such, a solver is needed to be able to model the turbulence effects accurately to predict the performance of flapping wings. In particular, the interactions between the Leading Edge Vortex (LEV) and the Trailing Edge Vortex (TEV) and their influence on the lift and thrust generated need to be resolved.

Besides the unsteady turbulence effects have to be accurately modeled, the factors for selecting an appropriate solver includes: manipulability, procedure for preparation of mesh (pre-simulation stage), computational time and etc. Conventional solvers with body fitted meshing approach are having difficulty on meshing complex geometry and also hard for simulating moving object. In addition, conventional solvers require co-ordinate transformation in order to solve the governing equation and it is very time consuming. Hence, the following sections highlight the background, advantages and some shortcomings of the selected solver (Large Eddy Simulation with Immersed Boundary method).

4-2 Numerical simulation for Turbulence flow and Large Eddy Simulation

Amongst the various approaches to numerical simulation, the most accurate approach for evaluating turbulent flows is the Direct Numerical Simulation (DNS).

This technique solves the instantaneous continuity and Navier Stokes equations directly and is used in conjunction with an extremely fine mesh [45]. Shyy and Liu [20] have performed series of simulations for flapping wings using DNS, which are generally limited to very low Reynolds number (order of 10^2) on minuscule-scale flyers such as insects. However, DNS is unsuitable for modeling animals which travel in higher Reynolds number such as bird or bats as it requires large computational costs [46].

Most commercial solvers are based on the Reynolds-Averaged Navier-Stokes (RANS) approach [46]. Here, the Reynolds-decomposition of splitting the velocity component into a mean value and a fluctuating value ($u(x, t) = U(x) + u'(x, t)$) is applied to the Navier-Stokes equation and then the time was averaged. In this approach, the unclosed terms, which refer to the Reynolds-stresses, requires additional closure. Turbulence models were developed in order to predict the Reynolds stresses for the closure of the system of mean flow equations. RANS turbulence models can be classified according to the number of additional transport equations that needed to solve together with the RANS flow equation. For example, the K- ϵ model requires the solution of two additional equations and the Reynolds-stress model up to seven additional equations.

Since most RANS turbulence models are based on the eddy-viscosity approach, which defines the eddy viscosity ν_t to account for the effects of turbulence; some additional viscosity is introduced and thereby rendering accurate prediction of the LEV as the LEV tends to be dissipated too quickly. In order to avoid the premature dissipation of the LEV or TEV to numerical dissipation from large strokes of the

flapping wing that needed to be modeled, the RANS model is a less ideal solution as it dissipates the LEV in addition to the numerical dissipation [25].

Taking into consideration with the above-mentioned factors, the Large Eddy Simulation (LES) is an alternative approach for simulating the flapping wings. The LES model solves the low-pass filtered Navier-Stokes equations instead of time averaging [47] using a spatial filter to separate the larger and smaller eddies as the small scale turbulences are more homogeneous and less affected by the boundary condition than the large eddies and are also usually easier to model. In LES model, the large eddies [47] or large vortex structures, which usually control the main properties of a turbulent flow, are resolved (such as the LEV). Hence, the unresolved scales in LES known as Sub-Grid Scale (SGS) turbulence are modeled. Similar to Reynolds stresses in RANS, those unresolved small scale eddies is describe as the SGS stresses and require an SGS model in order to close the system equations.

As for the filtering process for LES, spatial filtering technique is employed on the unsteady Navier Stokes equations in three dimensional spaces and removes the scales of wave-numbers higher than the cut off wavenumber. The filter function $G(x, x', \Delta)$ is applied to the velocity field, the filtered velocity flow field is therefore can be represented as follow [37]:

$$\bar{U}(x, t) \equiv \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(x, x', \Delta) U(x', t) dx'_1 dx'_2 dx'_3 \quad (4-1)$$

Where $U(x', t)$ is the unfiltered flow field and Δ is the filter cutoff width. The cutoff width (Δ) is normally defined as the cube root of the grid or cell volume:

$$\Delta = \sqrt[3]{\Delta x \Delta y \Delta z} \quad (4-2)$$

Hence, after the application of filtering on the Navier Stokes equation, the filtered Navier Stokes can be represented as follow:

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial (\bar{u}_i \bar{u}_i)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j^2} - \frac{\partial (\bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j)}{\partial x_j} \quad (4-3)$$

The SGS unresolved scales are represented in the last term on the right side of the filtered Navier Stokes equation and the SGS tensor can be defined as:

$$\tau_{ij} = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j \quad (4-4)$$

The filtered continuity equation for incompressible flow can be described as:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (4-5)$$

From Equation (4-7), as mentioned, the SGS stresses have to be modeled by the SGS model in order to close the system. The standard Smagorinsky model [46] was developed by Smagorinsky in 1963. In this model, the SGS stress tensor is defined as the filtered rate of strain tensor and the turbulent stress tensor τ_{ij} can be represented in diffusive form as follow,

$$\tau_{ij} = \frac{1}{3} \tau_{kk} \delta_{ij} - 2\nu_t \bar{S}_{ij} \quad (4-6)$$

ν_t is the eddy viscosity at the subgrid scale, $\nu_t = (C_s \Delta)^2 |\bar{S}|$. C_s is the Smagorinsky constant, Δ is the filtered width and $|\bar{S}| = (2\bar{S}_{ij}\bar{S}_{ij})^{0.5}$; the filtered strain rate tensor $\bar{S}_{ij}$ are,

$$\bar{S}_{ij} = \frac{1}{2} \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (4-7)$$

However, there are several drawbacks for this standard model as it changes the model parameter C_s from one case to another. The energy is also unable to transfer from unresolved smaller scales back to the larger scales. Bardina [46] has proposed an advanced SGS model by applying two filtering operations. In dynamic model, the parameter is calculated dynamically as it is re-adjusted according to the local flow conditions by applying a second test filter that is larger than the grid filter. The resolved turbulent stresses L_{ij} is,

$$L_{ij} = T_{ij} - \widehat{\tau_{ij}} = \widehat{u_i u_j} - \widehat{u_i} \widehat{u_j} \quad (4-8)$$

The subtest stress (STS), T_{ij} is equal to $\widehat{u_i u_j} - \widehat{u_i} \widehat{u_j}$; the SGS stress and the STS are therefore can be modeled and represented in diffusive form as,

$$\tau_{ij} - \frac{1}{3} \tau_{kk} \delta_{ij} = C \alpha_{ij} \quad (4-9)$$

$$T_{ij} - \frac{1}{3} T_{kk} \delta_{ij} = C \beta_{ij} \quad (4-10)$$

From above equations, the resolved stress has become,

$$L_{ij} - \frac{1}{3} L_{kk} \delta_{ij} = C \beta_{ij} - \widehat{C \alpha_{ij}} \quad (4-11)$$

However, the above mentioned dynamic model cannot calculate the model parameters directly and requires further modeling. Thus, in 1986, Germano [46] proposed a different approach to decompose turbulent stresses which formed the basis of the dynamic SGS model. The SGS and STS stresses in Germano proposed model are,

$$\tau_{ij} - \frac{1}{3} \tau_{kk} \delta_{ij} = 2 C_d \Delta^2 |\bar{S}| \bar{S}_{ij} = C_d \alpha_{ij} \quad (4-12)$$

$$T_{ij} - \frac{1}{3}T_{kk}\delta_{ij} = 2C_d\widehat{\Delta^2} \left| \hat{S} \right| \hat{S}_{ij} = C_d\beta_{ij} \quad (4-13)$$

The dynamic constant C_d is,

$$C_d = \frac{\hat{S}_{ij}L_{ij}}{\beta_{kl}\bar{S}_{kl} - \widehat{\alpha_{mn}}\bar{S}_{mn}} \quad (4-14)$$

Germano suggested that the model parameter has to be in homogeneous direction for avoiding numerical instabilities when the denominator of the dynamic constant (C_d) becomes zero. This particular dynamic model was reviewed by Leisieur and Metais (1996) than by Maneveau and Katz (2000) [46]. The advantage of this dynamic model is that the constant of the Smagorinsky model is computed from the resolved flow field, and hence, does not need to be defined beforehand.

The LES computation can be done with less effort and less computational time than a comparable DNS computation although it still requires fine meshes [45]. As such the computational costs are still higher than a RANS simulation. However, since the Large Eddy Simulation (LES) is an inherently unsteady approach, it is more suitable for the solution of transient cases combining the advantages of the DNS and RANS methods [47]. The LES approach with Germano proposed dynamic SGS model was therefore chosen for the numerical simulations in this thesis.

4-3 The Immersed Boundary (IB) method

Most of the conventional CFD codes use body fitted meshing technique for the discretization of the flow domain. However, for moving bodies within the flow, it requires re-meshing of the flow domain at every time-step. This can be time-consuming as well as a source of error as the automatic meshing between time-steps can yield distorted cells and negative volumes. This study uses a different approach, the Immersed Boundary (IB) Method, to describe the moving body inside the flow and the governing equations are formulated on a simple Cartesian grid. The body is represented with a body force term in the governing equations. As such, the body is “immersed” in the grid as shown in Figure 4-1, and is not aligned with the mesh cells. The “immersed” body in the domain can be defined as a series of linked points.

Figure 4-1 An immersed body in the simple Cartesian grid; Ω_b as body with boundary label as Γ_b and fluid domain Ω_f

The IB method has been formulated first by Peskin [48] for the purpose of simulating the blood flow in the heart. The main advantage of the IB method [49] is the simulation of moving objects in the flow. This is because the grid does not

need to be re-generated for each time step – which is the key difference from body fitted mesh methods [50].

The movement of the object boundary is incorporated simply by changing the body force term rather than re-meshing the flow domain and is hence, computationally less expensive [51]. In addition, complex geometries that are difficult to mesh using body-fitted meshes can also be solved with the immersed boundary method as only one Cartesian mesh is required. Furthermore, the simulation of the flow phase is very efficient as the solver can be optimized for an orthogonal hexahedral mesh. Since the code is based on the Navier Stokes equation (Equation 4-15); we can assume:

$$L(\underline{U})=0; \quad \text{in } \Omega_f \text{ (fluid domain)} \quad (4-15)$$

Where $\underline{U} = \underline{U}_\Gamma$ on Γ_b ; $L(\underline{U})$ indicates the governing equation in the fluid with the domain of Ω_f ; L is the operator of the Navier-Stokes equations and $\underline{U} = (\vec{u}, p)$. Γ_b represents the boundary of the immersed solid body Ω_b (Figure 4-1). In the conventional CFD code, the governing equation will be discretized into the body fitted grid, which is followed by the boundary conditions applied at the boundary grid point Γ_b . However, in the immersed boundary (IB) method, the forcing function will instead be added to the governing equation and can be classified into two approaches - the continuing forcing approach and the discrete forcing approach. For the solver that is employed in this study, a discrete approach was implemented. From Equation (4-16); the first two terms on left hand side represent the inertia term; while the right hand side represents the divergence of stress and body forces term.

$$\rho\left(\frac{du}{dt} + u \cdot \nabla u\right) = -\nabla p + \mu \nabla^2 u + F \quad (4-16)$$

After the Navier Stokes equation have been discretized; on a particular grid point (I,j,k) with the array of $[nx, ny, nz]$ in x, y, z direction, the discretized equations can be represented as:

$$\frac{\vec{u}_{ijk}^{n+1} - \vec{u}_{ijk}^n}{\delta t} = \overrightarrow{RHS}_{ijk}^{n+1/2} + \vec{F}_{ijk} \quad (4-17)$$

$$\overrightarrow{RHS}_{ijk}^{n+1/2} = \overrightarrow{RHS}\left[\frac{1}{2}(\vec{u}_{ijk}^{n+1} + \vec{u}_{ijk}^n)\right] \quad (4-18)$$

$$\overrightarrow{RHS}(\vec{u}) = -\rho u \cdot (\nabla u) - \nabla p + \mu \nabla^2 u + F \quad (4-19)$$

The right hand side vector $\overrightarrow{RHS}_{ijk}^{n+1/2}$ includes convective, diffusive and pressure term that were being calculated at the intermediate time step of $t^{n+1/2}$. At the moment when the particular point coincides with the immersed boundary, the discrete boundary condition is applied and the forcing term becomes:

$$\vec{F}_{ijk} = \frac{\vec{u}_{\Gamma,ijk}^{n+1} - \vec{u}_{ijk}^n}{\delta t} - \overrightarrow{RHS}_{ijk}^{n+1/2} \quad (4-20)$$

The boundary force is applied on the grid next to the immersed boundary and interpolated on the contour. The flow inside the immersed boundary is set to zero and no forcing term will be included on these grids. The boundary force is calculated at P_B , which is next to the point P_1 (equivalent to immersed boundary point P_{IB}) by interpolating the condition given from the surrounding grid points from P_1 to P_4 (Figure 4-2).

Figure 4-2 Boundary force conditions [52]

The pressure condition applied in the immersed boundary method is the same as the methods from body fitted or staggered grid. The pressure boundary condition for non-moving immersed boundary and the von Neumann pressure boundary condition are applied on the boundary of the body.

$$\nabla p \cdot \vec{n} = 0 \quad (4-21)$$

Figure 4-3 Location of immersed boundary

However, the location of the immersed boundary is important for the implementation of the pressure boundary condition. In Figure 4-3, the left graph indicates that the last interior point is a cell center of the grey color cell, while the

right graph indicates that the last interior point is the staggered grid point. Therefore,

$$\nabla p \cdot \vec{n} = \left(\frac{dp}{dx}\right)|_B = 0 \quad (4-22)$$

For the first case, the pressure condition can directly utilize the traditional approach for body fitted staggered grids by setting $p_{i-1} = p_i$. However, for the second case, the face W is an interior point and the pressure gradient is not equal to zero. Therefore, in order to apply the pressure boundary condition, it needs the information from the boundary point B, subsequently interpolating from point B to the grid point on the cell face W.

The method of applying the boundary condition on a body-fitted or staggered-grid is to set the pressure value of first exterior point P_B equal to first interior point P_p (Figure 4-3, left). Hence, this particular approach inspired the method of setting the pressure boundary condition on the immersed boundary method.

Figure 4-4 Location of P_p and P_B [42]

$$P_{i,j} \approx \cos^2(\alpha)p_{i+1,j} + \sin^2(\alpha)p_{i,j+1} \quad (4-23)$$

$$\cos^2(\alpha) = \frac{disty^2}{distx^2 + disty^2} \quad (4-24)$$

$$\sin^2(\alpha) = \frac{distx^2}{distx^2 + disty^2} \quad (4-25)$$

From Figure 4-4b, the pressure at P_B can be calculated by its neighbor values and with the direction normal to the immersed boundary. The pressure ($P_{i,j}$) on a particular grid can be represented by Equation (4-23).

Figure 4-5 Simulation setup (masking)

For the dynamic mode of simulation, the IB method requires the mask to be re-generated for every time step (Figure 4-5). However, the same mesh will still be used. The co-ordinate of the object will integrate with the code that allows it to move (translating, rotating or combined translation and rotation) relative to the original position. The velocity boundary condition (on the boundary) for moving non-slip wall can be represented as:

$$\vec{u}_\Gamma = \vec{u}_\Gamma(\vec{x}, t) \quad (4-26)$$

Lastly, the pressure on the moving boundary can be represented as:

$$P_{i,j} = \cos^2(\alpha)(1 + \frac{\partial p}{\partial x}\Delta x)p_{i+1,j} + \sin^2(\alpha)(1 + \frac{\partial p}{\partial y}\Delta y)p_{i,j+1} \quad (4-27)$$

Figure 0-6 Pressure boundary conditions

As discussed in the beginning of this chapter, body fitted approach requires highly skilled person to perform the meshing for complex geometry. Besides that, the preparation for conducting simulation of moving object is also tedious. Therefore, IB method seems promising for improving the shortcomings from the conventional solver as IB method only uses a simple Cartesian mesh which does not require re-meshing at every iteration for simulating moving object; in addition, no transformation of co-ordinate is needed for solving the governing equation; hence, the pre-simulation stage can be easily performed. In addition, Gianluca [53] also stated that the calculation from IB method is more efficient than the conventional CFD approaches.

However, there are some shortcomings for the IB method; for example, similar to RANS solver; IB method is also having difficulty on handling geometry with sharp edges [37]. Apart from that, most of the IB techniques are having difficulty on the issue of mass-conserving at the moving boundary, and causes wiggles appear around the moving object and high frequency oscillation noise appeared on the

forces and pressure curve. Therefore, ghost cells and cut cell method were developed for solving this difficulty although these approaches will complicate the solver code. Hence, besides these two methods, the effect from wiggles or high frequency peaks can be resolved by reducing the time steps from a particular grid resolution or improving the grid resolution from a fixed time step (Figure 4-7) [54].

Figure 4-7 Time history of pressure drag coefficient for oscillating cylinder on different grid resolution with fixed time step of 0.002 seconds (left) and different time step with fixed grid resolution, $D/\Delta x = 16$ (right). [54]

As a conclusion, due to all the shortcomings from the conventional solver with body fitted meshing approach which employed RANS turbulence model, the Large Eddy Simulation (LES) with Immersed Boundary (IB) method was evaluated for its ability on flapping wings study in this thesis. The development of the LES flow solver, which is selected for this thesis, will be discussed in the next section.

4-4 The Flow Solver

The original LES solver was developed and validated by Pierce [47] for the simulation of variable density flows with non-premixed combustion. The incompressible part of this solver was used for this study and combustion and scalar transport were not considered. The code is based on the finite volume method using staggered grids and on three dimensional Cartesian grids. The geometrical properties in the z-direction were kept constant for efficiency as well as the principal motion in this study is remained in two dimensional (Heaving and pitching in X-Y plane).

In order to solve the momentum equations, current solver uses a pressure correction technique. An initial “guess” pressure value will be used to calculate the velocity flow field where the momentum equations are solved by iterative, semi-implicit technique and only the cross flow direction is treated implicitly. Next, in the correction step, Fast-Fourier transform is only applied to the z-direction of pressure Poisson equation and compute the “corrected” pressure, followed by updating the velocity. This “correction” procedure will be repeated until the velocity field is converged.

Besides that, first order Runge-Kutta method is employed for the first iteration and the Poisson equation is solved in order to determine the pressure field by Multi-Grid (MG) or Successive Over Relaxation (SOR) solver. The Immersed Boundary (IB) method is implemented in the code for simulating the moving boundary. The original code was verified by Heieck [31], Theissen [49] and Zhang [55].

4 -5 Simulation Setup and Summary

In this thesis, numerical simulations on the oscillating cylinder, heaving hydrofoil (SD8020) and pitching of the flat plate were conducted for evaluating the accuracy of current solver. The example of the mesh structure (resolution: $320 \times 320 \times 32$) is shown in Figure 4-8, with a two dimensional hydrofoil located in the denser region. The length and width of the control volume for this simulation is labeled in terms of the chord length (c).

Figure 4-8 Grid resolution of 320x320x32

In order to validate the results from the numerical simulation with the experimental approach, the boundary and flow conditions have to be fixed across these two approaches. Therefore, the free-stream velocity (Reynolds number), size of model, dimensions of control-volume and the moving frequency of the model are in the same scale. Apart from the above conditions, the neighboring meshes from the immersed body, including the entire area of moving boundary, are finer as

compared to the meshes from another location. The purpose is to reduce the computational time for doing fewer calculations in less important areas.

The Courant Friedriches Lewy (CFL) numbers, which were investigated in this study, are ranged from 0.1 to 1. Within a simulation, the CFL number was fixed instead of fixing a constant time step for maximizing computing speed. The CFL number is also known as the Courant number. It is defined as the ratio of the free-stream velocity to the fraction of the dimensionless length of transport per time step from the simulation. In addition, the input parameters have to be converted into a dimensionless value as below:

- i) Reynolds number, Re ,

$$Re = \frac{\rho V d}{\mu} \quad (4-28)$$

- ii) Dimensionless oscillating amplitude, $\hat{A}_0$,

$$\hat{A}_0 = \frac{A_0}{d} \quad (4-29)$$

- iii) Dimensionless Oscillating frequency (Strouhal Number), St ,

$$St = \frac{f_0 d}{V} \quad (4-30)$$

where ρ is the density of the fluid, μ is the dynamic viscosity of the fluid, V is the free-stream velocity, A_0 is the actual oscillating amplitude, d is the reference length and f_0 is the actual oscillating frequency.

Throughout a simulation run, the reference length has to be fixed. For example, the reference length (d) for the oscillating cylinder is the actual diameter of the cylinder; the reference length in this case has to be fixed across Equation (4-28) to

(4-30). For the pitching and heaving hydrofoil and flat plate, the reference length is referring to its corresponding chord-length c .

In this chapter, the discussion on various turbulence models, the pros and cons of body fitted and immersed boundary approaches, and also the development of the current solver is presented. In summary, due to the unsteadiness of flow generated by flapping wings and the shortcomings of the conventional simulation solver, this thesis evaluated a novel numerical solver, which employed the LES turbulence model with the IB method, for the study of flapping wings.

4-5 Grid Independence Test

In numerical simulation, the mesh resolution is a very important factor affecting the accuracy of the calculations. The results may be inaccurate if the mesh is too coarse and the computational time will be significantly large if the mesh resolution is too high. Hence, this section presents one of the grid independence tests from this study. In order to obtain suitable mesh resolution for accurate numerical results, three different mesh size, $64 \times 64 \times 32$; $192 \times 192 \times 32$ and $384 \times 384 \times 32$ were applied for conducting the grid independence test.

This grid-independence evaluation is based on the test case of a symmetrically pitching flat plate with pitching amplitude of 20 degrees and rotational speed of 50 degrees per second; the corresponding Re_{chord} is 8000. These parameters are exemplary for all simulations conducted here. Figure 4-9 shows the simulation results with various mesh resolutions. The lift coefficient obtained from the mesh resolution of $384 \times 384 \times 32$ and $192 \times 192 \times 32$ are almost identical. Therefore, the mesh resolution of $192 \times 192 \times 32$ is considered adequate for this study.

Lastly, the parameters and simulation-conditions utilized for all prior work, together with an overview of the numerical simulation are summarized in Table 4-1.

Figure 4-9 Lift coefficients versus time plot

Table 4-1 Overview of the numerical simulation

	Oscillating cylinder	Heaving SD8020	Pitching Flat plate
SGS model	Dynamic Smagorinsky model		
CFL numbers	0.1 – 1		
Reynolds number	4,000	192,000	4,000 to 192,000
Number of time steps for initial divergence limit	20		
Number of iterations per	10		

time step			
Convergence tolerance	10^{-3}		
Mesh resolution	192 x 192 x 32 384 x 384 x 32	192 x 192 x 32 320 x 320 x 32 480 x 480 x 32	64 x 64 x 32 192 x 192 x 32 384 x 384 x 32 640 x 640 x 32

Chapter 5 Results and Discussion

5-1 Chapter Overview

This chapter presents and discusses the results obtained from the experiments and numerical simulations. The main factors which affect the flapping wings' generation of lift and thrust are as follows:

- Flapping frequency,
- Flapping amplitude,
- Flapping pattern (the heave, pitch or both),
- Reynolds number (factors of density, free-stream velocity, geometrical property and dynamic viscosity of the fluid).

A series of experiments (including direct force measurements, dye flow visualizations) and numerical simulations were conducted to study flapping wings' aerodynamics, these tests include:

1. Investigation to validate the result obtained from CFD solver to experimental setup for dynamic force measurements on an oscillating cylinder in a free-stream.
2. An oscillating hydrofoil was studied to further validate the CFD solver data so as to determine the capability of the symmetrical heaving mode to generate lift and thrust.
3. A symmetrical pitching flat plate was studied through both CFD and experimental approach at different free-stream velocities and pitching parameters to ascertain its lift performance. Apart from that, a simple

mathematical model for predicting lift from pitching flat plate was developed based on this set of study (Chapter 6).

4. Dye flow visualization and direct force measurement was conducted on symmetrical pitching SD8020 (with and without flexible trailing edge extension) to evaluate the effects of flexibility of flapper to the thrust.
5. The lift enhancement ability of the Leading Edge Vortex (LEV) was investigated through direct force measurement and dye flow visualization on non-symmetrical pitching of SD 7003 hydrofoil.

5-2 Oscillating Cylinder

The ability of the current experimental test rig and the CFD solver to obtain accurate measurements of small scale dynamic forces is important. Hence, static dead weight test on the force transducer and calibration of other equipment were conducted. Additionally, an oscillating cylinder test were performed to ensure the credibility of the research data as the results obtained from this oscillating cylinder test were validated to the results from the literature of Gopal [56]. Referring to Gopal's study, the force measurement was conducted in two phases: firstly, in water and secondly, without water (in air) to eliminate the inertia effects from the oscillating cylinder.

The non-dimensional frequency (Strouhal number) is defined in the following equation,

$$St = \frac{f_0 d}{u} \quad (5-1)$$

where f_0 is the actual oscillating frequency, d is the reference length (diameter of cylinder) and u is the free-stream velocity. The oscillating motion is described in the following equation,

$$Y(t) = Y \sin(2\pi f_0 t) \quad (5-2)$$

where Y is the maximum amplitude.

The experimental setup for oscillating cylinder is shown in Figure 5-1. The cylinder is attached to the force transducer; a linear guide is used to convert the rotary motion into a linear oscillating motion. The cylinder oscillates in sinusoidal motion with fixed amplitude in the cross-wise direction (Y-axis). The fluid flows past the cylinder in the perpendicular direction (X-axis). The same non-dimensional parameters applied in the Gopal's study were re-used for ease of comparison.

The diameter of the cylinder is 25 mm and the ratio of oscillating amplitude to cylinder diameter is 0.3. The test was conducted at $Re_{cylinder}$ of 4,000 which corresponding to the free-stream velocity of 0.16 m/s. A force transducer is fixed between the cylinder and the linear guide, with a sampling rate of 100 samples per second. Following the Nyquist-Shannon sampling theorem, this sampling rate is adequate, given that the maximum operating frequency is only 1.5Hz. Butterworth filtering was also applied at the cut off frequency of 5 Hz to filter any unwanted noises.

Figure 5-1 Experimental Setup

Figure 5-2 Simulation setup

The numerical simulation setup for the oscillating cylinder is shown in Figure 5-2. The parameters involved were cross-referred to the Gopal's test. The cylinder is located in between two free slip walls. The direction of flow is from the left toward the right with the prescribed Reynolds number. Similar study has also been conducted by Zhang [57] and Theissen [49], therefore, the grid independence test was not conducted in this work.

The following three parameters are measured from the study: First, mean drag coefficient (C_{dm}), which is defined as averaged value of instantaneous drag

coefficient over a time period T (Equation 5-3). The second and third parameters (Equation 5-4 and 5-5), which include oscillating drag (C_{do}) and oscillating lift (C_{lo}), was defined as the standard deviation of the mean drag or lifts coefficients (C_{dm} or C_{lm}) respectively.

$$C_{dm} = \frac{1}{T} \int_0^T C_d(t) dt \quad (5-3)$$

$$C_{do} = \sqrt{\frac{\sum_{i=0}^n (C_d(i) - C_{dm})^2}{N - 1}} \quad (5-4)$$

$$C_{lo} = \sqrt{\frac{\sum_{i=0}^n (C_l(i) - C_{lm})^2}{N - 1}} \quad (5-5)$$

C_{do} denotes the oscillating drag coefficient. C_{lo} denotes the oscillating lift coefficient and N is the total number of experiment data. The drag coefficient (C_d) and lift coefficient (C_l) obtained for the oscillating cylinder test are presented in Figure 5-3 and Figure 5-4.

Figure 5-3 Oscillating Lift Coefficient versus non-dimensional frequency

Figure 5-4 Mean and oscillating drag coefficient versus non-dimensional frequency

From Figure 5-3 and Figure 5-4, the magnitude and the trend of the lift and drag coefficients determined by the CFD solver and force measurement are considerably close to the literature data. The sudden increased in these coefficients between the Strouhal number of 0.15 to 0.2, which is due to the resonance of the oscillating frequency and the natural shedding frequency [56], can also be predicted by current solver and test rig. The main reason for the experimental oscillating drag coefficient to be relatively larger is due to the minuet range of force measured, which is below the order of 10^{-2} N. At high Strouhal number, the actuating mechanism that converts the rotary motion to linear motion became unstable, thus, the excessive vibration on the test rig caused the drag reading to fluctuate. Therefore, in order to avoid excessive structural vibration, another set of test rig is developed and employed for the rest of the study.

Although the measured forces are extremely small (in the scale of 10^{-2} N and below), the results reflected from the current experimental setup and computational

method agree considerably with the literature results in determining the dynamic forces (10^{-2} N and above, from mean drag coefficient). In conclusion, since the scale of measured forces for flapping wings study is above the scale of 10^{-1} N and coupled with the dead weight test, the accuracy of the results obtained for the flapping wings study can be assured. Furthermore, with this particular test, the limit of the test rig, the force balance and simulation solver can be determined.

5-3 Symmetrically Heaving/Oscillating SD8020 airfoil

Having established the accuracy of the experimental setup and the LES solver in predicting forces of periodically oscillating bodies at low Reynolds numbers, the setup and solver were applied to an oscillating hydrofoil (SD8020), to assess its ability to create lift and thrust.

In this section, the experimental setup (Figure 5-1) was identical to the oscillating cylinder experiment described in the previous section. The airfoil has a chord-length of 120 mm and a span-width of 400 mm. The corresponding flow condition is Re_{chord} of 19200 (free-stream velocity of 0.16 m/s); the heaving amplitude of the oscillating foil is 5 mm and four different heaving frequencies are applied. The properties of the flapper are highlighted as below:

Flapper profile	: SD 8020 (experimental)
	SD 8020 with truncated trailing edge (Numerical simulation)
Chord-length	:120 mm
Span-width	: 400 mm
Pivot point	: Quarter chord

Non-dimensional parameters corresponding to the experiment parameters were used for the computational analysis. The sharp trailing edge of the airfoil (Figure 5-5, right) was modified slightly to avoid its appearance within a single cell which causes difficulties in numerical modelling given that no unique boundary condition exists. The simulations were run on 8 processors over 5 periods. It took 3 days to complete a simulation with mesh resolution of $320 \times 320 \times 32$ and one week to complete the simulation with mesh resolution of $480 \times 480 \times 32$.

Figure 5-5 Simulation setup (left) and Truncated trailing edge SD8020 for numerical simulation (right) [58]

No.	RPM	frequency (Hz)	non dimensional freq
a	50	0.83333333	0.5
b	65	1.08333333	0.625
c	77	1.28333333	0.8125
d	90	1.5	0.9625

Figure 5-6 Motor rotational frequency for heaving motion of SD8020

Figure 5-7 Lift coefficient (C_L) versus time plot (Simulation and Experiment) from heaving airfoil with heaving frequencies of (a) $f = 0.833\text{Hz}$, (b) $f = 1.083\text{Hz}$, (c) $f = 1.283\text{Hz}$ and (d) $f = 1.5\text{Hz}$

Figure 5-7 compares the lift coefficients from the heaving hydrofoil by experiment and numerical simulation. The experimental results are represented by blue dots while the simulation results are represented by the continuous red curve. The range of the oscillating frequency is from 0.833 Hz to 1.5 Hz which corresponds to the Strouhal numbers of 0.5 to 1.

The trend and magnitude of these results obtained from both approaches are having good agreement. At lower frequencies, the disagreement is due to the deterioration in the accuracy of the force transducer in the measurement of small forces. The error bars in Figure 5-7 show the manufacturer's estimate of the maximum error (0.24 N). At low frequencies, the loads are small and lead to a large relative error in

the readings. At higher frequencies, the relative error decreases and the agreement between experiment and simulation results improve. Cross checking the experimental data, the computational data allows an assessment of both approaches since possible sources of errors in one approach may not be present in the other.

Next, it is also possible for this set of experiments to examine the symmetrical oscillating airfoil's ability to generate lift. It can be seen from Figure 5-7 that the magnitude of the peak of the lift curve increases with higher oscillating frequency. This is because the increase in oscillating frequency causes greater momentum of the fluid transferred to the hydrofoil. As the heaving direction is changed suddenly when the airfoil reaches the maximum heaving amplitude, the peak of the aerodynamic forces is produced [34].

However, the positive lift from the first half heaving cycle is always cancels out with the negative lift from second half heaving cycle. As a result, the averaged lift over entire heaving cycle is always zero. On the other hand, the results show that a half-cycle of the flapping motion with higher flapping frequency might be able to produce significant lift. Hence, in order to produce a non-zero averaged lift, the second half-cycle of the flapping motion needs to be altered or adjusting the flapping frequency to reduce the downwards force. In order to discover a suitable flapping pattern which is able to produce lift, other types of flapping motions (symmetrical and non symmetrical pitching motion) will be investigated.

5-4 Symmetrical Pitching of Flat Plate

In this section, the study on symmetrical pitching flat plate with different combinations of pitching amplitudes and rotational speeds is discussed, since the tests from the previous section were unable to obtain a set of flapping parameters which can produce significant positive averaged lift as the pitch-only motion is the other extreme compared to the heave-only motion. Hence, this section provides results on the pitch-only motion spectrum. Experiments on non-symmetrical pitching modes will be presented in Section 5-6.

Figure 5-8 Experimental setup (left) and Numerical setup (right)

Force measurement and numerical simulation were also conducted on a flat plate with symmetrical pitch-only motion in this set of study. The DC rotary motor was replaced by a high resolution Cool-Muscle stepper servo motor. The flapper properties are as below:

Flapper Profile	: Flat plate	Span-width	: 320 mm
Chord-length	: 120 mm	Pivot point	: Quarter chord

The differences between the symmetrical and non-symmetrical pitching mode are illustrated in Figure 5-9. For symmetrical pitching motion (Figure 5-9a), the up-pitch and down pitch angles and speeds are equal ($\alpha_1 = \alpha_2$ and $\omega_1 = \omega_2$). However, in non-symmetrical pitching motion (Figure 5-9b), the up-pitch and down pitch angles and speeds are different ($\alpha_1 \neq \alpha_2$).

Figure 5-9 (a) Symmetrical and (b) Non symmetrical pitching up and down motion

5-4-1 Investigation into the effects of the pitching parameters and free-stream velocity on lift in the symmetrical pitching mode

This sub-section compares the results obtained from the numerical simulations (LES) and force measurements on an oscillating flat plate which was undergoing pitch-only motion. Investigations on this particular pitching mode on the lift can be divided into two areas: First, the effect of pitching parameters with fixed free-stream velocity, and second, the effect of free-stream velocity with fixed pitching parameters. Table 5-1 summarises all the pitching parameters and their corresponding Reynolds numbers in the conducted tests.

Table 5-1 Pitching parameters and its corresponding Reynolds numbers

Pitching parameters	Reynolds numbers
Pitching amplitude (α): 40 degrees Rotational Speed (ω) : 100degree/second	4000 & 19200
Pitching amplitude (α): 20 degrees Rotational Speed (ω) : 50 degree/second	4000 & 19200
Pitching amplitude (α): 20 degrees Rotational Speed (ω) : 100 degree/second	4000, 8200, 12240, 16320 & 19200

The phase-averaged time history lift coefficients plots from the LES computations and force measurements for these tests mentioned in Table 5-1 are shown in Figure 5-10 and Figure 5-11. The error bars shown in these graphs are labelled according to the maximum error given by the manufacturer's specification (0.24 N). Phase averaging was applied to the results obtained from the LES computations (3 pitching cycles) and the force measurements (10 pitching cycles). Similar to the previous set of studies, Figure 5-10 and Figure 5-11 show that the results from simulation and experimental approach are close to each other in term of trend and magnitude. However, the discrepancy between these results might due to the sharp corner of the pitching plate existed in the simulation. Apart from that, the motion provided by the actuator might be slightly different to the prescribed motion in

numerical simulation. In order to obtain better agreement between these approaches, the time-step or the grid resolution plays as a very important role.

Re = 4000

Re = 19200

Figure 5-10 Time history of phase averaged lift coefficient plots of pitching flat plate at Reynolds number of 4000 (left column) and 19200 (right column)

Figure 5-11 Time history of phase averaged lift coefficient of pitching flat plate with pitching amplitude of 20 degrees and pitching speed of 100 degree/second at Reynolds number of 8200, 12240 and 16320

The following section discusses the effects of pitching parameters and Reynolds number to the lift. These results were re-arranged from Figure 5-10 and Figure 5-11 for the ease of comparison. The rationales for presenting the following charts in lift force instead of lift coefficient are, firstly, to reflect the actual measurement scale. Secondly, to compare the results across different Reynolds numbers. The lift coefficient for the cases with smaller force and very low free-stream velocity might be higher than the cases which have a larger lift but experiencing higher free-stream. Hence, in this circumstance, investigation of lift performance by lift coefficient is inappropriate.

To examine the effect of pitching amplitude, the following tests were conducted. The Reynolds numbers was fixed at 4000, corresponding to a free-stream velocity of 0.034 m/s. Figure 5-12 shows that, at the pitching speed (ω) of 100 degree/second, the pitching amplitude (α) of 40 degrees has a higher peak value of lift and it is almost 2.5 times higher than pitching amplitude of 20 degrees.

Figure 5-12 Phase averaged lift force of pitching flat plate with $\alpha=20$ degrees and 40 degrees to fixed $\omega = 100$ deg/s at $Re = 4000$

Next, in order to investigate the effect of pitching speed, the Reynolds number was fixed at 4000 and the pitching amplitude was also fixed at 20 degrees. The selected pitching speeds were 50 degrees per second and 100 degrees per second. Figure 5-13 shows that higher pitching speed allows higher lift peak to be produced. The peak lift from the red curve for rotational speed of 100 degrees per second is 3.75 times higher than the blue curve (50 degrees per second).

Figure 5-13 Phase averaged lift force of a pitching flat plate with pitching amplitude of 20 degrees and pitching speed of 50 degree/second and 100 degree/second

For the following study, investigations on the effect of the free-stream to the pitching plate were conducted across two test cases. First, the pitching amplitude (α) was 20 degrees and the pitching speed (ω) was 50 degrees per second; and the second case, the pitching amplitude was 40 degrees and the pitching speed was 100 degrees per second. The Investigated Reynolds number were 4000 and 19200. From Figure 5-14, which corresponds to the case of fixed pitching amplitude of 20 degrees and pitching speed of 50 degree per second, it shows that with the

increases in Reynolds number, the peak value of lift is also increased from 0.4 N to almost 2.5 N.

In another situation, for larger pitching amplitudes of 40 degrees (beyond static stall angle of attack) with fixed pitching speed; Figure 5-15 shows that, the same magnitude of lift peak is produced across the Reynolds number of 4000 and 19200. Therefore, it shows that, increases of the Reynolds number does not increase the magnitude of the peak of lift for the pitching amplitude which is beyond the static stall angle.

Figure 5-14 Lift curve for pitching flat plate with pitching amplitude of 20 degrees and pitching speed of 50 degree/second to the Reynolds numbers of 4000 and 19200

Figure 5-15 Lift curve for pitching amplitude of 40 degrees and pitching speed of 100 degree/second with Reynolds number of 4000 and 19200

Figure 5-14 shows that increases of Reynolds numbers leads to increases of the lift peak magnitude with fixed pitching parameters. Figure 5-14 and Figure 5-16 also show that the Reynolds number is the dominating factor for influencing the peak magnitude of lift but with the pitching amplitude lower to the static stall angle of attack.

Therefore, the above presented results (Figure 5-12 and Figure 5-13) indicate that, larger pitching amplitude and speed are suitable for the flapping vehicles to generate high lift or thrust at the beginning of flight in order to take off or accelerate from slow speed. The results from Figure 5-15 shows that large pitching amplitude is unable to increase the lift peak at high Reynolds number; but Figure 5-14 further reveals that lower pitching amplitude will be more suitable for retaining lift or thrust during high travelling speed as the lift increased significantly with higher Reynolds number.

Since large pitching angle, which is above static stall angle of attack, did not able to obtain higher lift while increasing the Reynolds number, therefore, in order to have detail investigation of the effect of free-stream, both force measurement and numerical simulation were performed with the following conditions:

Reynolds numbers: 4000, 8200, 12240, 16320 and 19200;

Fixed pitching parameters of:

Pitching amplitude, α = 20 degrees

Pitching speed, ω = 100 degree/second

Figure 5-16 Lift curve for pitching amplitude of 20 degrees and pitching speed of 100 degree/second from Re of 4000 to 19200

Figure 5-16 shows that, the peak lift increases with the higher Reynolds number although the pitching parameters were fixed. This results further showing that, for lower pitching amplitude (lower or around static AOA), increasing the free-stream velocity could increase the lift. Hence, this set of parameters could be tuned for the vehicle to obtain high lift while cruising in higher speed.

However, for all of the mentioned cases above in symmetrical pitching mode, the averaged lift over the entire pitching cycle is still approximate to zero as the positive lift from the first half cycle is always cancelled off by the second half cycle. Next section presents the image sequences obtained by the LES with IB computation in vorticity plots and further discuss the causes of the inability of positive lift generation by symmetrical pitching mode from these particular combinations of pitching parameters.

5-4-2 Image sequence for vorticity plot of pitching flat plate

In this section, the images sequence in term of vorticity, from the pitching flat plate obtained by the Large Eddy Simulation (Mesh resolution of 192 x 192 x 32) are presented. The images were extracted from EnSight 90 and the pitching parameters for pitching plate at different free-stream velocities (Re_{chord} of 8200, 12240 and 16320) are fixed and tabulated as below:

Flapper profile	: Flat plate	Rotational speed	: 100 deg/s
Pitching amplitude	: 20 degrees	Pivot point	: Quarter chord

The images are represented in the Z-component vorticity, which can be calculated from Equation (5-6). The blue and red colour in the image sequences indicates vortices in the clock-wise and anti-clock-wise rotations respectively.

$$\vec{\omega} = \text{curl } \vec{V} \quad (5-6)$$

$$\vec{\omega} = \omega_x \hat{i} + \omega_y \hat{j} + \omega_z \hat{k}$$

$$\vec{\omega} = \left(\frac{dw}{dy} - \frac{dv}{dz} \right) \hat{i} + \left(\frac{du}{dz} - \frac{dw}{dx} \right) \hat{j} + \left(\frac{dv}{dx} - \frac{du}{dy} \right) \hat{k}$$

where $\vec{V} = (u, v, w)$. The overview of pitching parameters and its corresponding Reynolds number for the test cases are shown in Table 5-2.

Table 5-2 Pitching parameters for numerical simulation image sequence

	Pitching parameters (amplitude and rotational speed)	Reynolds number
1	20 degrees; 100 degree/s	8200
2	20 degrees; 100 degree/s	12240
3	20 degrees; 100 degree/s	16320

5-4-2-1 Image sequences for vorticity plot of pitching flat plate with a pitching amplitude of 20degree and rotational speed of 100deg/s ($Re_{chord} = 8200$)

This section presents the vorticity plot obtained from an LES computation on a pitching flat plate with pitching amplitude of 20 degrees and a pitching speed of 100 degree/second. The corresponding Reynolds number is 8200 (0.064 m/s).

Since the Reynolds number is the lowest among these cases and the inertial of the flow is the least, therefore, the fluid (Figure 5-17) appears to be sticky as compared to the rest of the test cases. Figure 5-17 shows a vortex forming at the leading edge when the plate started to pitch down (at $t = 0$ T), this feature was detached from the flat plate while the pitching angle was further increased ($t = 0.25$ T). When the plate was pitched back in opposite direction ($t = 0.75$ T), another LEV was formed at the bottom of the plate and shed to the down-stream. As the pitching flat plate pitched symmetrically up and down and LEVs were subsequently formed on both the top and bottom regions of the pitching plate, the LEV did not assist in producing positive lift over entire pitching cycle.

Besides the above mentioned reasons, Dickinson [34] suggested that the wake capturing, which refer to the effect of momentum transferring from the vortices to the flapping wings at its wake region, significantly influences the performance of the flapping wings. He further explained that the aerodynamic peak is generated when the wing reverses its flapping direction and encounters the induced velocity thus transferring fluid momentum to the wing. However, for symmetrical pitching mode, the second half cycle repeats the first half cycle of pitching motion in opposite direction. Thus, the fluid momentum transferred to the flat plate during pitch-up and pitch-down motion neutralizes each other and causes the averaged lift over entire cycle to become zero.

Apart from that, the symmetrical pitching plate with this set of pitching parameters is found to be incapable of producing significant thrust as the thrust indicating vortex street did not appear at the down-stream of the pitching flat plate from these image sequences.

The Kármán vortex street can be observed from this set of image sequences, as refer to $t = 1.75 T$, the direction of the “mushroom head” is pointing to the up-stream where this particular feature indicates that the object is experiencing drag. Besides the direction of the “mushroom head”, the rotational direction of vortices at the wake region can also identified the Kármán vortex street where the top row of vortices is rotating clockwise (blue) and the bottom row of vortices is rotating anti-clockwise (red).

Figure 5-17 Z-component Vorticity plots for Reynolds number of 8200 with pitching amplitude of 20 deg and rotational speed of 100 deg/s in time sequence

5-4-2-2 Image sequences for vorticity plot of pitching flat plate with a pitching amplitude of 20degree and rotational speed of 100deg/s ($Re_{chord} = 12240$)

This section presents the vorticity plot of the pitching plate with the free-stream velocity of 0.102 m/s ($Re_{chord} = 12240$). As compared to the previous section, the inertia of the flow is higher with the Reynolds number increased. Hence, the “stickiness” of the fluid is reduced. The amplitude of the lift peak is higher as compared to the previous case because the increased in the fluid travelling velocity allows higher fluid momentum to be transferred to the pitching plate. This is analogous to a fixed wing aircraft which experiencing higher lift when it is

travelling at higher speed. As the Reynolds number is increased, the magnitude of the vorticity (Figure 5-18) is also increased from 1.5 rad/s to 3 rad/s.

The Kármán vortex street which is shown in Figure 5-16 is almost identical to the vortex street obtained from the previous case. As highlighted in the image sequences, the top row of the vortices is rotating clockwise (blue) and the bottom row of vortices is rotating anti-clockwise (red). Hence, this image sequences show that the pitching flat plate with this particular set of pitching parameters and the free-stream velocity was also unable to produce thrust.

Figure 5-18 Z-component Vorticity plots for Reynolds number of 12240 with pitching amplitude of 20 deg and rotational speed of 100 deg/s in time sequence

5-4-2-3 *Image sequences for vorticity plot on pitching flat plate with a pitching amplitude of 20degree and rotational speed of 100deg/s ($Re_{chord} = 16320$)*

The last set of image sequences present the vorticity plot of pitching plate with the free-stream velocity of 0.132 m/s ($Re_{chord} = 16320$). Although the averaged lift over a cycle is still remains at zero (Figure 5-16), the peak of the lift is the highest among $Re = 8200$, 12240 and 16320. The reason for the peak of lift is the highest in this case is due to the momentum of the fluid transferred to the pitching plate is the highest where the free-stream velocity is the highest.

However, the tiny thrust generated from the pitching motion is unable to overcome the drag as the high free-stream is creating significant large drag on the pitching plate. Thus, the Kármán vortex street appears again at the downstream instead of the thrust indicating vortex street. Similarly, as circled in Figure 5-19, at the wake of the pitching plate, the vortices at the top row are rotating in clockwise direction and the bottom row are rotating in anti-clockwise direction.

In order to obtain a set of parameters which can successfully produce thrust or lift, other pitching motions, such as non-symmetrical pitching, or larger pitching speed or amplitude can also be performed across range of Reynolds number.

Figure 5-19 Z-component Vorticity plots for Reynolds number of 16320 with pitching amplitude of 20 deg and rotational speed of 100 deg/s in time sequence

5-4-4 Conclusions on symmetrical pitching plate

The above study which was conducted on symmetrical pitching flat plate shows that the pitching frequency, amplitude and free-stream velocities have great influences to the flapping wings aerodynamic. At lower Reynolds numbers, higher pitching amplitude provides a higher peak of lift. However, lower pitching amplitude (smaller than the static stall angle), with increasing Reynolds number, allows a higher peak value of lift to be achieved. Therefore, during the travelling of micro UAV or UWV, the flapping parameters have to be tuned for different travelling mode (take off, accelerate or steady speed travelling). For example, if high thrust needed for moving forward from stationary, high pitching amplitude or frequency is more appropriate. Besides that, high flapping frequency and amplitude can also be utilized in hovering mode, which is similar to the hovering mode of humming bird. If the vehicle is in steady travelling mode, lower flapping amplitude and frequency will be recommended as it requires the least energy.

Lift and thrust play as important roles generation for micro UWV or UAV propulsion; however, up to this section, no discovery on the symmetrical pitching hydrofoil with the combination of pitching parameters conducted has the ability to produce significant lift. Since the symmetrical flapping mode with the tested parameters in the previous section is incapable of producing positive lift, to save for the effort for investigating on more combination of flapping parameters in symmetrical mode; the non-symmetrical pitching mode will be investigated in the continuing quest to discover a suitable flapping mode to produce a positive averaged lift.

In general, flapping wings kinematic which mimics animals' motion include:

- Non-symmetrical flapping motion which mimics birds or insects flight;
- Symmetrical flapping motion which mimics fishes swimming.

Hence, these two categories of flapping motions have to be studied in detail independently for the propulsion of the micro UAV or UWV.

In order to mimic birds or insects flight, the simplified kinematic motions and the lift enhancement mechanisms which were mentioned in Chapter 2 are necessary to be studied in order to utilize these features for improving the flapping wings performance. For birds flying, the motions can be generally divided into two stages [38], the down stroke (power stroke) and the upstroke (recovery stroke). During the down stroke, the angle of attack is increased and a lot of kinematic motions were involved by the bird in order to provide massive thrust and lift. The wing was twisted and allow varies of the angle of attack to be appeared along its wingspan. During the up stroke, the bird will fold its wings inward to further reduce the upward resistance and also reduce the angle of attack during this stage for optimizing the total lift.

However, complicated kinematic motions require a numbers of actuators to perform the motions as mentioned above, and these extra actuators will further increase the size of micro vehicle. Therefore, in the next study, these motions were simplified as non-symmetrical pitching and were investigated for its capable to retain the lift enhancement mechanism so as to obtain a set of flapping motion which can produce greater positive lift.

In contrary, it is noted that fishes are employing symmetrical pitching of flexible tail to produce thrust for moving forward; as discussed in Chapter 2, Triantafyllou [59] and Dickinson [60] discovered that oscillating hydrofoil in symmetrical mode which simulating the swimming motion of fishes can generate a significant positive thrust. Hence, together with the above factors, the flexibility of fish tail which flap symmetrically has inspired the author to conduct set of experiments on pitching rigid base hydrofoil and pitching hydrofoil with chord-wise flexible extension with fixed pitching parameters to investigate the relationship between the flexibility of the hydrofoil to the thrust. Therefore, the following section discusses the effect of the chord-wise flexibility of the pitching hydrofoil to the thrust performance. In addition, the combined heave and pitch motion was also studied for investigating the effect of phase different between pitch and heave to the thrust. This particular study will be discussed after the following section.

5-5 Thrust indicating Vortex Street from a symmetrical pitching hydrofoil

Figure 5-20 SD8020 (span width of 0.32m and chord length of 0.12m) with flexible trailing edge extension

Figure 5-20 shows the dimensions of the flexible trailing edge extension and Figure 5-21 presents the snapshot from dye flow visualization which was conducted on the pitching rigid foil with and without the 60 mm flexible chord-wise extension at its trailing edge. The force measurements results on pitching rigid hydrofoil, with 60 mm and 120 mm are plotted in Figure 5-24 and Figure 5-25. The purpose of conducting the dye flow visualization is to observe the presence of the Reverse Kármán vortex street as well as to investigate the effect of chord-wise flexibility to the thrust. The dimensions and the pitching parameters for this particular hydrofoil are summarised as below:

- Hydrofoil profile: SD 8020
- Chord-length: 120 mm
- Span-width: 320 mm

-
- Pitching amplitude: 40 degrees
 - Pitching speed: 0.87 rad/s (50 degree/s).
 - Pivot point: Quarter chord

The trailing edge extension is made from the cellulose acetate, which has a density of 1.3g/cm^3 and refractive index of 1.49. It has a tensile strength of 12 to 110 MPa and tensile modulus of 1.0 to 4.0 GPa. The commercial cellulose acetate is made from processed wood pulp which is processed using acetic anhydride to form acetate flake. [61] & [62].

From Figure 5-21a, the reversed Kármán vortex street cannot be observed from the pitching rigid hydrofoil without the flexible extension. However, after the flexible trailing edge extension was attached to the hydrofoil and pitched with the same pitching parameters, a strong reversed Kármán vortex street can be clearly observed at the wake (Figure 5-21b) and shed to the downstream. This set of reversed Kármán vortex street can be identified by the mushroom head with the arrows pointing to the downstream, as shown in Figure 5-21b.

Figure 5-21 SD8020 (a) without and (b) with flexible trailing edge extension for Dye Flow Visualization at $U=0.1028\text{m/s}$, $\theta=40^\circ$ and $w=0.873\text{rad/s}$

To find out the capability of flexible trailing edge extension for generating thrust, apart from dye flow visualization, direct force measurement was also conducted. In addition, the myth about the reversed Kármán vortex street as a thrust indicating vortex street can be verified as well. In this test, the selected pitching amplitudes are 30 degrees and 40 degrees; the pitching speed is fixed at 50 degree per second. In order to measure the pure thrust without the contribution of the drag from the free-stream, these set of measurements were conducted at zero free-stream velocity. As a reflection from the dye flow visualization, the measured thrust from the pitching hydrofoil with the flexible extension is indeed higher than pitching rigid hydrofoil. As shown in Figure 5-24 and Figure 5-25, the thrust generated by the

pitching hydrofoil with the flexible extension is almost doubled compare to the measured thrust from pitching foil without the extension. However, the length of the trailing edge extension (6 cm or 12 cm) did not have significant influences to the generated thrust.

The hybrid of rigid base hydrofoil and the flexible extension at the trailing edge allows the pitching hydrofoil for utilizing the momentum transferred from the fluid and produced a higher thrust where the elasticity of the flexible extension plays an important role for it.

Before the discussion on how the flexible extension able to enhance the thrust, the capability of pitching rigid hydrofoil to generate thrust can be explained as below:

When the hydrofoil is started to pitch from its origin (Figure 5-22a); the pitching hydrofoil will “carry” the fluid around the bottom side of the hydrofoil to travel in the same direction with the pitching motion. Once the hydrofoil has pitched to its maximum amplitude and pitched back instantaneously, the hydrofoil is experiencing both the reaction force from the fluid (due to the current pitch back motion, and it is opposite to the pitching direction) as well as the “remaining” fluid momentum which has been “carried” by the previous motion (Figure 5-22c). Hence, this increases the resultant force experienced by the hydrofoil and the peak of the thrust is produced at this instance.

<p>a)</p>	<p>$t = 0s$, the hydrofoil start to pitch</p>
<p>b)</p> <p>Reaction force from the fluid due to the pitching motion, ω</p> <p>Wake region</p> <p>V_1</p> <p>Fluid at the bottom of hydrofoil which is “carried” by the pitching hydrofoil and travels in the same direction with the pitching motion</p>	<p>$t < 1/4T$, the hydrofoil is pitching to the maximum pitching amplitude</p>
<p>c)</p> <p>Thrust</p> <p>$F_{Reaction}$</p> <p>“remaining” fluid from previous motion</p>	<p>$t = 1/4T$, at maximum pitching amplitude. The hydrofoil stops and pitches in reversed direction instantaneously</p>

Figure 5-22 Illustration on the thrust and pitching motions

Figure 5-23 Resultant forces acting on the pitching hydrofoil (a) without and (b) with flexible extension

As mentioned previously, the elasticity of the flexible trailing edge extension plays an important role for enhancing the thrust. With suitable degree of elasticity, when the pitching hydrofoil was pitching at the reversed direction (at $t = \frac{1}{4} T$) instantaneously, the flexible extension are able to sustain the reaction force (contributed by the back pitching motion) and the “remaining” fluid momentum from the previous pitching motion more effectively; if this flexible extension is rigid enough and yet can be bent to resolved the resultant force vector more towards to the direction of thrust as compared to pitching of rigid hydrofoil (Figure 5-23), a higher thrust can be achieved. As a conclusion, the elasticity of the

pitching hydrofoil could greatly improve the thrust. Therefore, it is suggested that more force measurements can be conducted on various combinations of flapping mode and different degree of flexibility of the hydrofoil with higher accuracy force transducer in order to obtain set of optimized parameters and the flexibility constant for producing higher lift, thrust and improve the propulsive efficiency for the flapping micro UAVs and UWVs.

Figure 5-24 Time history thrust with Pitching amplitude: 30deg; Pitching speed: 50deg/s

Figure 5-25 Time history thrust with Pitching amplitude: 40deg; Pitching speed: 50deg/s

5-6 Thrust from symmetrical heave and pitch SD8020 (In phase and 180 degrees out of phase)

Besides solely heaving or pitching motions, combination of these motions can mimic the fish swimming motion even closer [6]. Although micro fish-like vehicle might face the limitation of size and should avoid using extra actuators, the larger size UWV might be able to employed combined pitch and heave motion for propulsion in order to generate greater thrust. However, the phase different between pitch and heave motion has significant effect to the performance of thrust. Hence, this section reveals the influences of the phase different (in-phase or 180 degrees out of phase) to the thrust generated by the hydrofoil SD8020 (same hydrofoil as previous section) in combined heave and pitch motion. In order to investigate only the effect of phase different, the hydrofoil was moved with different phase angle but keeping the same pitching and heaving parameters across these two tests. The parameters are as below:

Pitching amplitude	: 40deg
Pitching speed	: 84 deg/s
Heaving amplitude	: 10 mm
Heaving speed	: 0.021m/s

Figure 5-26 Combined heave and pitch motion – in phase

Figure 5-27 Combined heave and pitch motion – 180 degrees out of phase

Figure 5-28 Experimental setup for combined heave and pitch study

Figure 5-26c illustrates the motion of SD8020 which is undergoing the pitching and heaving motion with in phase mode and Figure 5-27c illustrates the motion of SD8020 with 180 degrees out of phase mode.

The in-phase mode can be defined as:

The hydrofoil is pitch and heaves to the same positive direction and goes back to the origin in synchronized motion profile.

The 180 degrees out of phase mode can be defined as:

The hydrofoil is heaved to the positive direction but pitched to the negative direction at the beginning and go back to origin from different direction.

The individual heave and pitch motion of the hydrofoil are further illustrated in Figure 5-26 and Figure 5-27 (a & b). The experiment setup for this study is shown in Figure 5-28. The Cool muscle high resolution closed loop stepper motor was

employed for generating the pitching motion, while the THK linear guide and the slider were responsible for the heaving motion.

The dimensions of the hydrofoil are stated as below:

Hydrofoil profile SD 8020
Chord-length : 120 mm
Span-width : 320 mm
Pivoting point : Quarter Chord

The results from the instantaneous force measurement are shown in Figure 5-29 and Figure 5-30. By comparing the peak of the thrust curve from both cases, in-phase motion has a higher peak than the out-of-phase motion (180 degrees) by 50% (approximately increased by 0.75N) despite the motions and flapping parameters across these two cases are fixed.

Figure 5-29 Time history thrust by combined motion with in phase mode

Figure 5-30 Time history thrust by combined motion with 180 degrees out of phase mode

The main reason for the in-phase mode to obtain higher thrust might due to this particular flapping mode is able to capture the momentum transferred from the fluid which is contributed by the flapping motion more effectively.

In this mode, the hydrofoil was heaved and pitched to the same direction at the beginning. The fluid at the wake region of the flapper is “following” the moving hydrofoil. At this particular moment, the fluid that was “following” or being “bring” by the hydrofoil started to build up its momentum. When the hydrofoil is moving back to its opposite direction instantaneously at the quarter cycle (in phase), the thrust reaches its thrust peak as the total resultant force is not only from the force introduced by the current flapping motions and also include the momentum of the fluid transferred to the hydrofoil, which was created by the previous motion.

However, for the 180 out of phase motion, as the pitching and heaving motion are opposing to each other at the beginning, the momentum of the fluid that “following” the hydrofoil at the wake was reduced. At the quarter cycle, the hydrofoil was moved back to the origin with heave and pitch motion from different direction. At this moment, the peak of thrust occurs, but with the reduced momentum of fluid from the previous motion.

As a conclusion, this set of experiment shows that the phase difference between the heave and pitch motion is important for the wake capturing [23] ability. Hence, in order to obtain higher thrust for the UWV, the proper motion parameters and the phase angle have to be carefully tuned.

5-7 Investigation of LEV with Non-symmetrical Pitching Motion

As discussed in Chapter 2, many researchers have conducted series of experiments for investigating the ability of LEV to enhance the lift on combined heaving and pitching of hydrofoil in non-symmetrical mode. However, motions with more degree of freedoms involved will necessitate additional actuators. The limitation on the size of the micro UAV requires the design of the flapping wings mechanism to be as simple as possible. Hence, this section discusses the study on simplified non-symmetrical pitching only motion in a very slow free-stream, which mimics the birds' motion in the beginning of flight. The kinematic pitching motion for this study can be described as a pitch down, hold and pitch back motion. The hydrofoil used is with SD7003 profile. The dimensionless pitch rate (Ω^+) and dimensionless time (t^+) are defined in Equations 5-7 and 5-8:

$$\Omega^+ = \frac{\Omega c}{U} \quad (5-7)$$

$$t^+ = \frac{c}{U} \quad (5-8)$$

where Ω is the pitching speed (rad/s), U is the free-stream velocity (m/s) and c is the chord-length of the hydrofoil.

The experiment was conducted in a closed-loop water tunnel; a six-axis force transducer (ATI gamma[®] SI-32-2.5) was used for the force measurements. Dye flow visualizations were also conducted to investigate the flow structure and verify the influence on lift by the following factors: free-stream velocity, pitching speed, hold time under linear pitching motion as well as the formation of LEV (leading edge vortex).

A high resolution stepper motor (Cool muscle[®] motor CM1, tuned to 12,000 pulses per revolution) was used to generate the motion with the input parameters from a computer. The flow condition is $Re_{chord} = 1 \times 10^4$ (0.085m/s of free-stream velocity at the test section of the water tunnel) and the dimensionless pitch rates (Ω^+) of 0.2 and 1.4 were applied. A comparison of the the C_l curve with the dye flow visualization for every time increment will be presented in this section. The formation and detachment of the *LEV* and the dynamic stall effect were observed in this experiment.

The flapper is a SD 7003 hydrofoil which made from aluminium alloy Al 6061 with carbon coated surface. It has a span-width of 400 mm and a chord-length of 120 mm. The hydrofoil is pivoted at the quarter chord from the leading edge which has a maximum thickness of 10 mm. (refer to Figure 5-32). The experiment setup is shown in Figure 5-33. The non-symmetrical pitching motion and the flow conditions are illustrated in Figure 5-34. For ease of presentation and comparison of results to the other research group, the results were converted into dimensionless terms.

The motion parameters and dimension of the hydrofoil are as below:

Hydrofoil profile	SD 7003
Chord-length	120 mm
Span-width	400 mm
Pivoting point	Quarter Chord

Figure 5-31 Cross-sectional profile of SD 7003 hydrofoil [58]

Figure 5-32 CAD drawing of SD7003 hydrofoil

Figure 5-33 Experimental setup

Figure 5-34 Pitch up, hold and pitch down motion

As mentioned, the hydrofoil was undergoing pitch down, hold and pitch back motion. The hydrofoil was pitched to the maximum angle of 40 degree (beyond the static stall angle of attack) and pitched back after a holding time of t_{hold}/t^+ equal to 0.05 and 1.00 respectively in two pitching motion pattern, i.e. linear sudden pitching and smooth gradual pitching (Figure 5-34).

The experiment was conducted to investigate the effect of the angular velocity (ramp rates) and the acceleration (torque) caused by a rapid pitch down motion to the lift, i.e the Kramer effect. The angular position, angular velocities and acceleration versus t/t^+ for both pitching patterns are shown in Figure 5-35 and Figure 5-36 (the holding time was kept at $t_{\text{hold}}/t^+ = 0.05$ for both linear sudden pitching and smooth gradual pitching patterns).

The linear sudden pitching pattern allows the hydrofoil to experience sudden start and stop motion with the angular acceleration of 800 deg/s^2 (for the case of $\Omega^+ = 0.2$); whereas, the angular acceleration for the smooth motion is only 30 deg/s^2 . For the linear pitching pattern, the angular velocity was kept constant throughout the pitching motion for linear. In contrast, the angular velocity increases in magnitude with time (constant ramp rate) for the smooth pitching pattern.

The force measurements were also being conducted to investigate the effects of rotational speed (in terms of the dimensionless pitch rate, Ω^+) and the pitch rate (sudden pitch-delta function type pitching rate or smooth gradual pitching-linear function type pitching rate) to the lift. The force measurement results of are shown in Figure 5-37 and Figure 5-38.

The lift coefficients obtained from linear sudden motion with higher pitch rate are generally higher than that of smooth motion with higher pitch rate by approximately 20% as the acceleration and deceleration of the motion profiles are more significant for high pitch rate than low pitch rate (as circled in Figure 5-35 and Figure 5-36). The larger lift experience by higher pitch rate with sudden motion is caused by the torque required to produce such motion as it requires a large acceleration or deceleration (angular acceleration $\sim 800 \text{ deg/s}^2$) whereas the gradual motion needs only a small fraction of the sudden motion (angular acceleration $\sim 30 \text{ deg/s}^2$). In other words, the difference arises from the fact that a slowly increasing speed (instead of sudden motion) experiences less reaction force from the surrounding fluid. Hence, less lift force is produced.

a) $\Omega+ = 0.2$; sudden pitching (left) and smooth pitching (Right)

Figure 5-35 Motion profile of the non-symmetrical pitching motion ($\Omega+ = 0.2$)

b) $\Omega^+ = 1.4$; sudden pitching (left) and smooth pitching (Right)

Figure 5-36 Motion profile of the non-symmetrical pitching motion ($\Omega^+ = 1.4$)

a) $\Omega^+ = 0.2$; hold time of 0.072 Sec (left) and 1.4 Sec (Right)

b) $\Omega^+ = 1.4$; hold time of 0.072 Sec (left) and 1.4Sec (Right)

Figure 5-37 Lift coefficient Vs dimensionless time with linear sudden motion profile; a) $\Omega^+ = 0.2$; hold time 0.072sec (left) and 1.4 sec (right), b) $\Omega^+ = 1.4$; hold time 0.072sec (left) and 1.4 sec (right)

a) $\Omega^+ = 0.2$; hold time of 0.072 Sec (left) and 1.4Sec (Right)

b) $\Omega^+ = 1.4$; hold time of 0.072 Sec (left) and 1.4 Sec (Right)

Figure 5-38 Lift coefficient Vs dimensionless time with smooth motion profile; a) $\Omega^+ = 0.2$; hold time 0.072sec (left) and 1.4 sec (right), b) $\Omega^+ = 1.4$; hold time 0.072sec (left) and 1.4 sec (right)

Figure 5-38 shows that the C_l curve peak (represented in green) is coinciding closely with the angular position curve (represented in blue) for smooth pitching motion. On the other hand, the C_l curve peak does not follow the position of the angular position curve closely in Figure 5-37, especially at high pitch rate; this is because the ramp-up acceleration is greater. The sudden pitch up motion allows the hydrofoil to move faster than the rate that the surrounding fluid could ‘sense’ or in a proper word, response or settle in time. The shift in the C_l curve peak and sudden pitch up at the start, means that the surrounding fluid cannot respond in time and lags behind the motion of hydrofoil. At the end of the pitch up and down cycle, the C_l curve has a negative gradient, which follows the trends in the angular position curve.

Similarly, for the gradual pitch motion, the hydrofoil moves slowly enough to allow the surrounding fluid to ‘sense’ and respond before the motion completes. The gradual pitch up at the start allows sufficient time for the surrounding fluid to settle. One of these manifestations is the formation of leading edge vortex as shown in the dye flow visualization in Figure 5-39 and Figure 5-40. At the end of the pitching motion, the C_l curve reverses its trend and regains its positive gradient whereas the angular position curve still has a negative gradient. The upwards gradient is due to the flow reattachment prior to the completion of pitch-down motion.

The hold time influences the averaged lift over entire pitching significantly, but it appears to have no impact on C_l during the beginning of pitching, therefore, the C_l profile is similar in the first half of the cycle. The longer hold time allows the flow

to reattach back to the airfoil. Hence, the recovery of C_l at later half cycle then results in a higher averaged lift in total cycle.

In term of magnitude of peak lift, higher pitch rate ($\Omega^+ = 1.4$) in sudden pitching motion can produces greater peak lift. C_l peak of linear-sudden motion is 2.75 and C_l peak for smooth motion is 2.25. However, also at higher pitch rate, the averaged lift for linear sudden motion (0.77) is lower than the smooth motion (1.02) for short holding time (hold time = 0.072s), although linear sudden motion has a slightly higher peak lift. Next, for similar motions with longer hold time (hold time = 1.4s), the averaged lift is increased from 1.47 to 1.85. The above cases show that the LEV is allowed to stay above the hydrofoil with a longer holding time. In addition, when the hydrofoil is started to pitch back, the re-attachment of LEV allows the increment of the total averaged lift.

The following section compares the images sequence which obtained from dye flow visualization ($\Omega^+ = 0.2$, hold time of 0.072sec and free-stream velocity of 0.085m/s) and to the results from the direct force measurement. The purpose of this particular study is to investigate the influences of the LEV to the lift. The averaged lift coefficients for the above cases are tabulated in Table 5-3 and Table 5-4.

Table 5-3 Averaged lift coefficient over entire pitching cycle (Linear sudden motion)

	hold time = 0.072s	hold time = 1.4s
$\Omega^+ = 0.2$	0.79	0.84
$\Omega^+ = 1.4$	0.77	1.85

Table 5-4 Averaged lift coefficient over entire pitching cycle (Smooth motion)		
	hold time = 0.072s	hold time = 1.4s
$\Omega^+ = 0.2$	0.65	0.72
$\Omega^+ = 1.4$	1.02	1.47

Figure 5-39 Images sequence of smooth pitching ($\Omega^+ = 0.2$, hold time of 0.072sec and free-stream velocity of 0.085m/s) for observation of leading edge vortex (LEV) forming

Figure 5-40 Images sequence of smooth pitching ($\Omega^+ = 0.2$, hold time of 0.072sec and free-stream velocity of 0.085m/s) for observation of leading edge vortex (LEV) forming (cont.)

Figure 5-41 Lift and position curve for $\Omega^+ = 0.2$, hold time of 0.072sec and free-stream velocity of 0.085m/s (corresponding to the dye flow visualization)

The formation and the “bursting” of the LEV can be clearly observed from the dye flow visualization images sequence. Many researchers, for examples, Tani (1964) [63], Carmicheal (1981) [64], Ellington (1984) [65] and also Shyy (2008) [34], have described the LEV as an enhanced lifting mechanism for sustaining the lift for flapping flight.

In Figure 5-40 (when $t/t^+ = 0$), the hydrofoil is at its original position and the flow passing the hydrofoil stays attached. However, when the foil begins to pitch, flow separation can be clearly observed and a “bubble” [66] (flow reversal) starts to form at the leading edge (at $t/t^+ = 0.866$) and grows in size. As the LEV continue

growing, the lift is able to sustain even the hydrofoil is beyond the static stall angle of attack, causing the delayed stall to occur.

When the hydrofoil had reached the maximum pitching amplitude of 40 degrees, it was held stationary for 0.072 sec. The holding also allows the momentum of the fluid from the previous down-pitching motion to dissipate and reduced the downward force experience by the hydrofoil. At this moment (holding stage), where the AOA was at 40 degrees, the LEV is separated from the hydrofoil with large separation and the lift was dropped tremendously (Figure 5-41). During the “holding” stage, the LEV was grew in size and shed to the upper side of the hydrofoil. Therefore, the flow over the LEV was slightly accelerated and retained the lift slightly. As the hydrofoil started to pitch back, the LEV was further re-attach back to the upper surface of the hydrofoil for a short moment (at $t/t^+ = 4$) before the LEV was fully shed away from the hydrofoil. Hence, the drop of the lift was sustained. At $t/t^+ = 5$ and beyond, Figure 5-41 shows that the lift drop tremendously and the corresponding image from dye flow visualization shows the LEV was shed to the trailing edge and separated or expelled from the hydrofoil.

Explanation for higher pitch rate with short holding time cannot obtain higher averaged lift is as below:

The LEV, in this case, might be expelled and separated from the hydrofoil instantly during the pitching back motion. Therefore, the LEV was unable to assist the rapid pitching hydrofoil for increasing the averaged lift over entire pitching cycle (Figure 5-37 and Figure 5-38).

In conclusion, the lift charts (Figure 5-37 and Figure 5-38) from this section shows that non-symmetrical pitching motion can successfully produce a positive averaged lift over the entire pitching cycle.

The findings of this section on non-symmetrical pitching mode can be summarised as follows:

- Non-symmetrical motion, with pitching only at one side (simplified bird flapping motion); it can prevent the cancelation of the lift from the downward force created by the pitching motion at another side.
- Due to this half-cycle (non-symmetrical) pitching motion, the LEV was not formed at the bottom side of the pitching foil. Therefore, the LEV was able to enhance the lift significantly.
- In general, rapid rotation of the hydrofoil allows higher aerodynamic lift peak to occur, however, the holding time decides the magnitude of the averaged lift.
- Control of the duration of LEV for staying over the hydrofoil, by optimizing the hold time between down-stroke and up-stroke, combined with optimized flapping parameters, can significantly improve the lift performance.
- Extremely long holding time is not advisable for large pitching amplitude which is beyond the static stall angle of attack as the lift might drop abruptly once the effect of the LEV is diminished.

Chapter 6 Analytical Model for the Prediction of Peak Lift of a Pitching Plate

The aerodynamics of flapping wings is very hard to predict due to its non-linearity, unsteadiness of the flow and complex kinematic motions involved. Therefore, Liu (Liu, 2007) and Kang (Kang, Aono, Trizila, Baik, Michael, & Shyy, 2009) [20] & [37] concluded that, in order to predict flapping wing aerodynamics accurately, the only technique is to solve the unsteady Navier stoke equation.

However, conducting extensive computational or experimental studies are costly and time consuming. Hence, from the experimental and numerical simulation data obtained in this thesis, a simple prediction model, which can predict the peak lift coefficient from pitching flat plate, can be derived.

Such a model aims to aid during the preliminary design stage of an MAV or UWV and can be used for optimization, before more extensive computational and experimental studies are performed.

6-1 Derivation of Analytical model

As discussed from the previous chapter, the pitching motion affects the lift and thrust significantly. Hence, this thesis aims to develop a simple analytical model which is in the form as below:

$$C_L = f(t, \alpha, \omega, \dots) \quad (6-1)$$

It has been shown, that a quasi-static analysis, which approximates the instantaneous forces acting on the flapping wings by calculating the steady forces during the steady motion at identical free-stream and angle of attack is insufficient

to predict the peak and the mean lift (Elington, 1984) [65]. Kramer [18] discovered that, besides the contribution of lift due to LEV, the wing could achieve higher lift due to rapid wing rotation and delayed stall. Hence, this current analytical model is being developed based on the combination of lifting line theory [67] and the Kramer effect. The derivation of the total lift (L) from the any airfoil can be expressed as:

$$L = \rho U_{\infty} (\Gamma_{rotation} + \Gamma_{AOA}) \quad (6-2)$$

The total lift coefficient ($C_{L,total}$) can be hence represented by:

$$C_L = \frac{L}{0.5 \rho c U_{\infty}^2} \quad (6-3)$$

$$C_{L,total} = \frac{\rho U_{\infty} (\Gamma_{rotation} + \Gamma_{AOA})}{0.5 \rho c U_{\infty}^2} = \frac{\Gamma_{rotation} + \Gamma_{AOA}}{0.5 c U_{\infty}} \quad (6-4)$$

$$C_{L,total} = C_{L,rotation} + C_{L,AOA} \quad (6-5)$$

Following thin airfoil theory, the lift coefficient for the lift due to the angle of attack (AOA) can be simplified as:

$$C_{L,AOA} = 2\pi\alpha \quad (6-6)$$

where the AOA, α , is in radian. This expression neglects stall effects. However, due to the effect that delayed stall is observed (see Kramer and the previous chapter), for the sake of simplicity stall is not considered. The implications are discussed below in the results section.

Next, the circulation due to the rotational speed of the pitching plate $\Gamma_{rotation}$ can be derived by as:

$$\Gamma_{rotation} = \oint_c \vec{V} ds \quad (6-7)$$

$$\Gamma_{rotation} = \pm 2 \int_0^c \left(\frac{\omega c}{4} - \omega x \right) dx = \pm \omega c^2 \quad (6-8)$$

Hence, the lift coefficient due to the pitching motion becomes:

$$C_{L,rotation} = \frac{\rho U_{\infty} (\Gamma_{rotation})}{0.5 \rho c U_{\infty}^2} = \frac{2 \omega c}{U_{\infty}} \quad (6-9)$$

Hence, total lift coefficient as is computed in the current model as:

$$C_{L,total} = \left(\pm \frac{2 \omega c}{U_{\infty}} \right) + 2 \pi \alpha \quad (6-10)$$

where the angle of attack α , and the rotation rate ω are time dependent.

6-2 Results from analytical model

The following section presents the estimated lift coefficient from the pitching flat plate by the derived model and its outcomes are compared with the experimental and numerical simulation results. The parameters used for comparison are the test cases that use a pure pitching movement and are summarised as below:

Table 6-1 Pitching parameters and Reynolds number

Reynolds number	Pitching amplitude (degrees)	Pitching speed (degrees per second)
19200	20	50
19200	40	100
8200,12240,16320,19200	20	100

The estimated total lift coefficient from Equation (6-10) consists of two components; first, the lift due to the free-stream acting on the flat plate at particular instant angle of attack (AOA) and second, the lift due to the rotational motion of the pitching flat plate.

The described motion of the symmetrical pitching flat plate (Figure 6-1) for the prediction model was saw tooth motion, and it can be described as; first, rotate in clock-wise direction to the maximum pitching amplitude in constant speed. Second, rotate counter clock-wise to the maximum pitching amplitude at the other direction and finally rotate clock-wise again and back to the origin (0 degree) with a constant speed as well

Figure 6-1 Symmetrical pitching motions of flat plate

Figure 6-2 Results from pitching flat plate with pitching parameters of 20 deg 50 deg/s (Left) and 40 deg 100 deg/s (right) with fixed Reynolds number of 19200

Firstly, the results are compared with the fixed Reynolds number of 19200 across the pitching amplitude of 20 and 40 degrees corresponding to the pitching speed of 50 and 100 degrees per second respectively in order to validate its ability for estimating the lift coefficient across different pitching parameters (Figure 6-2). It can be seen that this model has quite considerable overall differences in shape. This is to be expected, as the model cannot capture complex effects as the LEV. However, the model is able to predict the peak lift coefficient with considerably accuracy. At its peaks, the model matches well with the experimental and computational results.

Figure 6-3 elaborates further on the differences between model and experimental and computational results. At the beginning of the pitching cycle ($t=0$), the rotational speed is fixed and the starting lift coefficient is solely contributed by the first term of Equation 6-10, the lift due to the rotational motion of the flat plate. As the angle of attack increases, the lift due to the angle-of-attack increases and the overall lift increases as well. During the pitch-up motion the model agrees reasonably well with computational and experimental results. As the pitching motion reverses the model predicts a drastically lower lift, as the circulation due to the rotation introduces now negative lift. The computational results show that in that period of time the LEV passes over the upper side of the plate. As the present model cannot capture this non-linear effect, the differences between model and the current experimental and numerical results are particularly high. The second maximum peak, however, is well predicted in size and timing.

Figure 6-3 Illustration of predicted lift components (green dotted line)

Figure 6-4 Results from pitching flat plate with fixed pitching parameters (20 degrees and 100 degrees per second) across Reynolds numbers of 8200, 12240, 16320, 19200

Next, to determine the ability of the model to capture the effect of Reynolds number, the predicted results are compared with the experimental and numerical simulation results as well in the fixed pitching parameters of 20 degrees and 100 degrees per second across the Reynolds of 8200, 12240, 16320 and 19200 respectively (Figure 6-4). As the model is derived from simple mathematical models, the effect of viscosity is neglected (or modelled through the introduction of the circulation, Γ). The results show the same trend as previously observed: While the temporal lift prediction is not well predicted, especially after the apex of the pitching motion has been achieved, the peak lift is predicted reasonably well. In

particular, the peak lift prediction has a larger error at low Reynolds-number, which can be explained by the effects of viscosity.

6-3 Conclusion of analytical model

This chapter, a model to predict the lift distribution of a pitching plate has been derived. Although this particular analytical model is not able predict the temporal lift curve as compared to the results from the experimental and numerical simulation approaches, this model can still be employed for the preliminary study of flapping wings for estimating the peak lift.

Chapter 7 Conclusion and Recommendations

In this chapter, key findings on the conducted research works are summarized. Future developments and possible improvements for studying and optimizing the flapping wings aerodynamics performance are also presented.

7.1 Summary

From the past reviews, the study of flapping wings aerodynamics was found to be extremely challenging due to the unsteadiness of flow and the complicated kinematic motions involved from the flapping wings. In recent year, Platezer [17] and Guerrero [38] also stated that the study and application of flapping wings still remains open and the physics of the flapping wings aerodynamics are yet to be fully understood. Due to foregoing, this thesis investigated the feasibility of the flapping wings with simplified kinematic motion as propulsion unit for micro vehicles by studied the aerodynamics of the flapping wings at low Reynolds number through experiment (force measurement and dye flow visualization) and numerical simulation. The lift and thrust enhancement mechanisms, and the affecting parameters to the aerodynamic performance of flapping wings were also being investigated in detail in order to serve as database for optimizing the performance of flapping wings.

Measuring of small dynamic forces which generated by the flapping wing motion is challenging. Therefore, a test rig, which has the capability to produce the kinematic motions and to measure the forces, was carefully designed and developed. The capability of novel Immersed Boundary LES solver code has also

been evaluated for simulating flapping wing aerodynamics. In addition, to reduce the works needed for optimizing the performance of flapping wings by filtering the flapping parameters which are generating insignificant lift, a simple analytical model (based on Kramer effect) for predicting the peak lift was developed with the aid from the collected experimental and numerical simulations data.

In summary, with all the conducted works which presented in Chapter 5 and 6, this study demonstrated the factors for enhancing the lift and thrust and further revealed the hidden myth behinds the flapping wings aerodynamics which could lead to optimize the performance of micro UAV or UWV. Finally, the overarching goal for translating of knowledge from the flapping wings dynamics to the development of flapping wings micro UAV and UWV can be achieved.

7.2 Recommendation and future research

Apart from the findings mentioned in the previous section, recommendations on equipment upgrades and further improvement could be made for flapping wings study are listed as below.

- First, in order to further reduce the size of these miniature vehicles, another type of actuator, for example, piezoelectric or smart materials that can provide simple motion might be able to replace the motor for generating the simple pitching or heaving motion. The effect of the flexibility of the chord-wise extension to the thrust can be further investigated with more materials in different stiffness. Additionally, smart material, which can achieved higher stiffness during the down stroke and lower stiffness during the upstroke for re-capturing the momentum of the fluid generated by the flapping motion, could be developed.
- Second, evaluation of the capability of current solver for predicting thrust generated by flapping wings and improvement also can be made for simulating flexible flapping wings. Hence, with these capabilities, current solver can serve as a good tool for optimizing the performance of flapping wings aerodynamics.
- Third, the developed simple analytical model can be further improved in order to obtain better accuracy results as well as to capture the effects by the LEV and other factors which could affect the lift.

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- Fourth, a high speed and resolution video camera can be utilized for conducting the flow visualization in order to obtain better quality and clearer images for observing the important mechanisms in detail.
 - Finally, for quantitative unsteady flow measurements, Particle Image Velocimetry (PIV) with higher pulse rate and larger laser sheet also can be introduced. Hot-wire measurements at the down-stream of the flapping wing can also be an alternative approach for measuring the flow dynamics in the wake of a flapping wing, however, here the spatial correlation of turbulent quantities would be lost as measurements are limited to a single point.

Ultimately, the study of flapping wings is a new era of technology and improvements made to miniature UAV and UWV propulsion system will contribute greatly to the future development of autonomous unmanned vehicles which can perform important tasks as mentioned in Chapter 1.

Figure 7-1 Hummingbird micro UAV [68], robotic fish [69] and finger tip size micro UAV [12]

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APPENDIX II ATI Calibration Report

FT7892 Gamma Load Test for Einst / RMA9610

Unit: FT7892

Test date: 10/18/2010

Type: Gamma SI-32-2.5

Data collected by: Ulrich Weninger

Scan Rate: 1000 Hz

Data analyzed by: Penny Fusco

Filter Level: 100 samples

NOTE: Test conducted prior to re-calibration

Fx Test Data:

Mass [g]	Equivalent Force [N]	measured Fx [N]	error in sensing axis [N]	error as % of full scale
0	0	-0.000193	0.000193	0.000604%
2	0.019613	0.018310	0.001304	0.004074%
5	0.049033	0.046686	0.002347	0.007335%
10	0.098067	0.092779	0.005287	0.016523%
31	0.304006	0.281953	0.022054	0.068917%
51	0.500139	0.460046	0.040093	0.125291%
81	0.794339	0.729304	0.065035	0.203235%
102	1.000278	0.909233	0.091046	0.284518%

Fy Test Data:

Mass [g]	Equivalent Force [N]	measured Fy [N]	error in sensing axis [N]	error as % of full scale
0	0	-0.000203	0.000203	0.000634%
2	0.019613	0.016641	0.002973	0.009289%
5	0.049033	0.042050	0.006983	0.021822%
10	0.098067	0.083804	0.014262	0.044570%
31	0.304006	0.260776	0.043230	0.135085%
51	0.500139	0.427672	0.072467	0.226459%
81	0.794339	0.679692	0.114646	0.358270%
102	1.000278	0.847290	0.152988	0.478089%

Fz Test Data (-Fz):

Mass [g]	Equivalent Force [N]	measured Fz [N]	error in sensing axis [N]	error as % of full scale
0	0	0.0058761	0.005876	0.005876%
2	0.019613	-0.0116268	0.007986	0.007986%
5	0.049033	-0.0352953	0.013738	0.013738%
10	0.098067	-0.0914394	0.006627	0.006627%
31	0.304006	-0.2883036	0.015703	0.015703%
51	0.500139	-0.4849844	0.015155	0.015155%
81	0.794339	-0.7605458	0.033793	0.033793%
102	1.000278	-0.9651975	0.035081	0.035081%

Note: In Fx and Fy directions, tooling of mass 11.4g was used. In Fz, mass of tooling was 2.9g. The bias function was used to zero the system prior to data collection.

FT7892 Gamma Verification Test for Einst / RMA9610

Unit: FT7892

Test date: 10/26/2010

Type: Gamma SI-32-2.5

Data collected by: Ulrich Weninger

Scan Rate: 1000 Hz

Data analyzed by: Penny Fusco

Filter Level: 100 samples

NOTE: Verification test conducted after re-calibration

Fx Test Data (-Fx):

Mass [g]	Equivalent Force [N]	measured Fx [N]	error in sensing axis [N]	error as % of full scale
5	0.049033	-0.0468709	0.002162	0.006757%

Fy Test Data (-Fy):

Mass [g]	Equivalent Force [N]	measured Fy [N]	error in sensing axis [N]	error as % of full scale
5	0.049033	-0.0482271	0.000806	0.002519%

Fz Test Data (-Fz):

Mass [g]	Equivalent Force [N]	measured Fz [N]	error in sensing axis [N]	error as % of full scale
5	0.049033	-0.0509689	0.001936	0.001936%

Note: In Fx and Fy directions, tooling of mass 11.4g was used. In Fz, mass of tooling was 2.9g. The bias function was used to zero the system prior to data collection.

Overview of Test Procedures

- Use returned sensor from customer. Mount on calibration stand using the customer interface pattern on the mounting adapter plate.
- **For Fx test:**
Orient sensor so -X axis faces up. Mount a M6 screw to one of the mounting holes on the tool adapter plate. Attach the custom hanger assembly. *(The combined mass of the screw and hanger assembly is 11.40g.)* Bias. Apply weights to hanger with following loads in Fx: 2g, 5g, 10g, 31g, 51g, 81g, 102g. Record data output of all 6 axes for each load.
- **For Fy test:**
Orient sensor so -Y axis faces up. Repeat procedure used for Fx test using the same 11.40g hanger assembly.
- **For Fz test:**
Orient so +Z axis faces up. Place weight holder directly in the center of the TAP. *(The mass of the weight holder is 2.90g.)* Bias. Place weights into the holder with the following loads applied in -Fz: 2g, 5g, 10g, 31g, 51g, 81g, 102g. Record data output of all 6 axes for each load.
- Re-calibration per standard ATI procedures.
- After re-calibration, perform verification test for -Fx, -Fy, -Fz axes by applying only a 5g load in each orientation per the procedure above. Record data output of all 6 axes for each load.