AFRL-AFOSR-VA-TR-2024-0180

Unsteady Aerodynics of Goal-Bsed Propulsion and Flight Employing CPFD

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02/27/2024
Final Technical Report

Air Force Research Laboratory
Air Force Office of Scientific Research
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

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1. REPORT DATE	**2. REPORT TYPE**	**3. DATES COVERED** START DATE	END DATE
20240227	Final	20190401	20230930

4. TITLE AND SUBTITLE
Unsteady Aerodynics of Goal-Bsed Propulsion and Flight Employing CPFD

5a. CONTRACT NUMBER	**5b. GRANT NUMBER**	**5c. PROGRAM ELEMENT NUMBER**
	FA9550-19-1-0142	61102F
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

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USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**
Air Force Office of Scientific Research 875 N. Randolph St. Room 3112 Arlington, VA 22203	AFRL/AFOSR RTA1	AFRL-AFOSR-VA-TR-2024-0180

12. DISTRIBUTION/AVAILABILITY STATEMENT
A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
A fundamental aspect of the research is to study the interaction of vortices with structures and to consider efficiency, velocity, and thrust for the Unsteady Aerodynamic systems. The studies involve a vertical airfoil which is mounted to a carriage system, situated above a flowing water channel, which can propel itself in the fluid. This has represented a continuation and extension of our previous works, as well as novel research associated with self-propulsion. Key results from a comprehensive study on self-propulsion represent much of our current objectives. Our approach involves the use of the Cyber-Physical Fluid Dynamics (CPFD) facility to study aerodynamics of bodies with more than one degree-of-freedom motion. Although the research is fundamental, the results will be useful for the design of flapping-wing micro air vehicles, as one example, and we expect that new discoveries, phenomena and concepts will carry across to interesting problems that can be addressed with the CPFD Facility, not simply flapping wings. Much of our work is in vortex dynamics, and fundamental flow physics, and this is at the heart of those areas of flow research. The CPFD facility at Cornell is being used to study self-propulsion, with specified kinematics. There is no need to depend on tethered body investigations, because the CPFD facility can easily run self-propulsion experiments, without assumptions. We employ the CPFD facility and make use of contours in a "Heave-Pitch diagram". This is a simple idea where the y-axis of a plot represents pure heave, while the x-axis represents pure pitch, and inside these boundaries are controlled heave amplitude and controlled pitch amplitude, with contours of chosen variables; for example, vehicle velocity, or Propulsive Economy (efficiency), or maximum angle of attack during a cycle, or transverse impulse, etc. Although trivially easy to make these plots, it is nevertheless a powerful way to present the data as a set of related contour plots. The resolution of the "Heave-Pitch diagrams" depend heavily on the quality of the contour data. High quality data is enabled because experiments with CPFD are fast; the speed of running experiments with CPFD is significantly faster than pure experimental work. One of our studies uses 2000 virtual torsional springs. Obviously, this simply could not be done physically. In summary, there are a number of research papers, involving CPFD Facility design, and the design of non-linear virtual restoring forces in vortex-induced vibrations, which have been part of our AFOSR effort. Some of our other studies looked at direct measurements of efficiency and thrust of a pitching airfoil; the effects of combining active heave with passive pitch (and vice versa); the effect of pivot location for a pitching body; the implementation of "hybrid-heave" motions to increase propulsive performance of an oscillating airfoil or flicking sail. Our current principal effort is concerned with self-propulsion of combined heaving and pitching airfoils. This is one of the most energetic periods of study in our labs since the CPFD facility was completed. We look at the case where the airfoil is self- propelling forward and also the case where the airfoil is generating lift force to carry, in effect, a "payload". These experiments are studied in Section 4.1 and 4.2 and yield some new phenomena.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
U	U	U	UU	18

19a. NAME OF RESPONSIBLE PERSON	**19b. PHONE NUMBER** *(Include area code)*
GREGG ABATE	425-1779

Standard Form 298 (Rev.5/2020)
Prescribed by ANSI Std. Z39.18

UNSTEADY AERODYNAMICS OF GOAL-BASED PROPULSION AND FLIGHT, EMPLOYING *CPFD*.

FINAL REPORT

19 December 2023

For:

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Program Officer
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Abstract

A fundamental aspect of the research is to study the interaction of vortices with structures and to consider efficiency, velocity, and thrust for the Unsteady Aerodynamic systems. The studies involve a vertical airfoil which is mounted to a carriage system, situated above a flowing water channel, which can propel itself in the fluid. This has represented a continuation and extension of our previous works, as well as novel research associated with self-propulsion.

Key results from a comprehensive study on self-propulsion represent much of our current objectives. Our approach involves the use of the *Cyber-Physical Fluid Dynamics (CPFD)* facility to study aerodynamics of bodies with more than one degree-of-freedom motion. Although the research is fundamental, the results will be useful for the design of flapping-wing micro air vehicles, as one example, and we expect that new discoveries, phenomena and concepts will carry across to interesting problems that can be addressed with the CPFD Facility, not simply flapping wings. Much of our work is in vortex dynamics, and fundamental flow physics, and this is at the heart of those areas of flow research.

The CPFD facility at Cornell is being used to study self-propulsion, with specified kinematics. There is no need to depend on tethered body investigations, because the CPFD facility can easily run self-propulsion experiments, without assumptions. We employ the CPFD facility and make use of contours in a "Heave-Pitch diagram". This is a simple idea where the y-axis of a plot represents pure heave, while the x-axis represents pure pitch, and inside these boundaries are controlled heave amplitude and controlled pitch amplitude, with contours of chosen variables; for example, vehicle velocity, or Propulsive Economy (efficiency), or maximum angle of attack during a cycle, or transverse impulse, etc. Although trivially easy to make these plots, it is nevertheless a powerful way to present the data as a set of related contour plots.

The resolution of the "Heave-Pitch diagrams" depend heavily on the quality of the contour data. High quality data is enabled because experiments with CPFD are fast; the speed of running experiments with CPFD is significantly faster than pure experimental work. One of our studies uses 2000 virtual torsional springs. Obviously, this simply could not be done physically.

In summary, there are a number of research papers, involving CPFD Facility design, and the design of non-linear virtual restoring forces in vortex-induced vibrations, which have been part of our AFOSR effort. Some of our other studies looked at direct measurements of efficiency and thrust of a pitching airfoil; the effects of combining active heave with passive pitch (and vice versa); the effect of pivot location for a pitching body; the implementation of "hybrid-heave" motions to increase propulsive performance of an oscillating airfoil or flicking sail.

Our current principal effort is concerned with self-propulsion of combined heaving and pitching airfoils. This is one of the most energetic periods of study in our labs since the CPFD facility was completed. We look at the case where the airfoil is self- propelling forward and also the case where the airfoil is generating lift force to carry, in effect, a "payload". These experiments are studied in Section 4.1 and 4.2 and yield some new phenomena.

2. Cyber-Physical Fluid Dynamics

In general, aside from analysis, there are two major approaches to unsteady fluid–structure interaction problems, one experimental and the other numerical. We call the new approach CYBER-PHYSICAL FLUID DYNAMICS (in Mackowski & Williamson, 2011). CPFD refers to Cyber-Physical systems or Virtual-Physical systems with application to fluid-dynamics studies. It relies on the combination of a physical experiment (the physical side) and a computer control system (the cyber side) to achieve complete, parametric control over the forces experienced by an immersed object (Figure 1). One may imagine a simulation where everything about the fluid-structure interaction is solved on the computer, except that the Navier-Stokes equations and discretized flowfield are replaced by a real body with real fluid!

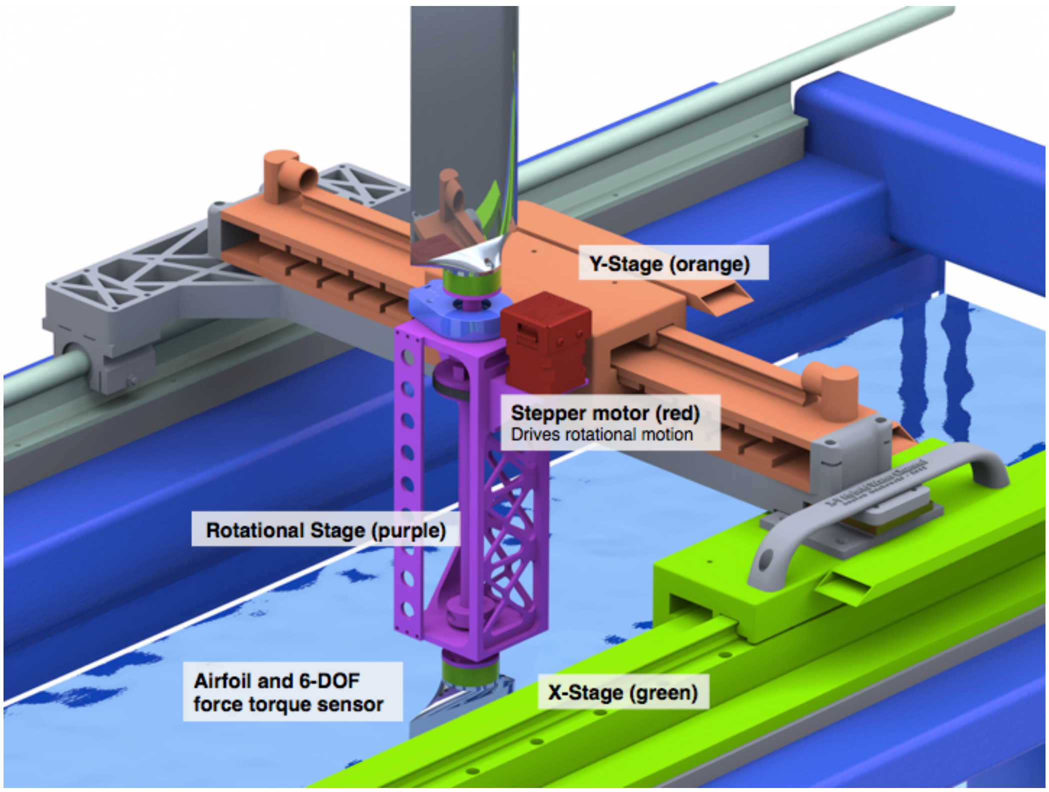

Figure 1. Illustration of the Cornell-AFOSR "CPFD Facility". 2010. High-performance linear actuators allow the vertical airfoil section to translate in the streamwise and transverse directions, and a rotational stage allows for precise movement in the θ direction. Having an airfoil and second transducer on the top of the setup enables subtraction of structural inertia forces and torques.

3. Prior research applying the Cyber-Physical Fluid Dynamics (CPFD) approach to Unsteady Aerodynamics

(PAPER 1) **A.W. Mackowski & C. H. K. Williamson** (2011) "Developing a Cyber-Physical Fluid Dynamics facility for fluid-structure interaction studies". *Journal of Fluids & Structures.* **27**, 748-757.

(PAPER 2) **A.W. Mackowski & C. H. K. Williamson** (2013) "An experimental investigation of vortex- induced vibration with nonlinear restoring forces ". *Physics of Fluids*, **25**, 087101.

Our first two papers **(PAPER 1), (PAPER 2)** demonstrated the "legitimacy," of the cyber-physical technique and implemented the technique on a problem of vortex-induced vibration, with nonlinear restoring forces. The second paper showed how easy it is to specify parameters in the computer rather than laboriously build a physical system with nonlinear springs.

(PAPER 3) **A.W. Mackowski & C. H. K. Williamson** (2015) "Direct measurements of thrust and efficiency of an airfoil undergoing pure pitching". *Journal of Fluid Mechanics*, **765**, 524-543.
In further work, we experimentally investigated the thrust and propulsive efficiency of a NACA 0012 airfoil undergoing oscillating pitching motion about its quarter-chord point. Despite the fact that Garrick first looked at this problem theoretically in 1937, the *direct measurement* of thrust had surprisingly not been done before.

(PAPER 4) **A.W. Mackowski & C. H. K. Williamson** (2017) " The effect of pivot location and passive heave on propulsion from a pitching airfoil". *Physical Review Fluids*, **2**, 013101. This constitutes the first of a pair of studies which have two degrees-of-freedom, one is ACTIVE and the other is PASSIVE, which we now label "ACTIVE-PASSIVE" as distinct from "ACTIVE-ACTIVE" (AA) imposed for example in Triantafyllou's research group at MIT (Read et al., 2003). It turns out that the linear theory proves remarkably useful and agrees well with most of the experimental measurements. In the case where the center of mass is independent of the pivot point, the airfoil's passive movement is the result of a combination of inertial forces and fluid forces. This combination achieves better performance than when the passive motion is only influenced by fluid forces.

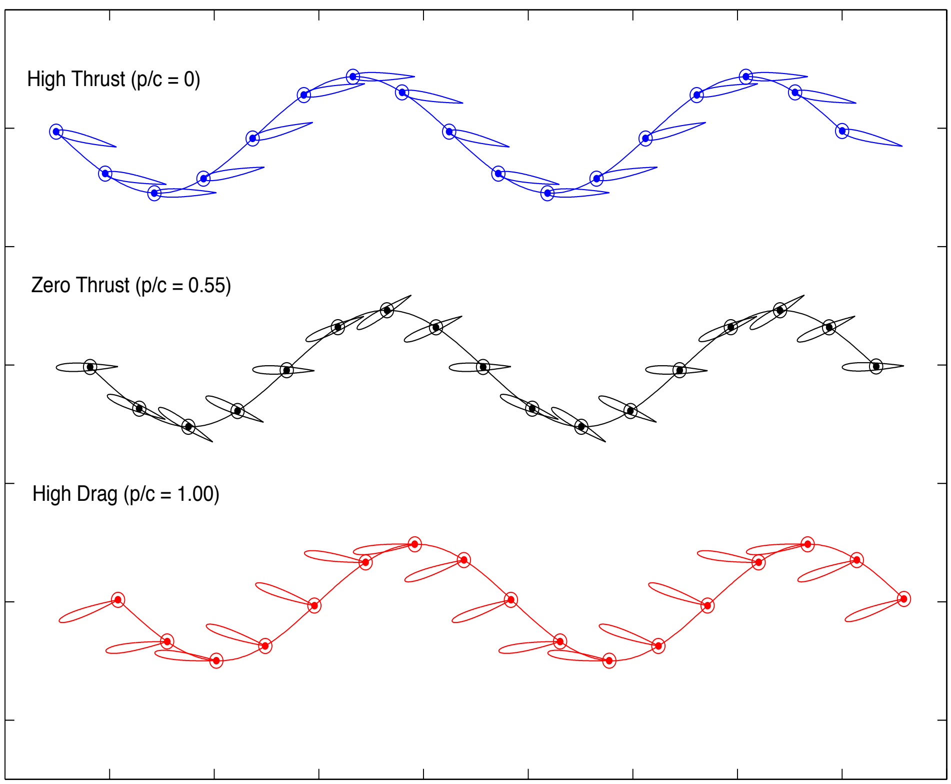

Figure 2. Using Trajectory plots to understand the physics of the flow around the vibrating airfoil. Using such plots, where the observer is fixed with respect to the undisturbed fluid, helps to understand thrust versus drag trajectories. The bull's eyes represent the torsional spring location; zero torque corresponding with a horizontal airfoil. These **unusual** trajectory plots are found in the study of **Paper 4**.

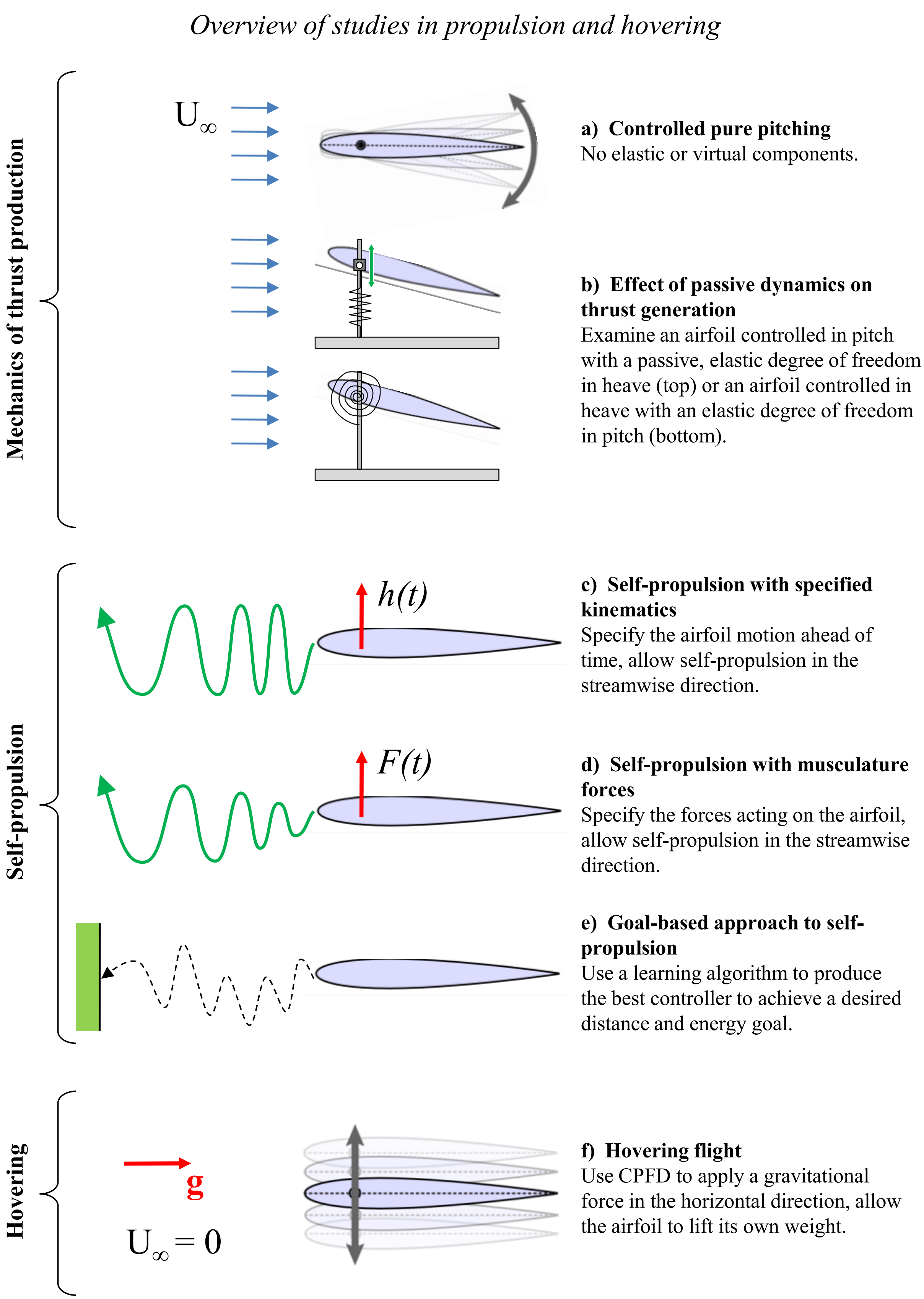

Figure 3. Natural experimental research sequence for unsteady airfoils with passive dynamics.

"Trajectory plots", using reference frame fixed with respect to the far fluid.

In these experiments, one chooses to translate with the fluid, which is moving from left to right. In relative terms the airfoil moves along a trajectory from right to left. This allows the airfoil to follow the sine wave dictated by its heave amplitude (h/c) and wavelength (U/fc). This is the natural reference frame to see the fluid-structure interaction, and to deduce some understanding of the mechanism generating a high thrust trajectory, or a high drag trajectory. In the case here, the bull's eyes represent the torsional spring location; zero torque corresponding with a horizontal airfoil.

Vortex Formation Modes

As expected, vorticity measurements yield, under a wide regime, an "inverse" Karman vortex street, which is essentially a jet downstream, associated with a vortex street advecting the pattern downstream. When the pivot is located *upstream* of the Center of Mass, this vortex pattern is produced and the flow is a jet. The mean velocity field exhibits anti-clockwise vorticity (red) on the upper side, and clockwise vorticity on the lower side (blue) in Figure 4a.

A different vorticity distribution is found when the pivot point is located *downstream* of the CoM. In this case, in Figure 4b, the upper vorticity comprises clockwise vorticity (blue), and the lower red vorticity is anti-clockwise. The resulting vorticity is principally contained in a recirculating region close to the rear of the vibrating airfoil. Interestingly, a vortex street is not generated.

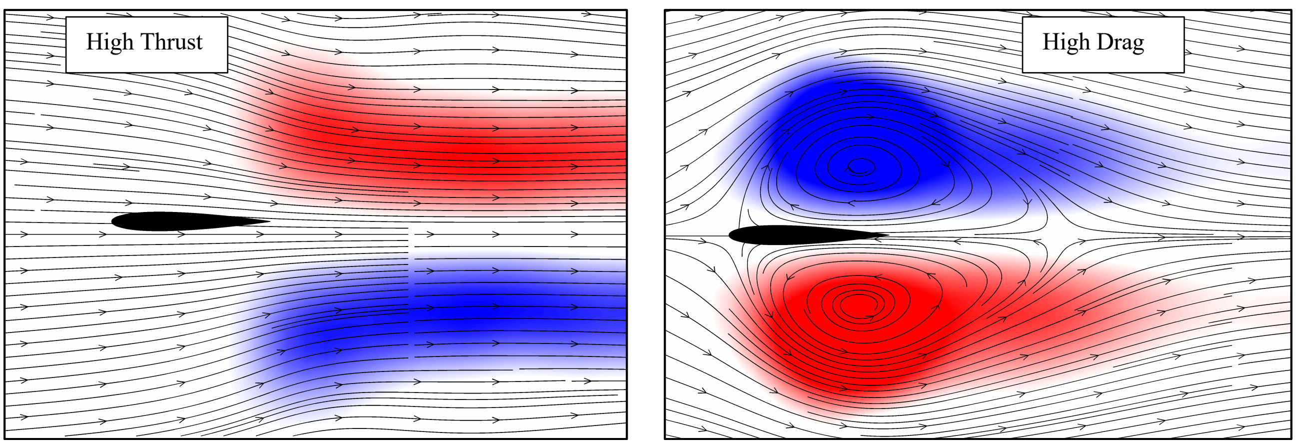

Figure 4. Average flow velocity, and average vorticity plot (a) JET FLOW: Positive Thrust Configuration. The Pivot is ahead of CoM, at leading edge. (b) WAKE FLOW: Negative Thrust Configuration. The Pivot is behind the CoM, at p/c=0.50. f/fN=0.85. Mean vorticity collects in a recirculating region.

(PAPER 5) J. D. Young, S.E. Morris, R.R. Schutt, C. H. K. Williamson (2019) " Effect of "hybrid-heave" motions of a sailing boat on the performance of an oscillating airfoil". *Journal Fluids & Structures*. 89:203–18.

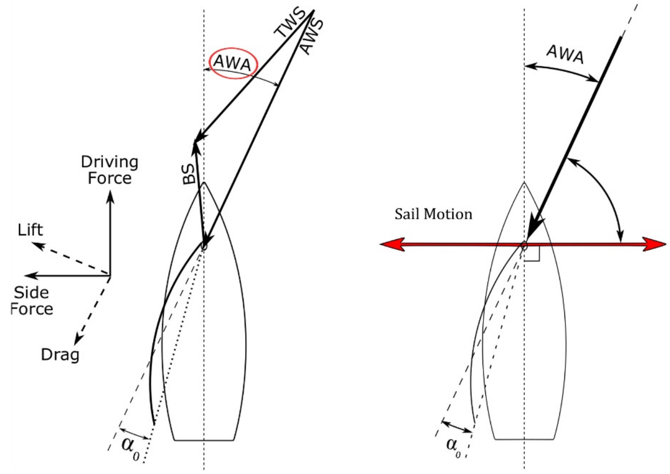

Figure 5. Schematic of sailing boat traveling through water. [Left] The apparent wind speed is the vector sum of the true wind speed (TWS) and the boat speed (BS). Our force of interest, driving force, is comprised of components of lift and drag. Note that we are interested in the angle of attack between the thin airfoil chord line and the apparent wind. [Right] The "sail flicking" motion creates a hybrid-heave oscillation which is non-normal to the apparent wind.

In light to moderate breeze, Olympic sailors generally roll the boat around the longitudinal axis as the boat is also changing direction (for example during a tack). It is the flicking of the sail during the induced motion of the boat that yields the aerodynamic forces that we wish to measure. The combined motion can dramatically increase the driving force of the boat towards the Apparent Wind (AWA in Figure 5).

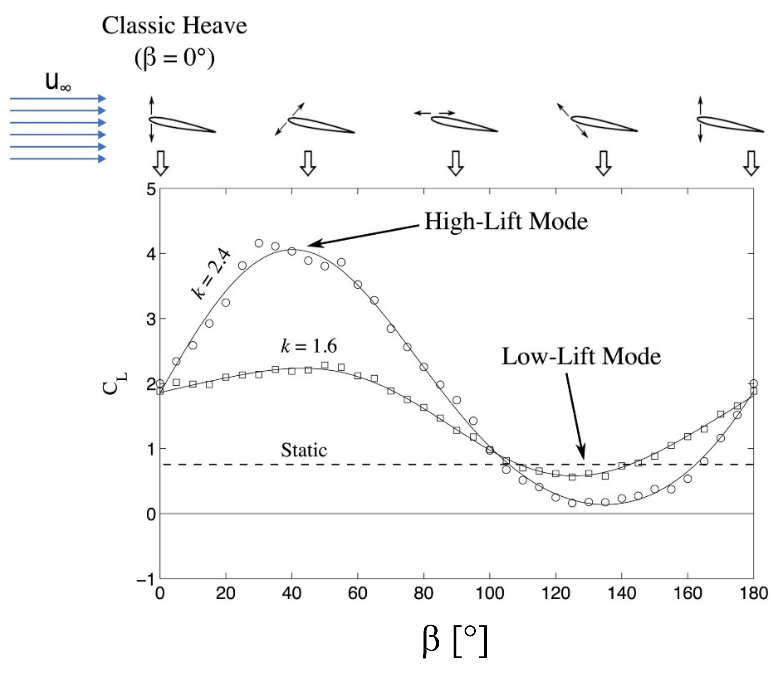

Figure 6. Effect of normalized frequency k on Lift Coefficient. We observe the presence of a "High-Lift" mode which becomes more evident as oscillation frequency (k) is increased. This leads to an amplification 5-6 times the static Lift coefficient for k = 2.4. The low-lift mode can yield lift coefficients less than for the static case.

4. Applying the CPFD Approach to Self-Propulsion

4.1 Self-Propulsion of an oscillating wing.

4.2 Lift generation of a wing in asymmetric self-propelled motion.

4.1 Self-Propulsion of an oscillating wing with specified kinematics (For submission to *Journal of Fluids and Structures)*

Most of the self-propulsion research in the literature has been conducted using CFD due to the difficult nature of approaching this topic experimentally, and the time it takes to conduct these studies. With CPFD, one can run the experiments much faster, and therefore generate more precise and detailed results.

Ultimately, we seek to balance the upstream motion of the airfoil with the downstream motion of the water channel, to thereby keep the airfoil effectively fixed in front of the researcher, in mid test section.

The Heave-Pitch Diagram. The first study here makes use of the simple idea of a "heave-pitch diagram". It is a trivial idea, but it is extremely useful. The first variable to be presented in the diagram is the self-propelled cruising speed of our wing, in the form of a set of contours, in Fig. 7. The data exhibits very good resolution.

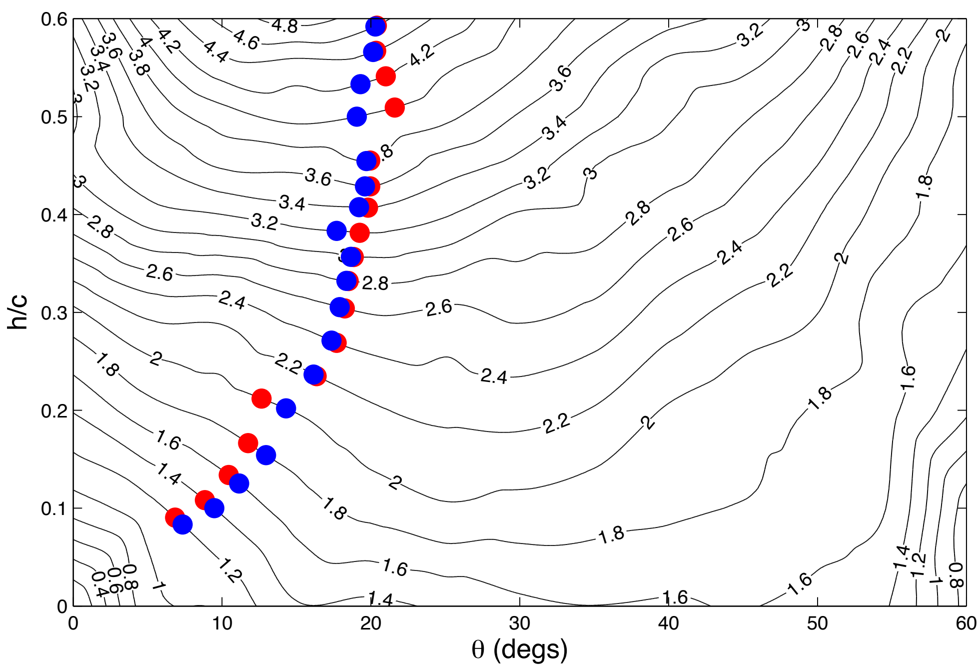

Figure 7. Heave-Pitch diagram, showing Contours of normalised velocity with points indicating maximum propulsive economy (red) & minimum transverse impulse (blue). Some Red symbols are hidden by corresponding blue symbols.

If the goal is to move upstream from A to B, we can select a cruising velocity (one of the contours in Fig. 7), and ask:

- **How much does it cost to go that fast ?**
- **What is the most economic way to travel from A to B at a selected speed ?**

We can readily move along each contour looking for a maximum in "propulsive economy". These experiments result in the red symbols in Figure 7. The locus of red symbols is called the "optimal curve".

The intersection of Propulsive Economy contours with velocity contours, both of which are in the heave-pitch diagram of Fig. 8, illustrates how the overlapping contour plots yield the special optimal curve of maximum efficiency in the heave-pitch diagram.

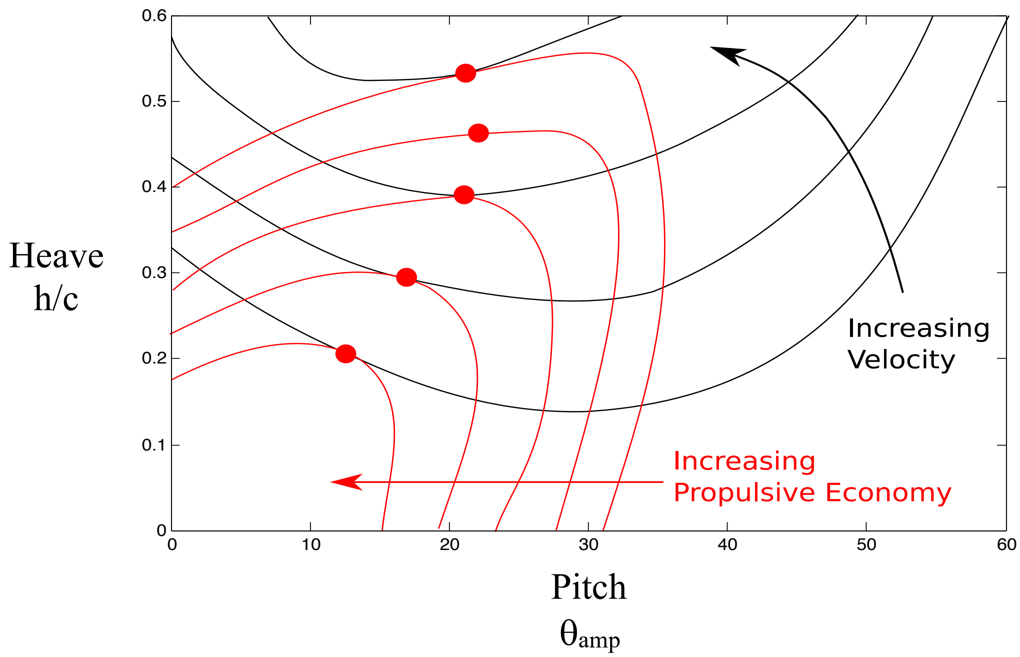

Figure 8. **Heave-Pitch diagram showing the maximum propulsive economy for a given velocity** is found by observing the point along the velocity contour at which the economy is maximized. (These are the red dots.)

- **What is special about the optimal case: What is the physical mechanism behind these results?**

Now we can look at the vortex formation as the airfoil sweeps up and down, generating the tall vortical structures in Figure 9(a). It is immediately noticeable that for the optimal conditions the vortices shed cleanly and travel downstream from the trailing edge of the body, with no evidence of any Leading Edge Vortex (LEV) formed during the periodic motion.

- **The special characteristic of the optimal case is the absence of an LEV above the airfoil, minimizing the wasted circulation.**

We can go on to make a contour plot in the **heave-pitch diagram** of maximum angle of attack over a cycle (α_{MAX}) experienced by the airfoil, in Figure 10. Note that this angle of attack is not the pitch angle; it is the maximum angle, over a cycle, between the instantaneous body motion vector and the incoming flow velocity vector.

We see straight away that the "optimal curve" now marks a line of α_{MAX} close to 18 degrees along almost all of the length of the optimal curve (Fig. 10). We can recall from the book by Abbott and von Doenhoff (1959) that for a steady NACA 0012 airfoil, it stalls sharply at 16 degrees. We can imagine that critical α_{MAX} for LEV formation will be greater in this unsteady situation, where critical α_{MAX} is exceeded only temporarily during each cycle. These are **unsteady aerodynamics** - there is a time delay for the flow to separate into a concentrated vortex after a sudden pitch-up, hence it seems the flow delivers an α_{MAX} to maintain attached flow, which can be somewhat larger than the steady stall angle of 16° in Abbott & von Doenhoff (1959).

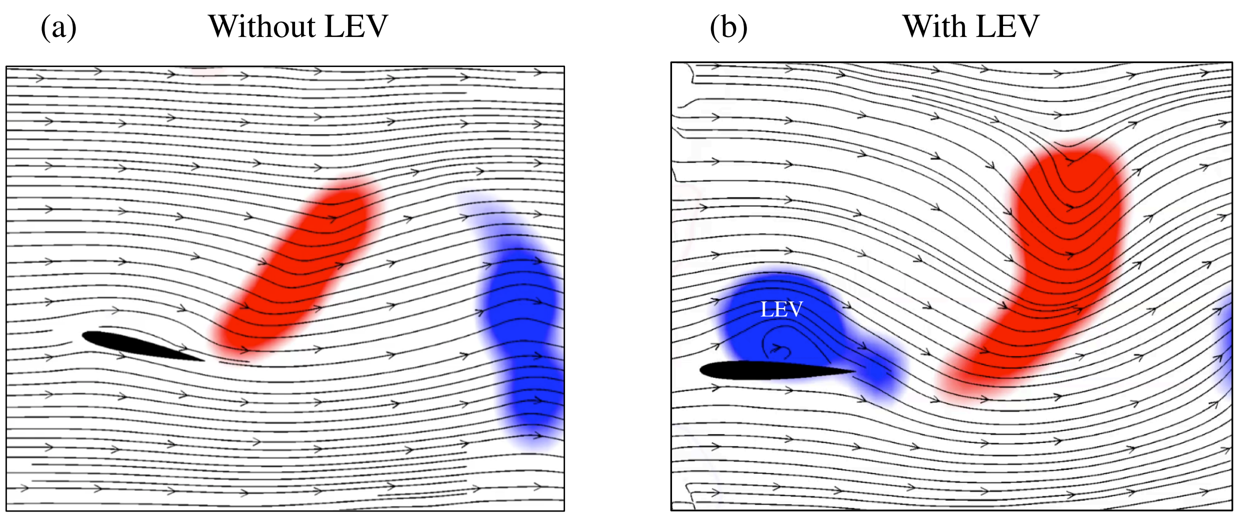

Figure 9. (a) Vorticity contours for the case of optimum propulsive economy. There is no apparent leading edge vorticity. (b) In contrast, sub-optimal pure heave exhibits an example of a discernible leading edge vortex.

To either side of the optimal curve, we find a dominating LEV (see Figure 9b). This is consistent with measurements of circulation in Figure 11. For example, to induce the same cruising velocity, the pure heave case has to produce 300% greater circulation, compared with the optimal curve measurements, so there is extensive **<u>wasted circulation</u>** ! Most of the waste goes into the Leading Edge Vortex.

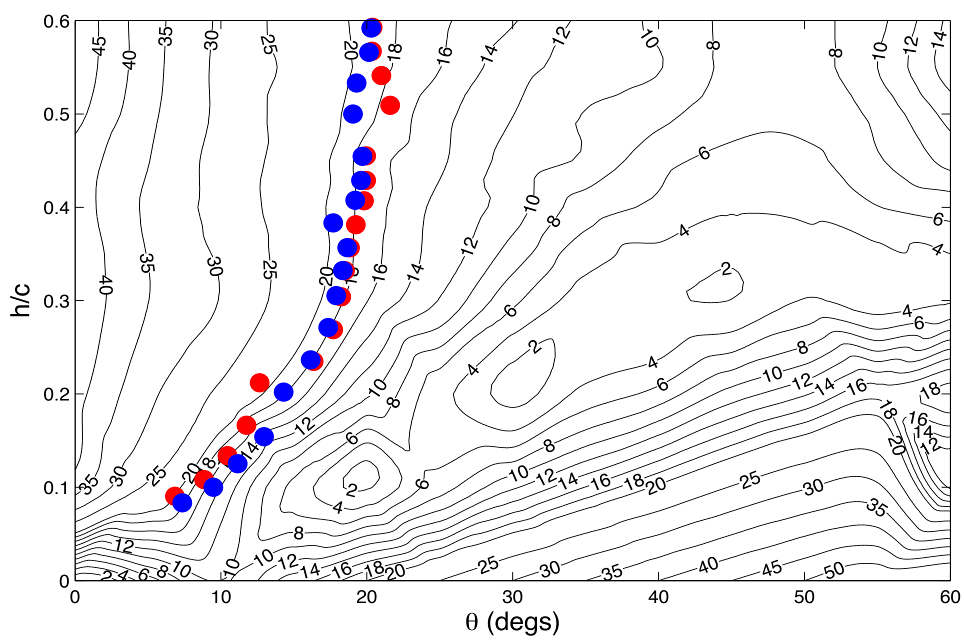

Figure 10. **<u>Heave-Pitch diagram, showing contours of maximum angle of attack during a cycle,</u>** as a function of heaving and pitching amplitudes with points indicating maximum propulsive economy (red) and minimum transverse impulse (blue). Some Red symbols are hidden by corresponding blue symbols. The optimum angle of attack is close to 18 degrees, which is on the borderline when leading edge separation and an LEV is expected to form.

<u>We deduce that maximum efficiency occurs for a minimum of leading edge vorticity shed into the flow in the form of an LEV.</u>

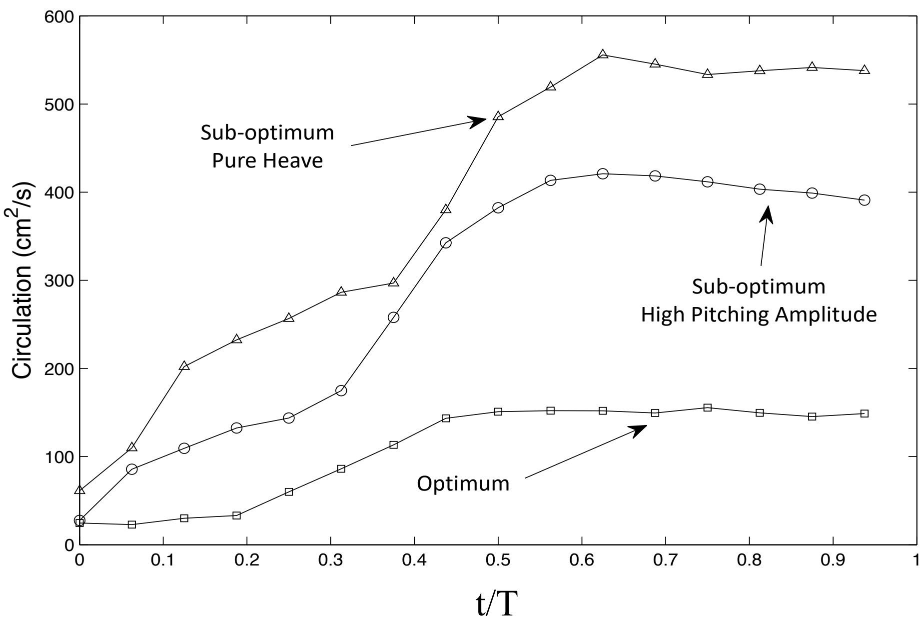

Figure 11. Circulation generated by the airfoil as a function of normalized time for the three cases, which includes "Optimal". When the motion profile is suboptimal, the total circulation is much higher, indicating that energy is being used to generate vorticity that does not contribute to propelling the airfoil in the desired direction.

<u>The optimal motion of the airfoil is one which minimizes the amount of energy expended per unit travel of the wing.</u> It is one where the wing maximizes the angle of attack of the incident flow but does not go beyond an angle (18 deg) where there is leading edge separation and formation of a Leading Edge Vortex (LEV).

4.2 Lift generation of an unsteady wing in self-propulsion

Our ongoing line of research aims to understand the mechanics of self-propulsion in the context of flight. In order to achieve flight and carry a payload, our flapping wing must generate a lift force. For the static wing, this is achieved by the introduction of an asymmetry into the problem – for example, a nonzero angle of attack or a cambered airfoil. For the unsteady wing, we generate lift by offsetting the pitching trajectory by an angle θ_{off}.

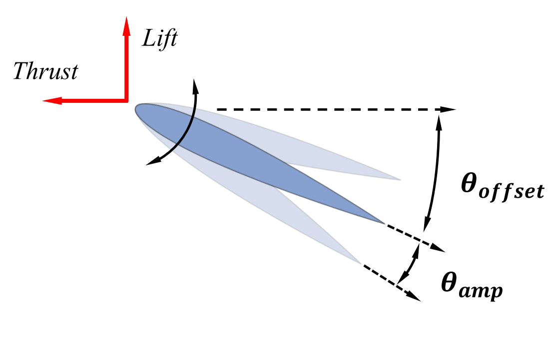

Figure 12. We develop a basic premise for an unsteady wing to pitch asymmetrically and generate both thrust and lift. In our *Symmetric Self-Propulsion* studies, transverse and rotational motion trajectories are symmetric, often yielding the well-known *reverse von Karman Street wake* and no net lift force over a cycle. By forcing asymmetry with the use of a pitching offset, our unsteady wing will generate *both thrust and lift*.

From symmetric self-propulsion (see Section 4.1), we learn that the optimum way to travel at a given velocity is when the maximum instantaneous angle of attack α_{MAX} is approximately 18°. For significantly larger values of α_{MAX} (e.g. the purely heaving airfoil) we find the following :

- **The airfoil begins to form discernable LEVs on both upstroke and downstroke.**
- **The airfoil experiences significantly larger transverse forces that are detrimental to efficiency.**
- **These larger transient lift forces are due to the LEVs acting as a low-pressure region on the surface of the airfoil – consequently, we refer to these LEVs as "wasted circulation".**

When it comes to generating *both propulsion and lift*, there are naturally tradeoffs associated between the two. However, based on our prior studies we hypothesize that we can manipulate the motion of our airfoil such that LEV formation only occurs on one side, thereby leveraging what used to be "wasted" circulation into "useful circulation" that generates lift. The existence of an LEV on *only one side of the airfoil* should yield larger net lift forces and its elimination on the opposite side should improve propulsive efficiency.

It is well documented and intuitive that maximum propulsion and maximum efficiency do not occur for the same motion configuration (in a similar vein, one will generally achieve better gas mileage while driving slower). The *Symmetric Self-Propulsion* study enabled by our CPFD facility has the unique advantage of being capable of determining the point of maximum efficiency *for a given velocity*. Because we are now introducing Lift, into this problem, we must now concern ourselves with the **tradeoffs** between all three results: *Normalized Velocity, Propulsive Economy, and Lift.*

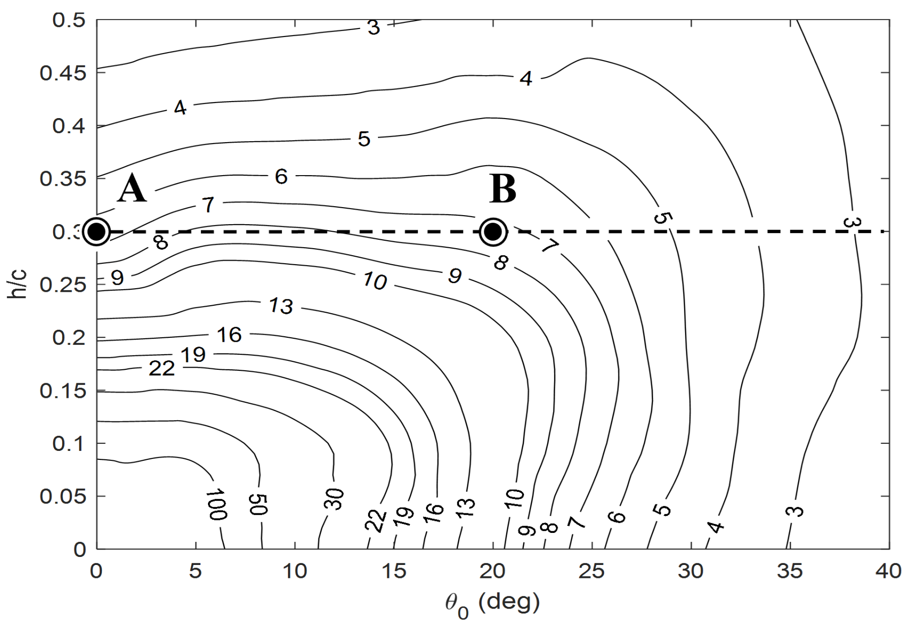

Figure 13. <u>Heave-pitch diagram, showing contours of Propulsive Economy</u> ($\eta = \overline{U}/\overline{P_{in}}$). The diagram qualitatively resembles the Propulsive Economy heave-pitch diagram from the symmetric self-propulsion study but shows quantitatively lower values for economy. Because we *cannot* by nature find maxima in Velocity, Lift, and Propulsive Economy at the same point, we must instead *characterize the tradeoffs* between the three. Red horizontal line shows the constant heave amplitude used to demonstrate these tradeoffs

To understand the flow physics that give rise to the tradeoffs between the results of interest, we consider a 'slice' of constant heave amplitude across the heave-pitch diagram, exemplified by the dashed line in Figure 13. Specifically, we look at two **cases A and B.**

		h/c	θ_{offset}	θ_{amp}
Case A	Pure Heave	0.3	15°	0°
Case B	Mild Pitching	0.3	15°	20°

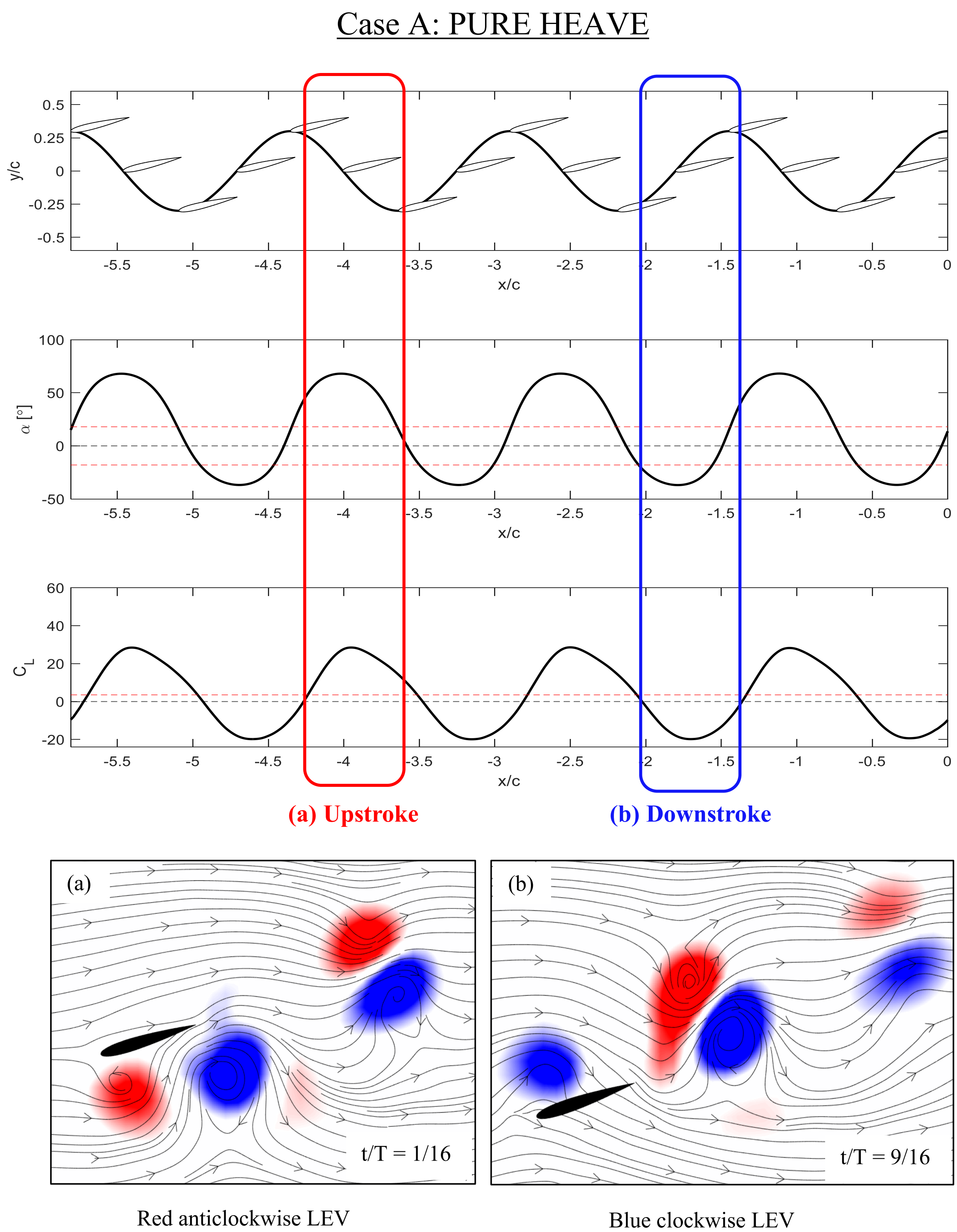

Figure 14. *Case A - Pure Heave. In (a) the heave amplitude and the pitch offset are kept constant* (h/c = 0.3, $\theta_{off} = 15°$)*, while the pitch amplitude is set to zero.* During the upstroke (a), the airfoil moves through the fluid at a relatively high incident flow angle, resulting in the formation of a red LEV under the airfoil at the end of the half cycle. On the downstroke (b), we observe similar net values of lift force as the airfoil once again moves through the flow at a high angle of attack resulting in a complementary blue LEV. The overall lift coefficient plot exhibits evident force cancellation over a cycle.

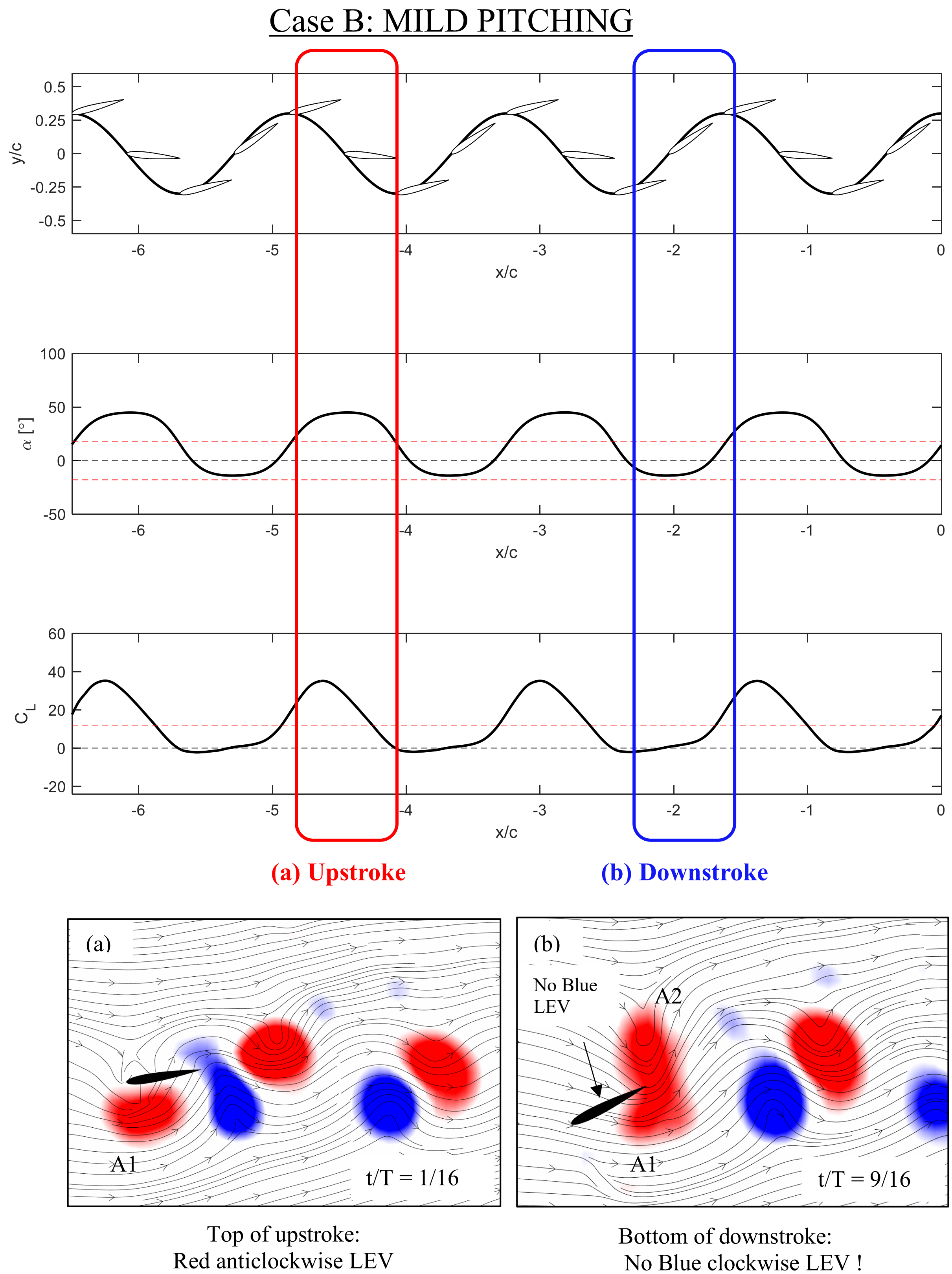

Figure 15. *Case B - Mild Pitching.* (h/c = 0.3, $\theta_0 = 20°$, $\theta_{off} = 15°$). During the upstroke (a), the airfoil assumes a high angle of incidence relative to the trajectory. However, on the downstroke (b), the airfoil aligns well with the trajectory, and the pitch angle is distinctly low, leading to a strong asymmetry of the lift force and a significant plateau of low lift force in each cycle. We find no blue LEV on the upper surface of the airfoil at the end of the downstroke.

These cases show that one can in effect "design" the flow around the airfoil. With an understanding of the underlying physics of the flow, we can enforce two *different* flow regimes within a cycle, leveraging our vortex formation modes to optimize force production.

In *Case A*, the pure heave case, we observe the formation of LEVs on *both upstroke and downstroke*. According to our heave-pitch diagram for a heave amplitude of h/c = 0.3, the pure heave case corresponds to minima in lift ($C_L = 3.5$), normalized velocity ($U^* = 1.4$), *and* propulsive economy ($\eta = 6.6\ m/J$). We can understand the dynamics behind this relatively weak performance by again returning to our trajectory plots at the top of Figure 14.

By forming an LEV on both upstroke and downstroke respectively, the airfoil will experience significant transverse forces during both half-cycles. However, these transverse forces act in opposite directions to one another, resulting in a *force-cancellation effect*. Consequently, the *net lift* generated over the cycle is near zero. Because our near-body vortex formation mode is mirrored between upstroke and downstroke, we are effectively operating in a regime that is similar to the purely heaving symmetric airfoil (Figure 9b). Our LEVs are cancelling one another out, and we are once again left with *wasted vorticity.*

Can we leverage our vorticity to be useful, rather than wasted ?

As we introduce pitching, we begin to observe the LEV being formed on *only the airfoil upstroke***.** There is no discernible LEV formed on the downstroke. This behavior can be understood by examining the trajectory plots for *Case B*.

Upstroke Mechanics: By moving through the flow on the upstroke at an angle more normal to the trajectory, the airfoil produces a red LEV and is subject to a large transverse force that can be seen highlighted in red in the bottom plot of Figure 15. We view this upstroke as a *force-producing stroke*, augmenting force by the same mechanism as introduced in Figure 9a.

Downstroke Mechanics: In contrast, the downstroke will move through the trajectory at a streamlined angle of attack and will *not* form the complementary blue LEV. We take the view that this stroke serves as a *recovery motion* that allows the airfoil to return to the original position without experiencing significant transverse forces. Afterwards, the airfoil is once more in position to make another, force-producing stroke.

We find that this motion configuration yields greater values for lift ($C_L = 12.0$), velocity ($U^* = 1.63$), and propulsive economy ($\eta = 12.98$ m/J) than Case A, pure heave. This leads to the interesting question:

Can we show, *in general*, that this vortex formation regime, which forms only one LEV in the cycle, will be more optimal than the regime which forms two LEVs?

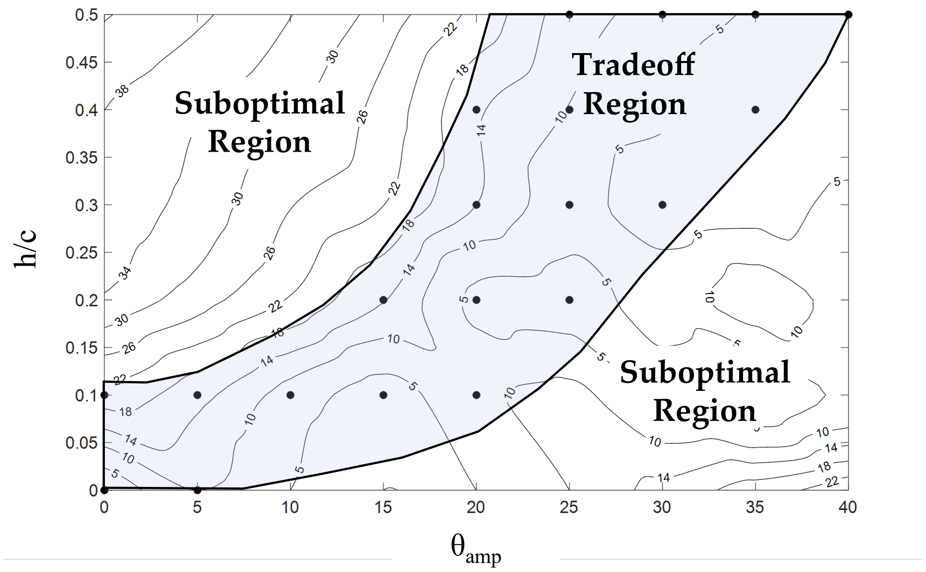

Figure 16. Heave-Pitch Diagram of Maximum Angle of Attack on *Downstroke*. Through a grid search, we identify *suboptimal points* within the diagram. The remaining points are *non-suboptimal points* and are marked as the red points within the Tradeoff Region. It can be seen that the border between the Tradeoff Region and Suboptimal Region coincides with the 15-18 degree contour, again suggesting the necessity of keeping angles of attack moderate to low to eliminate forming the LEV !

In order to understand our data and these flow physics in a more generalized sense, we numerically search through the data grid that comprises our Heave-Pitch Diagram and identify all test points that will be *strictly suboptimal* relative to another. For instance, because Case A is outperformed by Case B in all three performance metrics, we can deem Case A *strictly suboptimal* and place it within the suboptimal region. This methodology is used for all points in the Heave-Pitch diagram such that we are able to identify our three regions.

Similar to **Symmetric Self-Propulsion (4.1)**, we observe the importance of avoiding *wasted circulation*. But because we are also interested in generating a net lift force across a cycle, the situation is slightly more nuanced than simply stating that LEVs are strictly detrimental to the airfoil's performance. Instead, we find that we can form an LEV on one half cycle to *augment* our lift force and avoid forming the complementary LEV on the other half cycle to *avoid wasted vorticity* (Figure 15). If the airfoil's angle of attack on both strokes exceeds a threshold value (Figure 16), we once again find ourselves in a regime with *wasted vorticity*, as the complementary LEVs on both strokes will effectively cancel out and fail to augment the net lift force (Figure 14).

It is clear that the wake structure in the lift-producing case contrasts with the symmetric case – can we clarify the "signature" of this flow?

In Figures 14 and 15, we observe that the oscillating airfoil, with an offset pitch, forms a vortex pair in each cycle. In general, we also find that the formation of these vortex pairs occurs throughout our parameter space and is a point we would like to understand further.

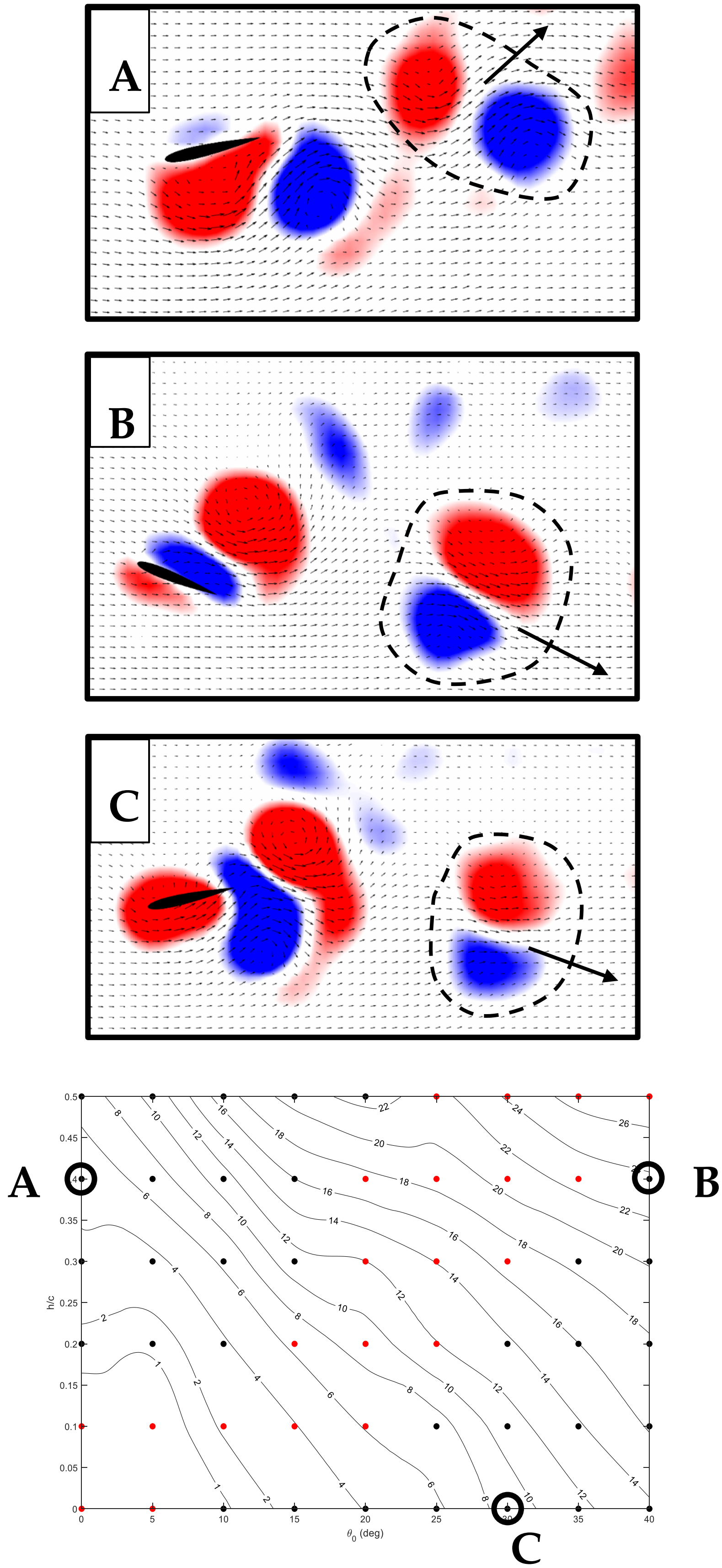

Figure 17. Examples of test points at opposite ends of the Heave-Pitch diagram that both shed vortex pairs, the characteristic feature of this flow. (a) h/c = 0.4, $\theta_0 = 0°$, $\theta_{off} = 15°$. (b) h/c = 0, $\theta_0 = 30°$, $\theta_{off} = 15°$.

5. Further areas of investigation

In the research described above, we describe work which is concerned with comprehensive force measurements, simultaneous vorticity measurements and flow visualizations for an airfoil undergoing combined heave and pitch motions. Despite the fact that there is an overwhelming quantity of work that has been carried out in fluid-structure interaction, or specifically fluid-airfoil aerodynamics, our particular approach has made it possible to explore and discover new aspects of these flows. We are led to many new questions.

Potential further areas of investigation within these research thrusts includes (but is not limited to) the following bullet points.

At the core of our studies is the Cornell-AFOSR Cyber-Physical Fluid Dynamics (CPFD) facility, that enables us to experimentally analyze a wide range of fluid-structure interaction problems.

- (1) Employing the CPFD facility, we are able to emulate a “self-propelled” airfoil, wherein the airfoil is free to move in the streamwise direction (as well as move in heave and pitch). By virtue of this approach, we are able to take an *energetics* viewpoint on the flow, asking how can one optimally travel from point A to B. We find that elimination of LEVs tends to guide the system towards optimal flow conditions. We have results which suggest scenarios where the presence or absence of LEVs can serve to “control” the ensuing force on the airfoil. **How robust is this manipulation, and how much control can be imposed ?**

- (2). We take the viewpoint that LEVs constitute a significant amount of the circulation that can be considered as “wasted circulation”. It is “wasted” in the sense that substantial vorticity is generated which does not take part in creating thrust. **Can the change in circulation over time be more rigorously quantified and related with the force or impulse to which the airfoil is subjected ?**

- (3). By introducing an offset into the airfoil’s trajectory, our airfoil produces a force that is now capable of carrying some sort of “payload”. We find that for certain motion trajectories, our airfoil will only form LEVs on *only one of its two strokes*, resulting in a flow regime that augments our lift forces - thereby leveraging our once “wasted circulation” as “useful circulation” that serves to augment our lift forces. **Going forward, can motion trajectories be imposed and expect the LEV formation mode a priori ?**

- (4) We find that both the symmetric and asymmetric unsteady airfoil flows yield distinct wake vortex dynamics. In the former case, we largely observe inverse von Karman streets while in the latter, we observe vortex pairs. The shed vortex pairs contribute to a more unsteady jet downstream of the airfoil. **Can the strength and direction of these pairs be related to the ratio of thrust and lift on the airfoil ?**

- (5) Taking the viewpoint that these wake vortex dynamics are effectively remnants of the upstream fluid-body interaction, can we begin to understand the physical linkage between body dynamics and wake dynamics ? **In so doing, can an organizational categorization of the “signatures” begin to form for this family of flows ?**