The Effect of Wing Shape and Ground Proximity on Unsteady Fluid Dynamics During the Perching Maneuver.

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THE EFFECT OF WING SWEEP AND GROUND PROXIMITY ON UNSTEADY FLUID DYNAMICS DURING THE PERCHING MANEUVER

by

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Mechanical and Aerospace Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

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Major Professor: Samik Bhattacharya
ABSTRACT

While landing, birds often perform a perching maneuver, which involves pitching their wings upwards while decelerating to a complete stop. By performing this perching maneuver, the birds can continue generating higher lift and drag force while slowing down, resulting in a smooth landing. The present study is motivated by the perching maneuver and aims to investigate two critical aspects of it. First, we want to explore how the proximity of the ground affects the unsteady forces and the flow field during the perching flight; and second, we want to analyze how a wing sweep influences a perching maneuver.

To explore the first aspect of this dissertation, we investigated the finite flat plate undergoing a perching maneuver in the ground effect. Our results showed that the instantaneous and time-averaged lift force increased as the plate came close to the ground, while the instantaneous peak drag coefficient stayed relatively constant with changes in the ground height. However, the negative drag force, or the parasitic thrust, at the latter stages of the perching maneuver increased with the increase of the ground proximity. We found that performing rapid pitching at the end phase of the decelerating motion, which is done by introducing the time offset between the decelerating and pitch-up motion, significantly reduced the parasitic thrust even when the perching plate was in close proximity to the ground. Our results revealed that the dipole jet induced by the counter-rotating vortices was lower for the pitching case executed at the latter stage of the decelerating motion, which affected the advection of the shed vortices, acceleration of the fluid between the wing and the ground, and varied the unsteady forces during the perching maneuver. For the highest shape change number considered in this study, at a time
offset of 0.5, the wing generated a positive averaged drag force and near zero averaged lift force, which is appropriate to land smoothly on the initial perching location without gaining altitude.

The second aspect of this dissertation is motivated by the observation that some birds fold their wings to create a wing sweep during such perching. This study aims to find out whether such a wing sweep helps during a perching maneuver. We use two flat plates: one with a sweep and another without any sweep, and consider a deceleration maneuver where both decelerate to a complete stop from a Reynolds number, \( \text{Re} = 13000 \). We consider two cases: one, where the wings undergo only heaving, and another, where the wings perform both heaving and pitching. The latter maneuver was designed to mimic perching. By performing experiments and simulations, we compare the temporal evolution of the instantaneous forces and the vortex dynamics of both these plates. We show that during a major part of the deceleration, the instantaneous lift forces are higher in the case of the plate with sweep compared to the plate with no sweep during both kinematics. Our results indicate that the higher lift in the swept plate case was contributed by a stable leading edge vortex (LEV) which remains attached to the plate. This increase in stability was contributed by the spanwise vorticity convection caused by a distinct spanwise flow on the swept plate, as revealed by the numerical simulation. We also show that combined pitching and heaving resulted in higher force peaks, and the forces also decayed faster in this case compared to the heave-only case. Finally, by using an analytical model for unsteady flows, we prove that the higher lift characteristics of the swept plate were entirely due to higher circulatory forces.

We also developed an analytical model that accounts for the variation of unsteady forces on a flat plate undergoing a perching maneuver. We model the flat plate using unsteady lifting line theory while the effect of ground height is incorporated using image vortices. We used
Wagner’s theory and the unsteady Kutta condition to model pitching and gradual deceleration. To include the ground effect, we updated the added mass force by accounting for the increase in flow acceleration between the wing and the ground. The model’s accuracy was tested against the experimental results on a finite wing undergoing identical kinematics. Our result demonstrates that the present analytical model captures the unsteady variation of forces during a perching maneuver.
DEDICATION

I dedicate this work to my loving parents, who instilled in me the value of hard work and dedication, and to my sweet nephew, Namah. whose innocent smile keeps me inspired.
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I am deeply grateful to my parents for their unwavering love, support, and encouragement throughout my life. As a child I was more interested in sports than academics. But during my seventh-grade midterm exam, my mum and brother grabbed my ears and urged me to study for my math test the following day. To my surprise, I aced the test, which changed my perspective on the importance of effort and hard work. I owe my newfound motivation to my mum and brother and am grateful for their influence on my academic journey. I would like to thank my dad for supporting my decision to study abroad, which broadened my horizon and provided me with a deeper understanding of my field. Their constant support and encouragement have made difficult times seem manageable in pursuing my dreams, and I thank them for helping me pursue my dreams.

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CHAPTER 1: INTRODUCTION

This introductory chapter explains the motivation behind the study of the perching maneuver considered in this dissertation research. A literature review on the fundamentals of unsteady flow physics is also summarized. Finally, the objective of this research study is introduced, and an overview of the experiments used to investigate the research questions is outlined.

Motivation

Natural flyers like birds and insects display impressive maneuvering behaviors like acceleration, turning, braking, and landing. They are able to produce large aerodynamic forces over a short period of time, allowing them to navigate swiftly while encountering gust and dense environments or during landing maneuvers. This has generated a lot of interest among researchers because of its potential to create bio-inspired innovations like Micro Air Vehicles (MAVs). MAVs involve unsteady motions, similar to the movements of the natural flyers, which make use of the beneficial unsteady forces. An investigation of this unsteady motion is a useful model in the study of the unsteady flow physics. The evolution of vortex dynamics deals with the production of unsteady forces and the resulting fluctuation in the aerodynamic loads. The design of the next generation of flying MAVs requires not only a comprehensive understanding of unsteady flow physics but also the development of simple analytical models. This is the main theme of this dissertation.

In this dissertation, we are particularly interested in a rapid pitching wing during deceleration motion, which is a prevalent mode of unsteady motion among perching and hunting
birds. During perching, birds rapidly pitch their wings from a near horizontal to almost 90° angle of attack (Berg and Biewener 2010; Provini et al. 2014). By using this aerodynamic mode of motion, birds are able to dissipate their kinetic energy quickly and come to a complete stop in a short period of time, allowing them to execute precise and fast landing (Provini et al. 2014). However, when the wing is pitched up rapidly and simultaneously decelerating, the flow fully separates from the wing resulting in wing stall, which leads to the loss of aerodynamic forces. This illustrates the need for further research to fully understand the mechanisms involved when the wing pitches rapidly during deceleration.

Unsteady dynamics, such as perching, are often associated with unsteady flow. During this unsteady motion, the airflow is separated at the wing’s edges, creating swirling patterns of air known as vortices. During perching, the rapid pitching of the wing also accelerates the fluid surrounding the body, resulting in added mass force. This added mass force, in combination with the formation of stronger vortices, leads to the generation of higher lift and drag forces, allowing perching birds to execute controlled and fast landing.

In this dissertation, the focus is on studying the evolution of the unsteady flow on rapidly pitching plates during deceleration. The degree to which the aerodynamic performance of the pitching plates can be enhanced is dependent (complex interplay between wing motion and wing shapes) on the correlation of various wing parameters and wing motions. In this study, we investigated the effect of various kinematics, wing planform shapes, ground heights, and aspect ratio (AR) on the development of the vortices and their relationship with the evolution of the unsteady forces on the wing. To accomplish this, a two-dimensional planar particle image velocimetry was used to measure the unsteady flow field around the pitching plates.
Additionally, a load cell was attached to the wing to measure the unsteady forces. All wing planforms used in this dissertation were fabricated using 6 mm thick aluminum sheets.

Vortex dynamics in unsteady motion

In this section, the fundamental principles of vortex dynamics in unsteady motion are addressed. A brief overview of the current state of research and understanding in the field is also presented, providing a comprehensive understanding of the topic.

Dynamic stall

During unsteady motion, such as rapid pitching, the airfoil’s effective angle of attack ($\alpha_{\text{eff}}$) increases rapidly and surpasses the static stall limit. At this point, the airfoil can no longer generate lift without stalling. However, this sudden increase in $\alpha_{\text{eff}}$ can lead to an enhancement of lift, known as dynamic stall. The phenomenon of dynamic stall, characterized by an increase in lift due to a sudden rise in $\alpha_{\text{eff}}$, was first experimentally documented by Kramer (Kramer 1932). Later, Bailey and Gustafson (Bailey and Gustafson 1939) and Gustafson and Myers (Gustafson and Myers 1946) employed tufts and a camera mounted on an autogyro rotor blade to provide additional evidence of dynamic stall on the retreating blade in forward motion. Cebeci et al. (Cebeci et al. 2005) showed that lift in dynamic stall exceeds that in static stall as the inviscid pressure field surrounding the airflow adjusts quickly to the instantaneous flow at the speed of sound, while the viscous pressure field takes a longer time to adjust.

Figure 1 displays the dynamics stall process experienced by a dynamically pitching airfoil. At low $\alpha_{\text{eff}}$, the unsteady lift curve closely follows the steady-state lift curve, as the boundary layer remains attached to the suction/upper surface of the airfoil in both cases. This
trend continues until $\alpha_{eff}$ reaches the static stall angle of attack, $\alpha_{ss}$. Beyond $\alpha_{ss}$, the steady state lift starts to decrease due to boundary layer separation, leading to the flow reversal over the airfoil’s surface and an adverse pressure gradient on the suction surface, which results in a decreased lift. In contrast, the unsteady lift continues to increase (stage 2) beyond $\alpha_{ss}$. In the unsteady case, although the boundary layer separates, the flow remains attached to the leading edge (LE) of the airfoil due to the formation of dynamic stall vortex.

In stage 3, the continuous change in $\alpha_{eff}$ leads to a roll-up of the separated boundary layer into a fully formed leading edge vortex (LEV). As long as the vortex continues to grow, the unsteady lift force increases. However, once the vortex accumulates enough circulation, it detaches from the LE and convects downstream, causing a drop in unsteady lift drops, which marks stage 4 of the flow development and the end of the dynamic stall event. A detailed explanation of dynamic stall can be found in the paper by Corke & Thomas (Corke and Thomas 2015).

![Figure 1: Depiction of the dynamic stall process experienced by a pitching airfoil.](image-url)
Leading edge vortex formation, growth, and detachment.

When a finite plate undergoes a rapid pitch-up motion, its angle of attack increases dynamically. This rapid increase in the angle of attack causes the boundary layer to separate from each corner of the wing. As the effective angle of attack continues to increase, the separated boundary shear layer accumulates near the wing edges, creating a low-pressure region behind the separation point. This low-pressure region further attracts the separated shear layer, causing it to accumulate and form stronger vortices.

The growth of these vortices can be described by the vorticity transport equation, which is expressed as:

$$\frac{\partial \omega}{\partial t} + (\mathbf{v} \cdot \nabla) \omega = (\omega \cdot \nabla) \mathbf{v},$$  \hspace{1cm} (1)

Where the terms on the left-hand side represent the local temporal change of the vorticity and vorticity convection in x, y, and z directions, respectively. The term on the right-hand side represents the spatial change of vorticity due to the velocity gradients in the fluid. The leading-edge vortex (LEV), which is the major accumulator of circulation in the flow, can result in a transient increase of the lift force on the wing, which can be explained by the impulse theory.

Based on impulse theory, any change in the momentum of fluid over time is proportional to the force being exerted on the fluid by the wing. The LEV acts as a sink to the surrounding fluid, attracting more of the separated shear layer and increasing its velocity. This increase in velocity increases the momentum of the fluid, resulting in an increase in the lift force, as described by the impulse theory. Studies by Ellington et al. (Ellington et al. 1996) and Dickinson et al. (Dickinson, Lehmann, and Sane 1999) have observed that insects can gain higher transient lift for an extended period by prolonging the attachment of the LEV to their wing.
However, as the LEV grows, it accumulates most of the circulation in the flow within the vortex. The increased circulation concentration leads to a larger and stronger LEV but also makes it unstable. This instability eventually leads to the detachment of the LEV from the LE of the airfoil and results in the loss of the unsteady lift force.

Two mechanisms are commonly attributed to the detachment of the LEV: (a) bluff body detachment mechanism, which connects the geometrical length scale to the formation and detachment of the LEV, and (b) boundary layer eruption mechanism, which focuses on the viscous interaction of the boundary layer between the airfoil and the LEV.

In the first mechanism, bluff body detachment mechanism, the LEV's stability depends on the airfoil geometry's characteristic length scale. An experimental study on the plunging airfoil by Rival et al. revealed that the chord length of the airfoil c should be used as the characteristic length scale for the detachment process (D. E. Rival et al. 2014). During the initial phase of the LEV generation, the vortex initially attaches to the airfoil surface behind the LE, and as the LEV grows, this reattachment point subsequently moves toward the trailing edge of the airfoil. When this point reaches the TE, flow reversal is initiated at the TE. This reversed flow, also known as secondary flow or secondary vortices, moves upstream and interacts with the shear layer feeding the LEV, interrupting the LEV growth and detachment.

However, Widmann and Tropea found that, the LEV can stop growing on the oscillating airfoil even before the reattachment point reaches the TE (Widmann and Tropea 2015). They concluded that the vortex detachment is not dependent on any characteristic length scale of the airfoil but is instead caused by the viscous response of the boundary layer between the vortex and the airfoil. As the LEV grows, it induces a velocity gradient that imposes an adverse pressure gradient on the boundary layer. This adverse pressure gradient initiates the boundary layer's
separation, accumulating this separated vorticity carrying fluid into a secondary vortex. This secondary vortex will grow and eventually detach the LEV from the feeding shear layer.

**Leading Edge Vortex stability**

Controlling the stability of the leading-edge vortex (LEV) can offer various advantages for enhancing the performance of flying vehicles, such as increased lift and generation of unsteady forces and momentum for improved flight control. A study by Rossow (Rossow 1978) revealed the generation of lift force that is an order of magnitude higher simply by controlling the vortices through the use of leading-edge flaps and suction. This highlights the potential benefits LEV stability can have on the flight performance, as discussed in (Eldredge and Jones 2019; Emanuel 2020; Gursul, Wang, and Vardaki 2007).

Several vorticity stability mechanisms have been postulated, where LEV stability can be achieved by controlling the LEV growth. Lentink and Dickinson (Lentink and Dickinson 2009) conducted a numerical and experimental study on a low aspect ratio revolving fly wings. They found that Coriolis and centripetal acceleration could stabilize the LEV on the rotating wing. Additionally, Harbig, Sheridan, and Thompson (Harbig, Sheridan, and Thompson 2013) performed a numerical study on a rotating fruit fly wing and showed that the Coriolis and centripetal acceleration could mediate the LEV stability over the wing surface regardless of the aspect ratio. However, an experimental study by (A. R. Jones, Ford, and Babinsky 2011) did not observe evidence of stable LEV on the sliding and waving wing with an aspect ratio ranging from 2 to 4.

Ellington et al (Ellington et al. 1996) performed a flow visualization around the wings of the Hawkmoth and suggested that the spanwise flow directed towards the wingtip is responsible
for stabilizing the LEV in insect flight. Hartloper and Rival (Hartloper and Rival 2013) showed that pitching planforms with spanwise leading edge curvature can induce outward-directed convection of vorticity towards the wingtip, which can mitigate the arch-shaped formation of the LEV and stabilize the vortex. Additionally, through analytical and experimental results, Wong and Rival (Wong and Rival 2015) studied two-dimensional flapping profiles and concluded that LE profile sweep enhanced the spanwise vorticity transport, and as a result, increased the relative stability of the LEV. However, when analyzing the vorticity transport within the LEV on rotating planforms, Wojcik and Buchholz (Wojcik and Buchholz 2014) found that, although the spanwise velocity within the LEV was significant, the spanwise convection of vorticity was insufficient to regulate the LEV circulation and its stability. Thus, it suggests that further study is needed to fully understand the mechanisms involved in LEV stability during unsteady motions.

Our investigation into the perching maneuver of birds revealed that some birds fold their wings to create a wing sweep. In this dissertation, we aimed to determine whether this wing sweep enhances the stability of the LEV, prolonging its attachment to the wing. To address this question, we conducted a combination of experiments and numerical simulations to study the flow physics around the swept wing during perching. Our findings shed light on the mechanics behind the observed behavior and provide insight into the potential benefits of wing sweep for enhancing LEV stability.

Objectives and Outline of the Dissertation

The objective of this dissertation is to improve our current understanding of unsteady dynamics in perching flight. Here, we want to quantify the wing vortex interaction in perching...
flight over a broad range of initials and boundary conditions. For this, we investigated the unsteady forces and flow fields developed around the finite wing over a wide range of wing kinematics and ground heights. Finally, we extend our understanding of unsteady vortex dynamics in perching flight at different wing shapes.

In chapter 2, the detailed experimental settings and the data processing methods used to measure the experimental results in this dissertation will be outlined.

In chapter 3, the effect of ground proximity on the unsteady dynamics during the perching maneuver is presented. A wide range of wing kinematics is tested at ten different ground heights to correlate the effect of ground on the evolution of the unsteady dynamics in perching flight. To examine the impact of frontal area expansion during the perching maneuver, we execute the rapid pitch up motion at various stages of the deceleration. To enhance the efficacy of these results, we test the asynchronous motion cases at three different pitch rates.

The effect of wing sweep during the perching maneuver is studied in chapter 4. Two flat plates are used: one with a sweep and another without sweep. A decelerating motion is considered where both plates decelerate to a complete stop from the Reynolds number, Re = 13,000. Two motion kinematics are used: one, where the wings undergo only heaving, and another, where the wing performs both heaving and pitching. The latter maneuver is designed to mimic perching.

In chapter 5, a detailed description of the unsteady analytical model used to simulate the perching maneuver is presented. The flat plate is modeled using the lifting line theory, and the effect of ground is incorporated using the image vortices. To model the unsteady motions, such as pitching and gradual deceleration, Wagner’s theory is used in combination with the unsteady
kutta condition. The added mass force component is updated to incorporate the increase in the acceleration of the flow between the wing and the ground to include the ground effect.
CHAPTER 2: METHODOLOGY

This chapter presents a detailed explanation of the experimental set-up used in this dissertation research. First, the combination of force and torque sensor and data acquisition device (DAQ) used to measure the aerodynamic forces on the wing are discussed. Then, the arrangement of 2D-planar PIV is outlined.

Experimental set-up

Experiments were conducted in a free surface towing tank of dimension 0.9 m (L) x 0.45 m (W) x 0.4 m (H). Figure 2 illustrates the schematics of the experimental set-up. A servo-driven linear stage (FSL120, FUYU Inc., China) was used to tow the wing models along the length of the water tank. The deceleration was applied by gradually slowing down this linear stage. The heaving motion was executed with a stepper-driven linear stage (LSQ150B-T3, ZaberTech. Inc., Canada) connected orthogonally to the servo-driven stage. The pitching motion was executed with the help of a stepper-driven rotary stage (RSW60A-T3, Zaber Tech. Inc., Canada). The pitch axis was located at the mid-chord point of both wings. The speed and acceleration of all the linear stages were measured using an ultrasonic motion sensor (PASCO PS-2103A3, USA). The movements of the heaving motor and the pitching motor were synchronized with the forward towing motion with the help of a proximity switch which generated a master pulse to drive the rest of the motors at specified intervals. A force sensor was attached below the pitching motor. The wing model was connected to the force sensor through a cylindrical rod. The wing model was submerged vertically in the towing tank, with a 0.09 m gap between the wingtip and the tank bottom.
Measurements of instantaneous forces

The instantaneous forces on the wings were measured with a six-axis force and torque sensor (MINI 40, ATI Inc., USA) connected to a 16-bit DAQ device (NI-USB-6211, National Instrument, USA). Force-sensor data were acquired at a sampling rate of 5 kHz, and they were averaged over five runs. Later, the force data were filtered with a Butterworth low pass filter with a cutoff frequency of 3 Hz. Thereafter, a moving average of 20 points was used to further smooth the data. The uncertainty in the force data is found to be around 7% at the peak and less than 4% for the smaller magnitude of the forces.

For taring, we employed both dynamic and static taring as outlined in the work of Granlund et al. (K. O. Granlund, Ol, and Bernal 2013). For dynamic taring, the tare experiments were conducted in the air using the same kinematics as in the water. When we compared the dynamic tare data with the lift force in water, the maximum difference between the two data is approximately 7%, which is at the peak and weighs relatively less at other instants (see Figure 3). Granlund et al. argued that if the apparent mass of the water accelerated along the model is
approximately ten times higher than the mass of the model and metric portion of the balance, it prevents the testing of the dynamic tare in the air (Barlow, Rae, and Pope 1999). Based on this argument, as the maximum value of the dynamic tare in air is around 7%, we also excluded the testing of the dynamic tare in air. For static taring, we measured the data in still water at every 3°. In the present study, the wing models produced negligible static tare, which was in the range of ±0.009 N. The resolution of the MINI40 force sensor is 1/200 N for Fx and Fy, which is close to the static tare value. As the wing models generated negligible static tare values and are in the range of published resolution of the force sensor, we also excluded the static tare in the present study.

Figure 3: Comparison between lift in water, dynamic, and static tare.

The cutoff frequency was computed using the spectral analysis of the raw force data. Additional information about the spectral analysis is presented in our response to comment number 10. The oscillatory frequency due to fluid forces (or frequency of vortex shedding) is found to be 4 Hz, whereas the fundamental frequency of the wing model due to structural
vibration was found to be 57 Hz. Analysis of the PIV data also showed a shedding frequency of approximately 4 Hz. In this study, we used the cutoff frequency of 7 Hz, which is well below the model vibration fundamental frequency, and therefore removes the contamination of structural vibration on the measured force data but at the same time retains most of the oscillatory peaks due to fluid forces.

Figure 4: (a) Impact testing on the wing model using a hammer excitation. Note the accelerometer attached to the mid-tip section of the wing; (b) hammer; (c) Spectral analysis of a signal obtained using a hammer excitation on the rectangular and swept wing.

Figure 5: Spectral analysis of the signal obtained using an accelerometer while the wing model is executing specific kinematics: (a) towing in the air (Air tow), heave-pitch case in the air (Air HP), and heave-pitch case in water (Water HP); (b) Comparison of the spectral analysis while the wing model is executing heave-pitch case in the air (Air HP) and water (Water HP).
To find the fundamental frequency of the wing model, we have performed additional detailed measurements with the help of accelerometers. We used a MEMS DC accelerometer (3711F122G, PCB Piezotronics, USA) which is particularly suited for measuring low-frequency structural vibration underwater. In this study, we attached the accelerometer at two locations: (1) at the tip and (2) at the mid-span (as shown in Figure 4). We performed the spectral analysis (FFT) of the accelerometer's output signal and found one peak at around 4 Hz and another at approximately 56 Hz (see Figure 5). The peak at about 56 Hz is related to the fundamental frequency of the wing model due to the structural vibration of the model. We also did the spectral analysis of the force sensor data and found similar results. We measured the shedding frequency of the TEV manually using the processed PIV flow fields. Later, we oriented the wing
at 0 deg and conducted a forward towing motion in water and air (no heaving). This was done to ensure that the flow was attached and no vortex formed. Here, we found a peak at 57 Hz in water and 78 Hz in air (see Figure 6). It suggests that the peak at 4 Hz results from fluid dynamics, mainly due to the shedding of the vortices.

As the fundamental frequency due to the structural vibration (56 Hz) is too high compared to the cutoff frequency, the influence of structural vibration is removed from the force data using a low pass filter. In contrast, the peak at about 4 Hz is associated with the frequency due to fluid dynamics. In the force data, we applied the low pass filter with a cutoff frequency of 3.

Flow-field measurements

Planar particle image velocimetry (PIV) was used to measure the velocity field at two separate planes located at (1) the 50% span, and (2) the 70% span of both wings. The water tank was seeded with neutrally buoyant, silver-coated hollow glass spheres (Conduct Phill, Potter Inc., USA) of 10μm diameter. The plane of interrogation was illuminated by a laser sheet generated using a continuous-wave green laser (FN Series, Dragon laser Ltd., China). The laser head generated a beam with a diameter of 2 mm, which was expanded into a 2 mm thick laser sheet using two cylindrical lenses. Images were recorded with a CCD camera (PCO2000, PCO Tech, USA) at a frame rate of 200 Hz and a resolution of 1280 x 1024 pixels. The field of view was 0.4 m x 0.32 m. The images were processed in PIVLab, a MATLAB based software. We used an iterative multi-pass algorithm with a window size of 64 x 64 pixels in the first pass and 32 x 32 pixels in the second pass, with a 50% overlap between each successive window. PIV data were phase-average over five runs. To calculate the circulation inside the leading-edge and
trailing-edge vortices, we used two scalar functions, $\Gamma_1$ and $\Gamma_2$, following Graftieaux et al. (Graftieaux, Michard, and Nathalie 2001). The dimensionless scalar function $\Gamma_1$ identifies the vortex core, whereas the dimensionless scalar function $\Gamma_2$ detects the vortex boundary. The scalar function $\Gamma_1$ and $\Gamma_2$ are defined as:

$$
\Gamma_1(p) = \frac{1}{N} \sum_{i=1}^{N} \frac{(x_p - x_i) \times (u_i) \cdot n}{\|x_p - x_i\| \|u_i\|} \tag{2}
$$

$$
\Gamma_2(p) = \frac{1}{N} \sum_{i=1}^{N} \frac{(x_p - x_i) \times (u_i - \bar{u}_p) \cdot n}{\|x_p - x_i\| \|u_i - \bar{u}_p\|} \tag{3}
$$

where $p$ is a fixed point in the two-dimensional domain. $x_i$ is the position vector, $u_i$ is the velocity vector, and $N$ is the total number of points in the flow domain. $n$ is the unit vector normal to the plane. In this study, a threshold value of $|\Gamma_1| > 0.9$ was applied, and the location of the vortex core was determined by the maximum local value of $\Gamma_1$. The maximum value of $\Gamma_2$ represents the vortex boundary. Here, a threshold of $|\Gamma_2| > 2\pi$ was used to represent the vortex boundary. After the vortex contour was identified, the vorticity within this vortex boundary was summed up to compute the circulation inside that contour.

A commercial software code, STAR-CCM+, was used to numerically simulate the flow of water over the rectangular and the swept plate during both the kinematics. This software uses a SIMPLE-C segregated solver with 2nd order special accuracy. The motion of the wings was simulated using an overset mesh scheme, which utilizes sliding meshes to solve solid body displacement. A no-slip boundary condition was used on the wing and floor boundary to capture any viscous vortex shedding interactions occurring with the floor boundary to replicate a true ground effect phenomenon. A symmetry plane boundary condition was applied on the sidewalls to avoid any fluid effects that could arise due to the wall boundary. In the experiment, the wing
was just under the water’s surface. Thus, our numerical model does not precisely replicate the experimental procedure; however, we assumed that the water-boundary effects were minimal and thus can be simulated using a symmetry plane boundary condition. To compute the numerical uncertainty due to the mesh size, we carried out a mesh-independence study. In this study, we systematically varied the mesh base size and time step to maintain a constant Courant number of unity. The rectangular wing with heave-pitch kinematics was considered for this mesh-independence study. Based on this study, for all the cases, we used a mesh base size of 0.002 m.

![Computational Mesh](image)

Figure 7: Computational Mesh
CHAPTER 3: RAPIDLY PITCHING PLATES IN DECELERATING MOTION NEAR THE GROUND

Introduction

The ability of natural flyers, such as birds, to accomplish different flying objectives, like acceleration, turning, breaking, and landing, through rapid wing pitching has generated a lot of interest from researchers to study the fluid dynamics of the pitching plates. Birds have been observed to pitch their wings for a variety of purposes, such as perching birds that rapidly pitch their wings upward to decelerate to a complete stop (Berg and Biewener 2010; A. C. Carruthers et al. 2010; Anna C. Carruthers, Thomas, and Taylor 2007; Provini et al. 2014), and hunting birds, which also use the same motion to slow down to catch a fish out of water before flying away (Collard III and Brickman 2021; Gerrard and Bortolotti 2014; Todd et al. 1982; Venable 1997). Motivated by such observation, we aim to study the primary aerodynamic mechanism at work on rapidly pitching plates during deceleration. We have two major objectives: to understand how natural flyers can accomplish different flying objectives by rapidly pitching their wings during deceleration and to investigate how the ground effect influences the unsteady dynamics of the perching maneuver.

Rapid pitching causes a quick change in the wing’s surface area facing the airflow, which can significantly impact the airflow over the wing. This rapid change in the wing’s surface area can have fascinating prospects for flow control, as the added mass changes with the change in the surface area, which can play a significant role in varying the dynamic forces on the wing. (Saffman 1967) showed that a body can propel itself by deforming its surface area through added mass recovery. (Childress, Vandenberghhe, and Zhang 2006) conducted an experimental study on
a flexible body in an oscillating air and concluded that exposing the variable frontal area to airflow due to wing flapping leads to changes in the added mass, resulting in stable hovering. Rapid area change can lead to boundary layer separation and the shedding of the vortices on a vanishing body (Wibawa et al. 2012). (Weymouth and Triantafyllou 2013) concluded that in addition to added mass recovery, the deforming body relies on flow separation elimination to achieve ultra-fast escape. However, our understanding of rapid area change is limited to decreasing surface area in acceleration. The study on how the flow behaves over an increased surface area during deceleration, commonly experienced by birds that perch and hunt, has yet to be extensively studied.

Recently, (Polet, Rival, and Weymouth 2015) conducted an experimental and numerical study on the unsteady aerodynamics of a two-dimensional NACA0012 airfoil undergoing simultaneous pitch-up and decelerating motion. They found that the significant lift and drag force on a wing during perching is mainly caused by the added mass effect and the formation of strong vortices at the leading and trailing edge of the wing. (Jardin and Doué 2019) also performed a numerical study on a perching airfoil and concluded that minimum kinetic energy could be achieved on the airfoil by increasing the pitch rate or the lift and drag force on the airfoil can be enhanced by increasing the pitch rate. Additionally, (Dibya Raj Adhikari et al. 2022) studied the unsteady dynamics of a finite wing undergoing a rapid pitch-up motion while decelerating and descending close to the ground. They showed that a perching wing can generate higher forces by using a combination of pitching and heaving motions during deceleration. However, in these studies, although the wing generated a higher drag force by increasing the pitch rate, which is appropriate for decelerating rapidly to a complete stop, the perching wing also generated a higher lift force. This higher lift force causes the wing to rise in altitude, which
may not be desirable for perching at short distances. Thus, more research is needed to understand the mechanics involved when the wing pitches rapidly during deceleration.

Rapid area change studies have also investigated the effect of varying the frontal area against the incoming airflow. (Spagnolie and Shelley 2009) found through a numerical simulation that by controlling the phase difference between the shape change and the background flow of an oscillating flow, a shape-changing body can generate vortex structures that induce a downward-moving dipole jet below the body. This jet of fluid enabled the body to hover or ascend vertically. (Weymouth and Triantafyllou 2013) observed that a rapidly shape-changing body can eliminate the flow separation from its surface if it deforms quickly. By eliminating flow separation, the drag force is reduced, and thrust force is increased, resulting in high acceleration, which is beneficial for escape maneuvers. The timing of the shape change in relation to the airflow influences the change in the added mass and the evolution of the vortices. In this study, we focus on how varying the timing of the rapid pitch-up motion relative to the decelerating flow affects the generation of unsteady forces and the flow field.

Furthermore, it is also important to study the effects of rapid pitching of a wing on the ground effect as perching or hunting usually takes place close to the ground surface. (Quinn et al. 2014) conducted an experimental and numerical study on a pitching airfoil in close proximity to the ground and found that pitching near the ground generates a vortex pair instead of a vortex street, resulting in an increased average thrust force. Additionally, they observed that as the airfoil comes closer to the ground, the lift force increases, pushing the airfoil away from the ground. (Deepthi and Vengadesan 2021) performed simulations of an inclined stroke plane flapping wing in ground effect and showed that the interaction of dipole jet with the ground boundary layer can enhance lift. (Polet, Rival, and Weymouth 2015) and (Jardin and Doué 2019)
also reported the creation of dipole jet during perching maneuvers; however, neither of these studies considered the effect of ground on the perching behavior. Therefore, further investigation is needed to fully understand the unsteady ground effect experienced by the perching or hunting birds.

This observation motivated us to understand the fundamental unsteady mechanisms at work that allow the birds to accomplish different flying objectives while rapidly pitching their wings upward during deceleration. In this paper, we consider a shorter pitch time than the deceleration time, enabling us to perform rapid wing pitch at various stages of the decelerating motion. When the start of the wing pitch and deceleration are in sync, the wing pitch-up motion stops while the plate continues to decelerate, representing the motion trajectory of predator birds that slows down but never stops while catching live fish. When the start of the wing pitch is delayed, the wing pitch-up motion and the wing deceleration both come to a complete stop simultaneously, representing the behavior of birds that perch. To study the impact of the ground effect, we conducted tests at different ground heights. This experimental investigation can provide new insights into the aerodynamic mechanisms natural flyers use to control their motion and how these mechanisms can be replicated in designing next-generation flying vehicles and aircraft.

**Wing model and problem description**

A finite rectangular wing planform was used as a perching wing model. The perching wing model had a chord length (c) of 0.05 m and a planform area of 0.0075 m². The aspect ratio (AR) of the perching plate was 3, and was fabricated from a 6 mm thick flat aluminum plate. The
leading-edge, LE, of the wing, was rounded while the trailing edge, TE, was sharpened to meet the Kutta condition.

To simulate the perching maneuvers, two scenarios were considered: synchronous motion and asynchronous motion. In both scenarios, the wing model was initially oriented at an angle of attack \( \alpha_0 = 0^0 \) and then rapidly pitched up to \( \alpha = 90^0 \) while undergoing deceleration.

![Figure 8](image)

Figure 8: (a) Comparison of the variation of non-dimensional velocity \( U^* \) between synchronous and asynchronous motions. Variation of velocity and angle of attack for two perching scenarios: (b) synchronous motion; and (c) asynchronous motion. Comparisons shown are represented as a function of non-dimensional time \( t^* = \frac{t}{t_p} \), where \( t_p \) is the time period of pitch-up motion. Here, the decelerating velocity is scaled by the steady state velocity, \( U_\infty \), while the total change in the angle, which is \( 90^0 \), scales the angle of attack during pitch-up motion. The ratio of the time period of deceleration between synchronous, \( t_{da} \), and asynchronous motion, \( t_{das} \), is \( r = \frac{t_{da}}{t_{das}} = \frac{1}{1.5} \). For the synchronous case, \( t_{da} = t_{ps} \), whereas for asynchronous case, \( t_{das} = 1.5 \cdot t_{pas} \).

In synchronous motion, the wing decelerated from steady velocity \( U_\infty \) of 0.1 m/s to a complete stop while pitching up, with both motions having the same motion duration, i.e., \( t^*_{decn} = t^*_{pitch} \) (see Figure 8 (b)). This means that the start and end of the deceleration and rapid pitch-up motions are in sync. The pitch-up motion causes a rapid increase in the frontal area of the wing facing the flow. This increase in the frontal area of the wing, combined with simultaneous deceleration, can be quantified using the shape change number:
\[ \Xi = \frac{V}{\Delta U} \]  

(4)

where \( V \) is the frontal area speed of the airfoil and \( \Delta U \) is the change in the translation speed of the wing during deceleration. We employed three shape change numbers, \( \Xi = 0.2, 0.4, \& 0.6 \), and executed each \( \Xi \) at ten non-dimensional ground heights ranging from \( h^* = \frac{h}{c} = 1.5 - 0.04 \).

Here, \( h^* = 1.5 \) will be referred to as far from the ground case, while \( h^* = 0.04 \) will be referred to as close to the ground case.

Table 1: Summary of the kinematic parameters

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>( \dot{U} (m/s^2) )</th>
<th>( \alpha (rad/s) )</th>
<th>( \Xi )</th>
<th>Synchronous</th>
<th>Asynchronous ((t_{os}^*))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0.0351</td>
<td>0.550</td>
<td>0.2</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>C1_0</td>
<td>0.0234</td>
<td>0.550</td>
<td>0.3</td>
<td>X</td>
<td>✓ (0.00)</td>
</tr>
<tr>
<td>C1_25</td>
<td>0.0234</td>
<td>0.550</td>
<td>0.3</td>
<td>X</td>
<td>✓ (0.25)</td>
</tr>
<tr>
<td>C1_50</td>
<td>0.0234</td>
<td>0.550</td>
<td>0.3</td>
<td>X</td>
<td>✓ (0.50)</td>
</tr>
<tr>
<td>C2</td>
<td>0.0877</td>
<td>1.377</td>
<td>0.4</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>C2_0</td>
<td>0.0585</td>
<td>1.377</td>
<td>0.6</td>
<td>X</td>
<td>✓ (0.00)</td>
</tr>
<tr>
<td>C2_25</td>
<td>0.0585</td>
<td>1.377</td>
<td>0.6</td>
<td>X</td>
<td>✓ (0.25)</td>
</tr>
<tr>
<td>C2_50</td>
<td>0.0585</td>
<td>1.377</td>
<td>0.6</td>
<td>X</td>
<td>✓ (0.50)</td>
</tr>
<tr>
<td>C3</td>
<td>0.1111</td>
<td>1.745</td>
<td>0.6</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>C3_0</td>
<td>0.0741</td>
<td>1.745</td>
<td>0.9</td>
<td>X</td>
<td>✓ (0.00)</td>
</tr>
<tr>
<td>C3_25</td>
<td>0.0741</td>
<td>1.745</td>
<td>0.9</td>
<td>X</td>
<td>✓ (0.25)</td>
</tr>
<tr>
<td>C3_50</td>
<td>0.0741</td>
<td>1.745</td>
<td>0.9</td>
<td>X</td>
<td>✓ (0.50)</td>
</tr>
</tbody>
</table>
In asynchronous motion, the deceleration time was extended compared to the synchronous deceleration time (see Figure 8 (a)) while keeping the pitching time constant. As a result, for asynchronous motion, the deceleration time is longer than time to pitch, i.e., \( t_{\text{decn}_{\text{as}}}^* = 1.5 \times t_{\text{pitch}_{\text{as}}}^* \), which creates a time offset between the two motions. This time offset allows the execution of the pitch-up motion at various deceleration stages. In asynchronous motion, the change in the velocity when the wing completes the pitch-up motion is \( \Delta U = U_{\infty} \frac{t_{\text{pitch}}^*}{t_{\text{decn}}^*} = U_{\infty} \times \frac{1}{1.5} \). Because of this, for the same pitch rate, the \( \Xi \) for asynchronous motion is higher than that of the synchronous case, i.e., \( \Xi_{\text{asyn}} = 1.5 \times \Xi_{\text{syn}} \). Here, for each \( \Xi \), we use three-time offsets \( t_{\text{os}}^* = 0, 0.25, \text{and} \ 0.5 \). When \( t_{\text{os}}^* = 0 \), the start of the deceleration and pitch-up motions are in sync, which results in the pitch-up motion ending before the wing decelerates to a complete stop. When \( t_{\text{os}}^* = 0.5 \), the start of the pitch-up motion lags the start of the deceleration motion, but the end of the pitch-up motion and deceleration motion are in sync. Each asynchronous motion case was executed at three non-dimensional ground distances \( h^* = 1.5, 0.25, \text{and} \ 0.04 \).

The steady-state velocity of the wing model was \((U_{\infty})\) of 0.1 m/s. Based on \( U_{\infty} \) and \( c = 0.05 \text{ m} \), the Reynolds number of the perching wing model was \( \text{Re} = 6,500 \). The kinematic parameters used in this experiment are summarized in Table 1.

**Results and discussion**

First, we present the results separately for synchronous and asynchronous motion. The synchronous motion refers to the cases where the start and end of deceleration and pitch-up motions are in synchrony. In contrast, asynchronous motion refers to the cases where the two motions are not in synchrony. Next, we discuss the scaling laws for perching maneuvers. Finally,
we compare instantaneous forces between the experimental results and the analytical model’s predicted results.

Synchronous motion: Unsteady forces and flow field

Figure 9 (a) shows the evolution of the lift coefficient for the synchronous motion at three shape change numbers $\Xi = 0.2, 0.4, \text{ and } 0.6$. At $t^* = 0$, the deceleration and pitch-up motion are initiated. The execution of simultaneous deceleration and pitch-up motion results in a steep rise in the lift coefficient and attains the peak value after a certain time instant. This initial rise in the lift coefficient is mainly due to the combined effect of non-circulatory and circulatory force. The peak lift force coefficient is found to increase with increasing $\Xi$, consistent with the results of (Polet, Rival, and Weymouth 2015) and (Jardin and Doué 2019). The peak lift coefficient rises by approximately 50% while increasing the $\Xi$ from 0.2 to 0.6. After this initial peak force, the wing experiences a decline in the lift coefficient. This decay in the lift is related to the detachment of the leading-edge vortex (LEV) from the wing leading edge (LE), leading to the stalled flow at the latter stage of the motion. This decline in lift coefficient can also be related to the decrease in the non-circulatory force due to the deceleration of the wing. Figure 9 (a) also shows that the lift force for $\Xi = 0.6$ starts decaying at a later stage of the motion compared to that of $\Xi = 0.2$. 
Figure 9: Comparisons of (a) lift and (b) drag coefficient on the rectangular wing for three Ξ. Each Ξ is presented at four non-dimensional ground heights, h*.

To illustrate the effect of ground proximity in the perching maneuver, Figure 9 (a) shows the evolution of instantaneous lift coefficient at various non-dimensional ground heights range, $1.5 \leq h^* \leq 0.04$. When $h^*$ decreases from 1.5 to 0.04, the initial peak lift coefficient increases and this behavior is consistent at each Ξ. For $Ξ = 0.2$, the initial peak lift force rises by approximately 19%, whereas for $Ξ = 0.6$, this rise is approximately 38%. Although the initial peak force increases with the decrease in ground height, the trough force also decreases when the wing is close to the ground. However, the instantaneous lift coefficient increases for a major portion of the perching maneuver when the wing is close to the ground.

The evolution of the drag coefficient for the synchronous motion is depicted in Figure 9 (b). It can be seen that the instantaneous drag coefficient is larger for higher Ξ. The peak drag coefficient increases by approximately 10% when the Ξ is changed from 0.2 to 0.3. It is also interesting to note the time instant for the initial peak drag force moves from $t^* = 0.45$ for $Ξ = 0.2$ to $t^* = 0.52$ for $Ξ = 0.6$. This trend is comparable with the lift coefficient, which suggests that the peak and decay of the forces occur at a higher angle of attack for higher Ξ. This phenomenon has
also been observed by (KleinHeerenbrink et al. 2022), who concluded that perching birds pitch faster to minimize the stall distance.

Unlike the lift coefficient, there is no clear benefit of the ground on the evolution of the drag coefficient. For each Ξ, varying the $h^*$ shows an insignificant initial peak drag force change. However, the parasitic thrust is influenced by ground proximity. For all Ξ, it is observed that the parasitic thrust increases when the wing is close to the ground.

Figure 10: Contours of the normalized vorticity field, $\omega^*$, for $\Xi = 0.2$ at the 50% of the wingspan at two different time-steps, $t^* = 0.25$ & 0.50: top plot represents PIV results at $h^* = 1.5$ (far from ground case); bottom plot represents PIV results at $h^* = 0.04$ (close to ground case).

To better understand our findings, we analyzed the vorticity field for $\Xi = 0.2$ and 0.6 at two extreme ground height cases. To normalize the vorticity field, we used the wing’s chord
length and steady state translational velocity, resulting in \( \omega^* = \frac{\omega \times c}{U_\infty} \). We present the normalized vorticity field at four different time instants, \( t^* = 0.25, 0.5, 0.75, \) \& 1.0, to highlight the key changes in the flow field due to the variations in \( \Xi \) and ground heights.

Our PIV results demonstrate that during deceleration, executing the rapid pitch-up motion causes the shear layer to separate and form counter-rotating leading-edge vortex (LEV) and trailing edge vortex (TEV) structures (see Figure 10). At \( t^* = 0.25 \) for \( \Xi = 0.2 \), we observe the formation of coherent LEV and TEV at both ground heights. As the wing continues to pitch-up dynamically, the size and strength of the vortices increase, correlating with the enhancement of
the lift and drag forces on the wing. By $t^* = 0.50$, difference in the evolution of vortices and wake between the two extreme ground height cases became apparent. Figure 11 shows the contours of normalized vortex structures at the end phase of the perching maneuver, i.e. $t^* = 0.75 & 1.0$. At later time instants, the vortices shed from the wing and advect away from the wing structures, reducing the impulse they generate on the wing. This results in a rapid drop in the aerodynamic forces on the wing at the end phase of the maneuver.

![Figure 11](image)

Figure 11: Contours of normalized vortex structures at the end phase of the perching maneuver, i.e. $t^* = 0.75 & 1.0$ at $h^* = 1.5 \& 0.04$ (close to ground case). Figure 12 shows the vorticity field for $\Xi = 0.6$. At $t^* = 0.25$, the evolution of vorticity field is similar to that observed for $\Xi = 0.2$, but the vortex structures are larger and stronger for $\Xi = 0.6$. This yields higher aerodynamic forces on a wing for higher $\Xi$. At $t^* = 0.50$, the vortices

![Figure 12](image)

Figure 12: Contours of the normalized vorticity field, $\omega^*$, for $\Xi = 0.6$ at the 50% of the wingspan at two different time-steps, $t^* = 0.25 \& 0.50$: top plot represents PIV results at $h^* = 1.5$ (far from ground case); bottom plot represents PIV results at $h^* = 0.04$ (close to ground case).
interact with the ground, influencing their growth, advection, and dissipation. For the near ground case ($h^* = 0.04$), the LEV and TEV are larger, and the shed vortices are more coherent, resulting in higher lift force on the wing.

For the near ground case ($h^* = 0.04$), the LEV and TEV are larger, and the shed vortices are more coherent, resulting in higher lift force on the wing.

Figure 13: Contours of the normalized vorticity field, $\omega^*$, for $\Xi = 0.6$ at the 50% of the wingspan at two different time-steps, $t^* = 0.75$ & 1.0: top plot represents PIV results at $h^* = 1.5$ (far from ground case); bottom plot represents PIV results at $h^* = 0.04$ (close to ground case).

At the end phase of the perching maneuver, we observe that the counter rotating vortex structures induces a dipole jet oriented downward and slightly forward, producing upward and backward forces. When the wing is close to the ground, the dipole jet impinges on the ground, potentially affecting the reaction forces on the wing depending on the impingement direction. Figure 13 shows that at $t^* = 1$, the impingement of the dipole jet with the ground advects the vortices, further separating the shed LEV and TEV. For the near ground case (for $\Xi = 0.6$), the x-
distance between the LEV and TEV is 0.92c compared to 0.76c for the far ground case. This results in lower impulse on the wing and potentially explaining the increased drop in the lift and drag force at the end of the maneuver on the perching wing close to the ground.

**Asynchronous case: Unsteady forces and flow field**

To examine the effect of asynchronous motion on the development of unsteady dynamics in the perching flight, three-time offsets, \( t^{*}_{\text{os}} = 0, 0.25, \text{and} \ 0.5 \), were introduced between the decelerating and pitch-up motions. Figure 14 (a) and (b) shows the lift and drag coefficient evolution on the rectangular plate at three Ξ and at three \( t^{*}_{\text{os}} \) between the two motions. For the asynchronous case, the pitch rate is the same as in the synchronous case; however, we reduced the deceleration value. As a result, for asynchronous cases, Ξ is increased by a factor of \( \frac{1}{r} \).

Figure 14 (a) shows that increasing Ξ enhances the instantaneous lift coefficient, similar to the behavior observed in the synchronous case. Although the pitch rate is the same between the synchronous and asynchronous motions, for \( t^{*}_{\text{os}} = 0 \), the peak lift coefficient for asynchronous motion is approximately 40% higher than that of the synchronous case. This can be explained by the higher translational velocity experienced by the pitching plate due to the slower deceleration in asynchronous motion. This higher translational velocity enhances the asynchronous motion’s circulatory and non-circulatory lift coefficient. At higher time offsets, \( t^{*}_{\text{os}} = 0, 0.25, \text{&} \ 0.5 \), the lift coefficient starts to increase at a later instant and generates a lower peak lift coefficient compared to that of \( t^{*}_{\text{os}} = 0 \). This delay in the increase in the lift coefficient is in line with the delay in the start of the pitch-up motion. In contrast, the reduction in the instantaneous and peak lift coefficient can be correlated with the slower translational speed due
to the deceleration of the wing. This trend is consistent for all $\Xi$ considered in this study, with a lower peak lift coefficient for smaller $\Xi$.

Figure 14: Comparison of the instantaneous (a) lift and (b) drag coefficient on the rectangular wing for $\Xi = 0.3$, 0.6, and 0.9. Each $\Xi$ is presented at three-time offsets, $t^{\ast}_{os} = 0, 0.25, and 0.5$, between the decelerating and pitch-up motions.

The drag coefficient for asynchronous motion is shown in Figure 14 (b) for three $\Xi$. All cases show an increase in the peak drag coefficient at $t^{\ast}_{os} = 0$ compared to that of the synchronous case and a reduction in the peak drag coefficient with the introduction of time offset between the two motions. Although the peak drag force is reduced at $t^{\ast}_{os} = 0.5$, the perching plate generates drag throughout the perching flight, which can result in the continuous
dissipation of the kinetic energy of the perching plate. Additionally, increasing the $t_{os}^*$ delays and decreases the generation of parasitic thrust. Continuous generation of the drag and reduced parasitic thrust is essential for a smooth landing.

To further analyze the influence of asynchronous motion, the time-averaged lift and drag coefficient during the pitch-up motion is plotted in Figure 14 (c & d). Figure 14 (c) shows that increasing the $t_{os}^*$ decreases the time-averaged lift coefficient, $C_{L_{avg}}$. For $\Xi = 0.9$, the $C_{L_{avg}}$ decreases from 0.7 to near zero when the time offset is changed from $t_{os}^* = 0$ to $t_{os}^* = 0.5$. Although the drag plot (see Figure 14 (d)) also shows a reduction in the time-averaged drag coefficient, $C_{D_{avg}}$, with the increase of the time offset, the decrease in the drag coefficient is small compared to that of the lift coefficient. For $\Xi = 0.9$, the $C_{D_{avg}}$ decreases from 0.52 to 0.4 when the time offset is changed from $t_{os}^* = 0$ to $t_{os}^* = 0.5$. This near-zero lift force and positive drag force can help birds to perch on the original landing or perching location without the gain of altitude.

Figure 15 displays the lift and drag coefficient behavior for $\Xi = 0.9$ at three non-dimensional ground heights, $h^* = 1.5, 0.5, and 0.04$. Figure 15 (a) shows that the instantaneous lift coefficient increases as the perching plate approaches the ground, which is similar to the behavior found in the synchronous cases. This increase in the lift force is consistent across all the time offsets considered in the present study. Moreover, the results indicate that a lower ground height provides a higher benefit, with the most enhancement found when $t_{os}^* = 0$. Note that ground proximity increases the peak lift force and the trough. At $t_{os}^* = 0.5$, the generation of negative lift force, which can impact the control authority of the bird’s flight, is delayed or reduced to a smaller instant.
Figure 15: Comparison of the (a) lift and (b) drag coefficient on the rectangular wing for $\Xi = 0.9$ at three non-dimensional ground heights, $h^*$. 

Figure 15 (b) highlights the drag histories on the rectangular plate at three ground heights for asynchronous cases. The effect of ground proximity has less impact on the development of the drag force at the early stage of the perching maneuver. However, at $t_{os}^* = 0$, when the perching plate is close to the ground, the drag force starts to drop rapidly after its peak, leading to the generation of a higher negative drag force or parasitic thrust force at the end phase of the perching flight. Although the rapid drop in the drag force is also observed at $t_{os}^* = 0.5$ for the near-ground case, the decrease in the drag force is relatively small compared to that of the far-from-the-ground case.

The change in the added mass can explain the generation of negative drag or parasitic thrust through variations in the frontal area. The one-dimensional added mass force can be rewritten as:

$$ F_{AM} = -\frac{\partial}{\partial t} (m_a U) = -\dot{m}_a U - m_a \dot{U} \quad (5) $$

From this equation, for expanding body, the addition of added mass from frontal area change creates drag from $-\dot{m}_a U$. This frontal area expansion increases total added mass, which
will make the body difficult to stop at the latter stage of the maneuver due to the generation of the net thrust through $-m_d U$. This sudden change in the forces would lead to uncontrolled perching maneuvers.

![Figure 16: Contours of the normalized vorticity field, $\omega^*$, for $\Xi = 0.9$ at $t_{\text{os}}^* = 0$ and at three different time-steps, $t^* = 0.25, 0.50 & 0.75$: left plot represents PIV results at $h^* = 1.5$ (far from ground case); right plot represents PIV results at $h^* = 0.04$ (close to ground case).]
For asynchronous cases, the generation of the net parasitic thrust through \(-m_a \dot{U}\) can vary depending on the time offsets. For \(t_{os}^* = 0\), the frontal area is fully expanded at \(t^* = 1\). As the frontal area is fully expanded at the early stage of the deceleration motion, this added mass would generate higher net parasitic thrust through \(-m_a \dot{U}\) during a major portion of the flight (see Figure 15 (b)). For \(t_{os}^* = 0.5\) case, the frontal area starts expanding at \(t^* = 0.5\) and fully expands at \(t^* = 1.5\). As the added mass of the expanding body increases at the late stage of the maneuver, this will generate a lower value of parasitic thrust through \(-m_a \dot{U}\). This delay in the frontal area expansion also leads to a gradual increase in the drag force.

To further analyze our findings, we computed the vorticity field for the highest shape changer number, \(\Xi = 0.9\) at two extreme ground height cases and at two starting time-offsets, \(t_{os}^* = 0 \& t_{os}^* = 0.5\). We normalize the vorticity field using the wing’s chord length and steady state translational velocity, \(\omega^* = \frac{\omega \cdot c}{U_\infty}\). We present the normalized vorticity field at four different time instants, \(t^* = 0.25, 0.5, 0.75, 1.0, 1.25, \& 1.50\), to highlight the key changes in the flow field due to the variations in starting time-offsets and ground heights.

Our PIV results show a distinct evolution of vorticity field at two extreme ground height cases for asynchronous case (see Figure 16). At \(t^* = 0.25\), we observe the formation of similar LEV and TEV vortex structures at both ground heights. As the wing dynamically pitches up, the vortices increase in size and strength, which correlates with the enhancement of the lift and drag forces on the wing. At \(t^* = 0.50\), we observe the difference in the evolution of vortices and wake between the two ground heights, and we can see the interaction of TEV with the ground boundary layer. The difference in TEV size and strength is also noticeable. The interaction of the vortex and ground boundary layer is more prominent at \(t^* = 0.75\). Contours of normalized vortex
structures are shown in Figure 17 at the end phase of the perching maneuver, i.e. $t^* = 1.0, 1.25, \& 1.50$. At later time instants, the vortices shed from the wing and move away from the wing, resulting in a rapid decrease in the aerodynamic forces at the end phase of the maneuver. Comparing the vortices between the two extreme ground height cases, we notice that the shed vortex pairs are further apart from each other near the ground, which explains the larger drop in the aerodynamic forces on the wing close to the ground.

Figure 18 and Figure 19 shows the vorticity field for $t_{os}^* = 0.5$. At $t^* = 0.25$, the wing is at its initial AoA, $\alpha_0 = 0^\circ$, and sheds the shear layer sheds that forms a wake downstream. This wake is the reason for an increase in the drag force at the start of this motion. At $t^* = 0.50$, the wing is decelerating and starting to pitch up dynamically. At $t^* = 0.75$, we observe the separated shear layer rolling up into vortex structures. At this time instant, the difference in the evolution of wake behind the wing at the two ground heights becomes apparent.

During the final phase of the perching maneuver, the counter rotating vortex structures induce a dipole jet oriented downward and slightly forward that generates upward and backward forces. When the wing is near the ground, the dipole jet impinges on the ground and affects the reaction forces on the wing, depending on the impingement direction. Figure 19 illustrates the generation of the vortices and dipole jet at the end of the motion, providing suitable lift and drag for a smooth touch down.

When we compare the x-distance between the LEV and TEV for $t_{os}^* = 0.5$ and $t_{os}^* = 0$, we observe that the vortices remain close to each other, even near the ground for $t_{os}^* = 0.5$. This explains why the wing generates lift and drag force at the end of the maneuver for $t_{os}^* = 0.5$, unlike that of $t_{os}^* = 0$ case.
Figure 17: Contours of the normalized vorticity field, $\omega^*$, for $\Xi = 0.9$ at $t_{os}^* = 0$ and at three different time-steps, $t^* = 1.0$, 1.25 & 1.50: left plot represents PIV results at $h^* = 1.5$ (far from ground case); right plot represents PIV results at $h^* = 0.04$ (close to ground case).
Figure 18: Contours of the normalized vorticity field, $\omega^*$, for $\Xi = 0.9$ at $t_{\nu s}^* = 0.5$ and at three different time-steps, $t^* = 0.25, 0.50$ & $0.75$: left plot represents PIV results at $h^* = 1.5$ (far from ground case); right plot represents PIV results at $h^* = 0.04$ (close to ground case).
Figure 19: Contours of the normalized vorticity field, $\omega^*$, for $\Xi = 0.9$ at $t_0^* = 0.5$ and at three different time-steps, $t^* = 1.0, 1.25, \& 1.50$: left plot represents PIV results at $h^* = 1.5$ (far from ground case); right plot represents PIV results at $h^* = 0.04$ (close to ground case).

Dipole jet

This study aims to investigate the mechanics of rapidly pitching plates during deceleration near the ground, with the goal of understanding how the perching and hunting birds...
achieve their impressive maneuverability. By executing rapid pitching at different stages of deceleration, such as when the forward translational velocity is still high versus when it is low, we observe distinct changes in the evolution of the vortex structures and forces acting on the plate.

![Image of dipole jet evolution](image)

Figure 20: Schematics showing the evolution of the dipole jet and its interaction with the ground. Executing a rapid pitch-up motion during deceleration causes the shear layer to separate, forming counter-rotating leading-edge vortex (LEV) and trailing edge vortex (TEV) structures, as shown by our PIV results. The pitch-up motion combines the counter-rotating vortices to form a comoving vortex dipole. Once a vortex dipole is created, they will interact with each other, creating a region of high vorticity gradient. This region acts as a source of fluid, moving fluid outward, supplying fluid to the vortices needed to maintain their coherent structures, and forming the jet flow of the dipole. At the same time, the region between the two vortices experiences a low-pressure zone due to the centrifugal forces generated by the counter-rotating vortices. This low-pressure region acts as a sink flow, drawing fluid in between the two vortices. This combination of source flow and sink flow forms a dipole jet that is characteristics of the counter-rotating vortices. The schematic diagram in Figure 20 illustrates the pitch-up motion of the wing and the resulting formation of dipole jet. This dipole jet moves the larger amount of momentum varying fluid with it, which can be used to generate unsteady forces on the wing.
Figure 21: Velocity field for close to ground case, $h^* = 0.04$. (a, b, & c) $t_{os}^* = 0$; (d, e, & f) $t_{os}^* = 0.5$. (a & d) $t^* = 0.5$; (b & e) $t^* = 1.0$; (c & f) $t^* = 1.5$.

Figure 21 illustrates the dipole jet formation during the asynchronous motion by analyzing the velocity field at two different time-offsets cases, $t_{os}^* = 0$ & $t_{os}^* = 0.5$. For $t_{os}^* = 0$ case, pitch-up motion is executed at a high forward translational velocity, resulting in larger, stronger counter-rotating vortices and a more significant induced dipole jet (as seen in Figure 21 (a)). Initially, the dipole jet is directed downward and forward producing lift and drag forces. At $t^* = 1.0$, the wing pitches up to its final effective angle of attack, $\alpha_{eff} = 90^0$, directing the dipole jet towards the ground, causing it to spill on the ground surface. This deflected jet moves towards the ground, causing it to spill on the ground surface. This deflected jet moves the vortex pair apart from each other, reducing the impulse they generate on the wing and causing a rapid drop in the lift and drag force at the end phase of the maneuver. At $t^* = 1.5$, some of the deflected jet orients backward producing a thrust force that hunting birds like eagles can use to accelerate after catching their prey, such as fish.
In contrast, for $t_{os}^* = 0.5$, a pitch-up motion is executed at a low forward translational velocity, generating smaller, weaker vortex structures. These smaller counter rotating vortex pair induces a slower jet that moves a lower amount of momentum-carrying fluid with it (see Figure 21 (c)). This motion generates vortices and dipole jet at the end phase of the maneuver, providing lift and drag force suitable for a smooth touch-down. As this motion induces a slower dipole jet, it does not displace the vortex pair further apart upon impact with the ground, reducing its influence on the rapid drop-off of the lift and drag force compared to $t_{os}^* = 0$ scenario.

Our findings show that the dipole jet plays a critical role in achieving specific flying objectives. We observed that the dipole jet moves a larger amount of momentum-carrying fluid with it, which can be used to generate lift, drag, or thrust force. By directing the dipole jet downward and forward, birds can achieve lift and drag during landing or perching. Conversely, by directing the dipole jet downward and backward birds can achieve lift and forward thrust to accelerate the body after catching prey. These insights can help to quantify the performance of perching or hunting birds and aid in the design of efficient flying vehicles.

Scaling Laws

The total lift and drag forces generated during the perching maneuver are critical for executing a smooth landing maneuver. Here, we analyzed the time-averaged lift and drag-coefficient for all cases considered during perching to determine the success of the smooth landing.
Figure 22: Time-averaged (a) lift and (b) drag coefficient on a finite rectangular plate at the non-dimensional ground height of $h^* = 1.5$ as a function of $\Xi$. Scaling of the (c) lift and (d) drag coefficients for all the $\Xi$ and ground heights considered in this experimental study. $C_{L_{avg}}$ is multiplied by a factor of $a$, which is the ratio of the pitch time to the deceleration time.

To investigate the relationship between the time-averaged forces and the $\Xi$, we first focus on a single value of non-dimensional ground height, $h^* = 1.5$. In synchronous cases, represented by the circular dot, we found a linear relationship between the time-averaged forces and $\Xi$: both the time-averaged lift and drag coefficient increased with the increase of $\Xi$. Higher drag force is beneficial for rapid dissipation of the kinetic energy or rapid deceleration during landing. However, a higher lift force can result in a gain in altitude, which may be undesirable, as it can hinder birds from landing or perching in their intended landing location.
In the asynchronous cases, executing pitch-up motion at different stages of deceleration generated the same $\Xi$, but resulted in distinct evolution of lift and drag forces. This led to a more complex relation between time-averaged forces and $\Xi$ in the asynchronous motion (represented by the diamond shape) (see Figure 22 (a) & (b)).

From the instantaneous lift and drag coefficient results, we observed that maximum $C_L$ and $C_D$ are inversely proportional to the starting time offsets, $t_{os}$. To quantify this relationship, we computed the rate of change of maximum lift and drag coefficient, $\frac{dC_L_{\text{max}}}{dt}$ & $\frac{dC_D_{\text{max}}}{dt}$, and multiplied it with $\Xi$. Using this scaling laws, we scaled the time averaged lift and drag coefficients for all tested scenarios, and the result demonstrate that our perching data scales properly with this new scaling law.

**Conclusion**

In this study, we conducted experiments to investigate the dynamics of a perching maneuver by examining the unsteady forces and the flow field on a rectangular plate undergoing rapid pitch-up motion during decelerating flight. We decelerated the plate to a complete stop from a Reynolds number of 13000. Our experimental investigation involved introducing various starring time-offsets between the deceleration and pitch-up motion to quantify the variations of frontal area change during deceleration. Each motion case was executed at different ground heights, ranging from far from ground case, $h^* = 1.5$, to near ground case, $h^* = 0.04$, to understand the unsteady ground effect experienced by the pitching plates during deceleration. Our results provides insights into the mechanics and dynamics underlying the perching maneuver.
of avian species, which can have potential implications for the design and development of flying vehicles.

Our result showed that for the synchronous case, the rapid pitch-up motion during a decelerating flight enhances both the lift and drag forces on the wing. This higher value of lift and drag force is favorable for the safe landing, which explains the reason why birds undergo the rapid pitch-up motion during the landing flight. As the wing approaches the ground, the instantaneous and time averaged lift increased, indicating that the perching wing benefits from the ground effect. For asynchronous case, at $t_{os}^* = 0$, the plate generated a higher initial lift force but also experiences a rapid drop-off of the lift and generates negative lift force at the end phase of the motion. However, introducing the pitch-up motion late in the deceleration delayed the drop-off of the lift force and wing stall. In this motion, the wing generated lift at the very end of the motion, enhancing control authority during this highly unsteady motion.

Our findings also suggest that introducing starting time-offsets has a significant impact on the generation of drag and parasitic thrust. At $t_{os}^* = 0$, the plate generated a higher peak drag force but also experiences a higher parasitic thrust at the latter stage of the motion, which makes the body difficult to stop at the end phase of the maneuver. However, increasing the starting time offsets to $t_{os}^* = 0.5$, reduced both the drag and parasitic thrust. Additionally, at $t_{os}^* = 0.5$, we observed that the wing continually generated positive drag force during major portion of the flight. This indicates that introducing the time offsets maybe an optimum way to execute this maneuver while landing, as it helps reduce the risk of losing control authority due to the increase in parasitic thrust.

Our study has shown that the proximity of the ground has a significant impact on the behavior of the vortices generated by the wing. This interaction alters the advection, dissipation
and impulse generated by the vortices on the wing. Furthermore, we observed that the counter-rotating vortices induce a dipole jet, which is injected to the ground when the wing is near the ground. We found that this interaction causes an acceleration of the fluid between the wing and the ground, which can help birds achieve different flying objectives. These findings highlight the importance of considering the ground effects in the study of birds flight.
CHAPTER 4: THE EFFECT OF WING SWEEP DURING A PERCHING MANEUVER

This chapter provides the effect of wing sweeps during a perching maneuver. Part of this chapter has been in Physical Review Fluids by Adhikari et al. (Dibya Raj Adhikari et al. 2022).

Introduction

Natural flyers, such as birds, are known for their agile flight characteristics during different stages of flight. Many of them perform a nimble maneuver, known as perching, which allows them to land smoothly. During this maneuver, they pitch up their wing to a high angle of attack, which has been shown to augment lift and enable a controlled landing (Anna C. Carruthers, Thomas, and Taylor 2007). The present study is motivated by this perching maneuver and has two major objectives: one, we want to investigate how a wing sweep influences a perching maneuver; and two, we want to find how the addition of pitch-up maneuver during a downward deceleration influences the unsteady forces and the flow field.

Perching is a complicated maneuver involving simultaneous pitching, heaving, and deceleration. A number of researchers have investigated the effect of these factors. For example, Polet et al. (Polet, Rival, and Weymouth 2015) used an airfoil undergoing a simultaneous deceleration and pitching, and investigated the effect of shape change number on the lift production during the terminal phase of deceleration. The shape change number quantifies the rapid area change due to a pitching motion. It has been shown that such rapid area change imparts forces on the body due to added mass effects (Weymouth and Triantafyllou 2012, 2013) and energy dissipation into the fluid by continuously shedding of vorticity both from the leading and trailing edge.
An unsteady maneuver, such as perching, also depends on the shape of the wing itself. A number of researchers have studied this aspect (D R Adhikari and Kim 2018; Dibya Raj Adhikari, Lee, and Kim 2017). Hartloper & Rival (Hartloper and Rival 2013) examined a rapid pitch-up motion on rectangular, lunate, and truncate planforms and noted that span-wise leading-edge curvature promotes the outboard convection of the vorticity into the wake leading to a favorable lift to drag ratio. Conversely, an experimental work by Granlund et al. (K. Granlund, OL, and Bernal 2011) on pitching rectangular and Zimmerman planforms found a minimal difference in the instantaneous forces and the flow field. In addition, Yilmaz & Rockwell (Yilmaz and Rockwell 2012) analyzed flow structures on the pitching rectangular and elliptical wings and found a similar vortex structure on both wing shapes. In fact, experimental studies by (Berg and Biewener 2010; Provini et al. 2014) showed that independent of the wing planforms, birds execute a similar perching maneuver during the landing motion. However, an unsteady maneuver such as rapid pitching is always accompanied by massive separation and the consequent formation of large-scale vortices. Several studies have also investigated the effect of pitch rate on the evolution of vortices (Baik et al. 2012; K. O. Granlund, OL, and Bernal 2013; D. Rival, Prangemeier, and Tropea 2009; Visbal and Shang 1989). It has been known from the research on delta wing that wing sweep stabilizes such leading-edge-vortices. Maxworthy noted that because of the angle between the leading edge and the incoming flow vector, an outward-directed spanwise flow is induced on the delta wing, which stabilized the LEV and delayed the shedding of the vortex (Maxworthy 2007). To understand the similar effect of wing-sweep during perching maneuvers, we compare the flow field of a rectangular and swept wing.

Since perching is executed during landing, the effect of ground needs to be taken into account. For smooth landing, it is acknowledged that birds capitalize on the ground effect (Blake
Ground effect is a phenomenon where the lift to drag ratio of the wing increases when the wing is close to the ground (Rayner et al. 1991; Rayner, Trans, and Lond 1991). An improvement in the performance due to the ground effect is well documented on many bird’s flights (Baudinette and Schmidt-Nielsen 1974; Blevins and Lauder 2013; Buchholz and Smits 2008), and it has inspired the development of wing in ground effect aircraft (Rozhdestvensky 2006). In the present study, we include the effect of ground in the wing-kinematics by subjecting the wings to decelerate to a stop close to the wall.

While several studies on pitching maneuvers with different planforms exist, very few have combined all the aspects of perching maneuver and considered rapid pitch-up motion while decelerating and descending close to the ground. Therefore, the role of wing planforms on the unsteady aerodynamic mechanism during a true perching flight is yet to be understood in its entirety. In this paper, we consider two types of unsteady motion: (i) heave-down in deceleration and (ii) simultaneous heave-down and pitch-up in deceleration, referred to as perching motion. Heave-down motion is performed to represent the gradual decrease in the ground height, while pitch-up motion is used to represent the rapidly increasing angle of attack (AOA) during the landing maneuver. We performed both experimental and numerical studies to understand flow physics. Finally, results from a two-dimensional analytical model are compared with the experimental result.
Two flat plate wing models were used in this study: one with a rectangular planform and another with a swept planform (Figure 23). Both these wings were fabricated from a 6 mm thick aluminum plate. Moreover, both these plates had the same planform area of 0.03 m$^2$. The thickness and planform were matched to ensure that both the plates have a mass of 0.46 kg. We matched the mass and the planform area of the plates to ensure that the inertial load on the force sensor and the added mass forces during an unsteady motion are not caused by differences in these parameters. We note, however, that maintaining the same planform resulted in dissimilar chord lengths. The rectangular plate had a chord (c) of 0.1 m. The swept plate had a maximum chord of 0.115 m. It had a sweep angle of 20° starting from the mid-span location. The leading-edge of both these plates were rounded while the trailing edges were sharpened to satisfy the Kutta condition.

**Wing models and kinematics**

![Wing models](image)

Figure 23: Wing planform shapes used to study the perching maneuver in landing flight: (a) rectangular planform; (b) swept planform.
Figure 24: Details of the kinematic: (a) variation of the ground height with \( t^* \), the plate is translating to the right while carrying out heaving-only, ‘h’, and heave-pitch, ‘hp’, motion. Y-axis is the non-dimensional ground height; (b) variation of the non-dimensional free-stream velocity with \( t^* \). Here, the effective velocity is defined as \( U_{\text{eff}} = \sqrt{U_{\infty}^2 + \dot{h}^2} \); (c) variation of the effective angle of attack of the plate with \( t^* \). In b and c, the variables are plotted as a function of the non-dimensional time, \( t^* = \frac{U_{\infty}}{c} \).

To simulate a landing flight, two comparable kinematics were considered. In the first case, a wing started a heaving motion from the centerline of the towing tank towards the sidewall, which acted as a ground, while simultaneously decelerating from a steady velocity \( (U_{\infty}) \) of 0.1 m/s. This case will be referred to as the “heave-only” case. In the second case, the wing performed a pitch-up motion while executing the same kinematics as the previous one. This case will be referred to as the “heave-pitch” case. The duration of the heaving and the pitching motions was 3.4 s, which was the same as the duration of the deceleration. In other words, heaving and pitching both started at the same time as the decelerating motion with zero phase difference. We note that only the “heave-pitch” case resembles a perching maneuver here. For both kinematics, the wing model was initially accelerated at 0.03 m/s² to reach the steady traverse velocity of 0.1 m/s. Then the wing model was towed forward at this steady velocity for at least 2
chord lengths, to achieve the steady flow around the wing model, before the start of the landing flight. The Re, based on $U_\infty$ and $c = 0.1$ m, was 13,000. Also, the wings were oriented at an initial AoA, $\alpha_0 = 15^\circ$, during the steady part of the motion. However, during the heave-only or heave-pitch case, the effective angle of attack ($\alpha_{eff}$) was changed as:

$$\alpha_{eff} = \alpha_0 + \tan^{-1}\left(\frac{\dot{h}}{U_\infty}\right) + \alpha(t)$$  \hfill (6)

where $\dot{h}$ is the heave velocity, and $\alpha(t)$ is the pitch angle. The resultant motion profiles of these two kinematics are shown in Figure 24. The kinematic parameters governing the overall motion of the foil are summarized in Table 2: Kinematic Parameters. At the end of both kinematics, the non-dimensional ground height clearance, $\hat{h}$, is fixed to a value of 0.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Heave-only</th>
<th>Heave-pitch</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traverse velocity ($U_\infty$)</td>
<td>0.1</td>
<td>0.1</td>
<td>m/s</td>
</tr>
<tr>
<td>Traverse acceleration ($\dot{U}_\infty$)</td>
<td>0.03</td>
<td>0.03</td>
<td>m/s$^2$</td>
</tr>
<tr>
<td>Heave velocity ($\dot{h}$)</td>
<td>0.05</td>
<td>0.05</td>
<td>m/s</td>
</tr>
<tr>
<td>Heave acceleration ($\ddot{h}$)</td>
<td>0.12</td>
<td>0.12</td>
<td>m/s$^2$</td>
</tr>
<tr>
<td>Pitch velocity ($\dot{\alpha}$)</td>
<td>0</td>
<td>15</td>
<td>deg/s</td>
</tr>
<tr>
<td>Pitch acceleration ($\ddot{\alpha}$)</td>
<td>0</td>
<td>36</td>
<td>deg/sec$^2$</td>
</tr>
</tbody>
</table>

**CFD simulations**

A commercial software code, STAR-CCM+, was used to numerically simulate the flow of water over the rectangular and the swept plate during both the kinematics. This software uses
a SIMPLE-C segregated solver with 2nd order special accuracy. The numerical simulations were solved based on the Navier-Stokes equations for the conservation of mass and momentum. The fluid was assumed to be isothermal, laminar, and have a constant density. With these assumptions, the reduced conservation equations used in simulation are expressed as:

\[
\frac{\partial u_i}{\partial x_i} = 0 \tag{7}
\]

\[
\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_i} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_i^2} \tag{8}
\]

The motion of the wings was simulated using the overset mesh schemes, which utilize the sliding meshes to solve for the solid body displacement. A no-slip boundary condition was used on the wing and floor boundary to capture any viscous vortex shedding interactions occurring with the floor boundary to replicate a true ground effect phenomenon. A symmetry plane boundary condition was applied on the side walls to avoid any fluid effects that could arise due to the wall boundary. In the experiment, the wing was just under the water surface. Thus, our numerical model does not exactly replicate the experimental procedure; however, we assumed that the water-boundary effects were minimal and thus can be simulated using a symmetry plane boundary condition.

To compute the numerical uncertainty due to the mesh size, we carried out a mesh-independence sensitivity study. We systematically varied the mesh base size and time step to maintain a constant Courant number of unity. The rectangular wing with the heave-pitch kinematics was considered for this mesh-independence study. Based on this study, for all the cases, we used a mesh base size of 0.002 m and an appropriate time-step of 0.005 seconds. The
time-step which resulted in the best match with the experimental data was selected for further analysis.

Analytical modeling of unsteady force

Added mass force

Added mass or non-circulatory force contributes to the change in unsteady forces during the acceleration or deceleration of the fluid. Following Polet et al. (Polet, Rival, and Weymouth 2015), the non-circulatory force coefficient for a decelerating, heaving, and pitching plate is determined from the following equation:

\[
C_{Fn_c} = \frac{\pi c}{2U_\infty^2} \left[ \dot{h} \cos \alpha + \dot{\alpha} \cos \alpha U + \sin \alpha \dot{U} + c\dot{\alpha} \left( \frac{1}{2} - x_p^* \right) \right]
\]

Eq. 9 shows that four distinct factors influence the non-circulatory lift coefficient. The first term on the right-hand side of Eq. 9 is related to the heaving acceleration, \( \dot{h} \), the second term represents the rate of change of the added mass, the third term is related to the added mass due to linear acceleration, and the last term represents the added mass due to rotational acceleration, \( \dot{\alpha} \). Here, \( (1/2-x_p^*) \) is the relative distance between the mid-chord and the hinge location, which is zero in the present case.

The resultant non-circulatory lift and drag coefficient is defined as:

\[
C_{L_{nc}} = C_{F_{nc}} \cos \alpha \\
C_{D_{nc}} = C_{F_{nc}} \sin \alpha
\]
Circulatory force

During both the kinematics, the circulatory forces ($F_c$) were calculated by simply considering the time derivative of the hydrodynamic impulse ($I$) caused by the counter-rotating LEV, TEV pair (Babinsky et al. 2016):

\[
\frac{dI}{dt} = \frac{d(\rho \Gamma d)}{dt}
\]

\[
F_c = -\rho \Gamma \dot{d} - \rho \dot{\Gamma} d_0
\]

where $\Gamma$ is the circulation of one of the vortices, $\dot{\Gamma}$ is the time rate of change of circulation, $d$ is the distance between the center of counter-rotating vortices, and $\dot{d}$ is the relative velocity between the two vortices. Eq. 13 indicates that the unsteady circulatory force is composed of convection of the LEV relative to the TEV and the growth rate of the circulation inside these vortices. We calculated the centroid and the circulation of the vortices at different instants from the PIV data by applying the $\Gamma_1$ and $\Gamma_2$ criteria. The circulatory lift coefficient is expressed as:

\[
C_{L_c} = -\frac{2}{\omega_e^2} \left[ (u_{LEV} - U_{TEV})\Gamma + (x_{LEV} - x_{TEV})\dot{\Gamma} \right]
\]

Finally, the total lift coefficient from analytical model is defined as:

\[
C_{L_{tot}} = C_{L_{nc}} + C_{L_c}
\]

The non-circulatory and circulatory forces defined in this analytical model are two-dimensional force coefficients. In the next section, we compare this two-dimensional force with the three-dimensional force produced on the finite perching wing. Although the two-dimensional model is not appropriate for the three-dimensional finite wing perching problem, this model
provides an important insight into the distribution of the unsteady forces on the plate performing unsteady perching motion.

**Results and Discussion**

In this section, we first compare the force histories—obtained from the force sensor as well as the numerical simulation—of both the “heave-only” and the “heave-pitch” cases. Next, we present the vorticity field obtained from the experiments and simulations. Then, we compare the results from the analytical model with the experimental data. Finally, we explain the 3D topology of the vortices developed on both plates during each kinematics.

**Instantaneous force**

Figure 25 shows the evolution of the lift coefficient ($C_L$) with non-dimensional time ($t^*$) on the rectangular and the swept wing during the heave-only and heave-pitch cases. The start of the towing motion is denoted by $t^* = 0$. At $t^* = 6$, the wing starts decelerating from a constant speed, $U_\infty$. The heaving motion for the heave-only case and the combined heaving and pitching motion for the heave-pitch case also start at $t^* = 6$. 
Figure 25: Comparison of the lift coefficient on the rectangular, ‘R’ and the swept, ‘S’, wing planforms between the experiment, ‘Exp.’ and simulation, ‘Sim.’ Data. The letter ‘h’ and ‘hp’ indicate heave-only and heave-pitch, respectively.

Figure 25 shows that during the steady motion, \( t^* = 5.5 – 6.0 \), the lift coefficient on the wing is reliant on the wing planform shapes. During this phase, the swept wing produces approximately 20% higher lift forces compared to the rectangular wing. It is to be noted that both the plates had the same planform area. The higher lift for a plate with a leading-edge curvature has also been noted by Hartloper and Rival (Hartloper and Rival 2013) and was attributed to a more stable LEV. After \( t^* = 6 \), when both the kinematics are initiated, the lift coefficient experiences a steep rise and reaches the peak value at \( t^* = 6.6 \). This initial rise in the lift coefficient is related to a non-circulatory and inertial-type force caused by the initial acceleration of the heaving motion in the heave-only case and to both the heaving and pitching acceleration in the heave-pitch case. These initial accelerations are related to the start of the linear stage responsible for heaving and to the rotary stage responsible for pitching. When each
of these stepper-driven stages starts from rest, they experience an initial acceleration to reach the desired speed. However, since the plates were at an AOA of 15°, an LEV and TEV were already present during the start of deceleration. Hence, these initial force peaks during the transient part of the motion cannot be attributed to non-circulatory forces alone. Rather, we argue that the peaks around $t' = 6 – 6.5$ are due to the combined effect of circulatory and non-circulatory forces, with a greater contribution from the latter.

Several additional observations are made in Figure 25. First, the $C_L$ peaks from $t' = 6.35$ to $t' = 7.5$, for both the rectangular and swept plate, are large in the heave-pitch case compared to the heave-only case. Higher magnitude in the peak force corresponds to a larger non-circulatory force due to the combined acceleration of the heaving and pitching motion. Moreover, the wing in the heave-pitch case was operating at a higher effective AoA (Figure 24 c) than the wing under the heave-only case, which also contributed to higher lift forces. Next, during both kinematics, the $C_L$ for the swept plate is always higher than the rectangular plate until $t' = 7.5$. We argue that this higher $C_L$ for the swept case during the unsteady phase is a direct consequence of the higher level of lift forces already present in the swept case during the steady phase, $t' = 5.5 – 6.0$. Finally, the rate of the decay of lift force in the heave-pitch case was found to be higher than the heave-only case. This higher decay is also partly related to the high effective angle of attack in the heave-pitch case leading to the stalled flow at the latter half of the motion.

The results from numerical simulations are also presented in Figure 25 as dotted (rectangular plate) and dashed line (swept plate). All the observations are also evident in the numerical results, except for one significant difference. The increase in the $C_L$ peak at the onset of the heave-only and heave-pitch kinematics occurs instantly compared to the gradual rise
observed in the experiment. This increase is due to the unsteady term in the Navier-Stokes equation which dominates due to the sudden change in velocity due to heaving or heaving and pitching kinematics. In the experiments, however, the $C_L$ is more gradual. This is related to the finite time response of the force sensor to any step change to the input.

![Comparison of the drag coefficient on the rectangular, ‘R’ and the swept, ‘S’, wing planforms between the experiment, ‘Exp.’ and simulation, ‘Sim.’ Data. The letter ‘h’ and ‘hp’ indicate heave-only and heave-pitch, respectively.](image)

Figure 26: Comparison of the drag coefficient on the rectangular, ‘R’ and the swept, ‘S’, wing planforms between the experiment, ‘Exp.’ and simulation, ‘Sim.’ Data. The letter ‘h’ and ‘hp’ indicate heave-only and heave-pitch, respectively.

The evolution of the drag coefficient ($C_D$) displays a similar trend observed in the lift coefficient (Figure 26). The drag coefficient rises initially following the onset of the unsteady kinematics, attains the peak, and then decreases gradually. During the early phase of the maneuver, the drag coefficient is higher for the heave-pitch case than the heave-only case. This is mainly due to the higher effective AoA in the heave-pitch case, which caused a higher projected area facing the flow. For a safe landing, birds or flying vehicles must achieve a complete stop at the final phase of landing. Provini et al. (Provini et al. 2014) observed that birds
generate most of the drag force from the wings than their legs during the last phase of the landing. It is interesting to note that the magnitude of the instantaneous drag coefficient is higher for heave-pitch case than the heave-only case. This higher drag force is favorable for the deceleration of the wing, which explains the reason why the birds undergo rapid pitch-up motion during landing flight. Note that the wing produces negative drag force at the end of the motion, which is more pronounced for the heaving with pitching case. Negative drag or parasitic thrust at the end of the perching maneuver is supported by results presented in Polet et al. (Polet, Rival, and Weymouth 2015), where they concluded an increase in the added mass due to frontal area expansion could generate parasitic thrust at the end of the motion. However, the averaged drag coefficient from the pitch up motion is higher, which is essential for the safe landing motion.

Flow features and development

We compare the normalized vorticity fields, $\omega^* (= \omega c/U\infty)$, over the rectangular and the swept plate, for both the kinematics, in Figure 27, Figure 28, Figure 29, and Figure 30. The vorticity fields were obtained at planes located at 50% and 70% span of the wing.
Figure 27: Contours of the normalized vorticity field, \( \omega^* \), for the heaving motion at 50\% of the wingspan at various timesteps: (a) PIV results for the rectangular plate; (b) simulation data for the rectangular plate; (c) PIV results for swept plate; (d) simulation data for swept plate.

Figure 27 shows the vorticity field at the 50\% span of the wing, obtained from both experiment and simulation during the heave-only case. The existence of a strong LEV (denoted by the blue contours representing negative vorticity) and a trailing-edge-vortex (TEV) (denoted by the red contours representing positive vorticity) is evident in these vorticity plots. During all the three-time instants shown, the LEV formed on the rectangular plate has a more pronounced contour, whereas, for the swept plate, the vorticity contours are more diffused. Moreover, the
center of the contour in the latter case appears closer to the heaving plate. We note that the simulation results contain boundary layer vorticity, which was not resolved in the experiment due to unwanted laser reflection. This boundary layer vorticity shows the development of the secondary vorticity (positive, red contours) behind the LE for both the kinematics. This secondary vortex weakens the connection between the LEV vortex and LE shear layer, which finally diminishes the mass flow from the feeding shear layer into the LEV. The vorticity plots obtained at the 70% span in the heave-only case show a reduced size for the contours in both the rectangular and swept plate cases (Figure 28). However, one significant difference is that at 70% span, the contours in the swept case are more compact compared to the same obtained at the 50% span. These spanwise differences in the sizes of vorticity contours in both rectangular and swept plate cases prove that the cross-sections of the LEV are different based on the span location. This difference also hints at a considerable degree of three-dimensionality in the flow.

The vorticity fields, at the 50% span, over both the plates in the heave-pitch case are shown in Figure 29. The addition of pitching created smoother contours for the swept plate (Figure 29 c and d) compared to the heave-only case (Figure 27 c and d). Another major difference is that the separated LEV ends up closer to the plate due to the higher effective angle of attack obtained in the heave-pitch case. When the plain of PIV was changed to the 70% span, similar well-defined vorticity contours were obtained (Figure 30). For the heave-only case, although positive vorticity is observed behind the LE, there is still a weak connection between the LEV and LE shear layer even at t' = 8.5 (Figure 27). However, for the heaving with pitching case at t' = 8.5, the LEV is fully detached from the feeding shear layer (Figure 29). Li et al. (Li et al. 2020) observed that secondary vortex forms earlier in the motion for larger αeff, leading to the early detachment of the LEV from the feeding shear layer. This may explain the reason for
the early detachment of the LEV and the rapid drop of the instantaneous forces Figure 25 & Figure 26 for the wing in heaving and pitching motion.

Figure 28: Contours of the normalized vorticity field, $\omega^*$, for the heaving motion at 70% of the wingspan at various timesteps: (a) PIV results for the rectangular plate; (b) simulation data for the rectangular plate; (c) PIV results for swept plate; (d) simulation data for swept plate.

A qualitative analysis of the vorticity plots between the heave-only and the heave-pitch cases shows that in the latter case, the contours are more defined, circular, and closer to the plate. Because of the pitch-up motion, the effective angle of attack of the wing is always higher than that of the heave-only motion. It has been observed that an increase in the effective angle of
attack, \( a_{\text{eff}} \), facilitates the feeding of the vorticity from the shear layer to the LEV during the early stage of the motion (Li et al. 2020).

Figure 29: Contours of the normalized vorticity field, \( \omega^* \), for the heave-pitch motion at the 50% of the wingspan at various time-steps: (a) PIV results for the rectangular plate; (b) simulation data for the rectangular plate; (c) PIV results for the swept plate; (d) simulation data for the swept plate.

A qualitative analysis of the vorticity plots between the heave-only and the heave-pitch cases shows that in the latter case, the contours are more defined, circular, and closer to the plate. Because of the pitch-up motion, the effective angle of attack of the wing is always higher than that of the heave-only motion. It has been observed that an increase in the effective angle of
attack, $a_{\text{eff}}$, facilitates the feeding of the vorticity from the shear layer to the LEV during the early stage of the motion. This continuous feeding of vorticity from the leading-edge leads to a pronounced LEV (Figure 29 & Figure 30). A well-defined and larger LEV, located closer to the plate, is supposed to impart higher impulse on the plate in the heave-pitch case, which will increase the circulatory forces leading to higher lift forces compared to the heave-only case.

Figure 30: Contours of the normalized vorticity field, $\omega^*$, for the heave-pitch motion at the 70% of the wingspan at various time-steps: (a) PIV results for the rectangular plate; (b) simulation data for the rectangular plate; (c) PIV results for the swept plate; (d) simulation data for the swept plate.
Figure 31: Circulation history on the rectangular, R, and swept wing, S, at 50 % and 70 % of the wingspan: (left) heave-only motion, ‘h’; (right) heave-pitch motion, ‘hp’.

To compare the evolution of the LEV over the rectangular and the swept plate during both the kinematics, we plot the normalized circulation over time in Figure 31. The circulation is computed using the $\Gamma_1$ and $\Gamma_2$ criteria on the velocity field obtained at planes located at 50% & 70% of the wingspan. For the swept-wing case, the circulation is higher at 70% than 50% of the wingspan during both the kinematics (Figure 31). The sweep angle, in this case, creates a spanwise component of the incoming flow. This outward-directed flow convects the vorticity towards the tip. This spanwise convection of vorticity is responsible for the higher LEV circulation at 70% than 50% span. However, for the rectangular wing, the circulation is higher on the inboard section, i.e., at 50% span. Higher circulation value on the inboard section on the rectangular wing is also supported by Hartloper and Rival (Hartloper and Rival 2013). Figure 31 (a) also reveals that in the heave-only case, LEV circulation at the 70% span in the swept-plate case reaches the peak value at $t^* = 8.5$, whereas in the heave-pitch case, it reaches the peak value much earlier at $t^* = 7.5$. A similar observation is also made for the swept plate case at 50% span length. The higher value of LEV circulation for the wing in the heave-pitch case is consistent
with the more compact vortices observed in the PIV results. An early peak at $t^* = 7.5$ and the subsequent plateau of the LEV circulation for the wing in the heave-pitch case is related to early pinch-off of the LEV from the plate (see Figure 29 & Figure 30). This finding also corroborates the higher rate of decay of lift forces in the heave-pitch case compared to the heave-only case (Figure 25).

![Graph showing lift coefficient](image)

Figure 32: Non-circulatory lift coefficient predicted from the analytical model.

**Decomposition of 2D aerodynamic load**

In this section, we calculate the sectional lift at the midspan using analytical models (Eqs. 10, 14, 15), and compare them with the lift coefficients obtained from the experiment. Figure 32 shows that the non-circulatory forces were significantly higher during the starting and the end of the unsteady kinematics. However, these forces were negligible during a major part of the motion. Hence, it is evident that most of the lift was caused by circulatory forces. In Figure 33 (left), we plot the total lift force using Eq. 15. It shows that for the rectangular wing undergoing heaving motion, the analytical lift coefficient follows the experimental ones closely, especially,
at the later part of the kinematics, at $t^* = 8$ and 8.5. The degree of deviation is more for the swept case. During the heave-pitch case Figure 33 (right), both the rectangular and the swept plate show considerable differences between the experimental $C_L$ and that determined by 2D analytical modeling. This indicates that for the wing undergoing unsteady motion, the aerodynamic load on the finite wing is not smoothly distributed along the wingspan. Here, the predicted lift force does not agree well with the experimental results; however, it provides an important insight into the distribution of the aerodynamic load on the wing undergoing unsteady perching motion.

Figure 33: A comparison between 3D lift coefficient from the experimental and 2D sectional lift predicted using added mass and 2D impulse method: (left) heaving motion, ‘h’; (right) heave-pitch motion, ‘hp’. The symbol ‘R’ and ‘S’ indicates rectangular and swept planforms respectively.

3D flow structures

In this section, we use the CFD results to plot the 3D flow field around the rectangular and the swept plate undergoing the heave-only and the heave-pitch kinematics. Figure 34 and Figure 35 show the iso-contours of the pressure coefficient, $C_P$, and the iso-surfaces of the z
component of velocity, \( w \). The iso-surfaces of \( w \) are plotted using the Q criterion. We selected two-time instants: Figure 34 represents the state of the flow field at \( t^* = 7.5 \), and Figure 35 represents the same at \( t^* = 8 \). We note that \( t^* = 7.5 \) is located before the traces of the \( C_L \) in the heave-pitch case crossed that of the same in the heave-only case. On the other hand, \( t^* = 8 \) is located after this crossing point.

Figure 34: Distribution of the pressure coefficient, \( C_p \), on the wing suction surface (1\(^{st}\) & 3\(^{rd}\) row) and the iso-surface representation of \( z \) velocity along the LEV and TEV using Q-criterion (2\(^{nd}\) & 4\(^{th}\) row) at \( t^* = 7.5 \): (a) rectangular wing in heave-only motion; (b) swept wing in heave-only motion; (c) rectangular wing in heave-pitch motion; and (d) swept wing in heave-pitch motion.

At \( t^* = 7.5 \), during the heave-only case, the LEV is pinned at the outboard section on the rectangular plate. The \( C_p \) is negative around the tip region where the LEV is pinned and where
the tip vortex is formed. One important observation is that the iso-contours of $w$ shows inward-directed spanwise flow from the tip to the root on the rectangular plate (Figure 34 a). However, on the swept plate, the spanwise flow has a distinct negative component denoting flow towards the tip (Figure 34 b). This outward directed spanwise flow is a direct result of the wing sweep, which creates a spanwise outward component of the incoming flow. This promotes the convection of vorticity from the inboard section towards the tip. This explains the reason behind the higher value of measured circulation at 70% than 50% span on the swept wing. In the heave-pitch case (Figure 34 c and d), the extent of negative CP is higher on the wingspan for both the rectangular and the swept plate case. In the latter case, the negative $C_P$ region is uniformly distributed along the leading edge, which proves that in the heave-pitch case, the LEV was located closer to the plate.
Figure 35: Distribution of the pressure coefficient, $C_p$, on the wing suction surface ($1^{st}$ & $3^{rd}$ row) and the iso-surface representation of z velocity along the LEV and TEV using Q-criterion ($2^{nd}$ & $4^{th}$ row) at $t^* = 8.0$: (a) rectangular wing in heave-only motion; (b) swept wing in heave-only motion; (c) rectangular wing in heave-pitch motion; and (d) swept wing in heave-pitch motion.

At $t^* = 8$, the LEV and the TEV are more lifted from both the plates. This is more evident in Figure 35 b, where distinct outward spanwise flow is observed on the swept plate. The $C_p$ contours show that in the heave-pitch case, the swept plate has a higher region covered by negative $C_p$ contours than the rectangular plate. Also, the TEV in both the rectangular and swept plate case is more compact and has a bigger core diameter in the heave-pitch case compared to the heave-only case. A stronger TEV will result in a stronger downwash. This can explain why in the heave-pitch case, the lift rolls off rapidly at the later part of the kinematics (Figure 25).
Conclusion

Using experiments and simulations, we studied the unsteady forces and the flow field of a rectangular plate and a swept plate, undergoing heave-only and heave-pitch kinematics, to investigate the dynamics of a perching maneuver. In addition to heave or heave-pitch, the plates also decelerated to stop from a Re = 13000. A simple analytical model, composed of added mass force and the circulatory force, was also used to predict the instantaneous sectional two-dimensional lift force on both the plates and is compared with the experimental results.

For a safe landing, birds must produce enough lift force to support their weight and drag force to decelerate to a complete stop. In the present study, both the experiment and numerical simulation results showed that rapid pitch-up motion while heaving down during a decelerating flight enhances both the lift and drag forces on the wing. This higher value of lift and drag force is favorable for the safe landing, which explains the reason why birds undergo the rapid pitch-up motion during the landing flight. The heave-pitch motion also showed faster decay of the lift forces, which was attributed to faster pinching of the LEV from the plates. The swept plate experienced higher lift compared to the flat case in the heave-pitch case. The isocontours of $C_P$ obtained from numerical simulation showed that in the swept plate case, the LEV was closer to the plate, causing a uniform distribution of negative $C_P$ along the leading edge.

It was also found that LEV circulation was higher at 70% of the wingspan for the swept plate. Iso-surface of the $z$-velocity, $w$, revealed that in the presence of LE angle, an outward spanwise flow was induced in the swept wing. This promotes the convection of vorticity from the inboard section towards the tip resulting in a higher value of circulation on the outboard section for the swept wing. A simplified analytical model revealed that non-circulatory forces are important during the acceleration or deceleration part of heaving and pitching motion. Otherwise,
the lift is contributed mostly by circulatory forces. To summarize, all these results indicate that wing-sweep does help in generating higher lift during perching.
CHAPTER 5: MODELING THE VARIATION OF UNSTEADY LIFT DURING A PERCHING MANEUVER

Introduction

Birds are known for their agile flight characteristics, which include performing nimble maneuvers and smooth landings. During landing, most birds execute a perching maneuver where they rapidly increase the angle of attack (AoA) of their wings. Such high AoA maneuvers have been found to generate extra lift at the terminal phase of deceleration and aid in a smooth landing (Polet, Rival, and Weymouth 2015). We hypothesize that this landing flight is also aided by the unsteady ground effect (Rayner et al. 1991; Rayner, Trans, and Lond 1991). Lift augmentation due to ground-effect is well-documented for near-ground steady flight (Zerihan and Zhang 2008). Flight data has also demonstrated the increase in the lift-to-drag ratio of a model aircraft due to the steady ground effect (Rozhdestvensky 2006). However, a decreasing ground height results in an unsteady ground effect, where the pressure distribution on the ground changes, leading to an increase in the magnitude of the lift coefficient (Luo and Chen 2012). In addition, the temporal variation of the lift force during perching can be attributed to several other unsteady factors, such as gradual pitching and deceleration. Such an unsteady problem becomes even more challenging to solve when we consider a finite wing since, in this case, we need to also account for the time-varying downwash velocities due to 3D effects such as the formation of tip vortices and a gradually varying wake.

Modified lifting line theory and Wagner’s theory

It is precisely the complications involved with 3D finite wings that the use of unsteady aerodynamic models, such as Wagner’s law (Wagner 1925), Karman and Sears model (von
Karman and Sears 1938), and Theodorsen’s model (Theodorshen 1935) have been mostly restricted to two-dimensional (2D) flows. For similar reasons, analytical models that were developed to model steady ground effect, i.e., with constant ground height, have been mostly 2D (GRATZER and MAHAL 1971; Saunders 1965). One significant exception is using Prandtl’s lifting line theory (LLT) which was developed to account for finite wing effects. A number of researchers have modified LLT for different unsteady cases, such as a periodically pitching wing (Sclavounos 1987), a flapping wing (Phlips, East, and Pratt 1981), or a generic rotorcraft application (Leishman 2000). In this letter, we model the unsteady dynamics of perching flight by adopting the previous approach. We develop a 3D, unsteady, aerodynamic model which considers finite wing effects and time-varying ground height. Wagner’s theory is combined with the unsteady lifting line model in a similar approach used by Boutet and Dimitriadis (Boutet and Dimitriadis 2018). The LLT is modified to include the ground effect behavior using image vortices.
Figure 36: Sketch of the flat plate wing in perching flight as a function of the non-dimensional time, $t^* = t \frac{U_\infty}{c}$. The plate is translating to the right while carrying out the heave-down and pitch-up motion. Y-axis (right) is the non-dimensional ground height and non-dimensional free-stream velocity, and Y-axis (left) is the effective angle of attack.

To validate our model, we used results from experiments and simulations reported by Adhikari et al. (Dibya Raj Adhikari et al. 2020), where a perching maneuver was recreated with a flat plate with a chord (c) of 10 cm and a span (b) of 30 cm which executed a simultaneous plunging and pitching motion from a fixed ground height. A sketch of the flat perching plate is shown in Figure 36. The flat plate operates at a Reynolds number ($Re = 13,000$), an initial AoA $\alpha_0 = 15^0$, and starts a plunging maneuver at a $t^* = 6$, where $t^* = t \frac{U_0}{c}$. Here t is time in seconds, and $U_0$ is the free-stream velocity. While executing the plunging maneuver, the flat plate is gradually pitched up from the initial AoA. The plunging and pitching motion are completed after $t^* = 9.6$ when the plate stops on the ground. It is to be noted that the plunging and pitching motion start simultaneously, implying there is no phase difference between the two motions. Figure 36 also represents the variation of the effective incoming velocity, $U_{eff}$. Here $U_{eff}$ is
defined as $U_{eff} = \sqrt{U^2 + \dot{h}^2}$, where $\dot{h}$ is the plunging velocity. The variation in the effective angle of attack, $\alpha_{eff}$ is shown in Figure 36 (dotted red line). Here $\alpha_{eff}$ is defined as, $\alpha_{eff} = \alpha_0 + \tan^{-1}\left(-\frac{\dot{h}}{U_\infty}\right) + \alpha_p(t)$, where $\alpha_p(t)$ is the airfoil pitch angle. We have conducted both experiments and numerical simulation with this plate geometry and kinematics. Details of the experiment, numerical simulation and the two motion kinematics can be found in Adhikari et al. (Dibya Raj Adhikari et al. 2020). In this letter we only focus on the analytical modeling and use results from experiments and simulations to validate the output of the analytical model.

![Figure 37: Geometry and vortex system of a flat plate wing in a dynamic ground effect.](image)

We represent the flat plate and the trailing vortex sheet with the help of a lifting line (Figure 37). However, as the flat plate approaches the ground, we incorporate an equivalent image vortex system to satisfy the ground’s zero normal flow boundary condition (Ariyur 2005). The image vortex system induces an additional up-wash on the original finite wing, which in essence adjusts the tip-vortex induced downwash velocity. From Prandtl’s lifting line theory, the downwash velocity, $w_y$, induced at $y$ along the wingspan is expressed as:
\[ w_y = -\frac{1}{4\pi} \int_{-S/2}^{S/2} \frac{dr}{dy_0} dy_0 \]  

(16)

Here, \( \Gamma \) is the strength of the vortex. For the unsteady case involving a finite wing, this strength is a function of time (t) and span location (y) distribution, which can be represented by a Fourier series as:

\[ \Gamma(t, y) = \frac{1}{2} \alpha_0 c_0 U \sum_{n=1}^{N} a_n(t) \sin n\theta \]  

(17)

where \( \alpha_0 \) is the lift curve slope, with \( \alpha_0 = 2\pi \) for an ideal airfoil, \( c_0 \) is the chord length of the wing, \( N \) is the number of spanwise stripes, and \( a_n \) is the time-varying Fourier coefficient. Here the coordinate transformation of \( y = \frac{s}{2} \cos \theta \) is applied, which is a mapping of the angle, \( \theta \), to the semi-span, \( \frac{S}{2} \), position of the wing. After substituting Eq. (18) into Eq.(17) and further applying the substitute of the Glauert integral (Glauert 1983), a simplified form of downwash can be obtained as follows:

\[ \omega_y(t) = -\frac{a_0 c_0 U}{4s} \sum_{n=1}^{N} \frac{n a_n(t)}{\sin(\theta)} \sin(n\theta) \]  

(18)

The upwash velocity, \( w_{yI} \), induced by the image lifting line can be represented following (Ariyur 2005):

\[ w_{yI}(t) = \frac{\cos 2\beta}{4\pi} \int_{-S/2}^{S/2} \frac{dr}{dy_0} \frac{(y-y_0)dr}{dy_0} dy_0 \]  

(19)

This upwash velocity is the main contribution of the approaching ground which changes the lift forces on the plate. After coordinate transformation and substitution of the derivative of \( \Gamma \) into Eq. (20), the upwash velocity can be expressed as:
\[ w_{ly}(t) = \frac{\cos 2\beta}{\pi} \int_{0}^{\pi} \frac{(\cos(\theta_0) - \cos(\theta)) \frac{dr}{r_{y0}}}{[(\cos(\theta_0) - \cos(\theta))^2 + 16(b/c^2)\cos^2(\beta)]} \, d\theta_0 \tag{20} \]

The unsteady sectional lift coefficient, \( c_l^e(t) \), can be calculated in terms of \( a_n(t) \) by using unsteady Kutta-Joukowski theorem (Katz and Plotkin 2001):

\[ c_l^e(t) = \frac{2r}{uc(y)} + \frac{2f}{u^2} \tag{21} \]

Substituting for \( \Gamma \) in the Fourier series representation of the vortex strength (Eq. 17) yields:

\[ c_l^e(t) = a_0 \sum_{n=1}^{N} \left( \frac{c_0}{c} a_n + \frac{c_0}{u} \dot{a}_n \right) \sin(n\theta) \tag{22} \]

The unsteady motion of the flat plate leads to the step change in the downwash velocity, \( \Delta \omega(y) \), along the span. The variation of circulatory lift coefficient due to the step change in the wing motion is given in terms of indicial function as:

\[ c_l^e(t) = a_0(y) \Phi(t) \frac{\Delta \omega(y)}{u} \tag{23} \]

where \( \Phi(t) \) is the indicial function, which represents the Wagner function. \( \Phi(t) \) is written as:

\[ \Phi(t) = 1 - \Psi_1 e^{-\epsilon_1 u t} - \Psi_2 e^{-\epsilon_2 u t} \tag{24} \]

where the constants \( \Psi_1 = 0.165, \Psi_2 = 0.335, \epsilon_1 = 0.0455 \), and \( \epsilon_1 = 0.3 \) are derived from Jone’s approximation of the (R. T. Jones 1938).

A Duhamel’s integral permits us to capture the continuous lift response of an airfoil undergoing an arbitrary motion. The continuous lift is calculated by superimposing the step response of the Wagner function \( \Phi(t) \) with the differential variation of the downwash velocity,
\( \omega(t,y) \). However, in our case, the flat plate is subjected to a gradual deceleration, and the free-stream velocity decreases with time. We write \( U = U(t) \) and modify the Duhamel’s integral formulation to account for this varying free stream velocity. A similar technique was applied by Van der Wall and Leishman (Van der Wall and Leishman 1992) and Hansen et al. (Hansen, Gaunaa, and Aagaard Madsen 2004), who suggested that \( \Phi \) can be used even in the case of time-varying free stream velocity \( U = U(t) \). Based on this result, we write Duhamel’s integral formulation with the time-varying free stream velocity as:

\[
c_l(t) = \frac{a_0}{U} \omega(0) \Phi(s) + \int_0^s \frac{\partial \omega(\tau)}{\partial \tau} \Phi(s - \tau) d\tau
\] (25)

where, \( s = \frac{c}{2} \int_0^t U(\tau) d\tau \) is the non-dimensional time scale.

Applying integration by parts on the Duhamel’s integral and performing the substitution of the first order differential equation, which was derived by differentiating the two-time lags terms of the \( \Phi(t) \) with respect to \( t \), yields the following expression of the sectional circulatory lift coefficient along the wingspan:

\[
c_l(t,y) = \frac{a_0(y)}{U} \omega(t, y)(1 - \Psi_1 - \Psi_2) + y_1(t) + y_2(t)
\] (26)

Where the state variables \( y_i \) is defined as:

\[
y_i(t) = \Psi_i \epsilon_i \frac{2}{c} \int_0^t \omega(t, y) U(t) e^{-\epsilon_i \frac{2}{c} \int_0^t U(\tau) d\tau} dt
\] (27)

In this study, the downwash on the wing is due to the motion of the wing and the 3D wake. The sources of downwash due to wing motion includes plunge, pitch, and angle of attack. The 3D downwash is calculated using modified lifting line theory, which includes downwash
due to the trailing vortex sheet and upwash due to the image vortex sheet. The total downwash \( \omega(t, y) \) on the wing is then expressed as:

\[
\omega(t, y) = U\alpha_y + \dot{h}(t) + \dot{\alpha}_y(t)d + \omega_y(t) + \omega_{I_y}(t)
\]  \hspace{1cm} (28)

Where \( d \) is the Theodorsen’s non-dimensional distance.

To remove the integrals from the state variables, new state variables, \( z_k \), are introduced:

\[
z_k(t, y) = \int_0^t e^{-\frac{2}{t^2} U^{(z)} dt} v_k(t, y) dt, \quad i = 1, 2
\]  \hspace{1cm} (29)

Where \( k = 1, 2, \ldots, 8 \), \( v_{1,2} = h \), \( v_{3,4} = \alpha \), \( v_{5,6} = \frac{\omega_y}{U} \), and \( v_{7,8} = \frac{\omega_{I_y}}{U} \). Here, \( i = 1 \) is used for \( k = 1, 3, 5 \), and 7, and \( i = 2 \) is used for \( k = 2, 4, 6 \), and 8.

To express the first-order differential equation of Eq. 30, we used Leibniz’s integral rule:

\[
\dot{z}_k(t, y) = v_k - \frac{e_i U}{b} z_k(t, y), \quad i = 1, 2
\]  \hspace{1cm} (30)

After combining Eqs. (23), (27), and (29), and performing the substitution of \( z_k \) into \( y_i \), we can now turn Eq. (27) at the \( j \)th stripe into a Wagner lifting line matrix equation. This is further expanded to incorporate all the \( m \) strips’ equation.

\[
D_{ym} \dot{a}_n = J_M \dot{q} + K_M q + L_M z + (W_{ym} + W_{I_{ym}} - A_{ym}) a_n
\]  \hspace{1cm} (31)

\[
\dot{z} = E_M z + F_M q + \frac{c}{U} (\omega_{ym} + \omega_{I_{ym}}) a_n
\]  \hspace{1cm} (32)

Where:

\[
q = [h(t, y), \alpha(t, y)]^T
\]

\[
z = [z_1(t, y) \ldots z_i(t, y) \ldots z_m(t, y)]^T
\]


\[ A_{y_M} = [A_{y_1} ... A_{y_i} ... A_{y_m}]^T \]

\[ D_{y_M} = [D_{y_1} ... D_{y_i} ... D_{y_m}]^T \]

\[ J_M = [J_1 ... J_i ... J_m]^T \]

\[ K_M = [K_1 ... K_i ... K_m]^T \]

\[ L_M = \text{diag}(L_1, ..., L_i, ..., L_m) \]

\[ W_{y_M} = \frac{a_0 \Phi(0)}{U} [W_{y_1} ... W_{y_i} ... W_{y_m}]^T \]

\[ W_{I_{y_M}} = \frac{a_0 \Phi(0)}{U} [W_{I_{y_1}} ... W_{I_{y_i}} ... W_{I_{y_m}}]^T \]

\[ E_M = \text{diag}(E_1, ..., E_i, ..., E_m) \]

\[ F_M = [F ... F ... F]^T \]

\[ G = [0 0 0 0 1 1 0 0; 0 0 0 0 0 0 1 1]^T \]

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**Added mass force**

Added mass or non-circulatory force contributes to the change in unsteady forces during the acceleration or deceleration of the fluid. The non-circulatory force coefficient for a decelerating, heaving, and pitching plate in ground effect is determined from the following equation:

\[ C_{F_{nc}} = \frac{\pi c}{2U_\infty} \left[ \dot{h} \cos \alpha + \dot{\alpha} \cos \alpha U + \sin \alpha U + \dot{c} \dot{\alpha} (1/2 - x_p) \right] \left[ 1 + a \left( \frac{1}{2} h^* \right)^2 \right] \]

Where \( h^* = \frac{h}{c} \) is the non-dimensional ground height and \( a \) is the constant. Based on our empirical results, we used \( a = 0.002 \).
Results

In this study, the wing is divided into $N = 15$ spanwise sections. When we apply Eqs. (32) and (33) to all the $N$ sections, a $9N$ differential equation is formed. A MATLAB built ODE function, ode15s, is used to solve the given systems of ODE. After computing the Fourier coefficients, $a_n$, Eq.(22) is used to calculate the lift coefficient along the wing span.

![Figure 38](image)

Figure 38: Comparison of the lift coefficient on the flat plate from the model to that of the experimental and CFD data (a) for the heave-only case, (b) for the heave-pitch case.

Figure 38 compares the time-varying lift coefficient for the two-motion kinematics between the theoretical model, experimental, and CFD data. For the first kinematic motion, during the initial deceleration phase $6.0 \leq t^* \leq 8$, there is a steep rise in the lift coefficient (see Figure 38 (a)). This initial rise in the lift coefficient is the combined contribution of the non-circulatory force and the growth of the circulatory force due to the acceleration of the heaving motion. The initial peak is followed by a sudden drop in the lift coefficient, which corresponds to the end of the acceleration of the heaving motion and the corresponding reduction in the non-circulatory force. Although the trend in the rise of the peak force from all the methods matches relatively well, there is a significant difference in the magnitude of the peak force. One
The explanation for the discrepancy is that the low pass filter is applied in the experimental and CFD data to remove the high-frequency noise. This leads to a reduction in the peak value of the experimental and CFD data. Once the heaving motion attains the constant velocity $t^* \geq 6.5$, the agreement between the theory, experiment, and CFD is considerable. The evolution of the lift coefficient for the second kinematic motion, where the wing gradually pitches up while heaving down, is shown in Figure 38 (b). As the plunging and the pitching motion started without any phase difference, the acceleration of both motions resulted in a higher peak force. Here, the predicted lift coefficient also shows a close agreement with the measured lift coefficient, except during the latter half of the motion. Recent experimental studies on the perching airfoil suggest that the shed leading-edge vortices dissipate rapidly during the later end of the motion, which the present model cannot predict. This may have led to the discrepancy between the predicted and the measured data at the latter half of the motion.

![Figure 39](image)

Figure 39: Comparison of the unsteady circulation along the wingspan between theoretical and CFD results at two non-dimensional times.
The circulation predicted from the model is compared with the unsteady circulation computed using CFD. Results of the comparison are shown in Figure 39. The model calculates the total circulation at each span location as the sum of vortex strength, \( \Gamma \), and unsteady term, \( \dot{\Gamma} \). In the simulation, the total circulation along the wing span is obtained by taking the contour integral around the wing chord. Here, the circulation is calculated at two different time instants i.e., \( t^* = 6.5 \) and \( t^* = 8 \). At \( t^* = 6.5 \), the predicted circulation agrees well with the simulated circulation, with some exceptions at the wing tips. One explanation for the discrepancy is that in the model, the circulation at either end of the wing tips was assumed to be zero, whereas, in the CFD computation, there was small flow speed which led to the non-zero circulation at the wing tip. At \( t^* = 8 \), the disagreement between the theoretical and CFD is high around the wing tips. However, there is relatively good agreement between the results in the mid-span. The considerable agreement on the circulation between the two results further increases the validity of the present model.

To demonstrate the significance of the unsteady ground effect, the net change in the lift force \( \frac{(L_{GE} - L)}{L} \) and the variation in the non-dimensional downwash velocity along the wingspan with and without the image vortices are plotted in Figure 40. The plot indicates an increase in the lift force in ground effect. Furthermore, it is also evident that the ground effect is dominant as the wing approaches the ground. The reduction of the vortex induced downwash velocity identified earlier by which the ground was hypothesized to obstruct the expansion of the trailing edge vortex is also addressed from Figure 40. The plot shows that that the downwash predicted by the model with image vortex sheet results in a reduction in the magnitude of the downwash velocity compared to the model without Image vortex sheet.
Figure 40: Net change in the lift force and the variation in the non-dimensional downwash velocity with and without incorporating the Image vortex. The net change is plotted as a function of non-dimensional ground height, Y-axis (left), and X-axis (bottom). The variation in the non-dimensional downwash velocity is plotted along the wingspan at $t^* = 8$, Y-axis (right), and X-axis (top).

In conclusion, in this letter, we modified an unsteady lifting line model to account for the ground effect for predicting the unsteady lift during a perching maneuver. The model presented here is a combination of modified lifting line theory and Wagner’s theory. The added mass component from Theodorson’s theorem has also been included in the model to consider the non-circulatory forces. A direct comparison with the experimental and CFD results illustrates the validity of the proposed model. The results also show a satisfactory agreement on the unsteady circulation generated along the wingspan between the model and the simulation data.
Effect of ground

Figure 41: (a) Circulatory, non-circulatory, and total lift coefficient on the rectangular plate predicted from the analytical model for $\Xi = 0.6$ at $h^* = 1.5$. (b) Evolution of lift coefficient on the rectangular plate predicted from the analytical model for $\Xi = 0.6$ at different ground heights.

Figure 41 displays the evolution of lift coefficient predicted from the analytical model over the course of perching maneuver. Figure 41 (a) illustrates the non-circulatory, circulatory, and the total lift coefficient generated by a rectangular plate for $\Xi = 0.6$ at $h^* = 1.5$. The plot reveals that during the initial deceleration phase $0 \leq t^* \leq 0.25$, there is a steep rise in the total lift coefficient (see Figure 41 (a)). This initial rise in the total lift coefficient is driven by the combined contribution of the non-circulatory force and the growth of the circulatory force because of pitch-up motion. However, the non-circulatory component contributed more to this initial rise. The peak is followed by a drop in the lift coefficient that aligns with the reduction in non-circulatory force. At $t^* = 0.25$, the wing operates at higher effective angle of attack, $\alpha_{eff}$, where the non-circulatory lift force decreases due to the dominance of the wing deceleration. In the end phase of the maneuver, the wing generates negative lift force, mainly due to the non-circulatory component, as vortices fully detach from the wing surface and move away, generating a lower circulatory force.
Figure 41 (b) depicts the evolution of total lift coefficient at different ground heights, ranging from $h^* = 1.5 - 0.04$, for $\Xi = 0.6$. Our model predicts an increase in the initial peak lift force and negative lift force at the end phase of the maneuver as the ground heights decreases, which is consistent with the experimental results.

**Conclusion**

In summary, our analytical model effectively accounts for the variations of unsteady forces on a flat plate during a perching maneuver. This model integrates multiple theories, including unsteady lifting line theory, image vortices to consider the effect of ground height, Wagner’s theory, and the unsteady Kutta condition to model pitching, heaving and gradual deceleration. The accuracy of the model was tested by comparing it with experimental results on a finite wing undergoing the same kinematics. Our findings demonstrate that our analytical model captures the unsteady variation of the forces during the perching maneuver.
CHAPTER 6: CONCLUSION

Birds often perform a perching maneuver while landing, which involves pitching their wings upwards while decelerating to a complete stop. This perching maneuver is an important landing technique, which helps them to generate higher lift and drag force while slowing down, resulting in a smooth landing. The aim of this study is to investigate two critical aspects of this maneuver: first, we want to analyze how the proximity of the ground affects the unsteady forces and the flow field during the perching flight; and second, we want to explore how a wing sweep influences this maneuver.

To study the first aspect, we examined a finite flat plate undergoing a perching maneuver in the ground effect. Our results showed that the instantaneous and time-averaged lift force increased as the plate came close to the ground, while the instantaneous peak drag coefficient stayed relatively constant with changes in the ground height. However, the negative drag force, or the parasitic thrust, at the latter stages of the perching maneuver increased with the increase of the ground proximity. We demonstrated that performing rapid pitching at the end phase of the decelerating motion, which is done by introducing the time offset between the decelerating and pitch-up motion, significantly reduced the parasitic thrust even when the perching plate was close to the ground. Our results revealed that the dipole jet induced by the counter-rotating vortices was lower for the pitching case executed at the latter stage of the decelerating motion, which affected the advection of the shed vortices, acceleration of the fluid between the wing and the ground and varied the unsteady forces during the maneuver. For the highest shape change number considered in this study, at a time offset of 0.5, the wing generated a positive averaged
drag force and near zero averaged lift force, which is appropriate for landing smoothly on the initial perching location without gaining altitude.

The second part of this dissertation is motivated by the observation that some birds fold their wings to create a wing sweep during such perching. This study investigated whether such a wing sweep helps during a perching maneuver. We use two flat plates: one with a sweep and another without any sweep and consider a deceleration maneuver where both decelerate to a complete stop from a Reynolds number, $Re = 13000$. We consider two cases: one, where the wings undergo only heaving, and another, where the wings perform both heaving and pitching. The latter maneuver was designed to mimic perching. By performing experiments and simulations, we compare the temporal evolution of the instantaneous forces and the vortex dynamics of both these plates. We show that during a major part of the deceleration, the instantaneous lift forces are higher in the case of the plate with sweep compared to the plate with no sweep during both kinematics. Our results indicate that the higher lift in the swept plate case was contributed by a stable leading edge vortex (LEV) which remains attached to the plate. This increase in stability was contributed by the spanwise vorticity convection caused by a distinct spanwise flow on the swept plate, as revealed by the numerical simulation. We also show that combined pitching and heaving resulted in higher force peaks, and the forces also decayed faster in this case compared to the heave-only case. Finally, by using an analytical model for unsteady flows, we prove that the higher lift characteristics of the swept plate were entirely due to higher circulatory forces.

We also developed an analytical model to account for the variation of unsteady forces on a flat plate undergoing a perching maneuver. The model incorporates unsteady lifting line theory, image vortices to account for the effect of ground height, Wagner’s theory, and the unsteady
Kutta condition to model pitching, heaving, and gradual deceleration. To include the ground effect, we updated the added mass force by accounting for the increase in flow acceleration between the wing and the ground. The accuracy of the model was tested against the experimental results on a finite wing undergoing identical kinematics. Our result demonstrates that the present analytical model captures the unsteady variation of forces during a perching maneuver.

In summary, this dissertation provides insight into how birds use the perching maneuver to land smoothly and how ground proximity and wing sweeps affects the maneuver’s unsteady forces and the flow field.
REFERENCES


