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Aerodynamics and Turbulent Wake-Flow Characteristics of Owls during Flapping Flight

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Aerodynamics and Turbulent Wake-Flow Characteristics of Owls during Flapping Flight

A thesis submitted in partial fulfillment of the Requirements for the degree of Doctor of Philosophy

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by

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Abstract

Owls exhibit unique flight capabilities in the low Reynolds number flow regime which is prone to complex viscous flow phenomena. They possess unique feather features and flexible wing structures which are postulated to help them fly nearly silently and stably at low speeds in a complex flow setting. Understanding the aerodynamics of owls could pave the way to enhance the future designs of small flying vehicles. Though it has been a focus of research over multiple decades, no conclusive agreement has been attained on the aerodynamic mechanisms associated with owl flight. Particularly, the aerodynamics of flapping owl flight is severely understudied and there is a gap in the literature regarding the energetics of the owl’s flight. The major goal of this research is to advance the understanding of the owl’s aerodynamics by investigating the near-wake turbulent flow features, aerodynamic force characteristics and energy expenditure during free forward flight. Understanding the downstream wake-flow dynamics of owl flight can elucidate the aerodynamic mechanisms employed by owls during flight and provide insight into the fluid-owl interaction characteristics. A great horned owl (Bubo virginianus) was chosen for the investigation in the current research. A similar-sized bird of prey, Harris’s hawk (Parabuteo unicinctus) was also chosen to conduct a comparative analysis between two distinct raptors. Both raptors were trained to fly inside a large wind tunnel in a perch-to-perch flight style. The wake-flows behind the freely flying birds were sampled with a high-speed, long-duration time-resolved PIV system, while the kinematics of the birds were captured using multiple high-speed cameras, simultaneously. Multiple flights were conducted over a span of two days and large velocity and kinematics data sets were acquired. The kinematics images enabled us to estimate the flight speed of the birds during each flight. Kinematic analysis has been performed to compare the characteristics of wingbeat kinematics between both birds. Using the theoretical models concurrently with the experimental data, the total aerodynamic power output during a level flight and an intermittent flight have been estimated for both the birds. In this study, a primary attempt has been made to estimate the mechanical power output of a great horned owl during its typical forward flight speed and to establish the power-speed relationship traits. Compared to the hawk owl displayed higher aerodynamic power output during level flight at relatively lower flight speed. Though both birds had similar wingspan, frequency, and amplitude, the owl displayed relatively shorter downstroke. The effect of wing morphology and the other kinematics parameters on the
aerodynamic power output has been highlighted. In order to examine the aerodynamic force characteristics during flapping flight, the sectional profile drag coefficient and lift coefficient are estimated over a single wingbeat cycle directly from the PIV wake velocity fields using viscous momentum equations and compared between both birds. The near wake-flow fields of both raptors have been described by mean velocity fields, vorticity field, and turbulent fluctuation fields. Besides, spatial and temporal correlation of the turbulent fluctuations, Reynolds stresses, turbulent kinetic energy, production, and dissipation terms have also been evaluated in the near wake-flow. It is found that the near wake of the owl is characterized by significantly higher turbulent activity than the hawk. To the best of our knowledge, it is observed for the first time that the turbulent eddies in the wake of the owl’s downstream flow field are characterized by small time scales (turnover time) which can have strong implications in its noiseless flight associated with turbulent generated noise.
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Chapter 1

Introduction

1.1 Motivation for current research

Micro-and-unmanned aerial vehicles (MAVs and UAVs) are miniature flying vehicles that are used in a vast number of sectors such as military, energy, construction, commercial, chemical, and agricultural. These vehicles are utilized for a variety of missions that include surveillance, reconnaissance, inspection, imaging, spraying, and payload transportation. Conventionally, these are fixed-wing fliers having dimensions of 15 cm or less, and flight speeds of about 8-15 m/s. The Reynolds number ($Re$) for such size and the range of flight speeds corresponds to 80,000 to 150,000 which is known as low-to-moderate Reynolds number flow regime ($Re$ in the range of $10^4$-$10^5$). This is a complex flow regime where flow over fixed wings experience unfavorable flow phenomena such as adverse pressure gradient, flow separation, and laminar separation bubble formation on the upper side of the wing (Mueller and DeLaurier, 2003; Shyy et al., 2008). These unsteady flow phenomena lead to drastic loss of lift and increase of drag, and detrimentally affect the aerodynamic performance of the fixed wings.

Due to their miniature size and autonomous nature, the usage of MAVs and UAVs is becoming prevalent. They can be operated to remote places for imaging, spraying, technical inspection of offshore wind farms, and defense surveillance where it is humanly difficult to access. Depending on the mission, they are required to fly steadily at a low and controlled speed, carry a heavy payload, and be stealthy to avoid detection (defense purposes). However, as traditionally fixed-wing configurations flying in the low $Re$ flow regime, these vehicles face difficulties to sustain flight due to the associated complex flow phenomena. This reinforces that new ways of lift and thrust generation mechanisms should be explored in the future generation aerodynamic designs of MAVs and UAVs to overcome the shortcomings posed by the fixed-wing configurations at low $Re$.

On the other hand, if we look at nature, while operating under the same low $Re$ flow regime (Shyy et al., 2008) birds exhibit extraordinary aerodynamic performance, though similar unsteady flow phenomena are likely to occur (Winzen et al., 2015). Compared to these manmade vehicles, one of the major differences found in natural fliers is the flapping wing configuration: insects, birds,
and bats predominantly use flapping flight to locomote during most part of their flight (Ho et al., 2003; Shyy et al., 2008).

Nature has always been a great source of inspiration for humans. Understanding the aerodynamics of flapping bird flight found in nature can help us to benefit from the evolutionary advantage and design aerodynamically advanced bio-inspired flying vehicles to meet the operational requirements. It is one of the predominant reasons that the aerodynamics of flapping flight has become one of the major research interests in the aeronautical community over the past few decades.

Having said that, among birds, owls can be the best candidates for bio-inspiration of future generation aerial vehicles to tackle all the three requirements i.e., silent flight, low-speed flight, and enhanced lift. Most owl species have evolved a hunting strategy that requires them to fly silently (Grahamn, 1934; Lilley, 1998). Besides, owls are typically low-speed fliers and can carry heavy prey which is often comparable or more than their weight.

1.2 Owls are unique candidates for the bio-inspiration of MAVs

“It's the little details I love. How to fletch your arrows with owl feathers, because owls fly silently, so maybe your arrows will, too.” - Michelle Paver

Fossil records show that owls are an ancient lineage of birds (Johnsgrad, 1988): the earliest record of the Strigiformes owl family is about 55 million years old (Mayr et al., 2020). Over millions of years of evolution, owls have attained silent flight capabilities. It has been established that owls fly nearly silently to their prey and even for humans when they are about 3 meters away (Lilley, 1998; Gruscka et al., 1971; Kroger et al., 1972). In contrast to other birds of prey (raptors), the majority of owl species are generally nocturnal hunters. Since they hunt during the night, the available visual information is very much limited, and they use their acute sense of hearing to locate prey. If their flight makes a noise that will either surpass their hearing to locate the prey or the prey might get alerted and escape. Owls have evolved silent flight to locate and attack their prey by surprise. The nocturnal owl species have been identified to possess unique wing and feather morphologies, generally characterized as leading-edge serrations, trailing-edge fringes, and
the velvety upper surface (Graham, 1934). These features have been postulated widely to enable them to fly silently.

Owls are known to fly typically at very low speeds in the range of 2.5 to 7.5 m/s when approaching their prey (Mebs and Scherzinger, 2000; Winzen et al., 2015, Roulin, 2020). Owls’ silent flight is also attributed to their low-flight speed (Liley, 1998). Flying at low speeds, owls are known to silently patrol over open fields while foraging for prey (Roulin, 2020). Though flow separation is likely to occur, owls' wings can generate strong lift to fly steadily at such low speeds. Their wings are characterized by highly cambered airfoils and enlarged nearly elliptical wing planforms (Bachmann et al., 2007). Strong camber and large planforms are characterized to produce high lift performance at low Reynolds numbers (Schmitz, 1980). In addition, the high flexibility of the owl wings is also attributed to their distinctive flight capabilities (Winzen et al., 2015). Besides their role in the silent flight, the leading-edge serrations and the velvety upper surface are also known to augment lift by stabilizing the flow over the upper surface of the wing by delaying the flow separation (Klaï et al., 2009; Rao et al., 2017).

It is rational to consider that the distinctive flight capabilities of the owl flight are the synergetic outcome of their unique feather features, wing planform, camber, and high flexibility that produce high lift and enables silent flight. Understanding the mechanisms of how owls manage to sustain lift at such low flight speed and at the same time fly silently in an unsteady flow setting provides an excellent scope to improve the operation of conventional aerial vehicles at the low Re flow regime and to develop aerodynamically advanced future generation aerial vehicles.

1.3 The problem statement

No conclusive agreement yet - Understanding owl flight has been a persistent problem for years in the scientific community. Most of the available studies on owl flight can be classified into three major categories; 1) studies on owl wing morphology (Mascha, 1904; Graham, 1934; Bachmann et al., 2007; 2012; Bachmann and Wagner, 2011), 2) gliding flight acoustic measurements (Thorpe and Griffin, 1962; Neuhaus et al., 1973; Geyer et al., 2009; 2012; Sarradj et al., 2011; Chen et al., 2012), and 3) aerodynamics and the aeroacoustics of the owls either in gliding flight or as fixed wings using prepared wings/owl-like wings. The latter studies principally focused on how the
aerodynamic characteristics and/or the acoustic spectrum change with and without the specific wing morphological feature (Kroger et al., 1972; Vad et al., 2006; Klan et al., 2009; Kondo et al., 2013; Winzen et al., 2014a, b; Winzen et al., 2015; Bodling et al., 2017; Rao et al., 2017; Anyoji et al., 2018). Though the unique owl wing morphologies have been postulated to function as potential aerodynamic devices, discrepancies exist between cases, and the physics behind the owls’ silent flight mechanism is not yet determined, conclusively. Moreover, the aerodynamics of owls’ during flapping flights is not widely studied and established yet.

**The physics of the turbulent flow-wing interaction should be understood first** - In contrast to conventional fixed-wing aerodynamics, the aerodynamic force production of the flapping wing mechanism largely depends on fluid-structure (bird) interaction characteristics: aerodynamic forces generated during flapping bird flight are intrinsically unsteady (time-varying), and these unsteady forces are involved in a complex interaction with the wing structure. Such interaction is a continuous loop and a complex phenomenon: the time-varying aerodynamic forces result in structural changes of the birds' wings, and the changes in the birds' wings alter the flow field around the flapping wings further (Birch and Dickinson, 2003). This interaction between the unsteady turbulent flow and the wing structure induces the aeroacoustics field downstream which emits and radiates noise farther. It is necessary to understand the role of this turbulent flow in the vicinity of the wings before associating with the wing features to gain insight.

**Power analysis is missing** - Flapping flight is energetically demanding and requires excessive physiological performance from flying birds. The flight muscles of the birds do the work to oscillate the wings to produce the lift to balance the weight, and the thrust to overcome the aerodynamic drag: the large pectoralis muscles depress the wings during the downstroke and the smaller supracoracoideus muscles elevate the wing during the upstroke (Biewener, 2011). Understanding the energetics of the flying birds can help to associate their performance traits with the wing morphology and their flight abilities. To the best of my knowledge, there is a gap in the literature that information on the power analysis of the owl flight is missing.

**Comprehensive analysis that includes all aspects of owl features is required** - Studying dried wings, experimentally prepared owl wings, owl-like wings, or owl-inspired airfoils cannot explain the aerodynamic mechanisms of owls in real flight. The fluid-structure interaction of the real owl wing and the experimental wings may greatly differ due to differences in the structural properties,
and they may behave differently in the same flow condition. Curet et al., (2013) showed that even in gliding flight, flexible bird wings can deform due to the interaction with the surrounding flow field. A flow field comparison between the natural barn owl wing and a rigid-owl like wing was provided by Winzen et al., (2014c) and showed that the flow field around the natural barn owl wing was significantly influenced by the flexibility of the natural wing. Aerodynamic characteristics of flapping flight are also hugely influenced by complex three-dimensional wingbeat kinematics, which are impossible to replicate in a prepared wing. Owls' unique flight capability is the synergetic outcome of their special morphological features, low-speed flight, wing planform geometry, structural flexibility, and their complex wing kinematics during flapping. In order to gain a comprehensive understanding of the aerodynamic mechanisms of owls during flapping flight, it is necessary to account for the influences of all the aspects inclusively.

**Wake-flow analysis can serve the purpose** - Analyzing the near wake flow fields behind the flapping wings could serve the purpose of accounting for all the aforementioned effects. Measuring the wake-velocity fields to study the aerodynamics characteristics of the freely flying birds have been widely used in the literature (Spedding et al., 2003; Rosén et al., 2007; Hedenström et al., 2006a; Hedenström et al., 2006b; Heningsson et al., 2008; Ben-Gida et al., 2013; Kirchhefer et al., 2013; Gurka et al., 2017; Lawley et al., 2019; Nafi et al., 2020). The near wake flow behind the flapping wings is directly influenced by the bird-flow interaction and comprises the time-history of the forces and flow dynamics associated with them (Johansson et al., 2008; Chin and Lentink, 2016; Gurka et al., 2017). Moreover, detailed time-resolved wake velocity field measurements of owls in flapping flights are severely limited. Recently, Lawley et al., (2019) conducted time-resolved near wake flow measurements of a freely flying boobook owl in a wind tunnel using the particle image velocimetry (PIV) technique and showed that the near wake region of the owl flight was disorganized and characterized by small turbulent scales. Investigating the velocity flow field characteristics of the near wake in the vicinity of the flapping wings presents a vast scope to gain a deeper insight into the owl-flow interaction (Lawley et al., 2019).

To advance the understanding of the aerodynamics and turbulent wake-flow characteristics of the silent owl flight, a comprehensive wake-flow analysis has been carried out in the current study behind the downstream of a freely flying owl. To conduct a comparative analysis with the owl, another similar-sized raptor, a hawk was also chosen for the investigation. We trained a great
horned owl (*Bubo virginianus*) and a Harris’s hawk (*Parabuteo unicinctus*) to fly inside a large wind tunnel in a perch-to-perch flight style and conducted *in vivo* flight experiments. Multiple flights were conducted with both birds on two days of experiments. The birds’ motion during the flight was sampled using multiple high-speed cameras while the velocity fields in the near wake were sampled with high temporal resolution using a long-duration and high-speed particle image velocimetry, simultaneously. The kinematics images helped us to estimate their typical flight speed and conduct kinematics analysis. The near wake velocity fields of the birds sampled with high temporal resolution enabled us to estimate the aerodynamic force characteristics and the near wake turbulent wake-flow characteristics during flapping flight.

### 1.4 The objectives of this research

With the global objective of developing a deeper understanding of owl’s aerodynamics in flapping flight, the following specific objectives are identified for the thesis research:

- investigate the near wake turbulent flow characteristics of the owl flight to determine the role of owl wing interaction in the resulting wake flow field and explain the characteristics of the mean and turbulent flow parameters
- analyze the correlation of turbulent flow scales (length and time) over a flapping wing cycle to better explain the nature of the downstream turbulent flow field
- examine the variation of the aerodynamic force coefficients over a flapping wing cycle to associate the role of wingbeat and the wing morphology in their aerodynamic performance
- establish the aerodynamic and metabolic power expense of owl during level flight to correlate it to their performance trait and flight behavior
- compare the aerodynamic performance and the turbulent flow characteristics of owl and hawk to distinguish the elements of owl flight that can be possibly associated with their unique features
1.5 Comparing owls to the hawks

Owls are phylogenetically distant and not closely related to other raptors such as eagles, hawks, and falcons (Jarvis et al., 2014; Clark et al., 2020). While other raptors are typically diurnal hunters, most owl species are nocturnal. Owls have been in direct competition with other raptors (Accipitriformes and Falconiformes) all through evolution (Johnsgard, 1988). Though not closely related, both groups have convergently evolved to share some major anatomical and behavioral similarities (Johnsgard, 1988). Fossil records suggest that in contrast to modern-day owls which use their beak to kill prey, extinct owls have used their feet to kill the prey like hawks (Mayr et al., 2020).

Owls and hawks also share ecological similarities and exploit a similarly wide range of prey such as small mammals, birds, lizards, and large insects. The special wing and feather morphologies that nocturnal owl species possess majorly distinguish owls from other hawk-like birds, anatomically. Though recently, it is reported that the velvet on the feather upper surface is variably present in hawks as well, it is very extensive in the owls (LePiane and Clark, 2020). The leading-edge serrations and trailing edge fringes have not been reported on the other diurnal raptors.

Further, silent flight capabilities have been widely established for the owls, though it is possible that other raptors have been overlooked (Clark et al., 2020). Thorpe and Griffin (1962) and Sarradj et al., (2011) studied the flight noise of Harris’s hawk along with few other owl species and showed that the noise generated during the flight of the Harris’s hawk exceeded considerably the noise generated in the owl’s flight over a whole range of frequencies. Particularly, in Thorpe and Griffin’s (1962) study where they reported acoustics measurements of free flight, all doves, a falcon, and a Harris’s hawk produced ultrasound, but most owls lacked ultrasound in flight.

Hence, comparing the aerodynamics and wake-flow characteristics of owl flights and characteristics of other hawk-like bird flights can help to consider the similarities and dissimilarities between the birds and the flight behavior, and distinguish the elements of owl flight to gain a better understating of the physical mechanisms involved in owls’ silent flight.
1.6 Outline of the thesis

The thesis is organized as follows. Chapter 2 is dedicated to the literature survey on the aerodynamics of airfoils/wings, owl and hawk aerodynamics, turbulent wake-flow characteristics, and the application of PIV to bird flight studies. The same chapter also includes the description of the special owl wing morphologies to better illustrate their role in owl aerodynamics. In chapter 3, the details of the experimental setup, the birds, the PIV system, and the data acquisition are provided. Concurrently with the results obtained from the experiments and using the theoretical aerodynamic models, the energy requirements of the steady level flight for the owl and the hawk are established in chapter 4. Further, in the same chapter, the estimation of the power expenditure by both birds in the intermittent flight style exhibited during the experiments is provided, and also shown is how intermittent flight can be energy-saving for birds compared to continuous flapping flight. In chapter 5, the time variation of lift and drag characteristics of the owl and the hawk over a single flapping cycle are estimated using the momentum equation for viscous flows and discussed how the aerodynamic force characteristics differ between the two distinct fliers. This chapter also covers the comparison between the wingtip kinematics of the two birds extracted from kinematic images. Chapter 6 addresses the comparison between the owl’s and the hawk’s near wake-flow characteristics during flapping. In particular, a detailed description of the following characteristics; instantaneous and turbulent velocity and vorticity fields, the integral turbulent length and time scales, the turbulent stresses, turbulent kinetic energy budget, and the spectral analysis are provided.
Chapter 2

Literature survey

2.1 Aerodynamics of airfoils and wings

A schematic of an airfoil with marked nomenclatures is provided in Figure 2.1. Mean camber which is a geometrical characteristic of the airfoil divides it into two equal parts (upper and lower). The forward end of the mean camber line is known as the leading edge where the oncoming flow meets, and the rearward end of the mean camber line is the trailing edge where the flow leaves, ideally. The chord line is the straight line connecting the leading edge to the trailing edge, and its length is usually referred to as chord \((c)\). The maximum width between the upper and lower part of the airfoil defines the thickness, and the camber is the maximum distance between the mean camber line and the chord line. Further, the upper surface of the wing is also called the suction side, and the lower surface of the wing is called the pressure side. The angle of attack \((AOA)\) is defined as the angle between the wing chord and the free stream flow direction.

The nature of the fluid flow (i.e., laminar vs. turbulent) around an airfoil/wing is characterized using an important non-dimensional number in fluid dynamics which is known as Reynolds number. Reynolds number is a ratio between the inertial force and the viscous force that is used to quantify the relative dominance of one force over another in a given flow situation. The chord-
based Reynolds number for flow over a wing section/airfoil is defined as, \( Re = \frac{\rho U_\infty c}{\mu} \), where \( c \) is the chord length, \( \rho \) is the fluid density, \( U_\infty \) is the freestream velocity and \( \mu \) is the dynamic viscosity of the fluid (Anderson, 1991). When the momentum of the fluid increases high enough to overcome the viscous forces, the nature of the flow changes from the more regular laminar state to a chaotic turbulent state. Laminar flow is an ideal case, and most flows occurring in nature are turbulent. It is difficult to provide an exact definition of turbulent flow (Tennekes and Lumley, 1972). Turbulence is a feature of the fluid flow and not of the fluid itself. Some characteristics of the turbulent fluid flow include that the flow is highly unsteady, irregular, random, and chaotic. It exhibits three-dimensional velocity and vorticity fluctuations and generally occurs at large Reynolds numbers. The diffusivity of the turbulence is another major characteristic that makes it an effective mixer of the momentum of the fluid. Moreover, turbulent flows are very dissipative and need a constant supply of energy to sustain (to balance the viscous losses) (Tennekes and Lumley, 1972).

When the flow becomes turbulent, the flow carries eddy motions of all sizes. A description of eddies is adopted from Pope (2000). Pope states, “The turbulence can be considered to be composed of eddies of different sizes. Eddies of size \( \ell \) have a characteristic velocity \( u(\ell) \) and timescale \( \tau(\ell) \equiv \ell /u(\ell) \). An ‘eddy’ eludes precise definition, but it is conceived to be a turbulent motion, localized within a region of size \( \ell \), … . The region occupied by a large eddy can also contain smaller eddies”. Once the turbulent flow arises, a large part of the kinetic energy of the turbulent flow goes into forming these eddies, which eventually dissipate the energy as heat through viscous dissipation. Energy-containing large-scale eddies (which are often compared to the characteristic flow scale determined by the geometry) are unstable and undergo break-up, transferring their energy to relatively smaller eddies (see, Figure 2.2). These smaller eddies undergo a similar process forming further smaller eddies until the sizes of eddies are comparable to the viscosity of the fluid where the viscous dissipation decays the turbulence (Tennekes and Lumley, 1972; Pope, 2000). The process of turbulent energy being transferred from larger eddies to successively smaller and smaller eddies is known as an energy cascade (Richardson, 1922).
Turbulent flow is often dominated by vortical motions (vortices) and the dynamics of vortices play a major role in the turbulent flow dynamics. A generally accepted definition of vortex or vortices is still lacking (Jeong and Hussain, 1995). The motion of the fluid flow can be described by the velocity vector, and the curl of the velocity vector, also known as vorticity, characterizes the rotation of the fluid elements. Saffman and Baker (1979) define a vortex as a finite volume of rotational fluid, bounded by irrotational fluid or solid walls. Wu et al., (2007) generalize a vortex in inviscid fluids as a connected fluid region with a high concentration of vorticity compared with its surroundings. Intuitively, a vortex is a concentrated fluid region that rotates about its center axis due to the effect of velocity gradients. The evolution of a vorticity field is governed by vorticity dynamics (Tsinober, 2001). Further, vortex dynamics govern the spatially coherent and temporally evolving vortical motions, often called coherent structures (Hussain, 1986).

The aforementioned fundamentals will guide through the understanding of the nature of the low-to-moderate Reynolds number flow regime where most birds and small flying vehicles fly. In low-to-moderate Reynolds number cases (Re on the order of 10^4 – 10^5), the flow over the immersed body is inherently viscous, and viscosity plays a crucial role. This flow regime is dominated by complex viscous flow phenomena such as flow separation, reverse flow, laminar-to-turbulence transition, bubble formation, and flow reattachment all occurring close to the body surface. These low Re flow phenomena have gained more attention in the past two-to-three decades and have been understood well qualitatively (Lissaman, 1983, Anderson, 1991, Shyy et al., 2008). For the case of an airfoil, a laminar boundary layer formed at the airfoil surface experiences an adverse
pressure gradient towards the trailing edge which causes the boundary layer to separate from the solid surface (see, Figure 2.3). The separated flow region is occupied by recirculation and reverse flow vortices. When the Reynolds number is large enough to cause the shear layer between the separated boundary layer and the recirculation zone to transit to turbulence, a laminar-separation bubble is formed, and reattachment occurs further downstream for possible cases. Eventually, the boundary layer grows and the flow becomes inherently unsteady and vortex shedding occurs. This flow separation and bubble formation have detrimental effects on the aerodynamic performance of the airfoils. These separation phenomena can lead to a deep stall (drastic loss in the lift) and an increase in pressure drag due to flow separation. Depending on the size of the separation bubble, it can be classified as either short (which covers a short portion of the airfoil) or long (which covers the major portion of the wing). The large separation bubble has a significant effect on the velocity and pressure field distribution around the airfoil and also changes the effective shape of the airfoil (Shyy et al., 2008).

Figure 2.3: Laminar boundary layer separation and bubble formation phenomena at low Reynolds number flow regime (Mueller and DeLaurier, 2003)
2.1.1 Birds’ aerodynamics

Most birds fly in the same low-to-moderate $Re$ number regime where small flying machines operate. As discussed above due to the complex nature of the flow regime, fixed-wing flying vehicles suffer to sustain lift and experience detrimental effects on flight performance. Yet, birds exhibit high aerodynamic performance in the same flow regime, though similar flow phenomena are likely to occur: in Figure 2.4, a snapshot of a barn owl in flight is shown. The fluttering feathers represent the unsteady nature of the flow regime due to the flow separation and bubble formation.

![Figure 2.4: Snapshot of a wing of a barn owl in flight: fluttering feathers represent the flow separation and bubble formation (Bachmann and Winzen, 2014)](image)

Even against large manmade aircraft, birds display high aerodynamic performance. For example, in terms of the body lengths traveled per second, a supersonic aircraft SR-71 travels at ~3 Mach number covers ~32 body lengths per second whereas a European starling can cover ~120 body lengths per second and a pigeon often covers ~75 body lengths per second (Shyy et al., 2008). Unlike fixed-wing flyers, birds utilize flapping wings during most of their flight. Besides, they have flexible wings to adapt to the flow environment and display complex wing kinematics: birds can adjust their wing planform, change their wingspan, wingtip amplitude, wingbeat frequency,
and angle of incidence during flight based on the flight requirements. The combination of these configurations enables birds to complete a variety of maneuvers and cover several flight modes.

Flapping flight is an efficient way of locomotion found in nature. The momentum of the air in the vicinity of the birds is altered by the flapping wings during the flight in the way to produce aerodynamic forces to balance the weight (lift) and overcome the drag (thrust) to keep the bird aloft. Flapping flight consists of two phases conventionally; downstroke and upstroke, where downstroke produces the majority of the aerodynamic forces, and the wing recovers during the upstroke phase. The aerodynamics of the flapping bird flight is strongly influenced by the complex three-dimensional wing kinematics and intrinsically the aerodynamic forces associated with flapping wings are unsteady (time-dependent). Unsteady aerodynamic mechanisms play a major role in the aerodynamic forces generated by the flapping wings. The circulation around the wing is not constant throughout a wingbeat cycle (Gurka et al., 2017), and both the lift and drag forces exhibit large variations over a wingbeat where the role of the unsteady components cannot be neglected (Ben-Gida et al., 2013; Stalnov et al., 2015).

2.2 Power and energetics during the flight of birds

Flapping is known as powered flight in contrast to unpowered modes such as gliding and soaring. Powered flight is energetically demanding and requires excessive physiological performance from flying birds. The flight muscles of the birds do the work to oscillate the wings to produce the lift to balance the weight, and the thrust to overcome the aerodynamic drag: the large pectoralis muscles depress the wings during the downstroke and the smaller supracoracoideus muscles elevate the wing during the upstroke (Biewener, 2011). The aerodynamic power requirement or the metabolic cost of the birds heavily depends on the mode of their flight, flight speed, wing morphology, wingbeat kinematics, and the nature of the flying condition. Natural selective pressures have a huge influence on the changes of the physiological structures and the locomotion abilities of the flying birds (Warrick et al., 2012). Hence, understanding the energetics of the flying birds can help to understand the aerodynamic performance of the birds and to associate it with the wing morphology and the evolution of the birds’ flight, which has been an interest for ecologists and biologists for a long time.
Birds need to sustain their weight and propel themselves through the air using their own power to complete a successful activity. In a steady level flight (unaccelerated), the power required to fly forward is consumed by three components: profile power – the power required to overcome the drag of the wings, parasite power – the power required to overcome the drag of the body, and induced power – the power required to balance the weight/lift. Additionally, during an accelerating flight or climbing flight (take-off), the components of changes in kinetic and potential energies over time (which represent the power required to accelerate or climb) should also be accounted for in the total aerodynamic power. The profile, parasite, and the induced power outputs represent the rate at which work is done on the surrounding air by the bird. To complete a successful flight activity, the bird should have enough available power to meet the total power requirement including any losses. Further, birds also adapt intermittent flight patterns (a combination of powered and unpowered flight phases) such as bounding and undulating flights which result in moderate to significant energy savings during flight. By converting the available potential and kinetic energies for aerodynamic work and flapping intermittently, the birds can achieve a lower mean power output and a wide range of airspeeds (Ward-Smith, 1984; Rayner, 1985; Rayner et al., 2001).

The energetics of the birds’ flight is not understood well yet. Tucker (1968) measured the oxygen consumption and carbon dioxide production of budgerigars (Melopsittacus undulatus) flying freely in a wind tunnel and estimated the energy requirements of the flight during different modes, i.e., ascending, descending, and level flight, at various flight speeds. It was shown that the energy consumption of the bird during the ascending flight was significantly higher than the level flight. In general, take-off (ascending), hovering and low-speed flights are energetically expensive for the birds compared to the sustained level flight at a moderate speed (Warrick et al., 2012). The lift-to-power ratio plays a significant role in determining the flight ability of the birds. Commonly, large birds are limited in carrying of range of payloads compared to small birds as their available energy is majorly dedicated to balance their heavy weight (Pennycuick, 2008). The maximum mechanical power output available from the flight muscles defines the maximum load-lifting capabilities of flying birds (Wang et al., 2019).
Bird flight studies have majorly focused to establish the relationship between the power output of the bird to the forward flight speed (power curve) which is essential to understand their flight capabilities and to determine their performance limits. Though it has not been established widely for many bird species, some information is available in the literature for few species on the energy requirements of flight. A generally ‘U-shaped’ power curve has been associated with the power requirements of the flying birds at different flight speeds, although it is yet controversial (Tobalske et al., 2003). An example of this is illustrated in Figure 2.5: it is shown that while the cockatiel displays a deeply concave U-shaped power curve, the magpie’s power curve is almost flat over a range of speeds. The trend of the dove is intermediate, and the dove exhibits relatively higher mass-specific power output at most speeds compared to the other two. In general, the aerodynamic power output is maximal during the lowest speed and reduces until minimum power speed as flight speed increases, and then increases further to a maximum at the highest speed range.
2.3 Wake flow of wings

A wake is a region behind any immersed solid body where free shear flow governs the phenomena, and a wake flow can be described as a disturbed flow (the signature of the body) behind any solid body moving through the fluid: every solid body (i.e.: airfoils, wings) experiences resistance to the fluid motion and the flow field is perturbed due to the presence of the body. The wake carries the signature of this perturbation and can contain recirculating flows and organized or non-organized vortices (shedding phenomena). Wakes can be dominated by eddies and vortices when vortices shed and trail far downstream behind the body.

The wake of the flying bird is more complex and consists of ordered vortex structures that possess high-level momentum and kinetic energy. The momentum of the air in the wake flow reflects the aerodynamic forces required to support and propel the bird (Pennycuick, 1988). Experimental studies on birds show that vortex patterns are generated at each wingbeat throughout at both upstroke and downstroke (Spedding et al., 2003; Rosén et al., 2007; Hedenström et al., 2006a; Hedenström et al., 2006b; Hennigsson et al., 2008; Kirchhefer et al., 2013; Gurka et al., 2017). The circulation around the wing and the changes in wing speed control the vortex shedding, strength, and vortex structures. The downstream wake and vortices contain the history of the aerodynamic forces acting on the wing. As a result, the aerodynamic characteristics of birds can be evaluated by investigating the downstream wake flow field (Hedenström and Spedding, 2008).

2.3.1 Mean flow characteristics

When the flow leaves the trailing edge of the wing, the formation of the wake region stems from the instability of two shear layers moving across the airfoils and interacting beyond it. The wake flow is known as free shear flow as fluid is not subjected to any solid boundary. The velocity field in the near wake region is governed by a streamwise velocity deficit that is formed from the merger of the two-shear layers (Goett, 1939; Hu et al., 2011; Dufresne and Wosnik, 2013). The velocity deficit indicates a high level of shear in the wake region, as well as vorticity (Hu et al., 2011). The dynamics of the vorticity in the downstream wake flow induces the flow field farther.

The root and tip vortices roll up and merge in the wake (Johansson and Hedenström, 2009), and their interaction with the high mean shear of the wake flow results in complex wing-wake
interaction. Though the interaction of streamwise vortices and the wake flow is three-dimensional in nature, the vorticity calculated from the two-dimensional measurement can also carry the projection of such interaction (Kirchhefer et al. 2013). The mean velocity field is commonly utilized to calculate the mean aerodynamic forces associated with the flapping wings (Koochesfahani et al., 1989). Bohl and Koochesfahani (2009) analyzed the vortical field in the wake of an oscillating airfoil. Their study demonstrated that large spatial gradients in the mean vorticity occur near the trailing edge for high reduced frequencies. Ashraf et al., (2015) studied the wake structure behind the pitching airfoil in low Reynolds numbers. Their study showed that the gradient of the streamwise velocity in the wake has a significant influence on the convection of wake vortices downstream.

2.3.2 Wake turbulence behind wings at intermediate Reynolds number

When the Reynolds number is sufficiently high enough, the flow associated with the flapping wing becomes turbulent (Shyy et al., 2008; Chin and Lentink, 2016). In addition to the interaction between the flapping wing and the turbulent wake, several other factors can probably have a direct influence on configuring the turbulent flow dynamics in the near wake, viz., boundary layer separation (Shyy et al., 2008), laminar separation bubbles (Mueller and DeLaurier, 2003), leading and trailing edge vortices (Usherwood and Ellington, 2002), and vortices-wake turbulence interactions (Hubel et al., 2009; Song et al., 2014).

The laminar-to-turbulent transition over the wing surface plays a crucial role in defining the turbulent wake flow formation downstream of the wings at intermediate Reynolds numbers (Yarusevych et al., 2009). As has been discussed earlier, the flow over the airfoil/wing is prone to separate at the low Re regime. The starting perturbation in the separated shear layer grows exponentially leading to the transition to turbulence (Watmuff, 1999). At the end of the transition, nonlinear interactions between the perturbations arise, and the flow rapidly transits to turbulence if the Re number is sufficiently high.
Figure 2.6: Smoke-wire visualization of wake vortex shedding behind a NACA0025 airfoil at 5° AOA. a) $Re = 55 \times 10^3$, and b) $Re = 150 \times 10^3$ (Yarusevych et al., 2009)
The inherently unstable separated shear layer on the wing surface either reattaches to form a separation bubble or failing to reattach forms a wide wake. In either case, turbulent wake vortex shedding occurs behind the trailing edge of the wing (Yarusevych et al., 2009). Smoke-wire visualization of turbulent wake behind a NACA0025 studied by (Yarusevych et al., 2009) is shown in Figure 2.6 for two Re cases. In Figure 2.6a, at the low Re = 55x10^3 case, the flow separates early at the quarter of the chord length and a wide turbulent wake is formed. For the moderate Re = 150x10^3 case (see, Figure 2.6b), the separated flow appears reattached until the trailing edge. The authors reported that the surface pressure measurements revealed the formation of a separation bubble on the upper surface of the airfoil for Re = 150x10^3 and 5° AOA. The two turbulent wakes appear distinct from each other: the low Re case displays large scale vortices from the separation of the wing and the moderate Re case display comparatively smaller wake with less organized structures. This study attributes the turbulent wake vortex shedding to the near wake instability. Though the wake vortices in the near wake region are shed from both the upper and lower surface turbulent wake, the coherence and length scale of the wake vortices decreases significantly when the separation bubble forms on the upper surface.

2.4 Raptors: owls and hawks

Owls are birds of prey (raptor) and are found almost throughout the world, except Antarctica. Owls belong to the order Strigiformes which covers over 200 species. They are divided into two families: the barn-owls, Tytonidae, and the typical-owls, Strigidae. Tytonidae includes approximately 16 species whilst the Strigidae is the largest family with close to 190 species. The families differ from each other through a number of minor osteological features. For example, the characteristic facial disk is heart-shaped for tytonid owls and circular for strigid owls. Tytonid owls have relatively smaller eyes than strigid owls.

Most owl species are solitary and nocturnal hunters, except a few which are primarily active during the day. Owls hunt a variety of prey that includes small mammals, lizards, insects, and other birds. There are few owl species that hunt fish. As most species are active hunters at night, they have certain evolutionary advantages for this lifestyle (Cholewiak, 2003). Their large forward-facing eyes help them with an improved vision to see even in low light. They have an excellent sense of
hearing covering a wide range of frequencies, and some species use their hearing skills to hunt prey that cannot be seen. Their short, hooked, downward-facing bills help to provide a clear field of vision and the coloration of their feathers helps them to blend into the environment to mimic their surroundings. In addition to these, owls’ hunting strategy hugely depends on silent flight. Most of the owl species, especially nocturnal species, fly nearly silently and they have certain feather adaptations that are assumed to help them to achieve silent flight. Diurnal species or the owls which hunt over water lack these feather adaptations, where silent flight may not be of great importance (Cholewiak, 2003).

Hawks are similar birds of prey to owls, but generally diurnal raptors. They belong to the order Accipitriformes and the family Accipitridae which also covers other raptors such as eagles, kites, and harriers. The subfamily of hawks includes Accipitrinae and Buteo which are categorized based on their distribution in different regions. The sizes of the hawks vary from medium to large, and they typically have large and broad wings, long legs, and equally long tails. Like owls, hawks hunt a range of prey including small mammals, birds, lizards, and large insects. They have the capacity to hunt both large prey such as jackrabbits and small birds. As a diurnal raptor, the hunting strategy of the hawks generally depends on their fast flight to pounce and attack the prey.

In this current research, two specific species, a great horned owl and a Harris’s hawk are studied. The great horned owl belongs to the genus Bubo in the Strigidae family and the Harris’s hawk belongs to the genus Parabuteo in the buteo subfamily. Harris's Hawk is similarly sized to the great horned owl, and both birds have typically large wingspans. The general color pattern of great horned owl is camouflage, and the general color pattern of the Harris’s hawk is dark brown overall and reddish on the feathers of wings and thighs (Dwyer and Bednarz, 2011). Whilst great horned owls are known as mostly solitary hunters, Harris’s hawks usually hunt as a group of two to six birds cooperatively. The group hunting of Harris’s hawk tends to be more successful than the solitary hunting of a single hawk. While great horned owls use surprise attack and stealth as their hunting strategy, Harris's Hawks usually hunt low over the ground, with one leading bird scouting out potential prey. They are usually fast and vigorous. They chase their prey to exhaustion and if the prey hides, one hawk flushes out and the rest wait to pounce (abcbirds, 2019).
2.4.1 Owl wing’s morphology

One of the major characteristics that distinguish owls from the hawks and the other raptors, is their unique wing and feather features. Understanding the description of these wing features is necessitated to understand their role in the aerodynamics of owl flight. Graham (1934) was the first to provide a detailed report on the special feather adaptations of owls that are assumed to act as silencing devices. He compared the wings and feathers of the nocturnal owls to another fish-eating owl species called tawny fish-owl (*Ketupa flavipes*), which is found in tropical Asia. Based on the comparisons, Graham listed three special features that are common to nocturnal owls or silent owls and missing in the tawny fish-owl. These special features include leading-edge serrations, trailing-edge fringes, and the velvety upper surface of the feather. Graham reasoned that these features are indeed silencing devices of the wings, as the silent flight is common in nocturnal owls but not in the diurnal or fish-eating owls: he suggested that silent flight is not of great importance for tawny fish-owl as its prey being submerged in water are unable to hear them approaching, thus it has not evolved with these features, or lost them over time due to relaxed natural selection.

A brief introduction of owl wing and feather morphology is required to understand the unique owl wing’s features. An owl wing is formed by the attachment of the feathers to the wing skeleton (see, Figure 2.7). Wing feathers are divided into two major categories, remiges (flight feathers) and coverts. Further, two major group of remiges exists; primary remiges, or primary flight feathers, which are the outer flight feathers attached to the bone of the hand, and secondary remiges, or secondary flight feathers, which are the inner flight feathers attached to the ulna (Bachmann and Winzen, 2014; Wagner et al., 2017). The shape of the wing planform comes from the shape of the remiges, and the shape of the airfoil results from the combination of skeletal elements, feathers, muscle, and skin arrangement (Bachmann and Winzen, 2014). The anatomy of a typical feather is shown in Figure 2.8. A typical feather consists of a central shaft (the rachis) and vanes. The vane is laterally attached to each side of the rachis, and the rachis divides the vane into the inner vane and outer vane. The outer vane usually has less surface area than the inner vane. The rachis of the feather also can be divided into two parts; the distal part, which is toward the direction of the top of the rachis, and the proximal part which is toward the direction of the root of the rachis. Vanes are made up of parallel branches known as barbs. In addition, barbs consist of a central shaft and
a series of laterally extended branchlets known as radiates (or barbules). These radiates extend in different directions; those extended in the distal direction are called hook radiates, and in the proximal direction are called bow radiates. Hook radiates have tiny hooklets which hook to the bow radiates of the adjacent barb to form the vane surface. Further, both hook and bow radiates terminate in a filament-like structure called the pennulum. In most owl species, these pennula are extremely elongated and form one of owls’ special wing features (Bachmann and Winzen, 2014).

The primary unique owl wing and feather feature is the leading-edge serrations. Leading-edge serrations are the closely placed comb-like serrated structures resulted from the separated barb tips of the outer vane (see, Figure 2.9). These serrations are typically found in the 10th primary flight feather. But they are sometimes found in the primary feathers 7, 8, and 9 (Weger and Wagner, 2016), and the alula as well. Serrations are found only on the feathers which makeup the leading edge and, which are subjected to direct airflow.

The second predominant owl wing and feather feature is the trailing edge fringes (see, Figure 2.10). Fringes are found at the inner vanes of all the remiges (Bachmann et al., 2007, 2012; Winzen et al., 2015). Fringes are formed by separated barb endings; normally the hooklets of the hook radiates are lost at the end of the barbs leaving the barb endings separated. The length of the fringed region usually decreases from the base toward the tip of the feather. Typical fringe length varies between 1 mm and 4.5 mm (Wagner et al., 2017). During flight, it appears that fringes occur at the trailing edge of the extended wing and at the trailing edge of each feather (Bachmann and Winzen, 2014).
Figure 2.7: Anatomy of a barn owl’s wing (Bachmann and Winzen, 2014)

Figure 2.8: Anatomy of a barn owl’s feather (Bachmann and Winzen, 2014)
Owls have a soft velvet-like coated upper surface which contributes to their third unique wing and feather feature. Though Graham (1934) originally termed it as a downy upper surface, it is now commonly referred to as velvety upper surface or velvet-like surface. Figure 2.11 shows the velvety surface texture of a 10th primary feather of a barn owl at different magnifications. This velvety surface is caused by the elongated pennula of the barbs: usually in other bird species the elongated pennula of the hook radiates ends before the start of the adjacent barb base (see, Figure 2.9 and Figure 2.10).
2.11d, pennula of a pigeon feather), but, in the case of most owl species the pennula are extremely elongated forming the velvety surface. This pennula can be up to 2mm long. Though it is found in both inner and outer vanes of each feather, their development is different at different locations along the wing planform. The pennula of the outer vane is usually shorter than the inner vane, and besides the part of the feather which is subjected to the airflow during flight has a shorter pennula length than the part which is covered by the adjacent feathers. Due to the effect of this, the owl wing surface becomes fluffy and porous (Wagner et al., 2017).

The aforementioned wing and feather adaptations are unique features of nocturnal owl species. Much research has been carried out over multiple decades focusing either on separate features or combinations of any together in different configurations to study their association in the owl flight. A review of the available studies of the energetics, aerodynamics, and turbulent flow interaction characteristics of the owls and hawk is provided in the following section.
2.4.2 Power requirement of owl and hawk during flight

Neither the power curve of an owl flight nor the total aerodynamic power output of an owl at level flight flying at their typical flight speeds is found in the literature. The power requirement for climbing flight of the Harris’s hawk was conducted by Pennycuick et al., (1989). The authors conducted multiple flights of trained Harris’s hawk in a wind tunnel with added payload which was increased gradually to estimate the hawk’s load lifting capability and the maximum power available in the flight muscle. The estimated maximum power output of the hawk was ranging from 41 to 46 W, which corresponds to an average of 337 W/Kg pectoralis mass-specific power output. From a power curve estimation, the same study reported that the total aerodynamic power output of the Harris’s hawk in level flight was 13.1 W with an all-up mass of 1 Kg and flying at its minimum power speed of 10 m/s, which corresponds to the pectoralis mass-specific power output of 101 W/Kg. Marden (1990) conducted a similar estimate of the maximum load-lifting power output of Harris’s hawk and yielded 39.7 W which was comparable to Pennycuick et al., (1989). Askew et al., (2001) used the information from Pennycuick et al., (1989) and estimated the total aerodynamic power output of the Harris’s hawk during take-off flight and obtained a pectoralis mass-specific power output of 320 W/Kg.

2.4.3 Aerodynamics of owl and hawk flight

Mascha (1904) studied the morphology of bird feathers and first reported that owls have some special feather adaptations such as leading-edge serrations and elongated pennula. Then, Graham in 1934 provided the first detailed description of the three special owl feather features. Though owls are studied for multiple decades since then, the major focus of available literature has been on either owl wing morphology (Bachmann et al., 2007; 2012; Bachmann and Wagner, 2011) or gliding flight acoustic measurements (Thorpe and Griffin, 1962; Neuhaus et al., 1973; Geyer et al., 2009; 2012; Sarradj et al., 2011; Chen et al., 2012). Studies on the aerodynamics and the flow characteristics around the wing are limited.

Owls have a wing geometry that is characterized/suitable for the low Reynolds number flows: nearly elliptical planform, highly cambered airfoils, low aspect ratio, and maximum thickness close to the leading-edge (Liu et al., 2006; Bachmann et al., 2007; Winzen et al., 2015). Bachmann
et al., (2011) used advanced three-dimensional imaging techniques to investigate the barn owl wing and feathers in high spatial resolutions. This study showed that each owl wing has highly cambered airfoil sections which would generate high lift coefficients during flight. Bachmann et al., (2007) compared the features of wing feathers between the barn owl (Tyto alba) and pigeon (Columba livia) at the microscopic and macroscopic levels. This study showed that owl feathers were generally larger than the pigeon feathers, indicating low wing loading of the owl flight. Owl feathers had longer pennula, lesser radiates, and were more porous than the feathers of the pigeon. Owls’ reduced wing loading allows them to glide steadily at relatively lower flight speeds (Bachmann et al., 2007).

Owls appear to have poor lift-to-drag ratios. Kroger et al., (1972) conducted wind tunnel experiments with owl wings for varying AOA. They found that at the Reynolds number on the order of $10^5$, the lift-to-drag ratio of the owl wing was 2.25. March et al., (2005) studied a great horned owl wing in a wind tunnel as a fixed airfoil/wing for a range of AOA and at various free stream speeds. It was observed that the owl wing showed no sign of stalling at this range. The profile drag coefficient estimates of this study ranged from 0.08 to 0.2 at the range of AOA from -5 to 19 degrees. Winzen et al., (2014a) conducted experiments on owl-inspired wings with owl-like velvet surfaces. The experiments were conducted for $Re = 60,000$ and 120,000 cases. The measured profile drag coefficient of the owl-like wing ranged from 0.06 to 0.28 for a range of AOA from 0 to 20 degrees. The lift coefficient ranged from 0.1 to 0.8 for the same flow parameters. It was observed that the owl-like surface increased the drag and slightly reduced the lift at both the $Re$ case.

Wind tunnel experiments with prepared wings of a barn owl with and without leading-edge serrations in a gliding flight were carried out by Geyer et al., (2017). This experiment focused on revealing how owls’ adaptation of leading-edge serrations affects aerodynamic performance during the gliding flight phase. Experiments were conducted for different flow velocities at a range of AOA. It was found that the leading-edge serrations caused a small increase in the lift in gliding flights at high AOA. Rao et al., (2017) prepared owl-inspired single feather wing models with and without leading-edge serrations and conducted a combined study of numerical simulations, particle image velocimetry, and force measurements in a low-speed wind tunnel. According to their results, leading-edge serrations reduced the aerodynamic performance below 15° AOA compared to the
non-leading-edge serration wings, whilst achieving significant augmentation in lift production at higher than 15° AOA. The experimental estimates of the owl-inspired wing model in this study showed a maximum lift coefficient of 0.6 around a 10-degree AOA, and the profile drag coefficients ranged from 0.05 to 0.25 for AOA from 0 to 20 degrees. Nafi et al., (2020) conducted particle image velocimetry-based wake measurements behind a freely flying boobook owl (Ninox boobook) in a wind tunnel to study the aerodynamics of the owl during flapping. This study showed that the owl exhibited considerably higher time variation of lift and highest total drag over a single wingbeat cycle in comparison with the other two bird species studied, confirming that the aerodynamic performances of owls are characterized by a low lift to drag ratio. The estimated average sectional drag coefficient over a single wingbeat in this study was 0.12.

Regarding the hawk aerodynamics, only limited resources are available in the literature and no flow field characteristics around Hawks during flight have been established. Similar to owls, hawks are also characterized by highly cambered airfoils and low aspect ratio wings (Tucker and Heine, 1990; Pennycuick et al., 1992; Bansmer et al., 2012). Tucker and Heine (1990) studied the gliding flight of Harris’s hawk in a wind tunnel at a speed range of 6 to 16 m/s. According to their study, Harris’s hawk showed low drag characteristics with their estimates of the profile drag coefficients ranging from 0.003 to 0.097. The measured lift coefficients in this study ranged from 0.4 to a maximum lift coefficient of 1.6 with the maximum lift-to-drag ratio of 10.9 which was comparable to a similar fast flier large falcon. They also stated that no sign of stalling was observed at any speeds and the hawk ‘actively’ adjusted its wingspan during flight depending on the speed and aerodynamic force requirements. Pennycuick et al., (1992) studied the gliding flight of Harris’s hawk in a wind tunnel and measured the profile drag using the wake sampling. The values of measured profile drag coefficients in this study ranged from 0.008 to 0.052. Pennycuick reported an average profile drag coefficient of 0.02 from 92 estimates. This study also revealed that the hawk was able to ‘actively’ change its wing shape to either increase or reduce profile drag during flight.
2.4.4 Owl-turbulent flow interactions

The turbulent flow characteristics around the hawk wings are not known or established widely. The study conducted by Pennycucik et al., (1992) reported that the flow over the hawk wings was either mostly fully turbulent or partly separated at most flights. Regarding the owls, the available works of literature suggest that the interaction between the flow and the unique owl wing morphologies leads to ‘passive’ flow control mechanisms that either helps in the aerodynamic force enhancement at higher angles of attack or enable the owls to fly silently.

According to Graham (1934), the potential aerodynamic function of the leading-edge serration is to gradually slow down the velocity of the air by letting it pass through a few distances before meeting the leading edge. Thus, it reduces the suddenness of the pressure drop in the boundary layer and lets the fluid flow more closely over the upper surface of the wing than the normal feathers. Regarding the trailing-edge fringes: Graham suggested that the presence of the trailing-edge fringes lets the airstream from the lower part to pass through the fringes for a short space before breaking into the upper part which delays the mixing and smooths the combined stream over the wing. Further, he postulated that the role of the velvety upper surface is to muffle the small fluctuations in the upper side of the wing or continuing the retardation of the boundary layer initiated by the leading-edge serration.

The first flow visualization experiments with and without serrations/fringes were conducted by Gruschka et al., (1971) and Kroeger et al., (1972) to study their role in the flow control mechanisms during flight. Major conclusions made from their findings include: 1) the leading-edge serrations act as vortex sheet generators that work in combination with the leading-edge slot and tip feathers to promote attached laminar flow over the entire outer half of the wingspan (flow separation was observed immediately after the leading edge when serrations were removed). 2) the velvety upper surface allows a uniform film of air to pass between the feathers so that an evenly distributed porosity could be produced. Thus, such flow between the feathers could produce a chordwise thickening of the boundary layer. Anderson (1973) revisited the data from Kroeger et al., (1972) and in addition, physically examined the comb-like leading-edge serrations found on the wing of the great horned owl using microphotography. The microphotographs revealed that the comb-like serrations resembled a row of spanwise twisted airfoils oriented to form a cascade. Thus, inspired by the great horned owl, Anderson built several conventional airfoils with different configurations.
of leading-edge serrations and conducted flow visualization (smoke) experiments in a wind tunnel. The results showed that the comb-like leading-edge serrations act as a cascade that turns the flow into the spanwise direction, hence producing a stationary spanwise vortex that delays flow separation at high AOA. They also related this function to the vortex lift phenomenon (known as leading-edge vortex (LEV)) observed on delta-wing aircraft.

Based on the work of Graham (1934) and the results of Kroeger et al., (1972), Lilley (1998) suggested that leading-edge serrations act as equally spaced co-rotating vortex generators, which prevent the laminar separation by stabilizing the boundary layer on the wing upper surface and keeping the flow attached up to the trailing edge. Lilly further hypothesized that owl wing features might dampen the turbulence developed over the wings and diminish the scattering of turbulence behind the trailing edge compared to wings without the morphological characteristics of owls. Regarding the velvety upper surface, Lilley speculated that velvety feather acts as a compliant surface and damps the turbulence inside the turbulent boundary layer, such that the small velvet-like fibers absorb the energy of the small eddies in the turbulence. Klański et al., (2010) studied reconstructed owl wing models with and without leading-edge serrations. The effect of the leading-edge serrations on the flow field of the reconstructed wing model was investigated using particle image velocimetry and showed that the effect was strongly dependent on multiple factors such as the AOA, Reynolds number of the flow, and the spanwise position of the serrations. It is generally accepted that the role of leading-edge serration is to delay the flow separation and promote the flow to be a pseudo-laminar flow attached over most part of the wing.

Klański et al., (2009) conducted 2D PIV experiments on two types of wings; an owl-based wing with an owl-like velvety surface and a similar wing without the owl-like feature (‘clean’). The experiments were conducted for three different AOA and three different chord-based Reynolds numbers. Compared to the clean wings, the owl-like wing is shown to reduce the flow separation and to promote upstream flow reattachment. It was observed for all cases that the velvety-like surface reduced the size of the vortices and the distance between them compared to the clean wing. Besides, an increase in the Reynolds shear stress was reported over the owl-like wing. It was also noted that the stress increase was identified upstream to promote the flow transition and reattachment earlier.
Winzen et al., (2013, 2014a) conducted particle image velocimetry-based experiments on several natural owl-inspired wings: with artificial velvet-like surfaces replicating the length, density, and softness of the natural owl wing pennula. These studies also included a comparison with the clean wing (without the velvet-like surfaces). The major observation of the clean wing was the occurrence of the laminar-to-turbulent transition separation bubble on the upper side. The size of this separation bubble depended on the Reynold number and the AOA. It was noticed that in the case of velvet-like surfaces the flow separation was reduced, and the boundary layer on the suction side was energized. The authors concluded that the owl's velvet surface redistributes the turbulent kinetic energy of the wall-bounded shear layer at moderate AOA and as Reynolds number increases. As a result, the size of this separation bubble was reduced or eliminated, and the points of separation and reattachment moved further upstream.

Winzen et al., (2015) conducted time-resolved PIV experiments on a prepared natural owl wing for a range of chord-based Reynolds numbers between 40,000 to 120,000 and in a range of AOA from 0° to 6°. It was found that at these AOA no flow separation was observed on the upper side of the wing, instead of flow separation with large-scale vortices was observed on the lower side. The size of the vortices is shown to increase with increasing Reynolds number and to reduce with increasing AOA. Besides, it was observed that these vortices cause structural deformation and propagate in a streamwise direction in a slightly elliptical shape normal to the streamwise direction. The amplitude of the trailing edge deflection was either reduced or eliminated significantly at a higher AOA suggesting that the owl wing might have the ability to ‘passively’ adjust its camber to the surrounding flow field during flight. These results were attributed to the flexibility of the owl wing structure and the intricate fluid-structure mechanisms associated with it. Kondo et al., (2014) conducted two-dimensional laminar flow simulations over an owl-like airfoil under a range of AOA from -3° to 9° at chord-based Reynolds number 23,000. They observed flow separation and bubble formation on the lower side of the wing at a low AOA similar to Winzen et al., (2015). Wind tunnel experiments with similar owl-like airfoil were conducted by Anyoji et al., (2018) for a range of Reynolds numbers from 23,000 to 60,000 over a range of AOA from -10° to 20°. This study also reported flow separation on the lower side of the owl-like airfoil. All the studies observed that the presence of the flow separation and bubble formation improved on the lower side and moved to the upper side as the AOA increases. Bodling et al., (2017) conducted large-eddy simulations on a NACA 0012 baseline airfoil and an additional airfoil fitted with finlet fences.
inspired by owl velvety surface. The simulations were conducted at a zero-degree AOA at chord-based Reynolds number $5 \times 10^5$. This study showed that bio-inspired fences reduced the turbulent kinetic energy near the airfoil surface (trailing edge) and redistributed it above from the fences. A study conducted by Chen et al., (2012) concluded that trailing-edge fringes and leading-edge serrations work together to dampen the pressure fluctuation of the turbulent boundary layer.

The aforementioned studies mostly have conducted fixed-wing experiments with either natural owl wings or owl-like wings that replicate a gliding flight. The owl-flow interaction characteristics during the flapping flight have not been investigated yet. Doster et al., (2014) conducted stereo PIV measurements of both gliding and flapping flight of barn owl. It was shown that a comparatively different and complex vortex system developed in the wake of the flapping flight compared to the gliding. Recently, Lawley et al., (2019) conducted particle image velocimetry experiments to compare the downstream wake flow characteristics of a freely flying boobook owl to two other bird species that are measured under similar conditions: a passerine songbird: European starling ($Sturnus vulgaris$), and a non-passerine shorebird: western sandpiper ($Calidris mauri$). They showed that the near wake region of a boobook owl was disorganized and characterized by small turbulent scales and reduced dynamic pressure field.

### 2.5 Principles of PIV and its application to bird flight studies

The invention of the experimental techniques that facilitated us to measure the instantaneous flow field characteristics is considered one of the major advancements in experimental fluid dynamics. PIV is one of the most effective flow measurement techniques that allow us to extract the instant flow velocity vector components through correlating the flow field images illuminated in a specified time gap (Raffel et al., 2007). The major advantage of the PIV is that it is non-intrusive, and it enables us to retrieve the velocity flow field without causing any disturbance to the flow. The standard PIV technique measures two-component velocity vectors in a two-dimensional plane. In time-resolved PIV, high-resolution PIV images are acquired at high frame rates using high-speed cameras and a fast laser. The PIV technique is based on capturing images of illuminated flow fields using tracer (seeding) particles and high energy light source, and later post-processing the images to get the instantaneous velocity vector fields. The experimental setup of a PIV system
is typically composed of multiple components as shown in Figure 2.12 which usually includes tracer particles, laser apparatus, and imaging equipment. In most cases, the tracer particles have to be added to the flow. These tracer particles scatter the light when illuminated with high-energy monochromatic light sources. The flow should be illuminated at least twice in a short time interval and the time interval between the pulses must be chosen with respect to the flow velocity and the magnification at the imaging system. The scattered light is then recorded using an imaging system either in a single frame or in a sequence of frames (Raffel et al., 2007). The major requirement of the PIV is to find ideal tracer particles that obey and follow the flow without disturbing, and not interacting with each other. The ideal tracer particle ensures that the velocity of the tracer particle is equal to the local fluid velocity between the two illuminations. The concentration of the tracing particles determines the appearance of the image. In a low concentration density, the average distance between the particle diameters is higher, and in a high concentration density, the tracer particles overlap on each other. These low and high seeding densities have an undesirable influence on the images. So, coherent distribution of the tracer particle becomes a requirement for a clear illumination of the image. The accuracy of the velocity field determination is ultimately limited by the ability of the tracer particles to follow the instantaneous motion of the continuous phase. A compromise between reducing the particle size to improve flow tracking and increasing the particle size to improve light scattering is, therefore, necessary (Melling, 1997).

To illuminate the flow field, high-energy light sources are needed for producing a uniform and pronounced light scattering. The high-energy laser beam is widely used in PIV for illuminating the flow. The laser beam passes through a series of optical arrangements to create a thin light sheet by taking a cross-section at the flow. The size of this light sheet controls the depth of the flow field. The tracer particles in the laser sheet scatter the light which is captured using a high-quality camera lens that is placed perpendicular to the laser light sheet. Nowadays, high frame rate digital cameras are normally used in PIV to capture the illuminated flow fields. To extract the velocity vectors from the PIV recordings, the PIV image area is further divided into small subareas called “interrogation windows”. Statistical methods such as auto and cross-correlations are used to determine the local displacement vector for the images of the tracer particles of the first and second illumination images. This evaluation is repeated for all the interrogation windows of a PIV image. The projection of the vector of the local flow velocity into the thin light sheet plane (two-
component velocity vector) is calculated taking into account the time interval between the two illuminations and the magnification at the imaging system.

![Diagram of PIV system](image)

**Figure 2.12:** Typical set-up of a two-dimensional and two-component PIV system (Raffel et al., 2007)

Conducting experiments with live birds is very challenging. Conducting experiments with dead wings or model wings cannot replicate the real flight as the complex bird kinematics makes realistic aerodynamic analysis of the birds more challenging. Quantitative analysis of the aerodynamics and flow characteristics of the bird flight remains perplexing yet. Development in high-speed imaging and particle image velocimetry (PIV) technique has led researchers to widely use PIV to investigate the wake and kinematics characteristics of a variety of flying birds. Technological advancements in experimental techniques have helped to both qualitatively and quantitatively analyze the wake gaits and vortex structures of different bird flights. Following Rayner’s (1979a, 1979b, and 1986) proposal of idealized theoretical wake models of flying birds, experimental investigations focused on analyzing the wake gaits. One of the earliest PIV investigations of bird wake topology was done by Spedding et al., (2003). A thrush nightingale was studied in a wind tunnel for a range of flight speeds. The wake analysis far downstream of the
bird showed that over a range of flight speeds the bird’s wake progressively changed from a discrete vortex gait to a continuous vortex ring gaits. The distinct vortex gaits were not generated abruptly at specific flight speeds.

Hedenström et al., (2006b) and Rosén et al., (2007) analyzed the far wake topology of robin (Erithacus rubecula) and house martin (Delichon urbicum), respectively, using PIV. The study showed that the wake of robin and house martin qualitatively matched with the wake of the thrush nightingale. The robin wakes studied by Hedenström et al., (2006b) looked similar to thrush nightingale wake (Spedding et al., 2003) and there was no significant difference observed between the wakes of two robins as well. However, even a small variation in-flight style seemed to have a pronounced effect on the generated downstream wake topology. Henningsson et al., (2008) studied the vortex wake of a swift (Apus apus) in cruising flight in a wind tunnel using high-speed PIV. It was proposed that although the wake resembled some extent with the other birds in cruising flight, the wake model belongs to a new empirical model. This study also observed that the vortices were continuously shed throughout the wingbeat and the upstroke was aerodynamically active. Similarly, Tobalske et al., (2010) studied the wake of the flap-bounding flight of zebra finch (Taeniopygia guttata) using PIV and showed that the wake was considerably different from the wake of the flapping bird flight.

Using long-duration, time-resolved PIV, Gurka et al., (2017) experimentally studied the near wake of freely flying forward flight of three distinct bird species: European starling, western sandpiper, and American robin. Their study showed that the near wake flows of these birds were dominated by complex vortex structures and distinct similarity exists in the near wake topology downstream irrespective of the bird species. Their results suggested that irrespective of bird species, the near-wake flow structures of the forward flying birds contain the signatures of unsteady aerodynamics that appear to be consistent. Though the wake topology resembled continuous vortex gait, during the transition phases distinct ‘double branch’ vortex patterns which consisted of quadruple regions of vortices were observed for all three species. It was suggested that the transition phases between consequent wing strokes (upstroke-to-downstroke or vice versa) contribute to the aerodynamic forces through unsteady motion.

Investigating the wake-flow properties downstream of the flapping wings using PIV has enabled researchers to analyze and understand the aerodynamics of flying birds. The qualitative analysis
of all the complex wake structures of different birds has shown a degree of similarity among the different configurations suggesting the existence of common wake patterns and associated aerodynamic mechanisms between the birds which are needed to be further explored comprehensively. However, high spatial and temporal resolution samples of wake velocity field data are necessitated to investigate the complex wake flow field which is intrinsically unsteady during flapping flight.

2.6 Summary

The low-to-moderate flow Regime where birds and small fixed-wing fliers typically fly is dominated by complex flow phenomena that have a detrimental effect on the flight performance of the fixed-wing fliers. Birds’ flapping wing aerodynamic mechanisms enable them to fly successfully in this regime. Estimating the power curve of a flapping flight can help to gain insight into the flight capabilities of the flying birds. The flapping wings generate aerodynamic forces by changing the momentum of the air in their vicinity. The near wake behind the downstream of the flapping wing is directly influenced by the separation flow phenomena, unsteady wing motion, and involves complex wing-wake interactions. The interaction of the unsteady moving wing with the downstream wake alters the wake-vortex flow dynamics further.

Analyzing the near wake flow characteristics of the flying birds paves the way to understand the aerodynamic mechanisms associated with the flapping flight. Although the aerodynamics of both the owl and the hawk has been studied over multiple decades, the resources on hawk aerodynamics or the flow characteristics around the wing are very limited. On the other hand, regarding the owls, the available studies have majorly focused on specific owl wing features during gliding flight. Even though the potential functions of these individual features are identified, no deterministic conclusion is achieved on the aerodynamic mechanisms of owl flight, especially during flapping. The degree of the effects of the specific wing feature also depends on AOA and the Re number and the optimum configuration is unknown. Moreover, the owls’ flight capabilities appear to be augmented with multiple parameters apart from the wing features, such as higher wing flexibility, and low-speed flight, and the high camber of the airfoil. It is recommended from the literature that the studies which collectively account for all the aspects of the flapping flight are demanded to
gain deeper insight into the aerodynamics of the owl flight. Besides, the power requirements of the owl flight also needed to be established to evaluate the range of their flight capability. Investigating the near wake characteristics of the flying birds can enable us to elucidate the aerodynamic characteristics of flapping flight which contains all the history of the flow affected by the flapping wing structure, and the advancements in the PIV techniques can be used to achieve the said goal.
Chapter 3

Experiments

The aerodynamics of the owl and the hawk were studied by analyzing the characteristics of the wake flow fields acquired using long-duration, time-resolved particle image velocimetry measurements in a wind tunnel. Simultaneously, the flights of the birds were also captured using multiple cameras to conduct kinematic analyses. Experiments were conducted with live birds in a large wind tunnel. To study the free flapping flight, the birds were trained to fly in a perch-to-perch flight style. This chapter reports the details of the experimental setup, the birds and their training, the PIV system, the kinematics acquisition, the series of experiments, and the error analysis.

3.1 Raptors

In July 2018 a great horned owl and a Harris’s hawk were brought from the African Lion Safari in Cambridge, ON, Canada to the Advanced Facility for Avian Research (AFAR) at the University of Western Ontario, London, ON, Canada under animal protocols from the University of Western Ontario Animal Care Committee (UWO #2018-092) and the African Lion Safari (BOP-15-CS). The tame, highly trained show animals were sheltered at AFAR for two weeks before the experiments, weighed every day (weight variation during the experiments was about 2%), and trained to fly at the wind tunnel on a daily basis. A perch-to-perch flight was chosen for the current study given their relatively large size, and the birds were trained to fly from one perch to another perch for food. The birds initially perched on the trainer’s hand who was located downstream away from the PIV system (see, Figure 3.1). The birds left the trainer on their own accord flying headwind to reach the perch for food which was placed upstream. The average oncoming flow speed was approximately 3 m/s. As the PIV experiments should be conducted in the dark, only the light directly above on the landing perch was left on for the birds to locate and land. Opto-isolators operated six infrared (IR) transceivers were integrated into the PIV system (located upstream away from the laser sheet location, see, Figure 3.1) which prevented the direct contact between the bird and the laser sheet and ensured the safety of the birds (Kirchhefer et al., 2013). The laser light
sheet was emitted only when the bird flew through the IR transceivers system. For further safety of the birds, both the upstream and downstream ends of the wind tunnel were covered with a net. Once the birds reliably completed the flight routine repeatedly, final experiments were conducted over the span of two days. During the experiments, the birds were released from a height of approximately 1.7 meters from the floor, which was the shoulder level of the trainer, and this level was maintained for all the flights. The typical flight path employed by the birds during the experimental flights is shown in Figure 3.1. It was observed that both birds adapted the same flight path and behaved almost in the same fashion during the experiments. During the flight experiment, the birds completed one-to-two flapping cycles close to the PIV measurement zone. The birds were approximately 5 chord lengths away from the PIV field of view when the PIV measurements were taken, after which they flew upstream for an additional 10 meters to reach the destination perch.

Figure 3.1: The schematic of the experimental setup at BLWT-I. The green shaded area represents the PIV laser light sheet. The position of the bird at the IR location indicates that the light is emitted when the bird crosses the IR. The trainer is located downstream away from the PIV system and the birds flew upstream from left to right toward the landing perch into a headwind. The dashed curve from the location of the trainer until the perch represents the typical flight path chosen by the birds in this study. The highspeed and mobile cameras installed around the IR location mark the kinematics capture zone. The Laskins represent the seeding of the flow with olive oil particles from the upstream end of the tunnel.
3.2 Wind tunnel

The experiments were conducted at the Boundary Layer Wind Tunnel I (BLWT-I) located at the University of Western Ontario, London, Canada. This is an open circuit wind tunnel with dimensions of 33 m length, 2.4 m width, and varying in height between 1.5 m to 2.15 m (from the entrance to the test area). The long test section allows the development of a natural atmospheric boundary layer. The turbulence intensity in the tunnel was measured to be 5.8% at the low wind speeds used in the current study. The turbulence intensity in the tunnel during the birds’ flights was: 1.5% for the hawk and 2.1% for the owl. The pressure, temperature, and humidity conditions during the experiments were at standard atmospheric levels. A detailed schematic of the experimental setup at BLWT-I is shown in Figure 3.1. The green shaded area represents the area where the flow measurements were taken indicating the location of the laser light sheet downstream behind the bird’s wings. The wind was blowing from right to left whilst the birds were flying upstream against the wind from left to right as depicted in Figure 3.1.

3.2.1 Blockage ratio

The flow field birds encounter in the wind tunnel is different compared to the open field, even under the same operating conditions, as the interference of the cross-sectional area of the wind tunnel can introduce a blockage. In the aerodynamics field, traditionally, the blockage ratio is calculated as a ratio between the projected frontal area of the object to the cross-sectional area of the wind tunnel (Barlow et al., 1999). A blockage ratio of less than 3% is recommended in low-speed wind tunnel testing, though up to 10% blockage is typically allowed (Choi and Kwon, 1998). In our case, the blockage ratio for both the owl and the hawk was estimated using the allometric relation of the frontal area of the birds \( S_b = 0.00813m^{0.666} \) provided by Pennycuick et al., (1988), and the estimated blockage ratio was less than 1%, which ensured no blockage effect was present. Moreover, the minimum clearance between the wingtip and the wind tunnel walls is about 0.6 meters which is significantly smaller than the flow scales characterized by the wing chord (which is about 0.2 meters), so it can be assumed that the effect of the interference between the wingtip and the walls can be negligible.
3.3 Particle image velocimetry

A long-duration, time-resolved PIV system was utilized for the wake flow measurement (Taylor et al., 2010). The PIV system was capable of continuously acquiring images at 1000 Hz using two cameras for 20 min, consecutively. It consisted of two high-speed cameras (Photron FASTCAM-1024PCI) with a spatial resolution of 1024×1024 pixel² operating at a rate of 1000 Hz and a high energy laser (80 W double-head diode-pumped Q-switched Nd:YLF laser) operating at a wavelength of 527 nm, as shown in Figure 3.1. Olive oil particles were seeded using three Laskin generators (Echols and Young, 1963) located upstream of the wind tunnel (at the inlet flow zone) to ensure homogeneous distribution within the tunnel. The seeding particle diameter size was approximately 1 μm. One of the PIV high-speed cameras was used for the wake flow field image capturing and a second camera was used for capturing the wingbeat kinematics of the birds' flight, simultaneously. The kinematic images were synchronized with the PIV images in order to provide a direct relationship between the wake formed by the wing motion and its kinematics. The PIV field of view was 21×21 cm² and the kinematics camera field of view was 45×45 cm² for both birds. A picture of the PIV setup inside the wind tunnel is shown in Figure 3.2, and a picture of the Harris’s hawk which was about to land on the destination perch during one of the experimental flights is sown in Figure 3.3.

The velocity fields were extracted from the PIV images using Insight 4G (TSI, 2015). A 64x64 pixel² interrogation window was chosen to process the PIV images. Extracted vector maps were further post-processed to identify and replace erroneous vectors using statistical filters and bi-cubic interpolations. A right-handed Cartesian coordinate system was used in the current experiments, where x, y, and z correspond to the streamwise, normal, and spanwise directions, respectively. The streamwise and normal instantaneous velocity components are denoted by $u$ and $v$, respectively.
Figure 3.2: Picture of the PIV system inside the BLWT I

Figure 3.3: Flight of Harris’s hawk, which was about to land on the destination perch.
3.4 High-speed imaging for kinematics

To facilitate the coupling between the wake flow characteristics behind the bird’s wing and the relevant wingbeat kinematics which played the role in producing them, the PIV images, and kinematics images were recorded simultaneously. Apart from one high-speed camera, seven additional cameras (which included, four GoPro cameras and three mobile phone cameras) recorded videos of the birds’ flight from both sides, and the top and bottom of the wind tunnel around the infra-red sensor location (see, Figure 3.1). These cameras initiated the recording before the first flight started and continued to record until the last flight of each bird. Approximately 20-30 minutes of flight recordings were acquired for each bird on both days. This footage was manually processed, and each flight corresponding to its relevant PIV scenes was identified and treated separately. Kinematic images were extracted from these single flight videos. The flight speed of the birds during each flight was extracted from the kinematics images. Multiple points along the wing planform were manually traced using a freeware motion analysis software: Kinovea (https://www.kinovea.org) to extract the wingbeat kinematics over a single wingbeat cycle.

3.5 Data acquisition and selection

The final experiments for data acquisition were conducted over two days, once the birds successfully completed their training for the perch-to-perch flight mission. The PIV and the kinematics cameras were calibrated on each day of experiments. It should be noted that the only constraint in the experiments was the trained perch-to-perch flight of the birds and nevertheless the birds flew of their own volition. Though the flight path was not in our control, the PIV field of view was aimed to be in line with the mid-span location of the right-wing of the birds. Multiple flights were conducted with both birds and a large data set of near wake flow fields were acquired on each day of the experiments. Details of the number of flights conducted and the total number of vector maps acquired on each day are provided in Table 3.1: approximately 7 flights were conducted for Harris’s hawk, and 8 flights were conducted for the great horned owl on each day of experiments, and on average 1700 vector maps were collected per flight.
It is essential to identify the relative location of the PIV field of view along the wingspan of the planform to evaluate where and how certain wake characteristics formed and evolved. Only the characteristics of wake-flow produced at a certain wing section along the span can be compared and correlated between the birds or between the different flights of the same bird. The location of the PIV field of view along the wingspan was manually identified from the available kinematic images captured from different views around the PIV field of view location. The flight speeds of the birds were extracted individually for each flight from the kinematics videos. The time series of each flight were evaluated from the PIV images to identify wingbeat cycles (refer, Chapter 6). For the flight energetics study of both birds, all the flights were considered each day. For the analysis of turbulent wake flow characteristics and the aerodynamic force characteristics, only the flights which matched the following two criteria were chosen from the available data:

1) data which showed at least one distinct wingbeat cycle.

2) data which showed a distinct wake at the wing mid-span location.

The choice of mid-span was to focus on the wing-wake interaction with the minimal interface from the tip or the root vortices.

Table 3.1: Details of the number of flights and the total number of obtained data on each day

<table>
<thead>
<tr>
<th></th>
<th>Number of flights</th>
<th>Total number of vector maps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great horned owl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>On day 1</td>
<td>7</td>
<td>12,180</td>
</tr>
<tr>
<td>On day 2</td>
<td>9</td>
<td>15,785</td>
</tr>
<tr>
<td>Harris’s hawk</td>
<td></td>
<td></td>
</tr>
<tr>
<td>On day 1</td>
<td>8</td>
<td>14,621</td>
</tr>
<tr>
<td>On day 2</td>
<td>6</td>
<td>10,825</td>
</tr>
</tbody>
</table>
3.6 My contribution in the experiments

Conducting *in vivo* flight experiments with birds is a highly challenging task, and it is noteworthy to mention that these types of experiments cannot be performed alone, and a group of people are required to participate to enable the success of the experiments. In the current study, six people were running the experiments, where my role was essential for their success. The birds were brought and trained in the tunnel by professional trainer Mr. Morgan. While every one of them was involved in setting up the boundary layer wind tunnel to fly birds and conduct experiments: the overall design of the experiments was carried out by Dr. Gurka, and Dr. Guglielmo helped with the bird care at AFAR during experiments, and Dr. Kopp enabled us the tunnel facilities and characterizing the turbulence level in the test section. Another then graduate student Hadar and I were involved in relocating the PIV system to the BLWT-I, reassembling, calibrating, and setting up the working system for both bird training days and the final experiments days. Based on the experiences during the bird training days, we planned the location of kinematic and PIV cameras and the wake sampling distance from the birds. On data acquisition days, I did regulate the wind tunnel flow speed and the IR control for each flight, whilst Hadar operated the ‘Insight 4G’ PIV image acquisition interface.
Chapter 4

Powered flight

In this chapter, a comparative analysis of the energetic cost of the flight between the owl and the hawk has been carried out. The current analysis aims to estimate and compare the total aerodynamic power output, the pectoralis-mass specific power output, and the specific work done by both raptors during flapping flight at their average forward speed which can help to gain an insight into their performance traits. The analysis is carried out in two parts: 1) estimation of aerodynamic power required to fly at a steady level flight, and 2) estimation of power expenditure in intermittent flight exhibited during experiments.

First, in part 1, the power required to fly and the specific work done by the flight muscles to support the weight and propel the birds in a steady level flight has been predicted using the aerodynamic models and better approximated with the advantage of the available experimental data. In addition, the analysis is extended to establish the power curve for both raptors as a function of different forward flight speeds in a level flight, and assuming allometric relation-based conversion efficiency, the metabolic power during the level flight is calculated from the aerodynamic power output derived from the models. In part 2, the energetic cost of the birds has been estimated directly using the energy budget along the geometry of the flight path for the intermittent flight, where the flight consisted of alternating powered (flapping) and unpowered (gliding) phases. This intermittent flight style was exhibited by both raptors during the experimental flight runs.

4.1 Introduction

The energy required for flying is spent by oxidative metabolism (Tucker, 1968). Direct measurement of the power requirement of flying birds has been challenging and severe limitations prevail. One way to measure the energy consumption of the birds at a given speed is to measure the oxygen consumption or carbon dioxide production during the flight using respiratory masks (Tucker, 1968; Morris et al., 2010). Tucker (1968) measured the oxygen consumption and carbon dioxide production of budgerigars (*Melopsittacus undulatus*) flying freely in a wind tunnel and estimated the energy requirements of the flight during different modes, i.e., ascending, descending,
and level flight, at various flight speeds. This method measures the rate of metabolic work (the power input) instead of the mechanical power output. The mechanical power output required for the flight can be calculated from the metabolic energy input if the conversion efficiency at which the chemical energy is converted by the bird to do the mechanical work is known (Ward et al., 2001; Bishop, 2005). The metabolic energy estimation based on oxygen consumption is fairly accurate. Another method to measure the aerodynamic power output of the bird flight is to conduct in vivo or in vitro bone-strain measurements of pectoralis muscle force (Dial et al., 1997; Tobalske et al., 2003; Morris and Askew, 2010a; Morris and Askew, 2010b).

However, due to the challenges associated with the direct measurements, simple aerodynamic models based on fixed-wing aerodynamic theory and rotor blade theory have been proposed and utilized widely to estimate the power output during flight (Pennycuick, 1968, 1975; Pennycuick et al., 1989; Pennycuick, 2008; Tucker, 1973; Rayner, 1979a, 1979b, 1999; Ellington, 1984; Norberg, 1990). For forward flights, generally, Pennycuick (1975) and Rayner (1979a) models are used and for slow or hovering flights Rayner (1979b) and Ellington (1984) models are used. Generally, a U-shaped power curve versus the flight speed is established for flying birds (Norberg, 1990; Tobalske et al., 2003; Pennycuick, 2008). The aerodynamics and the force generation associated with the flapping flight are unsteady time-dependent. Hence, the major issue with the aerodynamic models is that these are simplified models that rely on major assumptions and provide a mean estimation of aerodynamic power requirement for a chosen flight style. Nevertheless, available studies evidence that even if not accurate to the measured values, the aerodynamic model-based estimations effectively predict to the appropriate range (Tucker, 1973; Hedrick et al., 2003; Tobalske et al., 2003; Askew and Ellerby, 2007; Morris et al., 2010; von Busse, 2014) and provide insight into the power requirement and energy consumption at given flight speed.

To estimate the power from the aerodynamic models, studies often use typical values for input parameters i.e., morphological specifications and parasite or profile drag coefficients irrespective of species. In the case of the current study, most of the input parameters are used from our direct experimental measurements to predict the flight power requirements.
4.2 Aerodynamic & metabolic power in a steady level flight

In steady level flight, at constant cruising speed, the power required to sustain lift and thrust forward is consumed by three components (Pennycuick, 1968):

1) Profile power (\( P_{pro} \)) – the power required to overcome the drag of the wings.

2) Parasite power (\( P_{par} \)) – the power required to overcome the drag of the body.

3) Induced power (\( P_{ind} \)) – the power required to balance the weight/lift.

The total aerodynamic power (\( P_{aero} \), also regarded as mechanical power, required for a flying bird to sustain a steady, unaccelerated flight is:

\[
P_{aero} = P_{pro} + P_{par} + P_{ind}
\]

Besides, flapping flight requires additional kinetic energy to oscillate and accelerate the wings which come from the work of the flight muscles. This kinetic energy of the wing (rotational kinetic energy) multiplied by the wingbeat frequency provides inertial power. The aerodynamic power output from the flight muscles equals the sum of the aerodynamic power and inertial power (Tobalske, 2007). But generally, inertial power is unaccounted and \( P_{aero} \) alone is used to estimate the flight power output and the specific work done by the flight muscles. According to Pennycuick (2008), an efficient bird recovers all of its power spent on accelerating the wings later in the downstroke and utilize it as part of the aerodynamic work at each wingbeat. Thus, it is suggested that the wing kinetic energy is reconverted into aerodynamic work and not necessary to account separately. According to Norberg (1990), the inertial power has some significance in hovering or very slow flights, and it can be neglected in moderate and fast forward flights as it is very low. Additionally, during an accelerating flight or climbing flight (take-off) the components of changes in kinetic and potential energies over time are also accounted for the total aerodynamic power.

4.2.1 Profile power

In flapping flight, the fluid-wing interaction is a complex two-way coupled phenomenon, and the aerodynamic forces are time-dependent. The average forces balance each other in a steady level
flight and the aerodynamic theory accounts for the mean aerodynamic drag forces to estimate the power requirement.

The mean profile power to overcome the wing drag can be estimated using:

\[ P_{\text{pro}} = \frac{1}{2} \rho V^3 S_w C_{D,\text{pro}} \]  

(4.2)

Where \( \rho \) is the air density, \( V \) is the forward speed of the bird (on-air speed), \( S_w \) is the area of the wing, and \( C_{D,\text{pro}} \) is the profile drag coefficient. In flapping flight, the value of the profile drag is not constant along the wingspan. It depends on both the forward flight speed and the angular speed of the flapping wing as the relative airflow over the wingspan and the relative angle to the flow determines the drag value for each section from the root to the tip. Therefore, typically wing strip analysis is carried out to estimate the profile drag where multiple sections along the wingspan are considered as each strip and the drag value is integrated over the whole wing. However, the aerodynamic theory assumes a single drag coefficient and extends to the wing area to estimate the mean profile power. The magnitude of the profile drag coefficient is very challenging to measure for a flying bird and is not widely established for many bird species yet. A profile drag coefficient of 0.02 was assigned by Rayner (1979b) as a typical value for any bird wing, and Pennycuick et al., (1992) estimated \( C_{D,\text{pro}} \) of 0.02 as a mean profile drag coefficient from approximately 92 flights of a gliding Harris’s hawk in a wind tunnel. Studies have commonly used suggested \( C_{D,\text{pro}} \) of 0.02 to estimate the profile power of bird wings irrespective of species and irrespective of flight speeds (Norberg, 1990; Askew et al., 2001; Hedrick et al., 2003; Tobalske et al., 2003; Pennycuick, 2008).

In our case, the profile drag coefficient estimated from our PIV experiments (refer, chapter 5) is used for both the owl and the hawk. The mean profile drag coefficient used in the current study is 0.049 for the Harris’s hawk (measured from a single flight) and 0.091 for the great horned owl (averaged value measured from two flights). The used profile drag coefficient of the great horned owl is comparable to the average drag value of 0.12 for a boobook owl flight reported by Nafi et al., (2020). Regarding the Harris’s hawk, Pennycuick et al., (1992) reported the profile drag coefficients to range from 0.008 to 0.052, and a mean value of 0.02. In another study, Tucker and Heine (1990) found \( C_{D,\text{pro}} \) of Harris’s hawk to range from 0.003 to 0.097. The used value of the Harris’s hawk in our study is comparable and inside the reported ranges of both studies.
4.2.2 Parasite power

The parasite power needed to overcome the body drag can be estimated as:

\[ P_{par} = \frac{1}{2} \rho V^3 S_b C_{D,par} \]  (4.3)

Where \( S_b \) is the body frontal area and the \( C_{D,par} \) is the parasite drag coefficient. To approximate the body frontal area, an allometric model proposed by Pennycuick et al., (1988) has been used:

\[ S_b = 0.00813m^{0.666} \]

where \( m \) is the mass of the bird in kilograms and the frontal area is in meter square. The values for parasite drag coefficient of birds vary widely in literature and the typical values of \( C_{D,par} \) are in the ranges of 0.1 to 0.4 (Hedenström, 2002). Pennycuick (1975) and Tucker (1973) have recommended estimating body drag coefficients from mass allometric relations. But it comes with the limitation that the features of the body are neglected, and the dependency of Reynolds number is omitted. Therefore, it may lead to under or overestimation.

Wind tunnel measurements of body drag coefficients on frozen bodies ranged from 0.25 for large raptors to 0.39 for smaller birds, in the \( Re \) range 145,000 to 462,000 (Pennycuick et al., 1988). But parasite drag estimated with frozen bodies are known to overestimate the body drag (Tucker, 2000), and \( C_{D,par} \) of most of the living birds are unknown. However, based on his experimental analysis on frozen bodies, Pennycuick et al., (1988) suggested the following relation between the body Reynolds number and the parasite drag coefficients for large raptors in the \( Re \) range from 50,000 to 200,000:

\[ C_{D,par} = 1.57 - 0.108 \ln(Re_b) \]  (4.4)

where \( Re_b = \rho V w / \mu \) is the body-based Reynolds number, where \( w \) is the body width and \( \mu \) is the dynamic viscosity of air. Pennycuick et al., (1996) suggested accounting for one-eighth of the estimated values for \( C_{D,par} \) using Equation 4.4 due to the discrepancies observed in that study. Later, based on direct measurements on a few bird species, Rayner (1999) suggested that the reduction in \( C_{D,par} \) should be around one-third of the estimated values instead of one-eighth (Askew et al., 2001). Based on the recommendations, Rayner (1999), Askew et al., (2001), and Tobalske et al., (2003), used 0.13 for a typical value of \( C_{D,par} \) for their aerodynamic power calculations.
Our measured body widths of Harris’s hawk and the great horned owl are 0.10 and 0.11 meter respectively. The average body-based $Re$ is 68,100 and 61,300 for the hawk and the owl respectively. Based on the relation (Equation 4.4) suggested by Pennycuick et al., (1988), the estimated parasite drag coefficient for the owl is 0.38 and the hawk is 0.37. Further, one-third of the estimated values are chosen for the $C_{D,par}$ which is 0.127 for the owl and 0.123 for the hawk. These values are close to the suggested $C_{D,par}$ of 0.1 for raptors (Tucker, 2000) and the measured body drag coefficient of 0.18 for Harris’s hawk (Tucker, 1990).

### 4.2.3 Induced power

The classical actuator disc model is commonly used in the literature to estimate the induced power where the wings must impart required downward momentum flux to the air flowing through its swept area to balance the weight/lift:

$$P_{ind} = \frac{kL^2}{2\rho V S_d}$$

(4.5)

where $k$ is the induced power factor to correct for the effective lift distribution compared to the ideal case of an elliptical lift distribution. $k$ is usually ranging from 1.1 to 1.2 (Norberg, 1990) and for flapping flight, it is suggested as 1.2 (Pennycuick, 2008). $L = \text{mass of the bird (m) x gravitational acceleration (g)}$, is the lift balanced by the weight in the steady level flight, and $S_d = \pi B^2 / 4$, is the wing swept area approximated by the circular disk area whose diameter is the full wingspan length ($B$).

### 4.2.4 Wing kinetic energy

The kinetic energy ($E_{iner}$) required to oscillate the flapping wing depends on the moment of inertia of the wing ($I_w$) and the angular velocity ($\omega$), which is defined as:

$$E_{iner} = \frac{1}{2} I_w \omega^2$$

(4.6)

To estimate the kinetic energy of the rotating wings, the wingbeat frequency ($f$) of the owl and the hawk were calculated from the kinematics analysis, and the angular velocity is calculated as, $\omega$
\[ = 2\pi f. \] The moment of inertia of the wings \((I_w)\) are approximated from the relation (Kirkpatrick, 1990; Pennycuick, 2008): \(I_w = 9.23e^{-4} \times B^{5.8}\).

### 4.2.5 Metabolic power input

Direct measurements of the metabolic power input \((P_{met})\) during the flight of birds are difficult to make. Alternatively, metabolic power can be calculated from the mechanical power output with the appropriate flight muscle efficiency \((E_{FM})\), using (Ward et al., 2001):

\[
P_{met} = 1.1 \left[ \left( \frac{P_{aero}}{E_{FM}} \right) + P_{BMR} \right]
\]

(4.7)

where and \(P_{BMR}\) is basal metabolic power. The basal metabolic power is the rate at which the bird consumes fuel energy when it is inactive. Although the \(P_{BMR}\) is not accounted for the mechanical power requirement of the flight, it is added while converting to the metabolic power (Pennycuick, 2008). To calculate the \(P_{BMR}\), we used the allometric relation suggested by Prinzinger and Hanssler (1980) and Bishop (2005): \(P_{BMR} = 5.4M_b^{0.72}\).

Further for the value of \(E_{FM}\), Pennycuick (1975) suggested it to be 0.23, but usually a range of values are used in the literature from 0.2 – 0.25 (Norberg, 1990). In our case, we used the allometric relation suggested by Bishop (2005) to estimate the conversion efficiency: \(E_{FM} = 0.23M_b^{0.182}\).

### 4.2.6 Statistical analysis

Both the owl and the hawk were flown repeatedly on each day of experiments \((N = 16\) for the owl and \(N = 14\) for the hawk, totalling two days). To indicate the uncertainty around the estimate of the mean measurements of flight speed, total aerodynamic power, mass-specific power, and metabolic power, the standard error of the mean (S.E.M) is calculated. All data presented are with mean ± S.E.M, unless specified. Further to test the statistical significance, a one-sample t-test was carried out for each bird for the respective variables. Additionally, an independent samples t-test was carried out to assess the significance of differences between the owl and the hawk. All the statistical analyses were performed using MATLAB 2018b (https://www.mathworks.com/): P values of \(\leq 0.05\) were used to denote the level of probability at which results were regarded as
significant. Regarding the power curves: the aerodynamic and metabolic power output predicted using the aerodynamic models for a range of forward flight speeds were fitted with the approximate function using polynomial fit with bi-square robust fitting from the MATLAB 2018b statistical toolbox. In addition, a 95% percent confidence interval was predicted for the fitted data and presented along with the power curves.

4.2.7 Estimated total power expense during steady level flight

The current analysis is carried out to estimate the total aerodynamic power requirements for both raptors during the continuous forward flight at their typical flight speed, and to predict both the mechanical and metabolic power output as a function of a range of flight speeds.

As discussed in the experiments (refer, chapter 3), two days of flight experiments were conducted with both birds. The owl comprised of 16 flights and the hawk comprised of 14 flights together for two days. After our flight experiments were completed the morphological specifications such as chord length, half-wingspan length, body length, body width of both raptors were measured with both wings extended at a mid-downstroke position. Besides, the birds were weighed daily before the experiments. The comparison between the morphological data between both the birds is provided in Table 4.1. It was coincidental that both the owl and hawk used in this study were similar in size. They had the same wingspan length (57 cm) and closely the same mean chord length (~20 cm), while the owl weighed 30% heavier than the hawk. By manually processing the kinematic images of each flight, the flight speeds of both birds were estimated, and the on-air speeds of the birds were accounted for together with the tunnel headwind. The average forward flight speed of the owl (8.14 ± 0.28 m/s; P < 0.001) was about 2 m/s lower than the hawk’s forward flight speed (9.95 ± 0.37; P < 0.001). These measurements agree with the general notion that the owls are typically slow fliers (Winzen et al., 2015) and hawks are typically fast fliers (Pennycuick et al., 1992; Tucker and Heine, 1990). It is interesting to note that the hawk probably accelerated toward its minimum power speed during the experimental flights (Pennycuick et al., 1989), though no information on the minimum power speed of the owls is found in the literature. The average flight duration of the owl was 3.65 ± 0.06 s and the hawk was 3.29 ± 0.06 s. Both birds exhibited intermittent flight styles from the launching perch to the landing perch. The relative flapping duration was significantly smaller than the flight duration.
Table 4.1: Morphological and kinematics data of the owl and the hawk

<table>
<thead>
<tr>
<th></th>
<th>Great horned owl</th>
<th>Harris's hawk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body mass, $m_b$ (kg)</td>
<td>1.199</td>
<td>0.918</td>
</tr>
<tr>
<td>Pectoralis muscle mass, $m_p$ (kg)</td>
<td>0.179</td>
<td>0.128</td>
</tr>
<tr>
<td>Half wingspan, $b$ (m)</td>
<td>0.57</td>
<td>0.57</td>
</tr>
<tr>
<td>Chord-length, $c$ (m)</td>
<td>0.19</td>
<td>0.20</td>
</tr>
<tr>
<td>Body frontal area, $S_b$ (m²)</td>
<td>0.009</td>
<td>0.008</td>
</tr>
<tr>
<td>Wingbeat period, $T$ (s)</td>
<td>0.23</td>
<td>0.25</td>
</tr>
<tr>
<td>Wingbeat frequency, $f$ (Hz)</td>
<td>4.29</td>
<td>4</td>
</tr>
<tr>
<td>Wing moment of inertia, $I_w$ (Kg.m²)</td>
<td>0.0018</td>
<td>0.0018</td>
</tr>
<tr>
<td>Forward flight speed, $V$ (m/s)</td>
<td>8.14 ± 0.28</td>
<td>9.95 ± 0.37</td>
</tr>
<tr>
<td>Average flight duration, $T_{flight}$ (s)</td>
<td>3.65 ± 0.06</td>
<td>3.29 ± 0.06</td>
</tr>
</tbody>
</table>

The mass values are from the experiment day 2. (mean ± S.E.M values are provided for 16 flights of the owl and 14 flights of the hawk).

4.2.7.1 Wing kinetic energy estimates

Our measured wingbeat frequency values from the kinematics analysis are 4.29 Hz for the owl and 4 Hz for the hawk (see, Table 4.1). Pennycuick (2008) provided an allometric plot of steady flight wingbeat frequency as a function of body mass for about 220 bird species. From the plot, a typical bird with a mass around 1 Kg (comparable to the mass of both raptors) yields a wingbeat frequency around 4-5 Hz. The measured frequency places well in that range. Compared to smaller birds, the wingbeat frequencies of both birds are very low, i.e., the wingbeat frequencies of the European starling and sandpiper at level flight are 12.5 Hz and 10 Hz, respectively (Gurka et al., 2017). The kinetic energy of the wing is determined by both wingbeat frequency and the moment of inertia. Both raptors display the same wing moment of inertia, calculated as a function of wingspan reported by Kirkpartick (1990) from the analysis of about 18 birds. Based on these parameters, the estimated kinetic energy of the rotating wings is 0.65 J for the owl and 0.57 J for the hawk. Both birds exhibit similar values: the small difference between the birds arises from the small difference in the wingbeat frequency. Nonetheless, it is also worth mentioning that the wing kinetic energy of the heavier owl may relatively differ from the hawk if the wing moment of inertia is calculated as a function of the body mass: as wing mass is also a function of body mass (Kirkpartick, 1990) which good produce a different value for the moment of inertia.
4.2.7.2 Aerodynamic and metabolic power estimates at average flight speed

The aerodynamic power components such as the profile power, parasite power and induced power are estimated using Eq. 4.1, 4.3, and 4.5, respectively. The measured morphological data are used to estimate the power along with the profile drag coefficient measured from the PIV flow field measurements.

The estimates of the aerodynamic power output, metabolic power input, and pectoralis mass-specific power requirements are estimated individually for each flight and the averaged values are summarized in Table 4.2. The estimates show that the required total aerodynamic power, $P_{aero}$, of the owl is $15.53 \pm 0.51$ (P < 0.001) W and the hawk is $12.1 \pm 0.89$ (P < 0.001) W. Pennycuick et al.’s (1989) showed an estimate of 13.1 W for Harris’s hawk with an all-up mass of 1 Kg flying at minimum power speed of 10 m/s. Our estimated value of 12.1 W for Harris’s hawk is very close to Pennycuick et al.’s estimate. Similar confidence can be reserved on the $P_{aero}$ estimation of the owl for the chosen forward speed as well. Comparing the individual power components: the estimated $P_{pro}$ of the owl is $6.86 \pm 0.72$ W and the hawk is $7.5 \pm 0.94$W. Though the profile drag coefficient of the owl is higher than the hawk, the predicted profile power is comparatively lower as the power varies as a function of the cube of the forward velocity. The same goes for the difference in the $P_{par}$ between both birds. The estimated $P_{par}$, which is $0.4 \pm 0.04$W for the owl and $0.6 \pm 0.08$ W for the hawk, is very low compared to the other two power components. The major contributor for the owl in the total aerodynamic power comes from its induced power component. The values of $P_{ind}$ are $8.27 \pm 0.26$ W and $4.0 \pm 0.13$ W respectively for the owl and the hawk. The $P_{ind}$ of the owl is almost 2-fold higher than the hawk. This difference arises as the induced power varies directly as the square of the lift and inversely to the forward speed. The owl is about 1.3-fold heavier than the hawk and flies about 2 m/s slower. This requires the owl to relatively spend more power to push air downwards to balance the weight and stay aloft. The metabolic power estimated using Eq. 4.7 shows that the metabolic power input is significantly higher than the aerodynamic power output. The metabolic power of the owl at their typical forward speed is $78.65 \pm 2.38$ W (P < 0.001) and for the hawk it is $64.13 \pm 4.0$ W (P < 0.001). The profile, parasite, and induced power outputs represent the rate at which work is done on the surrounding air by the bird. To complete a successful mission, the bird should have enough available power to meet the total power requirement including any losses. Overall, the power required for the owl in steady-level
flight is relatively higher than the hawk to fly at a relatively slower speed ($P = 0.003$ for the total aerodynamic power output and $P = 0.008$ for the metabolic power output between both the birds).

The work on the surrounding air is exerted during each stroke. The aerodynamic work done by the bird per wingstroke, $W_{aero}$, can be calculated by dividing the aerodynamic power output with the wingbeat frequency. The estimated values of the $W_{aero}$ are $3.62 \pm 0.12$ J and $3.01 \pm 0.22$ J for the owl and the hawk, respectively, which is comparatively higher for the owl than the hawk.

Table 4.2: The estimates of power requirements of both birds during a mean level flight speed

<table>
<thead>
<tr>
<th></th>
<th>Great horned owl</th>
<th>Harris’s hawk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward flight speed, $V$ (m/s)</td>
<td>8.14 ± 0.28</td>
<td>9.95 ± 0.37</td>
</tr>
<tr>
<td>Coefficient of profile drag, $C_{D,pro}$</td>
<td>0.091</td>
<td>0.049</td>
</tr>
<tr>
<td>Coefficient of parasite drag, $C_{D,par}$</td>
<td>0.127</td>
<td>0.122</td>
</tr>
<tr>
<td>Profile power, $P_{pro}$ (W)</td>
<td>6.86 ± 0.72</td>
<td>7.5 ± 0.94</td>
</tr>
<tr>
<td>Parasite power, $P_{par}$ (W)</td>
<td>0.4 ± 0.04</td>
<td>0.6 ± 0.08</td>
</tr>
<tr>
<td>Induced power, $P_{ind}$ (W)</td>
<td>8.27 ± 0.26</td>
<td>4.0 ± 0.13</td>
</tr>
<tr>
<td>Total aerodynamic power, $P_{aero}$ (W)</td>
<td>15.53 ± 0.51</td>
<td>12.1 ± 0.89</td>
</tr>
<tr>
<td>Metabolic power, $P_{met}$ (W)</td>
<td>78.65 ± 2.38</td>
<td>64.13 ± 4.0</td>
</tr>
<tr>
<td>Work per wing stroke, $W_{aero}$ (J)</td>
<td>3.62 ± 0.12</td>
<td>3.01 ± 0.22</td>
</tr>
<tr>
<td>Specific-power, $P_{spec}$ (W/Kg)</td>
<td>86.55 ± 2.83</td>
<td>94.06 ± 6.86</td>
</tr>
<tr>
<td>Specific metabolic power, (W/Kg)</td>
<td>438.6 ± 13.3</td>
<td>500.8 ± 31.47</td>
</tr>
<tr>
<td>Specific work, $W_{spec}$ (J/Kg)</td>
<td>20.19 ± 0.66</td>
<td>23.51 ± 1.71</td>
</tr>
</tbody>
</table>

(mean ± S.E.M values are provided for 16 flights of the owl and 14 flights of the hawk).

If we know the mass of the pectoral flight muscles, the aerodynamic power output, and the work done by the flight muscles can be estimated. Both the large pectoral muscle (pectoralis) and the small pectoral muscle (supracoracoideus) contribute to the flight power. The pectoralis muscle depresses the flapping wing and the supracoracoideus muscle elevates it. The pectoral flight muscles of both sides amount to about 10-25% of the total body mass of the flying birds (Hartman, 1961; Bauchinger et al., 2011). Marsh and Storer (1981) found that the large pectoral muscle mass of the Copper’s hawk ($Accipiter cooperii$) was about 17% of the body mass. Pennycuick et al., (1989) used the same ratio for Harris’s hawk in their study. Askew et al., (2001) used 14% of the body mass for the pectoral mass of Harris’s hawk based on mean flight muscle mass in 17 species in the family $Accipitridae$ reported by Hartman (1961).

In this current analysis, 14% of the body mass is considered for the Harris hawk which was measured by Hartman (1961) from eight individuals of a common black hawk ($Buteogallus anthracinus$) which is a similar species to Harris’ hawk. Greenewalt (1962) measured that the
pectoral flight mass of Eurasian eagle-owl (*bubo bubo*) amounts to be 15% of the body mass. Both great horned owl and Eurasian eagle-owl belong to the same family and genus and share a similar ecological niche. Therefore, 15% of the body mass is assumed for the pectoral muscle mass of the great horned owl. Based on the assumptions, the pectoral muscle mass of the owl is 0.179 Kg and the hawk is 0.128 Kg in the current analysis. The pectoral mass-specific power, $P_{\text{spec}}$, and the pectoral mass-specific work done, $W_{\text{spec}}$, are calculated by dividing both the $P_{\text{aero}}$, $W_{\text{aero}}$ with the pectoral muscle mass. The calculated $P_{\text{spec}}$ for the owl is about $86.55 \pm 2.83$ W/Kg ($P < 0.001$) and the hawk is $94.06 \pm 6.86$ W/Kg ($P < 0.001$). The estimated $W_{\text{spec}}$ for the owl is about $20.19 \pm 0.66$ J/kg ($P < 0.001$) and the hawk is $23.51 \pm 1.71$ J/Kg ($P < 0.001$). Though the aerodynamic power output of the owl is comparatively higher than the hawk, both the $P_{\text{spec}}$ and the $W_{\text{spec}}$ are relatively lower. These estimations suggest that the heavier owl requires either relatively less or comparable aerodynamic work per flight muscle mass and specific power output at their typical forward flight speed compared to the similar raptor (hawk): relatively large owl spends less effort by flying slowly with the enhanced lift to keep aloft.

Figure 4.1: Comparison of pectoral mass-specific power with estimates of other species at steady flight
4.2.7.3 Comparisons with power estimates of other species at steady flight

The theoretical model-based estimations are shown to be sensitive to the input parameters (Morris and Askew, 2010b). Even though the accuracy of the estimation of the power output using aerodynamic models is still in question, the models have been proven to effectively predict to an acceptable range. Here in this current study, lesser approximations are involved in the input parameters as most parameters are directly available from the experimental measurement. The power output of an owl at its typical forward speed is unknown. To the best of my knowledge, the only available information for a similar-sized bird is Harris’s hawk studied by Pennycuick et al., (1989) which is close to the current estimation. Besides, the estimated pectoralis mass-specific power output of the owl and the hawk (~87 W/Kg (at 8 m/s) and ~94 W/Kg (at 10 m/s), respectively) lies inside the range of directly measured values for other bird species flying at the steady level closely at the same forward flight speed: zebra finch - 50 W/Kg at 8 m/s (Askew and Ellerby 2007), pigeon - 51 W/Kg at 8 m/s (Dial and Biewener, 1992), magpies - 80 W/Kg at 8 m/s (Dial et al., 1997), European starlings - 104 W/Kg at 13.5 m/s (Biewener et al., 1992), and dove – 123 W/Kg at 7 m/s (Tobalske et al., 2003). Both owl and the hawk are relatively larger than the other birds listed and their pectoralis mass-specific power output falls inside the range. A summary of the comparison between the other species is provided in Figure 4.1.

4.2.7.4 Prediction of mechanical and metabolic power curves

Further, to extend the estimation of the power requirement of both raptors at a range of flight speeds and to establish the power curve of the owl and the hawk, the power analysis is carried out for different speeds from 0 to 18 m/s. It is emphasized here that the illustrated power curves as a function of the flight speed are not measured at each flight speed but rather predicted results using Eq 4.1, 4.3, 4.5, and 4.7. The measured profile drag coefficients at the mean level speed are assumed as a generic value for all flight speeds for both birds. The total aerodynamic power output and the pectoralis mass-specific power output of the owl and hawk are compared as a function of different forward velocities in Figures 4.2 and 4.3, respectively. The metabolic power input and the body mass-specific metabolic power as a function of different forward speeds are compared between both the birds in Figures 4.4 and 4.5, respectively. In all four plots, the 95% confidence bands of the fit to the data are indicated using the dashed lines. The power curve of both birds
represents clear ‘U-shaped’ dependence of the forward flight speeds, which is a characteristic of most bird species (Norberg, 1990; Tobalske et al., 2003; Pennycuick, 2008). At all speeds, the power output of the owl is higher than the hawk (P = 0.03 for the total aerodynamic power output and P = 0.04 for the metabolic power output between both the birds) (see, Figure 4.2 and 4.4). The differences narrow around the minimum power output ranges and diverge as the flight speed increases. The divergence at the higher speeds is due to the sharp increase of the owl’s profile power component as a function of the cube of the speed, in addition to the relatively more contribution of the induced power than the hawk. For both raptors, the aerodynamic power output is maximal during the lowest speed and reduces as speed increases until minimum power speed and further increases to maxima at the highest speed. While the hawk’s curve gradually decreases from the lowest speed and remains relatively flat for a range of minimum forward speeds, the owl curve decreases steeply to a narrow range of minimum power speed and again increases steeply. The minimum power speed of the hawk is in the range of 5 to 9 m/s. Though the upper end of the hawk’s minimum power speed is comparable to Pennycuick et al., (1989), the models might have underestimated the range. The owl’s minimum power speed is in the range of 6 to 7 m/s, which is inside the typical flight speed of owls i.e., 2.5 to 7.5 m/s (Mebs and Scherzinger, 2005; Winzen et al., 2015, Roulin, 2020). Although the similar under-or-over estimation of the range of minimum power can be associated with the owl, the steep decline of the power curve from the highest and lowest speeds suggests the inclination of the minimum power speed anywhere toward the low-to-moderate speeds. Although the power output of the owl is considerably greater than the hawk at all speeds, the difference in the pectoralis mass-specific power output between both birds is relatively less (see, Figure4.3). According to Tobalske et al., (2003) flying birds did not share minima between the wingbeat frequency and the mechanical power output, implying that the wing morphology, kinematics, and overall style of flight can have a great effect on the magnitude and shape of a species’ power curve. The minimum power speed of the owl is inclined toward their typical flight speeds which suggests that owls’ characteristic low flight speeds are optimized for their minimum power output requirement. The maximum power available from the flight muscles of the owls is unknown: flying at minimum power speeds, the owls might have higher power available from the flight muscles to carry even heavier prey, i.e., great horned owls are known to carry preys that are relatively heavier e.g., jackrabbit (Smith, 1980). The higher power output of Harris’s hawk (40 W) observed at the lowest speed is comparable to the maximum power available
from Harris’s hawk from 41-46 W (Pennycuick et al., 1989) and 39.7 W (Marden et al., 1990). The estimated pectoralis mass-specific power of the hawk at the lowest speed is about 300 W/Kg, which is comparable to their take-off flight power of 320 W/Kg shown by Askew et al., (2001).

Figure 4.2: Comparison between the aerodynamic power output of the owl and the hawk during steady level flight as a function of different forward velocity. Blue color represents the owl and red color represents the hawk. Solid lines are polynomial fit to the estimated data for each forward speed. The dashed lines represent the 95 % confidence bands of the fit to the data.
Figure 4.3: Comparison between the pectoral mass-specific power output of the owl and the hawk during steady level flight as a function of different forward velocity. Blue color represents the owl and red color represents the hawk. Solid lines are polynomial fit to the estimated data for each forward speed. The dashed lines represent the 95% confidence bands of the fit to the data.
Figure 4.4: Comparison between the metabolic power input of the owl and the hawk during steady level flight as a function of different forward velocity. Blue color represents the owl and red color represents the hawk. Solid lines are polynomial fit to the estimated data for each forward speed. The dashed lines represent the 95% confidence bands of the fit to the data.
Figure 4.5: Comparison between the body mass-specific metabolic power input of the owl and the hawk during steady level flight as a function of different forward velocity. Blue color represents the owl and red color represents the hawk. Solid lines are polynomial fit to the estimated data for each forward speed. The dashed lines represent the 95% confidence bands of the fit to the data.
4.3 Power expense during intermittent flight

Rather than using a steady continuous flight, many birds alter the geometry and dynamics of the flight path adapting simultaneously different flight modes such as gliding, flapping, soaring, and bounding. This is known as intermittent flight pattern and many birds exhibit intermittent flight patterns aiming to optimize flight performance (Rayner et al., 2001).

In Figure 4.6, the typical flight style exhibited by both birds during the experiments is illustrated. It is worth mentioning that both the owl and the hawk irrespectively adapted similar flight styles and flight paths during the perch-to-perch flight experiment. It was observed during the experiments that both birds glided down steeply once launched, covered one or two wing strokes, and glided again further. Based on these observations during each flight, the flight geometry is simplified consisting of three alternating unpowered and powered flight phases (see, Figure 4.6):

- **Gliding phase I** – steep descending in a glide mode immediately after launching at the height of the *start*.
- **Flapping phase** – quick flapping around the height of *kinematics-zone*, usually bursting of single wingstroke during most flights and occasionally two wing strokes. The duration of the flapping phase was significantly shorter than the gliding phases.
- **Gliding phase II** – moderate gliding toward the *end*, as the landing perch height was almost at the same level as the kinematics zone.

The experimental flight was similar to but not an exact replication of the regular flap-gliding intermittent style, where usually a powered climbing is followed by glide diving and so on (Rayner, 1985; Norberg, 1990): bounding flight is where the flapping is followed by an unpowered ballistic phase with folded wings, so this flight style can be better associated with the flap-gliding.

To stay aloft, irrespective of flight mode, mechanical (aerodynamic) work should be done to overcome the aerodynamic drag. In flapping (powered) forward flight, this work is done by the flight muscles where metabolic chemical energy is converted into mechanical work to act against the drag. In unpowered flight cases, such as gliding and soaring, birds utilize the potential and kinetic energies to their benefit to work against the aerodynamic drag. Gliding flight in particular, the bird balances its weight with its wings, and it loses height as potential energy is depleted and converted into mechanical work against drag. The kinetic and potential forms of mechanical
energy are temporarily stored in the birds’ bodies and can be used interchangeably; the birds can accelerate by depleting the potential energy or gain altitude by losing the kinetic energy (Pennycuick, 2008).

Figure 4.6: The intermittent flight style exhibited by the birds during experimental runs. The start of the curve represents the location of the bird’s launch and the end of the curve represents the location of the landing perch with respect to the tunnel floor. The typical flight path exhibited by the birds during each run is represented by the parabolic black curve. The sinus like the curve on the flight path symbolizes the intermittent flapping during the course. The x- and y-axis represent the length (m) and height (m) of the tunnel. The x- and y-axis are not on a linear scale

### 4.3.1 Work output during flapping flight based on the energy budget

The flight path in the intermittent flight represents the dynamics of the change in the total mechanical energy along the flight curve. This total mechanical energy ($E_{tot}$) is the sum of instantaneous potential ($E_P$) and kinetic ($E_K$) energies and can be estimated directly from the geometry of the flight path if the mass, instantaneous locations, and speeds are known. The change in $E_{tot}$ is closely interrelated to the aerodynamic power output from the bird to the surrounding air during the flight (Rayner et al., 2001).

The total mechanical energy at the three known instances (start, kinematics-zone, and end) are given as:

\[ E_{tot} = E_{P,start} + E_{K,start} = E_{P,kin} + E_{K,kin} = E_{P,end} + E_{K,end} \]  
\[ E_{tot} = m_b g h_{start} + \frac{1}{2} m_b U_{start}^2 = m_b g h_{kin} + \frac{1}{2} m_b U_{kin}^2 = m_b g h_{end} + \frac{1}{2} m_b U_{end}^2 \]
where \( h \) is the height, \( U \) is the on-air speed of the birds. The start, kin, and end represent each property at the start, kinematics-zone, and end locations respectively. The masses of the birds were available from measurements made before the experiments each day. The \( h_{\text{start}} \) and \( h_{\text{end}} \) are fixed, which are respectively the heights from where the birds were launched and the landing perch height. The \( h_{\text{kin}} \) is the location of the bird from the tunnel floor during its presence in the kinematics zone. This height was considered as an average height from the known location of the kinematics cameras. The \( U_{\text{kin}} \) is the airspeed of the birds at the kinematics zone. The speed of the birds for each individual experiment was estimated from processing the kinematics images and the airspeed of the bird was calculated relative to the oncoming wind tunnel flow. The choice of frame of reference for the kinetic energy needs careful consideration as the useful kinetic energy available to the bird depends on its airspeed instead of ground speed (Pennycuick et al., 2000). When the bird is perching on the hand at the start, though its ground velocity is zero, the useful kinetic energy available to the bird comes from the oncoming tunnel flow in which the bird is holding. Accordingly, the mean tunnel flow speed was considered as the airspeed of the bird at the start, \( U_{\text{start}} \). The summary of all the estimated properties is provided in Table 4.3 for calculating the total mechanical energy for each day of the experiment.

<table>
<thead>
<tr>
<th></th>
<th>On day 1</th>
<th>On day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of the great horned owl, ( m_b ) (Kg)</td>
<td>1.192</td>
<td>1.199</td>
</tr>
<tr>
<td>Mass of the Harris’s hawk, ( m_b ) (Kg)</td>
<td>0.912</td>
<td>0.918</td>
</tr>
<tr>
<td>Height at the start, ( h_{\text{start}} ) (m)</td>
<td>1.83</td>
<td>1.83</td>
</tr>
<tr>
<td>Height at the kinematics zone, ( h_{\text{kin}} ) (m)</td>
<td>1.208</td>
<td>0.76</td>
</tr>
<tr>
<td>Height at the end, ( h_{\text{end}} ) (m)</td>
<td>0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>Bird speed at the start, ( U_{\text{start}} ) (m/s)</td>
<td>2.87</td>
<td>2.87</td>
</tr>
<tr>
<td>Speed of the owl at the kinematics zone, ( U_{\text{kin}} ) (m/s)*</td>
<td>8.14 ± 0.28</td>
<td>8.14 ± 0.28</td>
</tr>
<tr>
<td>Speed of the hawk at the kinematics zone, ( U_{\text{kin}} ) (m/s)*</td>
<td>9.95 ± 0.37</td>
<td>9.95 ± 0.37</td>
</tr>
</tbody>
</table>

* (mean ± S.E.M values are provided for 16 flights of the owl and 14 flights of the hawk).

The total mechanical energy is conserved along the flight path. The change in \( E_{\text{tot}} \) occurring between any two instances should arise from other sources. Based on the observation of the flights during experiments, it is approximated that during a major part of the flight path no mechanical work is done and only in a short phase the bird does any useful mechanical work (flapping). It is emphasized here that in the current analysis, we did not account for any initial acceleration arising,
which partly could be imparted by the leg muscles when the birds launched into the oncoming air. If the bird has utilized its available mechanical energy to balance its weight and counteract the aerodynamic drag during the unpowered flights, then it requires additional work to accelerate or gain additional kinetic energy. This additional kinetic energy can be interchangeably used to convert into potential energy to fly farther unpowered to land on the perch. This change in the total energy ($\Delta E_{tot}$) between an unpowered and powered phase denotes the additional work output from the bird during the flapping phase ($W_{flap}$)

$$\Delta E_{tot} = m_b g (h_{start} - h_{kin}) + \frac{1}{2} m_b (U_{start}^2 - U_{kin}^2) = W_{flap}$$ (4.10)

The $W_{flap}$ is closely related to the mechanical work output from the bird and directly characterizes the energy it has spent. From the flight path geometry and the dynamics of the total mechanical energy, it is apparent that the work output from the bird to complete the flight range is represented by $\Delta E_{tot}$. If we know the average flight duration of the birds, then the rate of work done ($P_{flight}$) by the birds can be estimated, which signifies the aerodynamic power output of the birds during the intermittent flight range.

| Table 4.4: The intermittent flight aerodynamic performance of the birds in the wind tunnel flight |
|---------------------------------------------------------------|---------------------------------|---------|-------------|
| Potential energy at the start, $E_{P,start}$ (J)            | Great horned owl               | 21.47   | 16.43       |
| Potential energy at the kinematics zone, $E_{P,kin}$ (J)    | Harris’s hawk                  | 11.52   | 8.82        |
| Potential energy at the end, $E_{P,end}$ (J)               |                                | 8.69    | 6.65        |
| Kinetic energy at the start, $E_{K,start}$ (J)             |                                | 4.92    | 3.77        |
| Kinetic energy at the kinematics zone, $E_{K,kin}$ (J)     |                                | 40.34 ± 2.80 | 46.17 ± 3.68 |
| Average flight duration, $T_{flight}$ (s)                  |                                | 3.65 ± 0.06 | 3.29 ± 0.06 |
| $\Delta E_{tot}$ (work done), $W_{flap}$ (J)              |                                | 25.14 ± 2.45 | 35.08 ± 3.38 |
| $\Delta E_{tot}$ power output, $P_{flap}$ (W)             |                                | 6.90 ± 0.67 | 10.68 ± 1.03 |
| $\Delta E_{tot}$ specific work, $W_{flap, spec}$ (J/Kg)  |                                | 140.18 ± 13.65 | 273.84 ± 26.35 |
| $\Delta E_{tot}$ specific power, $P_{flap, spec}$ (W/Kg) |                                | 38.44 ± 3.74 | 83.36 ± 8.02 |

In regard to analyze the power expenditure of the birds during the intermittent flight, the energetic quantities along the flight geometry are calculated individually for each flight for each day of experiments using the Eq. 4.8 and 4.9. The results of each flight are averaged together and summarized in Table 4.4 between the two birds. The birds have launched approximately ten meters away from the PIV and kinematics zone, and they flew upstream about the same distance to land
on the perch. The average flight duration is estimated based on the average flight speed over the whole flight distance. By dividing the work done and the flight power output during flapping with the known values of pectoralis muscle mass, the pectoralis mass-specific work and power output of the birds are estimated.

The birds possessed $E_{P,start}$ because of their elevation to launch into flying further. Besides, they also accumulated $E_{K,start}$ because of the tunnel gust, however, it is relatively weaker. This total energy at the start ($E_{tot,start}$) is immediately available for the birds to be used as the mechanical work output without doing any muscular work. This accounts for approximately 26 J for the owl and 20 J for the hawk. The available $E_{tot,start}$ is higher for the owl as they are relatively heavier than the hawk. Based on the measured forward speed of the birds in the kinematics zone and the location, the total energy available ($E_{tot,kin}$) in the kinematics zone comes out to be $51.86 \pm 2.8$ J ($P < 0.001$) for the owl and $55 \pm 3.68$ J ($P < 0.001$) for the hawk. Though the birds depleted some $E_{P,start}$, gained a massive amount of kinetic energy: $E_{K,kin}$ is about 8-fold of the $E_{K,start}$ for the owl, and 12-fold of $E_{K,start}$ for the hawk.

Consequently, the change in total energy, $\Delta E_{tot}$, during the flapping phase is around $25.14 \pm 2.45$ J ($P < 0.001$) for the owl and $35.08 \pm 3.38$ J ($P < 0.001$) for the hawk. This $\Delta E_{tot}$ change for the hawk is about 1.4-fold higher than the owl. Though the owl is a heavier bird, apparently owl has spent less work than the hawk for the same flight style. This difference might be the result of the higher potential energy owl possessed at the start and also their relatively slow flight than the hawk. The hawk was flying approximately 2 m/s faster than the owl. Hence, the hawk should require relatively more work to accelerate during flapping. If we compare the specific work done by the pectoralis muscle mass between the two birds the hawk has done more work ($273.84 \pm 26.35$ J/Kg) than the owl ($140.18 \pm 13.65$ J/Kg). This attributes almost two times higher energy expenditure by the hawk than the owl for the same flight distance and similar flight style. The same goes for the comparison of pectoralis mass-specific power output for the intermittent flight between the two birds.

Further, if we compare the $P_{aero}$ estimation from steady level flight analysis, with the $P_{flap}$ estimation during the intermittent flight for each bird, it can be observed that the birds display reduced mean aerodynamic power output. While the $P_{aero}$ of the owl is $15.53 \pm 0.51$ W, the $P_{flap}$ is
about 6.90 ± 0.67 W. Likewise for the hawk, the estimated $P_{\text{aero}}$ at the steady flight is 12.1 ± 0.89 W and $P_{\text{flap}}$ is about 10.7 ± 1.03 W. These results reestablish that the intermittent flight patterns result in moderate saving of aerodynamic energy requirements and minimize the total power output (Rayner et al., 2001). Still, when comparing the power output during the steady level and the intermediate flight, the owl yields relatively higher benefits than the hawk. This is due to the higher potential energy available to the owl at the starting perch, and the need to attain to relatively lower speed during the flapping compared to the hawk. Perching-and-pounding is one of the hunting strategies of many owl species (Javis and Holt, 1996). In this technique, owls perch comfortably until zeroing down a prey, then glide down upon it and pounce. With higher potential energy at the start, owls can utilize the available mechanical energy to counteract the aerodynamic drag during gliding, and accelerating to their typical low flight speeds can reduce the power requirement from the flight muscles through intermittent flapping. Though the experimental flight was short duration (~4 seconds) trained perch-to-perch kind of flight, nevertheless, these estimates provide insight into the choice of intermittent flight pattern adapted by the birds compared to the steady level flight. Both birds used intermittent flight patterns probably reflect that both aimed to benefit the perch-to-perch flight mode employed during the experiments.

4.4 Summary

Bird flight studies have majorly focused on establishing the relationship between the power output to the forward speed which is essential to understand the performance traits of flying birds. Even if not accurate, aerodynamic theories still can be utilized to estimate the power components during flight to gain insight into the energetics of flight. Both the owl and hawk are raptors with distinct hunting strategies: the owl is the nocturnal hunter, and the hawk is the diurnal hunter. Both birds are characterized by low aspect-ratio wings and highly cambered airfoils (Tucker and Heine, 1990; Pennycuick et al., 1992; Liu et al., 2006; Bansmer et al., 2012; Wagner et al., 2017). However, owls have unique wing morphologies and are characterized by low flight speeds and highly flexible wing structures compared to the hawk. The total power (aerodynamic and metabolic) output of the owl and the hawk during a steady level flight and the intermittent flight are estimated in this chapter. With most of the input parameters available directly from the experiments, the
aerodynamic models have been used to estimate the profile, parasite, and induced power components.

- Mechanical and metabolic power output analysis of large raptors are scarce in the literature, and particularly for owls, no information is found. From the approximated analysis using the aerodynamic models and experimental data, it is attempted in this chapter to fill the identified gap in the literature and gain insight into the power expense of two similar-sized but distinct raptors which can be associated with their functionalities.

- The owl is about 30% heavier than the hawk and the average forward speed of the owl is ~ 2 m/s slower. Though the total aerodynamic power output of the owl (~16 W) is higher than the hawk (~12 W) at its average forward flight speed, the pectoral mass-specific power is comparatively lower (~87 W/Kg for owl, and ~94 W/Kg for hawk). The heavier owls flying at their typical low flight speeds suggest requiring relatively less effort from their flight muscles than the similar raptor (hawk) by flying at lower speeds. Compared to the other two power components parasite power component is substantially lower for both birds, which is common for flying birds (Pennycuick, 2008).

- A predicted aerodynamic and metabolic power-speed curve for both raptors is established for a range of flight speeds from (0 to 18 m/s). The power curves display U-shaped dependence on the forward speed which is common for most flying birds (Norberg, 1990; Tobalske et al., 2003; Pennycuick, 2008; Morris and Askew, 2010; Askew and Ellerby, 2007). At all speeds, the owl showed higher power output than the hawk which can be related to the contribution from the induced power due to its heavy body mass and higher drag. As the forward speed increases the power output of the owl gradually diverges from the hawk. This can be explained as the contribution of the forward speeds of the owl in the other two power components significantly increase in addition to the induced power. Although the power output of the owl is substantially higher than the hawk along the power curve, the difference in the pectoralis mass-specific power output is lower as the flight muscle mass of the owl is higher than the hawk. The power curve shows the minimum power speed of the owl is inclined toward their typical low flight speed (2.5 to 7.5), which suggests owls’ characteristic low flight speeds are optimized for their minimum power output requirement. The maximum power available from the flight muscles of the owls is
unknown: flying at minimum power speeds, the owls might have higher power available from the flight muscles to carry even heavier prey.

- Further, we estimated the energetic cost of the birds directly using the geometry of the flight path for the intermittent flight, where the flight consisted of alternating powered and unpowered phases, exhibited during the experimental runs. Though the launching height is the same for both birds, the owl has higher potential energy available to be converted for mechanical work due to its higher mass. Besides, during the powered phase (flapping) the hawk accelerates to a relatively higher speed than the owl as a characteristic fast flier and involves more mechanical work from its flight muscle. The mechanical energy conversion along the flight path geometry demonstrated that the total power output of the powered phase during the intermittent flight is substantially lower for the owl than the hawk, which is contributed by the higher energy available for the owl at the start of the flight and its relatively lower speed during the powered phase. Nevertheless, the intermittent flight style reinforces the resulting energy savings and reduced aerodynamic power output for the flying birds compared to the continuous flapping flight (Rayner et al., 2001).
Chapter 5

Aerodynamic forces

The main interest of this chapter is to estimate the aerodynamic forces from the wake flow field measurements and compare between the owl and the hawk. Using the momentum equation for viscous flows, the circulatory lift coefficient and the sectional profile drag coefficient have been estimated during the flapping phase over a single wingbeat period. Comparing the aerodynamic force characteristics of a nocturnal owl flight with a diurnal hawk flight may help to connect with their flight behavior, morphological characteristics, and to deduce the associated flow control mechanisms.

5.1 Introduction

Both the owl and the hawk are distinct fliers. Owls are known to fly typically at very low speeds of 2.5 to 7.5 m/s when approaching their prey (Mebs and Scherzinger, 2000; Winzen et al., 2015, Roulin, 2020). Hawks are generally identified as relatively fast and agile fliers. The speed range of Harris’s hawk observed during the wind tunnel study of Tucker and Heine (1990) was from 6 to 16 m/s. Studies from Pennycuick et al., (1989; 1992) reported that the observed airspeed of Harris’s hawk during the experiments was in the range of 10 to 13 m/s. With an average chord of 18 cm, these flight speeds belong to the low-to-moderate Reynolds number regime on the order of $10^4$ – $10^5$, where complex viscous flow phenomena occur which have adverse aerodynamic effects. Nevertheless, both these raptors exhibit successful flight performance in this flow regime.

The wake and vortices in the near wake behind the flapping wings are the results of complex wing movement and viscous drag of the flow over the bird. The near wake flow carries the time-history of the forces associated with the flapping wings. In order to measure the aerodynamic forces of a flying bird, force balances cannot be used. Hence, alternative methods have been used to estimate the aerodynamic forces from the history of the near wake flow field. The coupling between the wing kinematics and the wake measurements is required to correlate the time variation of aerodynamic forces over the wings with the wake flow field information (Ben-Gida et al., 2013; Gurka et al., 2017). Flapping flight kinematics along with the wing morphology unambiguously
impact the aerodynamic characteristics associated with the flow over the wing and its wake. It is essential to associate the relevant wingbeat phases to explore the effect of wing kinematics in the downstream wake (Lin-Lin et al., 2016).

5.2 Kinematics

The vertical displacement of the wingtip traced over a wingbeat cycle is compared between the owl and the hawk in Figure 5.1. The kinematics images of the birds were used to reconstruct generic wingbeat kinematics at multiple locations along the wingspan: one point at the center of the wingtip, three points at the leading edge, and three points at the trailing edge. Only wingtip kinematics is presented here for clarity and discussion. The y-axis in Figure 5.1 represents the translational amplitudes of the vertical displacement (y) normalized by the respective half-wingspan length (b) of each bird. The x-axis in Figure 5.1 corresponds to the wingtip translational timestep (t) normalized by the respective wingbeat period (T). The owl and the hawk were comparable in size and their estimated wingbeat period was approximately similar, around 0.23s and 0.25s, respectively. The downstroke and the upstroke phases of the wingtip translations are identified for both birds and marked. The hawk exhibits a little longer downstroke than the owl. For clarity, two regions are shaded in Figure 5.1: the end of the light-grey region marks the start of the owls’ upstroke and the end of the dark-grey region marks the start of the hawk’s upstroke. The trend of the wingbeat cycle appears to be similar between the birds and the peak of the wingtip amplitude is about 0.7 times the half-span length for each bird.
5.3 Calculation of aerodynamic forces

5.3.1 Estimating the drag force
In order to estimate the profile drag of both raptors over a single wingbeat cycle from the near wake-velocity fields, a similar approach demonstrated in Ben-Gida et al., (2013) is utilized. A schematic of a two-dimensional wing section of a bird surrounded by the control volume (ABCDEFGHIA) and immersed in an incompressible flow is sketched in Figure 5.2. The wing section has chord length $c$ and its width in the spanwise direction ($z$) is unity. Within the control volume, the drag per unit span, $D'$, acting on the wingspan can be expressed using the $x$-component (streamwise) of the momentum equation as:

$$D' = -\rho \frac{\partial}{\partial t} \iiint_V u dV - \rho \oint_S (\vec{u}. dS)u - \iint_S (p. dS)_x$$  \hspace{1cm} (5.1)$$

Where $V$ is the control volume, $S$ is the enclosed surface area, $\vec{u} = (u, v)$ is the velocity vector in the two-dimensional Cartesian coordinate system, $p$ is the pressure, and $\rho$ is the density. The viscous terms of the momentum equations have been neglected as they scale with $Re^{-1}$.

The last term on the right-hand side of Equation 5.1 is the $x$-component of the pressure force exerted on the elemental area $dS$ of the control surface. For the control surface $S$, sufficiently far enough from the body, $p$ is constant along the boundaries (Anderson, 1991) and equals to free-stream pressure ($p_{\infty}$) which leads to $\iint_S (p. dS)_x = 0$.

Thus Equation 5.1 becomes,

$$D' = -\rho \frac{\partial}{\partial t} \iiint_V u dV - \rho \oint_S (\vec{u}. dS)u$$  \hspace{1cm} (5.2)$$

The sections ED, FG, and BAI are streamlines of the flow. By definition $\vec{u}$ is parallel to the streamlines and $dS$ is perpendicular to the control surface. As $\vec{u}$ and $dS$ are perpendicular vectors, along these sections $\vec{u}. dS = 0$ (Anderson, 1991). Consequently, the contribution of these sections ED, FG, BAI in the surface integral $S$ are zero. Among the rest of the sections (BC, DG, EF, and HI), the sections BC and HI are adjacent to each other. Their contributions also cancel each other, as the mass flux out of one section is identically the mass flux into the other one. The sections, EF and DG, are oriented in the $y$-direction, and the width of the control volume is unity in the $z$-direction. Hence, for these sections, $dS = dy(1)$. Hence, the contributions of EF and DG are valid and Equation 5.2 becomes:

$$D' = -\rho \frac{\partial}{\partial t} \iint_{S_{EDGF}} u dx dy - \left(-\rho \int_F u_1^2 dy + \rho \int_G u_2^2 dy\right)$$

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Applying the integral form of the continuity equation for the control surface:

\[-\rho \int_{F}^{E} u_1 \, dy + \rho \int_{G}^{D} u_2 \, dy = 0\]

\[\rho \int_{F}^{E} u_1 \, dy = \rho \int_{G}^{D} u_2 \, dy\]

Multiplying the above equation by \(u_1\) (a constant in the current case), we get

\[\rho \int_{F}^{E} u_1^2 \, dy = \rho \int_{G}^{D} u_2 u_1 \, dy\]

i.e.,

\[D' = -\rho \frac{\partial}{\partial t} \int_{S_{EDGF}} u \, dx \, dy + \rho \int_{G}^{D} u_2 (u_1 - u_2) \, dy\]

The drag is composed of steady (second term) and unsteady (first term) components. For the freestream velocity \((U_\infty)\), and the normal \((h)\) and streamwise \((l)\) extent of the PIV velocity field, the drag per unit span is (Ben-Gida et al., 2013):

\[D' = -\rho \frac{\partial}{\partial t} \int_{0}^{h} \int_{0}^{l} u \, dx \, dy + \rho \int_{0}^{h} u (U_\infty - u) \, dy\]

\[(5.3)\]

The steady drag per unit span is the classical velocity deficit drag (Goett, 1939), and the unsteady drag per unit span results due to the flapping motion. Comparing to the continuous flapping flight, the role of the unsteady drag component in the current study may not be substantial and can be negligible: due to the nature of the current experiment, it was observed that the birds exhibited merely one or two wing strokes around the measurement zone. Hence, only the steady drag component is accounted for both birds in the current study, and the time variation of the steady drag over a single wingbeat cycle is calculated using:

\[D' = \rho \int_{0}^{h} u (U_\infty - u) \, dy\]

\[(5.4)\]

The steady drag per unit span of the owl and hawk is estimated using the above Equation 5.4 over a single wingbeat cycle. The drag per unit span is further normalized with the product of dynamic pressure \((0.5 \rho U_\infty^2)\) and the chord length \((c)\) to produce the drag coefficient, \(C_d\). The drag coefficient allows us to directly compare the estimated drag between the owl and the hawk. As a dimensionless measurement of the drag, the profile drag coefficient can be expressed by the following relation:
\[ C_d = \frac{d'}{0.5\rho U_\infty^2 c} \]  

To calculate the steady drag per unit span, different streamwise velocity profiles are sampled at different \( x \)-positions for each velocity map and are spatially averaged into one profile for describing the mean velocity deficit. The integrals are performed for each instantaneous velocity field over a single wingbeat cycle to describe the time evolution of the steady drag in the near wake.

### 5.3.2 Estimating the lift force

The time-varying lift generated during a flapping motion can be accounted to comprise of two components: a circulatory component and a non-circulatory component (Theoderson, 1935). The non-circulatory component is essentially a virtual mass effect (added mass term) that arises due to the acceleration of the fluidic body. The circulatory component is due to the vorticial flows arising from the airfoil which can be estimated from the flux of the vorticity in the wake (Panda and Zaman, 1994). The time-dependent lift of the owl and the hawk during a flapping phase has been estimated using the same method employed by Stalnov et al., (2015) and Nafi et al. (2020) which is based on Wu's viscous flow approach (Wu, 1981). Assuming that the lift variation in flapping flight is contributed primarily with the circulatory lift component, Wu’s time-dependent lift is expressed as:

\[ L'(t) = -\rho \frac{d}{dt} \iint x \omega_z(t) dx dy \]  

(5.6)

where the integral is the first \( x \)-moment of the vorticity. The spanwise vorticity, \( \omega_z(t) \) at the wake is defined as:

\[ \omega_z(t) = \frac{\partial \upsilon}{\partial x} - \frac{\partial u}{\partial y} \]  

(5.7)

which is evaluated directly from the PIV data. Here \( u \) and \( \upsilon \) are streamwise and normal velocity components, respectively. According to Wu’s approach (Equation 5.6), the circulatory lift is equal to the time rate of change of the first moment of the vorticity field. By applying Taylor’s hypothesis, \( dx = U_\infty dt \), the spatial derivative in Equation 5.6 can be transformed into a temporal one. However, based on the unsteady thin airfoil terminology, the circulatory lift component is
only a part of the total lift that is acting on the flapping wing. As the lift at the beginning of the flapping cycle is not known, the estimated lift component can be referred to as an increment in the circulatory lift (Stalnov et al., 2015) that is generated from the beginning of the cycle, thus equal to \( \Delta L_c(t) \) which is expressed as:

\[
\Delta L_c(t) = \rho U_\infty \int \zeta(t) \, dt
\]

(5.8)

where \( \zeta(t) \) is the vorticity flux in the near wake that can be estimated as:

\[
\zeta(t) = \int U_c \omega_x(t) \, dy
\]

(5.9)

where \( U_c \) is the convection velocity that collectively carries the wake characteristics downstream. The vorticity flux is defined by Equation 5.9 corresponds to the spanwise vorticity component which is integrated over a selected region in the velocity map, and it is estimated individually for each velocity map as a function of time. The convection velocity at each time instant is defined as the mean streamwise velocity component along the \( x \)-direction for each velocity map, and the spanwise vorticity field is estimated as the local mean spanwise vorticity along the \( x \)-direction for each velocity map. Then the vorticity flux \( \zeta(t) \) is obtained by integrating over the \( y \)-direction for each time instant. Following in the results, in order to represent the lift over a wingbeat cycle instead as the increment in the circulatory lift, the weight of the bird in Newtons is added: the lift at the beginning of the flapping cycle is not known, but during a steady level the bird’s weight is always balanced by the lift to stay aloft, which is accounted as the initial lift.

The increment circulatory lift produced during the flapping phases of the owl and the hawk is estimated using Equation 5.8 and the weight of the birds is then added to represent the circulatory lift per unit span over a single wingbeat cycle. The lift per unit span \( (L’) \) is further normalized with the product of dynamic pressure \( (0.5 \rho U_\infty^2) \) and the chord length \( (c) \) to produce the lift coefficient \( (C_l) \). The estimated non-dimensional lift force per unit span quantity \( C_l \) enables us to compare the lift characteristics of both the owl and hawk directly.

\[
C_l = \frac{L'}{0.5 \rho U_\infty^2 c}
\]

(5.10)
5.3.3 Error estimation: instantaneous velocity and aerodynamic forces

The instantaneous flow velocity \( u \) at a point \((x, y)\) by means of the average displacement \((\Delta X)\) of the ensemble of the tracer particles between the successive PIV images captured during a short time interval \((\Delta T)\) (Adrian and Westerweel, 2011) is:

\[
    u = \alpha \left( \frac{\Delta X}{\Delta T} \right)
\]

(5.11)

where \( \alpha \) – is the scaling factor, identified from the calibration process which is a ratio between the object size and the image size (meter-to-pixel ratio). In the current study, \( \alpha = 2.1 \times 10^{-4} \) meter-per-pixel.

The error \( \epsilon_u \) in the instantaneous velocity vector estimated using the PIV technique can be obtained from the following equation:

\[
    \epsilon_u = \frac{\partial u}{\partial (\Delta X)} \epsilon_{\Delta X} + \frac{\partial u}{\partial (\Delta T)} \epsilon_{\Delta T} + \frac{\partial u}{\partial \alpha} \epsilon_{\alpha}
\]

(5.12)

where \( \epsilon_{\Delta X}, \epsilon_{\Delta T}, \) and \( \epsilon_{\alpha} \) are the uncertainty estimates of \( \Delta X, \Delta T, \) and \( \alpha, \) respectively.

\( \epsilon_{\Delta X} \): Keane and Adrian (1991) and Westerweel (1997; 2000) showed that the uncertainty of the \( \Delta X \) is determined by the particle-image diameter, particle image density (mean number of the particle images in the interrogation window, particles/pixels\(^2\)), and the sub-pixel interpolation fitting. Their estimated error for high-density particles in the 32 x 32 pixels interrogation window with Gaussian sub-pixel displacement interpolation is 0.05 pixels. Westerweel (2000) suggested that the typical values of minimum errors can range from 0.05 to 0.1 pixels. Using an adaptive multipass technique, first with 64 x 64 pixels interrogation window and then 32 x 32 interrogation window, the error can be reduced to 0.03 pixels (Huang et al., 1997).

\( \epsilon_{\Delta T} \): The uncertainty of the laser pulse delay \( \Delta T \) cannot be retrieved from data statistics on repeated observation and it is generally provided by the manufacturer (Sciacchitano, 2019). The typical value of this uncertainty is of the order of 1 ns and it can be considered negligible for low speed flows where the typical pulse delay is of the order of 100 \( \mu \)s or higher (Bardet et al., 2013; Sciacchitano, 2019). Such uncertainties can play significant importance in the micro PIV experiments or hyper/supersonic experiments where the typical pulse delay is of the order of lower
than 1 μs. If \( \epsilon_{\Delta T} \) is considered as the one-thousandth of the time delay between the two laser pulses (Gurka, 2003), in our case, it would be \( 8 \times 10^{-7} \) s for \( \Delta T = 800 \) μs.

\( \epsilon_\alpha \): The uncertainty of the calibration (\( \alpha \)) can be calculated based on the following relation:

\[
\epsilon_\alpha = \frac{\partial \alpha}{\partial O_s} \epsilon_{O_s} + \frac{\partial \alpha}{\partial I_s} \epsilon_{I_s}
\]

(5.13)

where \( O_s \) – object size and \( I_s \) – image size, and \( \epsilon_{O_s} \) – object size error, and \( \epsilon_{I_s} \) – image size error. \( O_s = 21 \) cm and \( I_s = 1024 \) pixels, which were measured from the calibration. The uncertainty of the physical length of the object size affect the scaling factor and a well-structured calibration, the \( \epsilon_{O_s} \) can be considered as \( 1 \) mm. The uncertainty of the image size (\( \epsilon_{I_s} \)) on a single reference point will be \( 0.5 \) pixels. Based on these, the estimated \( \epsilon_\alpha \) is:

\[
\epsilon_\alpha = 9.77 \times 10^{-7} - 1 \times 10^{-7} = 8.77 \times 10^{-7} \frac{m}{\text{pixel}}
\]

For current experiments, substituting all parameters in Equation 5.12: \( u = 1.6 - 2.1 \) m/s, \( \Delta T = 800 \) μs, \( \Delta X = 6 - 8 \) pixels, \( \alpha = 2.1 \times 10^{-4} \) m/pixel, \( \epsilon_{\Delta X} = 0.05 \) pixel, \( \epsilon_\alpha = 8.77 \times 10^{-7} \), the estimated error for the instantaneous velocity vector is, \( \epsilon_u = \pm 0.0125 \) m/s which is less than 1%.

The drag and lift forces are evaluated using Equations 5.4 and 5.8, respectively along with the entire velocity map. The accumulation of errors in the estimated instantaneous velocity along the vector map will propagate into the uncertainty on the resulting integral aerodynamic forces. To determine the error (\( \epsilon_F \)) associated with the aerodynamic forces (\( F \)), the root sum of squares based error propagation formula is used:

\[
\epsilon_F = \sqrt{\left( \frac{\partial F}{\partial p} \epsilon_p \right)^2 + \left( \frac{\partial F}{\partial q} \epsilon_q \right)^2 + \left( \frac{\partial F}{\partial r} \epsilon_r \right)^2 + \cdots}
\]

(5.14)

where \( \epsilon_F \) is the total error associated with the estimated aerodynamic force value (lift or drag), which depends on the values of the measurements \( p, q, \) and \( r \) and their respective uncertainties, \( \epsilon_p, \epsilon_q, \) and \( \epsilon_r \). The errors were estimated as 2-3% for the lift and drag values.
5.4 Comparisons of the aerodynamic forces between the raptors

Based on the data selection criteria (see, chapter 3), two experiments of the great horned owl and one flight of Harris’s hawk were chosen for the current analysis. The comparison between the estimated drag coefficient of the two birds is illustrated in Figure 5.3: Figures 5.3a, b, and c describe the time variation of the profile drag coefficients over a single wingbeat cycle for the owl experiment 1, experiment 2, and the hawk experiment, respectively, and the Figure 5.4d describe the comparison of both the raptors. Besides, the upstroke and downstroke phases are marked in the figures to directly associate the role of wingbeat phases in the time variation of the drag over the wingbeat cycle.

Comparing the two experiments of the owl (Figures 5.3a and b), it can be seen that the trends of the drag components vary in an almost similar fashion over a single cycle. The profile drag starts increasing during the downstroke and reaches a peak around the mid-downstroke. During the downstroke to upstroke transition, it starts slightly decreasing but raises to stay almost constant over the rest of the cycle. Besides, irrespective of the experiments, the profile drag is positive throughout the wingbeat cycle. This observation is in agreement with the results of Nafi et al., (2020) where the steady drag coefficient of the boobook owl was shown to be positive throughout the wingbeat cycle. This study calculated the drag of the boobook owl during the continuous flapping flight from similar velocity flow field measurements in a wind tunnel. For the owl, the range of the drag values exhibited in both experiments is similar and the average total drag coefficient of experiment 1 is 0.096, and experiment 2 is 0.086. These values are comparable to the boobook owls’ average total drag coefficient of 0.12 (Nafi et al., 2020) during flapping flights. Looking at the profile of the drag coefficient of the hawk (see, Figure 5.3c), it can be observed that the trends of the two raptors vary significantly over a wingbeat cycle. The profile drag of the hawk is almost constant during the downstroke and starts reducing deeply close to the downstroke-to-upstroke transition phase. While the steady drag of the owl was always positive, the hawk’s profile reaches a negative value around the mid-upstroke, which refers to the thrust. However, the profile drag value of the hawk is always lower than the owl (see, Figure 5.3d). The average drag coefficient of the hawk is 0.043 which is about two times lower than the owl.
Figure 5.3: Comparisons between the estimated profile drag coefficients. a) owl experiment 1, b) owl experiment 2, c) hawk, and d) comparison of both raptors. $C_d$ represents the drag coefficient and $t/T$ represents time normalized by the wingbeat period.
A good agreement between the owls’ $C_d$ values is observed in a similar flapping case with Nafi et al., (2020). Other studies have reported either fixed-wing or gliding flight case studies, where our measured values lie well inside the observed ranges. In a study by March et al., (2005), at the freestream speed comparable to the on-air speed of the owl in the current study, the profile drag coefficient estimates of the great horned owl ranged from 0.08-0.2 at the range of $AOA$ from -5 to 19 degrees. An owl-like airfoil at the $Re = 23,000$ produced $C_d$ of 0.03-0.1 at the range of $AOA$ from 0 to 9 degrees, as reported by Kondo et al., (2013). An owl-like wing was studied with owl-like velvet surfaces by Winzen et al., (2014a) and the measured $C_d$ values ranged from 0.06-0.28 for a range of $AOA$ from 0 to 20 degrees. The profile drag of a hawk during flapping is not known. The reported wind tunnel measurements of the $C_d$ of Harris’s hawk in a gliding flight studied by Pennycuick et al., (1992) were relatively low in the range of 0.08-0.052. Tucker and Heine (1990) studied Harris’s hawk in gliding flight and the measured $C_d$ ranged from 0.003 to 0.097. Our measured value has a close agreement inside the range. To further support, Withers (1981a) studied a red-shouldered hawk’s wing in a wind tunnel and his profile drag measurements at positive $AOA$ were within 0.05.

The profile drag coefficient is distinctly influenced by the Reynolds number of the flow, wing camber and thickness, the aspect-ratio (Withers, 1981b), and the angle of attack. Both the owls and the hawks are characterized by low aspect-ratio wings and highly cambered airfoils (Tucker and Heine, 1990; Pennycuick et al., 1992; Liu et al., 2006; Bansmer et al., 2012; Wagner et al., 2017). Nevertheless, differences between the aerodynamic characteristics of birds may exist depending on their wing kinematics, morphology, functional requirements, and ecological constraints (Muijres et al., 2012). The observed high drag in the owl and the low drag in the hawk can be plausibly associated with their hunting strategies, flight behavior, and their morphology. Owls are nocturnal and solitary hunters. Considering that owls are generally recognized to perch while foraging and fly at low speeds while taking their prey, they ought to be more ‘lift-inclined’ than drag; owls are known for their low lift to drag ratio. High lift is required to sustain flight with additional payloads at low speeds and high $AOA$. Moreover, as nocturnal raptors, their hunting is heavily dependent on their stealth capabilities as well. On the other hand, hawks are diurnal and fast attackers. They are known for their cooperative foraging and group hunting (Bednarz, 1988; Coulson and Coulson, 1995). Hawks hunt both from perching and on wings. But their hunting on wings has a significantly more success rate than from the perch (Wakeley, 1978). Hawks are also
known to accelerate and chase the prey and pound them suddenly (Wakeley, 1978; O’Rourke et al., 2010). As though, they ought to be more ‘speed-dependent’. Both drag and lift increase as the square of the speed which enables them to fly at low AOA. As the drag coefficient is also the function of the AOA, at low-to-moderate values the hawk wings generate less drag to reduce the associated aerodynamic cost. Further, both Pennycuick et al.’s (1992) and Tucker and Heine’s (1990) study with Harris’s hawk revealed that the hawk was able to ‘actively’ adjust their wingspan to minimize their profile drag during flight. The estimated average profile drag of the hawk flight was almost two times lower than the owl. Hence, their low-drag characteristics can also be attributed to their ‘active’ control mechanisms. On the other hand, the owl’s high $C_d$ is associated with its typical high AOA flight as well as the wing morphology. Studies show that both leading-edge serration and velvet surface morphological features tend to increase the drag. In Winzen et al., (2014b)’s study, an owl-based wing with owl-inspired leading-edge serrations shown to substantially increase the $C_d$ compared to the clean wing (without serration), especially at the high AOA. Similarly, Winzen et al., (2014a) studied a clean wing (without velvet surface) and a wing with velvet surfaces inspired by the barn owl. Their comparison showed the owl-like velvet surface increased $C_d$ substantially compared to the clean wing. At moderate-to-high AOA, to sustain the lift, owls’ velvet surfaces are shown to reduce the size of the separation bubble by promoting the laminar-to-turbulent transition and flow reattachment earlier in the upstream, hence the turbulent boundary stayed attached over the wings (Klaï et al., 2009), which in trade-off increases the drag.
To keep the bird aloft, enough lift should be generated to balance the weight of the bird. While fixed-wing fliers generate steady lift to balance the weight, the birds’ flapping wing kinematics results in a time-dependent lift over a wingbeat cycle. Figures 5.4a, b, c depicts the lift coefficient of the owl experiment 1, experiment 2, and the hawk over a single wing beat cycle, respectively, and Figure 5.4d shows a comparison between the three flights. Besides, the wing stroke phases are marked in the figures to connect the role of wingbeat kinematics in lift characteristics. The curves in the figures represent the accumulation and attenuation of the lift over a single wingbeat cycle.

Comparing the two experiments of the owl (Figures 5.4a and b), the trends of the lift coefficient over a wingbeat cycle appear closely the same. During the downstroke phase, the lift coefficient starts increasing and reaches a peak close to the end of the downstroke. This positive lift increment demonstrates the generation of additional momentum in the vertical direction to support the weight. During the upstroke phase, the peak value of the accumulated lift stays almost constant throughout. The hawk’s result (Figure 5.4c) shows similar behavior of positive accumulation of lift during the downstroke phase which reaches the maximum around the end of the downstroke. But after the transition phase, the lift coefficient reduces gradually and falls drastically at the end of the upstroke. Comparing all the three flights in Figure 5.4d, the owl result demonstrates significantly higher lift generation compared to the hawk flight over a single wingbeat cycle.
Figure 5.4: Comparisons between the estimated lift coefficients. a) owl experiment 1, b) owl experiment 2, c) hawk, and d) comparison of both birds. $C_l$ represents the lift coefficient and $t/T$ represents time normalized by the wingbeat period.

The observed high lift characteristics of the owl are extensively supported in the literature. Owls’ successful flight ought to be a synergistic output of their low-speed flight, wing planform, high camber, morphological features, and flexible wing structure. Due to their heavy weight and relatively low speed, owls are more ‘lift-inclined’. Owls have nearly elliptical planform and strong camber to improve lift at low speeds. The nature of the low-Re flow is to separate at low speeds and high AOA. Videos of a barn owl in flight showed fluttering feathers close to the leading edge which is indicative of the unsteady flow phenomenon i.e., flow separation and bubble formation, is common to owls as well (Friedl, 2009; Winzen et al., 2012). Yet, owls’ wing morphologies and flexible wing planform may help them with additional flow control mechanisms to stabilize the flow over the wing surface to prevent the flow separation and the associated lift loss. Leading-edge serrations act as vortex generators producing leading-edge vortices, an unsteady mechanism to enhance lift. If the LEV grows bigger when convecting downstream may break down. But the spanwise flow induced by the leading-edge serrations (Kroeger et al., 1972) stabilizes the LEV by preventing it from growing large and the flow separation downstream. A similar agreement of lift augmentation by leading-edge serrations, especially at high AOA is shown by Rao et al., (2017). In addition, the velvet surface of the owls also has similar flow stabilizing effects. During flow...
separations at the high AOA, the velvety upper surface promotes the turbulent transition and earlier flow reattachment which reduces the sizes of the laminar separation bubble (Klän et al., 2009). However, the role of these morphological features is strongly dependent on multiple factors such as the AOA, Reynolds number of the flow, and the spanwise position of the serrations.

Another most important characteristic of the owl flight is its intrinsic fluid-structure interaction mechanisms and aeroelastic behavior. It is suggested here that the flexibility owl wing structure plays a major role in the ‘passive’ flow control mechanism over the owl wings, even compared to other features. Winzen et al., (2015) reported the presence of the flow separation and large-scale vortex formation at the lower side of the owl wing at low Re and low AOA: no flow separation was observed on the upper side of the wing at low AOA, instead, flow separation with large-scale vortices was observed on the lower side. The size of the vortices was shown to depend on the Reynolds number and AOA. As the Re increases the flow separation on the lower side is observed to increase. As the AOA increases the flow separation on the lower side reduces and gradually appears on the upper side. It was observed that these large-scale vortices on the lower side cause structural deformation which changes the wing curvature. Owls’ must control the flow separation and the size of the bubble on the lower side of the wing passively as a flow control mechanism to adapt its camber during flight depending on the surrounding flow. A similar behavior of the flow separation at the lower side of the airfoil with large scale vortices at low AOA in owl airfoils is reported by multiple studies (Kondo et al., 2013; Kondo et al., 2014; Anyoji et al. 2018).

However, a very recent study conducted by Omar et al., (2020) reports numerical simulations on four different bird airfoils (eagle, stork, hawk, and albatross) at a range of AOA at the Re on the order of $10^5$. This study also shows the large-scale flow separation is appearing at the lower side of the airfoil for the eagle, stork, and the hawk at low AOA, and the separation is improved as the AOA increases. Very similar behavior of flow separation at the lower side of the airfoil is observed to occur at the low AOA for a starling airfoil and improved as AOA increased (citation: unpublished work, personal numerical flow simulations conducted on startling airfoil section for a range of AOA at $Re = 10^5$). Hence, this behavior cannot be attributed as the unique behavior of owl wings/airfoil as reported, but to be the nature of highly cambered bird airfoils: the albatross in Omar et al., (2020) study did not show this behavior as albatross airfoil is not cambered like other bird airfoils. But one aspect, that distinguishes the owls from the others is the high flexibility of their
wings. Thus, this flow separation in the lower side of the wing has strong interaction with the shape and curvature of the owl wing to ‘passively’ control the flow depending on the $Re$ and $AOA$. Further to support, March et al., (2005) study also reported the aeroelastic behavior of the owl which helps them to passively control the flow. In their study, the great horned owl wing is studied in a wind tunnel and reported that no sign of stalling was observed at high $AOA$ where conventional wings typically stall. The observation was associated with their aeroelastic feature that owls have flexible wings which deform under aerodynamic loads. Deforming wing planform reduces the effective angle of attack and so the flow separation from the wing. Due to the flexible wing and the intrinsic fluid-structure interaction owl ‘passively’ stabilizes the flow over the wing to sustain high lift.

### 5.5 Summary

In this chapter, the aerodynamic force characteristics of the owl and the hawk are estimated and compared. Using viscous momentum equations, both the sectional profile drag coefficient and lift coefficients are estimated from the wake velocity fields measured using PIV. Estimates are carried out for two flights of the owl and one flight of the hawk over a single wing beat cycle which met the selection criteria. Both the owl and the hawk are distinct hunters and fliers. The comparisons of both the lift and drag characteristics clearly show that significant distinction exists in the trends of their drag and lift variation over a wingbeat cycle. The hawk showed low drag characteristics and the owl showed high lift characteristics. While the profile drag of the owl stayed positive throughout the cycle, the hawk showed negative drag values around the mid of the upstroke. Both birds accumulated lift starting from the downstroke and reached the maximum around the end of the downstroke. While the accumulated lift of the owl stayed almost constant for the rest of the cycle, the lift coefficient of the hawk started diminishing during the transition and reduced drastically at the end of the cycle. With the support of available literature, the low drag characteristics of the hawk are associated with the high speed and low angle of attack flights of the hawk in addition to their ability to ‘actively’ adjust their wing shape to reduce profile drag during flight. The high lift characteristics of the owl are attributed to their ‘passive’ flow control mechanisms which they might have achieved through their intrinsic fluid-structure interaction due to the flexible wings and the role of wing morphological features such as leading-edge serrations.
and the velvety upper surface. The owls might use a synergetic framework of low speed, wing morphology, and fluid-structure interactions to control their aerodynamics performance.
Chapter 6

Wake-flow characteristics

This chapter focuses on the flow characteristics of the turbulent wake behind the flapping wings of the great horned owl and Harris’s hawk during free-forward flight. The goal is to examine the wake velocity fields, vorticity fields, and turbulent properties estimated directly from the PIV measurements acquired from the near wake of both raptors. Comparing the wake-flow characteristics behind the unique owl wing with the hawk could help us to differentiate the flow features and associate them with the fluid-owl interaction mechanisms of distinguished owl flight.

6.1 Mean wake-flow field

6.1.1 Bird speed correction

The birds were flying from left to right on a headwind during the experiments. The PIV measurements were acquired on a fixed frame of reference behind the downstream of the flapping wings. Simultaneously, the kinematics images were also captured from a fixed frame of reference, while the birds flew on their own accord. Hence, in order to account for the speed of the birds, which transforms the data into a non-inertial coordinate system, the instantaneous PIV velocity values were adjusted with the flight speed of the birds (both horizontal and vertical components). Unless stated, all the data used further for post-analysis are corrected for bird speed to transform to a non-inertial coordinate system.

During the short powered phase, both raptors exhibited merely one or two wingbeat cycles. Assuming the bird speed was constant over that single wingbeat cycle, the additional translational acceleration term that appears in the Navier-Stokes equation is neglected. In Figures 6.1a and 6.1b, the spatially averaged streamwise, \( u \), and normal, \( v \), velocities over a single wingbeat cycle are depicted and compared between the original data (represented by ‘ORI’) and the bird-speed adjusted data (represented by ‘BSC’). Only the results of owl exp 1 are used here, for demonstration purposes. It can be seen that similar trends are obtained between the two profiles. However, the amplitude is different accounting for the bird's speed, which yielded a constant shift in the data. The velocity gradients are calculated for each case of the data and a comparison of the
spatially averaged spanwise vorticity and strain over time are provided in Figures 6.1c and 6.1d, respectively. It can be observed that the calculated spanwise vorticity and strain profiles, from both the original data and the bird-speed corrected data, overlap demonstrating that Galilean transformation did not change the velocity gradients distribution. Thus, the bird speed correction did not affect the trends of the velocity at the wake and the spatial derivatives fields assumed to be invariant of the velocity field.

Figure 6.1: Comparison between the original data and the bird-speed corrected data over a single wingbeat cycle for owl exp 1. a) spatially averaged $u$-velocity time series, b) spatially averaged $v$-velocity time series, c) spatially averaged spanwise vorticity time series, and d) spatially averaged strain time series. In each plot, the $x$-axis represents the respective quantity and the $y$-axis represents the time normalized with the wingbeat period.
6.1.2 Mean velocity field

As discussed in chapter 3, multiple flights were conducted on two days of experiments. Here in Figures 6.2 and 6.3, spatially averaged $u$- velocity and $v$- velocity time series are illustrated for both the owl and hawk (the presented data includes only the flights conducted on experimental day 2). The spatially averaged velocity time series is calculated by taking the mean of the velocity field over each map and plotting it over the measurement time (flow time) for each flight. The $x$-axis represents the time in seconds and the $y$-axis represents the respective velocities normalized with the freestream velocity. The time evolution showing decay in the streamwise velocity represents that the bird is flying away from the PIV field of view toward the perch. The earlier time represents the proximity of the bird to the PIV measurement location. The pronounced magnitudes around the starting time in both the vertical and the streamwise velocity profiles demonstrate the flapping of the birds around the measurement zone. The attenuated velocity profiles away from the measurement zone demonstrate the less perturbed velocity field during the gliding phase of the birds toward the perch.

Based on the selection criteria (see, chapter 3), two flights of the owl and one flight of the hawk are chosen from the available data sets for further analysis: owl flights 2 and 7, and hawk flight 1 matched the selection criteria. The spatially averaged time-series of the streamwise and normal velocity components of the selected three flights are presented in Figures 6.4a and 6.4b, respectively. Here, the $x$-axis represents the time normalized with the wingbeat period of the birds, and the $y$-axis represents the velocity components normalized with the freestream velocity. The distinct two consecutive peaks (maximum and minimum) in the normal velocity temporal profiles demonstrate one wingbeat cycle of the respective flight. It can be clearly seen from the normal velocity profiles that the birds complete one or two wingbeats close to the PIV field of view (indicated as $t = 0$s) and then soar/glide farther toward the perch. The streamwise velocity temporal profiles complement the normal velocity profiles depicting distinct peaks that result from the wing motion. Further, only the distinct wingbeat cycle is chosen from each flight to analyze the turbulent flow characteristics over a single wingbeat cycle. For a clear demonstration, Figure 6.5 depicts the streamwise velocity over only the chosen single wingbeat cycle of the flights shown in Figure 6.4. It can be observed that the velocity at the wake for both flights of the owl is in similar ranges and relatively little lower than the hawk.
The time-averaged $u$- and $v$- velocity contours of the owl (the presented data include owl exp 1) and hawk are shown in Figures 6.6 and 6.7. The wake flow field is averaged over a single wingbeat cycle and the mean velocity field maps are illustrated. Both $u$- and $v$-velocity values are normalized with the freestream velocity and the $x$- and the $y$-axis represents the streamwise and normal distance of the wake flow field normalized with the relevant chord length of the birds. It is noted here that different ranges in the color contours are used for both birds to distinguish properly as the range of velocities is different between both birds since the deficit at the wake owl is comparatively higher. From Figures 6.6a and 6.6b, it can be seen that the mean velocity fields of both raptors exhibit a velocity deficit in the near wake region with dominated shear where the changes in the velocity along the normal direction are relatively higher than the changes in the velocity along the streamwise direction. While comparing both raptors, it can be seen that the near wake flow field of the owl is dominated by relatively lower velocity values than the hawk, indicating the mean velocity field of the owl exhibits a larger velocity deficit. The higher velocity deficit in the owl wake suggests reduced mean local velocity where the wake flow structures collectively travel further downstream. Besides, the streamwise course of the velocity deficit of the owl wake differs comparatively from the hawk wake: the owl wake shows a streamwise extended wide wake deficit than the hawk from the bottom of the flow field. The average normalized velocity value of the owl is around 0.93 and the hawk is around 0.97. Further, the $v$-velocity fields of both raptors in Figures 6.7a and 6.7b also demonstrate higher changes in both the streamwise and normal directions. The velocity field of the hawk is dominated by a relatively higher normal velocity than the owl wake.
Figure 6.2: Spatially averaged $u$-velocity time series of all flights conducted on experiment day 2. a) owl and b) hawk. The x-axis represents the time, and the y-axis represents the velocity components normalized with the freestream velocity.
Figure 6.3: Spatially averaged $\nu$-velocity time series of all flights conducted on experiment day 2. a) owl and b) hawk. The $x$-axis represents the time, and the $y$-axis represents the velocity components normalized with the freestream velocity.
Figure 6.4: Time evolution of mean velocity components of the selected three flights. a) $u$-velocity time series and b) $v$-velocity time series. The $x$-axis represents the time normalized with the wingbeat period, and the $y$-axis represents the velocity components normalized with the freestream velocity.
Figure 6.5: Spatially averaged $u$-velocity profile of selected single wingbeat cycles: the $x$-axis represents the time normalized with the wingbeat period, and the $y$-axis represents the streamwise velocity normalized with the freestream velocity.
Figure 6.6: Time-averaged $u$-velocity contour over a single wingbeat cycle. (a) owl and (b) hawk. The $x$-axis and the $y$-axis represent the streamwise and normal distance of the wake flow field normalized with the chord length, respectively. The color contours represent the normalized velocity values.
Figure 6.7: Time-averaged $v$- velocity contour over a single wingbeat cycle. a) owl and b) hawk. The $x$-axis and the $y$-axis represent the streamwise and normal distance of the wake flow field normalized with the chord length, respectively. The color contours represent the normalized velocity values.
6.1.3 Mean vorticity field

The velocity deficit indicates a high level of shear in the wake region, as well as vorticity (Hu et al., 2011). The two-dimensional PIV measurements enable us to calculate the spanwise vorticity \(\omega_z\) component. The calculated instantaneous spanwise vorticity is illustrated in Figure 6.8 where spatially averaged vorticity is plotted over a single wingbeat cycle. The owl’s profiles exhibit a similar range and show a slightly higher positive vorticity value compared to the hawk. Nevertheless, both birds display a similar trend of vorticity profile where the peaks are observed around the start and the end of the wingbeat cycle. In order to qualitatively compare the vorticity distribution at the wake between the two birds, five consecutive instantaneous vorticity maps extracted from the PIV images are shown as color contours in Figure 6.9. All contours in Figure 6.9 are colored with the same color levels shown by the colorbar at the right of the figures. The flow is being convected from right to left. Red represents positive vorticity values and blue corresponds to negative vorticity. The consecutive vorticity maps demonstrate the wake evolution and the convection of vortices in the downstream wake-flow field. Chosen wake segments belong to the same range of upstroke wing phase for both birds. It can be observed, qualitatively, that the hawk shows (bottom) larger vorticity regions of the same levels while the owl shows (top) more concentrated relatively smaller vorticity regions indicating that the owl’s wake is characterized by smaller vortices. The qualitative observation of owl’s wake flow field characterized by small vortices matches well with the similar observations by Lalwey et al., (2019) for a boobook owl, where it was shown that compared to starling and sandpiper, the area occupied by the concentrated vortices in owl’s wake was relatively smaller. Though a somewhat large blob of negative vorticity region is observed in the owl’s wake field, the majority of the field is typically populated with relatively smaller vortices. This large vorticity blob can be attributed to the projection of tip vortices, which contain large positive and negative vorticity regions, rolled up and upwash-ed into the downstream. The available field of view did not cover the projection of related positive vorticity. Even though the owl’s field suggest a disorganized population of small vorticity zones with a relatively clear background, no distinguished structured shedding is apparent for both birds at the current visualization. A better identification technique is necessitated to distinguish the spatial distribution of the vortices in detail between the owl and hawk and which was not available owing to the quality of our data.
Figure 6.8: Spatially averaged vorticity profile of selected single wingbeat cycles. The $x$-axis represents the time normalized with the wingbeat period, and the $y$-axis represents the spanwise vorticity normalized with the chord length and the freestream velocity.
Figure 6.9: Few consecutive vorticity maps extracted from the PIV images demonstrating the wake evolution. The top contours represent the owl exp 1 and the bottom contours represent the hawk. All contours are colored with the same levels shown by the colorbar at the right end. The flow is being convected from right to left and red represents positive vorticity and blue corresponds to negative vorticity values.
6.2 Wake turbulence characteristics

It is of interest to investigate the turbulence characteristics in the owl and the hawk wakes during a flapping flight in order to conduct a comparative analysis between the turbulence footprints generated by two similar-sized birds of prey flying under similar conditions. Correlation between the resolved fluctuating velocity components, the gradients of the velocity fluctuations, and the interaction between the mean flow properties allow the characterization of the turbulence quantities. Given the unsteady nature of the flow which results from the wing motion, it is challenging to describe how the turbulence evolved during the wingbeat cycle. The notion presented by Reynolds and later by Taylor requires us to analyze turbulence in the context of statistical evaluations (von-Karman 1948; Taylor 1935). Hence, the characteristics of turbulence are described using first and second-order movements of normal statistics.

The first requirement in analyzing the turbulence characteristics is to extract the turbulence from the instantaneous flow field data. The wake behind a flapping bird flight is highly unsteady and averaging the highly unsteady flow to extract the fluctuating velocity field is intrinsically challenging. The most appropriate way to average the unsteady flapping flight is to phase averaging the velocity fields while the data is acquired for multiple wingbeat cycles. However, in the present study, only one-to-two full wingbeat cycles are available whereas the rest of the flight corresponded to the gliding phase. Hence, based on the currently available data ensemble averaging (Tennekes and Lumley, 1972) was applied to the instantaneous flow field to the best to extract the turbulent fluctuations: \( u' = u - \bar{u} \), \( v' = v - \bar{v} \), where prime represents the fluctuating part of the instantaneous \( u \) and \( v \) velocity components and overbar represents the average (calculated from the entire set of PIV data per flight) quantities of respective velocity components. First, instantaneous PIV velocity fields were corrected for the bird-speed (see, section 6.1) and then the average of the entire sample data was removed from each instantaneous velocity value to define the fluctuating velocity fields. The resultant fluctuating part of the velocity is high compared to the case of gliding flight because it is governed by the wing motion (translational and rotational).

A comparison between the instantaneous fluctuating velocity fields of both birds measured around the end of the downstroke wing phase is provided in Figures 6.10 and 6.11. For demonstration purposes, only owl exp1 and hawk experiments are shown here. A single instantaneous streamwise velocity fluctuation field is depicted in Figure 6.10 and the normal velocity fluctuation field is...
depicted in Figure 6.11 for both birds. In both figures, the fluctuating velocity values \( (u' \text{ and } v') \) are normalized with the freestream flow speed. The \( x \)-axis represents the horizontal extent of the PIV flow field and the \( y \)-axis represents the vertical extent of the flow field, both normalized with the relevant chord length of the birds. It can be observed from the velocity contours that turbulent activity is significant and apparent for both birds in the near wake behind the flapping wings. Although it is, the velocity field of the owl wake flow is dominated by higher magnitudes of the velocity fluctuations than the hawk wake for the same wingbeat phase. At the end of the downstroke phase, the owl wake appears to be highly perturbed compared to the hawk wake leading to relatively higher turbulent wake activity.
Figure 6.10: Instantaneous streamwise turbulent fluctuation velocity field for the owl exp1 and the hawk around the end of the downstroke phase. a) owl exp 1 and b) hawk. The $x$-axis and the $y$-axis represent the streamwise and normal distance of the wake flow field normalized with the chord length, respectively. The color contours represent the normalized velocity fluctuation values.
Figure 6.11: Instantaneous vertical turbulent fluctuation velocity field for the owl exp1 and the hawk around the end of the downstroke phase. a) owl exp 1 and b) hawk. The $x$-axis and the $y$-axis represent the streamwise and normal distance of the wake flow field normalized with the chord length, respectively. The color contours represent the normalized velocity fluctuation values.
6.2.1 The scatter plot of the turbulent fluctuations

In Figure 6.12, a scatter plot is used to describe the relationship of the distribution of streamwise and normal velocity fluctuations in the wake of the owl and the hawk. The cloud of points in the scatter plot represents $u'$ and $v'$ velocity fluctuation pairs at different times over the velocity flow field. The $x$- and $y$-axis represent the normalized velocity fluctuations, respectively. Each data point in the PIV velocity field over a single wingbeat cycle is plotted together for both velocity fluctuations. It can be seen that the distribution of the streamwise and normal fluctuation samples over a wingbeat shows a distinct trend between both birds. Figure 6.12a illustrates that the directional dependence of the velocity fluctuations is a little less pronounced in the hawk wake compared to the owl wake: the scatter dot samples appear more like a symmetric distribution, even if not very close. It appears as positive streamwise velocity fluctuation has an almost equal probability to be aligned with positive or negative normal velocity fluctuation. The fluctuation velocity samples of owl exp1 and owl exp2 are illustrated in Figures 6.12b and 6.12c, respectively, which display almost similar orientations. In contrast to the hawk wake, the distribution of the velocity fluctuation samples in the owl wake is kind of skewed and spread on the left. The owl figures show a case where the positive streamwise velocity fluctuation associates more with positive normal velocity fluctuation. Moreover, the scatter of the data is more enclosed in the hawk wake while it is more spread in the owl wakes.
Figure 6.12: Scatter plot of the streamwise and normal velocity fluctuation samples in the near wake flow field. a) hawk, b) Owl exp1, and c) Owl exp2. The $x$-axis represents the normalized streamwise velocity fluctuation, and the $y$-axis represents the normal velocity fluctuation, respectively.

6.2.2 Temporal correlation of the turbulent fluctuations

The deterministic mathematical description can not apply to turbulent flows due to their highly unsteady and random characteristics, and thus, a statistical description is necessitated. Taylor’s four-part papers (1935) introduced the statistical theory of turbulence, the concept of isotropic turbulence, and the correlation theory. The idea of the correlation function i.e., the degree of covariance between velocity components at different times or different points in space is considered to appreciably define the statistical quantities significant to the description of the state of turbulence. Although real turbulent flows are not isotropic, the mathematical techniques involved facilitate the depiction of the various scales of turbulence that explain the temporal duration or the spatial extent to which turbulent fluctuations are connected.
One of the fundamental statistical techniques to investigate the temporal evolution of wake flow structures in the turbulent wake is the multi-time autocorrelation of velocity fluctuations (Pope, 2000). The temporal correlation coefficient \( R_{ij}(s) \) of the velocity fluctuations at two different times is defined as:

\[
R_{ij}(s) = \frac{\langle u_i'(x,y,t) u_j'(x,y,t+s) \rangle}{\sqrt{\langle u_i'^2 \rangle \langle u_j'^2 \rangle}}
\]  

(6.1)

where \( s \) is the small time-step between the two measurements. Correlating a single velocity fluctuation component with itself at two different times provides the autocorrelation of the velocity fluctuation. The correlation hugely depends on the time difference \( (s) \) between the two processes rather than the actual time, and the correlation coefficient defines the degree of the dependency of the variable to the reference time. Turbulent flow is a random process, as a result, the correlation
coefficient decreases as the time difference increases; when time gap $s = 0$, the correlation is strongest and decays for the increasing time difference.

In Figure 6.13a the autocorrelation curve of the streamwise turbulent fluctuation ($R_{11}$) is provided. The $u'$ velocity fluctuation is autocorrelated for both the owl and the hawk over a single wingbeat cycle. Each point in the PIV velocity map is autocorrelated over time and a mean correlation curve is produced. The $y$-axis represents the dimensionless correlation coefficient, and the correlation time in the $x$-axis is normalized with the respective wingbeat cycle. Both curves of the owl wake show that the autocorrelation of the streamwise velocity fluctuation decays significantly rapidly compared to the hawk wake. The autocorrelation converges to zero quickly representing the flow structures in the owl wake are correlated only over a short time interval compared to the hawk. Integrating the area under this correlation curve enables us to estimate the integral time scale of the larger turbulent eddies (Pope, 2000). The integral time scale represents the characteristic time scale of the larger eddy in the wake, which by definition is the turnover time of the eddy. Besides, one eddy turnover time is related to the time taken for the larger eddy to traverse the inertial subrange, where the energy of the larger eddy is dissipated to subsequent smaller eddies (see, Figure 2.2): key assumption in the turbulent theory is that the large eddies supply a significant fraction of their kinetic energy to the smaller eddies within one eddy turnover time (Tennekes and Lumley, 1972). Thus, the dissipation of the large eddies is determined by their characteristic time scale, and the small-scale eddies depend only on the rate at which kinetic energy is supplied by the larger eddies and the rate it is dissipated due to kinematic viscosity (Tennekes and Lumley, 1972). The large-scale eddies have longer time scales than the smallest energy dissipating scales. As the Reynolds number of the flow increases, the magnitude of this separation increases. The estimated integral time scale of the owl exp1, owl exp2, and the hawk are 0.05, 0.06, and 0.14, respectively. It can be seen that the integral time scale of the flow structures in the owl wake is almost 2.5 times smaller than the hawk wake. The results suggest that the turbulent structures in the owl wake are characterized by substantially smaller time scales than the hawk wake which transfers their eddy kinetic energy to subsequently smaller scales at a quicker rate. The autocorrelation curve of the owl’s wake in both the exp1 and exp 2 matches closely and represent a high-frequency turbulent activity as the correlation decays to zero quickly. Pope (2000) showed that high-frequency turbulent processes have smaller time scales and narrower auto-correlation functions than low-frequency processes. The streamwise extent of the turbulent eddies in the hawk wake is connected
relatively longer duration than the eddies in the owl wake before getting dissipated. This time scale of both birds also demonstrates that the characteristic length scale associated with the streamwise turbulent fluctuation is smaller for the owl wake than the hawk, which can be confirmed by the $L_{11}$ as shown in the next section (see, section 6.2.2.1). Compared to the hawk, the owl’s wake is characterized by smaller-scale eddies. This is also supported by Lawley et al., (2019) where it is shown that the boobook owl wake had smaller length scales than the other two birds compared, and the wakefield was populated with unorganized smaller vortices. Reynolds numbers of the flow for both the owl and hawk are on the same order of magnitude. Thus, it is reasonable to attribute that the features of the owl wing structures and the wing kinematics might promote quicker turbulence dissipation of characteristic eddies, resulting in shorter correlations. Arndt and Nagel (1972) showed that the wake of the owl-like leading-edge serrated blade was represented by relatively smaller eddies which dissipated rapidly compared to regular blades. In Figure 6.13b, the autocorrelation curve of the vertical turbulent fluctuation component ($R_{22}$) is provided. The $v'$ velocity fluctuation is autocorrelated for both the owl and the hawk over a single wingbeat cycle. Similar to the $R_{11}$, each point in the PIV velocity map is autocorrelated over time and a mean correlation curve is produced. The comparison between both the birds shows no significant difference between the curves. While owl exp1 deviates little from the hawk, the owl exp2 almost overlaps. The vertical velocity fluctuation is correlated with itself over almost the equal time range for both the owl and the hawk over a wingbeat cycle. But a comparison between the autocorrelation of $u'$ and $v'$ velocity fluctuations for each bird (see, Figure 6.13a and 6.13b) shows a significant observation of the differences among the magnitudes of the streamwise and transverse time scales. Compared to the transverse autocorrelation, the streamwise autocorrelation of the owl wake drops rapidly which means the lifetime of the $v'$ fluctuations is significantly higher than $u'$ fluctuations. The disparity between the autocorrelation of the streamwise and vertical velocity fluctuations of the owl wake is distinctly higher than the hawk wake. Swamy et al., (1979) showed that in the region of higher turbulence production, the autocorrelation scales indicate a noticeable disparity between the time scales of streamwise and vertical velocity fluctuations but as the outer region is approached the disparity becomes smaller. The wake of the owl is characterized by higher turbulent production activity (see, Figure, 6.15).

Correlating the streamwise turbulent velocity fluctuation with the vertical turbulent fluctuation between two different times yields the cross-correlation of the velocity fluctuations at one point.
and multi-time. In Figure 6.13c, the correlation curve of the cross-correlation between $u'$ and $v'$ fluctuations ($R_{12}$) is provided. Velocity fluctuations at each point in the PIV maps are cross-correlated over a single wingbeat period and the mean curve is produced. The comparison between the owl and the hawk shows a significant difference in the trends between the birds. The trend of the hawk wake displays maximum positive and negative correlations around the middle at each half of the cycle, and the owl wake trends show maximum positive correlation around the middle of the whole cycle. The cross-correlation between the streamwise and normal velocity fluctuations complements the scatter plot of the fluctuation velocities. Compared to the hawk, the cross-correlation profiles of the owl suggest the non-zero interaction between the streamwise and normal velocity fluctuations over a single wingbeat cycle. For both birds, at the beginning of the cycle, the streamwise and vertical turbulent fluctuations are negatively correlated weakly.

To the best of our knowledge, the turbulent eddy characterization in the flow field of owl flapping flight has not been carried out greatly. This observation of the owl’s wake being characterized with small time scale eddies gives deeper insight into the owl’s silent flight capability and can be associated with the aerodynamic noise generation/propagation through the wake flowfield. In incompressible flows, the turbulent eddy momentum fluctuations act as quadratic noise sources which generate and radiate aerodynamic noise far-field (Lighthill, 1952). The quicker rate of energy supply in the owl wake from the energy-containing characteristic scales to the small scales might naturally return the small scale turbulence to local isotropy and effectively dissipate rapidly: one of the principles of Kolmogorov’s isotropic turbulence theory (Kolmogorov 1941) is that the rate of energy supplied by the large scale eddies is equal to the rate of energy dissipated by the small scale eddies, which leads to the assumption that small scale structure of turbulence is approximately isotropic. The large scale eddies are relatively slower. When the Reynolds number is high, the relatively faster small scale eddies are statistically independent of large eddies and local isotropy exists. Kresta and Wood (1993) showed that local isotopy appeared in the flow field close to the turbine blade where the turbulence activity is intense. As the turbulent intensity is higher close to the blade, it also decays quickly and the small scale turbulence return to local isotropy in the vicinity of the blade. The noise generated by the small scale eddies in the decaying isotropic turbulence is weak compared to that of the large scales eddies which do not contribute to the viscous dissipation (Proudman, 1952).
6.2.2.1 Estimating the integral length scale

The correlation of the velocity fluctuations with respect to space can be carried out in an analogous way to temporal correlation, which examines the wake evolution in space. The spatial correlation coefficient of fluctuating velocity components \( R_{ij} (r) \) at two different positions is defined as:

\[
R_{ij} (r) = \frac{u_i'(x,y,t) u_j'(x+r,y,t)}{\sqrt{u_i'^2} \sqrt{u_j'^2}}
\]

where \( r \) is the spatial separation between the two measurements. Integrating the area under the correlation curve enables us to estimate the integral turbulent length scale \( L_{ij} \):

\[
L_{ij} = \int_0^\infty R_{ij}(r) \, dr.
\]

Integral length scales provide a range of spatial scales where turbulence is active (Pope, 2000): it characterizes the extent of fluid mass as a single entity in space which represents the average size of the eddy. These scales are obtained from the autocorrelation of the fluctuating velocity components in different directions. To estimate and compare the representative flow scales in the near wake of owl and hawk, the autocorrelation of streamwise and normal velocity fluctuations are carried out in their respective and normal directions, as shown in Table 6.1. The length scales are averaged over each PIV field of view and cycle, and then normalized by the respective chord lengths for each bird: \( L_{11} \) is the longitudinal length scale of the streamwise velocity fluctuation \( (u') \) autocorrelated in the streamwise direction \( (x) \) and \( L_{22} \) is the longitudinal length scale of the normal velocity fluctuation \( (v') \) autocorrelated in the normal direction \( (y) \). Similarly, \( L_{12} \) and \( L_{21} \) are transverse length scales correspond to streamwise and normal velocity fluctuations autocorrelated in their normal directions, respectively, \( y \) and \( x \). The computed scales show that both experiments of the owls exhibit relatively smaller \( L_{11} \) and \( L_{12} \) length scales than the hawk. While the longitudinal length scale \( L_{22} \) is almost similar for both birds, the transverse \( L_{21} \) length scale is a little greater for the owl experiments than the hawk. Moreover, the length scales of both birds are relatively much smaller than the chord length. The integral length scales characterize over the distance velocity fluctuations are correlated. The estimated results imply that streamwise velocity fluctuation in the owl wake is relatively locally constrained compared with the hawk in both streamwise and normal directions. The normal velocity fluctuation is scattered higher than the streamwise velocity fluctuation for both birds.
Table 6.1: Characteristic length scales in the near wake of owl and hawk based on the autocorrelation of velocity fluctuations [All the scales are normalized with the respective chord length of the birds].

<table>
<thead>
<tr>
<th>Exp</th>
<th>L11</th>
<th>L12</th>
<th>L22</th>
<th>L21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawk</td>
<td>0.2062</td>
<td>0.2627</td>
<td>0.3007</td>
<td>0.2195</td>
</tr>
<tr>
<td>GHO Exp 1</td>
<td>0.1760</td>
<td>0.1919</td>
<td>0.3115</td>
<td>0.2258</td>
</tr>
<tr>
<td>GHO Exp 2</td>
<td>0.1746</td>
<td>0.1915</td>
<td>0.3006</td>
<td>0.2332</td>
</tr>
</tbody>
</table>

### 6.2.3 Reynolds stress

Momentum transfer is the key feature of the turbulent motion (Tennekes and Lumley, 1972). Reynolds stress represents the mean transport of turbulent momentum by the turbulent velocity fluctuations. Investigating the Reynolds stress enables us to describe the strength of the turbulent fluctuations in the wake flow which represents the relative unsteadiness. In tensor notation, Reynolds stress ($\tau_{ij}$) may be defined as: $\tau_{ij} = \overline{u'_i u'_j}$, where $i$ and $j$ are index notations corresponding to $x$- and $y$- directions, respectively. The Reynolds stress is a symmetric second-order tensor that consists of 9 components. The diagonal components are known as Reynolds normal stresses and the off-diagonal components are Reynolds shear stresses. The two-dimensional two components PIV used in the current study enables us to estimate the following three components of the Reynolds stresses:

- **Streamwise Reynolds normal stress**
  
  \[\overline{u'^2}\] (6.3)

- **Vertical Reynolds normal stress**
  
  \[\overline{v'^2}\] (6.4)

- **Reynolds shear stress**
  
  \[\overline{u'v'}\] (6.5)

The Reynolds stress components illustrated in Figure 6.14 represent the mean flux of the turbulent momentum by turbulent velocity fluctuations in the near wake of the owl and hawk over a single wingbeat cycle. The Reynolds normal stress profiles and the Reynolds shear stress profile show that the wake-flow of the owl carries higher fluctuating momentum flux than the hawk. The vertical turbulent stresses show (Fig 6.14b) significant higher values for the owl flights compared with the hawk flight whilst the streamwise turbulent stresses (Fig 6.14a) appear to be similar, ranging between $1 \times 10^{-3} U_\infty^2$. Overall, the vertical stresses developed in the wake of the owl are three times higher than the ones behind the hawk. Given that the two birds are of similar size and the
wing amplitude during the wingbeat cycle is similar, it is plausible to assume that either the flexibility of the owl’s wing vibrates more compared to the hawk flexibility or the morphological characteristics of the owl wing generates a fluttery motion that increases the vertical turbulent momentum in the wake. Also, it may be associated with the larger vertical \((v)\) velocity component values in the owl’s wake; thus, producing a larger vertical momentum than the hawk’s wake. Given that the owl is heavier than the hawk by \(~30\%\) and flew at a slower speed than the hawk, it could imply that the owl flies at higher AOA than the hawk, that is, the owl pushes more air downwards to stay aloft. The Reynolds shear stress (Fig 6.14c) depicts slightly higher values for the owl compared to the hawk. All three curves show the Reynolds shear stress changes sign around the center of the wake. It is accounted for the fact that the Reynolds shear stress herein accounts for the entire wingbeat cycle, covering upstroke, downstroke, and transition between the phases. The Reynolds shear stresses at the wake of both birds are almost comparable. Though the hawk wake and the owl experiment 2 are almost similar, owl experiment 1 shows an increase in turbulence activity. The discrepancy between the two owl experiments results from collecting data from two different experiments, thus; turbulence, as a chaotic phenomenon, behaves differently during the owl–flow interaction at every instance. The difference was observed at the half upper field of view, which may indicate that the owl flapped its wings a bit differently during the experiments.
Figure 6.14: Horizontally and time-averaged profiles of turbulent stresses and turbulent kinetic energy for single wingbeat cycle a) Reynolds normal stress - streamwise $\overline{u'^2}$ turbulent momentum flux, b) Reynolds normal stress - vertical $\overline{v'^2}$ turbulent momentum flux and c) Reynolds shear stress - $\overline{u'v'}$ turbulent momentum flux. In each plot, the x-axis represents the respective quantity normalized by the square of freestream velocity, and the y-axis represents the height of wake flow field normalized by the relevant chord length of the bird. The $y/c = 0$ in the y-axis marks the middle of wake flow field.

6.2.4 Turbulent energy budget

The turbulent kinetic energy equation (Tsinober, 2001) constitutively describes the inter-relations between the transport mechanism of turbulence within the flow. This scalar equation is commonly comprised form four main terms: rate of change of kinetic energy, turbulent transport, turbulent production, and dissipation. Turbulent kinetic energy ($TKE$) characterizes the energy in the fluctuating velocity field and it is the average kinetic energy per unit mass present in the fluctuating velocity field (Pope, 2000). The transfer of kinetic energy from the mean flow to the turbulent flow allows for the generation of turbulence. The loss of the kinetic energy of the mean flow appears as a gain for the turbulent flow. Here, estimating the $TKE$ facilitates the comparison of the order of the energy gain in the turbulent wake from the mean flow between both birds. The turbulent kinetic energy is generally defined as: $TKE = \frac{1}{2} \overline{u_i'u_i'}$, which has three components for a three-
dimensional flow. The 2D-PIV measurements lead to calculate the \( TKE \) using the streamwise and the normal fluctuating velocity components. When expanded, the turbulent kinetic energy appears as:

\[
TKE = \frac{1}{2} \left( \overline{u'^2} + \overline{v'^2} \right) \tag{6.6}
\]

Turbulent flow requires a continuous supply of energy to maintain itself (Tennekes and Lumley, 1972). The turbulent kinetic energy production (\( TKEP \)) measures the rate at which the kinetic energy of the mean flow is transferred to the turbulent velocity field. The turbulent kinetic energy production is generally defined as: \( TKEP = \overline{u'_i u'_j S_{ij}} \), where \( S_{ij} \) is the mean flow shear strain which can be calculated as, \( S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \); where \( U \) is the mean velocity field. It can be seen that the turbulent production accounts for the contribution of both the turbulent velocity fields (Reynolds stresses) and the mean flow field (velocity gradients of the mean flow). The mean flow velocity gradients define the rate at which turbulent stresses transfer the energy from the mean flow. The \( TKEP \) consists of 9 terms and the 2D-PIV provides the estimates of three individual terms which are contributed by the two Reynolds normal stresses and the Reynolds shear stress. When expanded, the \( TKEP \) for 2D PIV data appears as:

\[
TKEP = \overline{u'^2} S_{xx} + 2 \overline{u'v'} S_{xy} + \overline{v'^2} S_{yy} = \overline{u'^2} \left( \frac{\partial u}{\partial x} \right) + \overline{u'v'} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) + \overline{v'^2} \left( \frac{\partial v}{\partial y} \right) \tag{6.7}
\]

Viscous forces play a huge role in the dissipation of turbulent kinetic energy. The turbulent dissipation rate (\( TDR \)) is the rate at which viscous forces perform deformation work against the fluctuating strain rate and deplete the kinetic energy of the turbulence (Tennekes and Lumley, 1972). The turbulent dissipation occurs at the smallest scale of turbulence which is dissipated by viscous effects. When the steady-state conditions are assumed, in most flows, the rate at turbulent kinetic energy is produced and dissipated is often on the same order of magnitude (Tennekes and Lumley, 1972) assuming the transport term is small (i.e.: triple correlation of the velocity fluctuations). The turbulent dissipation rate is generally defined as: \( TDR = 2 \nu s'_{ij} s'_{ij} \); where the rate of fluctuating strain, \( s'_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \). The TDR comprises 9 components for a three-dimensional turbulent flow, but the 2D PIV measurements enable us to estimate the turbulent dissipation rate from the following three components:
From the fluctuating velocity fields, the turbulent kinetic energy, turbulent kinetic energy production, and the turbulent dissipation rate are calculated for both the owl and hawk over a single wingbeat cycle. A comparison of turbulent kinetic energy profiles of the two birds is depicted in Figure 6.15a. It can be observed from Figure 6.15a that both flights of the owl represent relatively higher turbulent kinetic energy than the hawk, which follows the trends observed for the normal turbulent stresses. The differences show that the turbulent kinetic energy of the owl wake is two times higher than the hawk. This contrasts with the Reynolds shear stress, which is comparable between the wakes of the two species. This is a somewhat contradictory result, as one would expect to see higher turbulent activity given higher rates of kinetic energy distributed to the fluctuating field from the mean flow: kinetic energy of the turbulence benefits from the deformation work done by the fluctuating Reynolds stresses on the mean flow. In many flows, the contribution of the Reynolds normal stresses is relatively less, and Reynolds shear stress is likely to exhibit a predominant role in mean turbulent momentum transport (Tennekes and Lumley, 1972). Compared to the hawk, the profiles of the owl imply more mean flow kinetic energy is lost as a gain for the turbulent fluctuations.

Figure 6.15b depicts the turbulent energy production term calculated from the PIV data. The turbulent production is shown to be suppressed at the hawk wake while the owl demonstrates values that are about 4-5 times higher. The distribution along the vertical direction of the wake shows that for both the hawk and the second experiment of the owl is close to constant, whilst for the owl’s 1st experiment it appears to increase along the vertical direction. This is in line with the Reynolds stress distribution for experiment 1. One possible explanation is an asymmetric flapping over the wingbeat cycle, for the owl, that causes more turbulence to be generated upward than downward. Given that the other two experiments were roughly constant, it is assumed here that this trend is not characteristics of the owl flight.

Figure 6.15c shows the dissipation distribution in the near wake of the birds during flapping flight. It appears that the dissipation at the near wake of the hawk is higher compared to the wake of the owl. The dissipation of the hawk is uniform along the wake whilst for the owl, one can observe some variations. It is expected that the dissipation to be uniform at the wake region since it is a
characteristic of the very small scales of the flow, where mixing is high and at high Reynolds numbers, one assumes that at these scales the flow appears to be more isotropic (Tennekes and Lumley, 1972). However, this is not the case for the owl. The obtained results are treated with care because unlike the production and kinetic energy terms, this term strongly depends on the measurement tool to resolve the smallest scales of the flow (i.e.: Kolmogorov (1941) scales). Here, the PIV resolution, was not sufficient as only the flow up to the integral scale has been resolved (see, Figure 6.16); thus, the turbulence dissipation is underestimated. The dissipation is underestimated also because in the current study 2D PIV data is used and the third direction contribution is lacking. Therefore, a comparison between dissipation and production, in this case, can be misleading.
Figure 6.15: Horizontally and time-averaged profiles of turbulent kinetic energy, production, and dissipation terms for single wingbeat cycle. a) turbulent kinetic energy \( \frac{1}{2}(u'^2 + v'^2) \), b) production term \( u'_i u'_j s' \), and c) dissipation term \( 2\nu s'_i s'_j \). The turbulent kinetic energy is normalized with the square of the freestream velocity and in the other two plots, the x-axis represents the respective quantity normalized by the cubic of freestream velocity divided by the relevant chord length. In each plot, the y-axis represents the height of wake flow field normalized by the relevant chord length of the bird, where \( y/c = 0 \) in the y-axis marks the middle of wake flow field.

6.2.5 Spectral analysis

In order to provide a full description of the turbulence characteristics in the near wake, a spectral analysis of the velocity field has been performed. The energy spectra estimates are based on the theory of Kolmogorov (1941) and the procedure performed by Saddoughi and Verevalli (1994) has been followed. Figure 6.16 depicts the energy spectra of the two velocity components in the streamwise and normal directions. The spectra are presented as a function of spatial wavenumber (Kolmogorov 1941), such that the energy of turbulence is distributed over a range of scales: here, \( E_{11} \) is the autocorrelation spectrum of streamwise velocity fluctuation in the streamwise direction, \( E_{12} \) is the autocorrelation spectrum of streamwise velocity fluctuation in the normal direction, \( E_{21} \) is the autocorrelation spectrum of normal velocity fluctuation in the streamwise direction and \( E_{22} \) is the autocorrelation spectrum of normal velocity fluctuation in the normal direction.
is the autocorrelation spectrum of normal velocity fluctuation in the normal direction. Irrespective of the birds, the energy spectra decay more linearly as a function of the wavenumber which almost follows the slope of the Kolmogorov $k^{-5/3}$ spectrum. Moreover, the observed spectra do not exhibit any clear distinction between the energy-containing range and the dissipation range (where the spectra decay rapidly (Pope 2000)). This suggests that the characteristic length scales of the flow have been resolved and the dissipation scales are under resolved.
Figure 6.16: Time-averaged energy spectrum of fluctuating velocity components for single wingbeat cycle: a) $E_{11}$ – autocorrelation spectrum of streamwise velocity fluctuation in the streamwise direction, b) $E_{12}$ – autocorrelation spectrum of streamwise velocity fluctuation in the normal direction, $E_{21}$ – autocorrelation spectrum of normal velocity fluctuation in the streamwise direction, $E_{22}$ – autocorrelation spectrum of normal velocity fluctuation in the normal direction. The dashed line in figures represents the slope of the Kolmogorov $k^{-5/3}$ spectrum. In all the plots, the x-axis represents the respective kinetic energy per wavenumber and the y-axis represents the wavenumber.
Overall, when comparing the wake-flow turbulent characteristics between both the raptors, the owl wake suggests carrying higher turbulence than the hawk wake. Though the streamwise turbulent stress displayed to be at an almost similar level for both birds, the vertical turbulent stress is almost three times higher for the owl. The TKE profiles of the owl represented a relatively higher value than the hawk as well, mainly because the TKE is comprised of summation of both the streamwise and vertical Reynolds stresses. Besides, the higher values of TKE than the Reynolds stresses are also a common feature in turbulent free shear flows (see figure 5.7; Pope, 2000). As turbulent momentum flux is known as an aerodynamic noise source (Lighthill, 1954), it can be expected that the turbulent signature in the wake of the stealthy owl is minimal than the hawk wake. However, it is observed here that the wake of the hawk is smoother and less turbulent compared to the owl. This observation is in line with the notion that a hawk being a fast flyer requires less drag, more thrust, and maneuverability. The drag formed over the body (viscous drag) during flight is proportional to the speed of the body and also to the turbulence intensity. Reducing the turbulence level (as shown in Reynolds Stresses and TKE) ensures smooth flight with relatively lower drag values for the hawk. On the other hand, the owl generating a higher level of turbulence at the wake might indicate that the drag developed during owl flight will be high, combined with relatively low flight speeds.

The increased turbulence level in the owl wake can plausibly be attributed to their low flight speed, flexible wing, and the features of owl-fluid interaction. The low flight speed requires the owl to fly at relatively higher angles of attack. As has been discussed earlier, stabilizing the flow field over the wing at the high AOA is a major task and involves complex flow features. The role of each special owl wing feature depends on both the Reynolds number and the AOA. At moderate-to-higher AOA, the interaction between the owl’s unique wing features and the flow develops a more complex flow field around, which results in the wake. Klain et al., (2009) showed that as the AOA increases, the Reynolds stress on the owl-like wing surface increases to promote laminar-to-turbulent transition and earlier flow reattachment. Vad et al., (2006) studied the effect of velvet coating on isolated airfoils inspired by owl’s velvety surfaces. The coating increased the wall friction and increased turbulence level at both 5 degrees and 15 degrees AOA. At the higher AOA, the turbulent intensity was increased both in the boundary layer and in the wake, and the wake was thickened. The trailing edge serrations of the owls exhibit a similar association with increased turbulence as well. The Trailing-edge serration-like fences used in the study by Bodling et al.,
(2017) demonstrated that the turbulent kinetic energy near the airfoil trailing edge was redistributed it away from the fences. Chong et al., (2013) showed that the near-wall flow over the airfoils with serrated trailing edges had increased turbulent intensity than those with straight trailing edges. Besides, the wake generated by the trailing-edge serration configuration was mostly turbulent with less identifiable coherent structures.

The temporal and spatial correlation of the turbulent fluctuations (see, Figure 6.13a and Table 6.1) in the current study reveals that the owl wake carries relatively smaller eddies characterized by smaller length and time scales than the hawk. The temporal correlation illustrates that the eddies in the owl wake undergo quicker deformations. The flow structures in the near wake of the owl are relatively less correlated in the streamwise distance than the hawk wake. These results are in agreement with the previous finding by Lawley et al., (2019) that the near wake of a boobook owl during the flapping flight was governed by un-energized small scales, where a distinct shedding at the vorticity field was not observed, unlike other birds where organized shedding was observed. Studies suggest that the owl and flow interaction result in the reduction of flow scales. Klañ et al., (2009) observed for all cases that the velvety-like surface reduced the size of the vortices and the distance between them compared to the clean wing. The size of the flow structures was rather smaller than the clean surfaces. At higher AOA, wing models without serrations are prone to separation bubbles that extend over the entire span of the wing. But the leading-edge serration localizes the separation bubbles and reduces the size of the separated region over the airfoil behind the root of each serration (Chen et al., 2016). This might reduce the coherence of the vortices in the spanwise direction as well which was not measured in the current study. Rao et al., (2017) showed that beyond 15 degrees AOA, the serrated wing models had leading-edge vortices broken into small eddies by the leading edges serrations which scatter and might suppress the vortex shedding. Arndt and Nagel (1972) showed that the eddies shed by leading-edge serrated blades dissipated rapidly compared to regular blades.

The population of the wake with small-scale turbulence increases the TKEP of the near wake region, as observed in Figure 6.15b. The TKEP indicates the process of energy from the large scales (mean flow) to their smallest scales (turbulence); as this value increases, it suggests that turbulence increases and is transported toward the small scales. One may assume that if the TKEP is high, given the energy balance equation for TKE, then the dissipation rate (see, Figure 6.15c)
will be high (see, e.g., figure 5.16; Pope 2000 depicting the energy budget components for a self-similar round jet). However, this is not shown in the current case. It is suggested that the dissipation depicted in Figure 6.15c is under-estimated due to the PIV resolution. In order to fully resolve dissipation, one should (1) measure the full 3D wake and (2) resolve the smallest scales of the flow (Kolmogorov, 1941). The PIV system used in the current study provided 2D data and the PIV resolution (which comprises the camera size, field of view, and the choice of interrogation window size) was sufficient to resolve the turbulent scales (see, Table 6.1) but not the dissipative ones. This notion is supported by Figure 6.16, where the energy spectra of the turbulent velocity components are estimated. It is shown that two cascades of the spectra were resolved, spatially (k = 10-100 m$^{-1}$) without indication of resolving the dissipative scales: the spectra curve would have trended downward, instead, the spectra tail curves which are an indication of the PIV resolution (Hackett et al., 2009). In conclusion, the near wake of the owl exhibited significantly higher turbulent activity than the hawk. It is suggested that the interaction between the features of the owl and the flow modulates the turbulence in the near wake by generating relatively small scales within the wake region, which could undergo relatively quicker deformations. The summary of the comparison between the estimated turbulent characteristics in the near wake of both birds is tabulated in Appendix A. Further, in Appendix B, the comparison between the turbulent wake-flow characteristics between both birds during the gliding phase is shown which demonstrates a similar difference between the two species and reinstates that the turbulent levels are comparatively higher during flapping than the gliding.
6.2.6 Uncertainty analyses of mean and turbulent quantities

The uncertainty of the estimated mean velocity components, instantaneous vorticity, Reynolds normal stresses, Reynolds shear stress, turbulent kinetic energy, integral length, and time scales have been calculated for both the owl and the hawk. The PIV uncertainty propagation methodology presented by Sciacchitano and Wieneke (2016) has been employed here to estimate the uncertainty of the mean and turbulent quantities measured from the experiments.

- The uncertainty of the mean velocity ($ar{u}$) is calculated as:
  \[ U_{\bar{u}} = \frac{\sigma_u}{\sqrt{N}} \]  
  where $\sigma_u$ is the standard deviation of the velocity component $u$, and $N$ is the sample size.

- The uncertainty of the streamwise Reynolds normal stress is given as:
  \[ U_{R_{uu}} = \sigma_u^2 \frac{2}{\sqrt{N}} \]  
  (6.10)

- The uncertainty of the vertical Reynolds normal stress is given as:
  \[ U_{R_{vv}} = \sigma_v^2 \frac{2}{\sqrt{N}} \]  
  (6.11)

- The uncertainty of the Reynolds shear stress can be calculated as:
  \[ U_{R_{uv}} = \sigma_u \sigma_v \sqrt{\frac{1 + \rho_{uv}^2}{N-1}} \]  
  (6.12)
  where $\rho_{uv}$ is the correlation coefficient between $u$ and $v$ velocity components.

- The uncertainty of the turbulent kinetic energy is obtained as:
  \[ U_{TKE} = \sqrt{R_{uu}^2 + R_{vv}^2} \cdot \frac{1}{\sqrt{2N}} \]  
  (6.13)
  where $R_{uu}$ and $R_{vv}$ are the streamwise and vertical Reynolds normal stresses, respectively.
• Besides, the uncertainty of the integral length scale and time scales have been obtained using the standard uncertainties for the mean quantities relation, similar to Equation 6.9.

• The uncertainty of the instantaneous vorticity is obtained using:

\[ U_\omega = \frac{u}{d} \sqrt{1 - \rho(2d)} \]  

where \( U \) is the local standard uncertainty of the velocity, \( d \) is the grid spacing and \( \rho(2d) \) is the cross-correlation coefficient of the measurement error at two points separated by the distance \( 2d \).

The local standard uncertainty of the velocity components is assumed to be equal for both velocity components and the grid spacing is considered uniform in both \( x \)- and \( y \)-directions. The second-order difference method based least squared scheme has been used to estimate the vorticity in the current case, which provides the smallest error in instantaneous vorticity (Raffel et al., 2007). To estimate the uncertainty of the vorticity, cross-correlation coefficient \( \rho(2d) \) is considered to be 0.45 suggested by Sciacchitano and Wieneke (2016) for \( 32 \times 32 \) pixels interrogation window and 75% overlap factor. The calculated uncertainty of the instantaneous vorticity fields ranges from 8-10%.

The estimated uncertainties of the other quantities are summarized in table 6.2 below.

<table>
<thead>
<tr>
<th>Quantities</th>
<th>Estimated uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Owl Exp1</strong></td>
<td><strong>Owl Exp2</strong></td>
</tr>
<tr>
<td>Mean velocity (m/s)</td>
<td>0.0003</td>
</tr>
<tr>
<td>Streamwise Reynolds normal stress (m^2/s^2)</td>
<td>0.0007-0.0015</td>
</tr>
<tr>
<td>Vertical Reynolds normal stress (m^2/s^2)</td>
<td>0.0090-0.0106</td>
</tr>
<tr>
<td>Reynolds shear stress (m^2/s^2)</td>
<td>0.0019-0.0040</td>
</tr>
<tr>
<td>Turbulent kinetic energy (m^2/s^2)</td>
<td>0.0051-0.0061</td>
</tr>
<tr>
<td>Integral length scale</td>
<td>9e-4</td>
</tr>
<tr>
<td>Integral time scale</td>
<td>2e-5</td>
</tr>
</tbody>
</table>
Chapter 7

Summary and conclusion

Owls exhibit unique flight capabilities in the low $Re$ flight regime which is prone to complex viscous flow phenomena. They are well known for their typical low-speed flight, flexible wing structure, and ability to fly silently. One of the major characteristics that distinguish owls from the other raptors is their unique wing and feather features, which are generally classified as leading-edge serrations, trailing-edge fringes, and the velvety upper surface. Besides the shape of their wing planform and flexible wing structure, these specific owl features are postulated to help them to fly stably at low speeds and high angles of attack, and yet fly silently in the unsteady flow setting. Though the flights of owls have been studied for multiple decades, no conclusive agreement has been attained behind the aerodynamic mechanisms associated with the owl flight. Moreover, most available studies focused either on prepared owl wings or owl-like wings that replicate gliding flight. The aerodynamics of owls during flapping flights is severely scarce in the literature. In order to gain a comprehensive understanding of the aerodynamic mechanisms of owls during flapping flight, it is necessary to account for the aerodynamic implications of complex wingbeat kinematics, all wing features, and the natural wing structure, inclusively. Analyzing the near wake flow fields behind the flapping wings could serve the purpose of accounting for all the aforementioned aspects.

The overall objective of the current research is to ameliorate the understanding of the aerodynamics of owls’ flapping flight by virtue of the turbulent wake footprint, the lift-drag characteristics, the energy required during flapping flight. Such comprehensive analysis of aerodynamic and flow characteristics exhibited during a wingbeat cycle can provide insight into the aerodynamic mechanisms associated with the features of owl-flow interaction. To fulfill the objective, the near wake flow behind a freely flying great horned owl was measured in a wind tunnel along with a similar-sized Harris’s hawk. The hawk is a diurnal raptor and the owl is the nocturnal raptor. The choice of the hawk along with the owl is to carry out a comparative analysis between two distinctive raptors which can help to differentiate the features associated with the unique owl flight. The birds were trained to fly inside a large wind tunnel in a perch-to-perch flight style due to their larger sizes. The near wake velocity fields behind the flapping wing of the birds were sampled
using a long duration time-resolved PIV system and the kinematics of the birds were characterized using high-speed imaging, simultaneously. The weight and the geometrical details of the birds were measured during the experiments. Multiple flights were conducted over a span of two days and large velocity and kinematics data sets were acquired; approximately 8 flights per day and 1700 vector maps per flight. Each flight was identified manually from the kinematics videos and the kinematics images were extracted. The extracted kinematics images enabled us to estimate the flight speed of the birds during each flight and the location of the laser light sheet along the wing planform. Both the owl and the hawk had the same wingspan length. Further, wing kinematics analysis revealed that both the owl and the hawk shared similar wingtip amplitude and wingbeat frequency.

The energy requirements of the owls during either gliding or flapping flight is a gap in the literature. While birds spend higher than the resting metabolic energy during gliding, it increases even further during the flapping flight (Dial, 1992). Understanding power expenditure during flight can help to associate it with the wing morphology, aerodynamic performances, and evolution of bird flight (Elliott et al., 2013). Due to the difficulties associated with measuring flight costs of the birds, models based on aerodynamic theories have been commonly used in the literature. These models assume typical values for input parameters such as drag coefficients and morphological data, if unavailable. Here, the aerodynamic and metabolic power requirements of owl and hawk during flapping flight have been calculated using theoretical models, in conjunction with most of the input parameters directly derived from our experiments. The owl is about 30% heavier than the hawk and the kinematic analysis revealed that the owl flew approximately 2 m/s slower than the hawk. The results showed that both the total aerodynamic power output and the metabolic power output of the owl are comparatively higher than the hawk at its average forward flight speed. It is in line with the notion that the owl experiences higher drag than the hawk (typically a fast flier) which requires relatively more aerodynamic power to fly. The induced power was less than the profile power for the hawk and higher than the profile power for the owl. Induced power scales are inversely proportional to the flight speed and directly proportional to the weight-squared (ref, Equation 4.5). Owl, as a heavy but slow flier, encounters a major contribution of its total power output coming from the induced power component. Even though both aerodynamic and metabolic power requirements of the owl were higher than the hawk, the flight muscle mass-specific power
outputs were comparatively lower. The heavier owls flying at their typical low flight speeds suggest requiring relatively less effort from their flight muscles than the similar raptor, hawk.

Further, a power-speed curve (aerodynamic and metabolic) for both raptors has been established for a range of flight speeds from 0-18 m/s. At all speeds, the total power output of the owl is considerably higher than the hawk which can be related to the contribution from the induced power due to its heavy body mass and higher drag. However, the divergence between the birds contracted when comparing the flight muscle mass-specific power output, particularly at low speeds. Both birds displayed U-shaped relationships with the forward flight speed and it is shown that the minimum power speed of the owl is inclined toward their typical low flight speed. The estimation of the power output at the average forward flight speed of both birds accounted for the effect of the Reynolds number and high confidence can be reserved on the estimation. But the aerodynamic models might under-or-overestimate the power curve. It is not known that how the profile power or parasite power varies across the Reynolds number for both birds and a typical value is assumed for all the speeds. Both drag coefficients are a function of the Reynolds number and it should be taken into account for improving the accuracy of the estimations for a range of flight speed. Nevertheless, it is shown that the aerodynamic model has estimated the power outputs to the appropriate range, though not accurate. Further, the experimental flight path has been simplified with alternating unpowered and powered flight phases, based on the observation during the experiments. The energy expenditure during the intermittent flight style has been estimated using the energy budget. The mechanical energy conversion along the flight path geometry demonstrated that the total power output of the powered phase during the intermittent flight is substantially lower for the owl than the hawk, which is contributed by the higher energy available for the owl at the start of the flight and its relatively lower speed during the powered phase. Nevertheless, the intermittent flight style reinforces the resulting energy savings and reduced aerodynamic power output for the flying birds compared to the continuous flapping flight (Rayner et al., 2001).

In order to compare the aerodynamic forces of both raptors during flapping, the sectional profile drag coefficient and the cumulative lift coefficient have been estimated using viscous momentum equations, directly from the wake velocity fields measured using PIV. Estimates are carried out for two flights of the owl and one flight of the hawk over a single wing beat cycle which met the selection criteria. The comparisons of both the lift and drag characteristics showed that a
significant difference exists in the trends of drag and lift variation over a wingbeat cycle between both raptors. While the profile drag of the owl stayed positive throughout the cycle, the hawk showed negative drag values around the mid of the upstroke, where the negative drag denotes the thrust. The hawk has been known to actively adjust its wingspan during the flight to reduce the profile drag (Pennycuick et al., 1992). Overall, the average drag produced by the owl is shown to be two times higher than the hawk over a wingbeat cycle. Both birds, accumulated lift starting from the downstroke and reached the maximum around the end of the downstroke. While the accumulated lift of the owl stayed almost constant for the rest of the cycle, the lift coefficient of the hawk started diminishing during the transition and reduced drastically at the end of the cycle. The ‘passive’ flow control mechanisms of owls as a result of fluid-structure interaction due to the flexible wings and the role of wing morphological features have been previously suggested (Winzen et al., 2015; Rao et al., 2017). It is shown that flying at relatively low speed and high angle of attack, the sustained high lift variation of the owl over a wingbeat cycle compared to the hawk can be attributed to its passive flow control mechanisms. Moreover, due to the nature of the current experiments only a single wingbeat cycle was available to estimate the lift-drag characteristics for each flight. Substantial data with continuous multiple wingbeat cycles is required to estimate and compare the evolution of lift-and-drag over time between both the raptors during steady level continuous flapping flight.

The near wake flow fields of both raptors have been described by mean velocity fields, vorticity field, and turbulent fluctuation fields. Besides, the spatial and temporal correlation of the turbulent fluctuations, Reynolds stresses, turbulent kinetic energy, production, and dissipation terms have also been evaluated in the near wake flow. Two flights of the owl and one flight of the hawk, which met the selection criteria, are used for the wake-flow analysis. Firstly, in order to account for the speed of the birds, which transforms the data into a non-inertial coordinate system, the instantaneous PIV velocity values have been adjusted with both the horizontal and vertical components of birds’ flight speed. The bird speed correction did not affect the trends of the velocity at the wake and the spatial derivatives fields showed to be invariant of the velocity field. The spatially averaged velocity time series has been calculated by taking the mean of the velocity field over each map and plotted over a single wingbeat cycle. The consecutive peaks in the normal velocity profiles demonstrated the single wingbeat cycle completed by the birds close to the PIV field of view. The decay of the velocity profile further represented the gliding of the birds toward
the perch. It is shown that the streamwise velocity temporal profiles complement the normal velocity profiles depicting distinct peaks that result from the wing motion. Comparisons of the mean velocity fields demonstrated that the near wake flow field of the owl is dominated by relatively lower velocity values than the hawk, indicating a larger velocity deficit. The owl wake showed a streamwise extended wide wake deficit than the hawk from the bottom of the flow field. The mean vorticity time series indicated that both birds display a similar trend of vorticity profile where the peaks are observed around the start and the end of the wingbeat cycle. A comparison between the consecutive vorticity contours which belonged to the same range of upstroke phase for both birds has been shown. The results demonstrated that, qualitatively, the owl’s wake is characterized by smaller vortices than the hawk. While the hawk showed larger vorticity regions of the same levels, the owl showed more concentrated relatively smaller vorticity regions.

In order to extract the turbulent velocity fluctuation field from the instantaneous velocity fields, an ensemble average has been applied. The normalized turbulent fluctuation fields displayed that the turbulent activity is significant for both birds in the near wake behind the flapping wings. The owl wake appeared to be highly perturbed compared to the hawk wake leading to relatively higher turbulent wake activity at the same wingbeat phase. The temporal correlation of the velocity fluctuations has been carried out to estimate the integral time scale of the larger eddies. The results suggested that the turbulent structures in the owl wake are characterized by substantially smaller time scales than the hawk wake which might deform at a relatively quicker rate. To estimate and compare the characteristic spatial flow scales in the near wake of owl and hawk, the spatial autocorrelation of streamwise and normal velocity fluctuations are carried out in their respective and normal directions. The computed scales showed that both experiments of the owls exhibited relatively smaller integral length scales than the hawk. The results implied that streamwise velocity fluctuation in the owl wake is relatively locally constrained compared to the hawk in both streamwise and normal directions. Further, the estimations of Reynolds stresses revealed that the vertical turbulent stress is almost three times higher for the owl than the hawk, while the streamwise turbulent stress exhibited to be at a similar level for both birds. The $TKE$ profiles of the owl represented a relatively higher value than the hawk as well, mainly because the $TKE$ is comprised of summation of both the streamwise and vertical Reynolds stresses. Both the Reynolds stresses and the $TKE$ have suggested that the owl wake is characterized by relatively higher turbulence levels than the hawk. As a stealthy flier, it can be expected that the turbulent signature
in the wake of the owl is minimal than the hawk wake; however, contractedly it is observed that the hawk wake is smoother and less turbulent than the owl. This observation is in line with the notion that a hawk being a fast flyer requires less drag, more thrust. The reduction of the turbulence level ensures a smooth flight with relatively lower drag values for the hawk. Though the owl wake showed higher turbulent levels, on the other hand, the temporal and spatial correlation of the turbulent fluctuations has shown that the owl wake carries relatively smaller eddies characterized by smaller length and time scales than the hawk. The smaller length and time scales ensure the flow structures in the wake of the owl undergo quicker deformations and dissipate early. Previously in other studies, the interaction between the owl wing morphology and the turbulent flow has been shown to produce less coherent structures and small-scale vortices. The population of the wake with small-scale turbulence increases the $TKE_P$ of the owl in the near wake region as shown. The increase in $TKE_P$ in the owl indicates that turbulence increases and the energy from the large scales are transported toward the small scales. As the $TKE_P$ is higher for the owl, given the energy balance equation for $TKE$, a higher dissipation rate can be expected for the owl wake. But, it is observed that the turbulent dissipation is underestimated. The PIV resolution in the current study is shown to be not sufficient to resolve the dissipation scales. Besides, dissipation is a strong three-dimensional phenomenon and the contribution of the third dimension is lacking in the current study. Therefore, a comparison between dissipation and production in the current case can be misleading. Overall it has been shown that the near wake of the owl is characterized by significantly higher turbulent activity than the hawk. It is suggested that the interaction between the features of the owl and the flow modulates the turbulence in the near wake by generating eddies that are characterized by relatively smaller time and length scales that could dissipate rapidly. The flexible wing structures, unique feather features and the wingbeat kinematics of the owls in synergy suggest generating small time-and-length scale turbulent eddies that can dissipate quickly and have strong implications in their noiseless flight associated with turbulent generated noise.
Appendix A

Comparisons of general characteristics and estimated turbulent characteristics of great horned owl and Harris’s hawk

<table>
<thead>
<tr>
<th>Bird</th>
<th>Great horned owl</th>
<th>Harris hawk</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Specifications</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size and weight</td>
<td>large, heavier</td>
<td>large</td>
</tr>
<tr>
<td>Flight speed</td>
<td>slow</td>
<td>fast</td>
</tr>
<tr>
<td>Wings aspect ratio</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>Angle of attack (flight)</td>
<td>high</td>
<td>low to moderate</td>
</tr>
<tr>
<td>Aerodynamic performance (L/D)</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td><strong>Flight features</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stealth</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Active time</td>
<td>nocturnal</td>
<td>diurnal</td>
</tr>
<tr>
<td><strong>Wake flow characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vorticity distribution at the wake</td>
<td>small patterns, higher values</td>
<td>large patterns</td>
</tr>
<tr>
<td>Vorticity averaged over the wingbeat cycle</td>
<td>similar</td>
<td>similar</td>
</tr>
<tr>
<td><strong>Turbulence characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integral time scale</td>
<td>small</td>
<td>larger</td>
</tr>
<tr>
<td>Integral length scale</td>
<td>small</td>
<td>larger</td>
</tr>
<tr>
<td>Vertical turbulent stress</td>
<td>high (×3&gt;)</td>
<td>low</td>
</tr>
<tr>
<td>Reynolds shear stress</td>
<td>slightly higher</td>
<td>slightly lower</td>
</tr>
<tr>
<td>Turbulent kinetic energy</td>
<td>high (×2&gt;)</td>
<td>low</td>
</tr>
<tr>
<td>Turbulent kinetic energy production</td>
<td>high (×4&gt;)</td>
<td>low</td>
</tr>
<tr>
<td>Turbulence dissipation</td>
<td>low</td>
<td>high</td>
</tr>
</tbody>
</table>
Appendix B

Near wake-flow turbulence characteristics during gliding phase

During the experiments, a significant portion of each flight corresponded to the gliding phase. Irrespective of both the birds exhibited intermittent flapping during the chosen perch-to-perch flight style. The choice of intermittent flight is energy-saving for flapping birds and they may need to impart lesser perturbations into the wake. In order to analyze the turbulent flow characteristics during the gliding phase, the same turbulent properties calculated over a single wingbeat cycle were estimated for the chosen three flights during the gliding flight. Omitting the dataset belonging to the flapping phase, the rest of the dataset was considered for the gliding phase.

In Figure B.1, the vertical profiles of the Reynolds stresses are compared between the owl and the hawk. The Reynolds normal stress profile \( u'^2 \) shown in Figure B.1a shows owl wake carries higher streamwise turbulent momentum than the hawk during gliding. The profile of the hawk is almost constant and the owl profiles are inclined downward from the upper part of the wake. While the values of the owl profiles range from 2.5-5.8 \( U_\infty^2 \), the value of the hawk profile is about 1.2 \( U_\infty^2 \). The \( v'^2 \) – normal stress profiles plotted in Figure B.1b demonstrates similar behavior between the birds. Though in this case, the hawk profile too varies downward, the range is relatively narrow of about 0.6-1.4 \( U_\infty^2 \). In comparison, the owl wake suggests carrying relatively higher vertical turbulent momentum flux than the hawk. Similar to streamwise turbulent stress, owl’s vertical turbulent stress also exhibits steep variation downward from the upper part of the wake. The range of the \( v'^2 \) varies from 1.5-4.3 \( U_\infty^2 \) for the owl profiles which is about three times higher than the hawk.

The comparison between the Reynolds shear stress profiles is provided in Figure B.1c. The values of the shear stress appear to increase downward for the owl while the hawk profile is almost constant. Similar to the normal stress components, the shear component of the owl is also higher than the hawk. The owl exp 1 exhibits a steep variation of the Reynolds shear stress from 1-8 \( U_\infty^2 \). The profile of the owl exp 2 shows little different behavior compared to the exp 1. For the owl experiment 2, the shear stress increases until around the center of the wake from the upper part and reduces during the lower part of the wake.
Figure B.1: Horizontally and time-averaged profiles of turbulent stresses and turbulent kinetic energy for single wingbeat cycle. a) Reynolds normal stress - streamwise $u'^2$ turbulent momentum flux, b) Reynolds normal stress - vertical $v'^2$ turbulent momentum flux and c) Reynolds shear stress - $u'v'$ turbulent momentum flux. In each plot, the $x$-axis represents the respective quantity normalized by the square of freestream velocity, and the $y$-axis represents the height of wake flow field normalized by the relevant chord length of the bird. The $y/c = 0$ in the $y$-axis marks the middle of wake flow field.
Figure B.2: Horizontally and time-averaged profiles of turbulent kinetic energy, production, and dissipation terms for single wingbeat cycle. a) turbulent kinetic energy \( \frac{1}{2}(u'^2 + v'^2) \), b) production term \( u_i' u_j' s_{ij} \), and c) dissipation term \( 2v' s_{ij}' s_{ij}' \). The turbulent kinetic energy is normalized with the square of the freestream velocity and in the other two plots, the \( x \)-axis represents the respective quantity normalized by the cubic of freestream velocity divided by the relevant chord length. In each plot, the \( y \)-axis represents the height of wake flow field normalized by the relevant chord length of the bird, where \( y/c = 0 \) in the \( y \)-axis marks the middle of wake flow field.
The comparison between the turbulent kinetic energy profiles of the two birds is provided in Figure B.2a. It can be observed that the owl wake carries relatively higher TKE than the hawk. The trend of the TKE profiles closely follows the trends of the normal stress components. The profile of the hawk is almost constant while the TKE values of the owl increase downward from the upper part of the wake. The range of the TKE for the owl profiles vary from around 2-5 $U_\infty^2$ while the value of the hawk is around 1.2 $U_\infty^2$. The comparisons of the three stress components suggest that the owl wake carries relatively higher turbulent momentum flux than the hawk during gliding, and the TKE profiles emphasize the higher turbulent activity in the owl wake than the hawk.

Figure B.2b depicts the comparison of the turbulent production term between the owl and the hawk. It can be observed that the hawk wake exhibits suppressed turbulent production and the owl values are 3-5 times higher. The hawk profile appears to be almost constant while the owl profiles increase downward similar to the other stresses and the TKE. The results suggest that the turbulent production in the owl wake is higher than the hawk during gliding flight. When comparing the two experiments of the owl, owl experiment 2 exhibits relatively higher turbulent production than the owl experiment 1. Figure B.2c shows the comparison between the dissipation distribution in the near wake of the two birds during gliding flight. It can be seen that the dissipation at the near wake of the owl is higher compared to the wake of the hawk. In line with the other turbulent profiles, the dissipation of the hawk is uniform along the wake whilst for the owl, steep variation can be observed from the upper part of the wake toward to lower part.
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