

Toward Efficient Bio-inspired Propulsion: The Effect of Propulsor Shape and Kinematics on System Performance and Efficiency During Bio-inspired Locomotion

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Academic Abstract

Both bird and fish locomotion are thought to be more efficient than the equivalent manmade vehicles driven by propellers/impellers and jet engines. Through studies that decompose the different kinematic and shape effects of these biological systems, we can understand what leads to their high cruising performance and efficiency. Two major studies were conducted. The first was on the effect of different kinematic parameters of large soaring birds on flight performance and the second was on the effect of caudal fin shape on the performance of thunniform swimmers. For the first study on flight performance, flapping, folding, and twist were the wing motions of interest. The second study on swimming performance observed how caudal fin sweep angle affects propulsion while isolating the effect of this shape difference from aspect ratio and area effects. Low order models were primarily used to conduct the bird flight study, though experimental methods were investigated as well. The thunniform swimming study was conducted through experimentation on a biomimetic system.

The flight study found that, under the right circumstances, both wing twist and wing folding have a positive effect on flight performance. However, the impact of wing twist is much larger. To incorporate this wing twist into a robotic system, a new reduced order model that partially accounts for 3D effects was developed and validated. In the future, this model can be used in conjunction with a flight controller to control wing twist.

The swimming study found that caudal fin sweep had a significant impact on performance, moderately swept fins showing the greatest improvement. Using an overly large sweep angle led to diminished performance when compared to the moderately swept fins, but still demonstrated improved performance over a non-swept fin. The increased performance of the moderately swept fins was due to how it affected LEV formation and stability.

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General Audience Abstract

Bird flight and fish swimming are thought to be more efficient than drones and submersible vehicles respectively. By conducting studies on the motion of the wing and the shape of the tail fin, we can gain a better understanding of how to produce efficient vehicles that are inspired by fish/birds. Two major studies were conducted. The first study analyzed the wing motion of birds such as seagulls. The three most important wing motions were analyzed using fast computational simulations. Functional flapping aircraft that can be used in future studies were also constructed. The second study analyzed the tail fin shape of tuna, specifically how the swept shape affects propulsion performance. This study was conducted by operating a robotic tuna with interchangeable tails in a water tunnel.

The computational studies on wing motion showed that controlling twist of the wing in addition to typical flapping motion could greatly improve performance of a flapping bird-like aerial vehicle. To incorporate this wing twist into a future system, a mathematical model that provided aerodynamic predictions was developed. This model can be used in conjunction with a controller to provide efficient real time control of the wing twist.

The experimental swimming study found that fin sweep had a significant impact on performance. Using a moderately swept fin (25-35 degrees) increases thrust production without increased energy expenditure. Fins with greater sweep angles start to yield diminished performance benefits. Using an elliptical area distribution can also lead to increased performance.

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1. Introduction

The flight of birds has inspired aviators and engineers since before the Wright brothers' historic first flight. In fact, the earliest aircraft designs like Leonardo da Vinci's flying machine utilized flapping wings to generate thrust rather than now traditional propellers and jet engines. While these are more effective methods of propulsion than flapping wings at the scale of passenger carrying aircraft, flapping flight is thought to be more efficient at the scale of the animals that employ it [1].

The same can be said for aquatic animals with hydrodynamic efficiencies that can exceed 90% based on Particle Image Velocimetry (PIV) results [2]. One genus that exhibits this high efficiency is thunnus (comprised of species of true tuna), which are known to swim at relatively high speeds for long periods of time [3]. It has even been suggested that thunniform locomotion may be the most efficient mode of swimming at high speeds [4]. Thus, there is interest in applying the swimming physics they utilize to autonomous underwater vehicles (AUVs).

During the first decade of the 21st century, there were numerous studies on the flight of birds, insects, and robots that attempted to mimic them. While research on insects continue and interest in bat flight has gained momentum [5, 6], the number of publications relating to the physics/application of flapping bird flight have decreased dramatically in recent years. This trend is ironic because the use and manufacture of "drones" has by contrast drastically increased. Most of these drones are multicopter aircraft that suffer from poor endurance and require a very high power to weight ratio to maintain flight. On the other hand, many avian species have excellent power to weight ratios that rival even the most efficient fixed wing aircraft. Some species of seagull have power to weight ratios as low as 45 W/kg [7]. If an avian-inspired robotic system could achieve this level of performance, it would make it ideal for long duration and range missions.

Unlike research on the flapping flight of birds, investigations into fish propulsion have continued at a steady pace. Moreover, unlike bird-inspired aircraft, fish-inspired vehicles have achieved efficiencies very close to those of similar biological systems albeit at lower velocities. For example, RoboTuna achieved theoretical hydrodynamic efficiencies of up to 91% when optimal swimming kinematics were used [8].

1.1. Objective

1.1.1. Avian-inspired flight

If avian-inspired robots have the potential to be so commercially effective, why did research in the area of mimicking bird flight diminish? The answer may be a lack of innovation or enhancement of performance in tested designs. Many of the designs used in the most recent literature today are identical to designs developed over a decade ago. These are designs with a single active degree of freedom at the root of the wing, a stiff leading edge spar, and a passively twisting/deforming membrane-like wing surface. This style of wing does not capture the intricacies of the avian wing, which have many more mechanisms, including sensing and actuation, which are utilized during avian flight. Furthermore, the structure and geometry of these wings are fundamentally different. Perhaps by imitating more from nature we can come closer to the performance demonstrated by soaring birds.

While flapping bird-sized systems in the literature have not evolved much there have been a handful of robotic systems that have achieved better performance, most notably Festo's SmartBird. This robotic system is already more than four years old and unfortunately still represents the pinnacle of avian-inspired flight. Even more unfortunate is the lack of published data on the system [9] All researchers can do is speculate about how it achieved flight with its impressively small 23 Watt DC motor. What is known is that SmartBird used a bird-like wing geometry. Both the wing cross-section and planform shape resemble that of a seagull's. In addition to basic wing root flapping, SmartBird also applied an active geometric wing twist towards the tip of the wing. Lastly, it utilized wing folding that was constrained to wing root flapping by a linkage system. It is speculated that the outer wing section provides lift and thrust while the inner wing section provides lift, an aerodynamic force distribution similar to what occurs during seagull flight [9]. The wing geometry, kinematics, and fluid dynamics are inspired by nature, and can be observed during seagull cruising flight. Thus, further implementing nature's mechanisms may be the key to improved artificial flapping flight.

With these gaps in the literature identified, this dissertation examines the effect of additional active wing degrees of freedom (DOFs) on flight aerodynamics and performance, specifically wing folding and wing twist. This has been done through low order computationally inexpensive modeling that allows for comprehensive parametric studies to be performed [10].

Low order models can be used not only for parametric studies, but also to provide aerodynamic force estimates to a control system on flapping aircraft. To facilitate advancement of avian-inspired aircraft with multi-DOF wings an improved aerodynamic model based on lifting line theory has been developed. This model is aimed at properly estimating not just total lift but also spanwise distribution to better estimate forces on the different joint separated wing sections.

1.1.2. Thunniform-inspired swimming

Several additional tuna-inspired robots have already been constructed and tested [11, 12]. Most of these have actuators concentrated in the rear of the body as thunniform locomotion is characterized by little displacement of a fish's anterior and greater posterior oscillation [4]. This dissertation presents two tuna-inspired robots that continue the trend of posterior focused actuation.

The robots discussed in this dissertation were chiefly designed and constructed to test the effect of the caudal fin's shape on swimming performance. Other studies have examined different aspects of the caudal fin in non-thunniform swimming fish. Currently in the literature are experiments examining the effect of fin aspect ratio, flexibility, kinematics, and coupled change in shape, area, and aspect ratio. [13-15] However, there is a lack of experimental investigations that isolate the effect of caudal fin geometric shape in not only thunniform swimming fish but also all caudal fin based locomotion. A computation fluid dynamics (CFD) study on the effect of caudal fin geometry has been published, but focuses on leading edge vortex (LEV) formation and fluid flow patterns rather than performance. Furthermore, the tested fins had different aspect ratios [16].

Thus, the presented robots will be used to determine the effect of not only caudal fin kinematic parameters, such as Strouhal number (St) and angle of attack, but also caudal fin geometric shape on thrust production and power. This is extremely relevant to future bio-inspired AUV design as understanding the effect of caudal fin shape would directly influence propulsor geometry. Correct selection of geometry could be very "cost effective" as it could increase performance and efficiency without increasing the complexity of the system.

1.1.3. Parallels between thunniform swimming and avian flight

At an initial glance, a tuna's locomotion and a bird's flight may seem disconnected, but there are many similarities in their mechanics. First, the Reynolds number (Re) of both seagull cruising flight and tuna swimming are both on the order of $Re \sim 10^5$. Second, both systems pitch their

propulsor as they oscillate it to generate thrust and maintain attached/reattached flow. In fact, unlike most other fishes, tuna generate most of their thrust via the leading edge suction phenomena and lift based mechanisms [4] similar to how birds generate lift and thrust.

Additionally, understanding shape effects through parametric testing of caudal fins rather than flapping wings is ideal as thunniform swimmer caudal fins demonstrate low flexibility. Also, unlike a flapping bird wing the entire fin experiences uniform oscillation and pitching. This means that propulsor shape and kinematics/deformation are more independent of each other in a fish caudal fin than in a flapping bird wing. For these reasons, the studies in this dissertation on fishing swimming and bird flight complement each other, and conclusions drawn from each are fairly cross compatible.

1.2. Approach

1.2.1. Avian-inspired flight

As mentioned previously, it is likely that by imitating more of DOFs in the avian wing that performance will increase. However, this increase in performance comes at the cost of complexity. Thus, it is important to understand the benefits of the DOFs independently. Wing folding and twist in addition to the root flapping motion were chosen for analysis as they seem to be two of the predominant motions during gull flight, and were utilized in SmartBird, the most efficient avian-inspired robot to date. To understand the effects of wing twist and wing folding independent of each other, many cases need to be examined. Multiple parameters describe the folding and twisting motions. Inclusion of each of these parameters increase the number of cases required to precisely analyze their effects by more than an order of magnitude each. High order modeling such as Naiver Stokes based computational fluid dynamics (CFD) can offer a great deal of fidelity, but is computationally expensive, and thus time consuming. This greatly diminishes the total number of cases that can be run in a parametric study when using CFD [17]. Low order models that still capture than major unsteady effects through corrections are ideal as they computationally inexpensive allowing for a vast number of cases to be run. A previously validated model is used for the parametric study, and thus it is assumed that the provided estimates are accurate.

While most low order models designed to analyze bird-like flapping wings can estimate total lift on single active DOF wings, they do not properly represent spanwise lift distribution. This is not an issue when the chord (the line between the leading and trailing edge of a wing cross-section)

at every cross-sectional slice along the entire wing lies on the same plane throughout the entire flap cycle. This results in all the cross-sectional lift and thrust/drag vectors pointing in the same directions. Once the wing starts to deform as in a multi-DOF wing, the sectional aerodynamic force vectors are no longer oriented in the same direction. Accurately estimating the magnitudes of these individual vectors instead of simply estimating their average becomes essential, as it will change the ratio between the total lift and drag components for the entire wing. Thus, a new low order model that is based on lifting line theory has been developed. Lifting line theory takes into account the effect of a cross-section's lift on its neighbors; this produces a more accurate representation of spanwise circulation, which in the case of a fixed wing, decreases from the wing root to wing tip [18]. The original lifting line formulation was not designed for unsteady situations, and thus modifications were made to account for the horizontal velocity component due to flapping, leading edge vortex formation (LEV), and unsteady wake effects. This model still assumes flow is attached at the trailing edge of the wing, meaning cannot be used to describe situations where relative angle of attack is extremely large (approximately greater than two times the static stall angle). Thus, this model is most applicable for cruising flight as well as basic maneuvering and not applicable for takeoff, landing and hovering flight. It also is not applicable for the flapping flight of very small birds and insects, which seem to consistently utilize very high angles of attack.

1.2.2. Thunniform-inspired swimming

An experimental approach was chosen to identify the effects of caudal fin shape, and was performed in a low velocity, low turbulence water tunnel. Water tunnel testing was chosen over free swimming assessment as it allowed for several elements that increased control of the study. First, use of a tethered robot in a water tunnel eliminates the need for the robot to self-stabilize reducing its complexity and increasing reliability. Second, using a water tunnel allows for direct measurement of thrust force produced by the caudal fin, while only velocity measurements via visual tracking are feasible during a free swimming assessment. Third, it allowed for the two key dimensionless parameters Re and St to be decoupled by varying flow velocity of the tunnel and frequency of the robots tail beat independently. Lastly, it allows for straightforward flow visualization. As the tunnel is circulating, diffractive microspheres can be evenly distributed throughout the moving fluid, which is not easily accomplished in a stagnant pool or tank. Using a laser sheet, flow directly around a 2D cross-section of the caudal fin could be visualized. For the investigation, the caudal fins tested all had the same thickness, planform area, and aspect ratio.

Flex of the fin was almost non-existent (less than a 0.5mm deflection at the tip), eliminating the effect of geometry on rigidity. Thus, shape was successfully decoupled from other kinematic and geometric parameters, something that has not been implemented in previous studies.

1.3. Outline

As this research contains many different elements, a roadmap of the document has been provided here. Chapter 2 provides background of flapping flight including information on structure and kinematics of bird wings as well as the aerodynamic mechanisms that make it different from fixed wing flight. Chapter 3 discusses how the effects of different degrees of freedom can be analyzed and what the effects of these different degrees of freedom. This discussion is primarily focused on reduced order methods, but also talks about how possible experimentation can be conducted. Chapter 4 presents an improved model to the one used in Chapter 3 as well as potential applications for it. In Chapter 5, the models used in Chapters 3 and 4 are compared with experimental results to check the validity and compare their accuracy.

Chapter 6 introduces the swimming portion of the research by providing background on the kinematics of fish locomotion, the tuna body shape, and the hydrodynamics of their swimming. In Chapter 7, a preliminary study of caudal fin shape effects is discussed. While the data from this preliminary study is not conclusive, many lessons were learned from it that were applied to a more in-depth study. This more in-depth study of caudal shape effects is presented in Chapter 8 where thrust data, energy expenditure, and flow structures are compared between tails.

The conclusion of the research is presented in Chapter 9, where the major contributions of this work is discussed. Potential experiments and simulations that could expand on what has been done or validate the current work are also presented in that chapter.

2. Background: Flapping flight

Flapping flight is used in more than one million species of insects [19], approximately ten thousand species of bird [20], and more than one thousand species of bats [21]. Despite all these groups coming from different evolutionary branches, they all use this type of aerial locomotion. Flapping flight is essentially the method that evolution has converged upon to achieve powered flight [22]. Biological flapping flight can generally be broken up into two categories, which are insect flight, and vertebrate flight. Apart from their members being in separate subphylum, they are distinguished from one another by the Reynolds number (Re) they operate at and their wing morphology. The Re represents the ratio between inertial and viscous forces and is used to describe nature's fliers and swimmers and is shown below in Eq. (2.1.) where U is freestream velocity, c is the characteristic length (wing chord length for fliers), and ν is kinematic viscosity. The Re of insects are much lower than that of vertebrates as they fly at slower speeds and have smaller wings.

$$Re = \frac{Uc}{\nu} \quad (2.1.)$$

Vertebrates and insects have very different wing morphologies as well. Vertebrate wings are morphologically more complex than insect wing. Bird and bat wings possess several more active degrees of freedom than insects that allows for control over shape and kinematics over a large portion of the span while insect wings are actuated only at the root. [22] Vertebrates may need to utilize more complex wing kinematics because they operate at higher Re than insects [22]. Unfortunately, this has not been confirmed and should be an area of future work. Even though the comparatively large wing complexity of vertebrates should warrant increased investigation, there is considerably less literature on flapping bird and bat flight than on insect flight [9, 22].

2.1. Avian wing structure and kinematics

The wing structure and kinematics of fliers can range from the relatively simple wings of insects, which only have three degrees of freedom at the shoulder, to the incredibly complex wings of bats, which can have 26 degrees of freedom per wing [23]. Birds fall in the middle of this range of complexity. As shown in Figure 2.1, a bird wing contains a significant number of bones. However, most wing movements can be modeled with three linkages derived from the humerus, radius/ulna, and carpus/phalanges. Attached to the carpus/phalanges are the primary feathers; the

secondary feathers are attached to the radius/ulna, and sometimes the humerus. As these feathers extend rearwards from the aforementioned bones, they do not cover them. This is the role of the coverts, which are connected to the tissue around the radius/ulna and metacarpus. Tertiary feathers, which extend from the region close to the humerus (but do not directly connect to the humerus), often are not visible on the wings of smaller birds. The tertiary feathers are not considered flight feathers because they do not contribute to lift thrust [24].

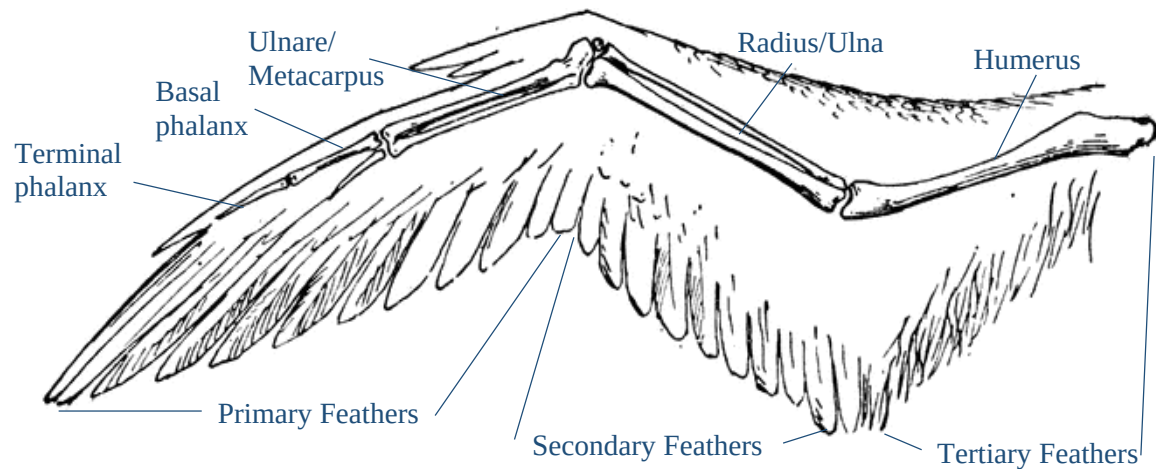


Figure 2.1: Bird wing skeletal structure (Reprinted from [25])

The relative lengths of the humerus, ulna, and carpus vary across species, and even more so across genera. Larger soaring bird wings tend to have a proportionally longer humerus and radius/ulna than smaller birds, which makes the secondary section of the wing longer, as shown in Figure 2.2 (taken from [26]). Conversely, smaller birds can have no visible tertiary feathers. Instead, they have proportionally longer primary feathers that extend from the phalanges. In many smaller birds, these primary feathers make up the majority of the wing as well as create a sharp leading edge [27] that is only as thick as the feather itself.

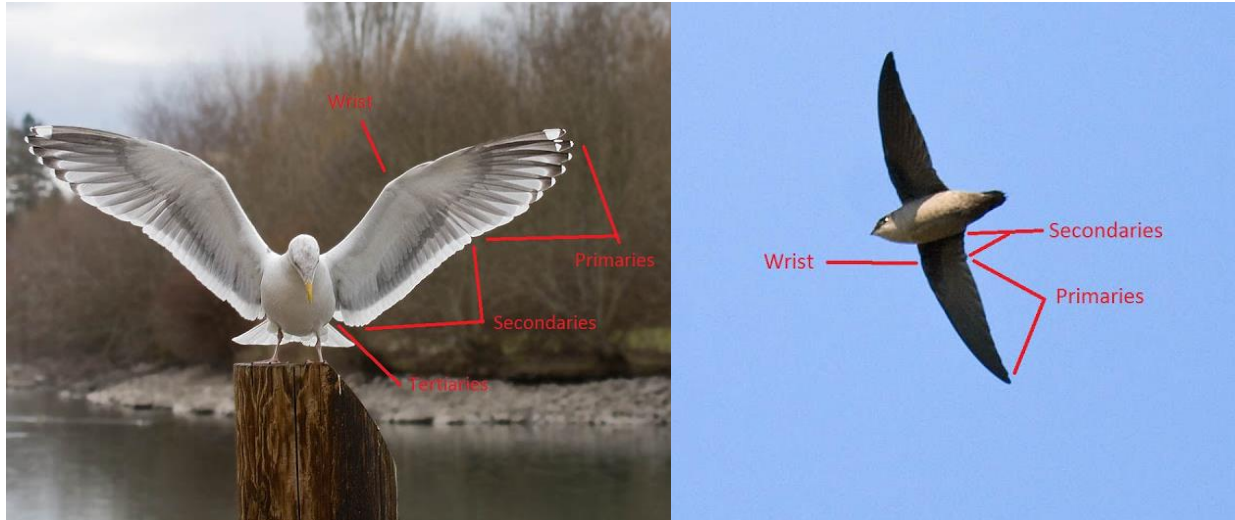


Figure 2.2: Western gull and Vaux's swift feather arrangement (Taken from [26])

While the full range of wing movement can be modeled with three linkages, it is believed that during level flapping flight, a reduced model with just two linkages and three to six degrees of freedom can be used [28]. The two-link model is supported by Figure 2.3, which shows the final wing position of the extreme up and downstroke of a gull. In both these positions, there seems to be only two points of rotation, one at the wrist and the other at shoulder. At the shoulder is a simple vertical flapping motion and at the wrist is a more complex vertical folding and lateral sweep [28]. Not discussed in [28] is torsion of the wing, which occurs at either the shoulder or the wrist, and is utilized by all birds [22]. The study conducted in [29] is the only known study providing detailed documentation of this dynamic wing torsion.

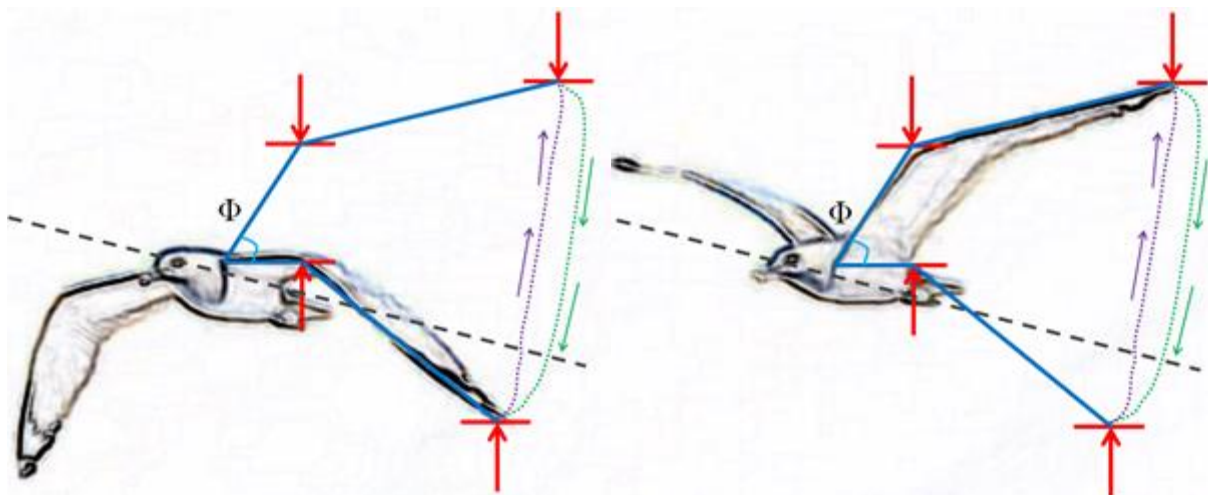


Figure 2.3: The up and downstroke of a seagull wing shows two clear points of deflection

2.2. Flapping aerodynamics

Low Re flapping the flight (generally insect flight) due to its high frequency is primarily governed by added mass, Leading edge Vortex (LEV) formation, and non-circulatory effects such as clap and fling, and wake capture [30, 31]. High Re ($Re > 10^4$) flapping cruising flight (generally vertebrate flight) due to low flap frequencies is governed primarily by traditional circulatory mechanisms. However, LEV formation does occur in vertebrate flight similar to insect flight [22]. The formation of LEVs are thought to produce large amounts of lift in forward flight of both slow flying birds and bats [32, 33]. However, the LEV may not be as important for faster flight. The sharp leading edge is one of the factors that assists in formation of LEVs in vertebrates [27, 34]. In bats, the sharp leading edge occurs along the whole wing, and in birds, along the primary section of the wing.

The LEV allows more downward momentum to be transferred to the fluid by avoiding full separation [31, 35]. LEV presence while increasing lift also increases the amount of drag acting on wing (still less than fully detached flow) [36]. In insect flight, the LEV does not just simply delay stall but instead remains attached through the entire stroke, causing stall to be avoided altogether [22]. It is not fully known whether stall avoidance, as opposed to delay, occurs in bird flight too, but it is suggested to be the case [22]. At the low Re associated with insect flight, axial flow along the wing, due to centripetal force, greatly stabilizes the LEV [37]. This stabilization, due to centripetal force, could occur for bird wings as well, as their rotational motion is similar to that of insect wings. In order to further prevent flow separation, birds tend to fly in the turbulent regime. To do this, they trip the flow at lower Re to force transition, because the turbulent regime is more resistant to flow separation [38].

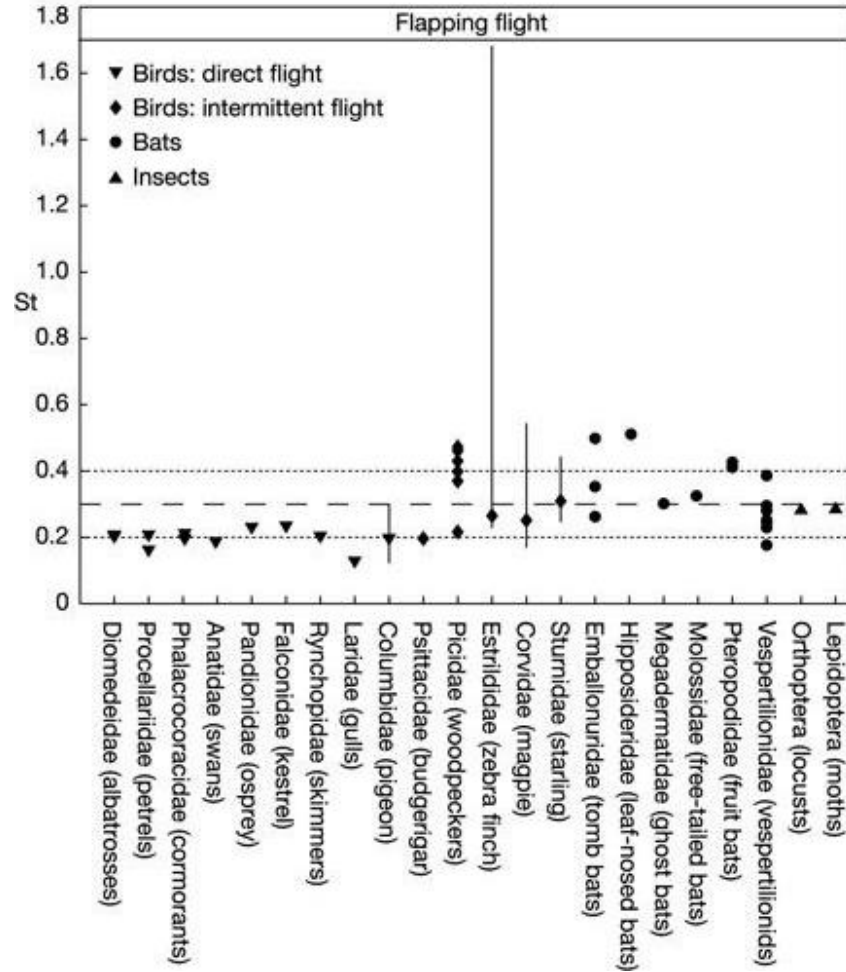


Figure 2.4: Strouhal number of different species of birds, bats, and insects (Taken from [39])

LEV formation, through the delayed stall effect, has several benefits, but typically generates unsteady wake effects that can reduce maximum lift and cause around a five degree shift in phase [9]. Moderately flexible wings similar to bird and insect wings can improve propulsive efficiency by flexing to reduce shedding [40, 41]. Also, wing flexibility helps compensate for the phase offset caused by delayed stall effect [42]. The ratio of the unsteady effects to inertial effects is given by Strouhal number (St), a dimensionless number. St is commonly used to describe different types of biological/biomimetic flapping and swimming systems that produce vortex shedding, and is given by Eq. (2.2.), where f is the operating frequency (flapping frequency of tail beat frequency), U is the freestream velocity, and L is the tip displacement of either wings in flyers or the oscillating fin in swimmers.

$$St = \frac{fL}{U} \quad (2.2.)$$

During an experimental studies on flexible flapping wings, propulsive efficacy peaks in the 0.1 to 0.2 St range [40]. At St higher than 0.2, wing flexibility becomes more important for maintaining efficient propulsion.[40] Moreover, many avian fliers utilize a St slightly higher than 0.2, as shown above in Figure 2.4 (taken from [39]). Flexibility while leading to increased thrust can also cause a large increase in drag if flexibility is too great [40]. As a result, control over amount of flexibility is crucial to performance. Lastly, wing flexibility also leads to improved stability during gusts [43].

2.3. Analysis multi-DOF avian and avian-inspired wings

There is limited literature available on the impact of multiple active DOFs in a bird-sized wing, and even less that includes a parametric study on these DOFs. There are two notable computational analysis in the literature. Han [44] used a boundary element method in which three different DOFs are varied to determine their individual aerodynamic contribution. The analysis indicated flapping with wing folding yielded a higher lift and thrust coefficient than single DOF flapping. However, in this analysis wing twist is fixed for all cases. Reichert et al. [45] uses an analytical model to predict the effect of wing folding, wing sweep, and twist amplitude on thrust production. This analysis indicated that wing folding and sweep, which are linked in this study, have a small impact on thrust coefficient when a wing has a high suction efficiency. Both of these studies [44, 45] do not consider energy expenditure.

Only two experimental studies examining a two or more DOF avian-sized wing exist in the literature [46, 47]. The first was a benchtop test in which freestream velocity was zero [46]. In the second [47], free flight testing was performed on an ornithopter with a passively folding wing. During the free flight testing, it was found that depending on folding joint stiffness, folding can increase thrust or lift production (depending on stiffness of the joint) with similar energy expenditure to a non-folding wing [47]. However, in this study wing twist is passive and not measured. Furthermore, the effect of twist is not discussed.

3. Decomposition of the effects of three avian mimetic wing motions

Many species of birds articulate their wings not only at the root, but also along the span. This motion is complex and varies among species. These complex motions could be a large contributor to the excellent flight performance and efficiency of birds [44]. Using a computationally inexpensive aerodynamic model and the avian based kinematics discussed in this chapter, a parametric study was performed. This study is unique in that it considers the effects of wing folding with independent variation of twist angle amplitude, time averaged twist angle, and twist angle phase on aerodynamics and energy expenditure. Furthermore, unlike many previous works, this study includes the effect of wing inertia in addition to aerodynamic forces on energy expenditure.

3.1. Nomenclature

Variable	Description
t	Time
dL	Sectional lift
dT	Sectional thrust
$L(t)$	Total lift
$T(t)$	Total thrust
x_s	Semispan length
x_f	Shoulder to folding joint length
$\kappa_1(t)$	Flapping angle relative to horizontal
$\dot{\kappa}_1(t, x)$	Flapping angular velocity
$\kappa_2(t)$	Folding angle relative to horizontal
$\dot{\kappa}_2(t, x)$	Folding angular velocity
$\alpha'(x)$	Effective angle of attack
$\alpha(x)$	Relative angle of attack
$\alpha_0(x)$	Zero Lift Line
$\bar{\theta}$	Mean wing pitch angle relative to freestream
ρ	Fluid density
$c(x)$	sectional chord length
c_{avg}	average chord length
U	Freestream velocity
$V(x)$	Sectional relative velocity due to free stream and wing motion

$\ddot{\theta}(t,x)$	Sectional pitch acceleration
$\dot{\theta}(t,x)$	Sectional pitch velocity
$\eta_s(x)$	Sectional suction efficiency
C_f	Friction drag coefficient
dF_n	Sectional normal circulatory force
dF_a	Sectional normal force due to added mass
dF_s	Sectional leading edge suction force
dF_c	Section drag force due to camber
dF_f	Sectional drag force due to viscous effects
$\phi(t,x)$	Sectional wing pitch angle relative to flapping axis
A_1	Dynamic twist amplitude at wingtip
A_2	Dynamic twist amplitude at folding joint
ψ	Dynamic twist and flapping angle phase offset (twisting wing)
ψ_1	Dynamic twist and flapping angle phase offset of secondary wing section (folding wing)
ψ_2	Dynamic twist and flapping angle phase offset of primary wing section (folding wing)
δ	Time averaged twist angle at wingtip (twisting wing)
δ_1	Time averaged twist angle at folding joint (folding wing)
δ_2	Time averaged twist at wingtip (folding wing)
f	Flapping frequency
x	Span location (x=0 shoulder joint)
m_{wing}	mass of wing semispan
g	gravitational acceleration
$P_{inertial}$	Effect of inertia power
P_{aero}	Effect of aerodynamic forces on power
M_{1i}	Moment around flapping axis due to inertia
M_{1a}	Moment around flapping axis due to aerodynamic forces
M_{2i}	Moment around folding axis due to inertia
M_{2a}	Moment around folding axis due to aerodynamic forces
F_{i2y}	y-component of force due to inertia at folding joint
F_{i2x}	x-component of force due to inertia at folding joint
F_{a2y}	y-component of force due to aerodynamics at folding joint
F_{a2x}	x-component of force due to aerodynamics at folding joint

3.2. Low order aerodynamic modeling

In order to obtain the aerodynamic forces acting upon a multi degree of freedom flapping wing, a version of Modified Strip Theory (MST) that was most recently improved by Kim et al [48] was used. The original MST model was developed by DeLaurier et al [49]. MST has several advantages over other low order aerodynamic models because it includes representations of several physical phenomena that occur during flapping flight. These are leading edge suction force, friction drag, and unsteady vortex wake effect. It also accounts for the transition point and different flow characteristics between the attached flow, dynamic stall, and post-stall regimes. Furthermore, as this is a low order model, many cases can be run in a reasonable amount of time.

MST calculates total lift and thrust force by summing the different forces acting on strips of the wing. If these strips have an infinitesimally small thickness, total lift $L(t)$ and thrust $T(t)$ can be given by the integrals shown in Eqs. (3.1.) and (3.2.) respectively. It is assumed that the kinematics of each semispan are identical; thus, each integral is multiplied by a factor of two.

$$L(t) = 2 \int_0^{x_f} \cos(\kappa_1) dL + 2 \int_{x_f}^{x_s} \cos(\kappa_1 + \kappa_2) dL \quad (3.1.)$$

$$T(t) = 2 \int_0^{x_s} dT \quad (3.2.)$$

According to MST, each of these strips have five forces acting upon them. When the flow is attached, these forces are as follows. dF_n , which acts perpendicular to the chord, is caused by fluid circulation around the airfoil. dF_a , which acts perpendicular to the chord, is due to the added mass (aka virtual mass, or apparent mass effect). dF_s , which acts parallel to the chord, is due to leading edge suction. dF_c , which acts parallel to the chord, is due to camber of the airfoil. Lastly, dF_f , which acts parallel to the chord, is caused by viscous friction effects. These five forces dF_n , dF_a , dF_s , dF_c , and dF_f are shown respectively below in Eqs. (3.3.)-(3.7.).

$$dF_n = \pi(\alpha' + \alpha_0 + \bar{\theta})\rho c V U dy \quad (3.3.)$$

$$dF_a = \frac{\pi \rho c^2}{4} \left(U \alpha - \frac{1}{4} c \ddot{\theta} \right) dy \quad (3.4.)$$

$$dF_s = \eta_s \pi \left(\alpha' + \bar{\theta} - \frac{1}{4U} c \dot{\theta} \right) \rho c V U dy \quad (3.5.)$$

$$dF_c = -\pi \alpha_0 (\alpha' + \bar{\theta}) \rho c V U dy \quad (3.6.)$$

$$dF_f = -C_f \frac{\rho c U^2}{2} dy \quad (3.7.)$$

The combination of the five forces that are responsible for total sectional lift and thrust force are shown in Eqs. (3.8.) and (3.9.).

$$dL = (dF_n + dF_a) \cos(\phi) + (dF_s + dF_c + dF_f) \sin(\phi) \quad (3.8.)$$

$$dT = (dF_s + dF_c + dF_f) \cos(\phi) - (dF_n + dF_a) \sin(\phi) \quad (3.9.)$$

When the flow detaches from the leading edge and reattaches along the tail of the airfoil, a leading edge vortex (LEV) is formed and the airfoil is understood to be in dynamic stall. MST accounts for this phenomenon and predicts its occurrence when $\alpha > \alpha_{(static, max)}$. MST models the LEV by rotating dF_s (suction force) 90 degrees so it acts perpendicular instead of parallel to the chord as shown in Eqs. (3.10.) and (3.11.).

$$dL = (dF_s + dF_n + dF_a) \cos(\phi) + (dF_c + dF_f) \sin(\phi) \quad (3.10.)$$

$$dT = (dF_c + dF_f) \cos(\phi) - (dF_s + dF_n + dF_a) \sin(\phi) \quad (3.11.)$$

MST can also attempt to account for post-stall behavior, which is where the flow is fully detached. However, lift and drag estimates of an airfoil operating within this regime have a high margin of error and thus cases that exhibit this behavior were excluded from the analysis.

3.3. Applying avian geometry and wing kinematics

In order to perform the wing twist and folding parametric study, the system analyzed had to have realistic geometric and kinematic parameters. In order to do this, these parameters were taken from observations made on nature's fliers, specifically birds of the *larus* genus, popularly known as gulls. The wings used in this analysis have a tip-to-tip span of 1.41 meters and a chord length of 0.162 meters. The mass of the system was 0.89kg and the operating frequency was 3.46 Hz.

Span, chord length, mass, and flapping frequency were based on measurements of the *larus dominicanus* and taken from [50]. The planform of the wings was estimated to be rectangular and the airfoil used was an s1223, which is designed to operate at lower Re (<200,000). The s1223 was chosen for its geometric similarity to a seagull's wing cross-section as discussed in [28].

Flight speed of the system was determined to be 11.9 m/s. It was taken from radar data on the *larus fuscus* provided by [51] as no flight speed data on the *larus dominicanus* was available. *Larus fuscus* is very similar to *larus dominicanus* in both mass and wingspan so this speed data was thought to be an adequate estimation.

The complex wing motion of the gull can be closely approximated by three degrees of freedom defined by three time variant angles. These are the flapping angle κ_1 occurring at the wing root, the dynamic twist angle ϕ , and the folding angle κ_2 . The location and orientation are given in Figure 3.1 below. The motion of κ_1 is given by the sinusoidal function represented by Eq. (3.12.). The amplitude of κ_1 is 20.9 degrees and the mean of κ_1 is 5.4 degrees. This is taken from kinematics data on seagulls as documented in [28]. κ_1 is positive when the wing root is angled above the horizontal. The variables f and t represent flapping frequency and time in seconds respectively.

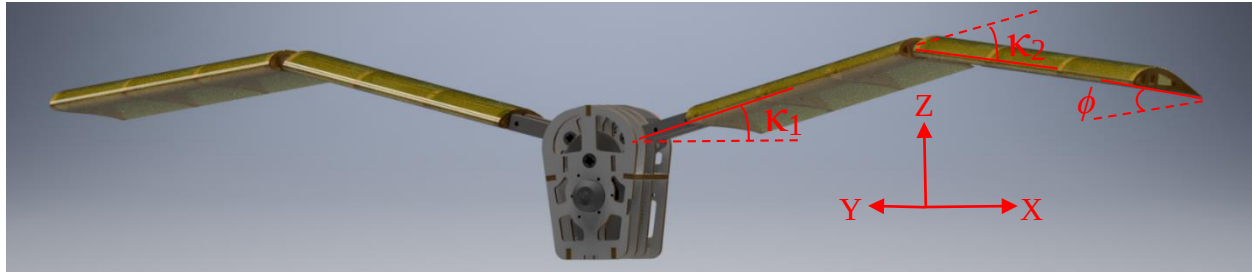


Figure 3.1: Three time variant angles, flapping angle κ_1 , the dynamic twist angle ϕ , and the folding angle κ_2 , utilized while flapping (Reprinted from [10])

$$\kappa_1(t) = \frac{20.9\pi}{180} \cos(2\pi ft) + \frac{5.4\pi}{180} \quad (3.12.)$$

For the folding wing scenario, the motion of κ_2 is given by Eq. (3.13.) and was originally derived in [28] from video. This equation closely approximates the wing kinematics of seagulls in cruising flight.

$$\kappa_2 = C_1 \sin(2\pi ft + C_5) + C_2 \cos(2\pi ft + C_5) + C_3 \sin(4\pi ft + 2C_5) + C_4 \cos(4\pi ft + 2C_5) \quad (3.13.)$$

$$C_1 = 17.3083 \quad C_2 = -11.0122 \quad C_3 = -9.6131 \quad C_4 = 1.3128 \quad C_5 = -1.1498$$

Folding occurs at the interface between the secondary wing section and primary wing section. Thus, the secondary wing section, sometimes referred to as the arm wing, can be defined as the section between shoulder joint (where x is equal to 0) and the folding joint (where x is equal to x_f). The primary wing section, sometimes referred to as the arm wing, can be defined as the section between the folding joint and the wingtip (where x is equal to x_s). κ_2 is positive when the primary section is angled below the plane extending from the secondary section.

For a non-folding wing, dynamic wing twist angle ϕ is a function of span location and is represented by Eq. (3.14.). ϕ is positive when the trailing edge of the airfoil is lower than the leading edge. The amplitude of ϕ is set to vary linearly along each semispan and is zero at the shoulder joint and A_1 at the wingtip. Time averaged wing twist also varies linearly along the entire wing and is equal to δ at the wingtip. The phase offset between the flapping motion κ_1 and the wing twist ϕ is given by ψ .

$$\phi(x, t) = \frac{x}{x_s} (-A_1 \sin(2\pi ft + \psi) + \delta) \quad (3.14.)$$

For a folding wing, ϕ becomes a piece wise function and is represented by Eqs. (3.15.) and (3.16.). For the secondary wing section, ϕ is the same as Eq. (3.14.). For the primary section of the wing, the amplitude of ϕ is set to vary linearly from the fold point, where twist amplitude is given by A_1 , to the wingtip, where twist amplitude is given by A_2 . Time averaged twist varies linearly in each of the two wing sections. The phase offset between the flapping motion and the wing twist is given by ψ_1 and ψ_2 for the secondary and primary sections respectively.

$$\phi(x, t) = \frac{x}{x_f} (-A_1 \sin(2\pi ft + \psi_1) + \delta_1) \quad (3.15.)$$

When $x < x_f$

$$\phi(x, t) = \frac{x - x_f}{x_s - x_f} (-A_2 \sin(2\pi ft + \psi_2) + \delta_2) \dots$$

$$\dots - \frac{x - x_f}{x_s - x_f} (-A_1 \sin(2\pi ft + \psi_1) + \delta_1) - A_1 \sin(2\pi ft + \psi_1) + \delta_1 \quad (3.16.)$$

When $x_f < x < x_s$

3.4. The effects of wing twist and folding on flight performance

3.4.1 Aerodynamics of a twisting wing

In order to perform the parametric study, MST as well as the kinematics of the system were coded using MATLAB. The semispan was broken into 25 equal segments, each with a width of 2.82cm. For each case, a full flap cycle was run. Since MST is not history dependent, subsequent flap cycles would be identical to the first.

For the non-folding scenario, A_1 was varied from 0 to 15 degrees in increments of half a degree, ϕ was varied from -10 to 10 degrees in increments of one degree, and δ was varied from 0 to 15 degrees in increments of half a degree. This totaled to 20181 cases for this scenario.

Based on data from the run cases, kinematic parameters for two optimal flight scenarios were determined. The first is where thrust is maximized with the condition that lift force is greater than or equal to the force of gravity acting on the system (8.72 N). This ensures level or climbing flight while maximizing speed. The second is where lift is maximized but thrust force is greater than or equal to zero (assuming negligible body drag). This ensures constant or increasing forward velocity while maximizing payload capacity or climb rate. Lift, thrust, and kinematic parameters are shown below in Table 3-1. In Figures 3.2-3.7, individual kinematic parameters are isolated to determine their effect on lift and thrust.

Table 3-1: Lift, thrust, and twist parameters of optimal flight scenarios for a twisting wing

	Maximizing Thrust	Maximizing Lift
<i>Lift (N)</i>	11.22	19.24
<i>Thrust (N)</i>	1.09	0.01
<i>A₁ (degrees)</i>	6.5	9.5
<i>ψ (degrees)</i>	-2	-4
<i>δ (degrees)</i>	3.5	11.5

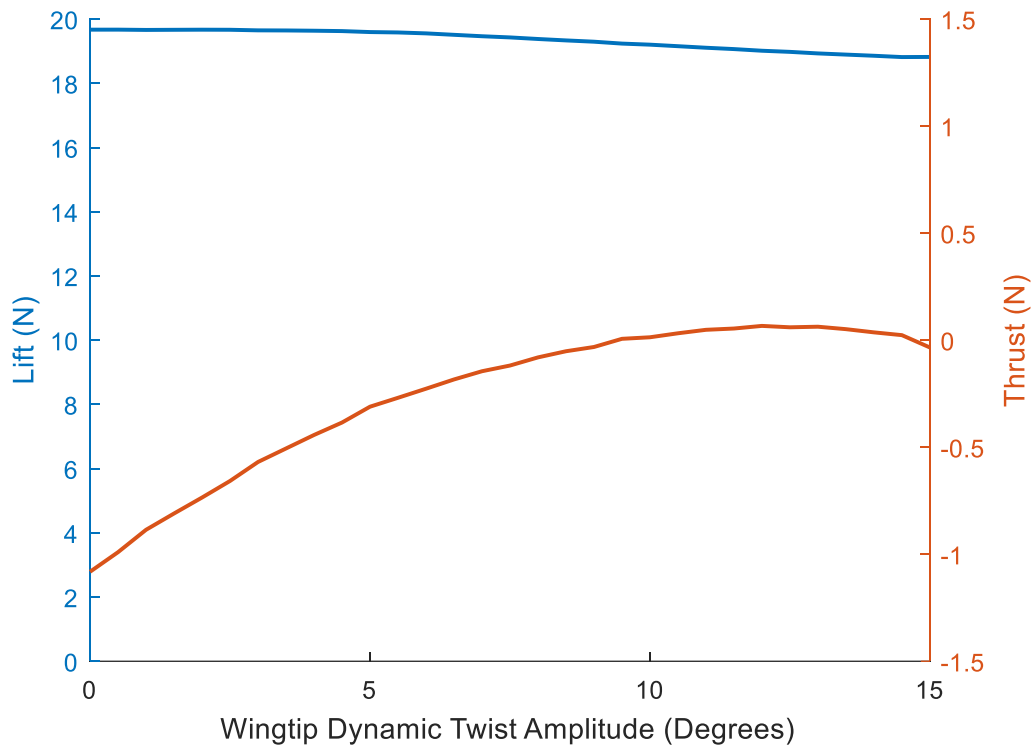


Figure 3.2: Effect of A_1 on lift and thrust, maximizing lift scenario (Reprinted from [10])

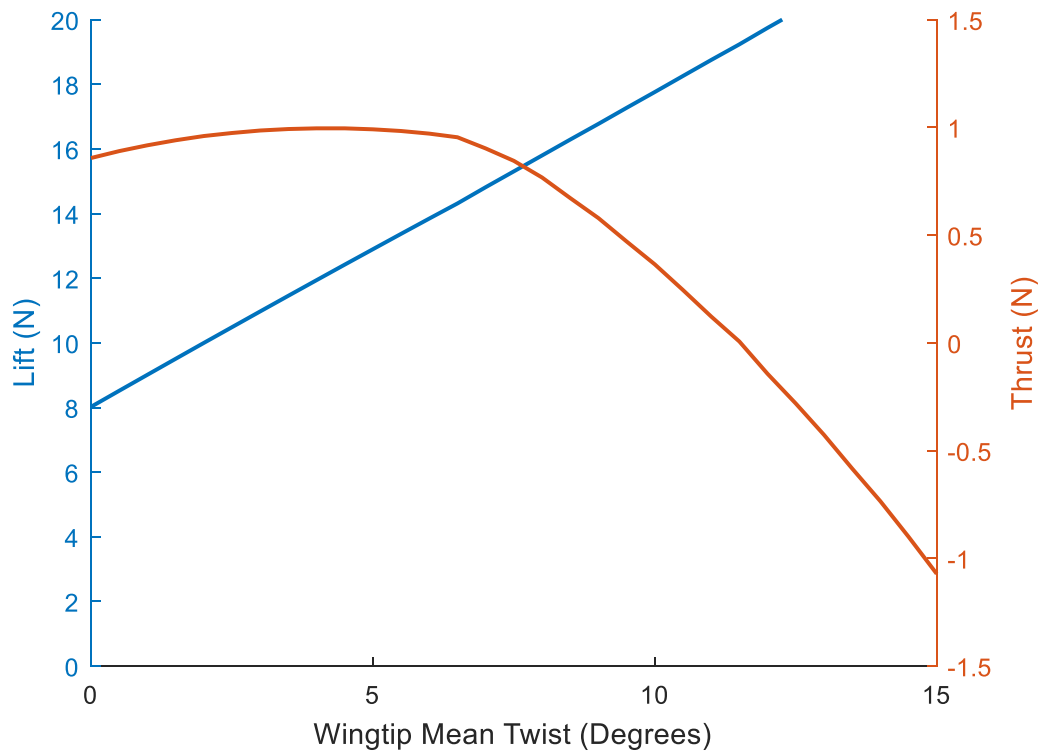


Figure 3.3: Effect of δ on lift and thrust, maximizing lift scenario (Reprinted from [10])

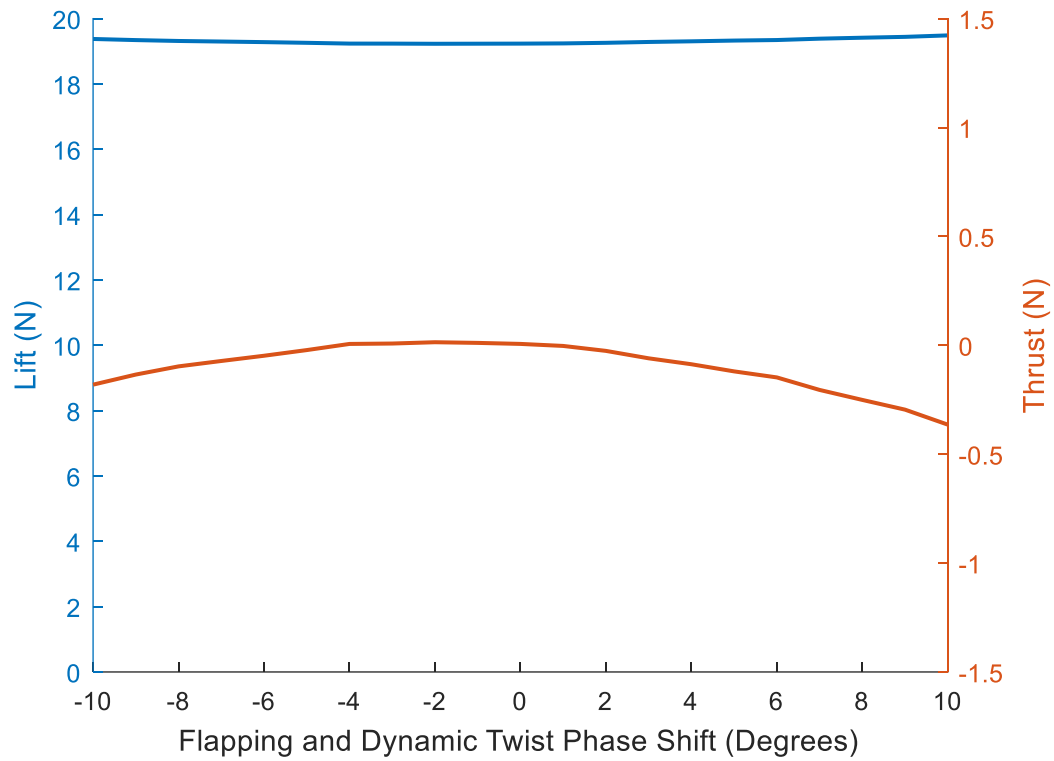


Figure 3.4: Effect of ψ on lift and thrust, maximizing lift scenario (Reprinted from [10])

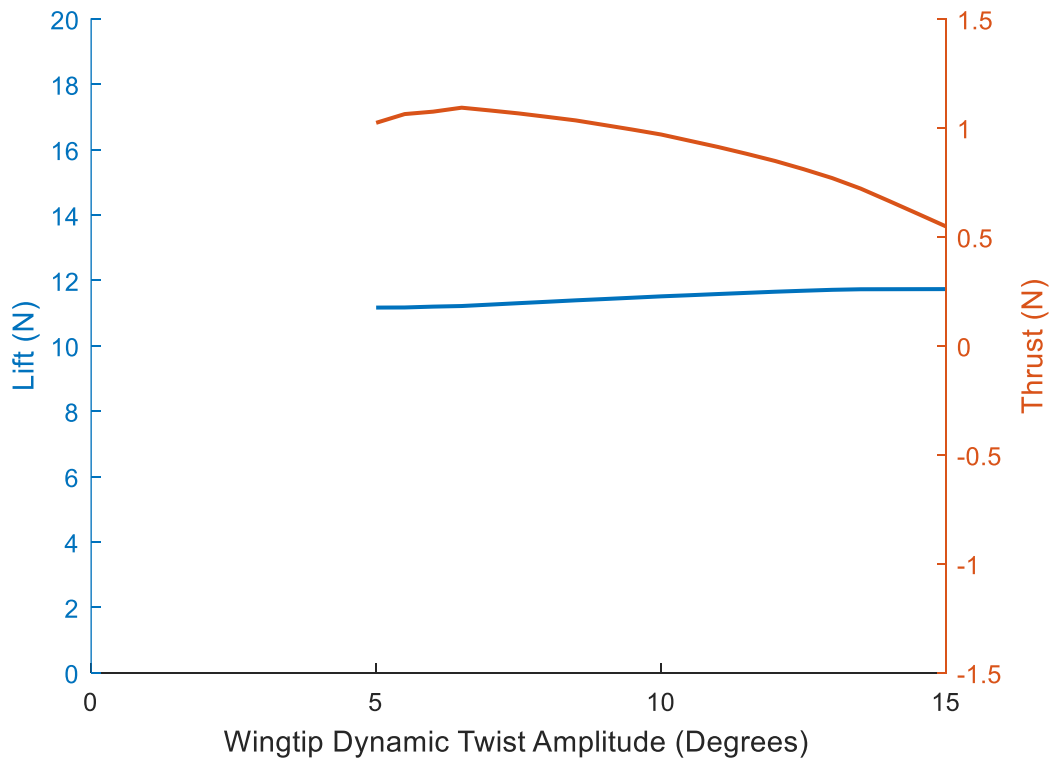


Figure 3.5: Effect of A_1 on lift and thrust, maximizing thrust scenario (Reprinted from [10])

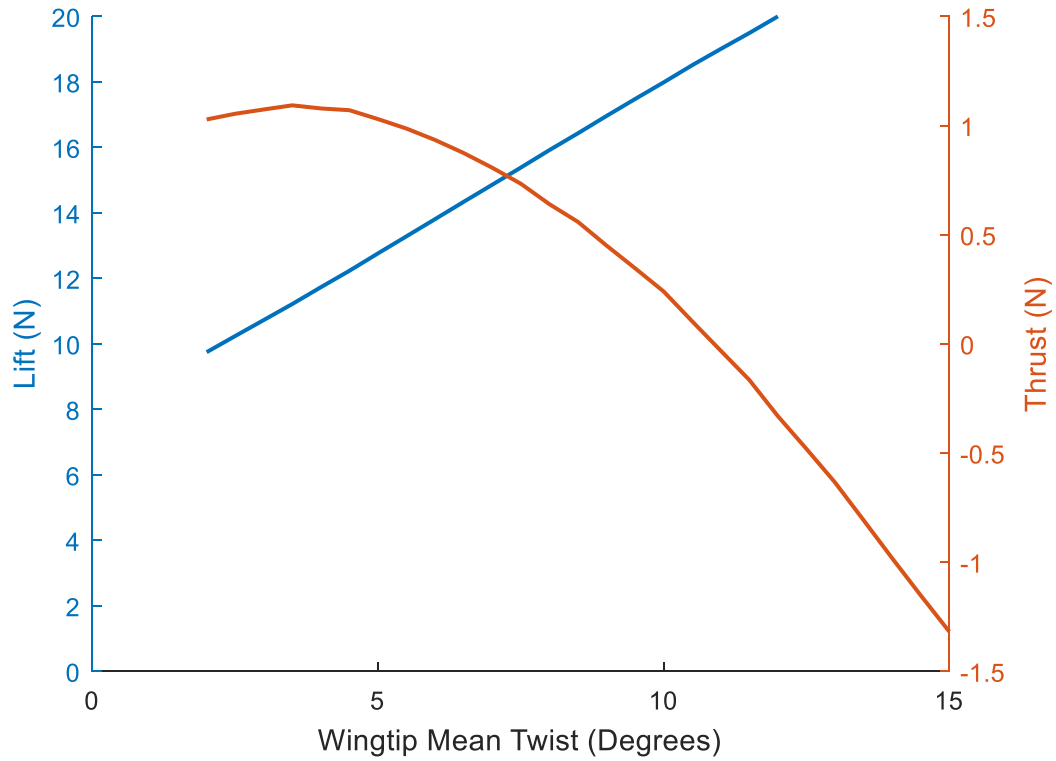


Figure 3.6: Effect of δ on lift and thrust, maximizing thrust scenario (Reprinted from [10])

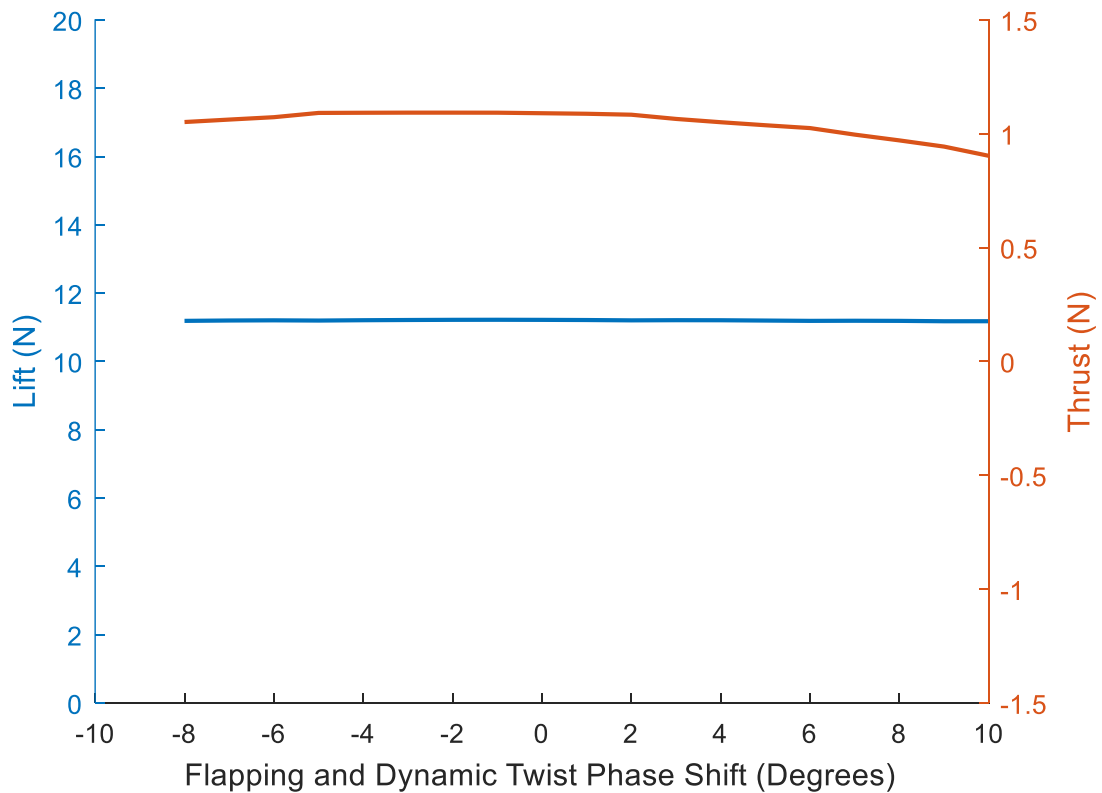


Figure 3.7: Effect of ψ on lift and thrust, maximizing thrust scenario (Reprinted from [10])

3.4.2. Power requirement of a twisting wing

The torque at the shoulder joint due to inertial effects as well as aerodynamic forces were calculated independently, so that both the aerodynamic and inertial contribution toward total power could be determined and is shown in Figure 3.8 and Figure 3.9. The equation for power due to inertia is given by Eq. (3.17.) where the moment due to inertia about the flapping axis is given by Eq. (3.18.). Eq. (3.18.) also includes the effect of gravity. The equation for power due to aerodynamic forces is given by Eq. (3.19.), where the moment due to lift about the flapping axis is given by Eq. (3.20.). As thrust acts parallel to the flapping axis in this model, it does not have any effect on power. Positive power results in energy expenditure while negative power suggests the possibility for regeneration.

In order to include inertial effects in this analysis, wing mass had to be estimated. Since a rectangular planform is used, the mass is assumed to be evenly distributed throughout the wings. A semispan mass of 0.068 kg was determined by assuming that body mass and wing mass were linearly related by wing mass being directly proportional to body mass by a factor of 0.075. The model was created from data on 29 species of birds ranging from 0.0095 kg to 2.14 kg taken from [52]. This relationship was considered strong and had an $R^2=0.9634$.

$$P_{inertial} = M_{1i} \ddot{\kappa}_1 \quad (3.17.)$$

$$M_{1i} = \ddot{\kappa}_1 * 2 \int_0^{x_s} \frac{c^2}{c_{avg}^2} \frac{m_{wing}}{b} (x)^2 dx - 2 \int_0^{x_s} \cos(\kappa_1) \frac{c^2}{c_{avg}^2} \frac{m_{wing}}{b} g dx \quad (3.18.)$$

$$P_{aero} = M_{1a} \dot{\kappa}_1 \quad (3.19.)$$

$$M_{1a} = -2 \int_0^{x_s} x dL \quad (3.20.)$$

In Figures 8 and 9, the downstroke occurs from 0 seconds to 0.145 seconds and the up stroke occurs from 0.145 seconds to 0.29 seconds. In Figure 8, the case where maximum thrust is achieved, negative lift is produced during the upstroke. As a result, lifting force acts against wing motion, which yields positive power except at the very end of the upstroke. In Figure 9, the case where maximum lift is achieved, the power has a higher peak on the downstroke than when

compared to the maximum thrust case. However, because positive lift is produced during the upstroke, the power is negative for this portion of the cycle.

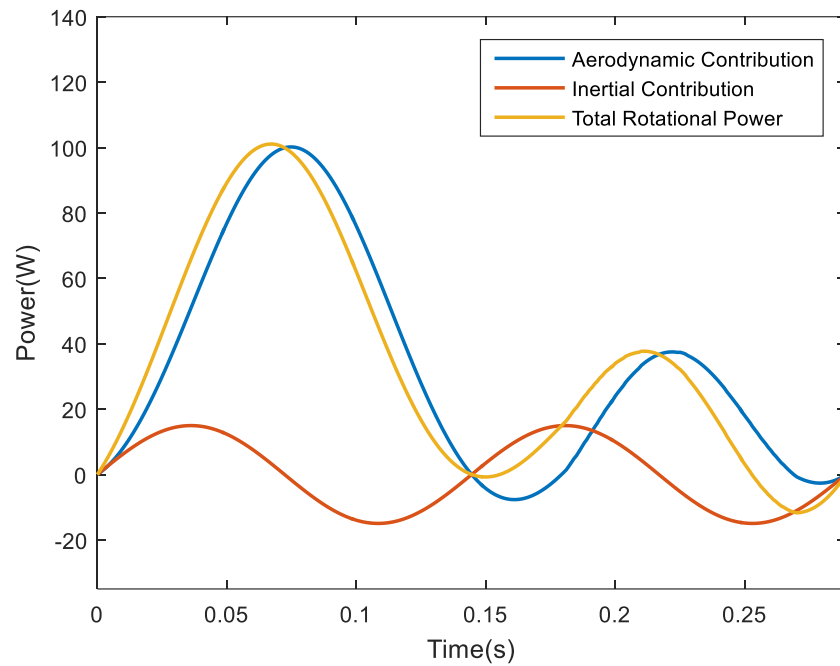


Figure 3.8: Power of a twisting wing as a function of time when maximum thrust is generated, downstroke 0 to 0.145 seconds and up stroke 0.145 to 0.290 seconds (Reprinted from [10])

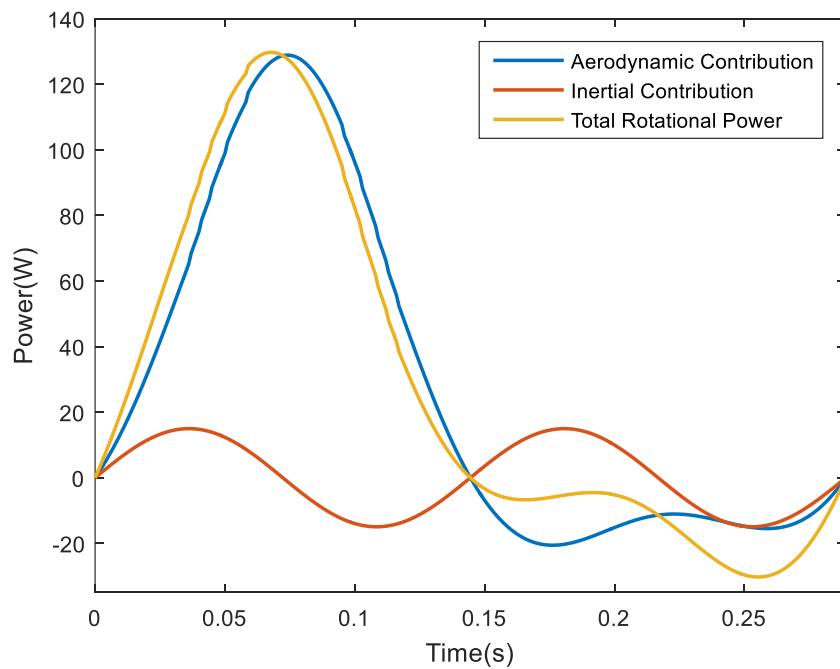


Figure 3.9: Power of a twisting wing as a function of time when maximum lift is generated, downstroke 0 to 0.145 seconds and up stroke 0.145 to 0.290 seconds (Reprinted from [10])

In the majority of studies, negative power indicates power generation. However, for most simple systems, the power supply still must provide power to the actuator to maintain ideal kinematics. Only systems with regenerative power supplies are able to do this, which adds cost and weight to the system. It is also questionable if biological systems are capable of storing energy from rotational motion. Table 3-2 shows average power for both the maximized thrust and lift scenarios when ideal regeneration is and is not used.

Table 3-2: Average power (Non-folding wing)

	Maximizing Thrust	Maximizing Lift
<i>No regeneration (W)</i>	34.39	41.51
<i>Regeneration used (W)</i>	32.93	27.92
<i>Power savings</i>	4.2%	32.7%

3.4.3 Aerodynamics of a folding and twisting wing

For the folding scenario, parameters that controlled the twist of the secondary wing section (A_1 , ϕ_1 , and δ_1) were held at constant values based on the results of the maximized lift and thrust scenarios performed in the previous subsections. For the folding scenario, parameters that controlled the twist of the primary section were adjusted to find maximum lift and thrust. A_2 was varied from 0 to 15 degrees in increments of 0.5 degrees, ϕ_2 was varied from -30 to 0 degrees in increments of 1 degrees, and δ_2 was varied from 0 to 15 degrees in increments of 0.5 degrees. This totaled to 29791 cases. The range of ϕ_2 was drastically increased and shifted because of a large negative phase offset between θ_1 and θ_2 . Lift, thrust, and kinematic parameters for the folding wing maximized lift and thrust scenarios are shown below in Table 3-3. In Figures 3.10-3.15, individual kinematic parameters are isolated to determine their effect on lift and thrust.

Table 3-3: Lift, thrust, and kinematics of optimal flight scenarios for a folding wing

	Maximizing Thrust	Maximizing Lift
<i>Lift (N)</i>	11.30	16.04
<i>Thrust (N)</i>	1.05	0.01
<i>A_2 (degrees)</i>	9	15
<i>ψ_2 (degrees)</i>	-12	-8
<i>δ_2 (degrees)</i>	2.5	14

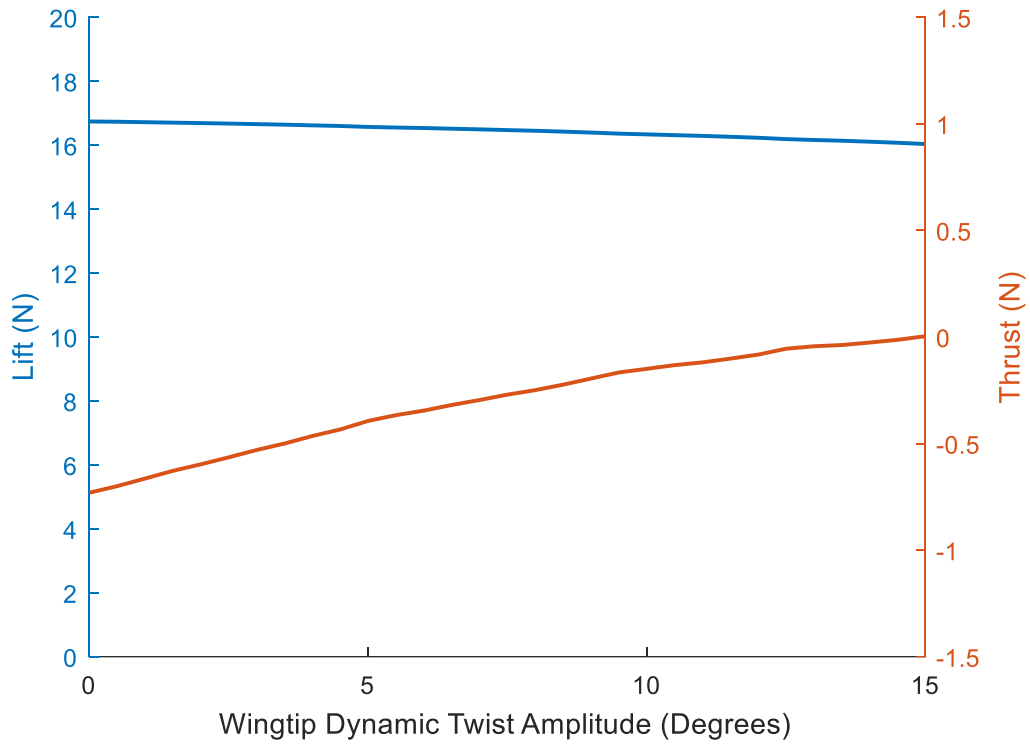


Figure 3.10: Effect of A_2 on lift and thrust, maximizing lift scenario (Reprinted from [10])

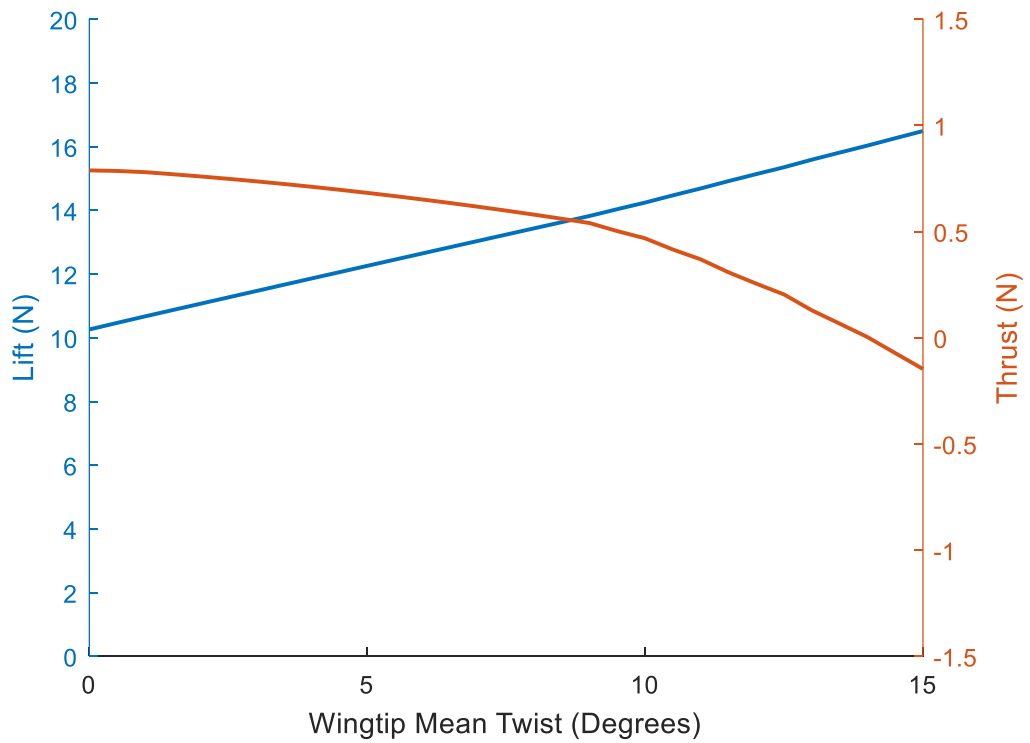


Figure 3.11: Effect of δ_2 on lift and thrust, maximizing lift scenario (Reprinted from [10])

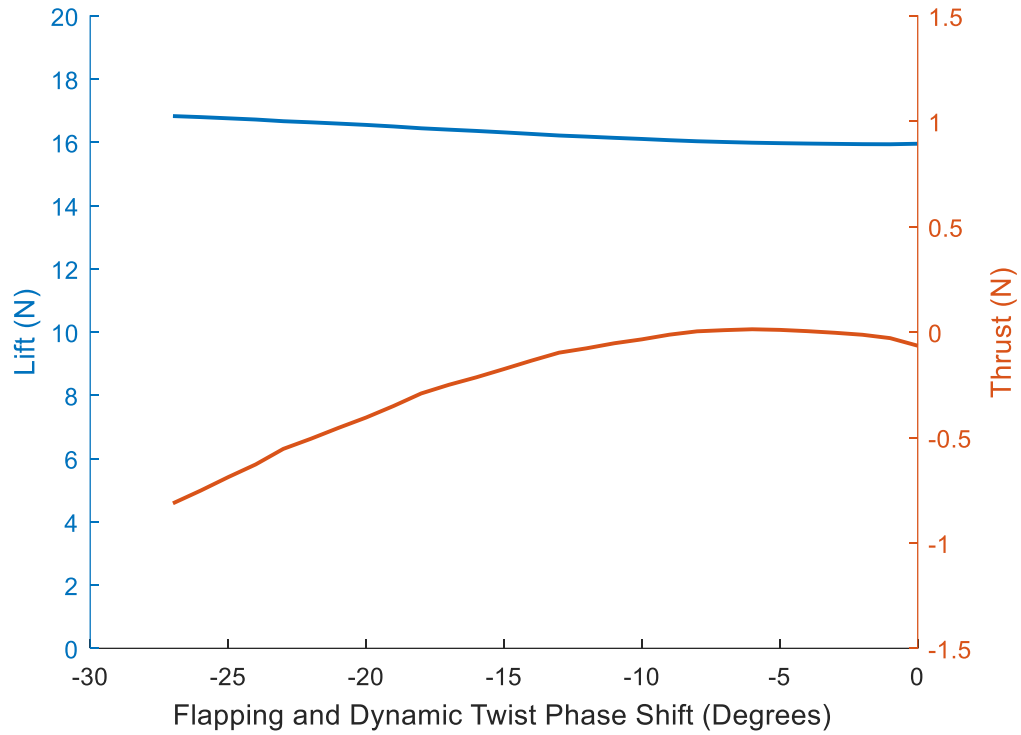


Figure 3.12: Effect of ψ_2 on lift and thrust, maximizing lift scenario (Reprinted from [10])

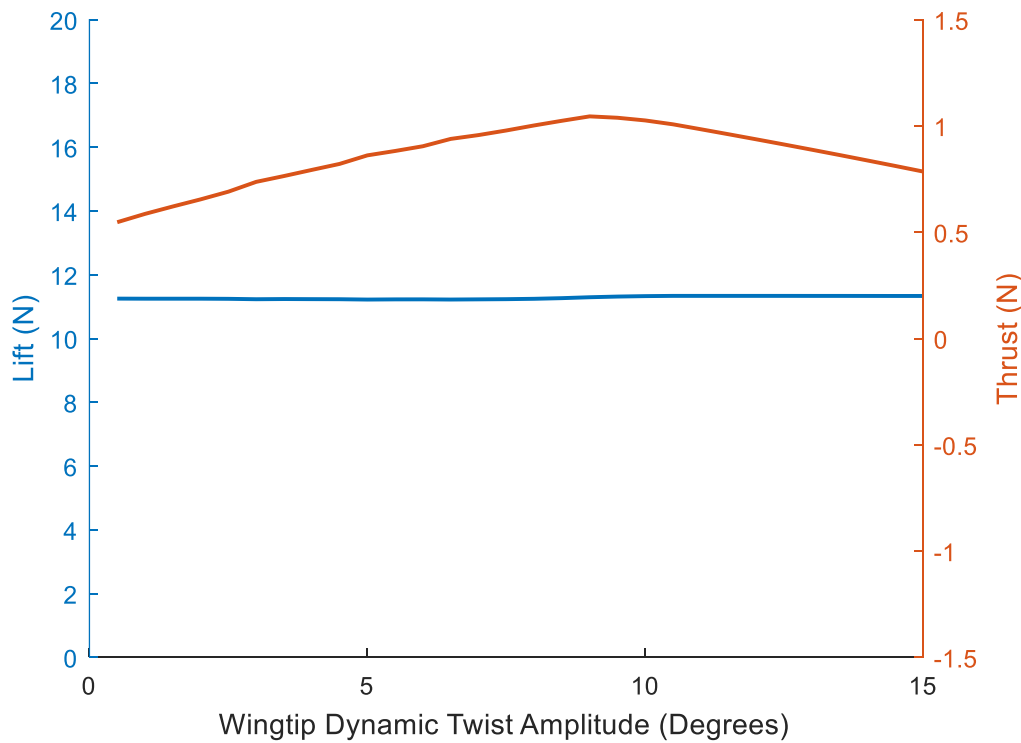


Figure 3.13: Effect of A_2 on lift and thrust, maximizing thrust scenario (Reprinted from [10])

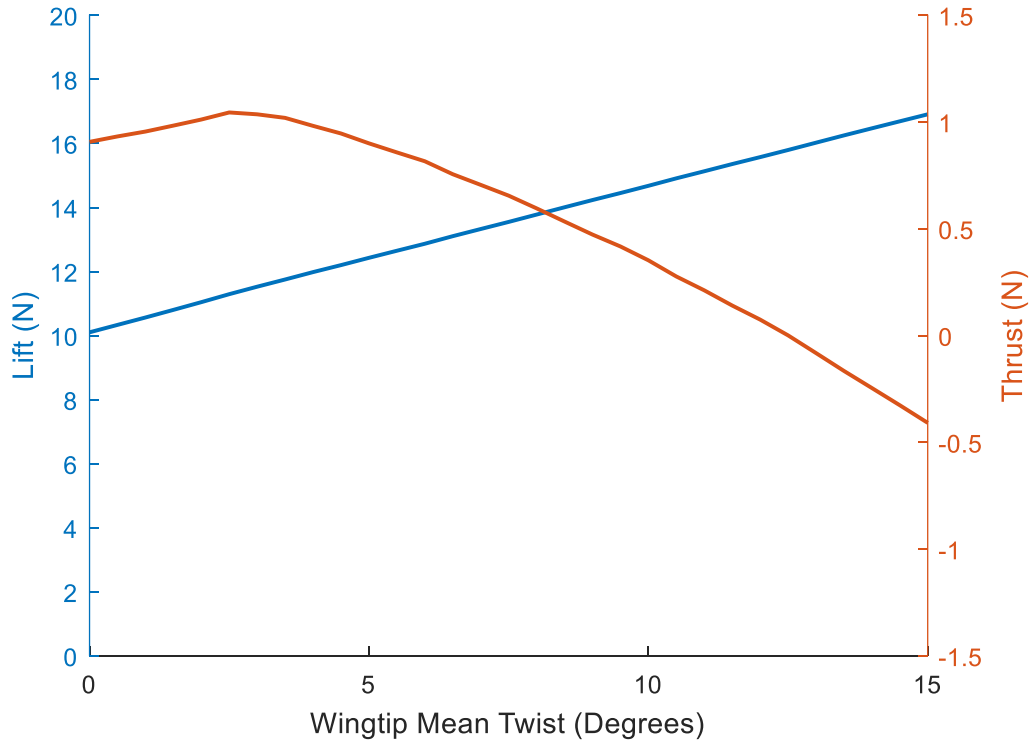


Figure 3.14: Effect of δ_2 on lift and thrust, maximizing thrust scenario (Reprinted from [10])

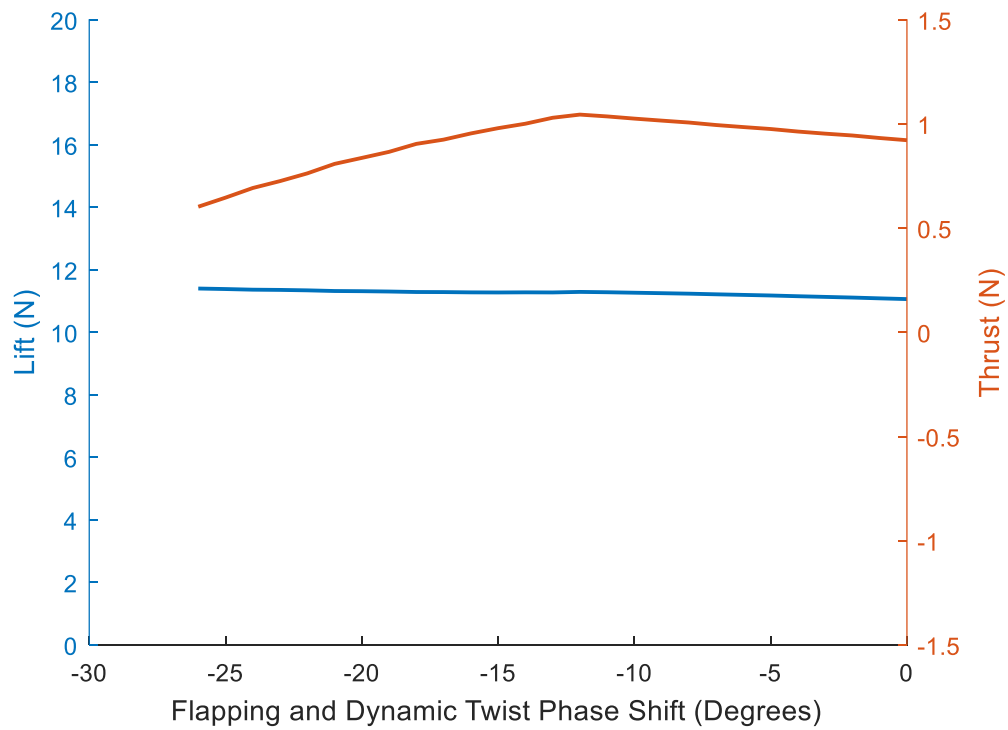


Figure 3.15: Effect of ψ_2 on lift and thrust, maximizing thrust scenario (Reprinted from [10])

3.4.4. Power of a folding and twisting wing

In addition to calculating torque about the flapping axis, torque about the folding axis had to be calculated as well, because wing folding was an active rather than passive degree of freedom in the parametric study. Figure 3.16 and Figure 3.17 show both the inertial and aerodynamic contributions toward power as well as total power for the folding wing scenarios. The equation for power due to inertia and gravity is given by Eq. (3.21.), where the moment about the flapping axis is given by Eq. (3.22.), and moment about the folding axis is given by Eqs. (3.23.). The equation for power due to lift is given by Eq. (3.24.), where the moment about the flapping axis is given by Eq. (3.25.), and moment about the folding axis is given by Eq. (3.26.). As in the twisting wing case, thrust acts parallel to the flapping axis in this model; it does not have any effect on power. Positive power results in energy expenditure while negative power suggests the possibility for regeneration.

$$P_{inertial} = M_{i1}\dot{\kappa}_1 + M_{i2}\dot{\kappa}_2 \quad (3.21.)$$

$$M_{i1} = \ddot{\kappa}_1 * 2 \int_0^{x_f} \frac{c^2}{c_{avg}^2} \frac{m_{wing}}{b} (x)^2 dx + M_{i2} - x_f \cos(\kappa_1) F_{i2y} \dots \\ \dots + x_f \sin(\kappa_1) F_{i2y} - 2 \int_0^{x_f} \cos(\kappa_1) \frac{c^2}{c_{avg}^2} \frac{m_{wing}}{b} g dx \quad (3.22.)$$

$$M_{i2} = \ddot{\kappa}_1 * 2 \int_{x_f}^{x_s} \frac{c^2}{c_{avg}^2} \frac{m_{wing}}{b} (x - x_f)^2 dx - 2 \int_{x_f}^{x_s} \cos(\kappa_1) \frac{c^2}{c_{avg}^2} \frac{m_{wing}}{b} g dx \quad (3.23.)$$

$$P_{aero} = M_{a1}\dot{\kappa}_1 + M_{a2}\dot{\kappa}_2 \quad (3.24.)$$

$$M_{a1} = -2 \int_0^{x_f} x dL + M_{a2} - x_f \cos(\kappa_1) F_{a2y} + x_f \sin(\kappa_1) F_{a2y} \quad (3.25.)$$

$$M_{a2} = -2 \int_{x_f}^{x_s} x dL \quad (3.26.)$$

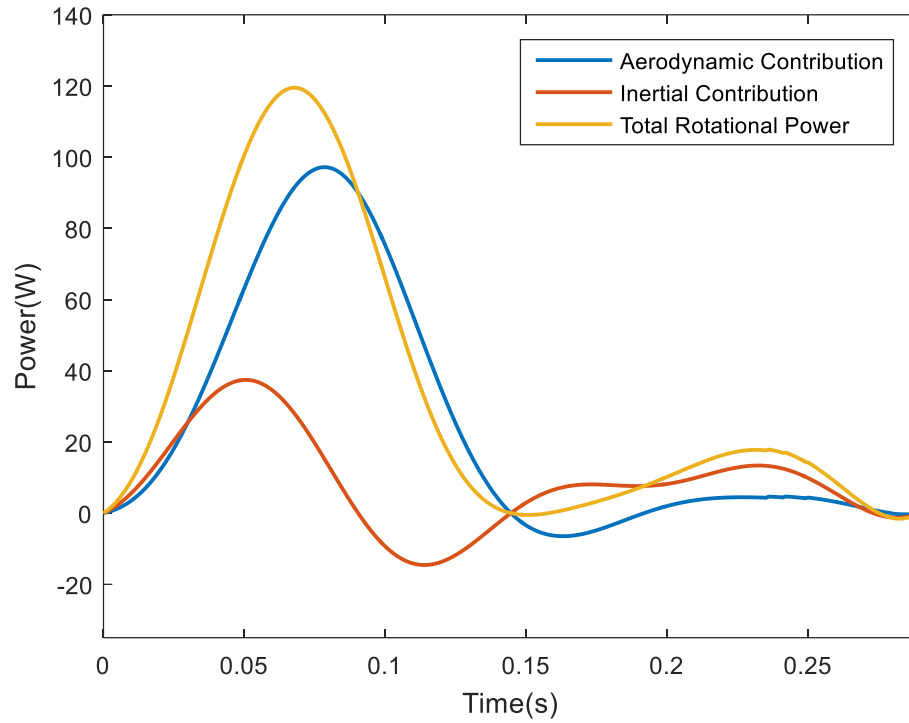


Figure 3.16: Power of a folding wing as a function of time when maximum thrust is generated, downstroke 0 to 0.145 seconds and up stroke 0.145 to 0.290 seconds (Reprinted from [10])

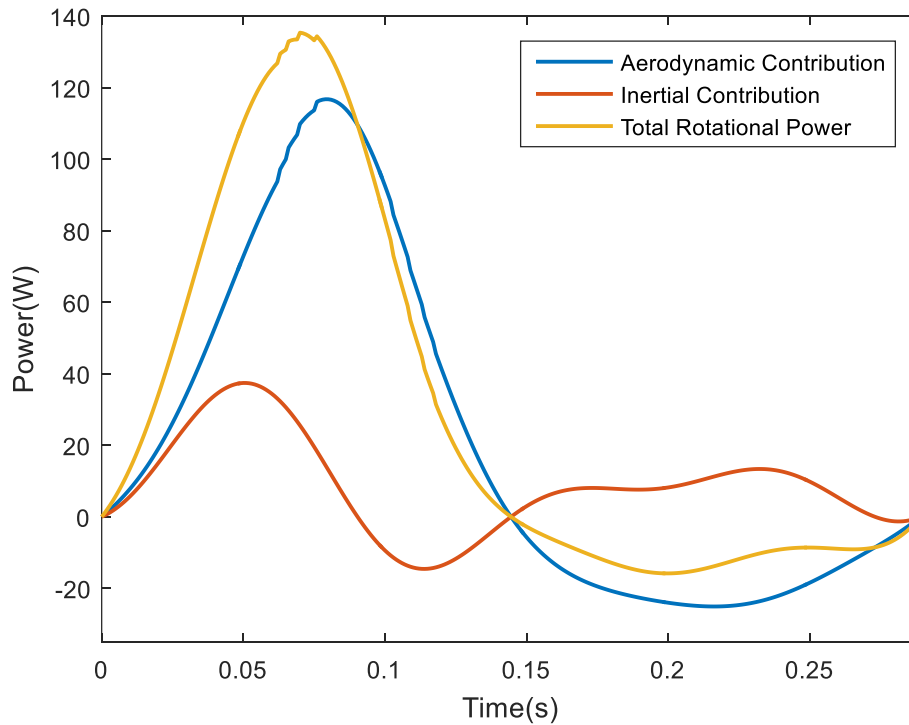


Figure 3.17: Power of a folding wing as a function of time when maximum lift is generated, downstroke 0 to 0.145 seconds and up stroke 0.145 to 0.290 seconds (Reprinted from [10])

Table 3-4 shows average power for both the maximized thrust and lift scenarios when both ideal regeneration is and is not used.

Table 3-4: Average power (Folding wing)

	Maximizing Thrust	Maximizing Lift
<i>No Regeneration (W)</i>	32.90	38.89
<i>Regeneration Used (W)</i>	32.76	28.98
<i>Power savings</i>	0%	25.5%

3.5. Discussion

This study suggests there is only a slight difference in aerodynamic performance between a folding wing and a non-folding wing system, especially for the maximizing thrust scenarios, as shown in Tables 1 and 3. However, there are energy savings when no regeneration is used. Wing folding reduced the inertial contribution to almost 0 watts during the upstroke, reducing overall energy expenditure as seen in Fig. 16. Biological systems likely have no efficient mechanism to store energy produced by rotation or translational motion. This is likely why wing folding is seen in nature. However, the mean power savings is small while the increase in complexity introduced by utilizing a folding wing may be high. Therefore, design and fabrication of a non-folding wing ornithopter with regeneration may be ideal and will be the focus of the rest of the discussion.

For a non-folding wing ornithopter, it appears, as shown in Figs. 4 and 7, that phase offset between flapping angle and dynamic twist angle has very little impact on performance and can be left at 0 to simplify control. It also appears that twist amplitude has a significant impact on thrust production but little impact on lift for this system, as shown in Figs. 2 and 5. Lastly, it seems that time averaged twist angle has a significant impact on both lift and thrust production. Increasing time averaged twist angle appears to increase lift while generally decreasing thrust, as shown in Figs. 3 and 6. Thus, time averaged twist angle and twist amplitude are the parameters that should be used to control the amount of lift and drag produced by the system.

It appears that for a non-folding wing ornithopter, with wings similar to that of their biological counterpart, inertial effects have limited impact on energy expenditure. Though inertial effects could have a bigger impact at higher flap frequency, due to larger angular accelerations, they also could have a larger impact when longer wingspans are utilized. A longer wingspan increases moment of inertia by a power of two, while it would only linearly increase aerodynamic torque.

For the maximizing thrust scenario, average energy expenditure was only slightly decreased when using regeneration, but much more so for the maximized lift scenario. This is because for the maximized lift scenario positive lift is produced for the majority upstroke and accelerates upward wing motion. This excess motion can be converted to stored energy if an electrical system that allows for regeneration is used.

Based on the results of the parametric study, it appears the inclusion of active wing twist in a bird-inspired robotic system could drastically effect performance, while wing folding appears to have a less significant effect.

3.6. Experimentally investigating the effect of wing DOFs

Initially an experimental investigation that would offer a comparison to the conducted analytical parametric study was planned. For the planned experiment, a unique robotic bird that used three active DOFs per wing was constructed. The first DOF was at the shoulder, and produced a vertical flapping motion. This DOF was driven by a 30 W brushless DC motor. The brushless motor was paired with a dual gear and crank system to drive both wings simultaneously. The second DOF was at the wrist, which produced an asymmetric folding motion causing the wing to bend at the bottom of the downstroke. This was driven by a RC servo located at the root of each wing. Transmission of force between the servo and the wrist was achieved by a four bar linkage system. The third DOF was also at the wrist, which controls twist of the wingtip. This was driven by another RC servo placed parallel to the twisting axis in each wing. These actuators can be seen in Figure 3.18.

Actuation at the root of the wing causes an oscillating motion along the entire span of the wing. Folding of the wrist allows for independent adjustment of the freestream velocity the primary section of the wing experiences. It also allows for reduction in the inertial force acting on the drive system, reducing power consumption. Lastly, actuation of wingtip twist allows for aerodynamic force normal to the chord to be directed in the forward flight direction, allowing for thrust production, as well as ensures that the wing maintains an angle attack where flow does not completely separate.

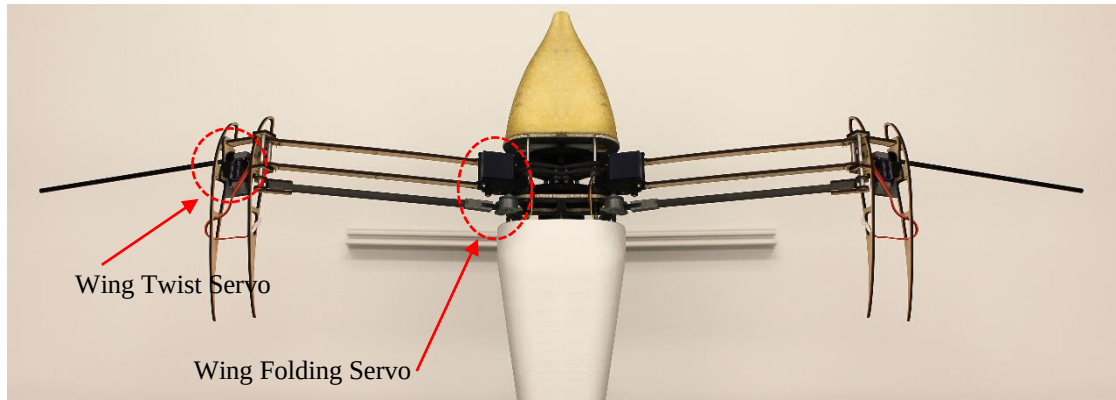


Figure 3.18: Three DOF robotic bird prototype (uncovered wing) with wing twist and folding actuators circled in red

The tip-to-tip span of the robot was 114 cm (the same as a medium sized gull and hawk). Total mass of the system was approximately 660 grams. This mass is slightly lower than birds with similar span lengths, which was a design constraint, as initially free flight capability was desired. Ultimately, free flight was not attempted, as while the structure exhibited the required strength for normal operation, it was not designed to have the toughness required to survive even a lesser impact, which is inevitable during flight testing. In order to achieve this low weight, the body was construed from hybrid carbon fiber/balsa frames that exhibited a very large flexural strength to mass ratio. Many of the wing spars and rods were also made from carbon fiber composite to reduce weight. Folding occurs 23 cm from the root flapping pivot so the primary and secondary wing sections (hand and arm wing sections respectively) are approximately equal with the primary section being just slightly larger at 27 cm. The servo actuated linkage system used for wing folding allowed for a bending range of 10 degrees above to 65 degrees below the horizontal. The primary section at its halfway fold point can be seen in Figure 3.19.

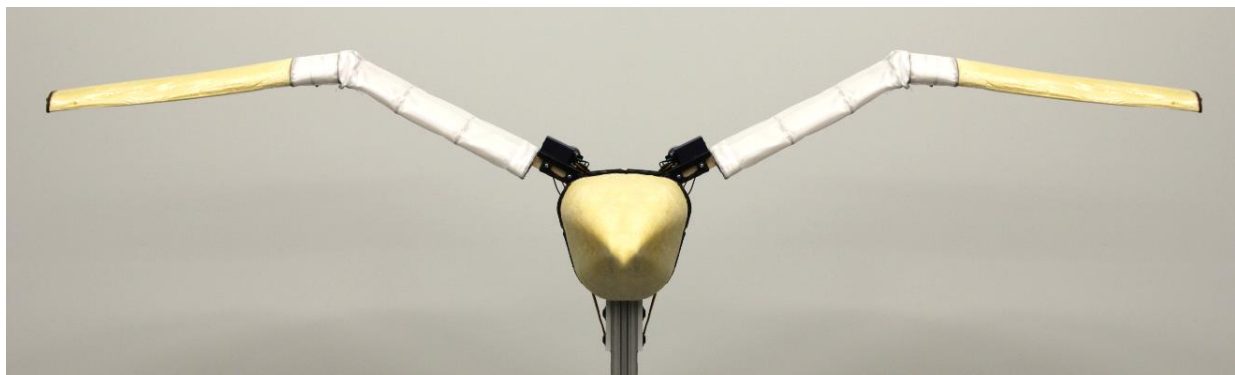


Figure 3.19: Three DOF robotic bird prototype during upstroke position

With the assistance of Dr. Jae Hung Han and the Smart Systems and Structures Lab he directs, wind tunnel testing was attempted at KAIST. There was no tunnel large enough to fit the whole prototype so a single semi span test was conducted with a six DOF load cell as shown in Figure 3.20. The tunnel had an operating range of 5-15 m/s. The system was able to successfully operate at frequencies up to 2.5 Hz at a freestream of 8 m/s. The prototype would likely be able to operate at even higher frequencies at higher freestreams due to the aerodynamic force counteracting the opposing torque caused by inertia of the wing. This inertial torque was substantial due to the wing having a mass 2.3 times larger than the wing of an equivalently sized bird. Due to using only a single semispan, there were very large moments that occurred about the x-axis almost equal in magnitude y-axis forces, and of greater magnitude than x-axis forces, contaminating the data. The rest of testing was canceled when this was realized.

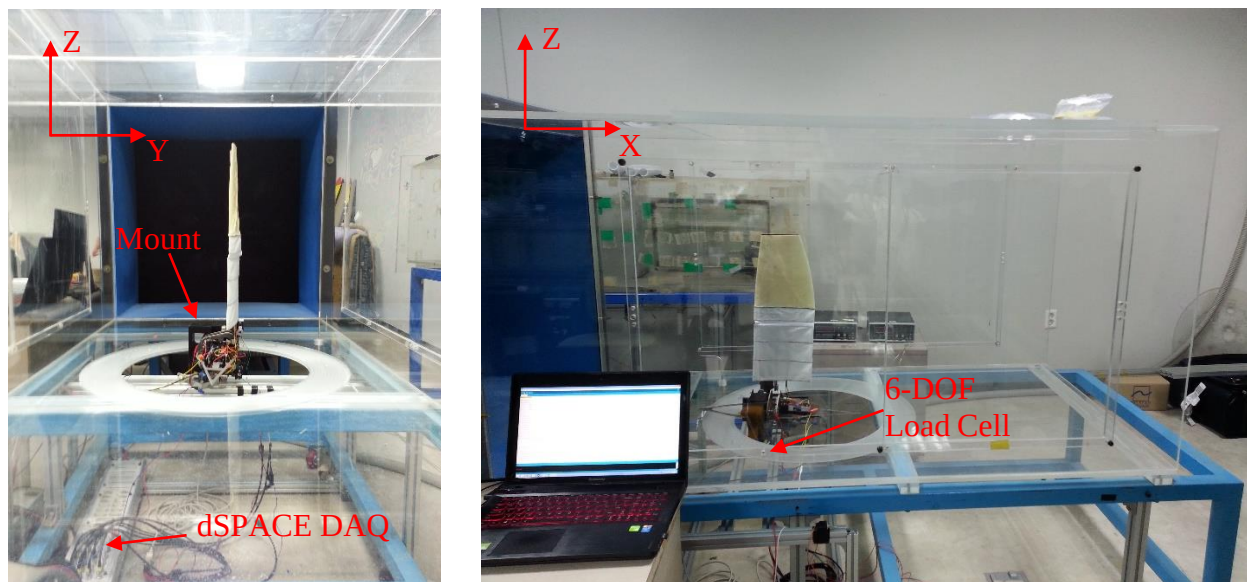


Figure 3.20: Wind tunnel testing of single semispan robotic prototype

A second smaller robotic system was built in hopes of performing a full span test. This system used a simpler passive wing as due to its smaller size, as actuators with appropriate specifications could no longer be fit into the wing structure. The second robotic prototype utilizes a lateral drive system to drive the base flapping motion. This drive system uses an 84 W brushless out runner motor with an RC electronic speed controller. Rotational output is then geared down 25x using a custom made sequential gearbox. This allows for a max no load flapping frequency of 11 Hz. The wing operating frequency was tested up to 5 Hz for the worst-case scenario of zero

freestream flapping. The majority of the structural components are made out of a unique 3D printed material called Alloy 910. This is a modified nylon with very high tensile strength for a thermoplastic. It possess higher rigidity then normal nylon, which is very flexible, but still maintains good impact resistance. The rest of the load bearing structure is made from aircraft grade 7075 aluminum. Steel comprises the bearings and screws. This prototype was specifically designed for impact resistance thus motivating the use of the nylon based material. The entire system shown in Figure 3.21 is approximately 350 grams. A potentiometer coupled to the flapping axis provides a signal proportional to the angle of the wing.



Figure 3.21: Second robotic bird prototype with lateral drive and passive wing

Benchtop testing of the new prototype was conducted, and the lift and thrust measurements appear to be more accurate than the previously attempted wind tunnel testing. Shown below in Figure 3.22 is averaged thrust and root mean square lift. RMS lift follows a parabolic trend with a y intercept close to zero, which is theoretically expected, as both lift force and inertial force are directly proportional to the square of the flapping frequency. The average thrust trend is not parabolic, but theoretically it should not be, as it is a function of both wing flexing (which is coupled to aerodynamic force) and the square of frequency. Instantaneous lift and thrust as well as wing position is shown in Figure 3.23. As this is a table top test, angles of attack are likely greater than 50 degrees [53]. The causes flow to detach from the wing resulting in the higher frequency oscillations in both vertical and horizontal force. Instantaneous lift being more in phase with flapping angle rather than being offset by 90 degrees is an indicator the magnitude of inertial forces is higher than that of aerodynamic force.

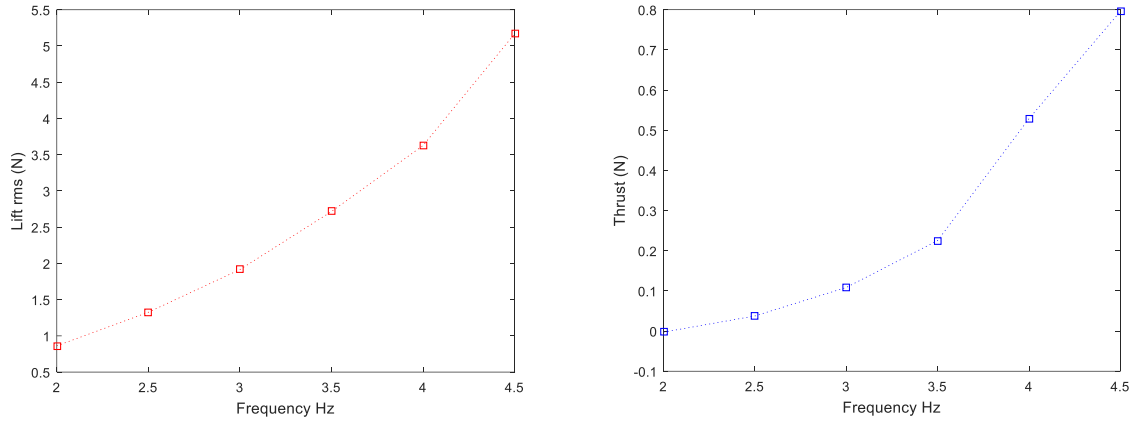


Figure 3.22: RMS lift and average thrust vs frequency

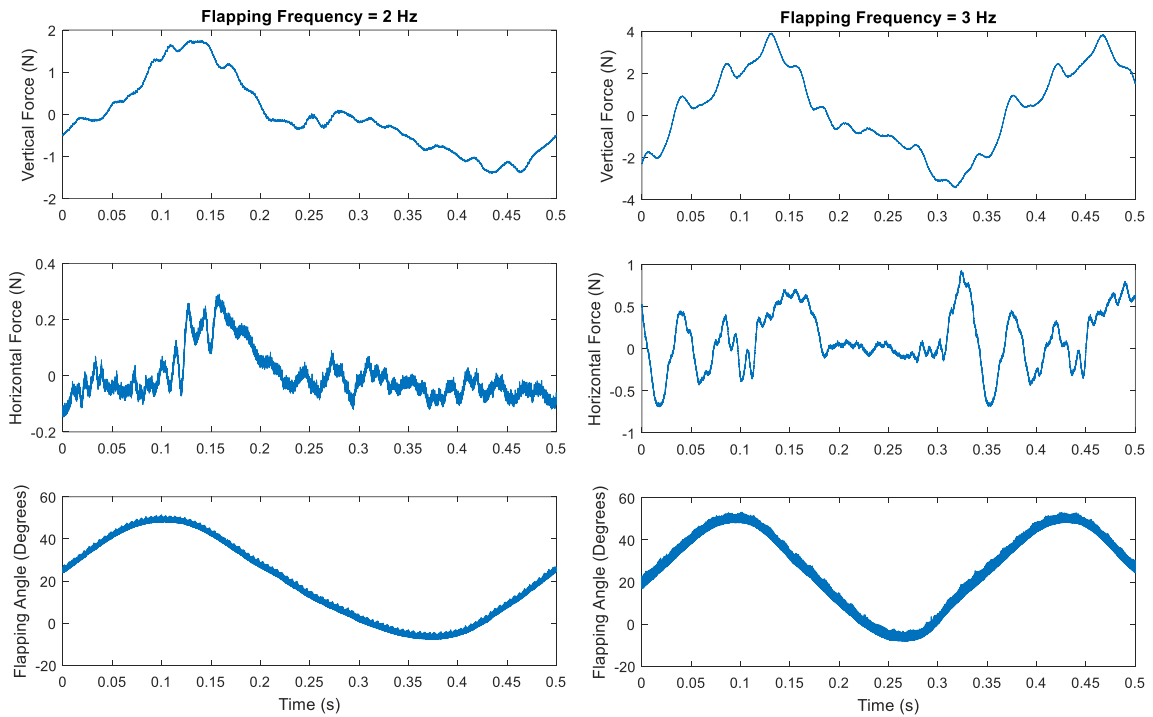


Figure 3.23: Instantaneous vertical and horizontal force as well as wing angle at a 2 and 3 Hz flapping frequency

As tabletop testing was successful, wind tunnel testing was planned. Unfortunately, the required wind tunnel never became available. The difficulty obtaining the necessary facilities to conduct flapping experiments is partially what motivated the experimental caudal fin studies.

4. An improved aerodynamic model

While the previously used MST has been validated in the literature, it does have some inherent flaws. It cannot effectively predict spanwise aerodynamic force as it treats each wing strip as its own independent 2D element. This chapter focuses on prediction of lift and drag of such flyers by utilizing a model that builds upon lifting line theory. Several models utilizing lifting line theory have already been developed, the most recent one by W.F. Phillips [54]. However, such models fall short of addressing some of the unsteady effects of flapping flight including the leading edge vortex (LEV) formation, and unsteady wake effects. LEV formation appears to be the main source of extra lift in large flapping flyers during cruising flight [55]. The proposed model includes the effect of LEV by using a variation of Polhamus' suction analogy [48]. Unsteady wake effects result in a diminished effective angle of attack and a slight phase delay of aerodynamic force development. The unsteady wake effects can be approximated using a Theodorsen function [56]. Earlier strip theories that used this suction analogy as well as applied approximations for unsteady wake effects and apparent mass have shown reasonable agreement with experimental results [48]. However, as stated above, strip theories are not ideal for prediction of lift distribution along the longitudinal axis of the wing and may not provide representative predictions for a twisting or folding wing [57]. It is important to note that both of these wing motions are commonly used in large birds [28].

4.1. Nomenclature

Variable	Description
L_{Total}	Total lift acting perpendicular to free stream
$L_{Attached}$	Lift generated from wing section with attached flow
L_{DS}	Lift generated from wing section with leading edge vortex
$(\alpha_{attached})_{max}$	Max angle of attack before airfoil stalls in non-dynamic scenario
$(\alpha_{attached})_{min}$	Minimum angle of attack airfoil stalls in non-dynamic scenario
φ	Angle of attack of flapping axis at root of wing
$\alpha'(x)$	Relative angle of attack
$\alpha_e(x)$	Effective angle of attack
$\alpha_i(x)$	Downwash induced angle of attack
$x_{Attached}$	Span location where wing transitions to dynamic stall condition
ρ	Fluid density

Q_{∞}	Free stream velocity
$Q'_{\infty}(x)$	Relative free stream velocity
ε	Wing flapping angle
$\Gamma(x)$	Circulation around wing cross-section as a function of span location
b	Span length
dF_s	Leading edge suction force of an infinitely small wing segment
$n_s(x)$	Suction efficiency
D_{Total}	Total drag acting parallel to free stream
D_i	Induced drag of the entire span acting parallel to free stream
D_f	Friction drag of the entire span acting parallel to free stream
$C_{df}(x)$	Friction drag coefficient
$m(x)$	Local lift slope as a function of span location
$c(x)$	Chord length as a function of span location
$\alpha_{L0}(x)$	Angle of zero lift line as a function of span location
$\gamma(x)$	Twist angle of wing chord as a function of span location
$\dot{h}(x)$	Heaving velocity
A_z	Displacement amplitude of uniformly oscillating wing
A_{ε}	Flapping angle amplitude
C'	Theodorsen function
f	Flapping Frequency
k	Reduced Frequency
x	Span location (wing root at $x=0$)

4.2. Formulation

The developed model is a modification of the original lifting line theory. There are three major assumptions: first, the relative angle of attack never exceeds dynamic stall range. Lifting line theory assumes attached flow. The circulation during dynamic stall is similar to the circulation during attached flow and thus lifting line theory may be able to still approximate behavior during dynamic stall. However, as soon as the wing fully stalls, lifting line theory is no longer applicable. For birds and bird-like ornithopters, this assumption is reasonable, as their angle of attack usually remains within the attached flow regime. However, this model is not appropriate for insect-like wings, which experience much higher angles of attack causing frequent and complex vortex shedding. This likely makes the circulation around an insect wing very dissimilar to the circulation in the attached flow condition. The second assumption is that pitching velocity of the wing has a

negligible effect on relative angle of attack. For this to be true, freestream velocity must be much greater than wing section pitching velocity $\times$ chord. The last assumption is that the wing is approximately elliptical. This is necessary to have a closed loop solution to the lifting line equation.

Total lift, given by Eq. (4.1.), is the sum of the lift generated within the inner wing section, where flow is attached. The outer wing sections are the locations where dynamic stall may occur. Based on traditional lifting line theory, lift generated by the wet sections of the wing, where flow is attached, is given by Eq. (4.2.).

$$L_{Total} = L_{Attached} + L_{DS} \quad (4.1.)$$

$$L_{Attached} = 2\rho \int_0^{x_{Attached}} Q'_{\infty} \cos(\varepsilon) \cos(\varphi + \gamma) \Gamma \, dx \quad (4.2.)$$

$$\text{Where } (\alpha_{attached})_{min} \leq \alpha' \leq (\alpha_{attached})_{max}$$

In this model, dynamic stall is assumed to occur when the relative angle of attack exceeds the 2D static stall angle. This assumption has been used in several other strip theory models [48, 49]. Eq. (4.3.) shows the relative wing angle of attack as a function of span location by including the effect of sectional heaving motion, as well as flapping axis angle of attack and wing twist. Eq. (4.4.) gives the relative freestream velocity as a function of span location by including the effect of sectional heaving velocity. Two commonly studied wing motions, flapping and uniformly oscillating, are included in this formulation. However, the model is not limited to these motions. Eq. (4.5.) underlines the heaving velocity of a uniformly oscillating wing (flapping angle is not a function of time and is equal to zero), while Eq. (4.6.) gives the sectional heaving velocity of a flapping wing with no folding or bending. For the flapping wing the motion is assumed to be sinusoidal, which is approximately what occurs for several observed species of birds [28]. Key wing kinematic parameters and flow angles are depicted in Figure 4.1.

$$\alpha' = \tan^{-1} \frac{\dot{h} \cos(\varphi)}{\dot{h} \sin(\varphi) + Q_{\infty}} + \varphi + \gamma \quad (4.3.)$$

$$Q'_{\infty} = \sqrt{(\dot{h} \sin(\varphi) + Q_{\infty})^2 + (\dot{h} \cos(\varphi))^2} \quad (4.4.)$$

$$\dot{h} = 2\pi f A_z \sin(2\pi f t) \quad (4.5.)$$

$$\dot{h} = 2\pi f y A_\varepsilon \sin(2\pi f t) \quad (4.6.)$$

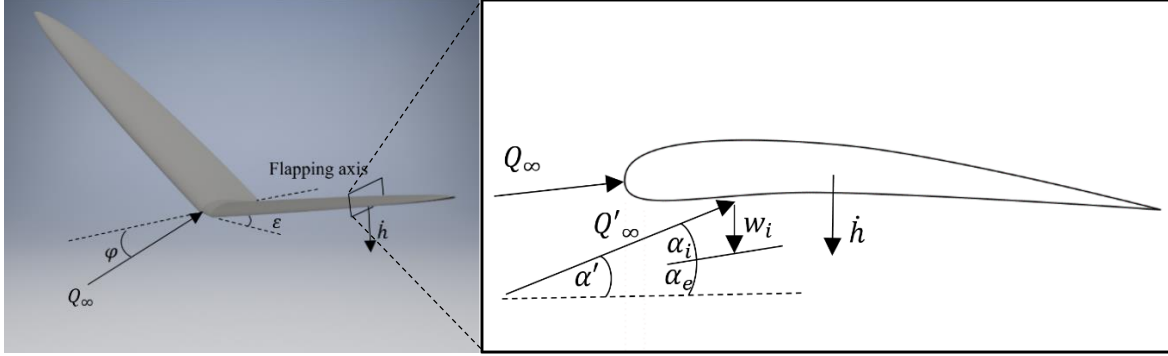


Figure 4.1: Absolute and relative flow angles experienced by flapping wing airfoil (taken from [57])

According to Polhamus' suction analogy, the suction force rotates 90 degrees during dynamic stall and acts perpendicular to the wing chord rather than parallel, representing formation of the LEV [58]. Lift of the wing sections in dynamic stall is given by Eq. (4.7.), where suction force and its coefficient for a 2D airfoil are provided by Eqs. (4.8.) and (4.9.) respectively [59].

$$L_{DS} = 2\rho \int_{x_{Att}}^{\frac{b}{2}} Q'_\infty \cos(\varepsilon) \cos(\varphi + \gamma) \Gamma dx ... \quad (4.7.)$$

$$... + 2 \int_{x_{Att}}^{b/2} \cos(\varepsilon) (\cos(\varphi + \gamma) - \sin(\varphi + \gamma)) dF_s$$

Where $\alpha' \leq (\alpha_{attached})_{min}$ or $\alpha' \geq (\alpha_{attached})_{max}$

$$dF_s = \frac{1}{2} \rho c C_s Q'^2_\infty dx \quad (4.8.)$$

$$C_s = 2\pi n_s \alpha_e^2 \quad (4.9.)$$

2π is the theoretical maximum local lift slope of an airfoil as stated by the thin airfoil theory. Therefore, 2π can be replaced by m , the local 2D lift slope of the airfoil as shown in Eq. (4.10.). Based on traditional lifting line theory the effective angle of attack α_e is given by Eq. (4.11.). Substituting Eqs. (4.10.) and (4.11.) into Eq. (4.8.) yields the simplified form of Eq. (4.12.).

$$C_s = m n_s \alpha_e^2 \quad (4.10.)$$

$$\alpha_e = \frac{2\Gamma}{mcQ'_\infty} \quad (4.11.)$$

$$dF_s = \frac{2\rho n_s^2}{mc} (\Gamma)^2 dx \quad (4.12.)$$

Total drag is calculated through Eq. (4.13.), which is the sum of induced drag and viscous drag. Although accounted for in this model, viscous drag is usually small and may be approximated as zero for noncritical estimates. Eq. (4.14.) gives the induced drag acting on the wing. The second term in the equation accounts for the rotation of the suction force over the dynamically stalled portion of the wing. Induced drag is dependent on induced downwash angle given by Eq. (4.15.), with viscous drag force represented in Eq. (4.16.). The viscous drag coefficient C_{df} can be determined numerically, but likely will be underestimated. For better estimation, skin roughness C_{df} should be determined from experimentation, such as a wind tunnel test. When thrust is being produced, D_{Total} becomes negative.

$$D_{Total} = D_i + D_f \quad (4.13.)$$

$$D_i = \rho \int_{-\frac{b}{2}}^{\frac{b}{2}} Q'_\infty \cos(\varphi + \gamma) \sin(\alpha'_i) \Gamma dx + 2 \int_{y_{Att}}^{\frac{b}{2}} -\cos(\varphi + \gamma) - \sin(\varphi + \gamma) dF_s \dots$$

$$\dots + 2 \int_{x_{Att}}^{\frac{b}{2}} -\cos(\varphi + \gamma) - \sin(\varphi + \gamma) dF_s \quad (4.14.)$$

$$\alpha'_i = \alpha' - \frac{2\Gamma}{mcQ'_\infty} - \alpha_{L0} \quad (4.15.)$$

$$D_f = \frac{1}{2} \rho \int_{-b/2}^{b/2} C_{df} (Q'_\infty \cos(\alpha'))^2 dx \quad (4.16.)$$

The circulation used in the previous Eqs. can be found by solving the lifting line integro-differential Eq. (4.17.).

$$\frac{-2\Gamma}{mcQ'_\infty} - \frac{1}{4\pi Q'_\infty} \int_{-\frac{b}{2}}^{\frac{b}{2}} \frac{[d\Gamma(x_0)/dx] dx_0}{x - x_0} + C'\alpha' - \alpha_{L0} = 0 \quad (4.17.)$$

In order to account for unsteady vortex wake due to the oscillating motion of the wing, a Theodorsen function is applied, shown in Eq. (4.18.), as a coefficient in front of α' . Theodorsen functions are commonly used when calculating the aerodynamic coefficients of oscillating wings [56]. If α' approximately fits the form $\alpha' = Ae^{ift}$, which is equivalent to $\alpha' = \sin(2\pi ft)$, then $C'\alpha'$ can be expressed in the form given by Eq. (4.19.) below. Both the previously described oscillating and flapping wing cases meet this criterion. A folding wing also would approximately meet this criterion as well. F' and G' are a function of reduced frequency and are closely approximated by Eqs. (4.20.) and (4.21.) below [60]. For the flapping wing motion given by Eq. (4.6.), reduced frequency takes the form of Eq. (4.22.).

$$C' = F' + iG' \quad (4.18.)$$

$$C'\alpha' \approx F'\alpha' + \frac{G'}{2\pi f} \dot{\alpha}' \quad (4.19.)$$

$$F' = 1 - \frac{C_1 k^2}{k^2 + C_2^2} \quad (4.20.)$$

$$G' = -\frac{C_1 C_2 k}{k^2 + C_2^2} \quad (4.21.)$$

$$C_1 = \frac{AR}{4.64 + 2AR}$$

$$C_2 = 0.181 + \frac{0.772}{AR}$$

$$k = \frac{\pi c f}{Q_\infty} \quad (4.22.)$$

The circulation previously shown in Eq. (4.17.) can also be described by a Fourier expansion, as shown in Eq. (4.23.). For the circulation to be described as a Fourier series, the spanwise coordinate must be changed from y to θ , whereby $y = \frac{-b}{2}$ is equivalent to $\theta = \pi$ and $y = \frac{b}{2}$ is equivalent to $\theta = 0$. The relationship between y and θ is shown in Eq. (4.24.).

$$\Gamma = 2b \sum_{n=1}^{\infty} A_n \sin(n\theta) \quad (4.23.)$$

$$x = \frac{b}{2} \cos(\theta) \quad (4.24.)$$

Substituting Eq. (4.23.) into Eq. (4.17.) yields Eq. (4.25.). The second term can be simplified using Glauert's integral resulting in Eq. (4.26.). The condensed form can be shown in the form of Eq. (4.27.).

$$0 = \frac{-4b}{mcQ'_\infty} \sum_{n=1}^{\infty} A_n \sin(n\theta) - \frac{1}{\pi Q'_\infty} \int_0^\pi \frac{\sum_{n=1}^{\infty} nA_n \cos(n\theta_0) d\theta_0}{\cos(\theta_0) - \cos(\theta)} + C'\alpha' - \alpha_{L0} \quad (4.25.)$$

$$0 = \frac{-4b}{mcQ'_\infty} \sum_{n=1}^{\infty} A_n \sin(n\theta) - \frac{1}{Q'_\infty} \sum_{n=1}^{\infty} nA_n \frac{\sin(n\theta)}{\sin(\theta)} + C'\alpha' - \alpha_{L0} \quad (4.26.)$$

$$\sum_{n=1}^{\infty} A_n \sin(n\theta) \left(\frac{4b}{mc} + \frac{n}{\sin(\theta)} \right) = Q'_\infty (C'\alpha' - \alpha_{L0}) \quad (4.27.)$$

An analytical solution to the above equation can be found for an elliptical wing with a uniform lift slope in which $c = c_{max} \sin(\theta)$, where c_{max} is the chord length at the root of the semispan. This results in Eq. (4.28.). As the right-hand side of the equation is a Fourier expansion, the coefficients A_n can be found using Eq. (4.29.).

$$\sum_{n=1}^{\infty} A_n \sin(n\theta) \left(\frac{4b + nmc_{max}}{mc_{max}} \right) = Q'_\infty (C'\alpha' - \alpha_{L0}) \sin(\theta) \quad (4.28.)$$

$$A_n = \frac{2mc_{max}}{\pi(4b + nmc_{max})} \times \int_0^\pi Q'_\infty (C'\alpha' - \alpha_{L0}) \sin(\theta) \sin(n\theta) d\theta \quad (4.29.)$$

4.3. Possible Applications

When used for a parametric study, this model can provide predictions that are more accurate than the previously used strip theory because it provides a correct spanwise circulation distribution. This is even more so the case when studying multi degree of freedom wings where the wing surface of different sections are angled in dissimilar directions. Thus, the lift and drag vectors of these sections will point in dissimilar directions affecting total vertical and horizontal force.

As the overarching purpose of this research is to increase performance of actual bio-inspired flying and swimming systems, this new model can be used in conjunction with onboard flight controllers. The lift and drag predictions from it can be used to define Q_a , of the generalized equations of motion shown in Eq. (4.30.) [61]. In the equation, $M(q(t))$ is the generalized inertia matrix, $C(q(t), \dot{q}(t))$ is the generalized damping matrix, $B(q(t), \dot{q}(t))$ is the nonlinear control influence matrix, and $\tau(t)$ is the vector of actuation forces and torques.

$$M(q(t))\ddot{q}(t) + C(q(t), \dot{q}(t))\dot{q}(t) + \frac{\partial V}{\partial q}(q(t)) = Q_a(t) + B(q(t), \dot{q}(t))\tau(t) \quad (4.30.)$$

Solving the Navier-Stokes equations for fluid around the wing provides highly accurate lift and drag values, but is computationally expensive and therefore, at current processing speeds, cannot provide fast enough feedback for the above equation. The proposed reduced order solution is computationally inexpensive with instantaneous solution computation time on the order of hundredths of a second. Theoretically this solution still maintains a good degree of accuracy, making it ideal for use with controllers. The actual accuracy of the model will be discussed in Chapter 5.

5. Validation of aerodynamic models

In order to validate the low order model used in Chapter 3's parametric study and the newly developed reduced order model presented in Chapter 4, they were compared with well documented basic flapping wing experiments found in the literature. The first experiment was conducted in a wind tunnel on a goose-inspired robot with a single degree of freedom flapping wing [55]. In this wind tunnel experiment, a high accuracy load cell and data acquisition system was used to capture instantaneous lift data. Furthermore in this wind tunnel experiment, the force on the load cell due to wing inertia was removed, allowing aerodynamic forces to be isolated [55].

The second experiment was conducted in a water tunnel on a single flapping semispan [62]. In this experiment, high precision DPIV was used to visualize LEV and tip vortex formation and provides instantaneous spanwise circulation distribution, allowing for comparison between predicted (modeled) spanwise circulation distribution and actual (experimental) spanwise circulation distribution [62]. This is key because more accurate prediction of spanwise lift and thrust distribution was a main motivator for formulation of the new model.

5.1. Validating instantaneous lift predictions

In the wind tunnel experiment, the wing root flapping motion of each semispan is coupled. The wings are rigid and do not allow for passive or active flex. The wings also have the same cross-section (Wortmann Fx 60-126 airfoil) along the entire span and have a fixed geometric AOA of four degrees. The relationship between C_L and AOA of the Fx 60-126 is given at a Re of 100,000. Based on this C_L curve, the static stall angle of the wing is 12 degrees, the lift slope 4.9 (theoretical maximum for airfoil is 2π), and the AOA of zero lift -4.5 degrees. As mentioned in Chapters 3 and 4, both of the models presented in this dissertation require the above airfoil parameters to provide accurate estimates.

In addition to the airfoil parameters, the wing kinematics must be known. The angular position of the actual flapping wing was not quite sinusoidal, so it was fitted to a three term Fourier series, shown below in Figure 5.1, in order to apply them to the models. The actual wing motion has a downstroke that is significantly longer than the upstroke. In addition, the maximum heaving velocity of the downstroke does not occur at the midstroke as it would normally but more around the two thirds point of the downstroke.

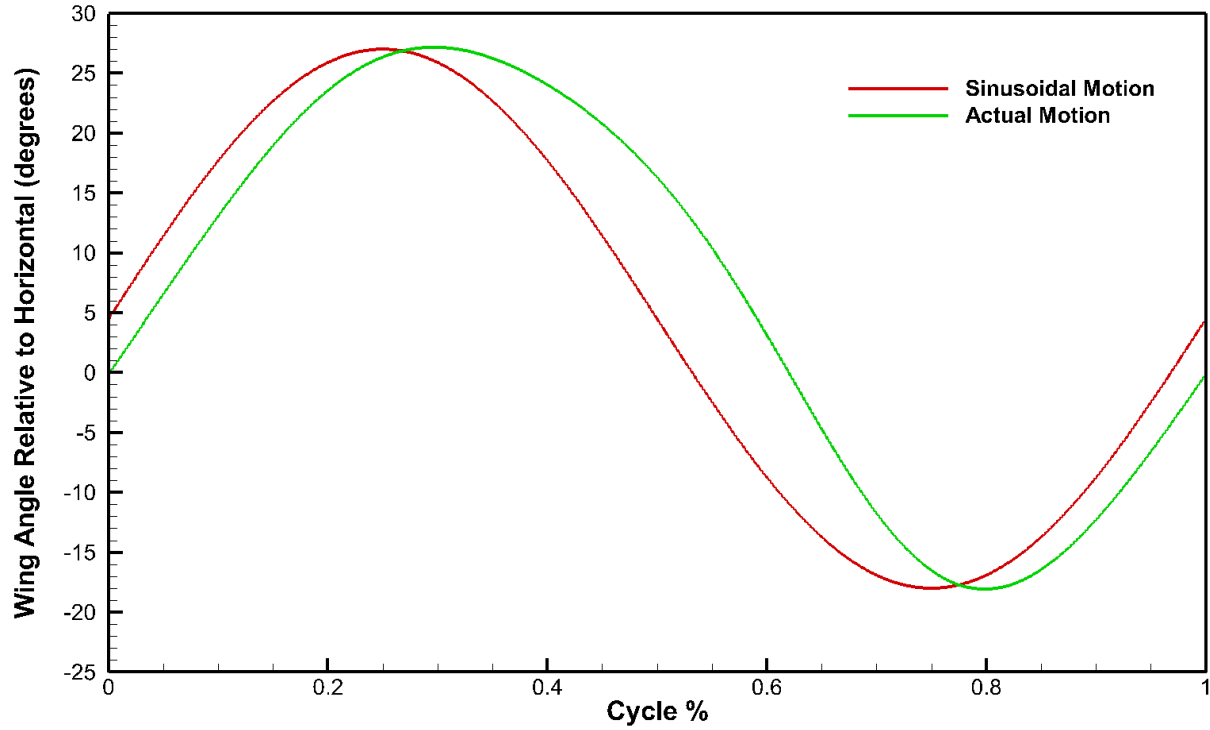


Figure 5.1: Flapping Angle as a function of non-dimensional time, typically used sinusoidal motion and actual motion

Below, Figure 5.2 displays a comparison of the vertical force coefficient C_z between load cell data from the experiment conducted in [55], the new lifting line based model presented in Chapter 4, and modified strip theory used in Chapter 3. The vertical force coefficient C_z is defined in Eq. (5.1.), where F_z is the total instantaneous vertical force caused by interactions with the fluid (the effect of the wing's inertia has been removed), ρ is fluid density, A is the tip-to-tip area of the wing (not including the body), and U_∞ is the freestream velocity far upstream from the model.

$$C_z = \frac{2F_z}{\rho A U_\infty^2} \quad (5.1.)$$

In the comparison shown in Figure 5.2, the flapping wing is operating at a St of 0.045 ($Re=113000$, frequency=1.28Hz). For this case, the maximum relative AOA at the wingtip is not large ($<20^\circ$), resulting in flow over the majority wing for the entire cycle to remain attached. Still, the slight hump in C_z peaking at a flap angle -5 degrees is likely caused by the small LEV formed on the outer part of the wing. This is expected to occur because the static stall AOA of the wing is 12 degrees and the outer part of the wing slightly exceeds this angle during part of the downstroke. Both the models capture this LEV formation, but the new model capturing its rate of growth

slightly better than MST. MST tends to overpredict C_z , while the new model tends to slightly underpredict it. MST's tendency to overpredict is probably a consequence of the model's inability to fully capture losses in lift due to its use of a lower aspect ratio wing.

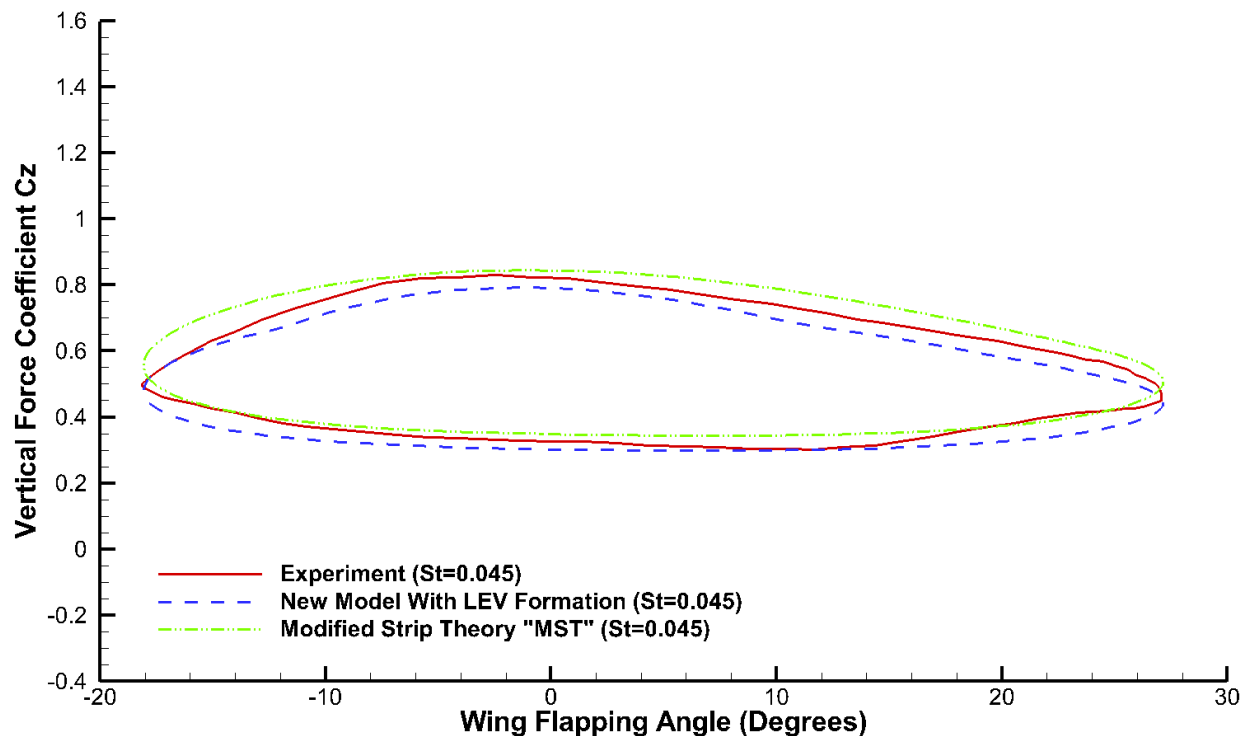


Figure 5.2: Vertical force coefficient vs flapping angle of a flapping wing operating at a St of 0.045, curves taken from lifting line based method, MST, and experimental results

Figure 5.3 shows the comparison when the flapping wing is operating at a St of 0.071 ($Re=113000$, frequency=2.02Hz). For this case, the maximum relative AOA at the wingtip ($\sim 28^\circ$) is considerably larger than the AOA of static stall. For this reason, an LEV is predicted to form over a larger portion of the wing and sooner during the downstroke, as shown by the deviation in C_z rate of growth. The increased rate of growth, due to LEV formation, starts around 18 degrees as opposed to 14 degrees, which occurred in the previous case. In this case, the new model also captures the shape of the C_z curve better than MST once again. MST does not seem to indicate a large lift contribution from the formation of an LEV. However, MST still overpredicts C_z through the downstroke while providing a very accurate prediction during the upstroke. The new model tends to slightly underpredict C_z during the upstroke, but does a better job with its prediction than MST during the downstroke.

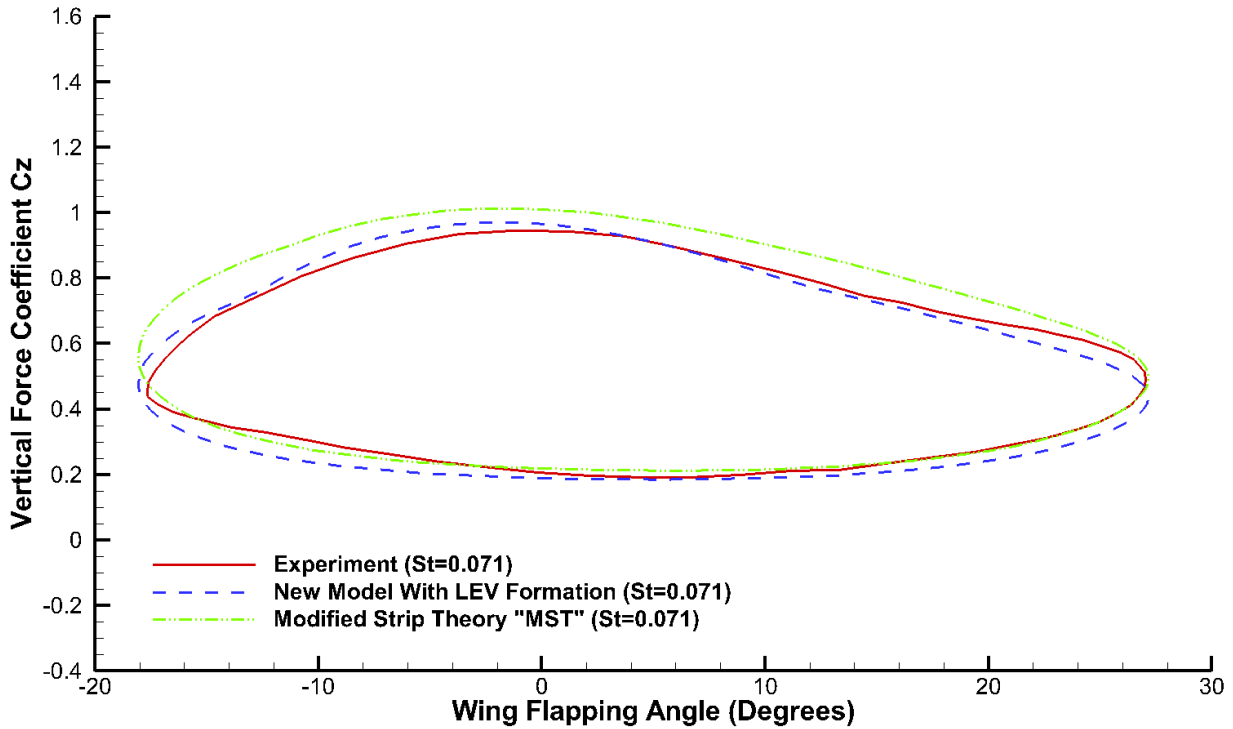


Figure 5.3: Vertical force coefficient vs flapping angle of a flapping wing operating at a St of 0.071, curves taken from lifting line based method, MST, and experimental results

Below in Figure 5.4, is the comparison for when the flapping wing is operating at a St of 0.141 ($Re=56000$, frequency=2.02Hz). For this case, the maximum relative AOA at the wingtip is extremely large ($\sim 46^\circ$). It is almost four times the static stall AOA, making it unlikely that a LEV would remain attached[48]. This causes much of the wing to fully stall rather than experience “dynamic stall”, which causes LEV formation. Fully stalled wings have lower lift coefficients than wings operating at angles of attack just below the stall AOA. This is why even though St of this case is double that of the previous $St=0.71$ case, Max C_z is less than 10% higher. As stated in the Chapters 3 and 4, neither model was designed to predict lift and thrust of a stalled wing, so the large overprediction shown in Figure 5.4 is expected. Although these models’ deficiency in accurately predicting force during stall is a disadvantage, higher order CFD methods, such as RANS, also have difficulty predicting the aerodynamic characteristics of a stalled airfoil [63]. Furthermore, it is highly inefficient for a bird or flapping vehicle to cruise in the stalled condition, and thus, should be avoided. Moreover, as this case was run at a Re of 56000, the airfoils lift characteristics are very different from characteristics at a Re of 100000, which were used with these models. This difference in lift characteristics in addition to hysteresis caused by stall, may

account for the other large deviations such as at the lower reversal point. Lift characteristics at a Re of 100000 were used for this case instead of characteristics at lower Re , as they were not available in the literature.

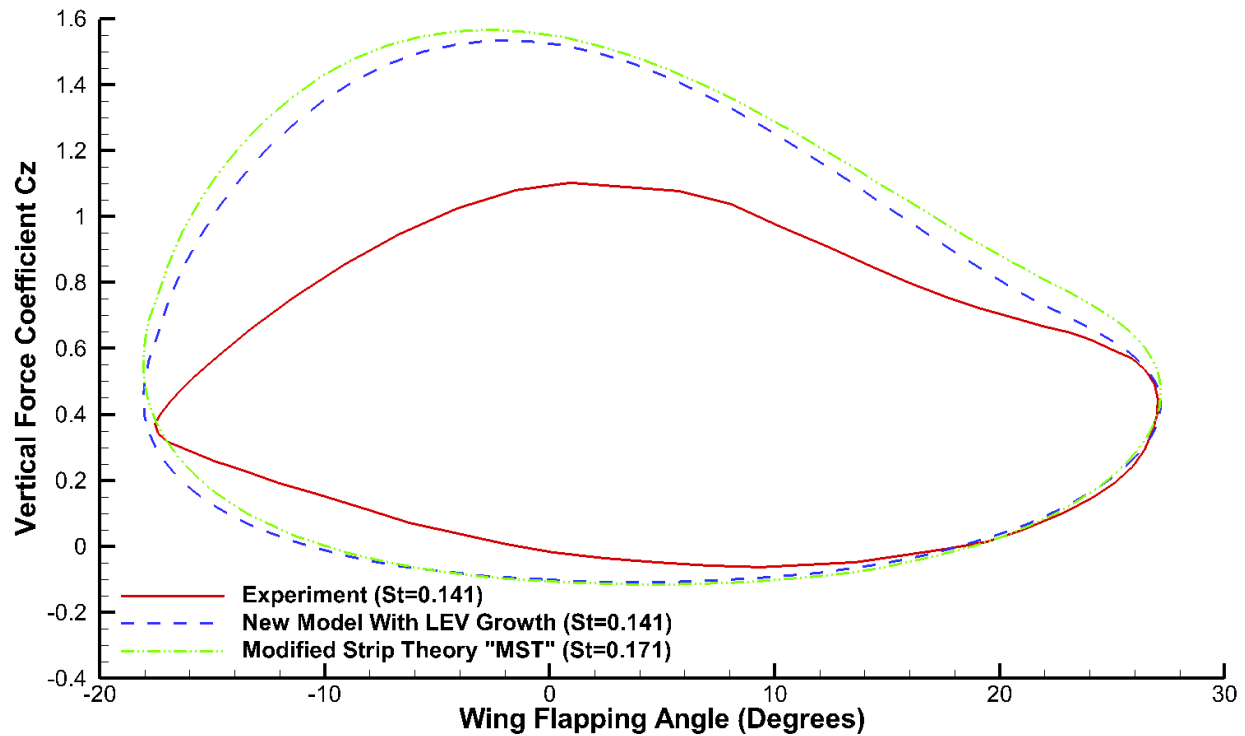


Figure 5.4: Vertical force coefficient vs flapping angle of a flapping wing operating at a St of 0.141, curves taken from lifting line based method, MST, and experimental results

Incorporation of LEV formation prediction was a key modification that the new model made to increase its accuracy over existing models based on lifting line theory. In Figure 5.5, Figure 5.6, and Figure 5.7, the effects of the incorporated LEV prediction are shown by comparing the added prediction with the more traditional approach, where the flow is assumed to be fully attached. As shown in Figure 5.5 and Figure 5.6, the LEV formation prediction significantly improves accuracy of the model and matches the rate of increase of C_z well. In these two figures, the point at which the LEV in the experiment starts to form is slightly before that of model. This suggests that the length of the LEV along the span is longer in the experiment than in the model. However, even though the length of the LEV that the model predicts is smaller than the experiments, the total contribution of the model's LEV to lift is similar. This is likely because a 100% suction efficiency for the LEV was assumed in the model, which is not normally the case in

reality as viscous effects reduce this efficiency. In Figure 5.7, even when not incorporating LEV formation, the model overpredicts vertical force for the reasons stated previously.

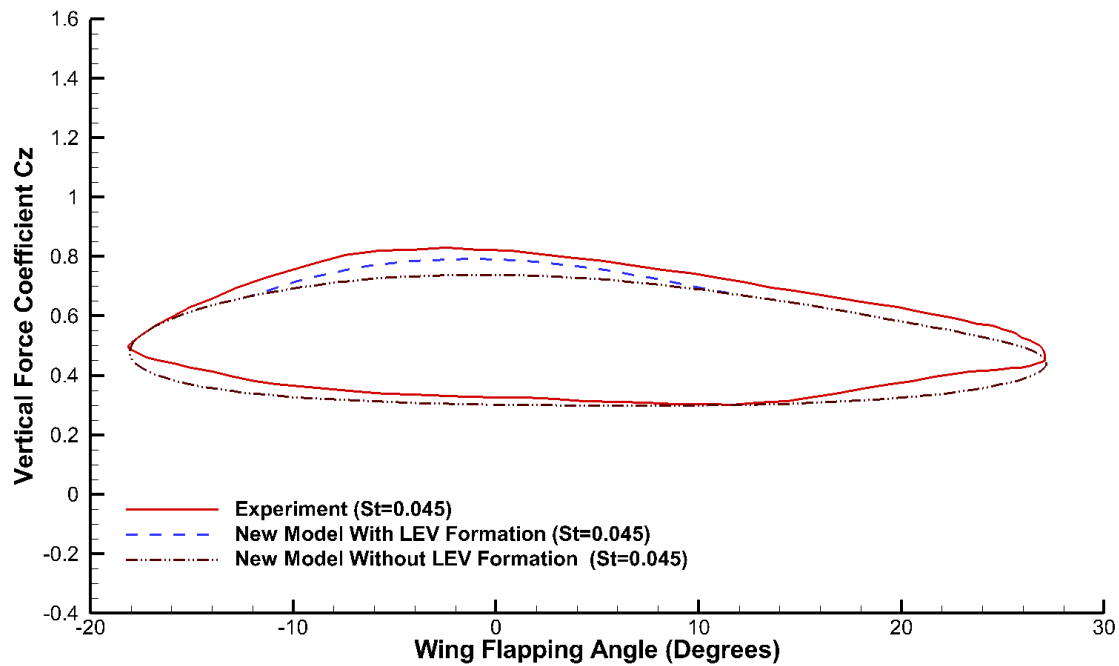


Figure 5.5: Vertical force coefficient vs flapping angle of a flapping wing operating at a St of 0.045, curves taken from lifting line based method with and without LEV formation, and experimental results

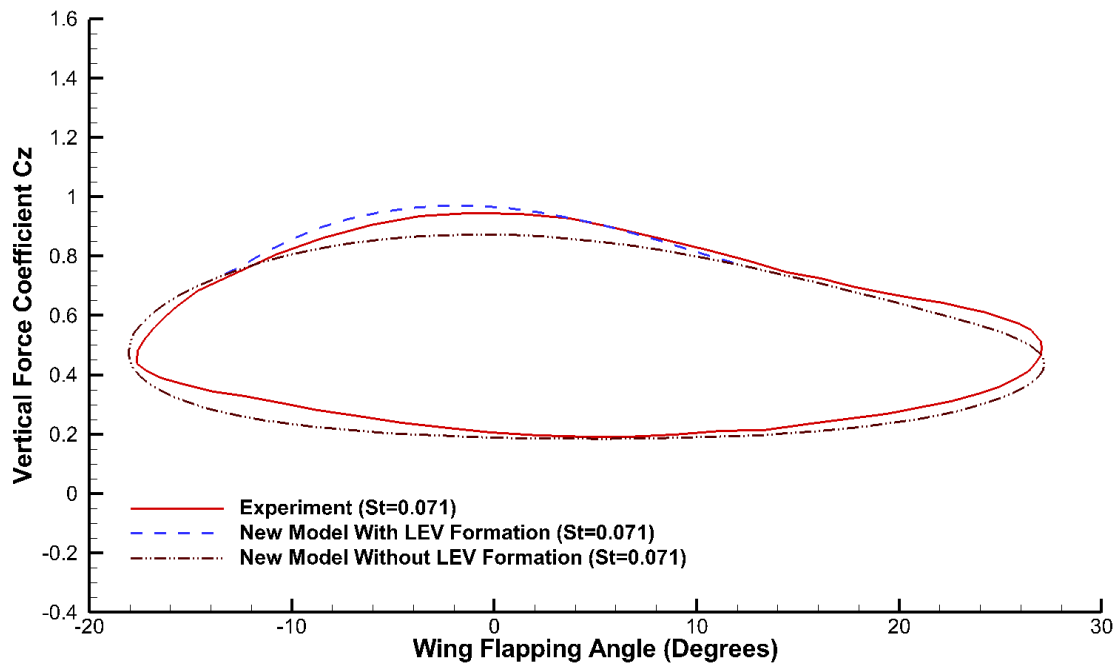


Figure 5.6: Vertical force coefficient vs flapping angle of a flapping wing operating at a St of 0.045, curves taken from lifting line based method with and without LEV formation, and experimental results

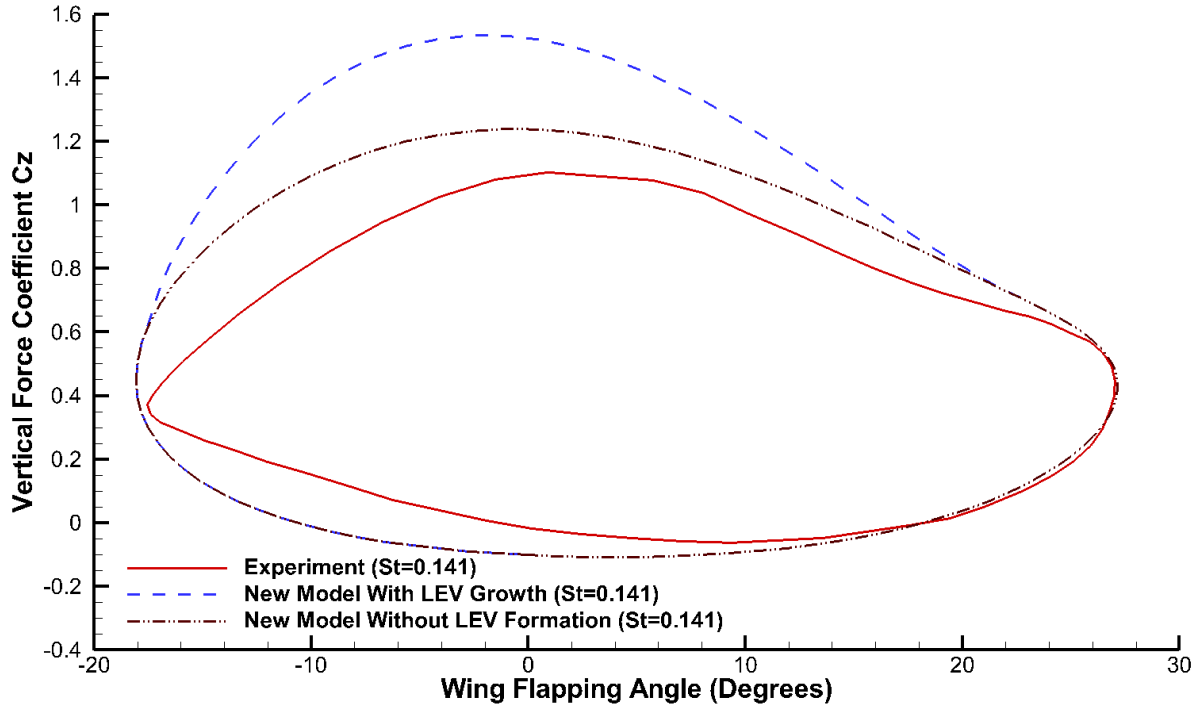


Figure 5.7: Vertical force coefficient vs flapping angle of a flapping wing operating at a St of 0.045, curves taken from lifting line based method with and without LEV formation, and experimental results

5.2. Validating spanwise circulation distribution

Accurate prediction of spanwise sectional force distribution, rather than just total force, was a primary motivator for development of the new lifting line based model. Thus, another set of comparisons were made to an experiment where the circulation distribution along the span of the wing was accurately captured using DPIV [62]. The circulation along the span is theoretically proportional to total lift and suction force acting on the wing, making it a good quantity to assess validity of the model. In Figure 5.8 - Figure 5.13 the circulation is captured at the midstroke where the wing has the highest angular velocity and relative angle of attack, thus the circulation should peak at this point.

In Figure 5.8, the relative AOA of the wingtip is much less than the cross-section's zero lift AOA due to the large geometric twist of 40 degrees. The new lifting line model captures both the shape and magnitude of the circulation distribution with the predicted circulation gradually tapering off from its maximum at the wing root to zero at the wing tip. MST does not match the shape of this distribution and underpredicts circulation magnitude. While circulation of the MST prediction decreases from the root to tip of the wing, there is a discontinuity in rate of change

where the wing planform transitions from rectangular to tapered at the 50% semispan point. This discontinuity occurs in all six cases, and MST never accurately captures the shape of the distribution for any of these cases.

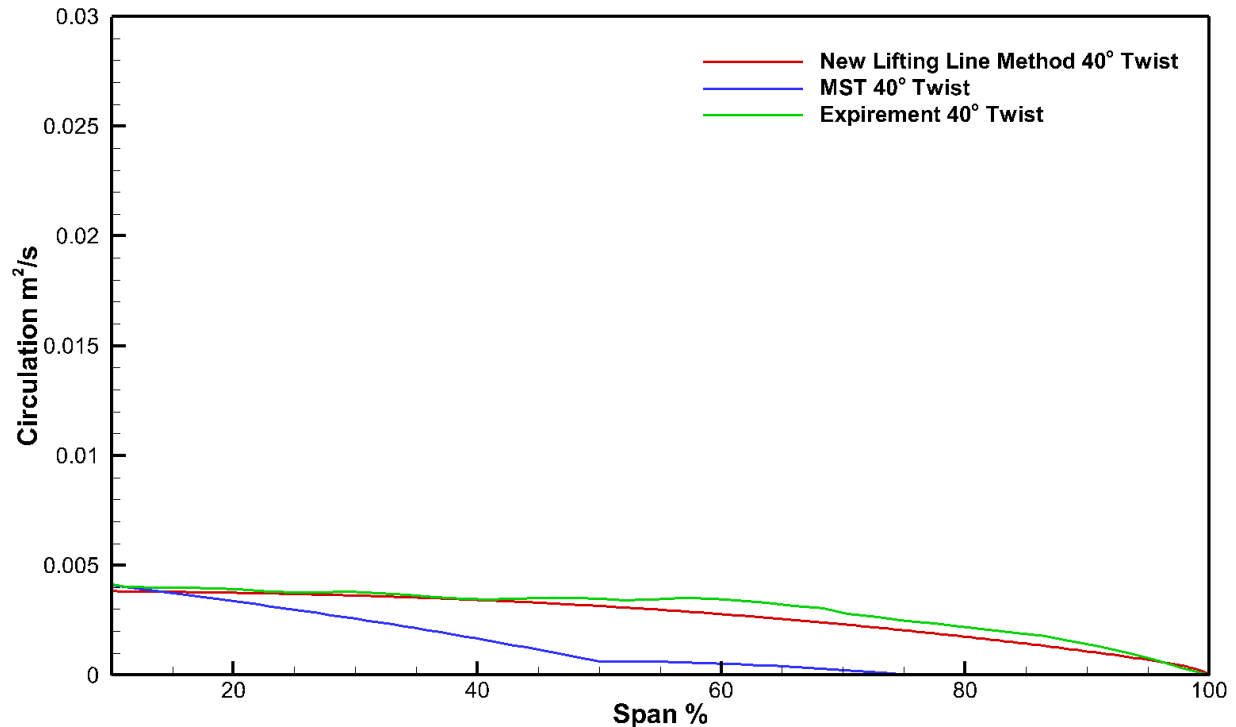


Figure 5.8: Cross-sectional circulation vs semispan location for a wing with 40 degree twist and operating at a St of 0.2, 0% at the wing root and 100% at the wingtip

In Figure 5.9, the relative AOA of the wingtip is close to the static stall angle due to the moderate geometric wing twist of 10 degrees. This causes the outer section of the semispan to produce a higher circulation than the inner part. The new model captures the shape of the circulation distribution for the outer portion of the semispan, with the predicted circulation gradually increasing from the wing root to reaching a maximum around the 50% span location, and then rapidly dropping to zero close to the tip. The magnitude of the distribution a nicely captured for the outer portion of the semispan, but not the inner portion where circulation is over estimated. MST does not match the shape or magnitude of this distribution and overpredicts circulation everywhere except the wing root. Also in this case and the following four cases, the circulation predicted by MST does not drop to zero at the wing tip, which occurs for all experimental cases.

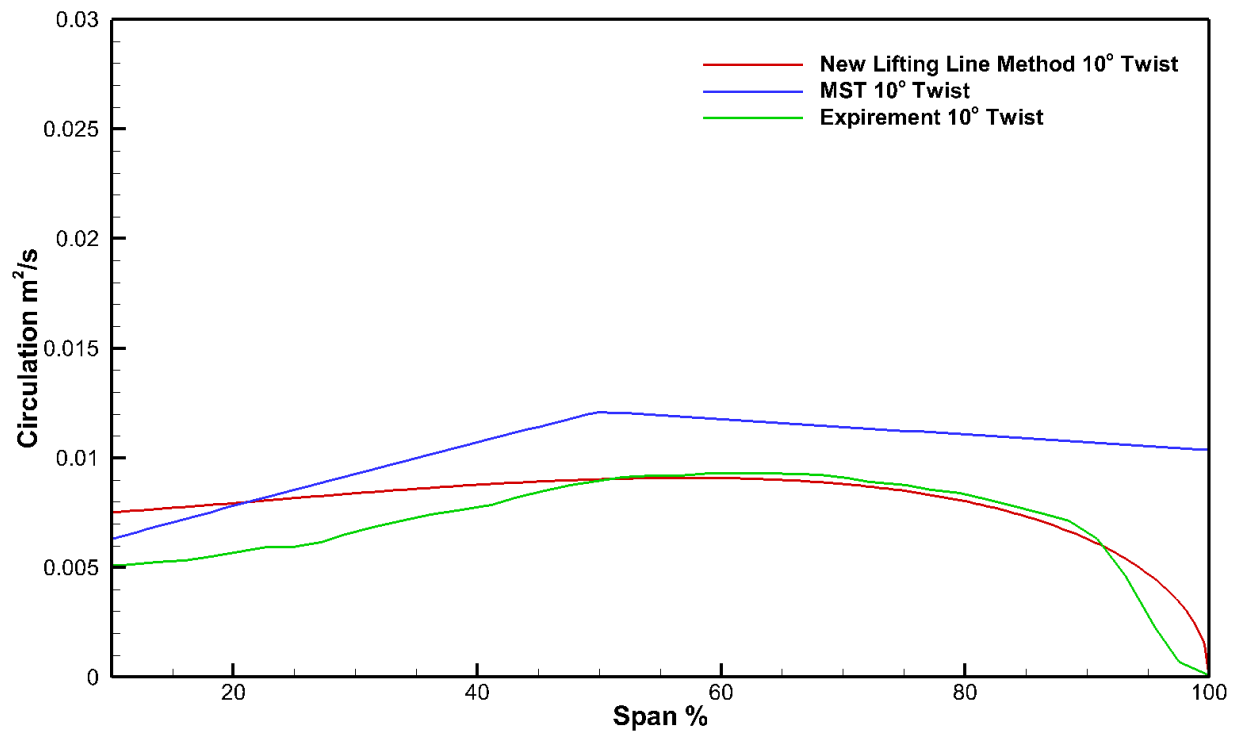


Figure 5.9: Cross-sectional circulation vs semispan location for a wing with 10 degree twist and operating at a St of 0.2, 0% at the wing root and 100% at the wingtip

In Figure 5.10, the relative AOA of the wingtip is considerably past the static stall angle due to no geometric wing twist. This causes the outer section of the semispan to produce a higher circulation than the inner part. The new model captures the shape of the circulation distribution for the outer portion of the semispan, with the predicted circulation increasing from the wing root to reaching a maximum between the 50% and 100% span locations, and then rapidly dropping to zero close to the tip. The magnitude of the distribution a nicely captured for the outer portion of the semispan, but not the inner portion were circulation is over estimated. MST does not match the shape or magnitude of this distribution and overpredicts circulation everywhere except the wing root.

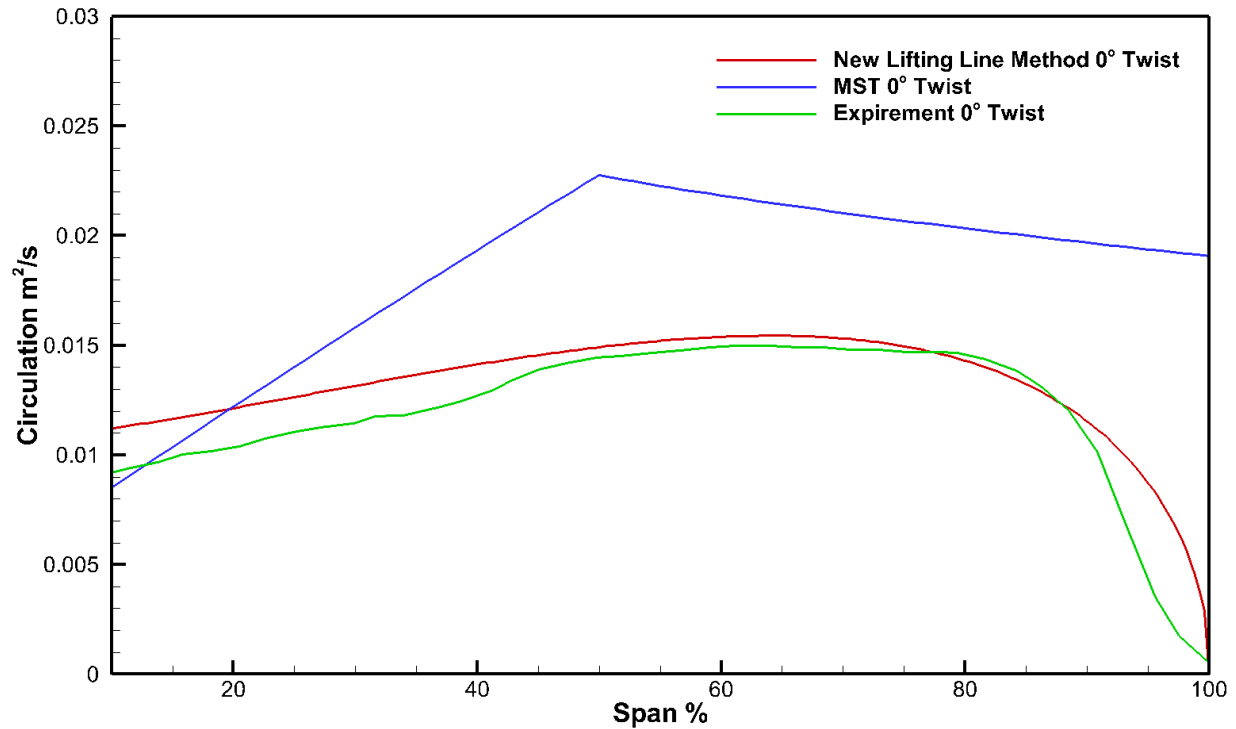


Figure 5.10: Cross-sectional circulation vs semispan location for a wing with 0 degree twist and operating at a St of 0.2, 0% at the wing root and 100% at the wingtip

In Figure 5.11, the relative AOA of the wingtip is below the static stall angle due to the large geometric wing twist of 40 degrees. This causes the inner section of the semispan to produce a higher circulation than the outer part. The new model captures the shape of the circulation distribution with the predicted circulation remaining relatively constant from the root to about the 60% semispan location, and then gradually dropping to zero towards the tip. The magnitude of the distribution is over estimated for the entire semispan. MST overpredicts the circulation even more than the new model except at the wing root.

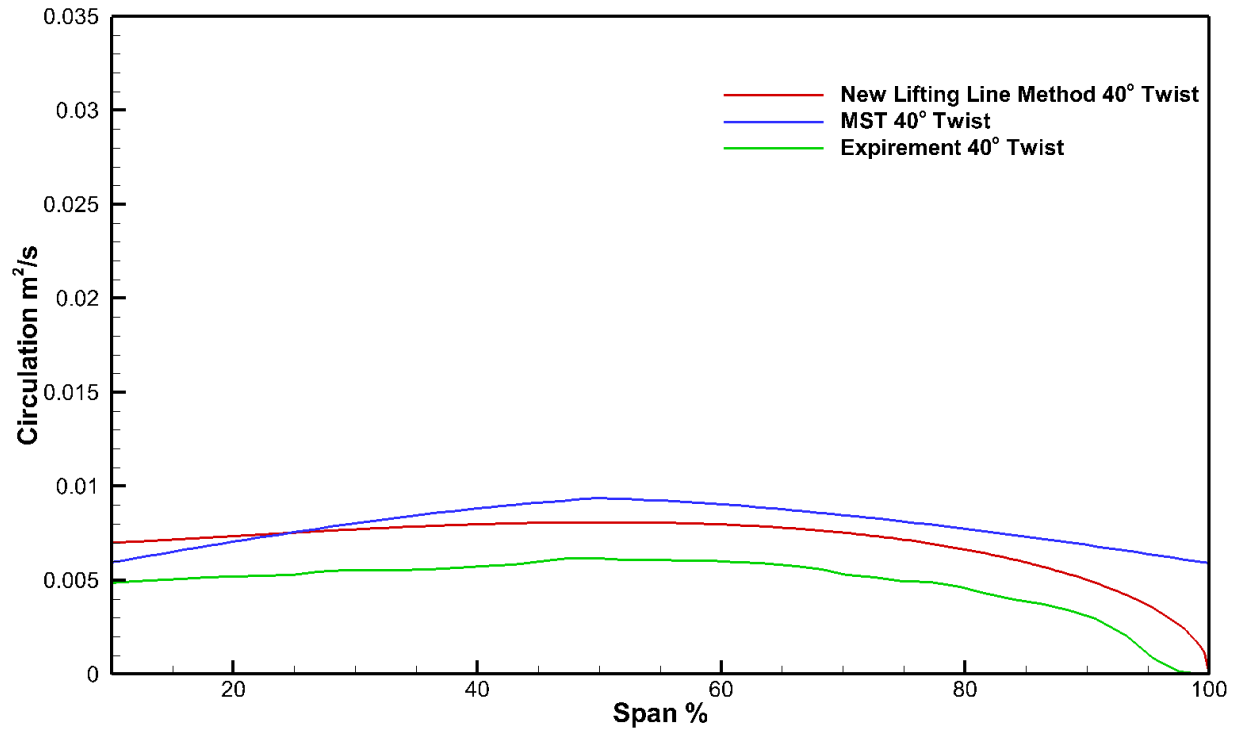


Figure 5.11: Cross-sectional circulation vs semispan location for a wing with 40 degree twist and operating at a St of 0.3, 0% at the wing root and 100% at the wingtip

In Figure 5.12, the relative AOA of the wingtip is past the static stall angle due to the moderate geometric wing twist of 10 degrees. This causes the outer section of the semispan to produce a higher circulation than the inner part. The new model captures the shape of the circulation distribution with the predicted circulation increasing from the wing root to reaching a maximum between the 50% and 100% span locations, and then rapidly dropping to zero close to the tip. With the new model, the circulation is overestimated for the entire semispan, more so for the inner section than the outer section. MST overpredicts the circulation even more than the new model except at the wing root.

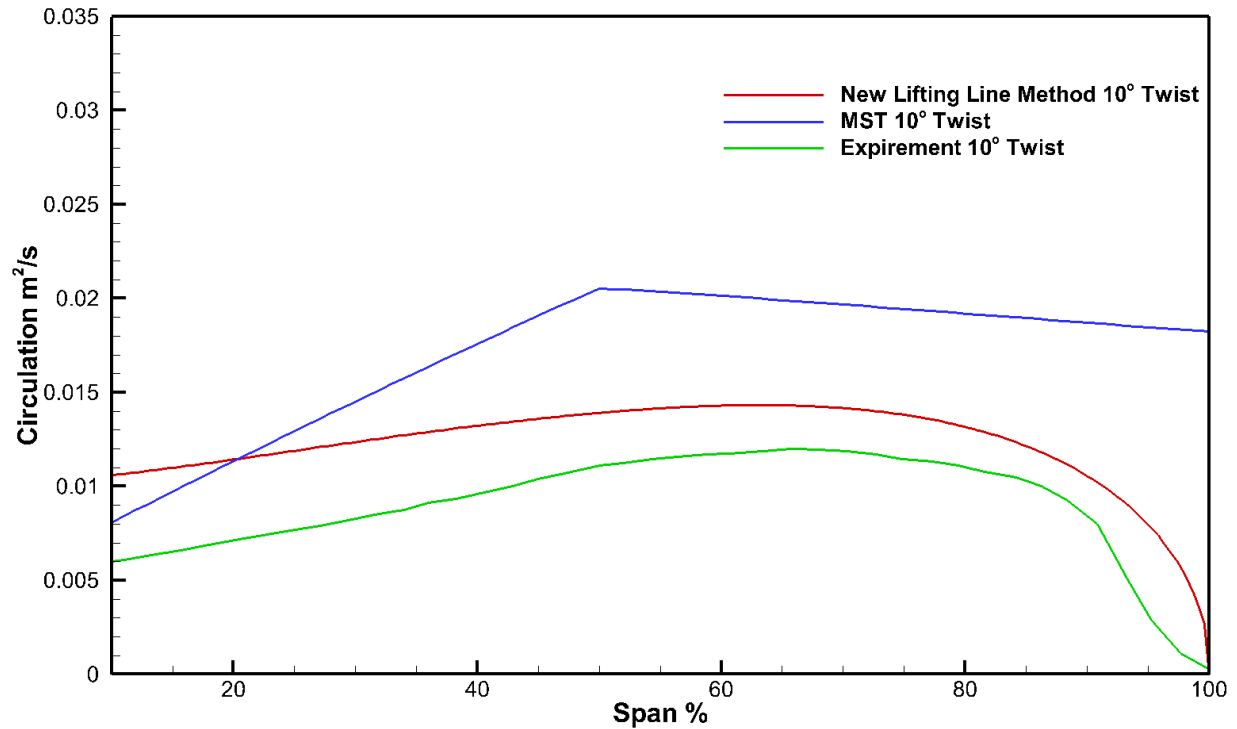


Figure 5.12: Cross-sectional circulation vs semispan location for a wing with 10 degree twist and operating at a St of 0.3, 0% at the wing root and 100% at the wingtip

In Figure 5.13, the relative AOA of the wingtip is considerably past the static stall angle due to the moderate geometric wing twist of 0 degrees. This causes the outer section of the semispan to produce a higher circulation than the inner part. The new model captures the shape of the circulation distribution with the predicted circulation increasing from the wing root to reaching a maximum between the 50% and 100% span locations, and then rapidly dropping to zero close to the tip. With the new model, the circulation is overestimated for the entire semispan, more so for the inner section than the outer section. MST overpredicts the circulation even more than the new model except at the wing root.

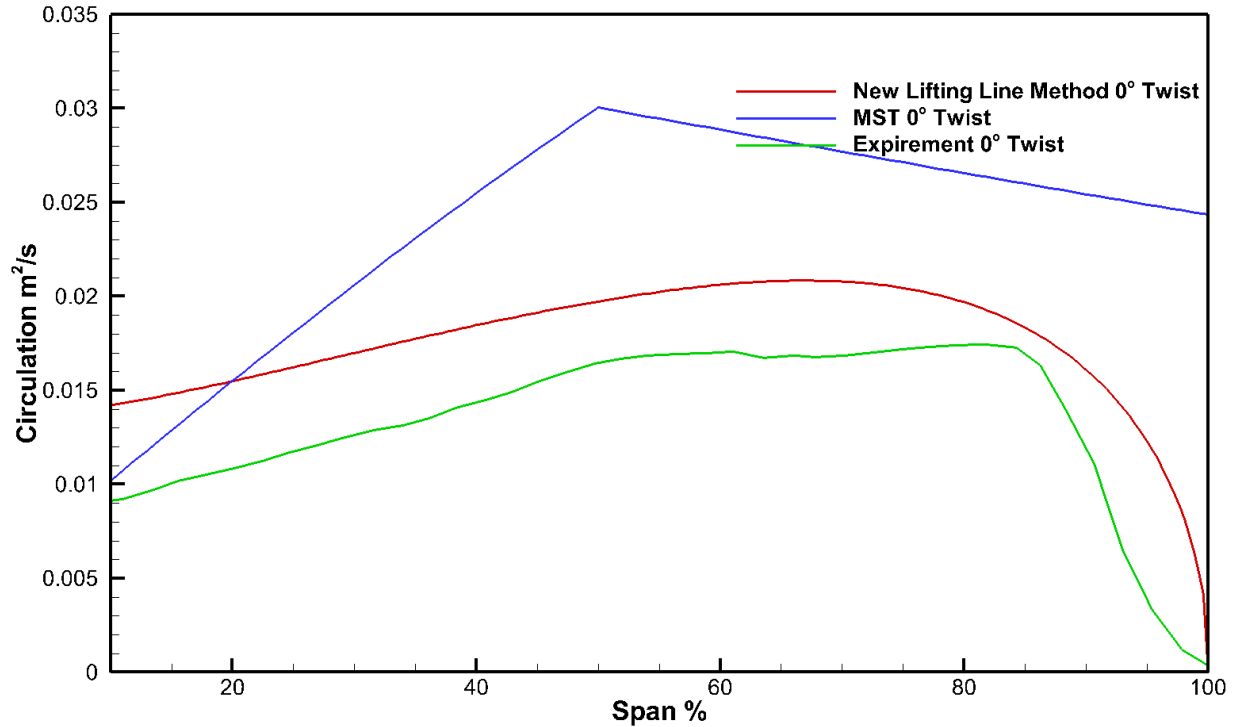


Figure 5.13: Cross-sectional circulation vs semispan location for a wing with 0 degree twist and operating at a St of 0.3, 0% at the wing root and 100% at the wingtip

While the new model is able to capture the general shape of the circulation distribution, it tends to overpredict circulation at the wing root and at the higher St of 0.3. This is likely caused by the 12 cm gap between the wing root and wall in the experiment [62]. Both the new model and MST assume no discontinuities in the span. The discontinuity at the wing root has even more of an impact on the new model as the sectional lift is dependent on adjacent sections. The adjacent section does not exist in the experiment and causes energy to be lost at the wing root due to a tip vortex which can be clearly seen in [62], and explains the new model's overestimation of wing root circulation.

Also, as there is a gap at the wing root, effective aspect ratio is smaller than calculated aspect ratio decreasing aerodynamic efficiency of the actual wing. As the models must use calculated aspect ratio rather than effective aspect ratio they overpredict circulation. MST overpredicts circulation even more as it is only accurate for high aspect ratio wings [49]. Even the calculated aspect ratio of the wing is only 5.5, which is considered low.

6. Background: Fish swimming

Unlike birds, bats, and insects, sea creatures did not all converge to a single form of locomotion. Even just among fish, there are two different distinct modes of locomotion. These are body/caudal fin (BCF) locomotion and median/paired fin (MPF) locomotion. BCF locomotion involves forming a propulsive wave along the body of the fish that transfers into the caudal fin. On the other hand, MPF involves using one or more fins apart from the caudal fin to generate thrust via propulsive wave or paddling. [4] Majority of fish species utilize BCF locomotion to achieve propulsion with few relying on MPF propulsion [64]. Thunniform swimming, the focus of the swimming portion of this dissertation, utilizes BCF locomotion. Thus, the kinematics and hydrodynamics of only BCF swimmers will be discussed in this chapter.

6.1. BCF locomotion kinematics

Four swimming gaits are typically used to classify BCF locomotion. These are anguilliform, subcarangiform, carangiform, and thunniform [65]. A fifth gait, termed ostraciiform, does not utilize a body wave and instead relays purely on paddling of the caudal fin [4]. These swimming gaits are distinguished by the body propulsive wavelength relative to body length as shown in Figure 6.1 (taken from [65]). Anguilliform swimmers use the shortest wave length followed by subcarangiform, carangiform, and lastly thunniform.

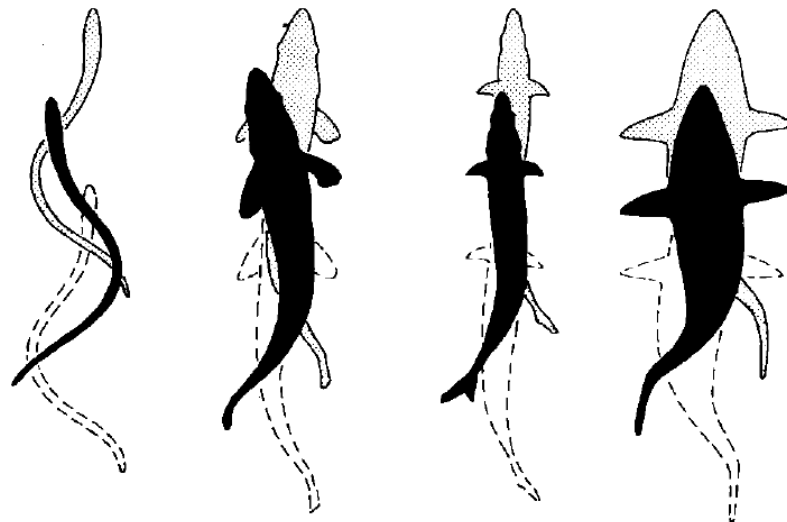


Figure 6.1: BCF swimming gaits (from left to right) anguilliform, subcarangiform, carangiform, and thunniform (taken from [65])

In addition to the difference in wavelength, the different gaits tend to have different amplitude variations along their body. An exponentially increasing amplitude envelope has been used to describe anguilliform swimmers while a quadratically increasing amplitude envelope has been used to describe carangiform swimmers.[66] There is no clear divide between each of the gaits [4]. Tuna, the primary users of thunniform locomotion, have propulsive waves 30-60% longer than other cruise-adapted fish [67]. Tuna adjust angular position of the tail independently of the body wave[68] and can be seen in Figure 6.2.

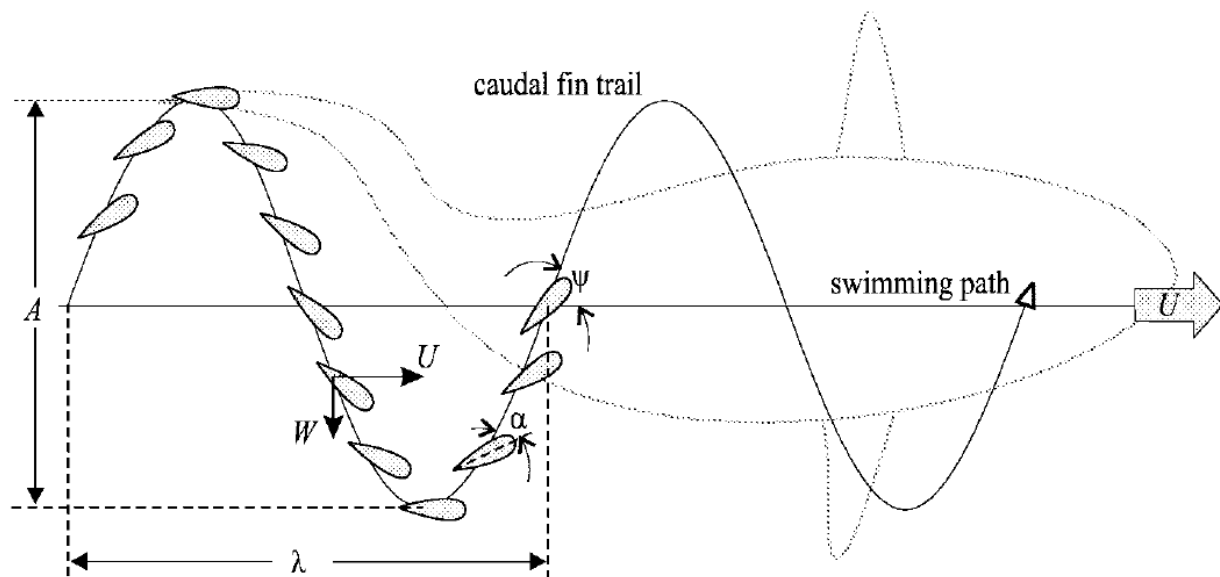


Figure 6.2: Trail of an oscillating caudal fin showing amplitude A , wavelength λ , feather angle ψ , and attack angle of the fin α (taken from [4])

In tuna rotation of the intervertebral joints is restricted by the zygapophyses and thus most rotation occurs at the end of the peduncle.[67] A two-wave system consisting of a body propulsive wave and a caudal fin oscillatory wave can be used to characterize the locomotion of thunniform and some carangiform swimmers. [69] Dewar et al found caudal amplitude of yellowfin tuna to be $0.17 L^{-1}$ - $0.2 L^{-1}$ [67]. Bluefin tuna have reportedly similar tail amplitudes of $0.16 L^{-1}$ [70]. In contrast the tail amplitude of tuna has been reported to be as high as $0.34 L^{-1}$ but at a speed of 8.2 body lengths per second [71] which was much higher than the previous two studies. Carangiform swimmers only undulate the rear one half and sometimes even one third of their body when approaching thunniform [66]. Mackerel, a carangiform/thunniform swimmer, has oscillations in its front half that have an amplitude that is less than 25% of the caudal amplitude. [72]

Several species of open ocean “highly-active cruising fishes”, such as tuna and mackerel, have a narrow peduncle and lunate tail (similar to a swept wing) that suggests this body shape improves efficiency. [73, 74]. In tuna, the caudal fin typically acts like a rigid propulsor, where the bony lateral keels run along the length of the peduncle making it rigid, thereby minimizing lateral caudal flexing [71, 75, 76]. This is very different from other fish where the caudal fin deforms or is even actively flexed [14].

6.2. Hydrodynamics

The hydrodynamics of swimmers vary across the swimming gates. Thunniform swimming and carangiform swimming are typically fast with Re greater than 10^4 where viscous effects are minimal small [77]. Thunniform and carangiform swimmers produce thrust via lift based mechanism, whereas anguilliform swimmers tend to produce thrust via undulatory pump mechanism [16, 78-80]. While lift based propulsion is effective in high-speed locomotion, drag based propulsion is effective during slower locomotion because it is conducive to rapid thrust production [81]. The difference in the physics of thrust generation between drag- and lift based propulsion is due to differences in vortex formation [82].

Vortex streets are commonly seen in the wake of BCF swimmer. Where at low St numbers, a normal Karman street is formed, resulting in drag production, at higher St numbers, a reverse Karman street may be formed, which is indicative of thrust. At even higher St numbers, a double row vortex street may also be formed. It has only been observed to produce thrust in swimming fish. [83]

CFD simulations indicate that anguilliform kinematics can achieve higher speeds at lower Re , whereas carangiform kinematics can only achieve comparatively higher speeds at higher Re [66]. Furthermore, they indicate that anguilliform kinematics allow a swimmer to accelerate faster at lower speeds [66]. Lastly, CFD simulations suggest that, at high Re , a fusiform body paired with carangiform kinematics exhibits the highest efficiency while at realistically low Re , anguilliform kinematics paired with an eel body is the most efficient [66]. This makes sense because, in nature, fish with fusiform bodies utilize carangiform/thunniform kinematics and swim at high speeds but

are less efficient at slower speeds [67], whereas eels utilize anguilliform kinematics and swim at lower Re .

Swimmers with narrow peduncles are considered the most economical swimmers [65, 66, 73, 76, 84]. The narrow tail of the fusiform body and the actuation of this tail separate from the body, as in thunniform swimming, allows the caudal fin to oscillate without energetically costly inertial recoil occurring during high amplitude anterior oscillation found in other body types [65, 76, 84-86]. The fusiform body has a tail with a long narrow peduncle that will not shed as much energy into the wake as a thicker tail [87], limiting its ability to produce thrust. Conversely, this means it also produces less drag. It is believed that, despite the lack of thrust produced by the anterior section of the fusiform tail, large amounts of thrust can still be produced by lunate and forked caudal fin by means of leading edge suction generation [76, 88, 89]. The fusiform body shape, along with a long propulsive wavelength, minimize tail resistance while increasing caudal fin thrust potential [67, 87].

Most fishes appear to swim optimally at a Strouhal Number (St) of 0.3; experimental flapping foils also achieved optimal efficiencies at similar St [77, 90]. It has been shown that St utilized by fish is not always the constant, notably at slower speeds characterized lower Re [83, 91]. At low swimming speed, Pacific salmon swim at St as high as 0.6 [91]. A numerical Navier-stokes based study on a mackerel swimming mackerel indicates that at an Re of 300, an St approximately equal to 1.1 is required, for an Re of 4000 an St of approximately 0.6 is required, and for inviscid flow, an St of approximately 0.25 is required [83].

7. A preliminary investigation of caudal fin shape effects

This chapter presents a preliminary study, in which a tuna mimetic robot is used to investigate the effects of caudal fin shape on thrust production and power. Other studies have examined different aspects of the caudal fin in both thunniform and non-thunniform fish. These studies include experiments examining the effect of fin aspect ratio, flexibility, and kinematics [13, 14]. There has also been a CFD study that presented how caudal shape affects LEV formation [16]. However, few studies, both experimental and numerical, isolate the effect of caudal fin shape on thrust production and power.

For this reason, this chapter will not only discuss the effect caudal fin kinematic parameters, such as frequency, amplitude of oscillation, and angle of attack, but also caudal fin geometric shape on thrust production and energy expenditure. In this chapter, the robot's design, experimental setup, and preliminary results of caudal fin shape studies will be discussed.

7.1. Robotic design

The tuna mimetic is not free swimming, but instead is designed to be fixed to a test stand within a water tunnel. This allows for straightforward collection of thrust force data and control over freestream velocity. It also increases simplicity of the robot by allowing for placement of the electronics outside of the tunnel.

The robot shown in Figure 7.1 is tuna mimetic and adopts a side profile that imitates that of *thunnus albacares* (yellowfin tuna). Using MATLAB, the outer edge of a yellowfin anatomical schematic was identified through careful manual selection. The resulting pixel coordinates were then converted into metric units based on typical yellowfin length. The total length of the robot is 1.07 m, measured from the front tip of the body to the end of the tail peduncle (the body part that connects the caudal fin rays to the rest of the tail).

The entire body structure was additively manufactured using a BCN3D Sigma printer that utilizes fused deposition modeling (FDM). The material used, polylactic acid (PLA), has a density of 1.2 g/cm^3 making it close to neutrally buoyant. Furthermore, the interior is hollow and designed to fill with water in order to bring the robot closer to neutral buoyancy.

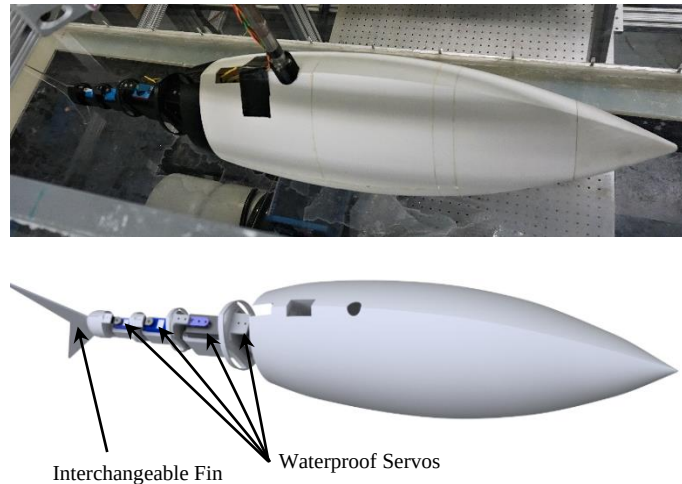


Figure 7.1: Biomimetic Robotic Tuna CAD (Top) Actual (Bottom) CAD model (taken from [92])

Actuation is concentrated in the rear third of the robot as its locomotive mode is Thunniform. Four waterproof servos are used for actuation of the four independent tail sections that discretize the propulsive swimming wave. All servos used are Hitec brand. The two servos farthest from the caudal fin are model D-845WP; they have a stall torque of $5.00 \text{ N}\cdot\text{m}$ and a no load speed of 58.8 rpm. The third servo is model HS-5646WP; it has a stall torque of $1.29 \text{ N}\cdot\text{m}$ and a no load speed of 55.6 rpm. Lastly, the servo closest to the caudal fin is model HS-5086WP; it has a stall torque of $0.36 \text{ N}\cdot\text{m}$ and a no load speed of 66.7 rpm. Servos were chosen because they allow for adjustment of not only tail beat frequency but also amplitude. The articulated section of the robot was not skinned, leaving the ribs exposed to oncoming flow. This is not ideal as the non-streamlined tail structure can overly disturb the flow before it reaches the caudal fin. Skin that could be used to cover the tail can be made out of silicone due to its high elasticity. However, this skin was never applied due to a second robot being constructed and used for subsequent experiments.

Five caudal fin shapes were planned to be examined, but for preliminary testing two basic shapes were investigated. These are a swept caudal fin, somewhat similar to what is found on tuna, and a trapezoidal caudal fin as shown in Figure 7.2. The three additional caudal fin shapes planned for further studies are a rectangular fin, elliptical fin, and a biomimetic fin that matches the side profile of an actual tuna caudal fin. To isolate the effect of fin shape, the vertical tip-to-tip caudal fin span equaling 30 cm, aspect ratio equaling 8.2, and planform area equaling 110 cm^2 were kept constant between fin designs.

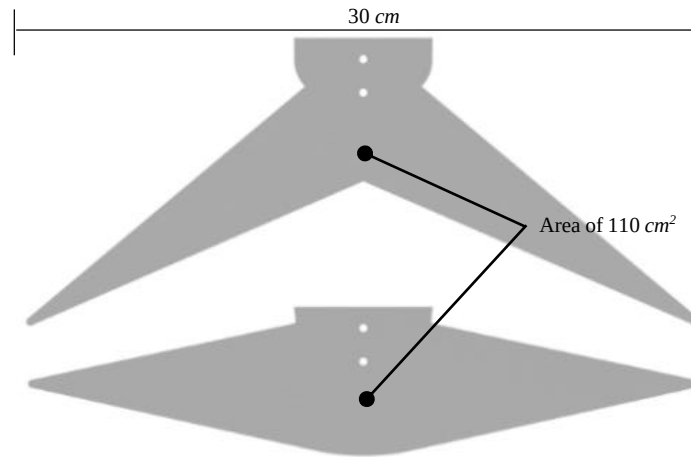


Figure 7.2: Swept (top) and trapezoidal (bottom) caudal fins with equal area and aspect ratio (taken from [92])

7.2. Experimental setup

7.2.1. Test rig

For testing, the robot was placed within a 24"x24" circulating water tunnel capable of freestreams greater than 0.5 m/s, but incapable of operating for long periods at those speeds. The purpose of the experiment is to measure thrust force and electrical energy expenditure at different swimming speeds. This is done via a lever assembly shown below in Figure 7.3. This lever assembly was chosen as it allows for adjustment of mechanical advantage, so that force transmitted to the load cell can be tuned to the range of the cell yielding increased resolution and a better signal to noise ratio.

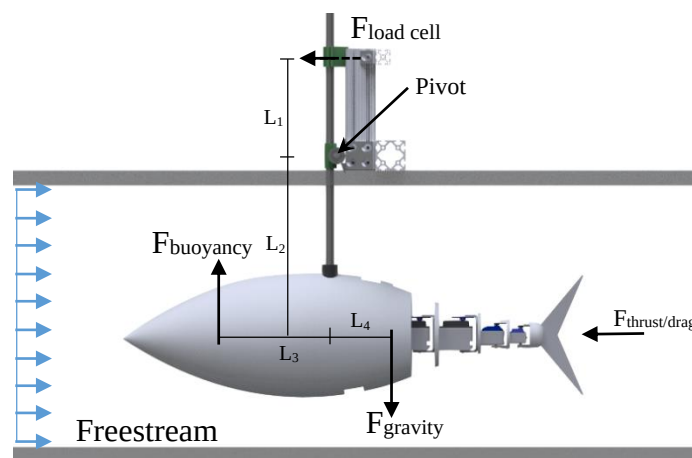


Figure 7.3: Robot fixed to force transfer assembly (taken from [92])

The force applied to the load cell is a function of the moments caused by the forces, shown in Figure 7.3, about the low friction pivot. This relationship is shown in Eq. (7.1.).

$$F_{load\ cell} = \frac{1}{L_1} (L_2 F_{thrust} + L_4 F_{gravity} + L_3 F_{buoyancy}) \quad (7.1.)$$

Oscillation of the tail causes slight shifts in the center gravity and buoyancy, resulting in changes to L_3 and L_4 . This could affect force applied to the load cell due to alteration of the moment arm. However, as the change in longitudinal length of the robot is predicted to be less than 1 cm, changes in L_3 and L_4 are considered negligible. Furthermore, as the robot's tail is designed to be close to neutrally buoyant, shifts in center of gravity and buoyancy have even less of an effect.

The front section of the robot is sealed and filled with air, causing the center of buoyancy to always be in front of the center of gravity. This pitch up configuration is preferred as it puts the load cell in significant pre-compression without the use of springs or other mechanical devices that may cause damping. Pre-compression is necessary so a ball transfer attached to the lever rod always remains in contact with the interface block attached to the load cell, as shown in Figure 7.4. The ball transfer was used to ensure that a unidirectional force parallel to the load cell axis was applied to the load cell.

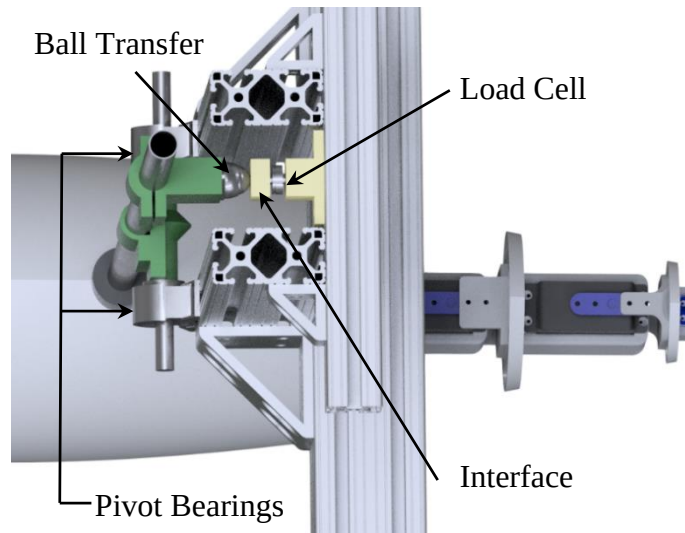


Figure 7.4: Load cell and force transfer assembly (taken from [92])

7.2.2. Prescribed Kinematics

The oscillation of a fish tail employing thunniform locomotion can be modeled with trajectory approximation. A gradually increasing propulsive wave is used to characterize this oscillation. The rate of increase of the propulsive wave is dependent on swimming gait, and can range from linear to exponential. The wave commonly used to describe the motion of tuna mimetic robots is quadratic and shown in Eq. (7.2.) [11], where y is the lateral displacement of the fish at a specific horizontal location x at time t . For the robot examined in this study, the propulsive wavelength λ was set at 1.32 times the body length based on data on 48 cm yellowfin Tuna [67].

$$y(x, t) = (c_1x + c_2x^2)\sin\left(\frac{2\pi}{\lambda}x + 2\pi ft\right) \quad (7.2.)$$

Since very small lateral anterior movement characterizes thunniform locomotion [4], the displacement of the front tip of the tuna was assumed negligible, and thus c_1 was assumed zero. The second coefficient c_2 was set as 0.061, which yields a caudal fin lateral displacement amplitude of 0.075 m. This amplitude is within the range provided by [67]. It also appears that, for yellowfin tuna, both fish size and swimming speed do not seem to have a significant impact on caudal fin amplitude and propulsive wavelength [67]. Thus, all of the aforementioned kinematic parameters were kept constant for all trials. Instead, tail beat frequency given by f , was varied from 0.5 to 1.0 Hz in increments of 0.1 Hz for each fin type and freestream combination. Unlike caudal amplitude and propulsive wavelength, it appears tail beat frequency is dependent on both fish size and swimming speed [67].

In order for the robot to approximate the propulsive wave given by Eq. (7.2.), MATLAB was used to discretize the wave into five links representing the robot's body and tail segments, as shown in Figure 7.5. All the segment endpoints, except the joints between segments 1 and 3, were set to lie on the propulsive wave. For each time step, the tracking of the right endpoints of these segments was achieved by sweeping the segment angle until there was a maximum error of 0.5 mm between the segment endpoint and the propulsive wave. The joint between segments 2 and 3 was set to track to only three quarters of the propulsive wave deviation from the centerline. This lowered amplitude of segment 2 was done to reduce load on the servomotor actuating that segment. The right endpoint of the body segment (segment 1) was set to remain stationary as the robot body was designed to remain fixed to the test stand, which prevents rotation.

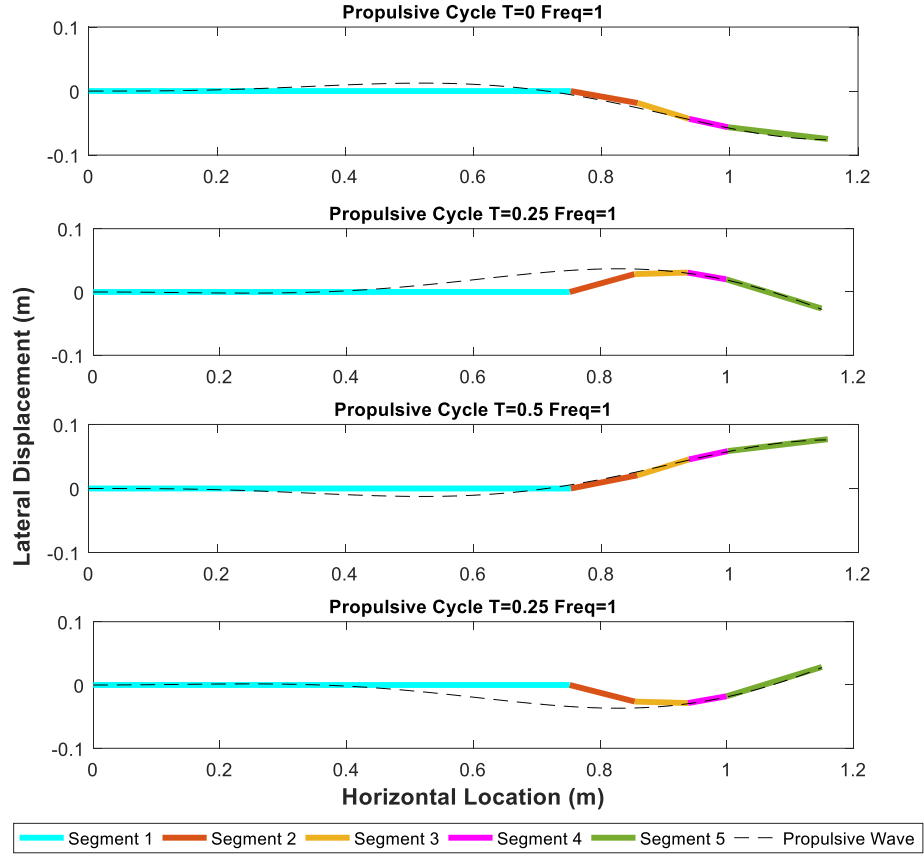


Figure 7.5: Trajectory estimation of the robot's body and tail segments. Segment 1 is the stationary body piece and segment 5 is the caudal fin attachment link (taken from [92])

Upon determination of the angles for each segment at each time step, the angles between adjacent segments as a function of time were fitted to a three term Fourier series again using MATLAB. A Fourier series was used, as the motion is cyclic but not quite sinusoidal. This Fourier series is what was used to program the robot's servomotor motion. The general form of this series is given below in Eq. (7.3.).

$$\theta(t) = a_0 + \sum_{i=1}^3 a_i \cos(i2\pi ft) + b_i \sin(i2\pi ft) \quad (7.3.)$$

The frequency f is the same as the operating frequency of the system. The coefficients for each of the four oscillating links are given below in Table 7-1. Joint_{a,b} corresponds with the joint between segments a and b.

Table 7-1: Coefficients of Fourier series estimating tail link angle

	Joint_{1,2}	Joint_{2,3}	Joint_{3,4}	Joint_{4,5}
a_0	0.5621	-0.006641	0.006971	0.02414
a_1	-11.07	-17.86	-12.61	-6.876
b_1	15.28	1.712	-10.08	-17.67
a_2	-0.01469	-0.008917	-0.008579	-0.001392
b_2	-0.003616	-0.001817	-0.009877	-0.01572
a_3	0.05767	0.1957	0.03581	-0.1162
b_3	-0.1068	-0.01255	0.1713	-0.07038

7.3. Preliminary results

Thirty six trials were performed consisting of all possible combinations of two different caudal fins (swept and trapezoidal), three different freestream velocities (0, 0.2, and 0.4 m/s), and six different frequencies (0.5, 0.6, 0.7, 0.8, 0.9, 1.0 Hz). Freestream velocities were kept below 0.5 m/s as the tunnel was unable to operate at speeds greater than that for extended periods.

Figure 7.6 highlights some sample thrust data collected with the trapezoidal fin installed when a frequency of 0.8 Hz and a freestream velocity of 0.2 m/s were applied. The data has not been filtered, indicating the lever assembly employed transmits data with an excellent signal to noise ratio. Using thrust amplitude as reference for signal power the signal to noise ratio is typically around 25 or 14 dB. The lever assembly was set to give a mechanical advantage of 3.85 and the preload on the cell due to weight/buoyance distribution was 3.37 N.

Shown in Figure 7.7, Figure 7.8, and Figure 7.9 are the relationships between thrust vs. frequency, and electrical energy expenditure vs. frequency. Electrical energy expenditure was calculated through the use of current sensors. Since servo operating voltage remains constant, electrical energy expenditure can be calculated using $P = V_{\text{operating}} \times I_{\text{sensor}}$. Thrust generally seems to have a positive correlation with frequency which is consistent with computation results from [93]. At all freestream velocities, it appears that, at comparable frequencies, the trapezoidal fin has lower electrical energy expenditure than the swept fin. It also appears that the trapezoidal fin usually produces more thrust at the two lower freestreams and the swept fin produces more thrust at the highest freestream of 0.4 m/s.

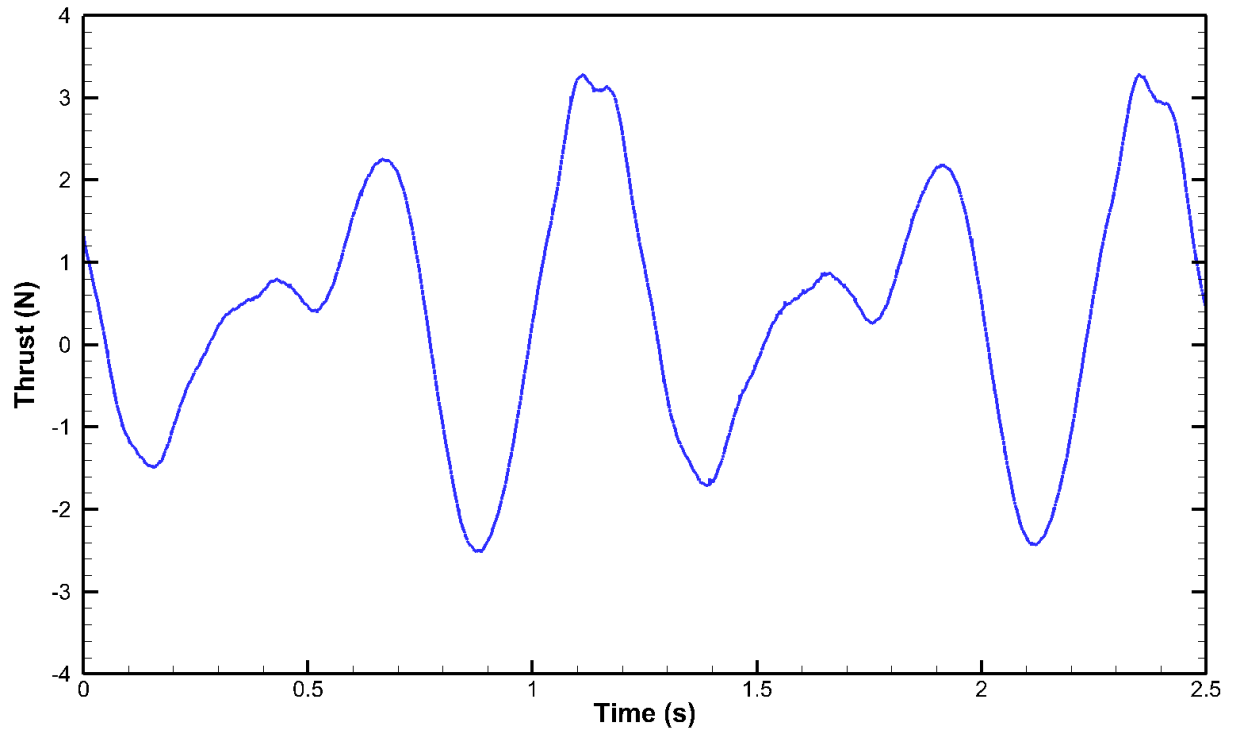


Figure 7.6: Thrust generated by the robot with trapezoidal fin attached for two tail beat cycles at a freestream velocity of 0.2 m/s and an operating frequency of 0.8 Hz (reprinted from [92])

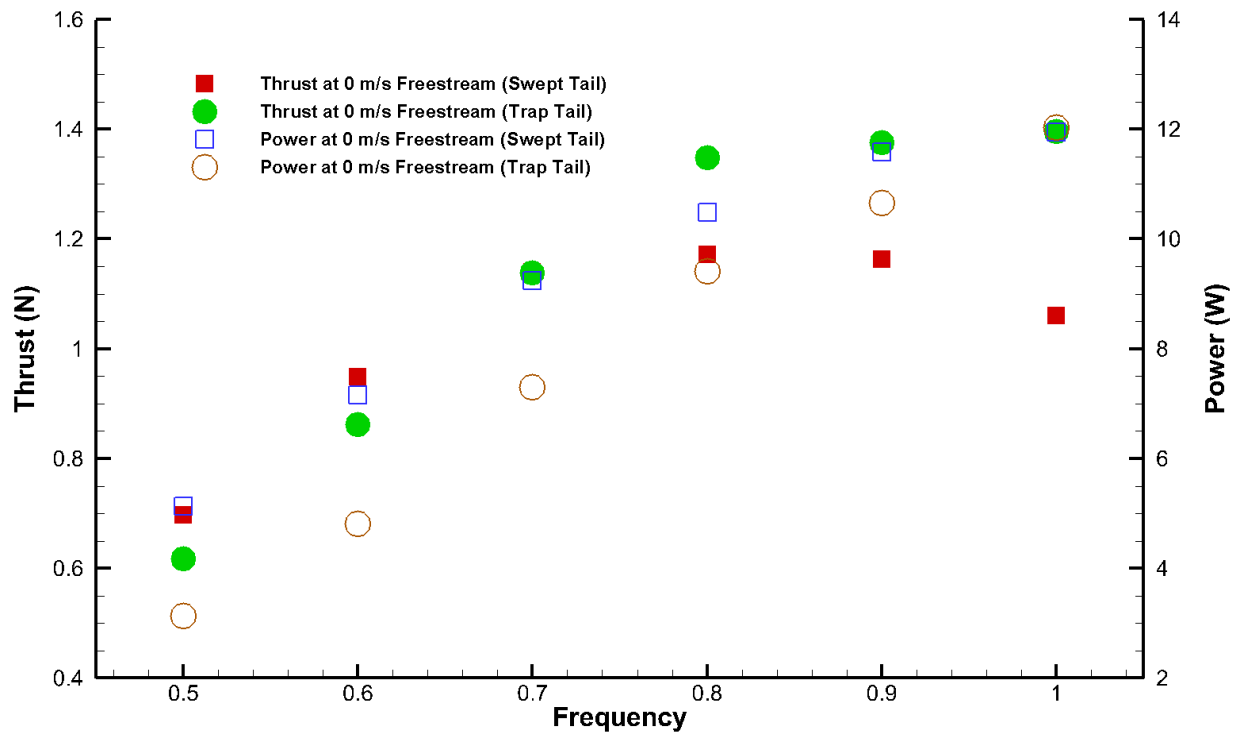


Figure 7.7: Thrust and power vs frequency at 0 m/s freestream velocity (reprinted from [92])

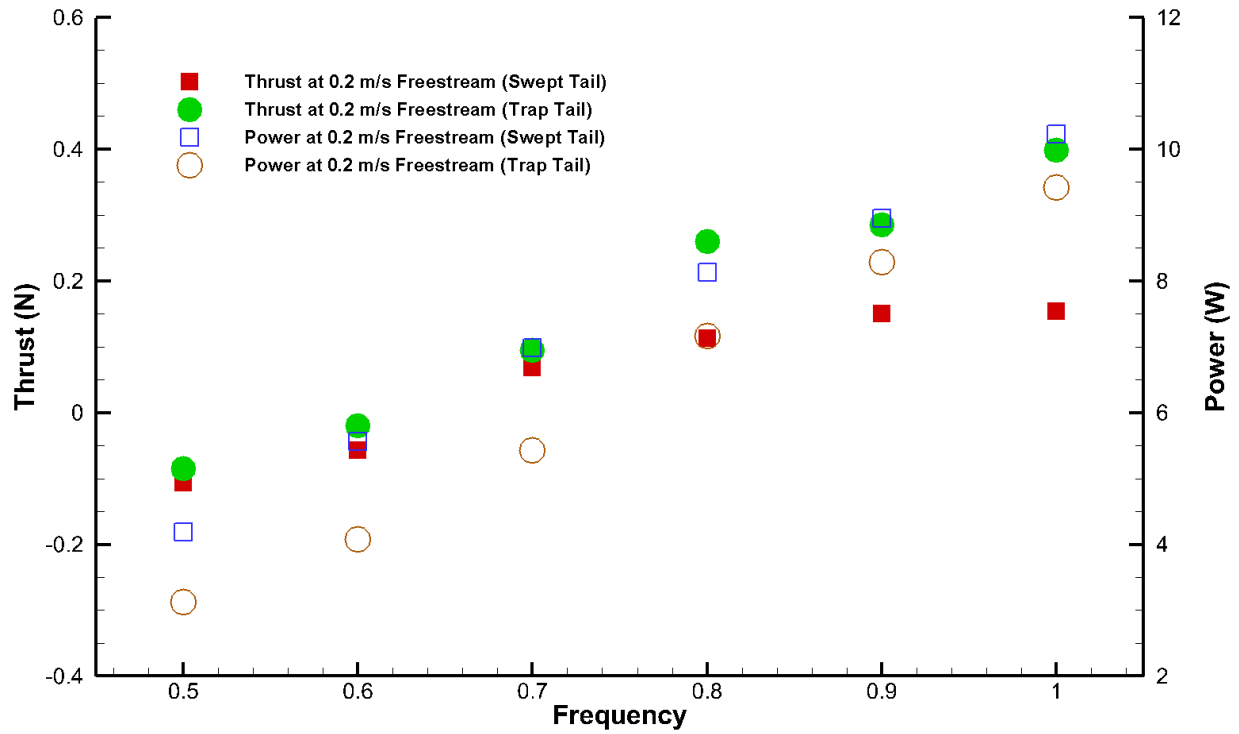


Figure 7.8: Thrust and power vs frequency at 0.2 m/s freestream velocity (reprinted from [92])

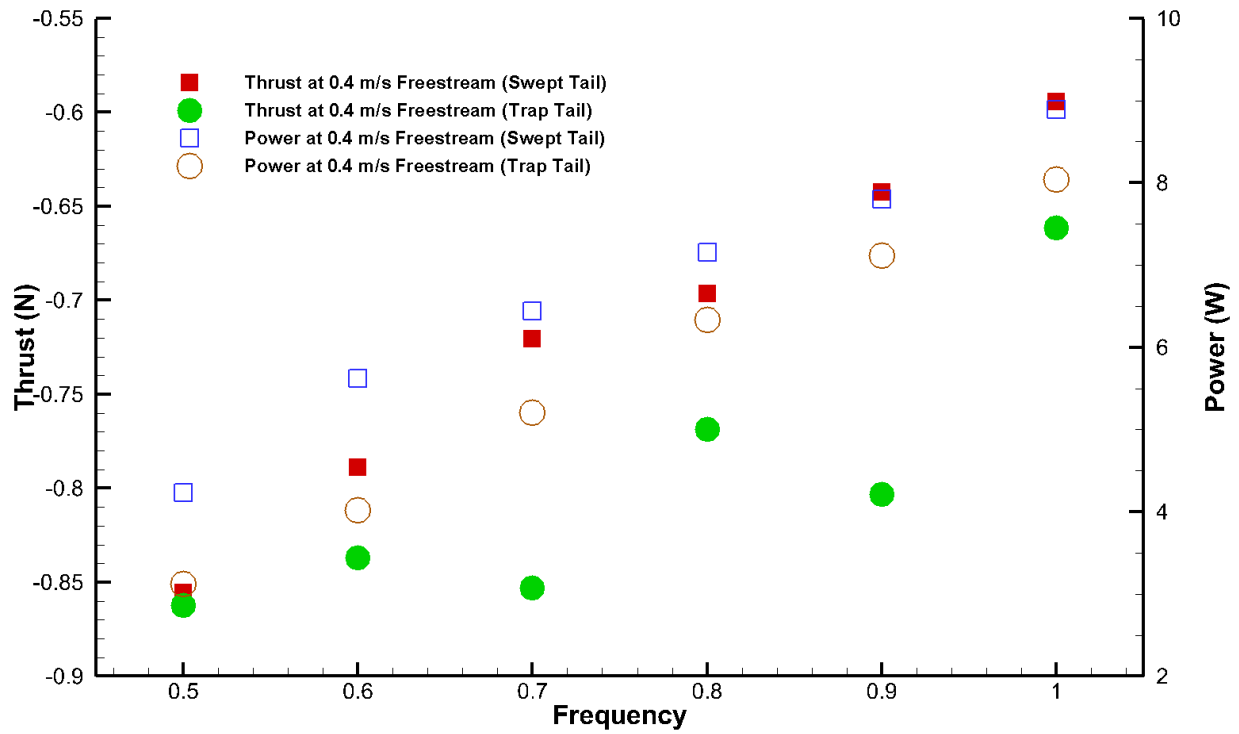


Figure 7.9: Thrust and power vs frequency at 0.4 m/s freestream velocity (reprinted from [92])

At a freestream velocity of 0 m/s, the trapezoidal fin has lower energy expenditure and produces comparable or more thrust than the swept fin. At a freestream velocity of 0.2 m/s, the trapezoidal fin has lower energy expenditure and always produces more thrust than the swept fin. At a freestream velocity of 0.4 m/s, the trapezoidal fin has lower energy expenditure, but always produces less thrust than the swept fin.

In Figure 7.10, Figure 7.11, and Figure 7.12, the relationship between thrust and electrical energy expenditure has been displayed. By comparing electrical energy expenditure to output force at a specific velocity, it provides an idea of efficiency between the two fin types. Again, at the two lower freestream velocities, the trapezoidal fin has a significantly better thrust to power ratio than the swept fin. However, at the highest tested freestream velocity, the swept fin starts to outperform the trapezoidal fin.

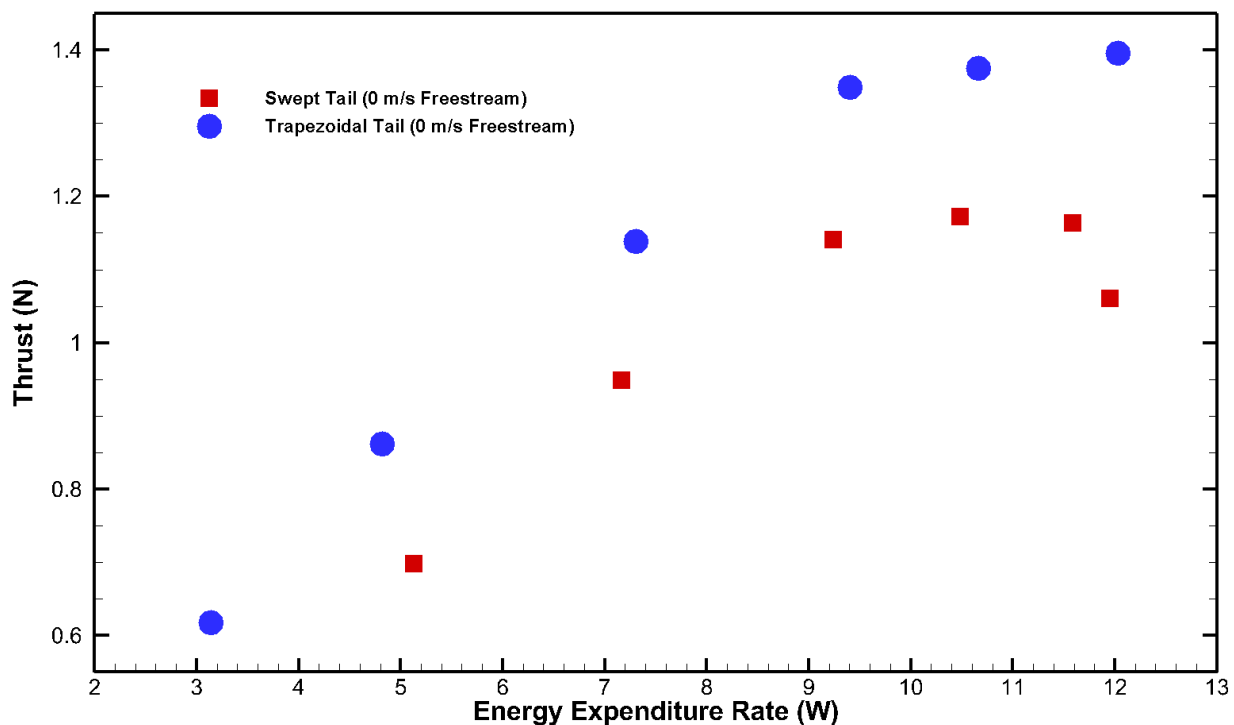


Figure 7.10: Thrust vs energy expenditure rate at a freestream of 0 m/s (reprinted from [92])

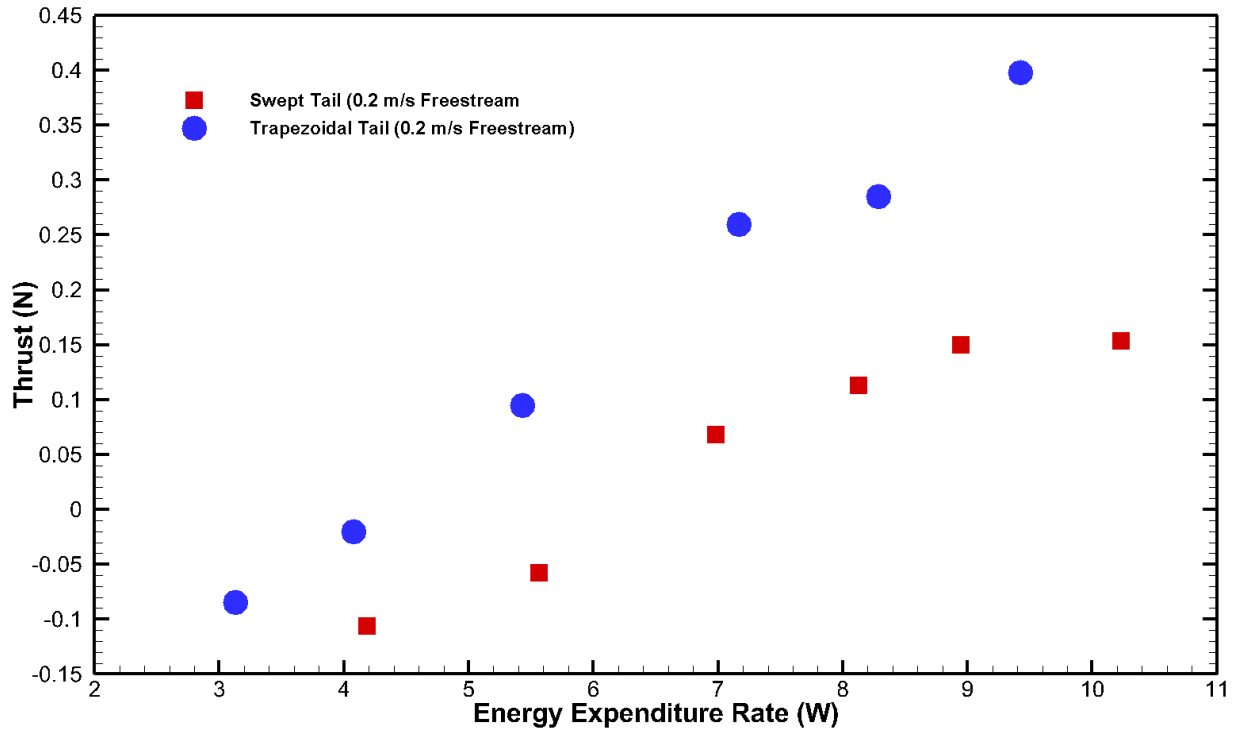


Figure 7.11: Thrust vs energy expenditure rate at a freestream of 0.2 m/s (reprinted from [92])

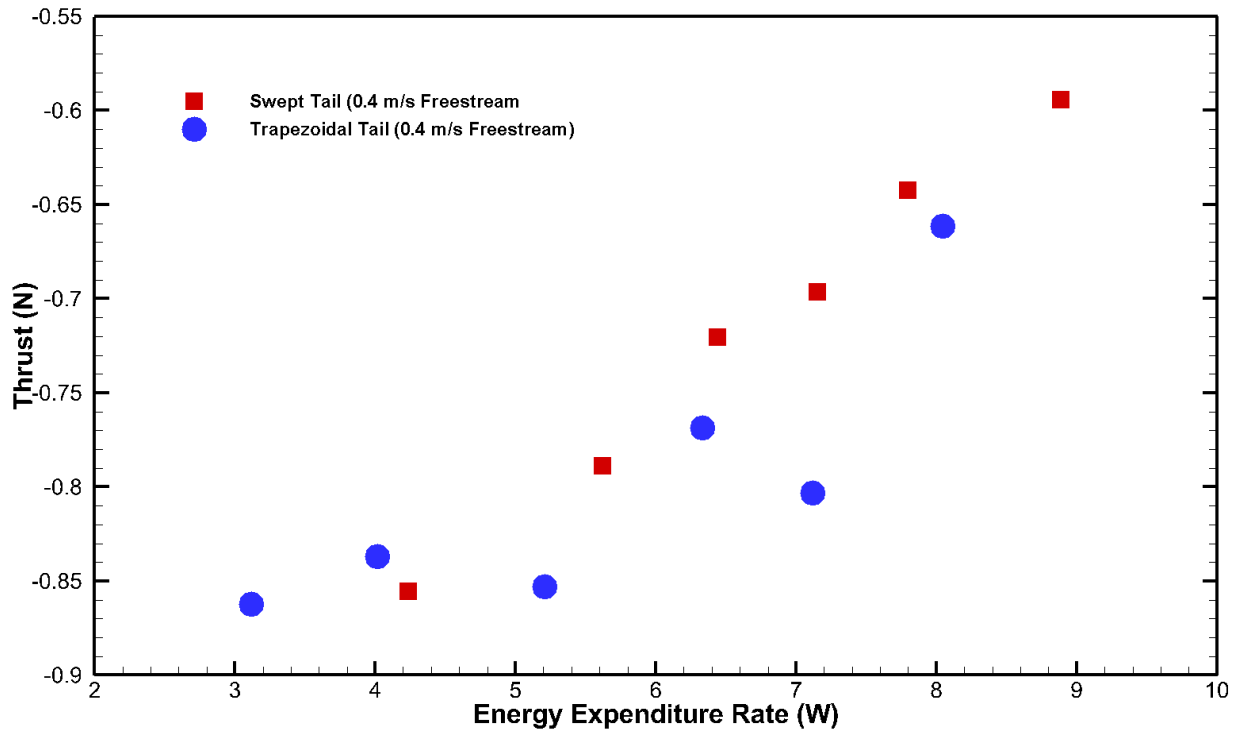


Figure 7.12: Thrust vs energy expenditure rate at a freestream of 0.4 m/s (reprinted from [92])

At a freestream velocity of 0 m/s, the trapezoidal tail consistently achieves a higher thrust to power ratio than the swept tail. At a freestream velocity of 0.2 m/s, the trapezoidal tail again

consistently achieves a higher thrust to power ratio than the swept tail. Conversely, at a freestream velocity of 0.4 m/s, the swept tail seems to achieve a higher thrust to power ratio than the trapezoidal tail, especially at higher thrust production values.

7.4. Lessons learned

While the data collected appears precise, there are likely a number of interference effects not present during the locomotion of biological systems. For example, in Figure 7.6 there is a considerable amount of asymmetry in thrust production that most probably does not occur in nature. This is likely due to insufficient rigidity in the body and at the body lever interface. Visible twisting of the entire robot can be seen at all operating frequencies. It also appears that this twisting is asymmetric with less resistance at certain parts of the cycle. This likely causes a difference in kinematics between each half of the tail beat.

In previous studies, formation of a reverse von Karman vortex street has been observed when the swimming propulsive wave produces thrust [93]. During the experiment presented in this paper, there was also vortex formation and shedding, which was especially strong at low freestream velocities and high frequencies. Clear vortex shedding was seen where the vortex structure is strong enough to deform the water surface causing light distortion. At low/zero freestream velocities, the vortices do not flow downstream rapidly enough and there is likely continued interaction between the tail and the stream. While prolonged vortex/tail interaction may not negatively affect performance, it may make the flow more chaotic, causing max instantaneous thrust production to vary considerably between cycles. Furthermore, as fish travel forward while swimming, the prolonged vortex/tail interaction observed in the experiment does not usually occur in nature. Thus, continued investigations of caudal fin shape will be performed at higher freestreams velocities that are closer to what occurs in nature. Additionally, the tail of the fish was not skinned, so flow over the non-streamlined ribs and linkages could lead to the caudal fin experiencing a more irregular flow.

Furthermore, the kinematics utilized by the robot may not be the most tuna-like. Discretizing the propulsive wave all the way to the end of the caudal fin is the cause of the fin experiencing very high angles of attack, which were always greater than 25 degrees at the middle of the stroke. Tuna's tend to actuate their caudal fins separately from the rest of the propulsive wave, allowing them to control its angle of attack [67]. This is also been done in other robotic systems to ensure

high efficiency [86]. Furthermore, it may be ideal to keep Strouhal number (St) constant between freestream velocities rather than keep frequency constant. It is widely accepted that efficient thrust production of oscillating foils occurs at St between 0.25 and 0.4 [4].

8. An in-depth investigation of caudal fin shape and kinematic effects

In chapter 7, preliminary data on the effect of caudal shape on thrust and power was discussed, but this data is likely to be inaccurate as the flow, tail kinematics, and body shape are not matching what occurs in nature. Thus, a more in-depth investigation that corrects the inaccuracies of the previous study was conducted while also analyzing the effect of more caudal fins and angle of attack (AOA).

8.1. Robotic design

A brand new robot was designed and constructed. This robot shared many similar characteristics to the previous but was approximately half the size with a fork length of 57cm. This was done to reduce the wall effects as the body occupied less than 1/5 of the tunnel width rather than more than 1/3. Furthermore, as the maximum freestream velocity was kept constant between experiments a higher body length per second swimming speed could be reached due to its smaller size. Lastly, while yellow fin tuna do reach the size of the robot from the previous experiment, most of the kinematic data available is on tuna that are less than 50 cm in length [67]. Thus, it is not known if larger tuna use significantly different kinematics from small tuna. Like the previous robot, the side profile applied to the body is based on a *Thunnus albacares* as shown in Figure 8.1.

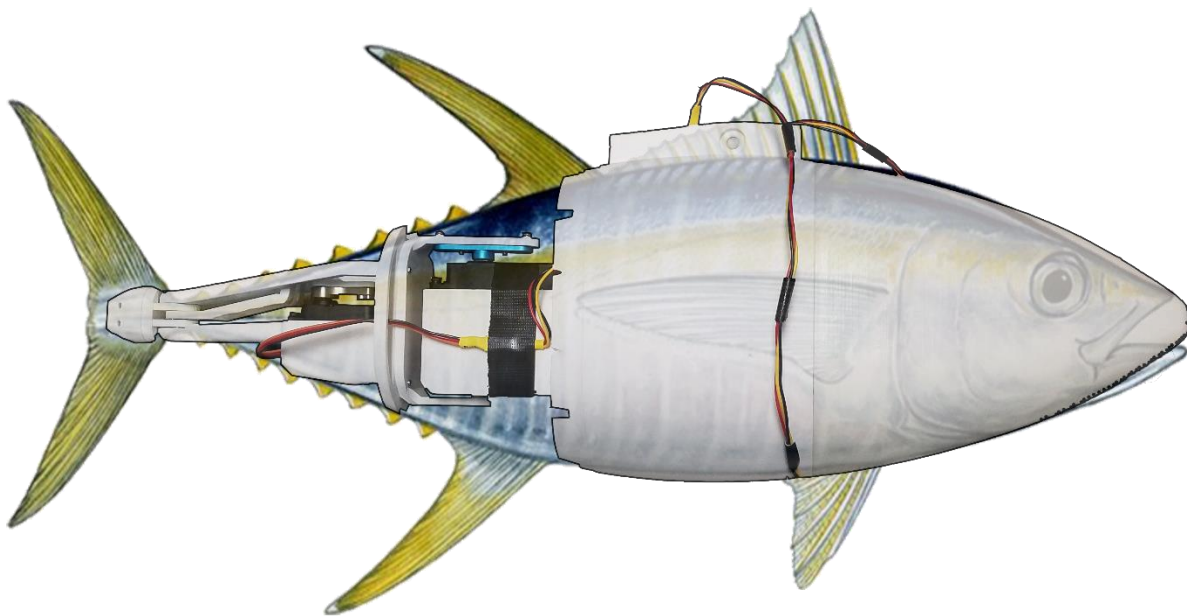


Figure 8.1: Second tuna mimetic robot and yellowfin tuna side profile

Unlike the previous robot, only two actuators were used. Again, both of these were servos. The larger tail actuator being a Hitec D-845WP with a stall torque of $5.00\text{ N}\cdot\text{m}$ and a no load speed of 58.8 rpm . The second smaller Savox SW-1210SG with a stall torque of $2.30\text{ N}\cdot\text{m}$ and a no load speed of 76.92 rpm . This decision was made because in the previous robot the first actuator attached to the front half of the body performed the largest sweep while subsequent actuators had small sweeps by comparison, causing an uneven distribution. Fine discretization of the body propulsive wave was deemed unnecessary, as the caudal fin is a much larger contributor to thrust production than the body wave for the thunnus genus [67, 87]. Since the actuators are placed in series, the uncertainty in motion compounds with each additional actuator. Thus, additional actuators decrease reliability of motion without a significant increase in thrust.

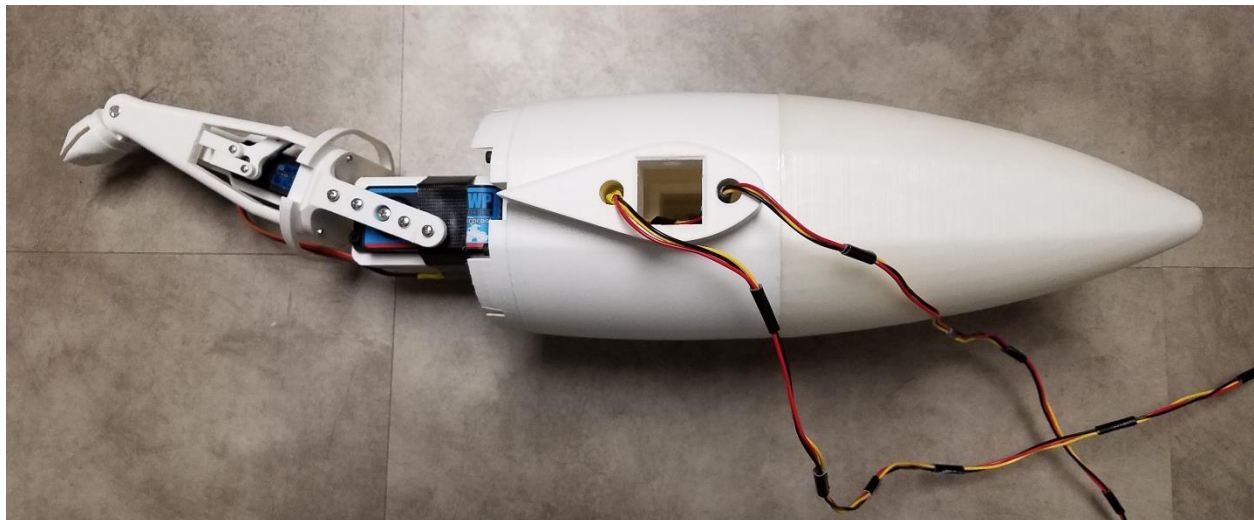


Figure 8.2: Top view of the second tuna mimetic robot

The pivot point of the body actuator was located approximately $1/3$ of the way between the tip of the peduncle (the body part that connects the caudal fin rays to the rest of the tail) and the nose of the robot. In order to control the caudal AOA separate from the body wave, the second pivot point was moved as close to the tip of the peduncle as possible without sacrificing structural integrity. A linkage system was used to couple the actuator rotation to the peduncle rotation as shown in Figure 8.2. This was done so an actuator that met the required torque and speed specifications could be used without increasing the width and height of the peduncle. The narrow peduncle is an important geometric characteristic of fusiform swimmers, of which tuna are a part. The fusiform body shape is what allows for decreased drag of the body during undulation.

Like the first tuna mimetic robot the majority of the parts were 3D printed. The printer used for the second robot was a Prusa I3 mk2. The structural parts were printed from Polylactic Acid (PLA) and are shown in Figure 8.3. The flexible skin that covers the tail that is shown farther down in Figure 8.6 was made out of Thermoplastic Polyurethane (TPU). Like the first robot, the front third the robot was designed to be buoyant and is thus hollow and sealed using a spray rubber sealant.

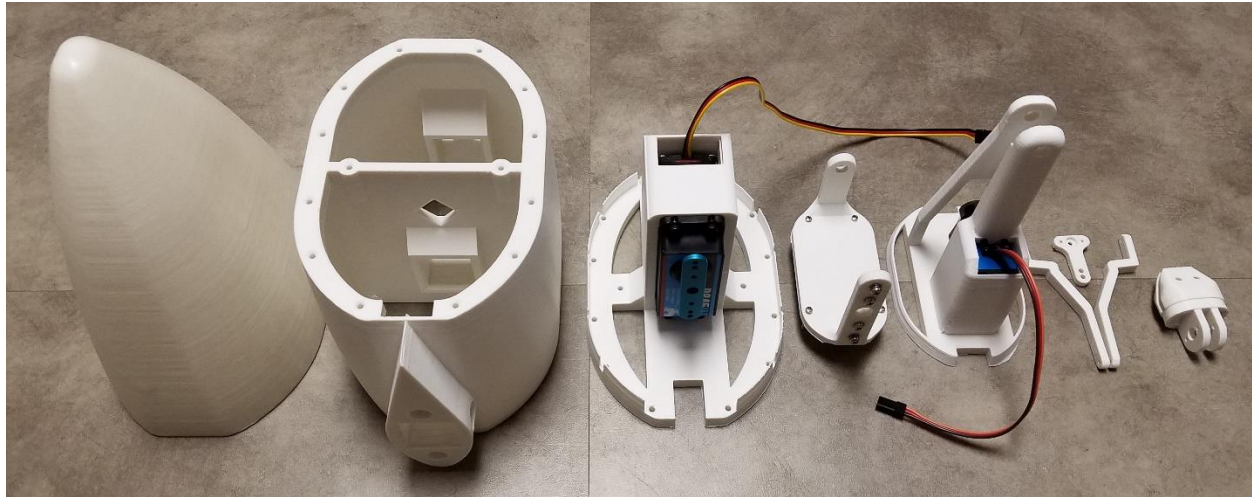


Figure 8.3: Individual structural components of the second tuna mimetic robot

A total of five interchangeable caudal fins were used in the study as shown in Figure 8.4. Each of the fins is laser cut from clear acrylic to ensure accuracy and transparency during flow visualization. Just like the first robot all of these fins have the same area of 4000 mm^2 and a tip-to-tip amplitude of 170 mm for each fin. This yields an aspect ratio of 7.2 which is comparable to a yellowfin tuna's caudal fin aspect ratio (typically 6.8-7.2)[76]. For the two non-swept tails, elliptical and rectangular shapes were used instead of a trapezoidal shape. While these two shapes are not found in nature, they both have characteristics that make them ideal for comparison. The rectangular fin was the closest shape to a control as it exhibits a uniform area distribution and no sweep. The elliptical fin was used because theoretically an elliptical area distribution has best hydrodynamic efficiency, where hydrodynamic efficiency is defined as the lift to induced drag ratio. In addition to the non-swept tails, three swept tails were investigated. These were designed to have sweep of 30, 40 and 50 degrees measured from the leading edge. However, the standard method for measuring wing sweep angle is along the quarter chord line. When using this approach, the tails have a sweep angle of 25.2, 36.3, and 47.4. From this point, forward the fins will be referenced by their quarter chord sweep angles.

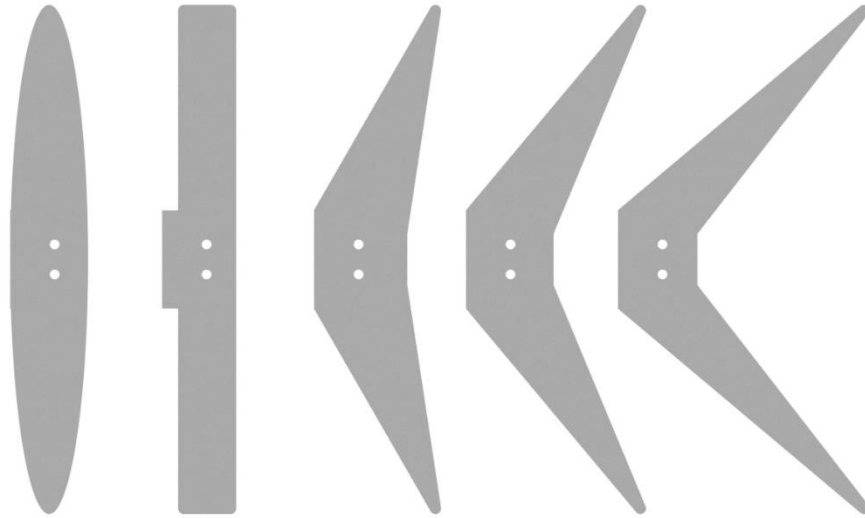


Figure 8.4: Caudal fin shapes from left to right elliptical, rectangular, 25.2° sweep, 36.3° sweep, and 47.4° sweep

Fish with fusiform bodies have sweep angles that range from 25 to 50 degrees; yellowfin tuna possess a sweep angle close to 45 degrees. However, this sweep angle is measured from the tip of the fin to the center. As yellowfin tuna possess a large amount of curvature along the upper quarter of the fin, the tip to center measurement yields a larger calculated sweepback angle than the quarter chord or leading edge measurement approach, as shown in Figure 8.5. The difference between the leading edge angle measurement and middle to tip sweep angle measurement was approximately 10 degrees, suggesting that the sweep of a yellowfin tuna's caudal fin is somewhere in between the 25.2 and 36.3 degree swept tails used in the experiment.

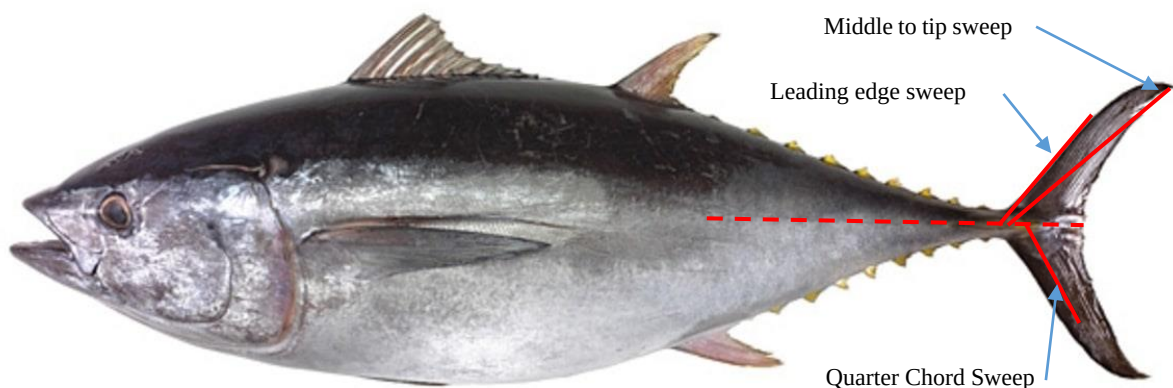


Figure 8.5: Fin sweep angle of yellow fin tuna

8.2. Experimental setup

This investigation utilized an experimental setup shown in Figure 8.6 very similar to the first but addresses some of the issues that were present in the initial study. First, the rod that connects the robot to the force transfer assembly is now enclosed within a streamlined cover, which can be seen more clearly in Figure 8.7. The circular rod used in the previous study shed a reverse Karman vortex street behind it that was possibly interacting with the tail. The new streamlined pylon prevents this. Secondly, the square 8020 rod, which featured a larger cross-section than the previously used circular rod, prevented uncontrolled rotation of the body. The aforementioned rotation of the body caused a yaw of the nose of approximately 2 cm horizontally that was due to the first robot's circular rod sliding at the connection point. The new square cross-section prevents this. Moreover, since the second robot was smaller than the first, the lateral moment generated by its tail is also smaller, further reducing lateral yaw of the nose that occurred previously. Thirdly, a flexible 3D printed skin covered the tail of the robot to maintain a more streamlined flow across the body preventing excessively disturbed flow from reaching the caudal fin. Fourth, the interface between the pivot and rod was significantly reinforced to prevent any motion except around the pivot axis. Lastly, a new nylon ball transfer was used at the rod load cell interface to further reduce any effect that friction, due to off axis motion, might cause. Like in the preliminary investigation, current sensors were used to determine servo power.

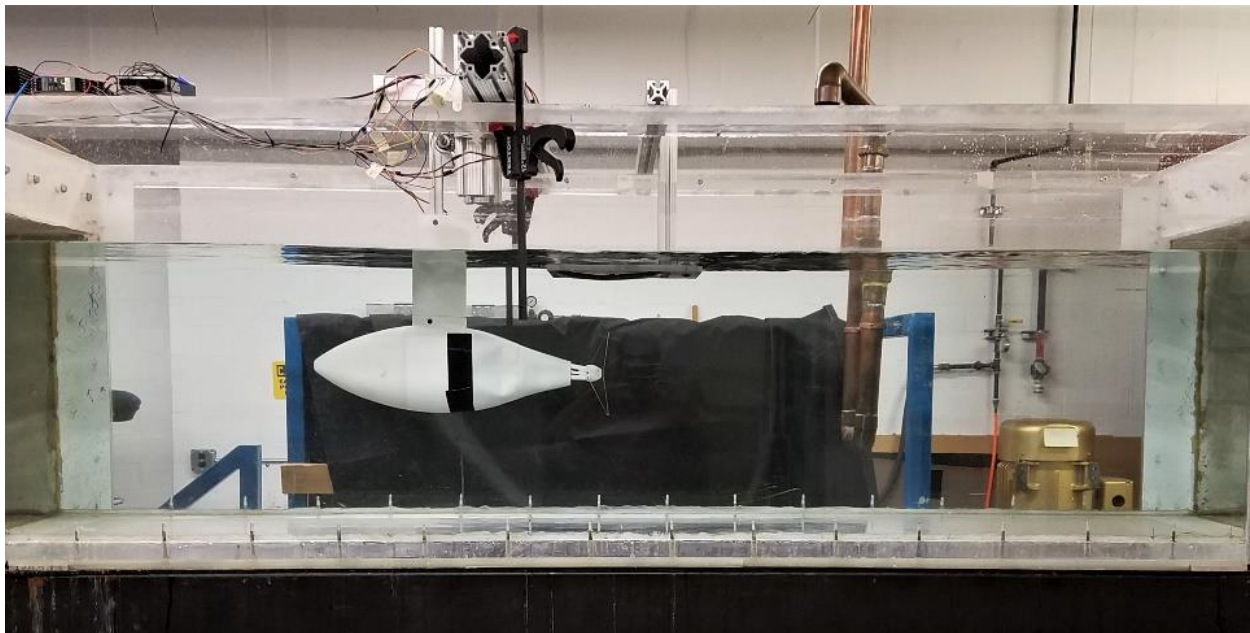


Figure 8.6: Side profile of second tuna mimetic robot in water tunnel

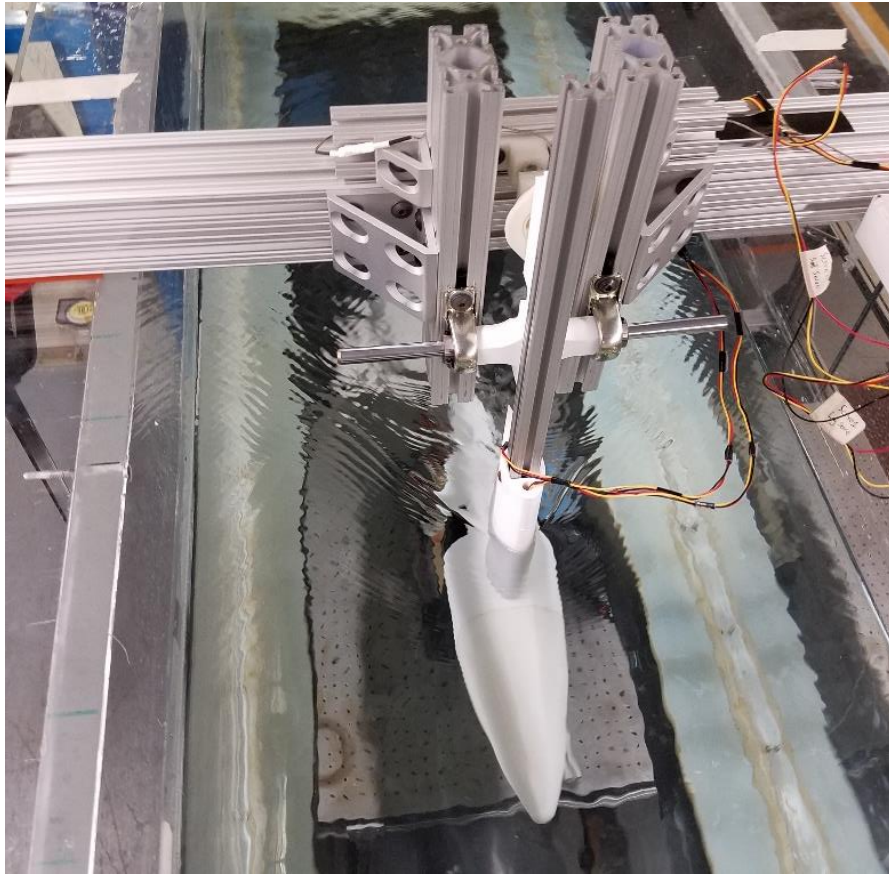


Figure 8.7: Top View of force transfer assembly

In addition to the force transfer assembly and current sensors, a setup for flow visualization was implemented. The water in the tunnel was seeded with refractive microspheres. A laser sheet was projected across the tunnel as shown in Figure 8.8. The laser sheet illuminated flow 5/9s of the way between the middle of the fin and the bottom. The sheet angle was small so very little spread occurred from one side of the tunnel to the other and was approximately 9.5cm wide. The fin was highly transparent, so the laser sheet could illuminate both sides of the fin evenly. A camera positioned horizontally below the tunnel recorded the particles moving through the laser sheet via a mirror angled 45 degrees. This orientation gave a bottom up perspective of the robot through the transparent tunnel bottom. This setup was not designed for PIV as the laser used was 50mW, which was not bright enough for fast shutter speed and frame rate digital video recording. Instead, 3840x2160 resolution video was recorded at 30 frames per second and at a shutter speed of 1/60 sec. Thus, visualization was performed solely to qualitatively examine flow structure and patterns.

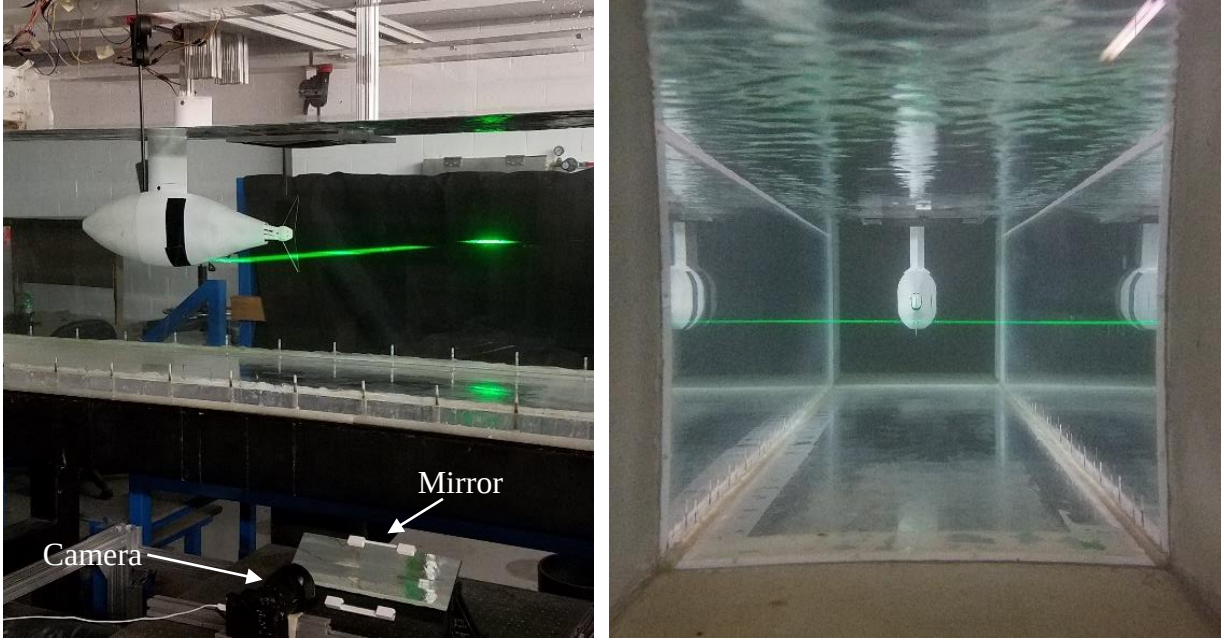


Figure 8.8: Caudal fin flow visualization laser sheet and imaging assembly

8.3. Assigned kinematics

In order to produce the tail and caudal fin motion, sinusoidal rotations were applied to the tail and fin links by the servos. The equations of the servo rotations as a function of time are given by Eqs. (8.1.) and (8.2.) below, where A_T is the rotational amplitude of the tail servo and A_F is the rotational amplitude of the fin servo. It was assumed that the rotation of the caudal fin would have a 90 degree phase shift from its heaving motion; hence the use of cosine for the tail servo and sine for the fin servo. Fish can deviate slight away from this [4], but just like with flapping wings a 5-10 degree phase deviation was deemed small and not worth sacrificing simplicity for.

$$\theta_T(t) = A_T \cos(2\pi f t) \quad (8.1.)$$

$$\theta_F(t) = A_F \sin(2\pi f t) \quad (8.2.)$$

As the second robot only had two actuators, one to control tail rotation and one to control fin rotation, the propulsive wave was not discretized like it was in the previous study. Instead, the servos were programmed to produce a sweep lateral displacement of 10 cm measured from the end of the peduncle shown in Eq. (8.3.) and a maximum AOA occurring at the midstroke (where t equals $\frac{1}{8f}$) of 15, 20, 25 degrees depending on the trial. A 10 cm sweep displacement was chosen as it is 0.17 times the fork length of the robot. This value falls within the range of reported in the

literature for live yellowfin tuna [67]. The angles of attack of 15, 20, and 25 degrees were chosen as [94, 95] states that the range of optimal angles of attack for oscillating foils is from 15-25 degrees. This AOA was again measured from the tip of the peduncle and is given by Eq. (8.4.) where U is freestream velocity, L_T is the length from the first pivot to the second, and L_F is the length from the second pivot to the end of the peduncle. Eq. (8.3.) and Eq. (8.4.) were set up as a system of equations and solved to determine A_T and A_F . Even though there are two equations and three unknowns (t , A_T , and A_F), the system was possible as t was equal to $\frac{1}{8f}$ for Eq. (8.4.) and only L_{smax} was of interest, eliminating the unknown time variable for both equations.

$$L_s(t) = \sin(A_F \sin(2\pi f t)) + \sin(A_T \cos(2\pi f t)) \quad (8.3.)$$

$$\alpha(t) = \tan^{-1} \left(\omega \frac{L_T A_T \sin(\omega t) \cos(\theta_T) - L_F A_F \cos(\omega t) \cos(\theta_F + \theta_T)}{U} \right) - (\theta_F + \theta_T) \quad (8.4.)$$

$$\omega = 2\pi f$$

8.4. Results and discussion

All possible combinations of five caudal fin shapes, four Strouhal numbers (St), three freestreams, and three angles of attack were tested. This resulted in 180 trials being conducted for the study. Thirty three seconds of data of 1000 Hz load cell data was collected for each trial with the first three seconds of data truncated. The load cell was zeroed between each trial to ensure consistency.

When calculating Re of swimmers, the characteristic length commonly used in the literature is body length. However, unlike the majority of swimmers, tuna have a large discontinuity between the body and the top two thirds of the caudal fins due to their fusiform body shape. Thus, it may be also useful caudal fin chord as a second characteristic length. For the freestreams tested 20 cm/s, 30 cm/s, and 40 cm/s the respective body based Reynolds number (Re_B) are 113500, 170300, and 227000 and the respective caudal fin based Reynolds number (Re_F) are 4000, 6000, and 8000. The difference between Re_F and Re_B is quite substantial and is the difference between laminar and turbulent flow.

8.4.1. Effect of angle of attack

Below in Figure 8.9 is thrust production of a 36.3 sweep fin as a function of St at 20 cm/s freestream. The three curves each correspond to a different AOA. These curves are best-fit polynomials of degree two. A second order fit was chosen as thrust theoretically depends on velocity squared and velocity should increase linearly across the St tested. It appears that as St increases, the AOA for optimal thrust production also increases as well. This can be seen, to varying degrees, for most of the other fins at all three freestreams and plots of this are located in Appendix-A. The cross over point tends to occur between Strouhal numbers of 0.4 and 0.55. The St that yields steady state swimming lies within this range for all shapes and freestreams. For the case shown in Figure 8.9, statistically there is no significant difference between angles of attack at a St of 0.5. However, statistically there is a significant difference between an AOA of 15 and 25 degrees at St of 0.4 and 0.6. This suggests that at this Re_B of 113,500 and Re_F of 4000, AOA has minimal effect on steady state swimming speed, but does have a significant effect when attempting to accelerate or decelerate. Again this trend continuous across the range of tested fins and freestreams suggesting that small changes in AOA effects acceleration/deceleration across Re_B range of 113500 - 227000 and Re_F range of 4000 - 8000.

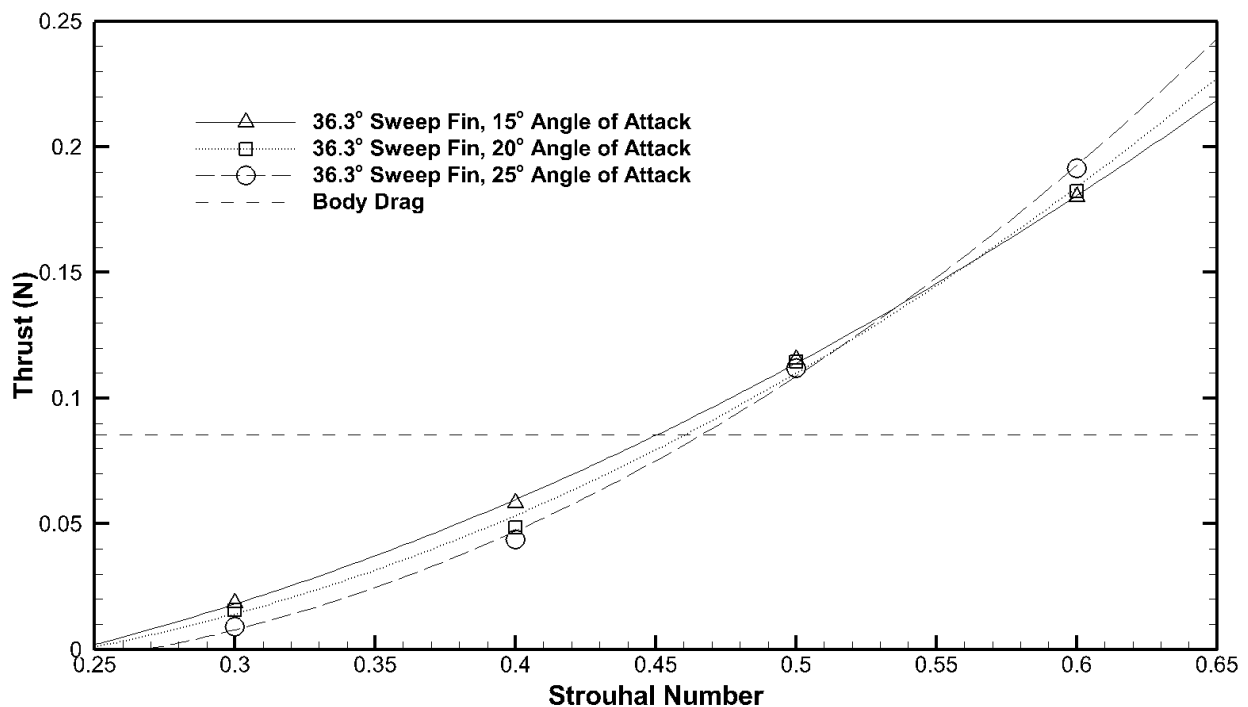


Figure 8.9: Thrust at three different AOA vs Strouhal number at 20 cm/s freestream

Table 8-1: Thrust uncertainty (N) of three AOA vs Strouhal number at 20 cm/s freestream (based on 95% confidence interval)

<i>Strouhal Number</i>	15° AOA	20° AOA	25° AOA
0.3	0.0076	0.0040	0.0055
0.4	0.0037	0.0076	0.0053
0.5	0.0045	0.0046	0.0052
0.6	0.0046	0.0058	0.0051

8.4.2. Effect of caudal fin shape on thrust production

Figure 8.10, Figure 8.11, and Figure 8.12 below show the effect of caudal fin shape on thrust production at a freestream of 20 cm/s, 30 cm/s, and 40 cm/s respectively. The total body drag of the fish in its neutral non-oscillating state is subtracted from the results to isolate the effect of the tail and caudal fin of the thrust production. The dashed line shows the body drag that was subtracted from the results. The intersection between the line and the curve is the point at which steady state swimming would be achieved. The sections above the dash line represents where acceleration would occur, and below the dashed line where deceleration would occur. Like in Figure 8.9, the curves are best-fit polynomials of degree two. Based upon the trend of optimal AOA for thrust production increasing with St , an AOA of 15 degrees was used for the data points at a St of 0.3 and 0.4, an AOA of 20 degrees was used for the data point at a St of 0.5, and an AOA of 25 degrees was used for the data point at a St of 0.6.

In Figure 8.10, the different fins can be sorted into three thrust performance groups. The highest performance group contains all the swept fins, the second highest performance group contains the elliptical fin, and the lowest performance group contains the rectangular fin. At the lowest tested St of 0.3, there was no statistically significant difference between any of the groups. At a St of 0.4, there is a statistically significant difference between the highest performance group and the other two groups, but the difference between the lower two groups is not significant. This is also the case for a St of 0.5. At a St of 0.6, there is a statistically significant difference between all three groups.

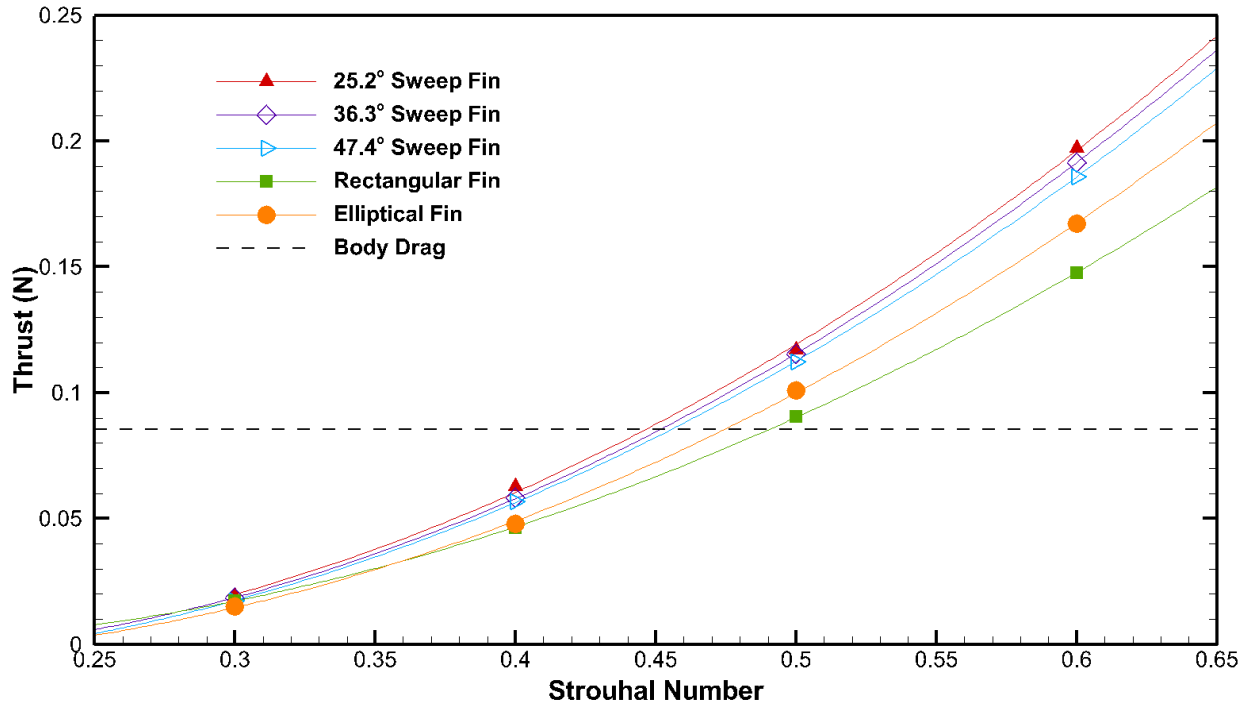


Figure 8.10: Thrust of five fins vs Strouhal number at 20 cm/s freestream

Table 8-2: Thrust uncertainty (N) of five fins vs Strouhal number at 20 cm/s freestream (based on 95% confidence interval)

<i>Strouhal Number</i>	25.2 Sweep Fin	36.3 Sweep Fin	47.4 Sweep Fin	Rectangular Fin	Elliptical Fin
0.3	0.0038	0.0076	0.0064	0.0027	0.0072
0.4	0.0041	0.0037	0.0038	0.0040	0.0036
0.5	0.0047	0.0046	0.0041	0.0070	0.0047
0.6	0.0035	0.0051	0.0043	0.0055	0.0044

Again, in Figure 8.11 the different fins can be sorted into three thrust performance groups. For Figure 8.11 highest performance group only contains the 25.2 sweep fin and the 36.3 sweep fin, the second highest performance group contains the elliptical fin and the 47.4 sweep fin, and the lowest performance group contains the rectangular fin. Again, at the lowest tested St of 0.3 there was no statistically significant difference between any of the groups. At a St of 0.4, there is a statistically significant difference between all three groups. For a St of 0.5, there is a statistically significant difference between the highest performance group and the other two groups, but there

is a slight overlap in the confidence intervals of the lower two groups. At a St of 0.6, there is a statistically significant difference between all three groups.

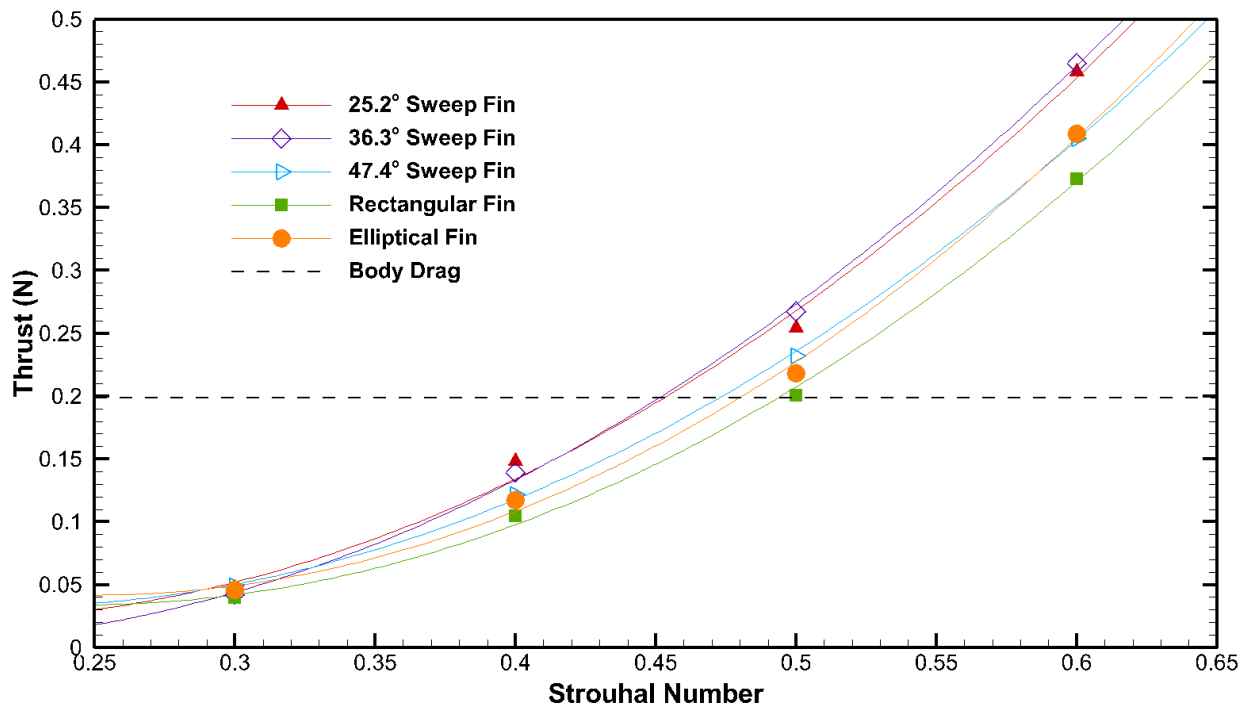


Figure 8.11: Thrust of five fins vs Strouhal number at 30 cm/s freestream

Table 8-3: Thrust uncertainty (N) of five fins vs Strouhal number at 30 cm/s freestream (based on 95% confidence interval)

<i>Strouhal Number</i>	25.2 Sweep Fin	36.3 Sweep Fin	47.4 Sweep Fin	Rectangular Fin	Elliptical Fin
0.3	0.0064	0.0060	0.0050	0.0049	0.0060
0.4	0.0086	0.0065	0.0061	0.0057	0.0070
0.5	0.0065	0.0074	0.0076	0.0100	0.0081
0.6	0.0086	0.0105	0.0090	0.0078	0.0081

Finally, in Figure 8.12 the different fins can be once again sorted into three thrust performance groups. The highest performance group only contains the 25.2 sweep fin and the 36.3 sweep fin, which have sweep angles most similar to a yellowfin tuna's fin. The second highest performance group contains the elliptical fin and the 47.4 sweep fin, and the lowest performance group contains the rectangular fin. Predictably, at a St of 0.3 there was no statistically significant difference between any of the groups. At a St of 0.4, there is a statistically significant difference between the

highest performance group and the other two groups, but the difference between the lower two groups is not significant. At a St of both 0.5 and 0.6, there is a statistically significant difference between all three groups.

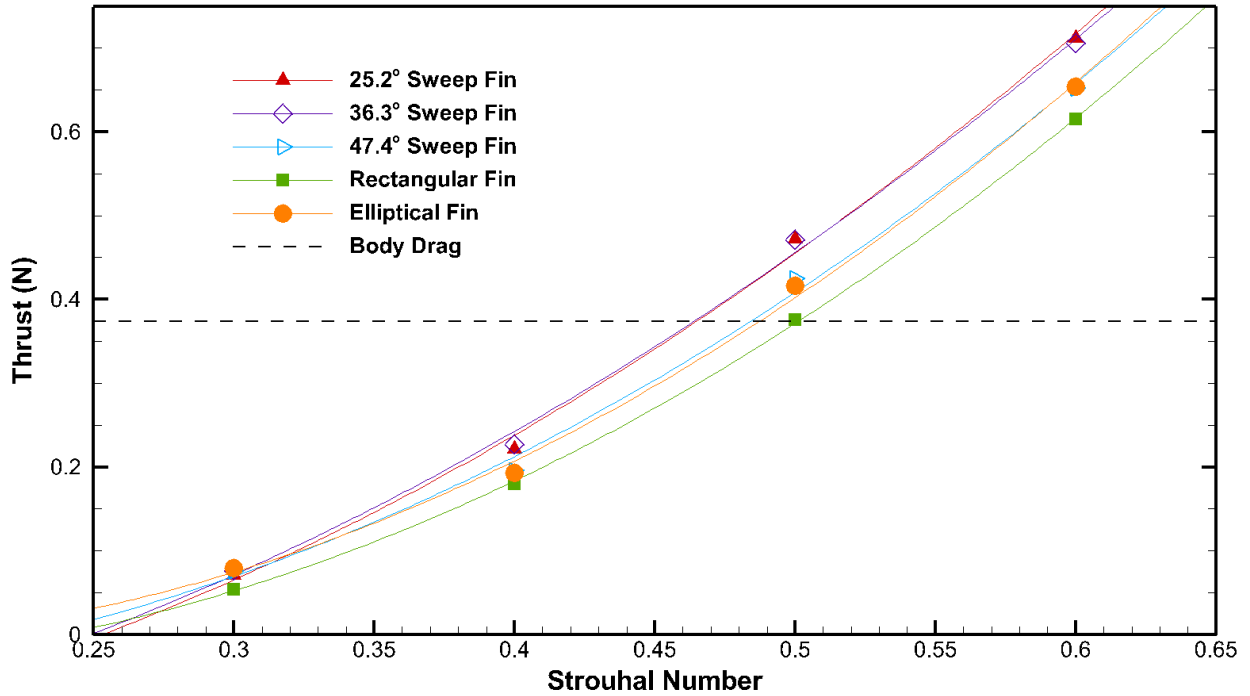


Figure 8.12: Thrust of five fins vs Strouhal number at 40 cm/s freestream

Table 8-4: Thrust uncertainty (N) of five fins vs Strouhal number at 40 cm/s freestream (based on 95% confidence interval)

<i>Strouhal Number</i>	25.2 Sweep Fin	36.3 Sweep Fin	47.4 Sweep Fin	Rectangular Fin	Elliptical Fin
0.3	0.0102	0.0115	0.0103	0.0122	0.0150
0.4	0.0110	0.0136	0.0107	0.0148	0.0105
0.5	0.0129	0.0108	0.0139	0.0107	0.0142
0.6	0.0150	0.0119	0.0128	0.0136	0.0155

These results indicate that moderately swept fins will produce more thrust at higher St across a Re_B range of 113500 - 227000 and a Re_F range of 4000 – 8000. At higher Re , this difference becomes more prominent suggesting that the increased thrust of the swept fins will also occur at cruising speeds. As the area, aspect ratio, and kinematics of all the fins are the same, the sweep of the fin likely has a significant effect on the hydrodynamics of the flow that will be discussed in a

following subsection. The elliptical fins also tended to produce more thrust than the rectangular fin. This was predicted as the elliptical fin has the highest theoretical lift to induced drag ratio.

8.4.3. Effect of caudal fin shape on thrust to energy expenditure ratio

In this section, the effect of fin shape and St on thrust to energy expenditure ratio is examined. As shown in Figure 8.13, Figure 8.14, and Figure 8.15 the trends in this section are essentially identical to that of the previous section. The moderately swept fins offer better performance accept at the lowest freestream velocity of 20 cm/s where all the swept fins offer comparably good performance. Also like the thrust results, the difference in thrust to energy expenditure ratio tend to be more statistically significant at higher St . The thrust to energy expenditure ratio was used as it was not possible to directly calculate efficiency. This requires torque at the joints to be measured. Measuring this torque is very challenging at such a small scale and in water. Thus, the thrust to energy expenditure ratio was to be used as an indicator of efficiency. However, conclusions drawn from this ratio are merely suggestive, as the energy expenditure of servos is not directly related to mechanical power. There is very little difference between the power curves shown in Appendix-B suggesting energy expenditure is more dependent on operating speed of the servos rather than load. Nonetheless, at the very least there is strong evidence that a rectangular caudal fin is inferior in both performance categories of thrust production, and efficiency while the 25.2° sweep fin (a moderately swept fin) is generally superior.

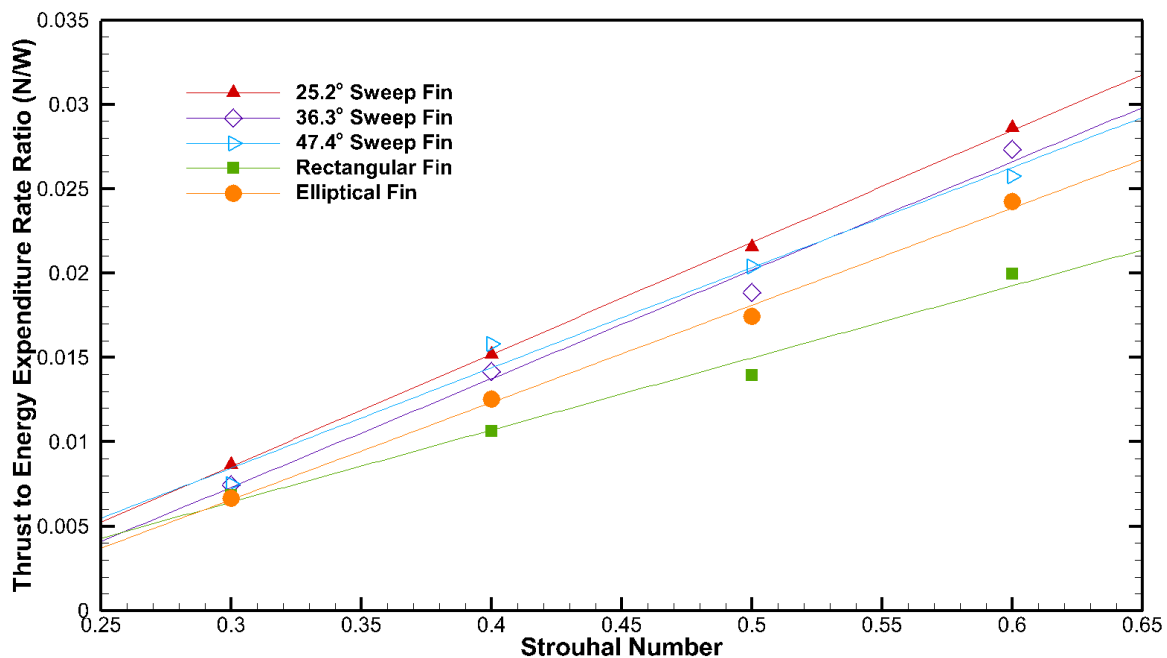


Figure 8.13: Thrust to power ratio of five fins vs Strouhal number at 20 cm/s freestream

Table 8-5: Thrust to power ratio uncertainty (N/W) of five fins vs Strouhal number at 20 cm/s freestream (based on 95% confidence interval)

<i>Strouhal Number</i>	25.2 Sweep Fin	36.3 Sweep Fin	47.4 Sweep Fin	Rectangular Fin	Elliptical Fin
0.3	0.0019	0.0035	0.0029	0.0014	0.0029
0.4	0.0021	0.0017	0.0012	0.0017	0.0018
0.5	0.0018	0.0023	0.0014	0.0020	0.0019
0.6	0.0019	0.0023	0.0019	0.0021	0.0016

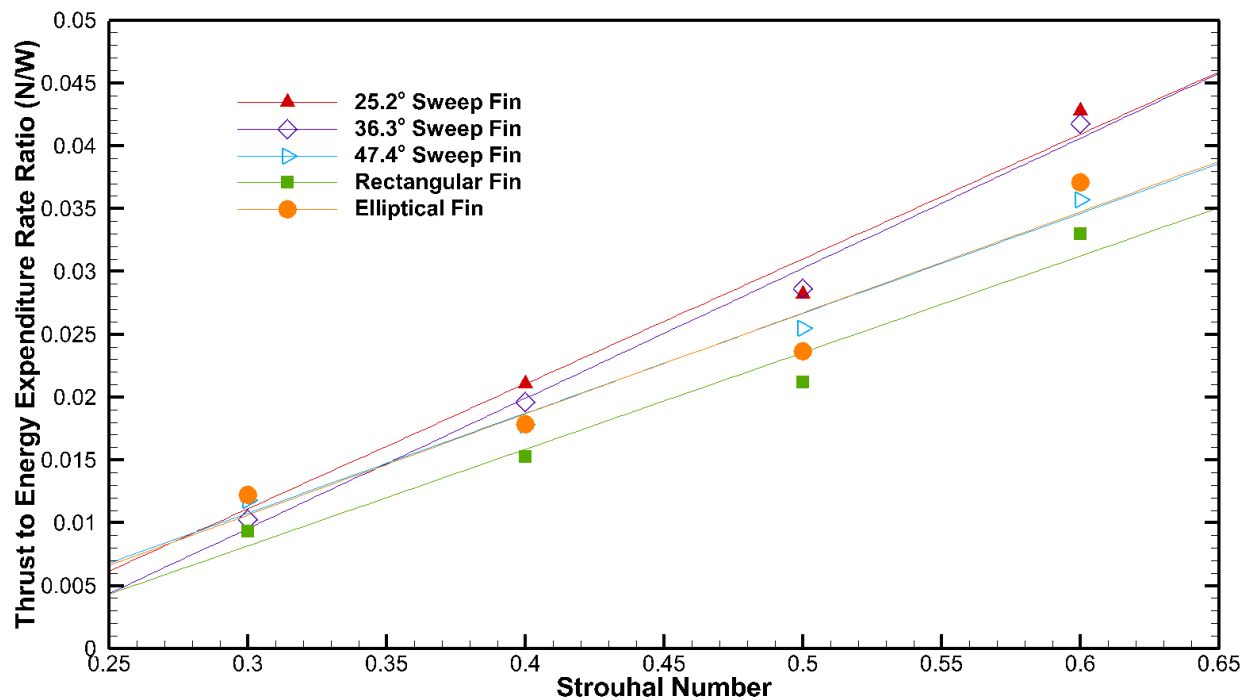


Figure 8.14: Thrust to power ratio of five fins vs Strouhal number at 30 cm/s freestream

Table 8-6: Thrust to power ratio uncertainty (N) of five fins vs Strouhal number at 30 cm/s freestream (based on 95% confidence interval)

<i>Strouhal Number</i>	25.2 Sweep Fin	36.3 Sweep Fin	47.4 Sweep Fin	Rectangular Fin	Elliptical Fin
0.3	0.0019	0.0018	0.0014	0.0016	0.0018
0.4	0.0018	0.0017	0.0011	0.0015	0.0014
0.5	0.0015	0.0018	0.0016	0.0019	0.0015
0.6	0.0016	0.0017	0.0014	0.0015	0.0015

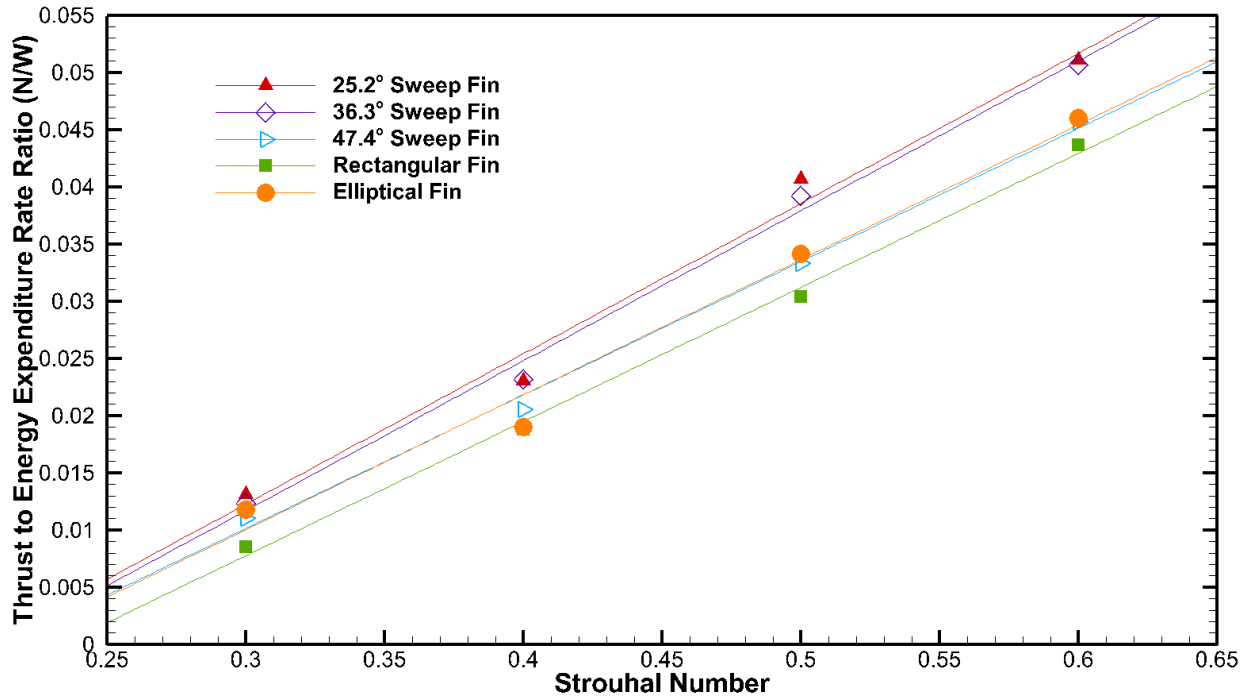


Figure 8.15: Thrust to power ratio of five fins vs Strouhal number at 40 cm/s freestream

Table 8-7: Thrust to power ratio uncertainty (N) of five fins vs Strouhal number at 20 cm/s freestream (based on 95% confidence interval)

<i>Strouhal Number</i>	25.2 Sweep Fin	36.3 Sweep Fin	47.4 Sweep Fin	Rectangular Fin	Elliptical Fin
0.3	0.0022	0.0020	0.0018	0.0022	0.0027
0.4	0.0016	0.0015	0.0013	0.0021	0.0017
0.5	0.0013	0.0013	0.0014	0.0011	0.0014
0.6	0.0012	0.0011	0.0010	0.0011	0.0012

8.4.4. Comparison between robotic system and equivalent biological system

In order to quantify the performance of the robotic tuna, it was compared to live tuna. As thrust data on live tuna is not available, the best metric for comparison is steady swimming speed at a given frequency. As the robot was tethered and not allowed to free swim, the frequency required to maintain steady swimming at a specific freestream was calculated by finding the intersection point between the line representing body drag and the thrust curves shown in Figure 8.13, Figure 8.14, and Figure 8.15. Interestingly the intersection point occurred at approximately the same St at all freestreams leading to a linear relationship between robot swimming speed and frequency as

amplitude was kept constant. The R^2 value of this fit is greater than 0.99 for all fin shapes. The linear fits of robot swimming speed vs frequency are shown in Figure 8.16. As expected, the moderately swept fins with a 25.2° and 36.3° could swim faster with lower frequencies than the other fins and possessed the smallest slope indicating an even bigger performance gap at higher speeds.

Dewar et al. performed a linear fit on the swimming speed vs frequency of 32, 42, and 52 cm tuna yielding an R^2 of 0.47, 0.69, and 0.68 [67]. Indicating there is a significant amount of variation in the data. This equation of this linear fit plotted in Figure 8.16. Similar to the robotic prototype, amplitude of the tuna fin stroke remains fairly constant at different frequencies [67]. The robotic prototype actually was able to achieve higher speeds at low frequencies over the range of speeds tested, but again there was a significant amount of variation in the live tuna data. Also based on the slopes of the robotic and live tuna speed fits, it appears that live tuna would perform better at higher speeds, which is expected as they fully discretize the propulsive body wave, and they possess a streamlined fin cross-section rather than the rectangular one of the robot.

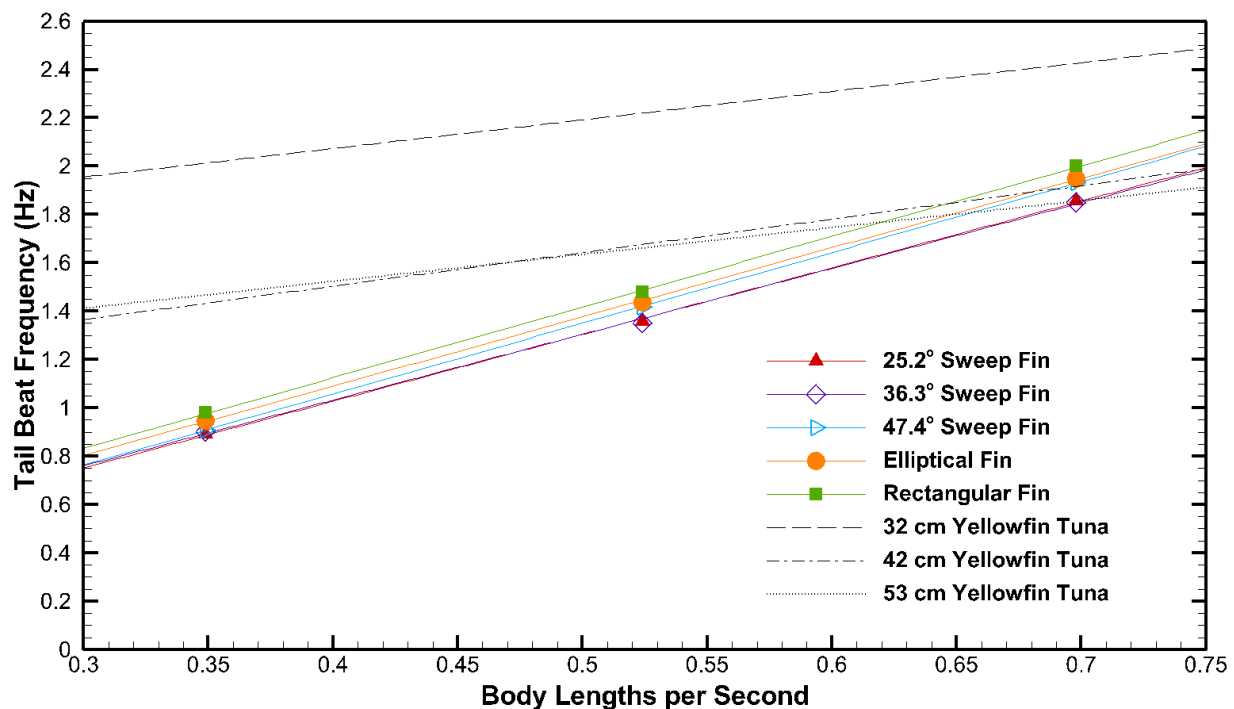


Figure 8.16: Required tail beat frequency vs swimming speed in body lengths per second of the robotic tuna and yellowfin tuna.

8.4.5. Instantaneous thrust production and flow visualization

Figure 8.18, Figure 8.22, and Figure 8.26 show the instantaneous thrust of the 25.2° , 47.4° , and rectangular fin at a freestream of 0.3 m/s. The results are not filtered; instead, the multiple cycles captured for each trial are averaged to reduce the random error. This was deemed acceptable as the hydrodynamics are cyclic and only small discrepancies exist among the major features. The flow is visualized for specific points in the fin stroke cycle where significant differences in thrust exist between fin types to try to understand their underlying cause. The visualization is a projected bottom view of the fin cross-section as shown in Figure 8.17.

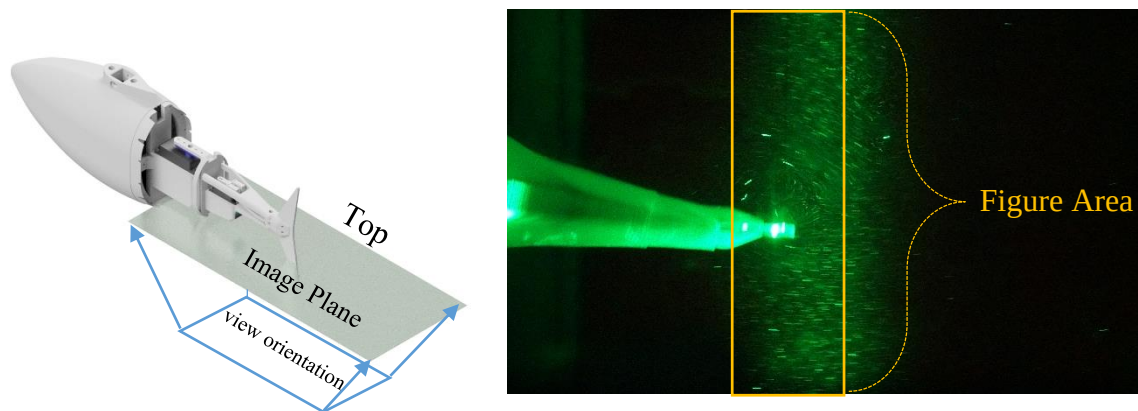


Figure 8.17: Flow visualization image plane and projected bottom view

In Figure 8.18, at 28% cycle completion, there is the 25.2° sweep fin has the highest instantaneous thrust production followed by the rectangular fin and then the 47.4° sweep fin. Shown in Figure 8.19 the 25.2° sweep fin and rectangular fins have generated LEVs with the 25.2° sweep fin LEV appearing to be slightly larger. The 47.4° sweep fin has not yet generated an LEV but instead a trailing edge vortex (TEV) that is usually an indicator of reduced lift.

At 40% cycle completion, there is the 25.2° and 47.4° sweep fin have the highest instantaneous thrust production followed by the rectangular fin. Shown in Figure 8.20, all fins have generated LEVs with the rectangular fin LEV appearing to be unstable with many smaller vortex cores inside the larger circulation. The 25.2° sweep fin LEV seems to be the most stable with the core remaining closest to the fin.

At 52% cycle completion, there is the 47.4° sweep fin has the highest instantaneous thrust production followed by both the rectangular fin and the 25.2° sweep fin. Shown in Figure 8.21 the all the fins have generated LEVs with the rectangular fin LEV exhibiting even less stability. The

47.4° sweep fin LEV seems to be the most stable at this point but it should be noted that part of the LEV has been shed away likely reducing the attached LEVs magnitude and reducing lift drag at this point in the cycle.

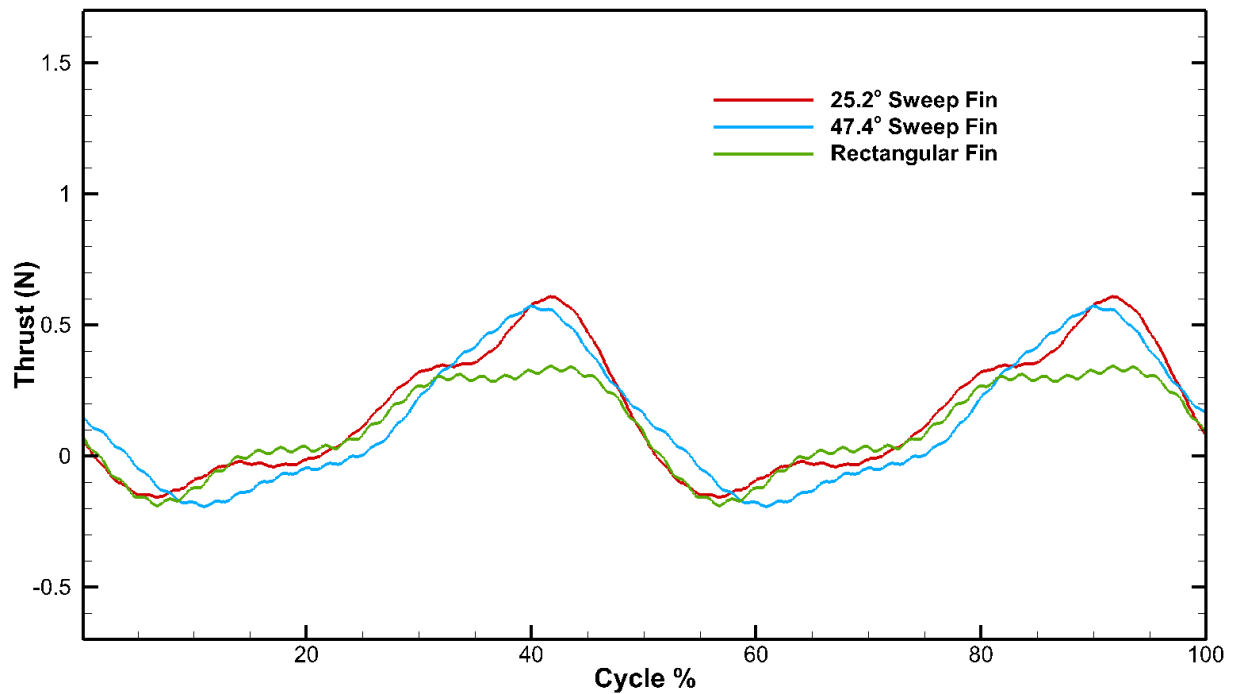


Figure 8.18: Instantaneous thrust production of the rectangular fin and the two fins with 25.2° and 47.4° sweep angles at a freestream of 30cm/s and a Strouhal number of 0.4

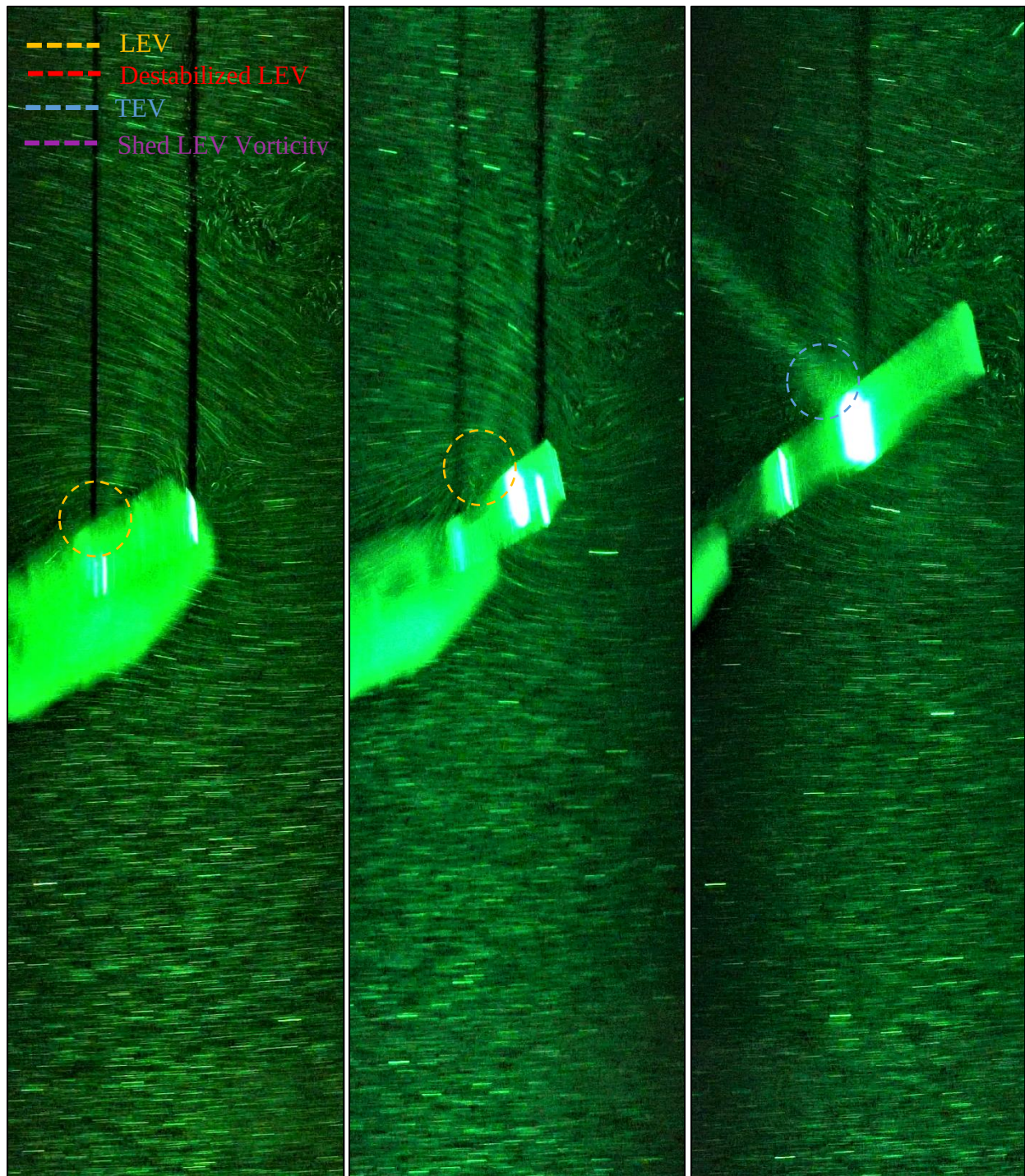


Figure 8.19: LEV development at 28% cycle completion and a Strouhal number of 0.4 of the rectangular fin (left) 25.2 sweep fin (middle) and 47.4 sweep fin (right)

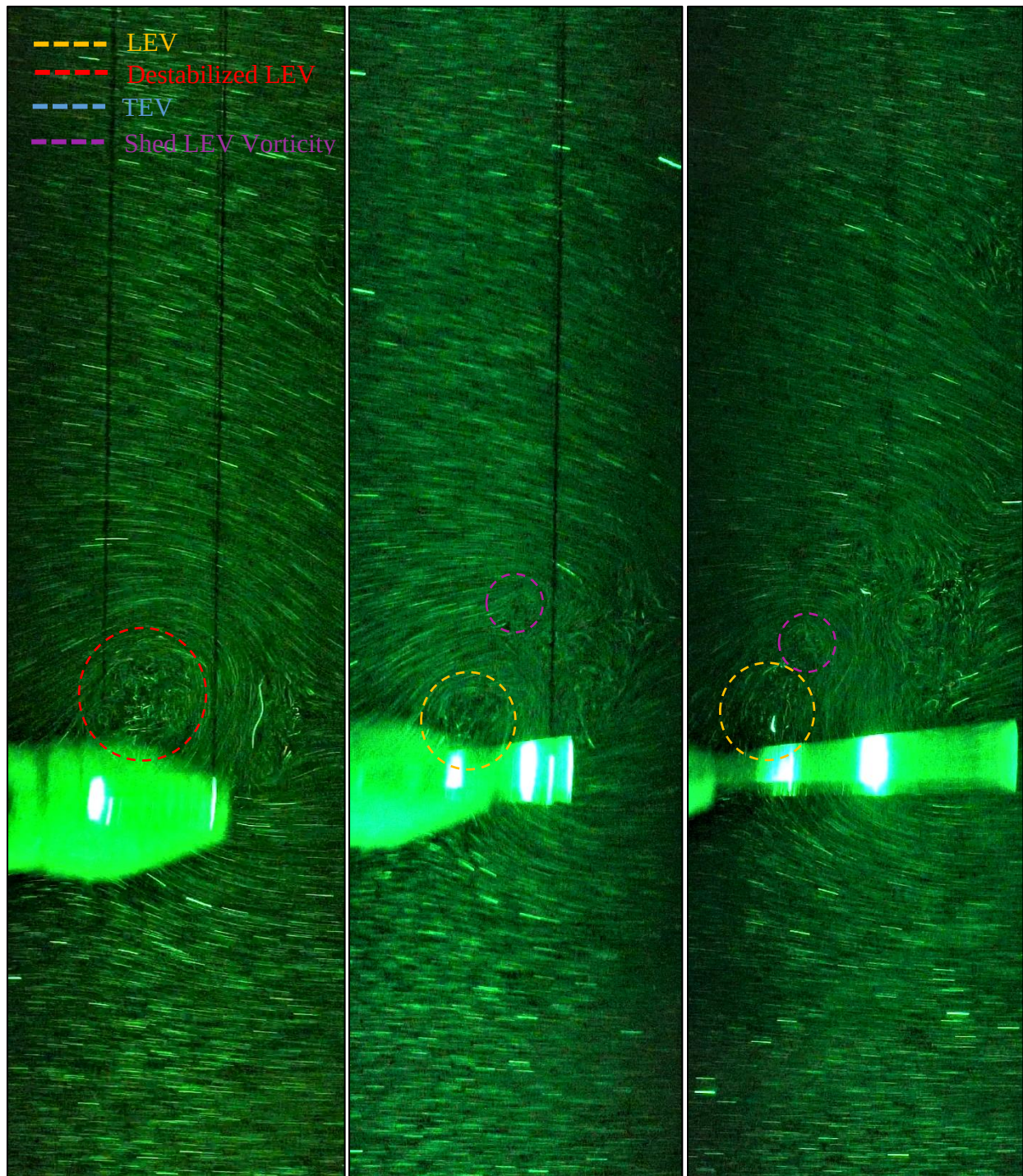


Figure 8.20: LEV development at 40% cycle completion and a Strouhal number of 0.4 of the rectangular fin (left) 25.2 sweep fin (middle) and 47.4 sweep fin (right)

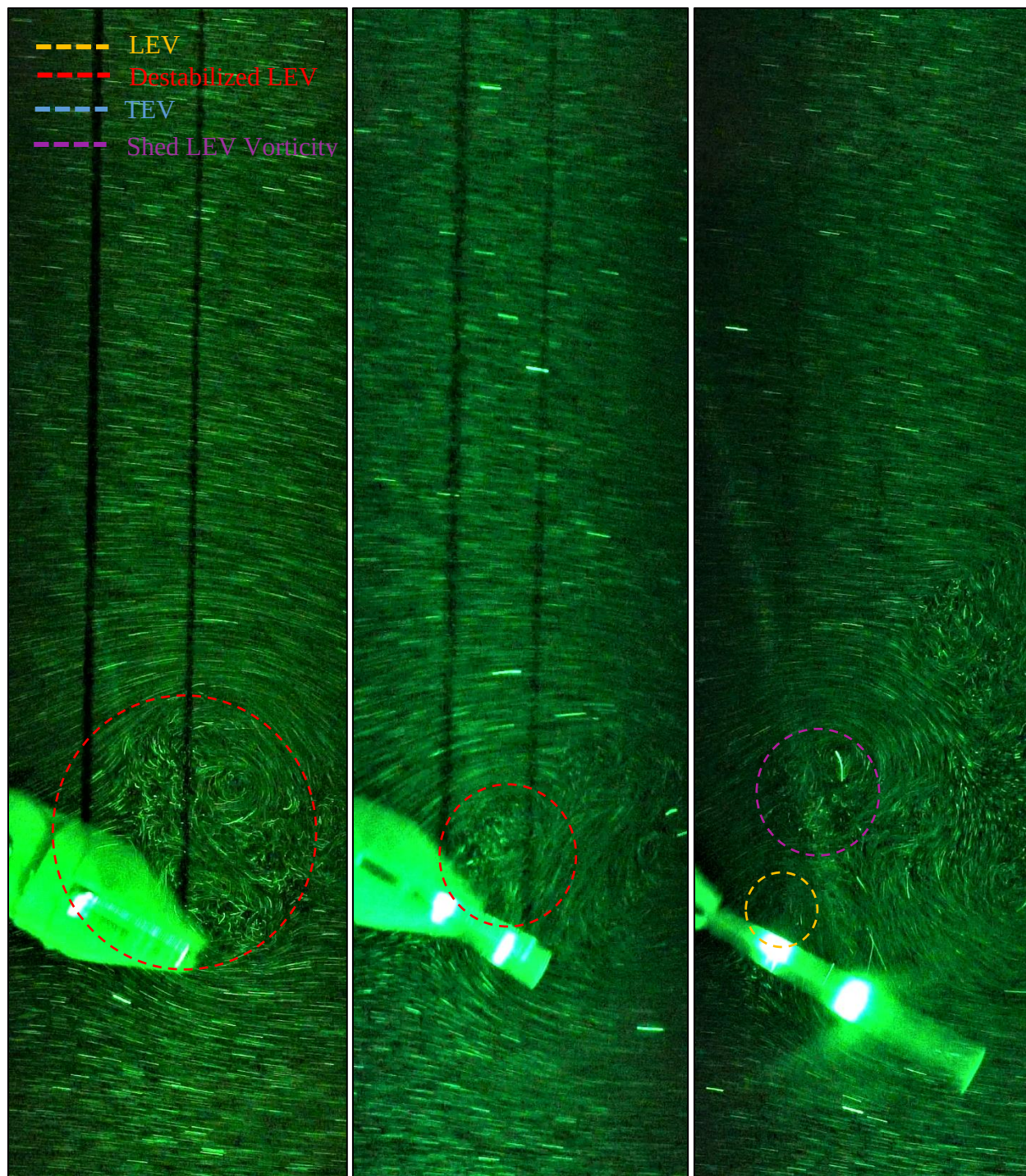


Figure 8.21: LEV development at 52% cycle completion and a Strouhal number of 0.4 of the rectangular fin (left) 25.2 sweep fin (middle) and 47.4 sweep fin (right)

In Figure 8.22, at 25% cycle completion, the rectangular fin has the highest instantaneous thrust production, followed by the 25.2° sweep fin, and then the 47.4° sweep fin. Shown in Figure 8.23, only the 25.2° sweep fin appears to have started to generate a small LEV.

At 45% cycle completion, the 25.2° and 47.4° sweep fin have the highest instantaneous thrust production, followed by the rectangular fin. Shown in Figure 8.24, all fins have generated LEVs with the rectangular fin LEV appearing to be unstable with many smaller vortex cores inside the larger circulation. The 47.4° sweep fin LEV seems to be the most stable at this point but it should be noted that part of the LEV has been shed away, likely reducing the attached LEVs magnitude and reducing lift drag at this point in the cycle.

At 60%, cycle completion, the 47.4° sweep fin has the highest instantaneous thrust production, followed by both the rectangular fin and the 25.2° sweep fin. Shown in Figure 8.25, the 25.2° sweep fin and 47.4° sweep fin have generated LEVs with the rectangular fin having completely shed its vortex and becoming stalled. The 47.4° sweep fin LEV seems to be the most stable at this point with the 25.2° sweep fin LEV connecting downstream as it begins to be shed.

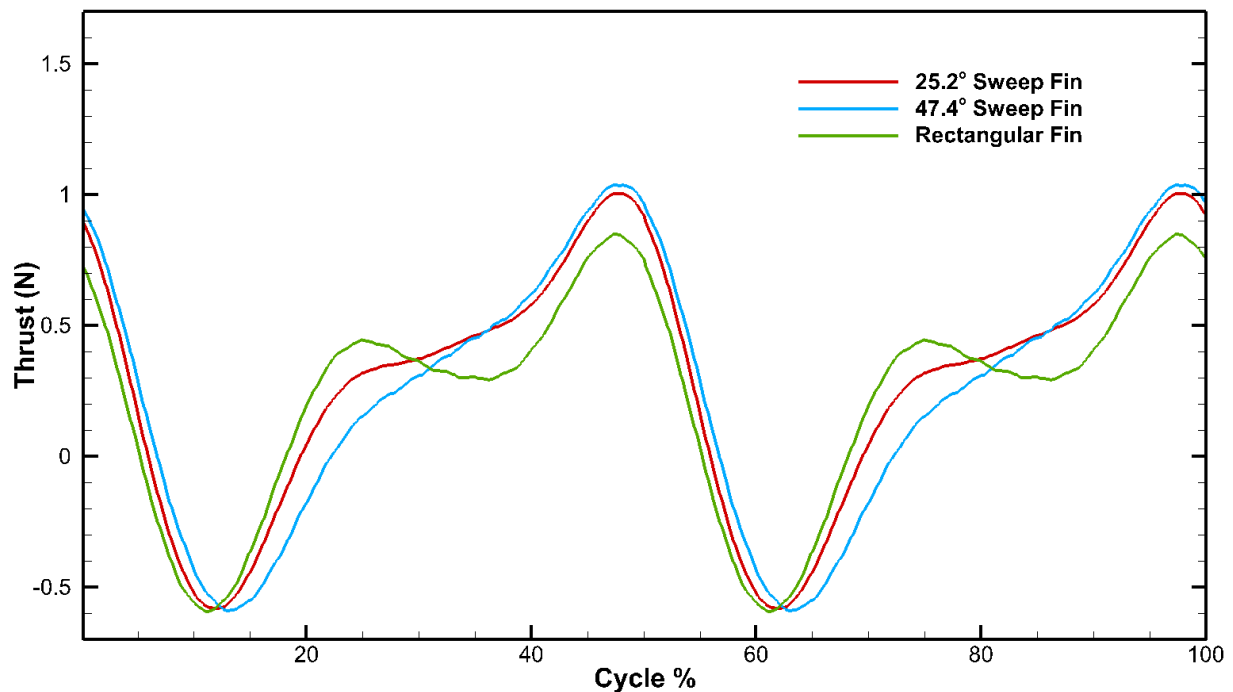


Figure 8.22: Instantaneous thrust production of the rectangular fin and the two fins with 25.2° and 47.4° sweep angles at a freestream of 30cm/s and a Strouhal number of 0.5

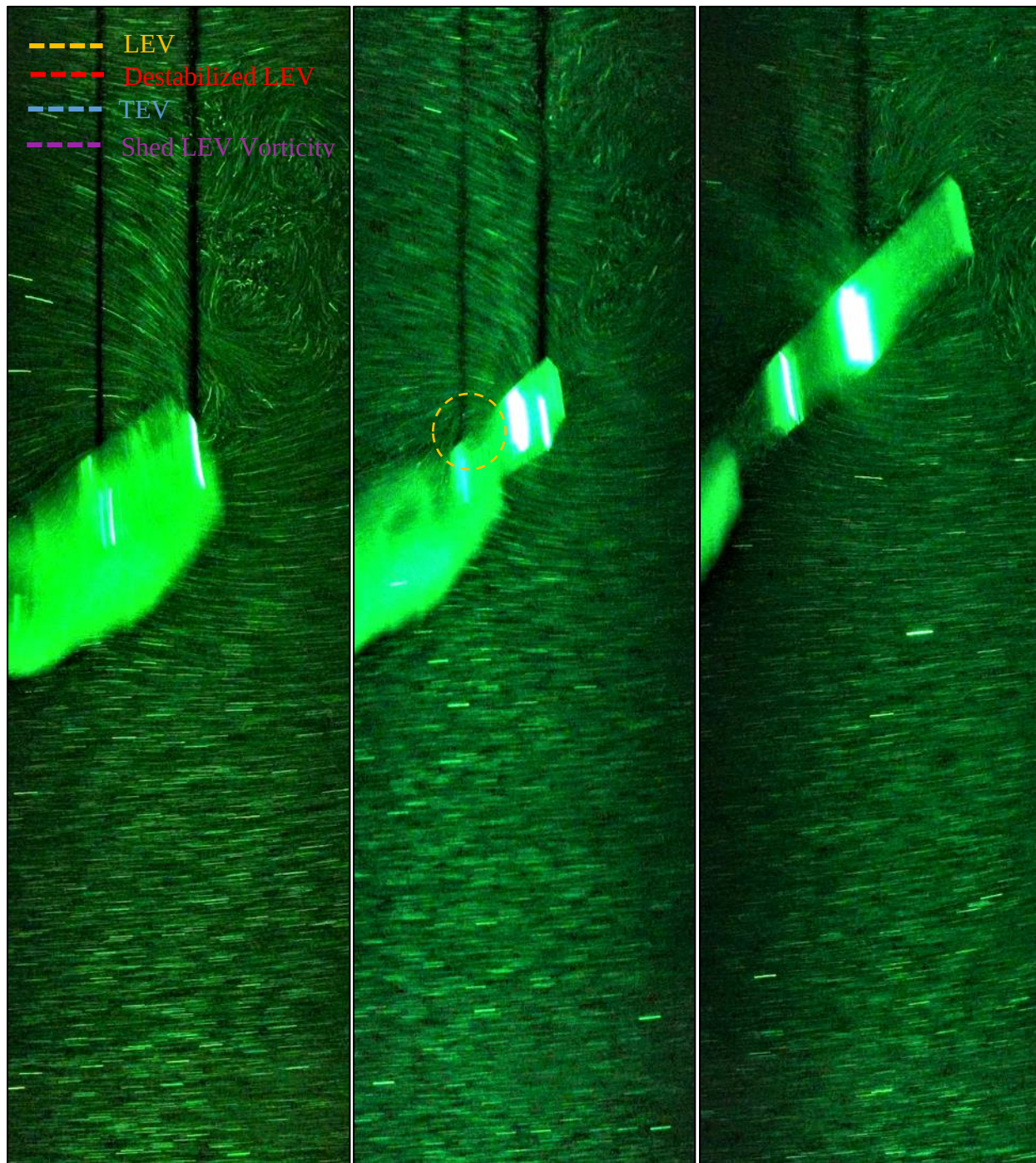


Figure 8.23: LEV development at 25% cycle completion and a Strouhal number of 0.5 of the rectangular fin (left) 25.2 sweep fin (middle) and 47.4 sweep fin (right)

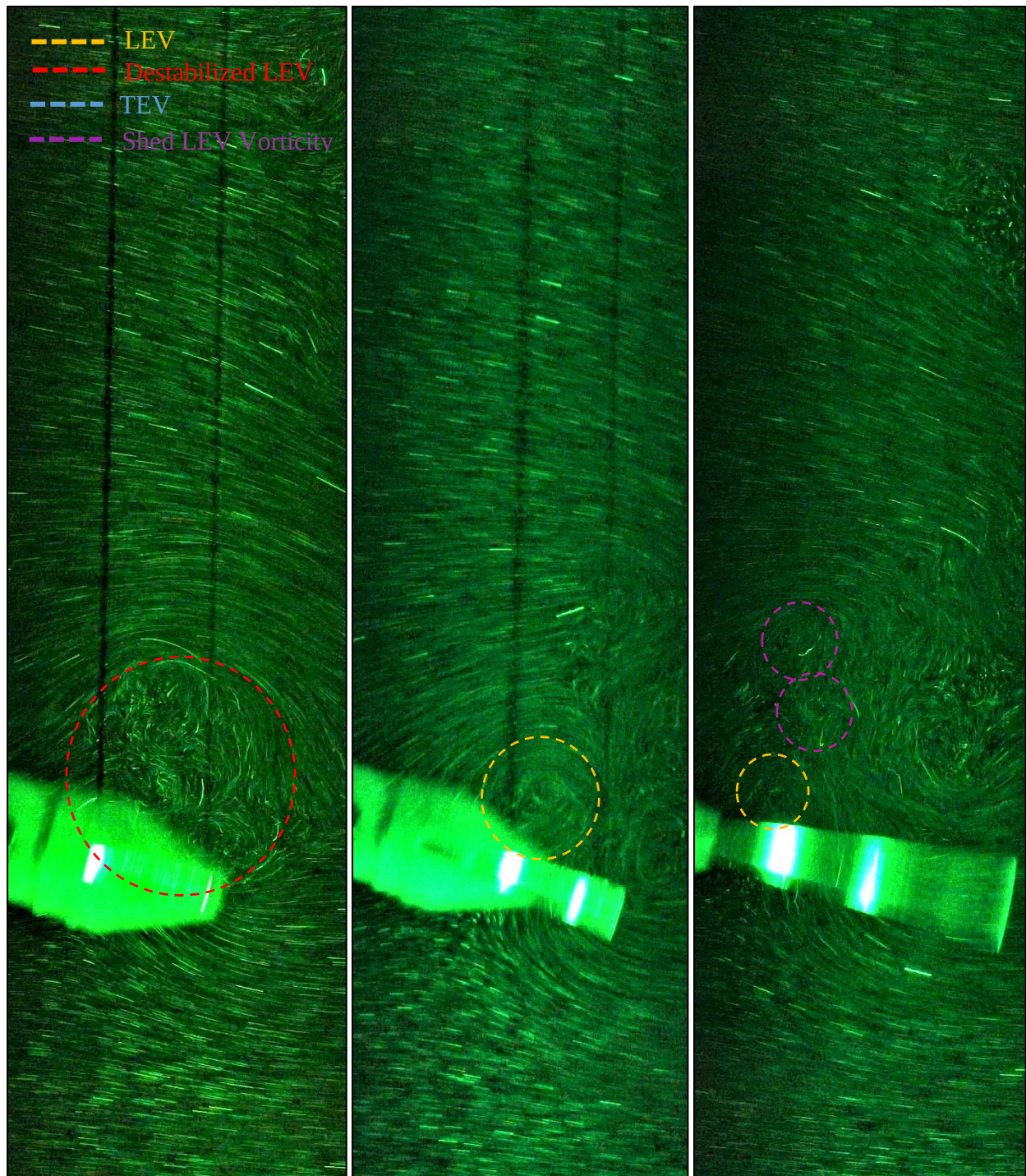


Figure 8.24: LEV development at 45% cycle completion and a Strouhal number of 0.5 of the rectangular fin (left) 25.2 sweep fin (middle) and 47.4 sweep fin (right)

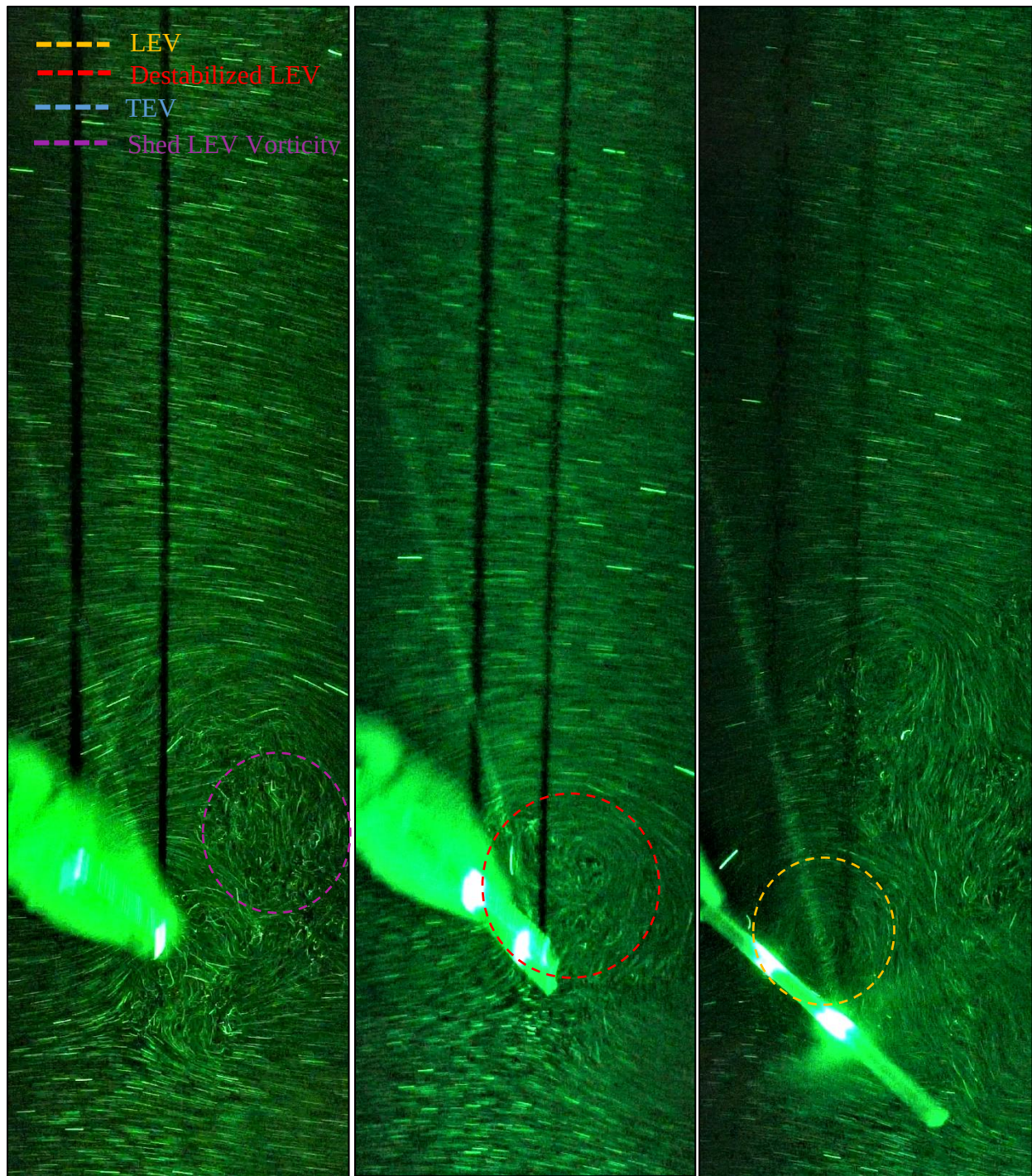


Figure 8.25: LEV development at 60% cycle completion and a Strouhal number of 0.5 of the rectangular fin (left) 25.2 sweep fin (middle) and 47.4 sweep fin (right)

In Figure 8.26, at 24% cycle completion, the rectangular fin and 25.2° sweep fin has the highest instantaneous thrust production, followed by the 47.4° sweep fin. Shown in Figure 8.27, the 25.2° sweep fin and rectangular fins have generated LEVs, the 25.2° sweep fin LEV appearing to be slightly larger. The 47.4° sweep fin has not yet generated an LEV.

At 36%, cycle completion, the 25.2° sweep fin has the highest instantaneous thrust production, followed by the rectangular fin. Shown in Figure 8.28, all fins have generated LEVs with 47.4° sweep fin LEV appearing to be unstable with several vortices shedding away from the main LEV. The 25.2° sweep fin has the most stable and largest vortex, resulting in its highest instantaneous thrust value. All fins appear to have part of their LEV shed.

At 54% cycle completion, the 47.4° sweep fin has the highest instantaneous thrust production, followed by the 25.2° sweep fin, and then the rectangular fin. Shown in Figure 8.29, all the fins have generated LEVs, the rectangular fin LEV again exhibiting the least stability. The 47.4° sweep fin LEV seems to be the most stable and just as large as the 25.2° sweep fin LEV.

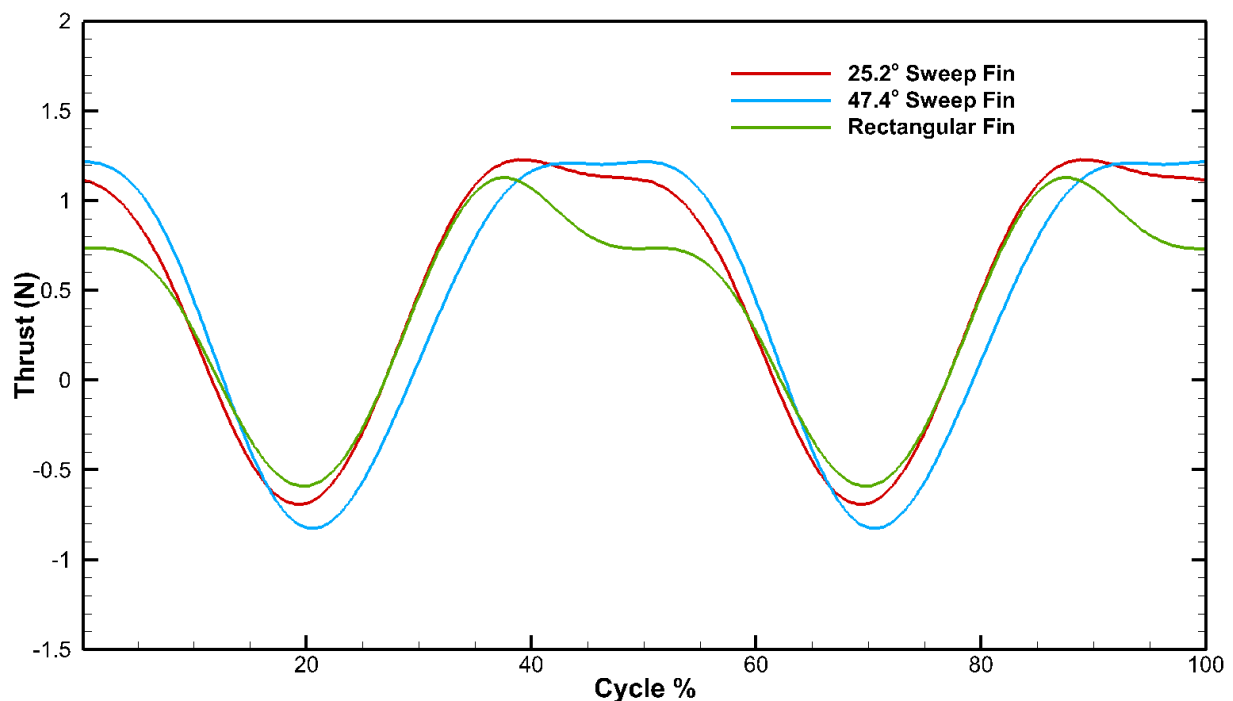


Figure 8.26: Instantaneous thrust production of the rectangular fin and the two fins with 25.2° and 47.4° sweep angles at a freestream of 30cm/s and a Strouhal number of 0.6

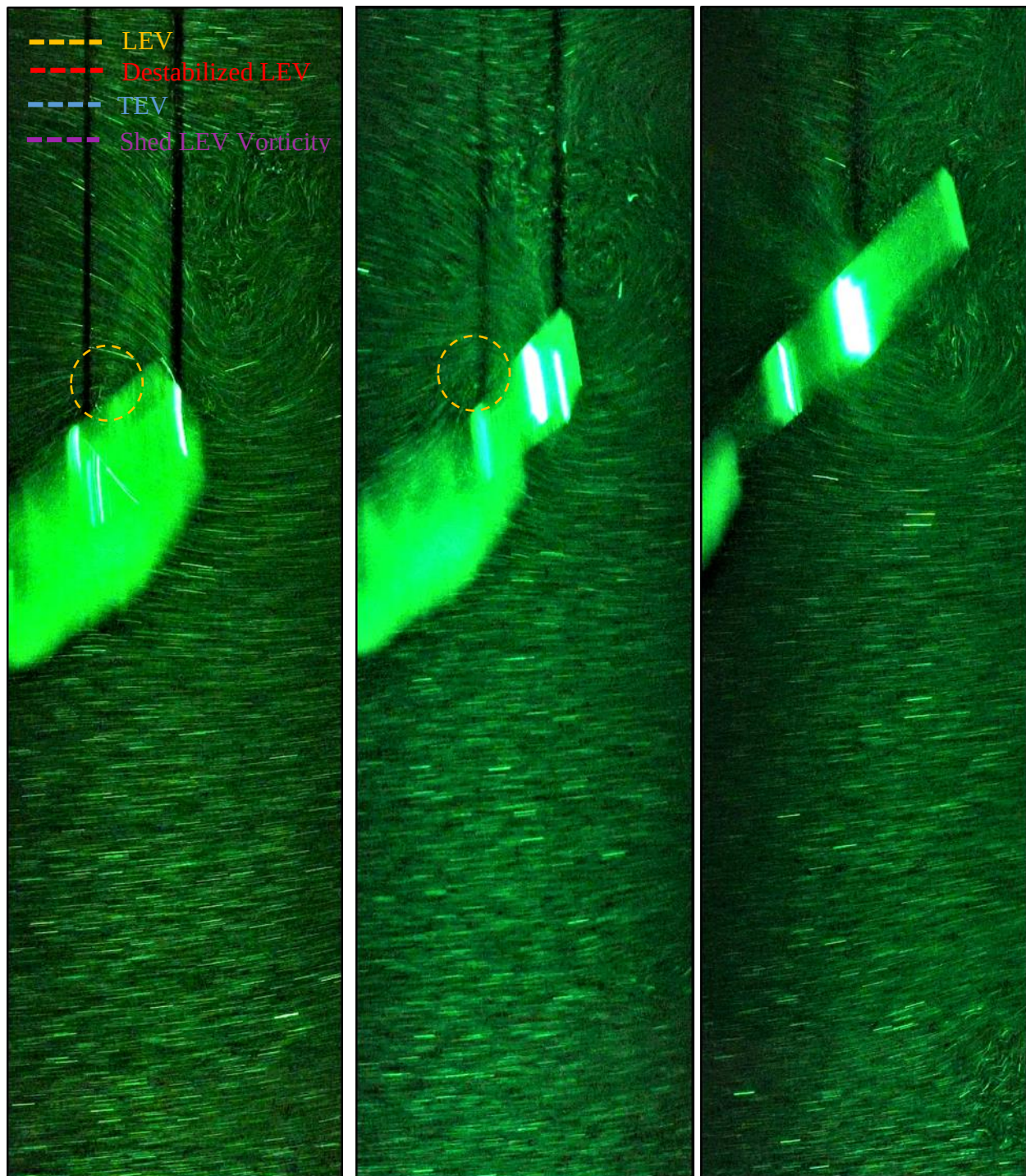


Figure 8.27: LEV development at 24% cycle completion and a Strouhal number of 0.6 of the rectangular fin (left) 25.2 sweep fin (middle) and 47.4 sweep fin (right)

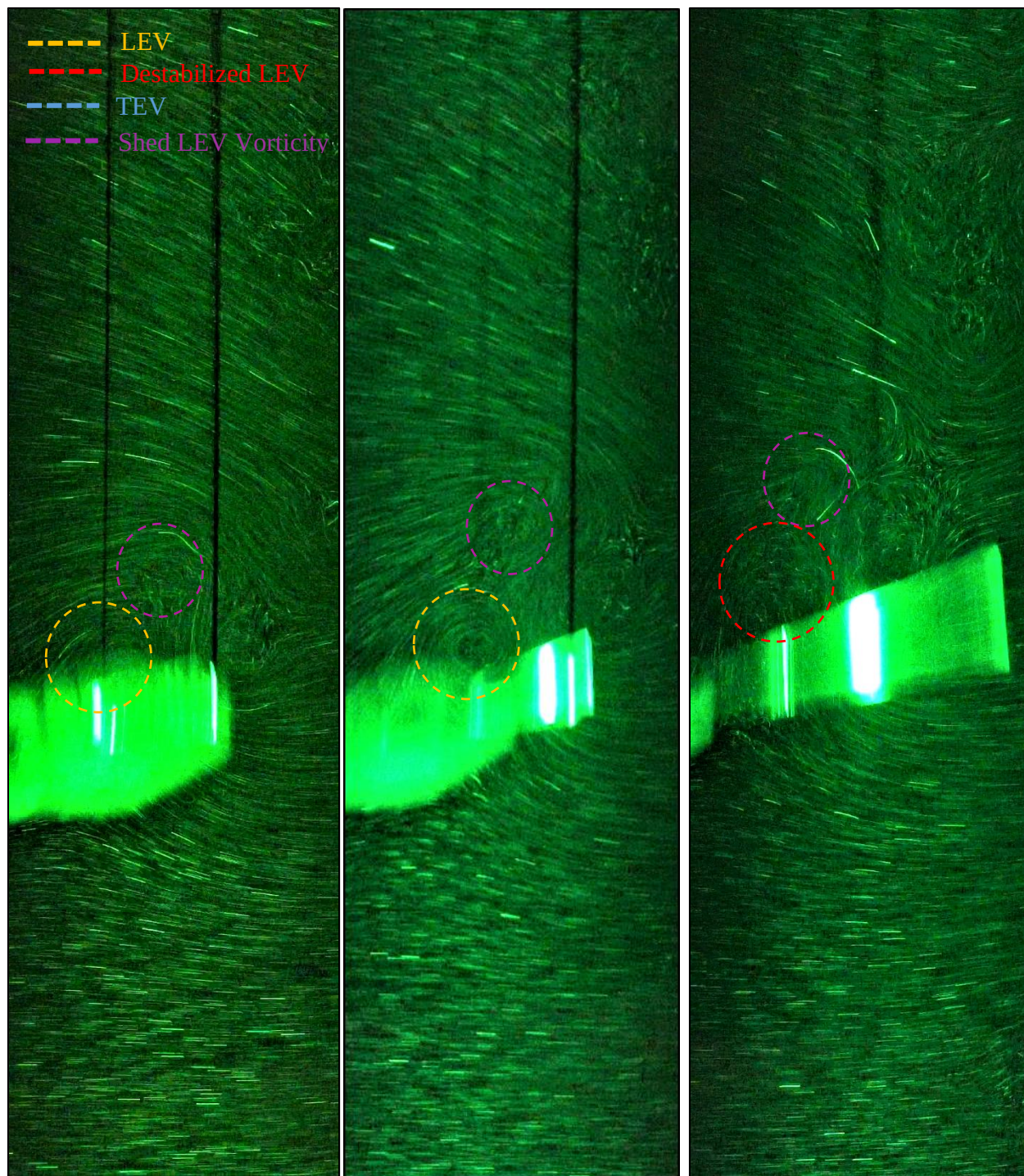


Figure 8.28: LEV development at 36% cycle completion and a Strouhal number of 0.6 of the rectangular fin (left) 25.2 sweep fin (middle) and 47.4 sweep fin (right)

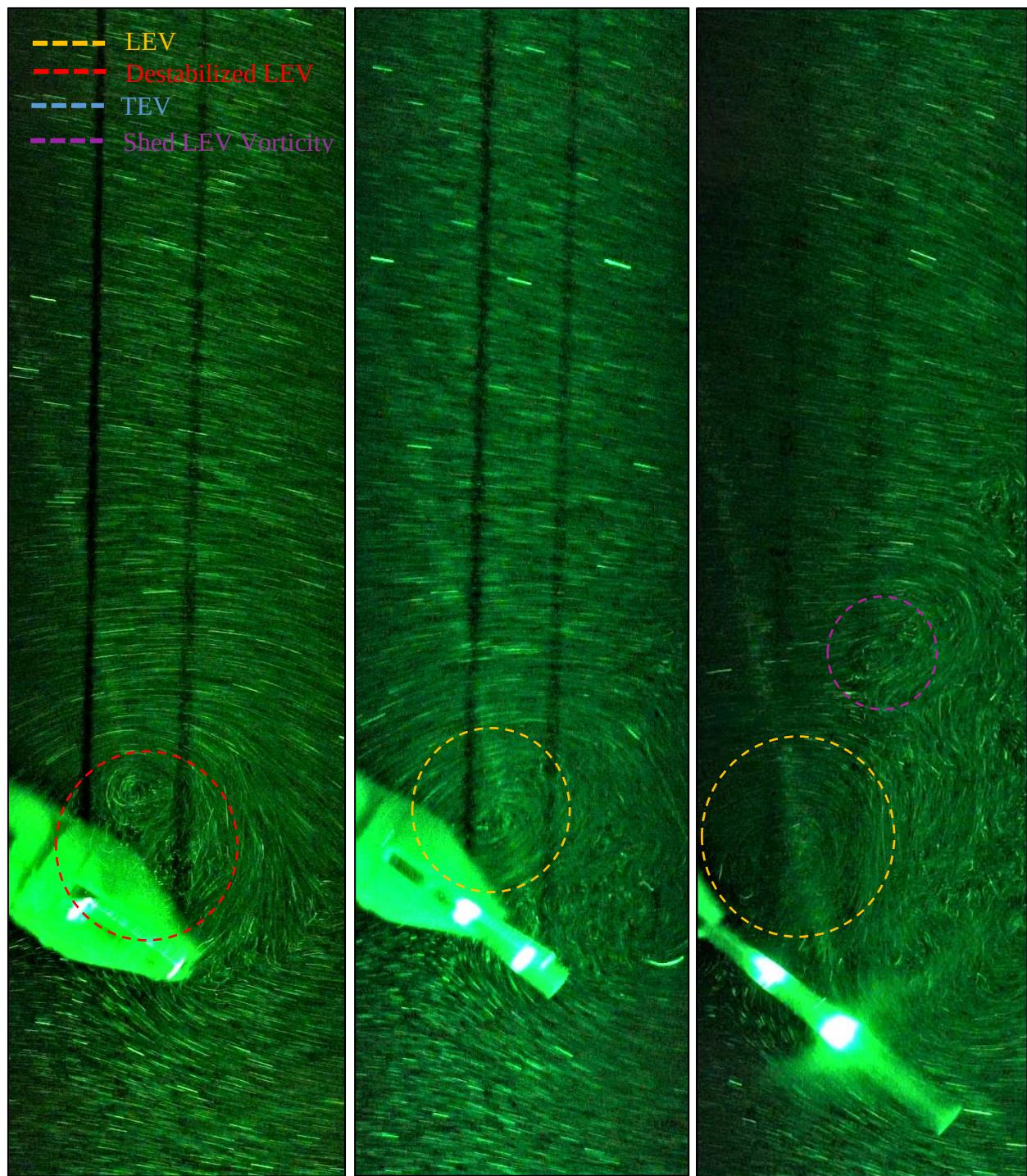


Figure 8.29: LEV development at 54% cycle completion and a Strouhal number of 0.6 of the rectangular fin (left) 25.2 sweep fin (middle) and 47.4 sweep fin (right)

Finally, it appears that the caudal fin sweep angle has an effect on the stability as well as the growth of LEVs. However, the relationship between sweep and LEV stability/growth does not appear to linear. While it seems moderately swept fins do promote beneficial LEV formation, this is not necessarily true for larger sweep angles. Why this might be the case is discussed in more detail in Chapter 9.

8.4.6. Thrust data frequency spectrum

In Figure 8.18, where St is 0.4, there is a high frequency low amplitude oscillation that can be seen in the in all three thrust curves. These oscillations are not noticeable at the higher St . In order to determine the frequency of this oscillation and its cause a Fast Fourier Transform (FFT) was performed on the cycle-averaged data shown in Figure 8.18 as well as the original raw data, and is shown in Figure 8.30.

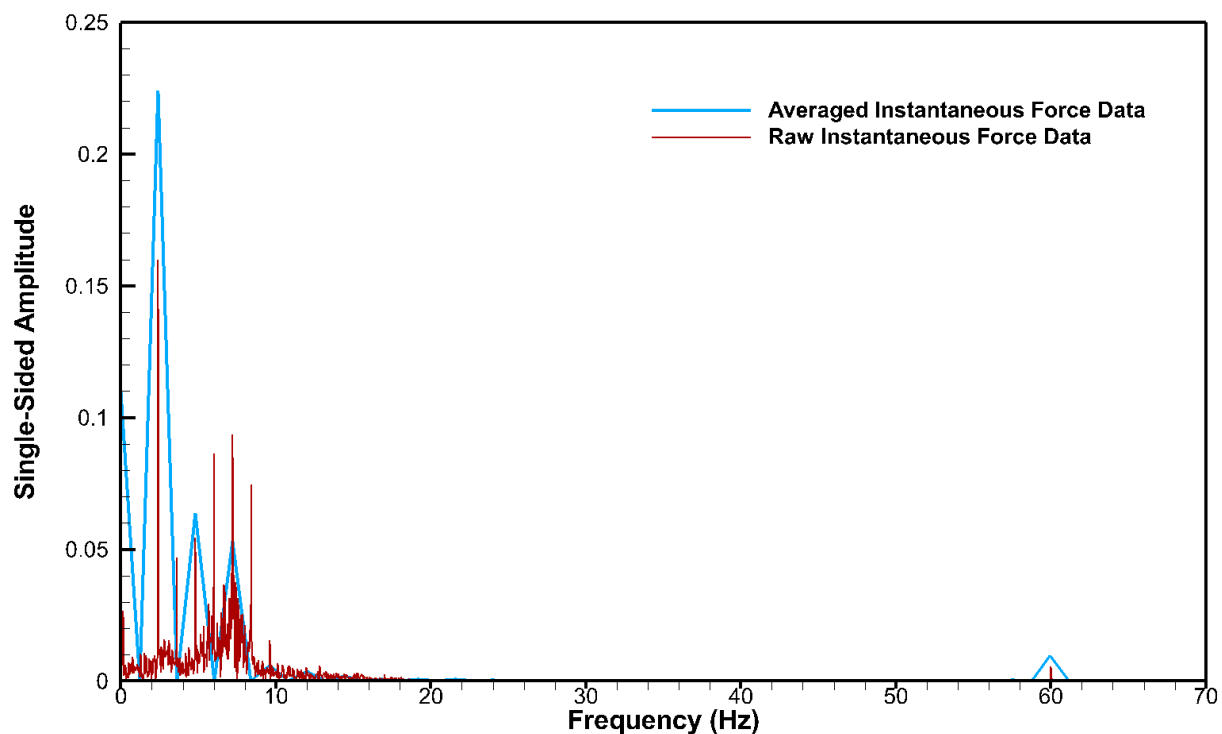


Figure 8.30: Instantaneous thrust single-sided amplitude spectrum of a rectangular fin operating at a Strouhal number of 0.4 and with a freestream of 30cm/s

The frequency with the largest amplitude is 2.4 Hz, which is twice the tail beat frequency for that case, is expected as two lateral strokes occur during each tail beat. Most other signals that significantly contribute to the thrust curve are frequencies below 10 Hz, and appear to be

harmonics of the tail beat frequency. The high frequency low amplitude oscillation that is noticeable in Figure 8.18 has a frequency of exactly 60 Hz. As shown in Figure 8.30, this 60 Hz oscillation appears in both the averaged data as well as the raw data, indicating that it is not an artifact of processing. As the oscillation is not visible in Figure 8.22, and Figure 8.26 it appears that this oscillation does not occur in the higher St cases of 0.5 and 0.6. However, a FFT on the raw data of the rectangular fin operating at higher St and other freestream velocities, indicates otherwise. The 60 Hz signal is still present for all cases. The amplitude of this signal decreased at higher St , suggesting that it is not caused by vibrations of the test structure, which would increase with tail beat frequency of the robot. The 60 Hz frequency also did not change with freestream velocity, which means it is not caused by vibrations from the water tunnel pump. This leaves two possible causes. The first is noise production inherent to the load cell amplifier, which could be caused from the electrical socket current that runs at 120 Hz and when rectified may cause 60 Hz noise. The second, which is the most likely case, is servo jitter. Servo jitter would have a constant frequency that is not affected by load or motion of the servo itself. However, the amplitude of this jitter would likely decrease with increased load, which was seen when comparing the FFT of higher St cases. Regardless, the amplitude of this 60Hz signal is very small compared to the signals associated with tail beat frequency (still less than 1/20 for cases when the 60 Hz signal has the greatest amplitude) and can be ignored.

9. Conclusion

Wing Kinematics Studies

The parametric study suggests there is only a slight difference in aerodynamic performance between a folding wing and a non-folding wing system. However, use of wing folding reduced the inertial contribution to almost 0 watts during the upstroke, thus reducing overall energy expenditure. Biological systems likely have no efficient mechanism to store energy produced by rotation or translational motion. This is likely why wing folding is seen in nature. When used it acts as a fly wheel of sorts. Still, the mean energy savings is small, while the increase in complexity introduced by utilizing a folding wing in a robotic system may be high. As the joint and supporting musculature are already present in bird's wing, their use of wing folding makes sense even if it only provides minor improvements to flight performance.

However, the parametric study shows that wing twist has a dramatic effect on flight performance as it can be used to prevent or promote LEV formation and stop full stall from occurring. Twist amplitude tends to directly influence thrust production while mean twist tends to influence both lift and thrust. Its use in a robotic system makes sense, as the tradeoff between added complexity and performance benefits is more reasonable than that of wing folding use.

Caudal Fin Studies

At the tested freestreams and angles of attack, the moderately swept fins with 25.2° and 36.3° sweep angles, which have a fin sweep similar to a tuna's, showed improved performance over non-swept tails most notably the rectangular tail. This is not surprising as the sweep of a yellowfin tuna is close to likely close to 35° by quarter chord method. The elliptical fin, while not producing as much thrust as the moderately swept fins, did showed improved performance over the rectangular tail and is expected has theoretically it possess the highest circulatory lift to induced drag ratio out of any projected area distribution.

Even though the experiment was conducted at low freestreams, the moderately swept fins would likely behave similarly at higher freestreams as the flow in the experiment had an Re greater than 10^5 which puts it in the inertial regime for swimmers according to the literature [77]. Once flow transitions to the inertial regime, there are minimal changes to hydrodynamics even at higher Reynolds numbers.

Wing sweep produces increased spanwise flow in aircraft, and according to the literature swept fins also produce more spanwise flow than non-swept fins especially during the pitching of the tail at the stroke reversal point [82]. In three dimensions, it has been shown the vortex stability is linked to spanwise flow [35, 36, 96]. This is because convection of the vorticity of the LEV towards the fin's tip ensures that the LEV does not grow too rapidly and destabilize [16, 35, 96, 97]. As vortex formation consistently occurred for all cases, stabilization of the vortex was critical to reducing drag force acting on the fin giving the swept fins that stabilized the vortices an advantage.

However, wing sweep does have disadvantages. Most notably swept wings have lower effective angles of attack leading to lower lift coefficients in attached flow. This is why the swept fins had lower instantaneous thrust values between the reversal points, where the previously attached LEV was shed, and the midstroke, where a new LEV was formed. In addition, greater spanwise flow, that swept fins have, increases boundary layer thickness which in turn increases viscous drag. A not so detrimental effect of this increased boundary layer thickness is that it encourages quicker flow separation. This would be detrimental in static cases. However, in the cause of dynamic caudal fin oscillation, increased boundary layer thickness can cause formation of an LEV sooner during the stroke. This is observed in Figure 8.23 where the moderately swept fin is the only one to have an LEV at the midstroke, and is suggested in Figure 8.19 and Figure 8.27 where the moderately swept fin LEVs are larger than the rectangular fin LEVs. It seems that the moderately swept fins provide a good balance between promoting LEV growth and stabilizing it. Conversely, the adverse effects of wing sweep dominate for the highly swept fin causing it to experience a low effective angle of attack preventing LEV growth and reducing lift due to traditional circulatory forces during the first half of the stroke.

9.1. Contributions

Through a four parameter study, it was determined that while wing folding maybe necessary for birds due to their anatomy, employing just an active sinusoidal wing twist with variable amplitude and offset provides almost equal aerodynamic performance.

A computationally inexpensive aerodynamic model was developed that accurately represents spanwise circulation distribution and provides an accurate estimate of lift and drag as shown through comparison against experimental studies. Due to its extremely fast computation time, it is

ideal for providing aerodynamic estimates to flight controllers and for use in many parameter parametric studies.

Two tuna mimetic robots were developed that perform similarly to their biological counterparts. These were used to experimentally study the hydrodynamics of different caudal fin shapes. This yielded several experimental discoveries not currently in the literature.

Load cell measurements have shown that changes in angle of attack as small as tens degrees can significantly impact thrust production when accelerating, but have a lesser impact on steady state swimming speed. Additionally, through load cell and energy expenditure measurements, this research has shown that use of moderately swept fins with fusiform body shapes and thunniform kinematics improves performance without any appreciable drawbacks. This makes use of them an ideal choice for future robotic systems.

Through flow visualization, the hydrodynamics of thunniform caudal fin propulsion is better understood. It was believed for many years that Tuna form LEVs on their caudal fin. This has been shown numerically, but this is the first experimental investigation to show consistent LEV formation occurring during tuna-like swimming. In addition, this is the first experimental study to show swept fins used in BCF propulsion have improved LEV stability and produce LEV earlier than a non-swept fin.

9.2. Future work

There are a number of directions that can be taken to expand our understanding of bird- and fish-inspired locomotion, especially as there are currently many gaps in the literature. Below are several approaches that expand specifically on the work done to produce this dissertation.

9.2.1. Avian mimetic flight analysis

First, there are very few experimental studies or high order numerical studies on the effect of active wing twist and none on the effect of active wing folding. Future work should include one of these approaches to further understand the aerodynamic contributions and flow field effects of these degrees of freedom. An experimental study would allow for a great number of cases to be run but full flow visualization would be challenging. A CFD study on the other hand would provide high fidelity but the number of cases that could be run would be limited.

Also, most studies do not include the motion of the body, which oscillates at the same frequency as the wings. This in turn affects the motion of the wings relative to the fluid stream. A coupled fluid and body dynamics analysis is needed to analyze the effect of body motion. The likely effect of this coupling is similar average lift, but with reduced oscillation amplitude due to body motion opposing wing motion. However, this hypothesis should be confirmed and may affect the impact of wing folding.

Effect of body motion can also be examined experimentally. By externally producing a controlled freestream velocity and attaching a flapping robot to a horizontal/vertical traverse and/or even a pivot that allows for body pitch oscillation, one or more DOF/s of base body motion becomes unrestricted. Lift force, thrust force, and pitching moment can be back calculated via measurements from an accelerometer and gyroscope. The freestream velocity and flapping frequency would have to be precisely set in unison so that the prototype maintains semi equilibrium where the body oscillates within the range of the traverse similar to how a bird's body can oscillate in free flight without a net change in elevation or forward speed.

Second, as stated in Chapter 3, implementation of active wing twist could greatly improve performance of a flapping robotic system. Both the hardware required for actuation (presented in Chapter 3) and the aerodynamic model (presented in Chapter 4) to assist with prediction have already been developed. Other requirements to successfully create and test an efficient flapping robot with active twist are accurate sensing of both body motion (relative to freestream) as well as wing motion that would provide feedback to a control system that could control tail pitch, root flapping motion, and wingtip pitch motion. Sensing could be done with a combination of gyros, accelerometers, GPS, and angular position/rotation sensors. Fusion of all these sensors is a challenging endeavor that constitutes a project of its own.

9.2.2. Fin shape effect and thunniform swimming analysis

It would be ideal to see if the trends found in the research persist for a free swimming robot rather than a tethered one. Only caudal fin thrust was examined in the current research, but caudal fin lateral force plays an important role in stability and body motion. This lateral force would affect the amplitude of yaw and lateral displacement of the body. Restriction of robot yaw and lateral displacement likely causes increased thrust production as the motion of the tail is not damped by the recoil of the body. Yaw motion of the body may also cause increased drag as projected area of

the body perpendicular to the flow would become larger. Thus, seeing how shape effects the lateral force would be the next logical step of the current research.

Tuna also have caudal fin cross-sections that are streamlined while fins tested in this study had a rectangular cross-section for consistency and easy of manufacture. It would be interesting to see if there are any interactions between fin cross-section shape and planform shape.

Furthermore, a 90° phase shift between tail and fin oscillation was applied in the current study. Other studies on oscillating foils and generalized body/caudal fin swimming have reported a 75-80 degree phase shift is ideal. It would be interesting to see if this slight deviation in phase has a significant impact on performance between the different caudal fin shapes.

Lastly, there is currently a lack of kinematic data on thunniform swimming, the latest observational study in the literature on tuna kinematics is from 1994 [67]. In this study, only four points along the body are captured and only the major parameters that describe this motion were presented. With advances in camera technology, more accurate and detailed kinematics of fish motion can be captured, and even in their natural habitat. A large array of GoPro cameras has been successfully used to capture the kinematics of bat flight [5]. In addition to being affordable, high frame rate, and offering decent resolution, GoPros are waterproof making them ideal for aquatic creature capture. A portable scaffold that contains 4 to 8 GoPros could be held by a diver and used to film tuna swimming in their natural habit. Using stereo triangulation, 3D coordinates of feature points can be extracted from each individual frame of video. The 3D motion of these feature points can be used to give us a better understand tuna swimming.

10. References

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Appendix-A: Effects of angle of attack on thrust production

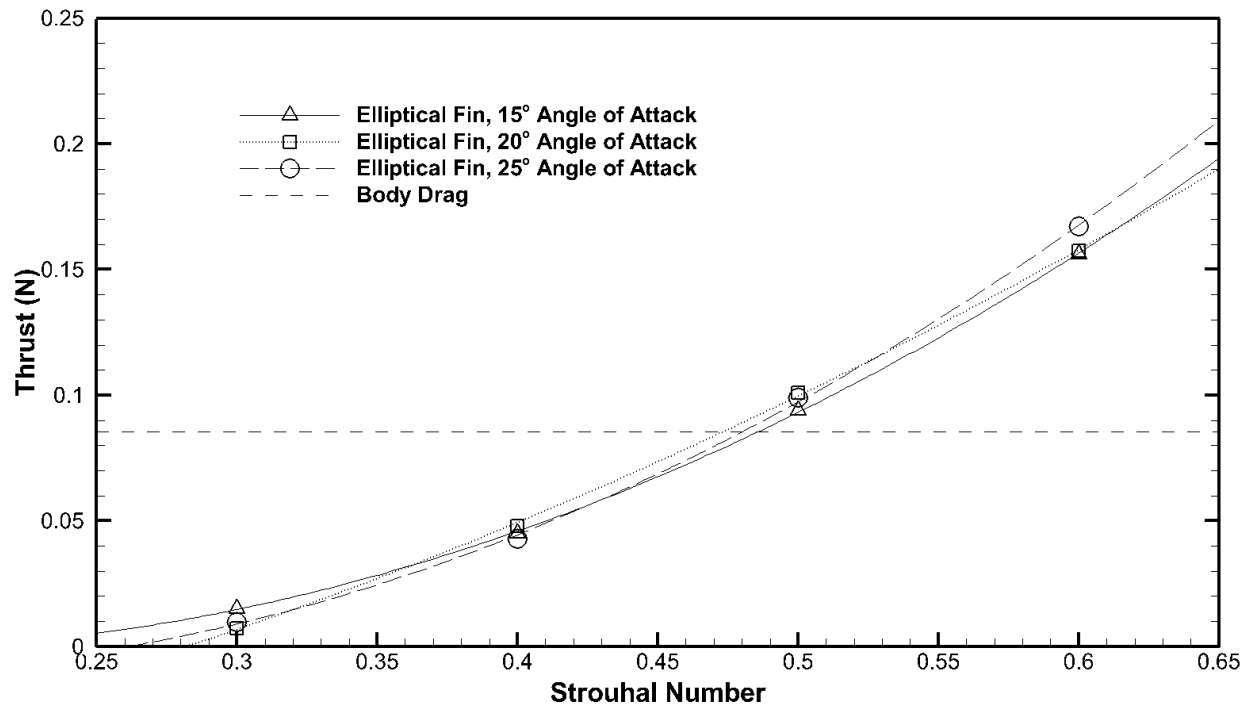


Figure A.1: Thrust vs Strouhal number of an elliptical fin at 20 cm/s freestream

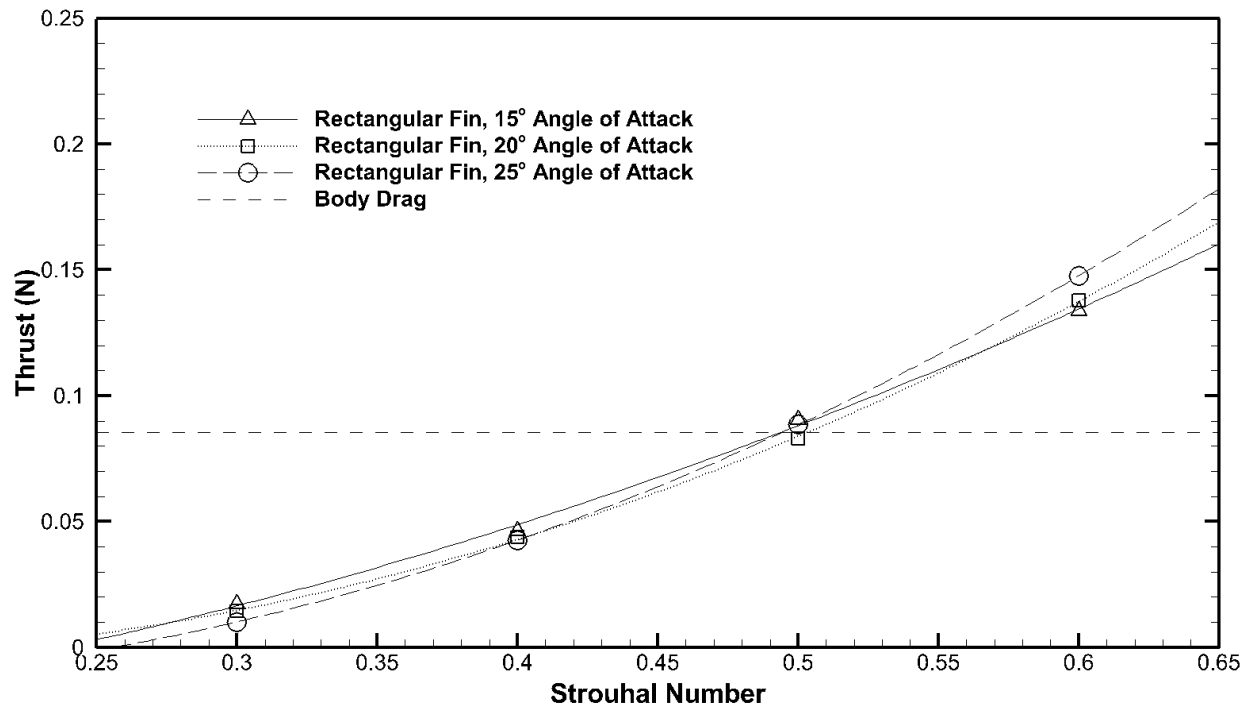


Figure A.2: Thrust vs Strouhal number of an rectangular fin at 20 cm/s freestream

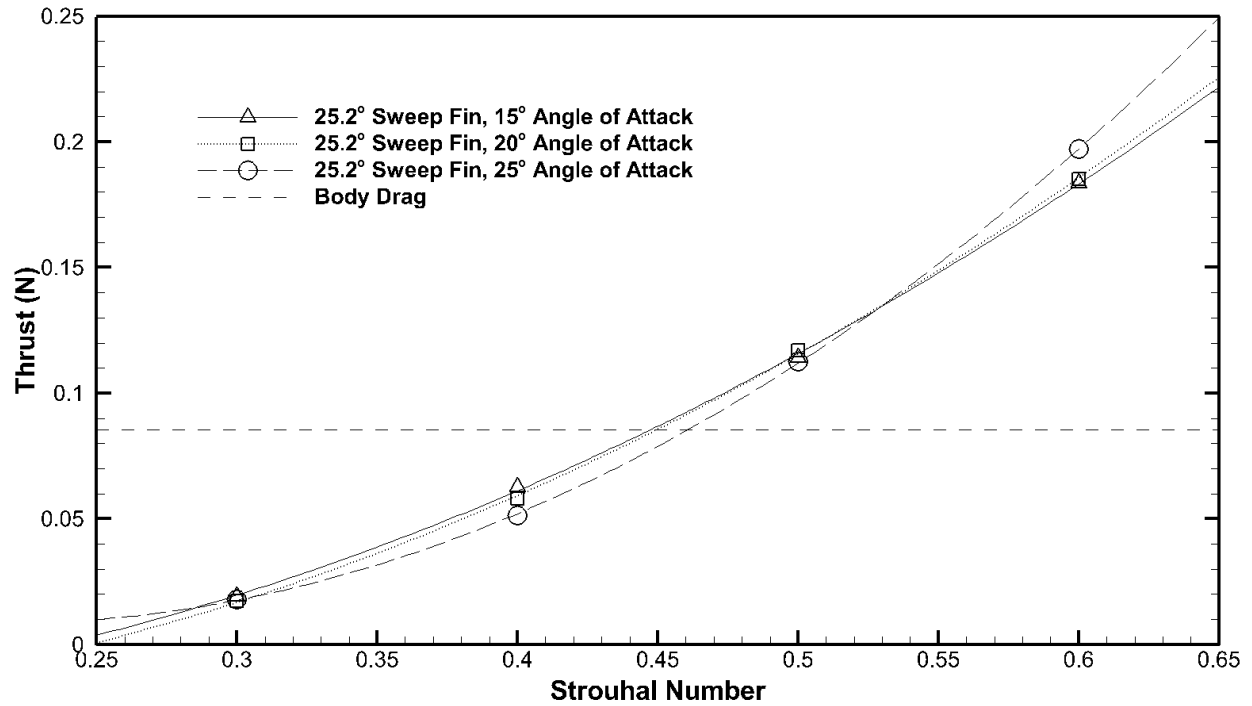


Figure A.3: Thrust vs Strouhal number of a fin with a 25.2° sweep at 20 cm/s freestream

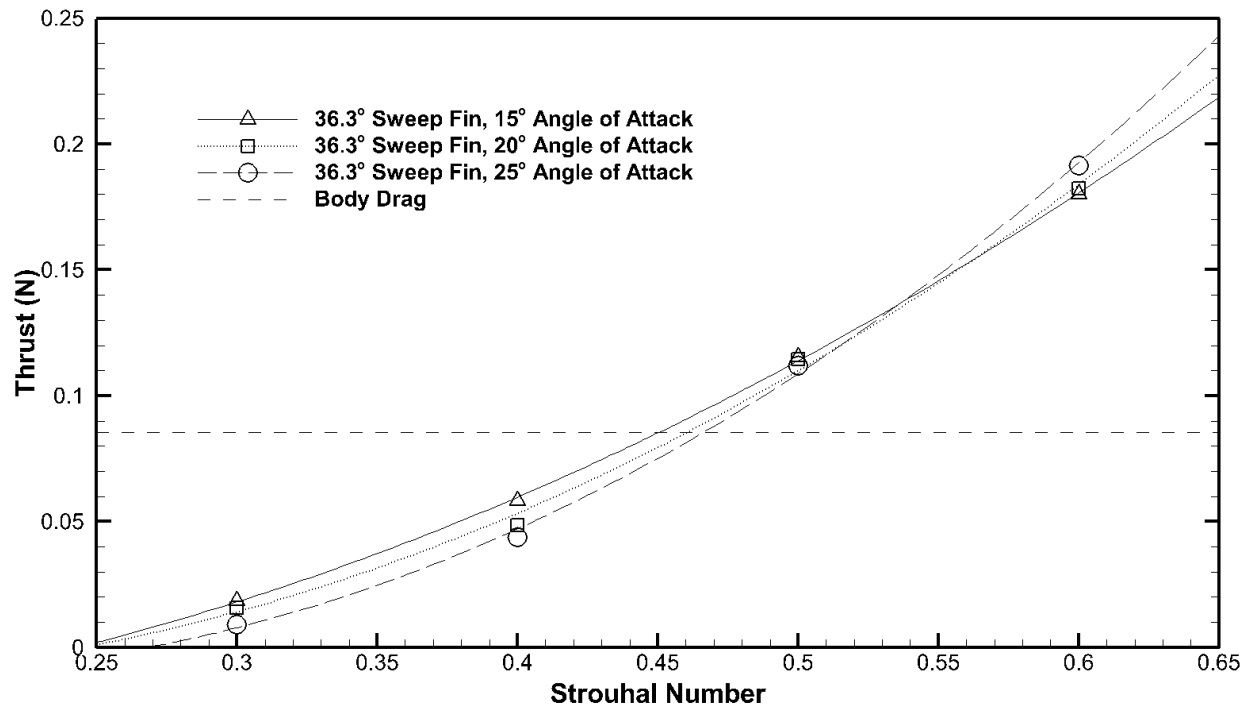


Figure A.4: Thrust vs Strouhal number of a fin with a 36.3° sweep at 20 cm/s freestream

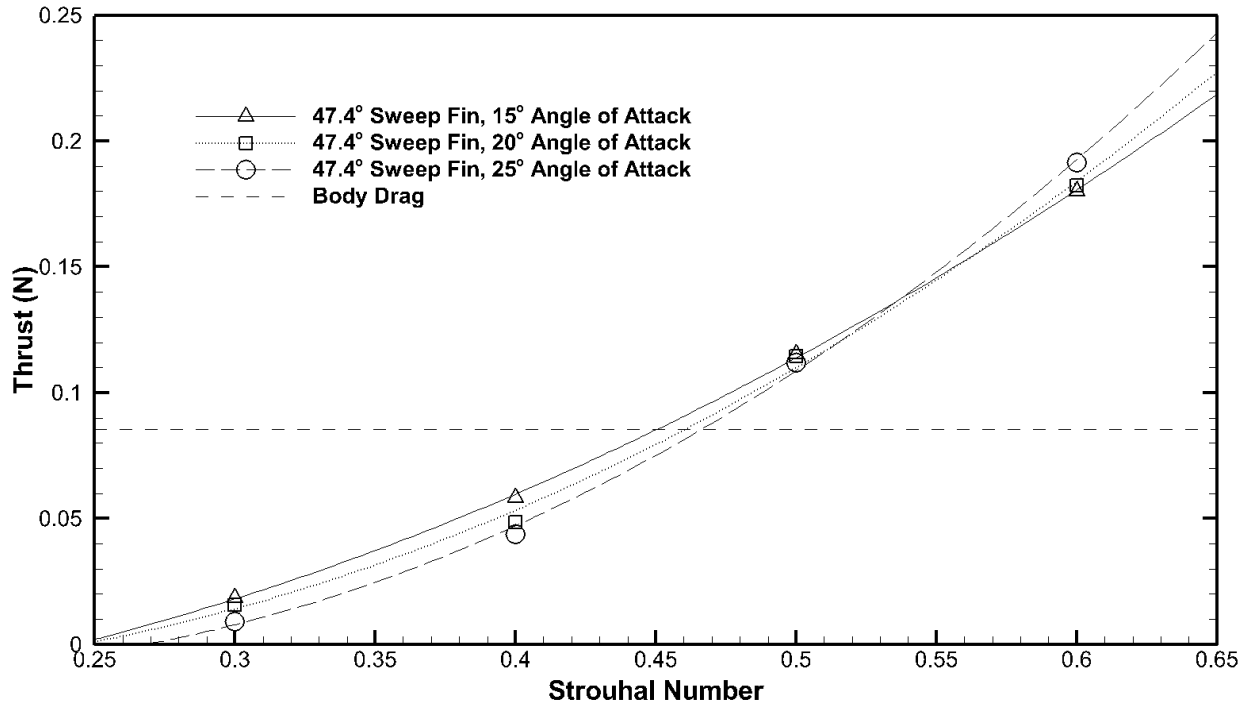


Figure A.5: Thrust vs Strouhal number of a fin with a 47.4° sweep at 20 cm/s freestream

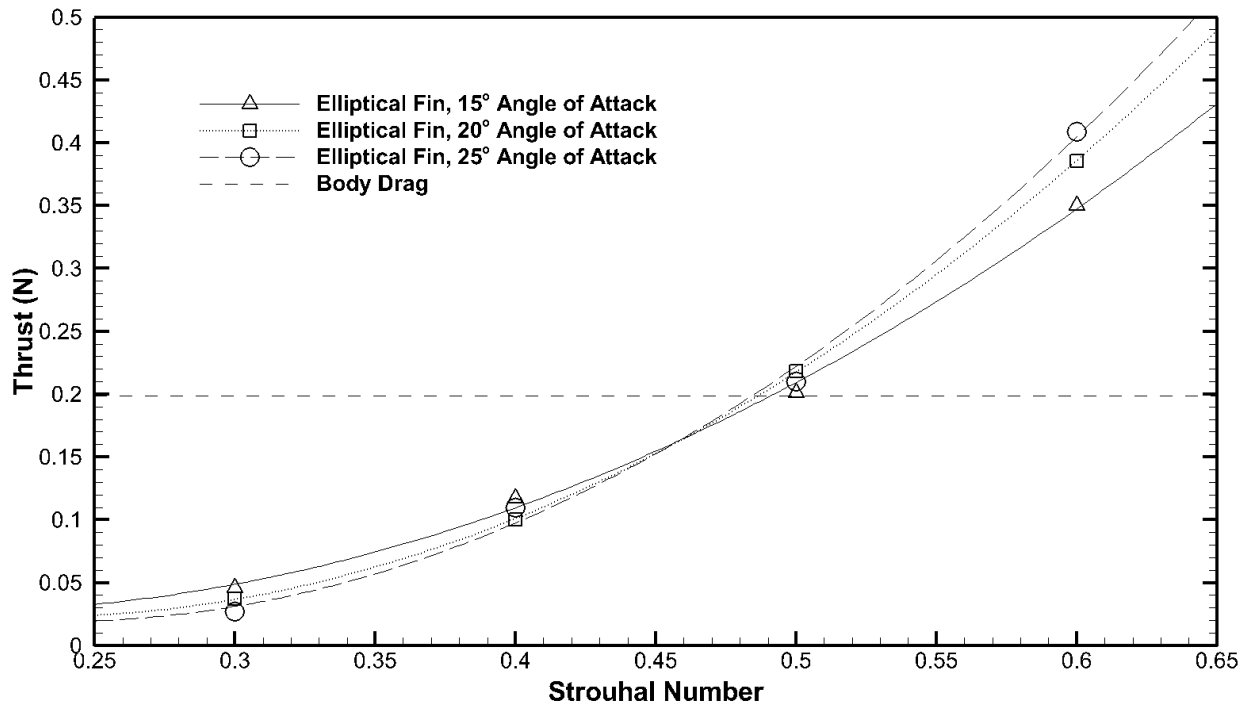


Figure A.6: Thrust vs Strouhal number of an elliptical fin at 30 cm/s freestream

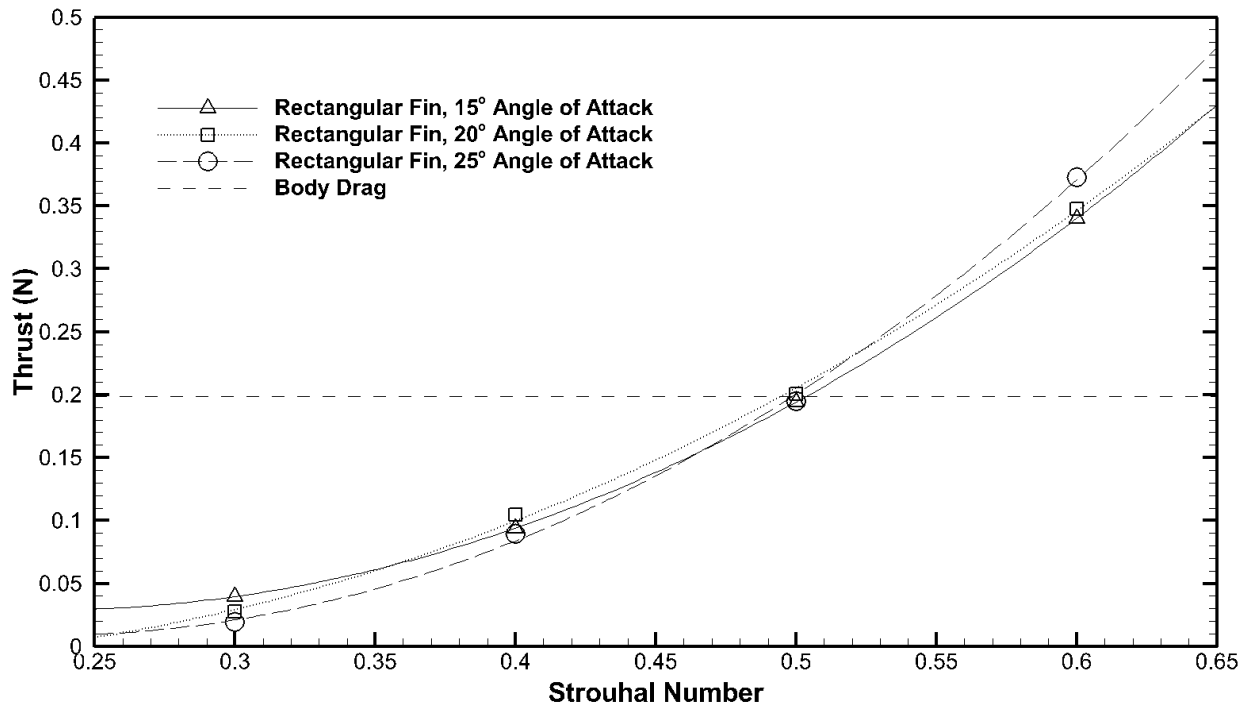


Figure A.7: Thrust vs Strouhal number of a rectangular fin at 30 cm/s freestream

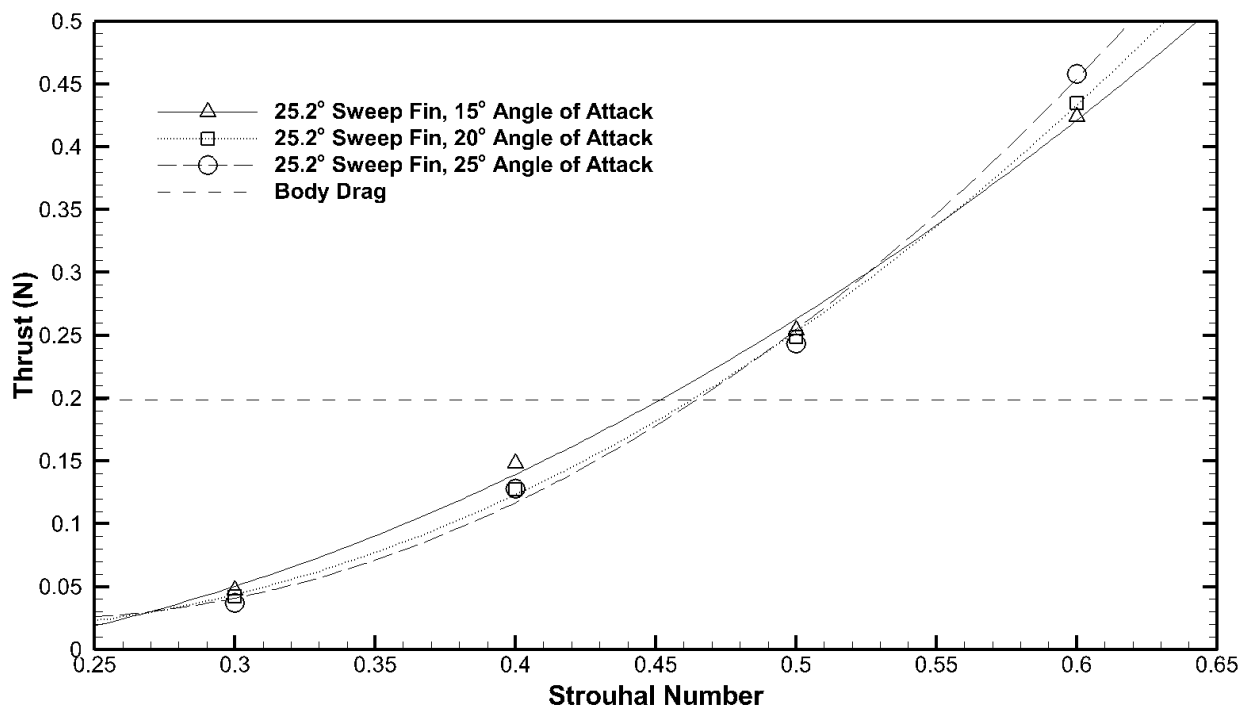


Figure A.8: Thrust vs Strouhal number of a fin with a 25.2° sweep at 30 cm/s freestream

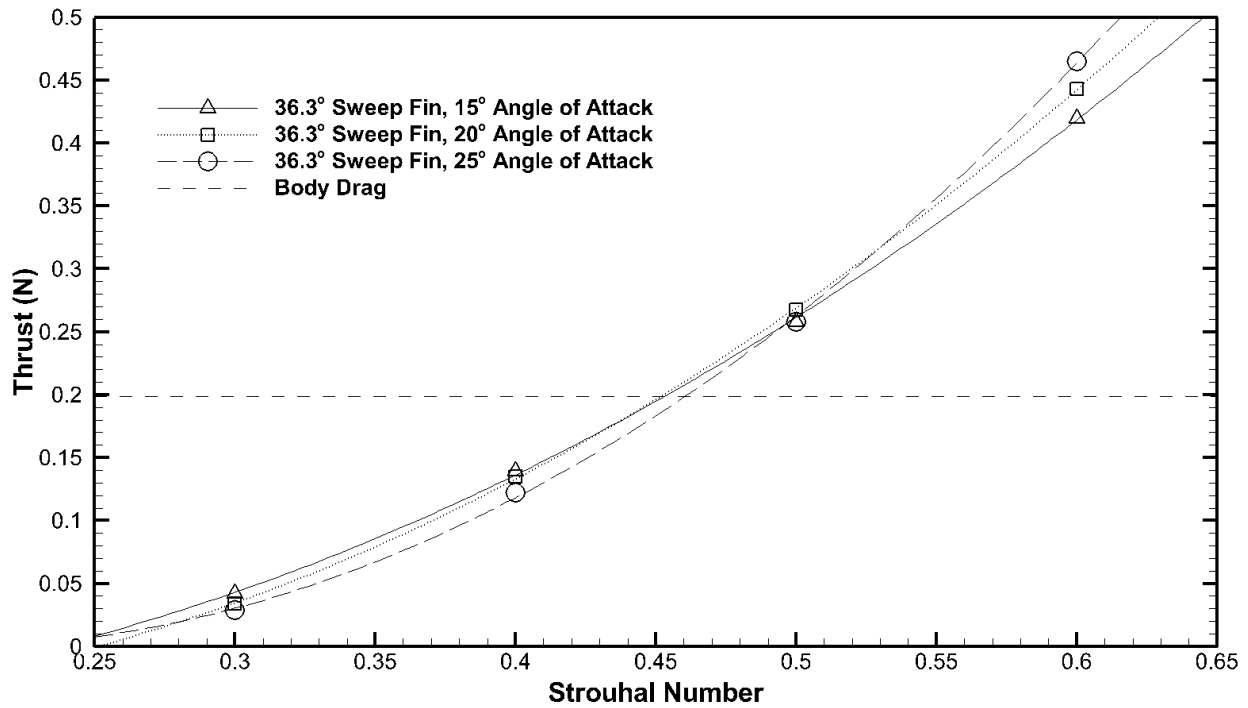


Figure A.9: Thrust vs Strouhal number of a fin with a 36.3° sweep at 30 cm/s freestream

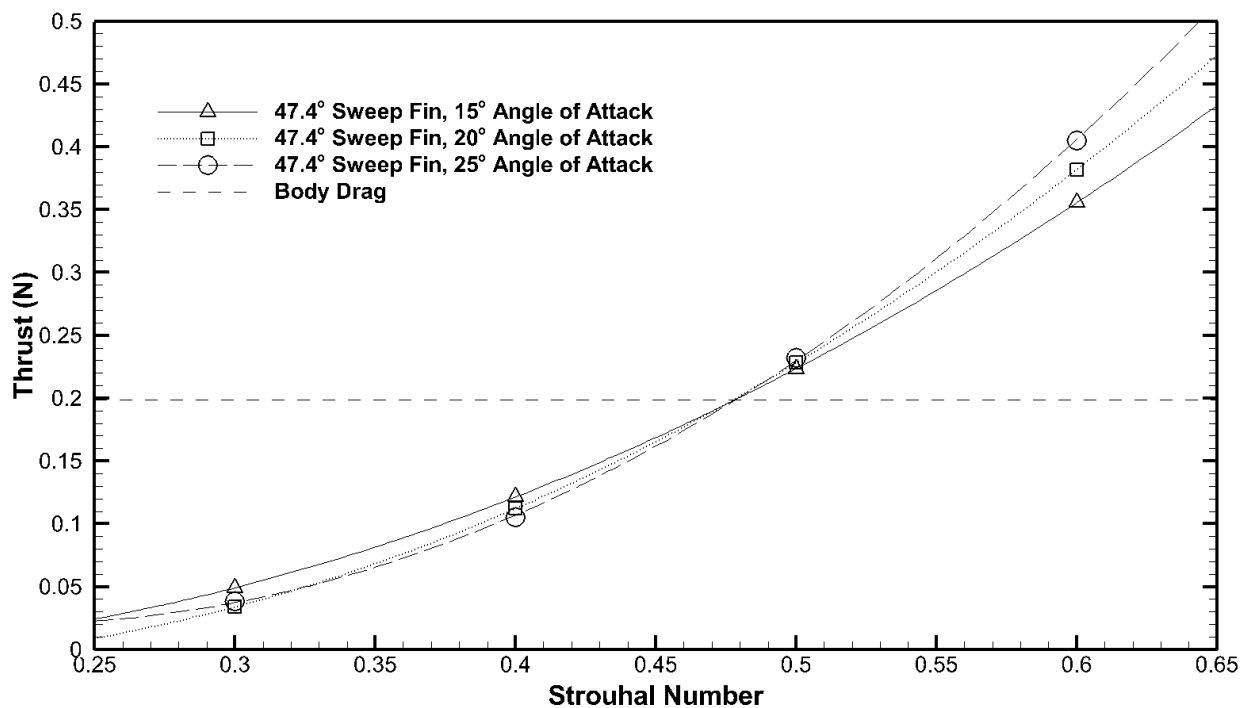


Figure A.10: Thrust vs Strouhal number of a fin with a 47.4° sweep at 30 cm/s freestream

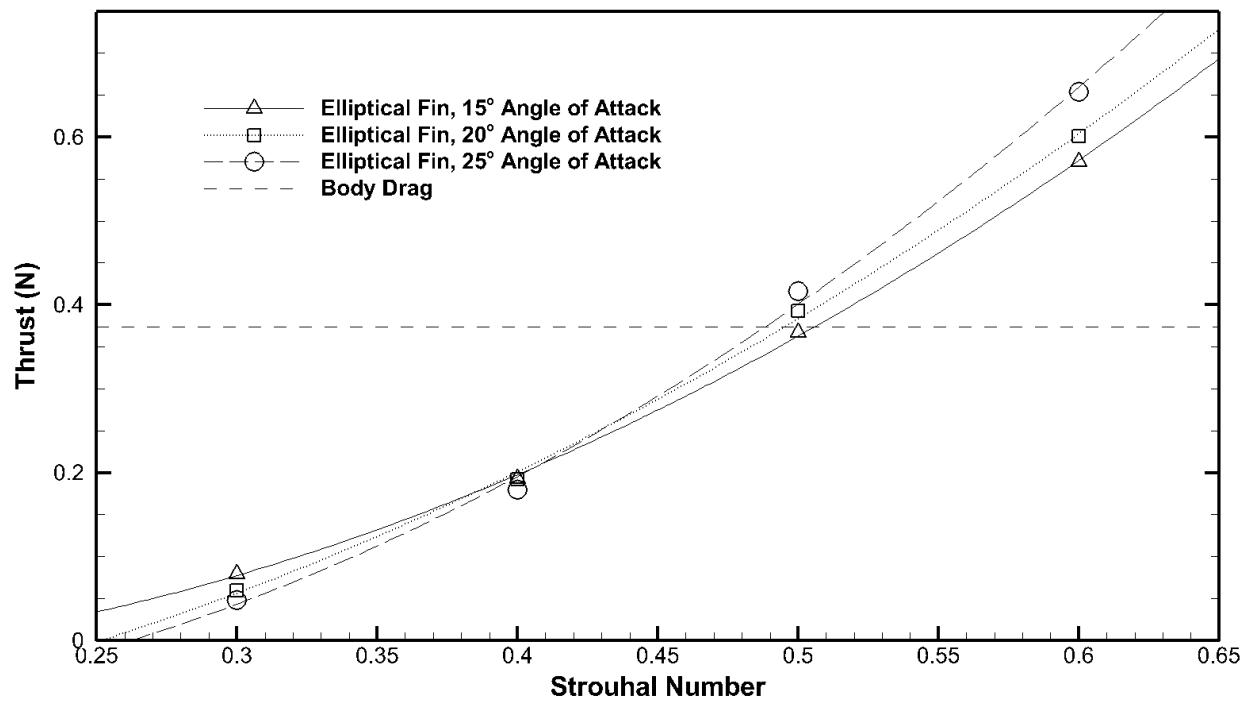


Figure A.11: Thrust vs Strouhal number of an elliptical fin at 40 cm/s freestream

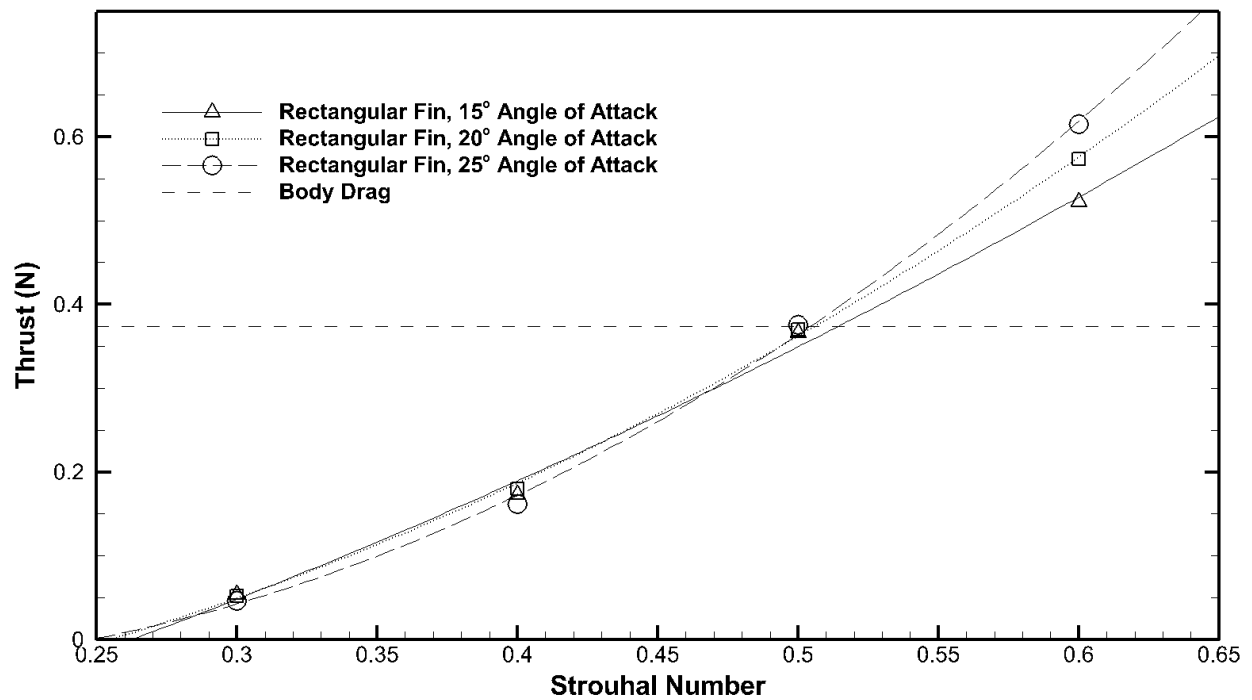


Figure A.12: Thrust vs Strouhal number of a rectangular fin at 40 cm/s freestream

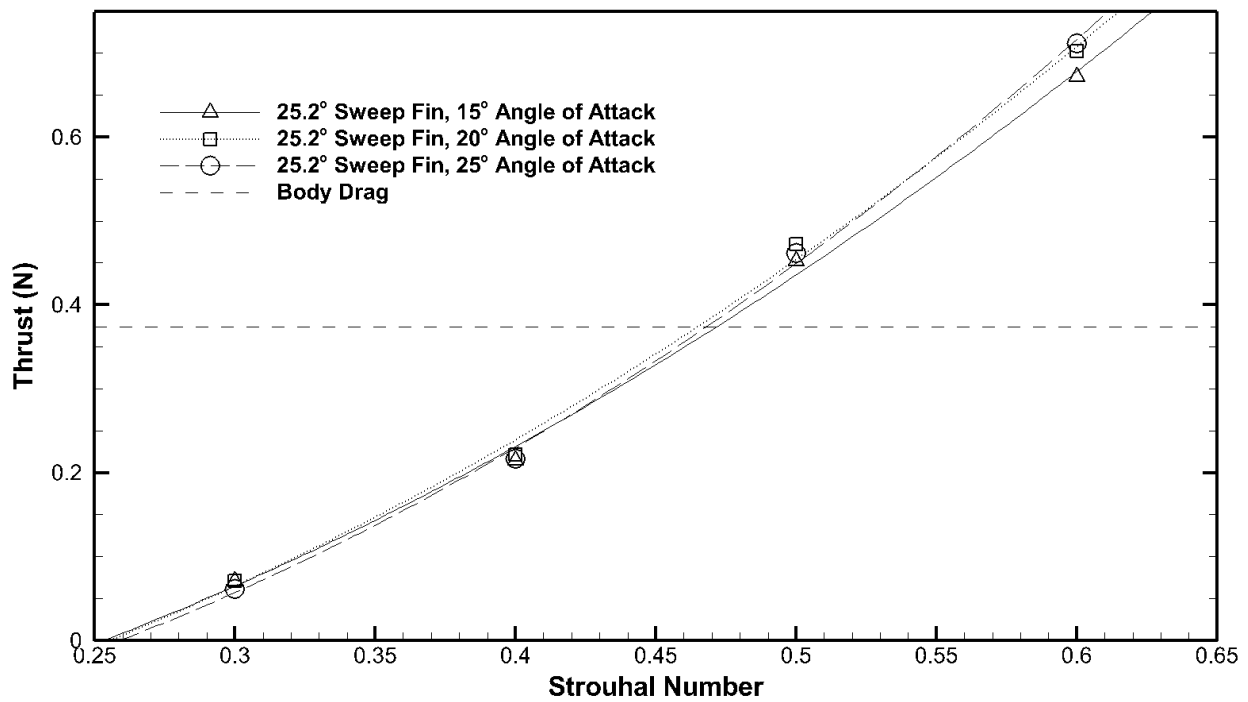


Figure A.13: Thrust vs Strouhal number of a fin with a 25.2° sweep at 40 cm/s freestream

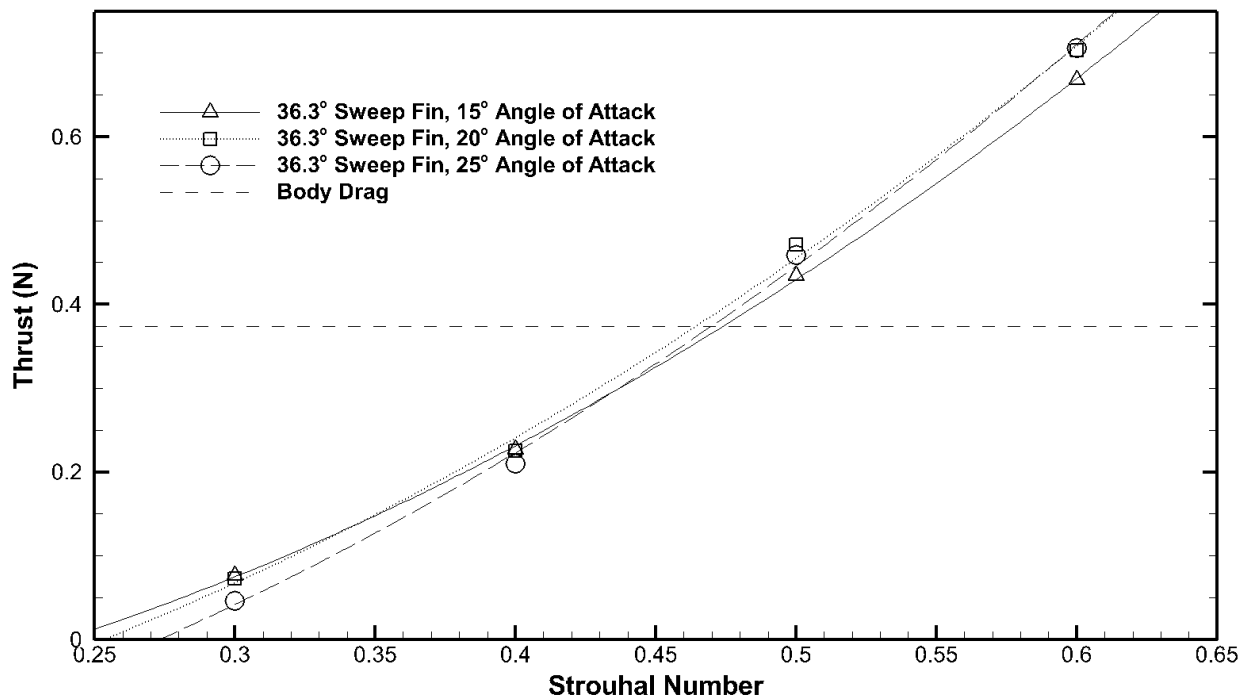


Figure A.14: Thrust vs Strouhal number of a fin with a 36.3° sweep at 40 cm/s freestream

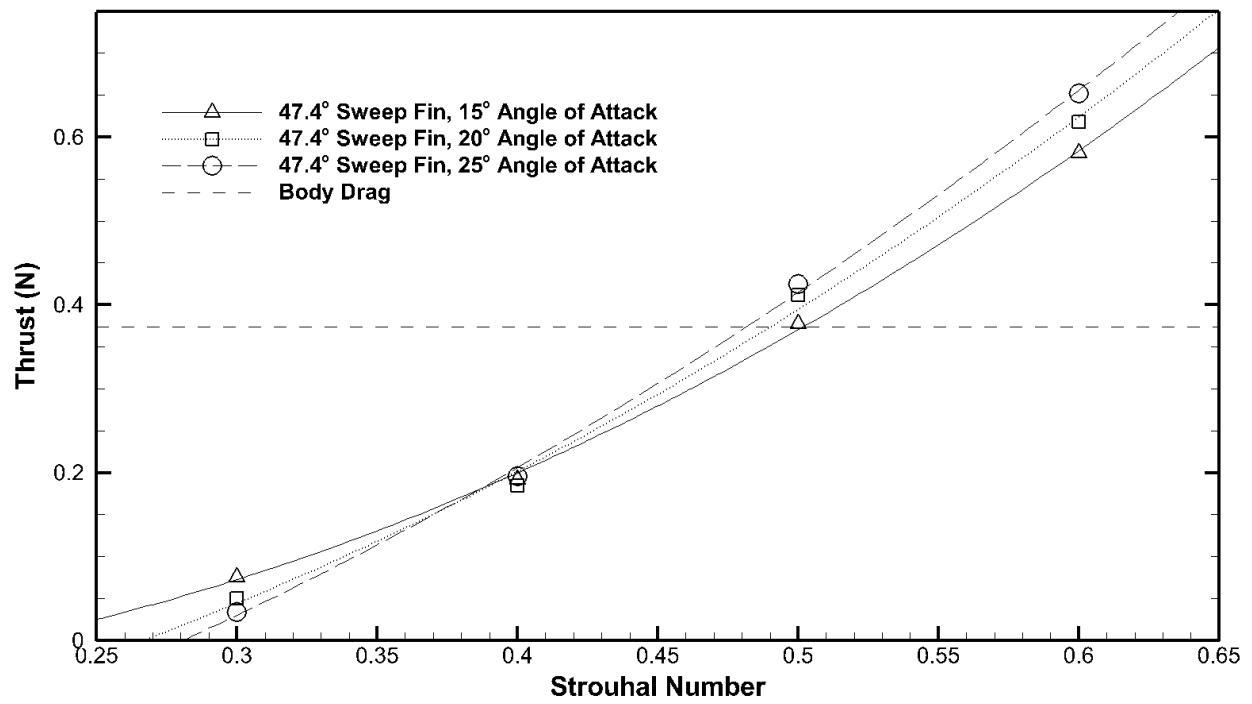


Figure A.15: Thrust vs Strouhal number of a fin with a 47.4° sweep at 40 cm/s freestream

Appendix-B: Effect of caudal fin shape on energy expenditure

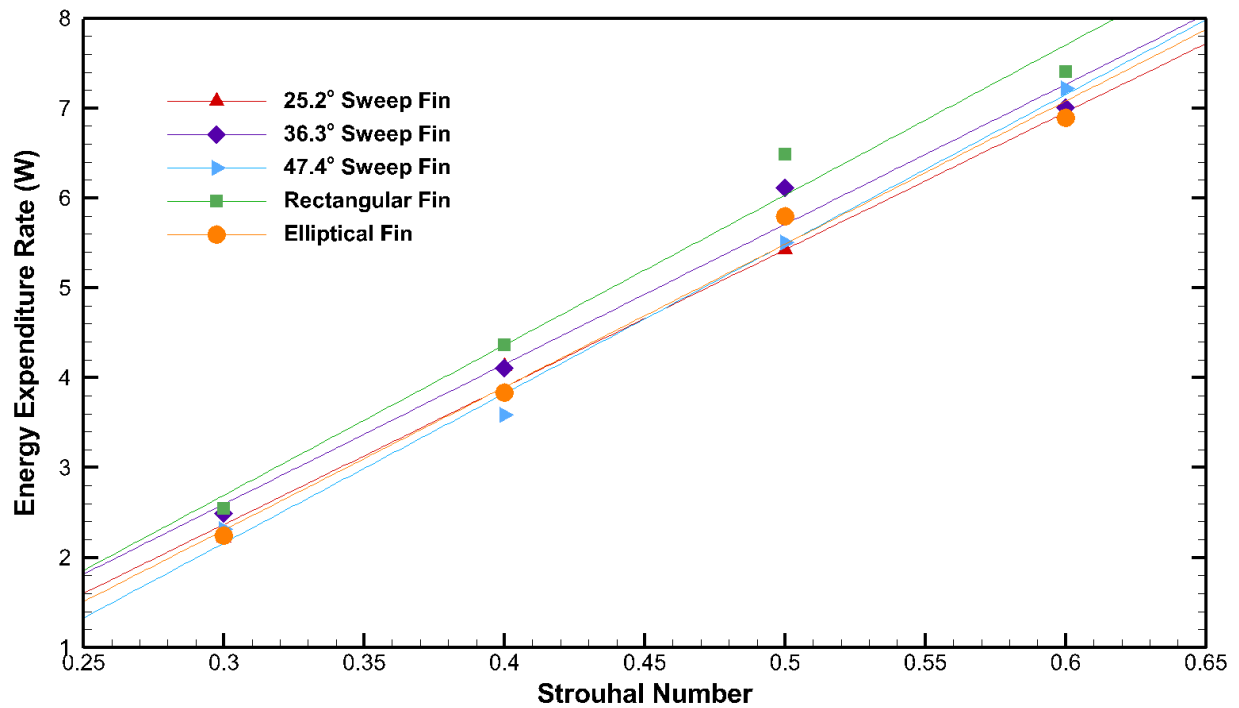


Figure B.1: Energy expenditure rate of five fins vs Strouhal number at 20 cm/s freestream

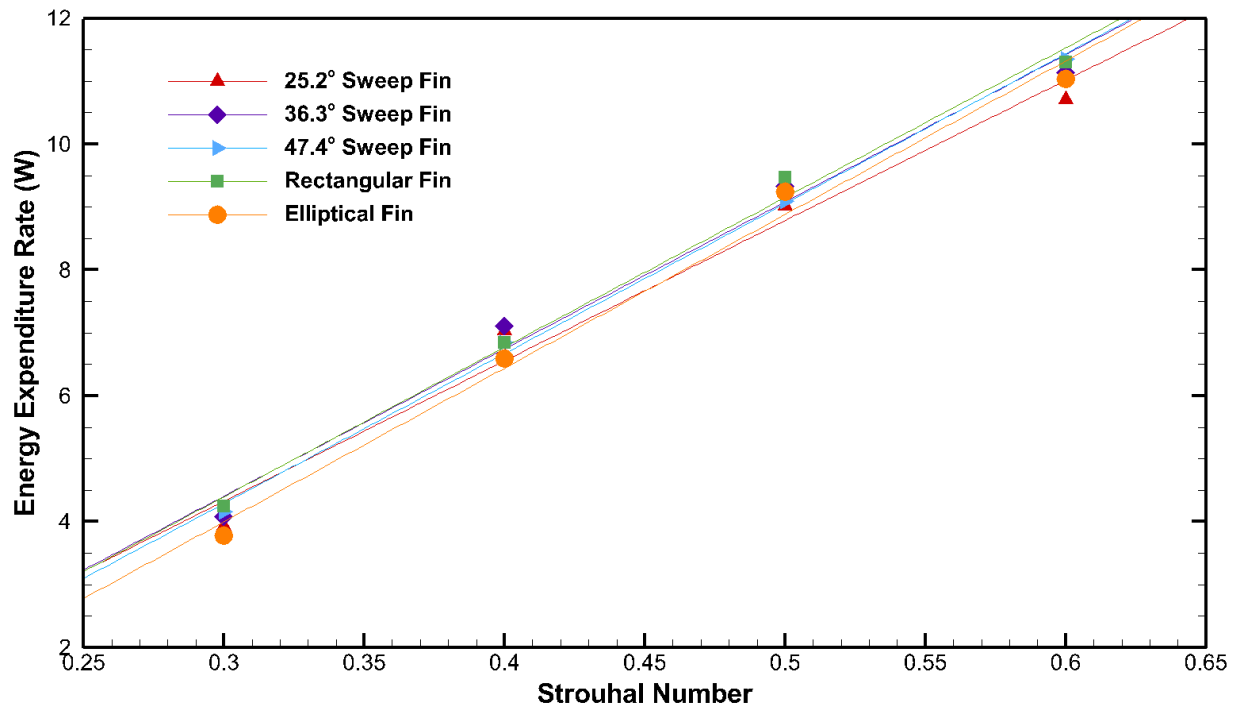


Figure B.2: Energy expenditure rate of five fins vs Strouhal number at 30 cm/s freestream

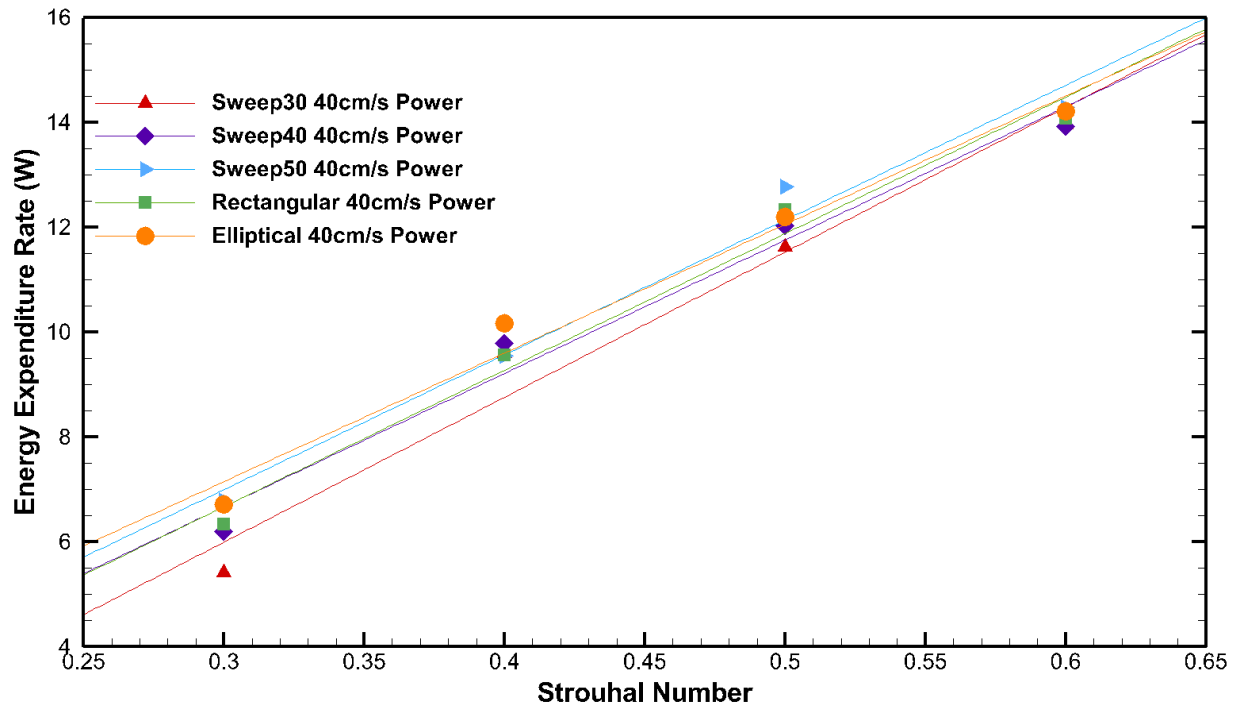


Figure B.3: Energy expenditure rate of five fins vs Strouhal number at 40 cm/s freestream